# University of Southampton

Faculty of Engineering and Physical Sciences

School of Mechanical Engineering

## Modelling Tribological Processes to Examine the Lives of Bronze Age Palstave Axes

### Volume 1 of 1

by

**Miriam Grace Andrews**

Thesis for the degree of Doctor of Philosophy

January 2021

# University of Southampton

## Abstract

Faculty of Engineering and Physical Sciences
School of Engineering

## Doctor of Philosophy

## Modelling Tribological Processes to Examine the Lives of Bronze Age Palstave Axes

by Miriam Grace Andrews

There have been few attempts to conduct sequential and highly-controlled experiments in the laboratory, to isolate how wear formation processes propagate on metal artefacts during simulated use. It was the aim of this research, therefore, to establish a multi-method approach to model the progression of surface wear and the appearance of major deformation phenomena on replica palstave axes, for the purpose of clarifying the use-intensity of their prehistoric counterparts. There is much uncertainty regarding the role of palstave axes; they very likely facilitated ongoing forest clearances, yet, expressed often in hearsay, is the 'pristine' nature of their recovery condition. This project involved using a drop tower (Instron CEAST 9350) to conduct experiments on replicas with several alloy compositions and post-production processing, to study the sequential development, form, and properties of surface wear and major deformation phenomena, in isolation from interfering variables. The analysis variably included photography, low-power microscopy (digital), high-power microscopy (SEM), and microhardness indentation. The results have demonstrated that the wear manifested at the cutting-edge of replica palstave axes during use can be successfully tracked by mechanical testing and sequential analysis. A better appreciation of underlying metallurgy, combined with insight from the experimentation with replica palstave axes, has permitted a more nuanced evaluation of wear characteristics and use-intensity of prehistoric palstaves. This, alongside damage assessment and available contextual data, has allowed the life trajectories of 102 ancient palstave axes to be determined, highlighting the considerable variability of their biographies.

Contents

## List of tables

## List of illustrations

# Author's declaration

Print name: Miriam Grace Andrews

Title of thesis: Modelling Tribological Processes to Examine the Lives of Bronze Age Palstave Axes

I declare that this thesis and the work presented in it is my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

   Andrews, M., Polcar, T., Sofaer, J. and Pike, A.W., 'The Mechanised Testing and Sequential Wear-Analysis of Replica Bronze Age Palstave Blades'. *Archaeometry*.

Signature:                                                            Date: 05/01/2021

# Acknowledgements

First and foremost, I would like to express my sincere gratitude to my main supervisor, Professor Tomas Polcar, for having the vision to bring together this interdisciplinary project and providing much invaluable enthusiasm, patience, and guidance throughout the last several years.

Additionally, I would like to thank my co-supervisors, Professor Jo Sofaer, and Professor Alistair Pike, for their exceptional teaching during my undergraduate degree and for supplying vital encouragement and expertise during my PhD studies.

My thanks also goes to Dr. Andy Robinson, Dr. Geoff Howell, and the EDMC staff, for their willingness to provide technical and practical support.

A massive thank you goes out to Jim Clift, who not only assisted me in producing all my experimental samples but also acted as a mentor and a key source of encouragement throughout my studies. I would like to thank Peter Northover for offering the chemical composition data for palstave axes from the south-west of England and for permitting me to analyse the associated mounted samples – my PhD would have turned out much for the worse without his generosity. I would also like to thank the staff who facilitated my museum visits, particularly Gemma Plumpton, Gail Boyle, Sarah Lloyd-Durrant, Thomas Cadbury, Janine Fox, Richard Breward, Michael Nendick, Ann Tanner, Nicholas Crowe, and Amal Khreisheh.

The depth of gratitude I feel towards family and friends for getting me to this point is absolutely immeasurable. Firstly, to my close family, Grandad, Mary, Colin, Nai, Daniel, Katrina, and Stu – thank you for always having faith in my abilities and for providing a pillar of unwavering support throughout my life. I am also so very grateful for the wonderful friendships I have formed with my fellow PhD colleagues, Heather Brown, Maria Thanaj, and Kamran Esmaeli, throughout the last few years. And, to Dr Joe, who I have shared my entire University of Southampton career with – I would not have wanted to revel in the wonderful euphoria and tragic hilarity of the last few years with anyone else. Sorry to anyone who has had to live with me during my PhD studies, especially Ben, Elle, and Rob. You all deserve a medal for your patience.

# 1 Introduction

## 1.1 Research problem

Artefacts are the most important source of evidence used by archaeologists to reconstruct the past. They are, however, often treated as static entities – tied to their location of final disposal with no sense of their existence prior to concealment within the ground. The reality is, of course, that most objects present within the archaeological record hide a rich history of human-substrate interactions that were negotiated throughout elements of their life, for example, during the procurement of raw materials, design, manufacture, use, maintenance, curation, and deposition. While all of these stages provide a unique perspective into the behaviour of past humans, the treatment of an object throughout its period of consumption (use) has the potential to provide a direct expression of how its meaning was embedded within society [1]. A valuable method for deciphering the application of an object in any given culture is the investigation of wear generated on the item during use [2, p. 1038]. Wear is the culmination of deformation and chemical processes at the external interface of a material when it is in relative motion with the surface of another substance [3, p. 313]. The manner and severity of this malformation on the exterior and interior of a prehistoric artefact can retain vital suggestions as to how the artefact contributed to the human world [4, p. 174].

Although examination of wear on archaeological material has been routinely applied to stone and bone items, metal objects have not received as much attention. In fact, the complexity involved in studying a material of which the properties are so incredibly altered by compositional differences, manufacture, reshaping, recycling, and corrosion, has led to a relative reluctance to investigate metal artefacts for evidence of wear [5, p. 120]. Despite these difficulties, a centralised approach was eventually formed for the use-wear analysis of metal artefacts. This has involved the simulation of task(s), by which wear was induced on the object in the past, during experimental trials with replicas, and the creation of a repository of marks to identify similar features on corresponding ancient specimens [2], [5], [6], [7], [8], [9], [10], [11]. Nonetheless, even with the recent development of more robust methodological frameworks, much of the use-wear analysis exacted on metal prehistoric items is reliant on the ambiguous classification of surficial features. Furthermore, the development of use-wear research methodologies new and old has been focused, almost exclusively, around the functionality of objects and tools [12, p. 79]. This narrow focus of inquiry has left substantial lacunae within the current appreciation of the importance of metals in past societies.

For example, there have only been minimal attempts to conduct sequential and highly-controlled experiments in the laboratory to isolate how wear formation processes propagate on the artefact during simulated use [8] [10]. Archaeological objects are likely to fall somewhere along a spectrum of use, from 'unused', to 'extensive use'; it makes little sense, therefore, to only use data retrieved from terminus replicas as a reference collection. In most cases, consequently, it is still not possible to differentiate metal artefacts that were in everyday use from those barely used and with a ceremonial function. As a result, the available insight into the biographies of past metals is restricted. Rather than simply asking, 'how was this object used in the past...?', surely we should also be seeking an answer to, 'how do the wear markers on this object progress during use?'. These observations can then be used to gain insight into the human-substrate relationship, and may potentially be used as a direct comparison to assess how *intensely* objects were used. To make the exploration of this question possible and enable quantitative investigation, it is necessary to consider the modification sustained to the object during both application and re-working. Thus, this project takes a materials science and engineering approach to attempt to investigate a fundamental dimension of use – the total amount sustained by the artefact – which has, here-in, been termed the 'use-intensity'.

Although in many respects, the present project hopes to enter untouched territory by developing novel methodological approaches, it also continues to build on previous work conducted in relation to the use-wear of Bronze Age metalwork from Britain. To be more specific, the objects at the centre of the present study are palstave axes originating from Bronze Age Britain and Ireland. The boundary implied by 'Britain and Ireland' here, is an attempt to restrain the research to an area with fairly synonymous customs and axe-morphology, though a large amount of regionality is still certainly expressed within this delimitation. The palstave axe was a ubiquitous form of axe found across the British Isles and continental Europe between the period 1500 BC and 1000 BC. Unlike both flat and socketed axes, palstave axes have never been subjected to use-wear analysis. This is, in part, related to the 'pristine' condition that palstave axes are often said to be found in, as well as long-standing ideas about their possible multi-functional purpose. If anything, such perceptions work only to raise the potential for fascinating revelations about the use of these objects, further substantiating their suitability for highly-controlled sequential experimentation and subsequent use-wear analysis. With so little currently understood about how the lives of palstave axes transpired within the Bronze Age, the addition of scientifically-grounded metalwork wear-analysis to the techniques available for extracting data from archaeological material, has the power to inform the synthesised life accounts of these objects in ways that challenge how they are thought about entirely.

## 1.2   Aims

The initial objective of this research is to establish a multi-method approach to model the progression of surface wear and the appearance of major deformation phenomena (e.g., bending/nicks/flattening events that are visible to the human eye) on replica palstave axes, for the purpose of clarifying the use-intensity of their prehistoric counterparts. This has involved using a drop tower to conduct experiments on replicas with several alloy compositions and types of post-production processing, to study the sequential development, form, and properties of surface wear and major deformation phenomena in isolation from interfering variables. Thus, the analysis of surface wear has variably included low-power microscopy (digital) to examine the rate at which striations appear at the cutting-edge, high-power microscopy (SEM) to identify the nature of these wear formation processes, and surface microhardness indentation to investigate the changing mechanical properties. The analysis relating to major deformation phenomena has involved photography and macroscopy to record the frequency and form of deformations at the cutting-edge, while metallographic techniques are employed to investigate the internal microstructural modification when deformation occurs. Some of these data outputs were intended as referential tools for use-wear analysis, while others assume more of an explanatory role in terms of accounting for the response of the material.

Subsequently, the resultant insight of the experimental work may be used to generate more nuanced accounts about use-intensity within the narratives of palstave axes from the south-west of England and across the British Isles. The metallographic samples pertaining to 112 axes were analysed or reviewed, and use-wear analysis was conducted on each corresponding artefact. The generation of the aforementioned experimental data presents a very unique opportunity for the differences in use-wear conferred by varying metallurgy to be taken into consideration properly. The manufacturing processes (evident from the metallographic samples), typology, use-intensity data, indications of damage, and any records about the provenance, are used to construct narratives for each specimen. This has allowed trends within the manufacture and the amount of use experienced by palstave axes, as well as the 'common' life trajectory, to be suggested. In addition, by dealing with each individual narrative independently, the analysis has highlighted the variability and diversity that exists within the lives of palstave axes. The data was also used to assess the bringing together of palstave axes with a variety of life trajectories for intentional deposition, and investigate what this demonstrates about the Bronze Age world view. Such ideas can be used to challenge modern rationalist views about the range and importance of embedded meanings within supposedly 'utilitarian' objects, in the past.

The precise research questions that relate to the aims delineated above are as follows:

➢ How does the use of mechanical testing and sequential laboratory analysis of replica Bronze Age palstave axes elucidate the progression, form, and properties of the surface-level wear and major deformation phenomena that appear as a response to increasing use-intensity?

➢ Using the insight produced by the experimental data here-in, to what extent can the archaeological data regarding metallurgy and use-intensity, be used, alongside damage and deposition characteristics, to identify general trends and outliers within the life trajectories of palstave axes?

➢ What is the potential for the results of the above, to support or challenge established arguments, and inform new ideas, about the relations that palstave axes helped to maintain within the society of Bronze Age Britain?

## 1.3    Approach

In order to frame the research project within a relevant discussion, Part One (Chapters 2, 3, and 4) provides a substantial literature review and background commentary. Chapter 2 discusses the archaeological perspectives that pertain to the study of the lives of prehistoric bronze axes, thus contextualising the development of these objects within the society of Bronze Age Britain, and suggesting the lines of inquiry that have been taken to investigate and bring 'life' to the narrative of such artefacts. From this review, it should become clear why palstave axes have been chosen for the present investigation and how the outcomes of this research may be used to inform the biographies of these artefacts further. Chapter 3 assesses the methods that have previously been employed during the investigation of wear on archaeological material, emphasising the necessity for new directions that consider and draw upon the knowledge and methods that are made available through materials science. This critique demonstrates the necessity for mechanised experimentation and an enhanced consideration of metallurgy, in addition to the adoption of new analytical techniques that allow the diversification of data collection. Chapter 4 introduces the scientific perspectives that comprise the study of prehistoric bronze in relation to Bronze Age axes, thus setting the scene for the mechanical attributes of this material. The aim of this section is to familiarise the reader with the key scientific concepts that are essential for understanding the tribological response of bronze.

The novel experimental work is addressed in Part Two (Chapters 5 and 6). Firstly, the materials and experimental setup are discussed in Chapter 5, alongside a comprehensive scrutiny of the

specifications, and associated assumptions. Subsequently, the analytical techniques specific to this project are reviewed and critiqued. The results of the experimental work relating to surface hardness, recording of macro-scale phenomena, SEM microscopy, and metallographic characterisation are then examined within Chapter 6. Suggestions are also made in relation to how the experimental data can be used in an insightful way to aid future metalwork wear studies. The archaeological analysis is addressed in Part Three (Chapters 7 and 8). Chapter 7 introduces the analytical study undertaken on prehistoric Bronze Age palstave axes and begins by explaining the materials, approach, and analytical techniques that were utilised during the analysis of each life stage of the objects. Chapter 8 reports and explores the dataset generated here-in, examining the results related to composition, casting, processing, use, damage, and deposition circumstances individually, and then when combined, so that biographies can be established and compared. This leads into a discussion regarding the common life trajectories of palstave axes belonging to different typological and contextual groups; which, in-turn, highlights the unique life paths of many artefacts. The main body of text is, therefore, cyclical in its consideration of the various relevant interdisciplinary elements; it begins with defining the archaeological perspectives relevant to the lives of prehistoric palstave axes, delves into the study of use-wear in an archaeological capacity and the scientific specifics of the tin-bronze tribological system, and then delivers the outcomes of materials-based experimentation before applying the insight gained within the biographical analysis of prehistoric palstave axes (*Figure 1*). In Chapter 9, the final words of this thesis will summarise the substantial contributions of the work presented here-in towards supplementing our understanding of the wear dynamics of palstave axes and the positions these objects assumed within Bronze Age society.
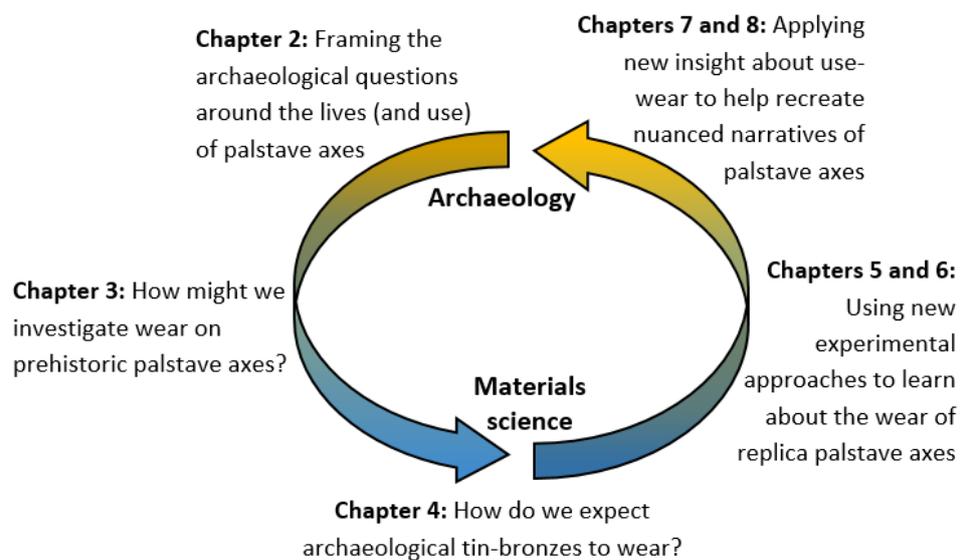


*Figure 1:* Diagram explaining the cyclical course that the thesis takes, from archaeology, to materials science, and then back to archaeology once more (Source: Author's own).

# PART ONE: BACKGROUND

## 2  Archaeological perspectives

To reveal the context in which the lives of Bronze Age palstave axes unfolded within, a review of the current understanding of human society during the Middle Bronze Age in Britain is undertaken below. Subsequently, the lines of inquiry that researchers have adopted to investigate Bronze Age axes in the past, for example, typological approaches, technological investigations, use-wear analysis, and depositional studies, are then examined. This discussion highlights the isolatory nature of the aforementioned approaches and emphasises that an integrated assessment of the life stages of an object is required to reveal rich and complex narratives. Hence, the following text aims to draw out the various stages associated with the life of Bronze axes to suggest the potential biographical elements that can be analysed and introduce what is currently understood about how palstave axes were engrained in Bronze Age society. Thereafter, a critical review of the biographical approach, and the place of measures of use-intensity within this (as an additional and untapped aspect of the lives of Bronze Age palstave axes), is discussed. To conclude the chapter, the text provides a realistic proposition for the production of 'individual narratives' and 'life trajectories' in relation to the prehistoric palstave axes analysed within the present project.

### 2.1  A period of transformation

The British Bronze Age spanned approximately 1700 years, between 2500 BC and 800 BC [13, pp. 231, 232]. Within this, three separate chronological periods have been determined, the Early Bronze Age (EBA), c.2500-1500 BC, the Middle Bronze Age (MBA), c.1500-1000 BC, and the Late Bronze Age (LBA), c.1000-800 BC [13, pp. 231, 232]. This project is concerned with the manufacture and use of bronze metalwork from the Middle Bronze Age, but a wider background of cultural change must be provided to avoid the metal-centric view that often dominates studies of bronze artefacts. In the past, the Bronze Age has been completely defined by the adoption of bronze; this has occurred superficially by nomenclature, but also, veritably, through its historiography, during which the material has often been placed at the centre of all changes in social structure [14, p. 165]. Given these deeply-engrained predispositions, it is difficult to avoid overemphasising the

importance of bronze within the social life of the Bronze Age. Nonetheless, to state that metalworking technology was the sole provocateur of change during the Bronze Age is to disregard the many autonomous traditions that were evolving during the preceding millennia. For example, the British Middle Bronze Age presents a very distinct and intriguing archaeological phase; during this time, agricultural intensification increased considerably (generating the proliferation of metal tools), the 'monumental' cemeteries and embellished inhumations of the EBA were replaced with cremation burials, and the practice of 'hoarding' became widespread. These cultural shifts, which are examined in the text below, clearly exemplify large-scale socio-economic alterations, as well as some clear breaks to the ontological underpinnings of the world view of Bronze Age people in Britain.

### 2.1.1   Agricultural intensification

Progressive evolutionist ideas mean that it has long been assumed that reliance on agriculture increased steadily over the course of the Neolithic and Bronze Age periods, however, the archaeological evidence is progressively pointing towards a significant boom of agricultural activities in the Middle Bronze Age in Britain after several millennia of reduced focus on arable and pastoral resources [15, p. 719]. This change in subsistence practices has been attributed to the slightly warmer and drier climatic conditions in the second millennium BC than experienced in the present day, which may have permitted the inhabitants of MBA Britain and Northern Europe to drastically increase their dependence on arable food sources [16, p. 146]. This succeeded a period of climatic downturn in the later Neolithic that generated stormier and colder conditions, which probably prohibited successful crop cultivation [17, p. 3] – a trend that has also been observed in the communities of later Neolithic Switzerland [18]. On the other hand, Yates has suggested a perspective that is less inclined towards environmental determinism; for instance, that agricultural reform was a much less significant aspect of the so-called 'Neolithic package' than the desire to honour the ancestors by monument construction [14, p. 65]. Thus, while these traditions clearly remained a social priority for the people of the Early Bronze Age, their importance was much diminished by the transition into the Middle Bronze Age, by which time labour- and land-intensive infrastructure projects were almost always related to creating ordered agrarian landscapes and settlements [14, p. 65], [20, p. 431], [21, p. 289]. This behavioural transformation was instigated by a combination of environmental and cultural adaptation, the latter of which was potentially the result of a flux of in-migration [15].

The data pointing towards a more permanent agricultural society in the Middle Bronze Age, comes from a diverse range of sources. Firstly, the environmental and dietary evidence spanning across prehistory, points towards a substantial shift in subsistence practices at this time. Data from pollen-inferred land-cover reconstructions indicates that the percentage of deciduous woodland was only around 10% in the mid-2nd century BC, while in the Neolithic and Early Bronze Age this figure may have been closer to 30-40% [22, p. 222]. Equally, the percentage of land covered with meadow and/or pasture in the Middle Bronze Age may have been as great as 50-60%, while comprising only approximately 20-30% in the periods that directly proceeded it [22, p. 222]. Pollen records also suggest considerable woodland clearance and the establishment of greater expanses of open land during the MBA [23, p. 163], [24, p. 229], [25, p. 105]. Furthermore, summed probability data of radiocarbon dates taken from cereal remains corroborates the conclusion that people in Britain may actually have still been fairly dependent on pastoral and wild food sources between 3300 and 1500 BC, with a movement towards crop cultivation in the Middle Bronze Age [15], [17] (cf. [26]). This is substantiated, additionally, by the emergence of a number of new crops, such as, spelt, pea, and bean, which indicates the renewed transfer of agricultural knowledge. In accordance with the increased consumption of cereal crops, the incidence of dental caries, while low in British Neolithic populations (generally less than 5%), is greatly increased in subsequent periods [27, p. 509].

Secondly, later Bronze Age agricultural activities made a significant impact on the landscape in the form of agrarian settlements, field systems, granaries, storage pits, droves, and waterholes. Middle Bronze Age homesteads were often arranged in manner that indicates a strong focus on arable farming: several post-built dwellings (usually roundhouses) containing storage pits, beside an ancillary structure, such as a granary, which were surrounded by an outer network of banks or ditches [28, p. 190]. It appears that each of these settlements would have managed areas of arable land, grazing pasture and woodland to permit self-sufficiency in food and other resources (like wood) [29, p. 477]. Thus, with an economy based on stable mixed farming, the communities of Middle Bronze Age Britain were beginning to form a fully agricultural society [14, p. 65]. The earliest evidence of the wide-scale implementation of field boundaries in Britain can be securely dated to the Middle Bronze Age; for example, the land divisions in the Thames Valley have been associated with Deverel-Rimbury pottery [19, p. 67], [30, p. 158]. The ability to divide land into smaller plots permitted different crops to be grown in close proximity to each other, e.g., at Reading Business Park, where nearby fields were used to cultivate either flax and leguminous crops, providing greater security if one crop failed [19, p. 66] [31, p. 120]. Of course, many fields-systems, especially in upland areas, would have been established to provide pasture for ruminant animals. The growing dedication to animal husbandry is also reflected in the construction of droves and metalled roads.

The MBA marks the appearance of spindle whorls and loom weights for the first time in Britain, with a high intensity of finds within the Sussex chalks and Middle Thames – perhaps indicating some economic specialisation in these areas linked to sheep husbandry and wool production [28, p. 190]. Furthermore, the diversification of metal tools (many with relevance for wood-working or agriculture) in the Middle and Late Bronze Age, is a strong indicator of the changing societal dynamics induced by an increased reliance on farming.

### 2.1.2    Wood and woodworking

As already alluded to in the passage above, the scale and range of construction and the associated tools to facilitate this increased substantially throughout the Middle Bronze Age. The material at the heart of this expansion was wood. There is widespread evidence of settlement construction during the MBA; for example, at the well-known site of Flag Fen, Cambridgeshire, which underwent a number of stages of construction between 1365 and 967 BC [32] and at Pen hale Round, Cornwall, where one roundhouse was well-preserved enough to still demonstrate the remains of waterlogged split oak timbers [33, pp. 59–62]. To better understand the changing intensity of settlement construction within the Bronze Age, Caswell used summed probability data from a total of 179 radiocarbon dates taken from 77 structures across 48 different BA sites. The results of the analysis demonstrated that at around 1700 cal BC there was a considerable increase in construction of settlements, with the peak of construction at approximately 1450 cal BC. This was followed by a recession in settlement construction in the period 1300-1200 cal BC and then another resurgence at 1000 cal BC [34, p. 253]. A total of 1488 sites with chronological classification based on the seriation of associated materials, for instance, Deverel-Rimbury pottery, indicated that, while there was only 117 settlement structures dated to the EBA, 488 structures were defined as MBA. Interestingly, the number of settlement structures classified as LBA was 840, which suggests that construction gradually grew throughout the Bronze Age, rather than peaking in the MBA as the summed probability suggested [34, p. 265]. The author, however, rightly urges caution regarding the accurate determination of structures based on the typology of associated material [34, p. 277].

In addition to settlements, there is evidence of many other types of wood-based infrastructure throughout the British Isles. Another well-documented use of wood is in the construction of trackways through wet areas of ground, for example, at the Somerset Levels [35], the remains of which illustrate the use and maintenance of these structures in this area throughout much of later prehistory, with the Meare Heath Trackway dated by dendrochronology to 1550-1450 cal BC [36],

[37, p. 223]. The use of wood in the construction of wells is also well-documented. At the Middle Bronze Age site of Perryoaks, near Heathrow, some pits revetted with roundwood stakes with wattles woven between them were uncovered, possibly indicating as well-type structure [37, p. 294]. At Chigborough Farm, Essex, a wooden platform and step were documented within a shallow well [37, p. 296], [38, p. 71]. Jetty construction dating to the MBA has been noted in Pilling, Lancashire, as well as on the Quarr beach on the Isle of Wight, where six posts were shown to stretch into the Quarr palaeochannel [37, p. 263], [39]. While evidence for bridges is scarce, two types of horizontal timber have been found at Eton rowing lake and may represent bridge superstructure [37, p. 294], [40, p. 21].

Besides infrastructure, a diverse range of wooden vessels and objects were in production during the Bronze Age. Evidence for boats, for example, is particularly strong. A number of sewn-plank boats were found at Ferriby (dating to 2030 cal BC) [41, p. 387], [42], and then there is the Dover boat, which dates to approximately 1600 cal BC [43]. From the LBA, there exists the Brigg boat/raft [44] (Roberts 1992) and the log boats found at Must Farm [45]. There is also evidence of shipwrecks, such as Langdon Bay, off the coast of Kent, and Salcombe, Devon, both dating roughly to 1300-1200 cal BC, which further suggest the use of maritime vessels during the MBA [46], [47]. As well as wooden hafts (which are covered in detail within section 2.2.1.4), there has been an array of other wooden tools and objects discovered. For example, there have been a number of ladders and pry bars, possible used for levering blocks of stone, found at Church Hill, Findon [48, p. 42]. A bucket and portions of a bowl were found at the Wilsford Shaft, Wiltshire [49, pp. 117–119]. Another bucket (dating to 1380-1050 BC) was found at Pode Hole Quarry, Lincolnshire, as well as rope made from honeysuckle [50, pp. 113, 125]. At Alderley Edge, a wooden shovel has been discovered intact and a hazel pitchfork has been found at Shapwick, Somerset [23, p. 244], [51]. Within the Somerset Levels, at Meare Heath, several two-part mallets and some carved pins were found [52, p. 33]. Lastly, a maple-wood ard, dated to the LBA, has been retrieved from the Thames [53].

Wood-working was, of course, already an established practice at the onset of the Bronze Age. The developments that occurred within the craft during the following millennia, therefore, unfolded upon a backdrop of extensive knowledge about flora and well-established crafting skills [52, p. 28]. The deliberate selection of certain types of wood for particular uses within the Bronze Age has been well-documented and suggests a close appreciation for the material properties of wood. Although it is a tough hardwood, ash also has elastic qualities, which is most likely why it frequently appears in association with bronze spears within the archaeological record [54]. Oak and ash, which can both be split easily when fresh, and are hardwoods, were both used consistently for axe hafts and

in the construction of buildings, particularly within settlements in the South of England [54], [55]. The construction of the Dover Boat also includes the use of oak for planks, and yew (another commonly used type of wood in the Bronze Age) for withies [56, p. 133]. Hazel, which is very flexible, was often chosen for the construction of hurdle trackways in the Early Bronze Age, but later examples of structures of these types were often found to contain alder instead; for example at Glastonbury Lake Village [37, p. 84].

The most significant transformation to the craft was in the adoption of bronze tools and the adapted crafting techniques that these were associated with. Crucial to the splitting, cutting, felling and hewing of wood was the bronze axe, a robust bladed tool. The axe was primarily used either, (when hafted) as a levered wedge that uses the energy gained through a swinging motion to cut an opposition material upon impact, or as a direct wedge that, when the blade is positioned in the same orientation as the grain, can be struck by another percussive tool to split the wood [57, p. 71] (Lee). There is substantial evidence for the use of bronze axes by means of cutting marks on preserved timber; for example, Sands [58, pp. 9, 44] identified the use of bronze axes to cut wood within the Somerset Levels and has also suggested that the observation of ridges and grooves on worked timber can indicate the number of tools at work on the material as well as the presence of poor strikes and the curvature of each axe blade [Ibid: 11]. Turning, carving, and precision-cutting were accomplished by a number of tools, including gouges, chisels and saws. Gouges generally have curved blades and are a carving tool primarily used to produce grooves or bore holes within wood [57, p. 71], for example, the stitch holes in the MBA Dover Boat [56, p. 133]. This is most commonly achieved by the percussive striking of the gouge by another object (like a mallet, for example) to facilitate removal of material. Chisels are a straight, sometimes bevelled, multi-functional tool used in the shaping and carving of wood [57, p. 72]. Like gouges, chisels were most likely positioned and then struck by another object in a percussive fashion. Bronze saws are blades with multiple teeth that use friction and grinding to progressively cut through timber.

Given the close parallels between the objects mentioned above, and modern day equivalents, Lee [57, p. 49] suggests that, "Bronze Age practices are likely to have had close similarities to modern-day 'traditional' wood-crafting". There are major differences, however, in the material properties of the Bronze Age tools, compared to their modern day steel counterparts. In accordance with this, Bronze Age wood-crafting tools are much more likely to become damaged (and require re-sharpening) quickly and so, as Lee attests, use of bronze tools "require[s] a slower, finessed approach" [57, p. 49]. The author has heard similar statements uttered by wood-crafting specialists

at Buster Ancient Farm, who administer a relatively measured axe-swing when using bronze axes to chop wood for the creation of round houses so as to limit the likelihood of damage.

### 2.1.3   Metalworking

Metal was slowly assimilated into the cultures of north-central Europe and the Iberian Peninsula at around 3000 BC [28, p. 146]; during the succeeding millennium gold-working and copper-working traditions were refined from a tentative kind of incomprehensible 'sorcery', to a fine art of extraction, manufacturing, and processing [59]. Throughout much of this time metal remained a rare material in the late Neolithic communities of Britain, though by the Early Bronze Age, copper objects were imported from the continent. By the beginning of the 2nd millennium BC, the skills required to work with metal were firmly entrenched in parts of Ireland and had begun permeating into areas of Wales and northern Scotland [25, p. 101]. In the following centuries, metalworking and its associated industries became a ubiquitous presence across the entirety of Britain, with a particular focus on the production of copper-tin alloys. In the Early Bronze Age, copper resources in the west of Britain were used, with some ore imported from Ireland, or collected from outcrops in Scotland, northern England, and south-west England, while native sources of tin were limited to Devon and Cornwall [60, pp. 3, 4]. Although the copper deposit at Great Orme, Wales, was used extensively throughout the Middle Bronze Age, a high proportion of the available copper and tin resources likely made their way to Britain from Brittany and the Rhineland (this is explored further in section 2.2.1.1) [60, p. 3].

A rapid speed of technological transfer was both an accessory to, and an impact of, the great level of contact between many cultures in the Bronze Age; as such, this period is considered a time of unprecedented invention and innovation [61]. Some of the earliest objects to appear in Britain were copper daggers and axes, though their susceptibility to deformation probably meant they had very little real functional use [62]. During the Middle and Late Bronze Age, however, these axes and daggers evolved into a range of tools and weapons, for instance, flanged axes, palstave axes, socketed axes, spear-heads, rapiers, dirks, and swords. These were complimented by an array of smaller hand-held items, such as, knives, saws, chisels, awls, and gouges. This selection of tools eventually supplanted their stone predecessors; copper-alloy objects could be much more easily shaped, and then resharpened, repaired, and recycled, which gave a definitive advantage over lithic technologies [63, p. 80]. A full tool-kit of metal objects was, nonetheless, relatively delayed – stone

was still preferred for items like sickles and hammers, and wood, for shovels and rudimental plough-blades, until the late Bronze Age or early Iron Age [23, p. 125].

## 2.1.4    Deposition

During the Middle Bronze Age, metalwork was not left within settlement sites in large volumes, nor does it form part of the grave goods of individuals. Instead, the majority of metalwork was deposited in large assemblages, frequently referred to as 'hoards', or as single isolated finds [64, p. 123]. In addition, many of the items included with hoards often appear to have been deliberately destroyed. The practice of hoarding was not a new phenomenon – assemblages of stone axes have been recovered from Neolithic deposits and single finds of EBA copper axes have been found in bogs – but deposits of this kind certainly start to appear more frequently and with consistent patterns in content and context within the MBA [28, p. 185]. Understanding the deposition circumstances of Bronze Age axes is vital for elucidating the final stage within the ancient relationship between people and material when the object was concealed within the ground. As a result, ascertaining the context and content of metalwork hoards to interrogate the reasons why Bronze Age material was deposited has been an overarching mission within prehistoric studies. The role of metalwork hoards has been aggressively debated over the last 150 years, as the merit of accidental versus deliberate motives for their interment are constantly reviewed, [28], [62], [63], [16], [24] [64]. Researchers have pondered over several questions; for instance, if these collections of metalwork were interred in the ground for safety or storage reasons, why were they never removed again, and how can the similar patterns in their content and context be explained? Equally, if the material was intentionally deposited in this way, how are we possibly meant to interpret the reasoning behind this? [65, p. 240]. This section introduces the prevailing interpretations in relation to these questions.

Several functional interpretations have been proposed for the presence of metalwork hoards in the archaeological record of the Bronze Age in Britain. Firstly, it has been suggested that these accumulations of metal reflect the burial of goods for storage purposes that were, later, unable to be recovered [16, p. 457], [66, p. iv]. Secondly, that the metal was deposited in the ground for safe-keeping during periods of threat, and was, thereafter, never disinterred [16, p. 457], [66, p. iv]. Where possible, the contents of the deposits have also been linked to certain owners. So-called 'scrap' hoards, have been said to comprise of fragmented material, alongside casting paraphernalia (moulds and crucibles) and debris. These have been attributed to a smith, who was perhaps

collecting items to be smelted together and transformed into new objects [64, p. 128]. Wiseman's [67, p. 45] use of random accumulation and fragmentation modelling for large Bronze Age hoards across Britain has suggested that by the end of the LBA between 85-95% of bronze objects were being collected as scrap metal, deliberately broken, temporarily buried and then recovered for recycling. Alongside continual recycling of scrap, it was likely that a substantial volume of bronze was entering Britain via cross-Channel trade at this time in order to meet demand. This trade has provided another form of (likely) utilitarian metalwork assemblage seen frequently in the archaeological record in the form of shipwrecks. There are twenty-three known Bronze Age shipwreck sites surrounding the coast of Britain. One of these is the MBA Langdon Bay wreck, which comprised of 360 bronze objects that were presumably in-transit prior to consignment to the seabed [68]. Another is the Salcombe Bay wreck, which has been associated with almost 400 metal objects [47]. In the case of shipwrecks, it is, of course, likely that the deposition of bronze metalwork was accidental. When a hoard consisted of many copies of the same item, it has often been suggested that it may have been the property of a trader [64, p. 123]. The idea that these hoards were of a utilitarian nature might seem plausible when the content of the hoard seems to be randomly assorted and arranged, but what if the items – like the four palstaves placed on their edges and arranged in a fan shape at South Dumpton Down, Kent – have been very deliberately positioned [69, p. 299]? The obviously deliberate features within the context and content of hoards suggest the ritualistic nature of these deposits; and, as Barber [14, p. 45] suggests:

*"We have clear and unambiguous evidence that deposition in the Bronze Age could be non-random, selective and purposeful, with no intention to recover. Furthermore, it appears to have been motivated by factors other than security or economics."*

There is, of course, some evidence that Early Bronze Age societies may have been status-driven [23], [25, p. 98], [60], [70, p. 62], [71, p. 39], and that the manner by which power was displayed may not have disappeared in the MBA, but was modified into deposition. For example, the destruction of property and hoarding may have been used by rival chiefs and clans to affirm wealth and power, like the potlatches of the Northwest Pacific [72]. On the other hand, the relationship between Bronze Age people and hoarding may have been more complex than just power and status. Bruck [69], [73], [74], [75] has continually asserted that personhood may have been perceived very differently in the Middle Bronze Age. The individual may not have been thought as a tightly bounded entity, but something that is spread spatially and temporally across their reciprocated actions during life [69, p. 308]. Thus, through gift exchange and hoarding, the rights and resources of many people would have become so intertwined that personal power would have been effectively removed, and not advanced [69, p. 310].

Hence, metalwork hoarding seems to defy modern rationalist explanations about the treatment of what could be considered as 'capital'. To comprehend why Bronze Age people would have wanted to deliberately discard such seemingly valuable objects in deposition ceremonies, one must first assess the significance of the metallurgical process to the world view of Bronze Age people. It is very unlikely that past cultures viewed metalworking, fundamentally, as a technological process [28, p. 187]. Ethnoarchaeological evidence from non-western societies indicates that metal smiths are often revered as ritual practitioners, able to transform ore into metal by strictly-regulated protocols that were perceived as 'magic', or divine intervention [28, p. 187], [64, p. 129]. Perhaps, since the ore was removed from the natural world, metalworkers felt the need to return some of the material to the ground to restore balance with the earth [76, p. 140]. Maybe it was necessary for Bronze Age people to thank their gods for the transforming the raw material into metal, or to provision the continued well-being and safety of the community, by offering a portion of the products at certain stages in the manufacturing sequence [77, p. 469]. It is easy to think of ritual activities as disparate behaviour, taking place independently of all the more practical elements of life. Bruck [78, p. 313], however, in her investigation of Middle Bronze Age sites from the south of England, has stressed that ritual practices could be described as:

*"constituting a culturally specific group of site maintenance practices that ensured the well-being of the settlement and its inhabitants".*

Bruck [78, p. 313] suggests that in the minds of Bronze Age people, ritual and practical convention may have, consequently, been considered as one and the same. The assurance gained by depositing metalwork within enclosure ditches may have been a functional solution – comparable to the erection of a palisade wall – for securing the safety of the community.

The destruction of metalwork could also represent the use of bronze to construct an ontological framework in which life could be better understood by Bronze Age people. To elaborate further, Bruck [69], [73], [74], [75], has persistently argued that manufacturing processes, such as, bronze working, building construction/demolition, and pottery fabrication, were construed as transformative cycles, through which creation, remodelling, and destruction are thought to represent birth, reproduction, and death [74, p. 157]. Thus, she argues that, "technologies such as metallurgy and potting acted as metaphors for the production of the self" [74, p. 157], since changes subjected to the material could reflect the biological and social development of a person as their self-identity was reconstituted through "rites of passage at critical stages in their lives which require[d] the destruction of the old social persona" [74, p. 157]. Similarities at death between bronze artefacts, houses, ceramics, and inhumations from the Middle Bronze Age in Britain are

particularly intriguing: Bronze Age swords are found in a fragmented state within hoards and were sometimes burnt (though this has also been interpreted as a ritual offering in the wake of successful conflict [28, p. 206]); houses were deliberately dismantled and there is occasional evidence of fire damage; pots were shattered and deposited in ceremonial circumstances; and the common burial rite was to destroy the body through cremation [69, p. 305]. This conceptualisation allows the treatment of metalwork to fall within a more structured world view of interconnected symbolism between diverse industries.

Bruck also suggests that further proof of this homage to metamorphosis are the locations in which metalwork was deposited, which often signify 'transition' [14, p. 167]. Axes, metalworking equipment and debris, for example, are most usually interred on land, sometimes within occupation sites (in enclosure ditches or entrances), but more often in areas of environmental distinctiveness (hilltops, caves, cliffs, rock fissures, and beside springs or streams), or ancestral importance (megalithic tombs, round barrows, cairns, burnt mounds, and stone circles) [28, p. 186], [64, p. 124]. It is possible that these collections of metalwork were displayed for an extent of time before burial, in which case, their location would have been known, but respected [76, pp. 29, 90]. As Bradley posits, placing hoards in such a predictable manner seems to further invalidate the idea that the objective of deposition was concealment or storage [76, p. 28]. Even single finds seem to have been placed with a 'certain formality'; those found on dry land were sometimes marked by a stone, and others were placed into water like their counterparts recovered from larger assemblages [28, p. 148]. Ornament hoards, including items of precious metal, are generally discovered in peatbogs, and are sometimes found with bones, but not in the arrangement of a formal burial [28, p. 186], [29, p. 482]. Weapons were most frequently deposited in rivers, and quite often they had been disabled prior to discard, i.e., they were broken in ways that could not have happened during their functional use [28, pp. 202, 203].

An alternative interpretation for the recurring context and content of Bronze Age metalwork deposition, suggested by Fontijn [79], draws upon the phenomenological changes to landscape during the Middle Bronze Age. As previously discussed, during the Early Bronze age there was a 'monumental emphasis on death', which involved the construction of round barrows and circular enclosures [80, p. 264]. Equally, there was a coinciding tradition of individual inhumations accompanied by extravagant grave goods [81], [82]. By contrast, in the Middle Bronze Age, Britons were cremated before burial, and grave goods, with the exception of pottery, were extremely rare [69, p. 299]. The move from imposing or elaborate funerary rites in the EBA, to the behaviours of cremation and hoarding in the MBA, suggests the desire for 'invisibility' within the landscape.

Juxtaposed with this, is the fervent adoption of agriculture in the MBA, which transformed landscapes into a very structured and unrecognisable form [20, p. 431], [21, p. 289]. For the first time, much of the environment was comprised of humanly-modified land with specific zones [21, p. 304]. Fontijn [21, p. 307], [20, p. 441] has suggested that this may have resulted in a move towards traditionality, such as honouring ancestral or natural locations, which may explain the spatial repetition of hoarding during the MBA.

## 2.2   Conceptualising the 'lives' of palstave axes

The lives of objects are multi-dimensional; however Bronze Age metalwork has oft been interrogated under the guise of the same traditional, largely static, approaches for the last several decades; for example, 'typological', 'technological', 'use-wear', and 'deposition' studies, which reveal only a fraction of the original meaning bestowed on the object. The limited scope of the approaches mentioned above will be expanded upon throughout the following text.

A long-standing focus of Bronze Age metalwork has been on the creation of typological frameworks, in which certain type-finds were ordered, as a way of constructing chronological schemes [83], [84]. The typological approach provides helpful insight into the morphological and chronological development of metal artefacts, thus establishing the relative regional chronologies of similar artefact types [76, p. 125]. When consolidated with radiocarbon data, typological identification becomes a robust method to quickly date metalwork belonging to certain phases [85]. There are, however, a number of difficulties with the use of the typological approach. Firstly, typological frameworks provide a very rigid classification system and are often not comprehensive enough. As such, it is common that finds (especially those that are damaged or incomplete) are placed within chronological schemes in which they do not fit [76, p. 125]. Consequently, typological frameworks do not help to reveal the true amount of variation that exists within morphology of certain forms of metalwork. Secondly, the typological approach puts the focus of metalwork analysis exclusively on the recognition of stylistic identifiers, rejecting any notion of how the tool was made or used. This narrow approach is problematic as it reduces the conceptualisation of Bronze Age metalwork to a technology that was modified through successive phases in design, and misses the subtleties of diversity conveyed by the individual narratives of the Bronze Age metal objects.

Investigations into the manufacture and metallurgical specifications of Bronze Age metalwork can provide insight into the stages of production that formed and altered objects, as well the wider

trends these they are a part of. However, the application of technological analysis without attempts to further contextualise the narrative of the object is considered to be reminiscent of the Processual approach. This movement taught that material culture should be quantified in terms of elemental composition, structure, properties, and mechanics, all of which that alter the 'performance characteristics' of the material in relation to its desired purpose [86, p. 5], [87, p. 2], [88, p. 47]. Within this perspective, objects were viewed as passive and mute items that were formed and altered by human agents in order to meet emerging material requirements [89, p. 329]. Thus, it has been suggested that technological investigations are restricted to assessing elements of the sequence of manufacture, instead of the full history of the artefact [90, p. 542]. These factors limit the interpretative potential of such studies to the reconstruction of the technological, economic, and adaptive decisions of past peoples [87, p. 2].

Evidence of wear on archaeological objects can emerge in relation to manufacturing techniques, the functional use of the object, and from environmental processes in the depository context. The aspect of this that is concerned with the wear introduced during the use of the artefact prior to discard comprises a sub-field of archaeological investigation known as 'use-wear analysis'. The aim of wear investigation in an archaeological context is to characterise and extract the relevant information for reconstructing the past curation of the object. By studying the patterns of modification made to materials by mechanical processes during use, it is possible to obtain information about the deployment of individual artefacts, such as, the opposing material, or the nature of contact and use [91]. This, in turn, helps to define the role of the object, in terms of its practical, social, ritual, and political significance, in the unique context bestowed on it by a particular society [86, p. 7], [4, p. 174]. Of course, use-wear studies exclusively focus on only one aspect of the life of an object (use) and do not consider the full scope of human-substrate interactions (this is discussed in more detail in section 3.3.2).

Deposition studies of metalwork hoards, as a way to elucidate the possible intention for discard, have dominated much of the discussion on Bronze Age axes and metalwork in general. Like technological studies, investigations of hoards only address the history of metalwork objects at one stage of their lifecycle – this time the very end of their contemporaneous existence. Furthermore, the emergent 'functional vs symbolic' dichotomy, and the numerous questions that surround it, have remained so loud and divisive that they have been responsible for the frequent overshadowing of other aspects of the lifecycle of Bronze Age metalwork. It is now emphasised that the different meanings bestowed upon bronze objects over their lives were not mutually-exclusive, but almost definitely existed simultaneously and were deeply interrelated, it is time to remove the

attention from these age-old debates. Investigations into bronze metal artefacts should recruit detailed analysis of the arrangement and composition of hoards as part of the arsenal of resources that are available for assessing the lives of individual objects, and hoards as a whole, but must apply care not to allow these interpretations to become the defining focus of the discussion [65, p. 242].

Although each of the approaches detailed above have value in their own right, the recurring issue among them is that they attempt to elucidate *either* the beginning, middle, or end of an artefact's life. The emphasis is placed on 'either', since rarely do studies aim to address more than one of these stages to produce a synthesised account of an artefact's past. These approaches fail to capture the nuances provided by a multi-component life assessment and push the object firmly to the background. Thus, the prevailing view is that it would be more beneficial to move towards a broader analytical framework that encompasses all aspects of the 'life' of archaeological objects. This was first envisaged by Leroi-Gourhan [92], in the form of the 'chaîne opératoire', which he defined as "a series of operations which brings a primary material from its natural state to a fabricated state" (this was later extended to also include the post-production narrative) [93, p. 6]. Schiffer [94], [95], [96] also suggested that the complete sequence of transformations that occur during an artefact's lifetime should be detailed, from choosing raw materials, through design, manufacture, use, recycling, discard, and decay, as well as the sequential considerations, techniques, and natural processes that develop alongside. This, as Sigaut [97] emphasises, should explore both the adaptations to the material and the actions of the people involved in the process. Though the life-history approach certainly offers a vast improvement on the disjointed frameworks that preceded it, some scholars [90], [98], still believe that, while it is a useful technique for analysing large-scale, long-term transformations to material culture, it often tends to "miss the dynamic interplay between people and objects" [98, p. 488]. Like the technological investigations before it, the life-history framework is hindered by issues of the subject/object dualism. In other words, it fails to consider that objects are not just acted upon, but have an active part to play in the formation of human-substrate relationships.

A more profitable way to visualise the multiplicity of relations between human and material may be achieved, alternatively, by examining the dependencies from a biographical stance. In his work titled, 'The Cultural Biography of Things', Kopytoff [99] suggested that an object biography could be established by examining the unique human-substrate relationships formed at the 'birth' of the artefact (when it was produced), during its 'lifetime' (when it was used), as well as the loss of these relationships at the point of 'death' (when it was discarded) [90, p. 540], [98, p. 488]. Hence, the biographical approach acknowledges that the meanings given to objects are not static, but are,

indeed, renegotiated and transformed over time throughout successive interactions with people [100, p. 169], [101, p. 442]. However, the significance of this approach is only fully realised upon consideration of the premise of materiality: that objects are not only the 'infrastructure of practice', but actively constitute practice and are, in-turn, shaped by their role in society [98, p. 486], [102]. In this sense, material culture is the method by which humans connect to their surroundings and construct their experience of the world, and these interactions simultaneously alter humanity; thus, human-substrate relationships confer the 'production of the social' [86, p. 4], [103, p. 274]. Since humans and materials are inextricably intertwined in this way, they form, in the words of Gosden and Marshall, "mutual biographies which unfold in culturally specific ways" [100, p. 173]. Consequently, if the accumulated histories of objects can be deciphered, then these relationships may expose narratives about past sociality [90, p. 540].

## 2.2.1   Life stages

Drawing on the ideas presented above, it is clear that the lives of palstave axes can be best investigated by synthesising an account of their object biography. Emphasised within this approach, is the abundant number of human decisions and activities that are enacted by the manifold agents that interact with any object [87, p. 18]. For instance, the 'beginning' of the lives of Bronze Age palstave axes, which includes stages such as, procurement, casting, manufacture and finishing, signifies a series of choices in regards to the form of the object and its material properties. Seeing that these characteristics apply limits to the way the object can be used within its given cultural context, the many craftspeople that engineered and shaped the artefact each had a part to play in defining its 'biographical possibilities' for the future [98, p. 486], [79, p. 28]. From this multi-faceted set of opportunities, the people who use and maintain the object determine its particular significance, carving a unique life path. Though, as Schinkel [104, p. 401] reinforces, alternative meanings always remain 'at hand' to assume dominance in subsequent reinterpretation as new uses are adopted and the object is bestowed with new connotations over time [101, p. 442]. Eventually the life of the object will cease at the point of destruction and/or abandonment; as it has already been discussed in great length above in relation to the deposition circumstances of Bronze Age metalwork, a significant number of interpretations about the nature of the human-substrate relationships can be extracted from this action.

The following sections propose a sequence for the life stages of a palstave axe (a schematic of this can also be seen in *Figure 2*). Each section below provides an overview of the investigational

approach and current appreciation of each stage in the life of a palstave axe in order to contextualise the sequence of interactions between human and palstave axe. It should be noted that much more detailed accounts of the scientific aspects of bronze metallurgy will be provided in Chapter 4. The information presented below is *not* a biography, as it does not represent the narrative pertaining to the same palstave axes, but many different objects and forms of evidence. However, it does suggest all the potential elements of the life of the palstave axe that may be recruited to create comprehensive biographies.
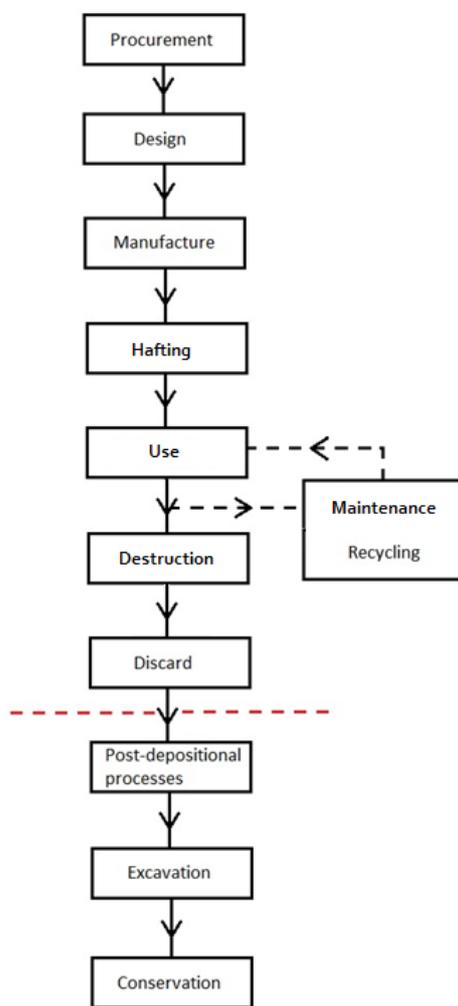


*Figure 2:* Life stages of a Bronze Age palstave axe;
the dashed line signifies the stages which will not be
assessed in the following text (Source: Author's own).

### 2.2.1.1   Procurement

Bronze Age palstave axes would have begun their lives at the point of ore prospection and procurement. The selection of the ore deposit is engrained in the chemical signatures of the metal. Efforts have been made to tie Bronze Age metal objects to certain ore deposits to better understand their provenance. Trace element analysis was used by Northover [105], [106], to establish the circulation of copper resources in the British Isles, suggesting that much of the early material originated from sources in Ireland, prior to the exploitation of mainland outcrops later in the period. Needham and Rohl [107] used trace element analysis and lead isotope analysis to test a substantial number of palstave axes and other bronze artefacts dated throughout the Bronze Age. Lead isotopic analysis uses the naturally varying compositions of lead isotopes in ores to reject the isotopic signatures present at certain sources, therefore, narrowing down the likely origin [108]. The results of the study confirmed that the majority of early copper artefacts have their origin in Irish ore sources, possibly, Ross Island, Co. Kerry, though some artefacts also demonstrated likely links to outcrops of copper in Devon or Cornwall [107, p. 87]. The signals from Ireland remain strong in Early Bronze Age metalwork, though the influence of Great Orme, Wales, becomes apparent and continental input was also detected [107, p. 95]. The Middle Bronze Age material largely points to Great Orme, though some isotope signals have also linked artefacts to Pyrenean deposits and the Middle Rhine [107, p. 97]. Specimens from the later phases showed much compositional mixing of the previously mentioned native and continental sources, with some exploitation of fresh outcrops in Wales [107, p. 106].

The main overriding issue with provenance studies is that a very wide database of artefacts and ores are needed before any metals can be, in any way, attributed to a certain source. While efforts are continuously made, by the persistent examination of further material, to try to minimise this issue, a new, and altogether negative, outcome has occurred. The more ore deposits that are examined, the more clear it is becoming that they are simply too heterogeneous, with varying degrees of overlap between sources, and some with the same isotope ratios completely [109], [110, p. 263]. The future for provenance studies will need to revolve around examining new parameters, such as isotope ratios of copper [111], osmium [112], and tin [113], to create a multi-dimensional character profile of ore sources and metal artefacts. The present study does not include the original sampling of palstave axes as it uses data that has already been produced for the basis of chemical characterisation. Hence, no attempts to provenance the ancient palstave axes will be undertaken.

There are four main types of Bronze Age axes: Flat, Flanged, Palstave, and Socketed – a schematic of their chronological placement can be seen in *Figure 3*. The first metal axes to arrive in Britain c. 2400/2500 BC were probably skeuomorphs of trapezoidal stone axes [14, p. 158]. It is likely, therefore, that copper flat axes (*Figure 4*) held mostly a symbolic value, as the polished stone axes and jadeite axes that they closely resemble are not generally native to Britain and often seem to have been deposited ceremonially within graves or bogs; and, accordingly, the metal axes that permeated into Britain were probably treated with similar reverence [62, pp. 44, 66]. The fairly rudimental shape represented by a flat axe suggests the limits of casting technology and metallurgical understanding in the earliest Bronze Age – axes would have been cast in open moulds and the unalloyed copper that was used would have been difficult to cast with [23, p. 223]. Furthermore, in addition to the fairly problematic hafting arrangement presented by the lack of any raised material to abut the handle to, the composition of these axes corroborates the idea that they probably had very little real functional ability [62]. Schmidt and Burgess [114] have suggested that there are fourteen main types of flat axe in total from the Early Bronze Age, but maintain that the evolution of these axes is deeply intertwined, so that they retain many of the same features. The later forms of flat axes had greater blade variability (toe and heel sweeping outwards), and were more robust, as a more developed understanding of the mechanical properties of copper and alloying substances was accrued. However, a considerable number of these axes are found with decoration, which indicates that while they were used in wood-cutting, they may have also played an important role as a prestige item or offering to the gods [62, p. 86]. From 1600 BC onwards these 'developed' flat axes begin to appear with flanges, hence delivering the 'flanged axe' type (*Figure 5*). The introduction of flanges meant that the haft would have been much more secure, since it could now be slotted between two raised rims each side of the butt.



**Figure 3:** Timeline of typological development of Bronze Age axes (Source: Author's own, based on [13, pp. 231, 232]; the photos are all separately credited within the figures below).

**Figure 4:** A copper flat axe found discovered in Monmouthshire, Wales. Photo courtesy of the Portable Antiquities Scheme (Source: [29]).



**Figure 5:** Flanged axe-head discovered in Cheshire. Photo courtesy of the Portable Antiquities Scheme (Source: [30]).

By 1500 BC, a new type of axe was emerging across the British Isles and in continental Europe: the palstave [85]. Given that Great Orme was at the height of production at approximately this time, it has been suggested that the palstave form may have originated from North Wales [114]. These axes were almost certainly cast in bi-valve moulds and were composed of tin-bronze, which permitted the emergence of more complicated features; primarily, this brought about the inclusion of a stop-ridge, developed from previous mid-ridge arrangements in later flanged axes, which advanced the hafting arrangement a step further (*Figure 6*). One of the earliest reviews of Middle Bronze Age axes was conducted by Smith [24], who delineated the classes of palstave axe that were uncovered in the Somerset hoards, for example, 'low-flanged', 'high-flanged' ('south-western'), 'transitional', and 'late' palstave types. Similarly, Butler [115] made a distinction between earlier and later palstaves by separating axes into 'broad-bladed' and 'narrow-bladed' categories within his classification system. Later, Rowlands [83] categorised the palstaves of southern Britain into a comprehensive classification system. Within this, palstave axes were separated by blade width, as suggested by Butler [115] and a numerical system of classes, based on observed differences in size, flange arrangement, and decoration, were suggested.

This classification system proposed by Butler (ibid.) was largely retained by Schmidt and Burgess [114] in their report of the axes of Scotland and Northern England, which separates the palstave axes into eight classes; this forms the most commonly accepted typological assessment for palstave axes. Group I (Primary Shield Pattern) comprise the earliest type of palstaves, dating predominantly to the Acton Park phase, with a wide distribution across the Midlands, East Anglia, and southern Britain [83, pp. 27, 28]. The defining characteristic of this type is the shield-pattern decoration that is exhibited on the upper blade face. The initial types do not have a clear distinction between blade and septum and have flanges that extend past onto the upper blade face to create a U-shaped enclosure [83, pp. 27, 28]. Later varieties have a developed cast stopridge, so that the thickness of the upper blade is substantially greater than the septum floor [83, pp. 27, 28]. The flanges do not often continue past the stopridge, and there is a much greater variety of decoration, e.g., shallow depression, raised moulding, raised panel, which may encompass ribs or hammer markings [114, p. 117]. The blade proportions of early shield pattern palstaves are, similarly, transformed over time. The earliest types have a narrow-blade expanding to a broad, crescentic cutting-edge, however, in later variants the cutting-edge is narrower and can be more triangular in shape [114, p. 117]. Another distinguishing feature is the short, high angled flanges that create a leaf-shape, though this shape becomes less exaggerated in later forms [114, p. 117]. Dating to a very similar time period as the above are the Group II, or 'Mid-ribbed' types; these exhibit side-flanges that extend from the butt, all the way to the blade edge, producing a distinctive 'H' outline (*Figure 6*).

These palstave axes can be determined by the median rib that descends down the blade [83, p. 27]. Similar to early shield pattern palstaves, the blade of the early mid-ribbed palstaves blade is often narrow and widely splayed, though in later versions blade shape is generally 'crinoline' or concave-triangular [114, pp. 125, 126]. A final diagnostic criteria for both Gr. I and Gr. II palstaves is the absence of a side-loop, since these types of axe were in favour before this feature was introduced.



*Figure 6*: Group II, mid-ribbed palstave with loop found in Wiltshire. Photo courtesy of the Portable Antiquities Scheme (Source [123]).

Group III, the 'Low-Flanged' types, are the most frequently identified palstave axes in Britain. In terms of chronology, it is apparent that this type of palstave succeeded the earlier shield and mid-ribbed traditions. Butler's [115] research has shown that the introduction of the low-flanged palstaves occurred during the time of the Frojk-Ostenfeld phase of Montelius IIb-c in northern Europe, which is roughly contemporaneous with Tumulus c in central Europe and the Taunton metalwork phase in southern Britain (c.1400-1300 cal BC) [114, p. 130]. The functional features of the low-flanged palstaves differ quite considerably from earlier palstave forms, breaching the void with later transitional varieties. The main discriminating factor of low-flanged palstave axes is that the height of the stopridge is greater than the connecting flanges; this represents quite a marked difference from the leaf-shaped flanges of shield pattern and mid-ribbed palstaves. The stopridge of low-flanged axes is well-defined, and usually straight, but is sometimes a little undercut. On most specimens the flanges taper away from the stopridge for a considerable length before forming a point at the butt of the axe, this creates a "long narrow socket with a shallow U-shaped septum" enclosure [83, p. 32]. The blade type of low-flanged palstaves is always broad, and usually falls into one of three categories; the first two, 'crinoline-outline' and triangular, display no expansion of the blade tip, but the third form exhibits a slightly expanded blade tip, though these blades are still splayed to a much less degree than earlier palstave forms [83, p. 32], [114, p. 129], [116, p. 117]. The low-flanged axes are found in both looped and un-looped forms [24, p. 167]. The stylistic

elements of shield palstaves and mid-ribbed palstaves were, however, often translated to the palstaves of the Taunton phase. As such, there is a great variation of decoration beneath the stopridge on low-flanged palstaves – most common are shield patterns, which are often a sunken U or V shape with internal short ribs [24, p. 167], [83, p. 32]. Some specimens also present numerous ribs on the septum floor. It is also not uncommon to find other types of ornamentation, like a midrib, or a trident, which is the result of implementing both shield and midrib patterns together [114, p. 129].

Gr. IV palstaves are least well-defined group of axes within this classification system. They are roughly contemporary with low-flanged palstaves and have a widespread distribution [114, p. 142]. These palstave axes exhibit flanges that are highest at the stopridge, and then run parallel for a short distance, before tapering off at the butt (ibid.). They also often demonstrate a crinoline blade, while some variants are said to lack a defined stopridge and patterning in the septum.

The South-western palstave group encompasses a type that is endemic to Wiltshire, Devon, Dorset and Somerset and is roughly contemporary with low-flanged palstaves (though they may have emerged slightly later) [114, p. 142]. South-western palstaves are generally easy to identify, due to the shape of their flanges; these extend from the stop until they reach the highest point and then drop steeply downwards, creating a lozenge-shape (ibid). Smith [24, p. 168] originally defined this group as those palstaves that exhibit a flange breadth higher than 38mm, but Knight [117, p. 204] has suggested that this excludes many axes that match the traits of a South-western palstave in every other way, but only have a flange breadth of around 33-34mm. Therefore, this diagnostic criteria has been widened to include "any palstave with a flange breadth of approximately 33mm or more (equal to a flange height of roughly 11mm above the septum)" (ibid.). This type of flange appears to be very similar to the Welsh Acton Park Type, and Smith [24] originally grouped these two types together, however they are distinct forms and there is little evidence to suggest that the emergence of lozenge-shaped flanges in the south-west was influenced by these axes at all [114, p. 142]. With the exception of the flanges, the South-western palstaves are very similar to low-flanged palstaves; they have a broad blade, are variably looped, and have same potential for decoration and blade treatment [114, p. 142]. A well-defined variant of the South-western group is the Crediton type. These have flanges that are similar in appearance to the wider group, but they can also extend onto the blade to form a V-shaped rib. They have a distinctive crinoline blade shape, and rarely exhibit side-loop. This variant is named after a specimen which was found within the Crediton hoard, Devon – examples of this type are mainly found in Cornwall and Devon.

The following three groups date between c.1275-800 BC and comprise the palstave axes with narrow blades; they are not found in such high abundance as the axes within Groups I-IV or South-western. Transitional palstaves (dating to the Ewart Park phase) have a narrow butt and blade, are commonly embellished with a midrib, always exhibit a side-loop, and have a lozenge-shape side profile due to the sloping flanges [114, pp. 145, 146]. Late (or narrow-bladed) palstaves (dating primarily to the Wilburton period) replaced earlier Transitional palstaves – these exhibit a narrow and elongated blade, and have very minimal flanges that start below the butt. These palstaves are most often looped, and sometimes exhibit three short vertical ribs under the stopridge [114, pp. 160–163]. The final palstave group that should be discussed is Double-looped palstaves (dating to the Penard phase), which are more commonly found in Iberia, but are still uncovered in Britain in small numbers.

It is likely that the morphological differences exhibited by palstave types of particular types did confer certain advantages. It is not hard to imagine that larger, very robust types, like the early Acton Park shield palstaves or Crediton palstaves, would have been more durable and, therefore, could have been used in particularly heavy duty work. Moreover, although based on a study of stone tools, the work of Collins [118] has suggested that curved blades were up to twenty-five percent more effective in removing material than straight, squared blades. This may suggest a differentiation in the roles of palstave axes with curved or straight blades and highlight that types that more often exhibit one of these forms of blade (for example, the South-western type, which frequently possess a straight blade), may have been designed with a specific role in mind. Given the regionality of morphologically distinct palstave types, there are also a number of questions surrounding their zones of production and distribution. It is likely that there were geographic centres of manufacturing where an abundance of resources coupled with innovation in production techniques lead to the development of new object forms. These local forms were then distributed via established trade networks and either accepted into other communities (also being used as patterns for the production of copycat designs) or recycled into locally desirable forms [119], [120, p. 387]. For instance, spatial analysis of shield pattern palstaves has illustrated a density of finds surrounding Great Orme (their likely point of origin) as well as in close proximity to riverine routes, like the Severn Valley corridor, known prehistoric trackways, and coastal routes [121, p. 1188]. Morphometric modelling of palstaves in northwest France have shown great potential in identifying the centres of production for Breton and Norman types [119], [122]. This approach has also been successful at indicating the areas where non-congruent types (those with a greater shape disparity compared with the usual type morphology) are frequently distributed, therefore, suggesting subsidiary production zones where copies were likely being manufactured [119, p. 514].

As suggested above, palstave axes continued to be utilised in the Late Bronze Age – albeit in different forms than their earlier counterparts – though socketed axes soon began to assume dominance [116, p. 117]. This new and highly divergent axe started to appear around the turn of the 1st millennium BC [85, p. 72]. The major modification exacted within the emergence of the socketed axe, again, involved the hafting arrangement; while the haft material had overlain the butt in flat, flanged, and palstave axes, the handles of socketed axes were enclosed within the axe matrix, providing a very secure attachment (*Figure 7*) [123], [124]. Socketed axes generally fall into four classes: south-eastern type, southern English ribbed axes, Stogursey ribbed axes, and Faceted axes [125].



*Figure 7:* Bronze socketed axe found in Berkshire (Source: courtesy of the Portable Antiquities Scheme, [124]).

### 2.2.1.3   Manufacture

Although the evidence is still fairly scarce, it is the assumed that Bronze Age smiths most likely conducted the casting of palstave axes by constructing a clay lined pit sunken within the earth. Within this, the crucible would have been buried underneath charcoal. When heated, the copper becomes reduced by the carbon monoxide produced from charcoal. Any gangue or dross (unwanted mineral waste) that formed on top of the molten metal was thereafter removed to reduce the likelihood of inclusions [4, p. 173], [60, p. 9]. Excavations of metalworking debris within the Late Bronze Age hillfort at Llwyn Bryn-dinas, Clwyd, have uncovered some remains of the clay

lining that would have enclosed earthen pit [126, p. 281]. To raise the temperature of the furnace, bellows made of animal skin would have injected oxygen around the coals through two wooden tubes and into a connecting tube, a 'tuyère', made out of clay, which intercepted the pit. No examples of Bronze Age bellows from Britain have been recovered – this is likely related to the improbable preservation of organic matter. As the most durable item in the Bronze Age smelting and casting setup, a number of tuyère fragments have been recorded throughout Britain, for instance, the Early Bronze Age context at the cremation cemetery situated at Ewanrigg, Cumbria [127]; the Late Bronze Age settlement on the Breidden Hill, Powys [126]; and the Late Bronze Age/Iron Age circular ring at Mucking, Essex [128].

The casting of Bronze Age palstave axes could be achieved by using one of several types of bivalve mould: stone, bronze, clay, or sand [61, p. 99]. The former of these two types of mould have been found in considerable numbers during archaeological investigation. The production of stone moulds was somewhat restricted to those with access to the upland regions of Britain, and this is reflected by the high distribution of finds in Scotland, Northern England, Wales, and Devon [60, p. 11]. In the Middle Bronze Age these moulds were used to create a great array of objects, for example, axes, weapons, awls, sickles, razors, but in the consecutive period stone moulds appear to have been manufactured for casting axes and ornaments only [129, p. 11]. Bronze moulds have been found in limited numbers across the British Isles; there are currently 55 recognised examples, though many date from the Late Bronze Age [129, p. 2]. These types of mould are largely found in East Anglia and the Thames estuary, which may suggest that they were an alternative to stone moulds in areas where lithics were not in easy supply. This interpretation is not infallible, however – in reality the two forms do not seem to be mutually exclusive, as bronze mould finds are also frequent in some highland areas, such as north Wales [129, p. 2]. The variety of bronze moulds is fairly limited, most are formed to cast axes (palstave and socketed), spearheads, and small tools (palstave-chisels, gouges and awls) [129, p. 2]. It has been suggested by Webley & Adams [129] that this small range in form reflects that Bronze moulds were only created for implements that were manufactured prolifically, since they can be reused repeatedly, but that the creation of these moulds would have been too time intensive to warrant their use for one-off items.

It is also probable that temporary moulds were regularly used during the casting process of bronze objects in Bronze Age Britain. Clay moulds would have been broken after use, so that the cast within could be released; it is for this reason that evidence for these moulds is particularly scant. Nonetheless, due to the high availability of clay in southern Britain, it is very likely that moulds made of this material were used for creating a wide range of tools [60, p. 11]. The production of sand

moulds, which are also invisible in the archaeological record, has also been suggested on several occasions [130], [61], [131]. Sand may have been conveniently gathered from any coastal area and then combined with another material, e.g., animal dung or fats, and plant oils, to induce the sticky quality which is needed to hold the mould together [130, p. 179]. Furthermore, experiments have demonstrated that it is entirely possible to cast bronze implements in bivalve sand moulds [132], [131], [133]. In addition, lost-wax moulds may have been used in the late MBA and LBA to cast intricate ornamental objects, though, like the other two temporary moulds, no evidence survives to attest this [129, p. 2].

Other than their easily accessible sources, multiple arguments have been advocated for the use of clay and sand moulds for casting bronze objects in the British Bronze Age. The principal suggestion relates to the vast disparity which exists between the number of stone or bronze casts and the quantity of bronze objects that have been uncovered; the former are relatively rare in comparison to the latter [61, p. 100]. This inequality is particularly evident for the Early and Middle Bronze Age periods. As such, the employment of materials which are destroyed post-use like clay and sand seems increasingly likely [130, p. 179]. A further argument by Rowlands [60] posits that there would be large numbers of identical Bronze Age tools in the archaeological record if most had been formed by lasting moulds of stone or bronze; instead, it is common to see copies that are very alike, but still retaining some slight variation. This individuality of each artefact may have been introduced by minor deviations that existed between the more transformable clay or sand moulds [60, p. 11]. More specifically, Rowlands [60] has also asserted that it highly probable that the palstaves of southern Britain and northern France were created by use of clay or sand moulds. This was deduced as a consequence of the curvaceous U-shaped septum on these specimens – unlike the very angular septums exhibited by the Irish palstaves, which are largely associated with stone moulds – implying a "plastic quality" to the casting material [60, p. 12].

The utilisation of characterisation techniques has allowed the composition of archaeological metals to be explored, opening up further discussions about design and manufacture. Many impurities from the ore, such as zinc, lead, arsenic, antimony, silver, nickel, bismuth, and cobalt, were often retained and appear in the metal at values of up to 2%. It is also evident that tin was intentionally added to the copper mixture throughout much of the Middle Bronze Age in Britain, when palstaves were the dominant form of axe. The intentional alloying of copper with tin has also been recorded by Allen [116] and Rowlands [60] in their respective analyses of the of the British and Irish material residing in the Pitt Rivers Museum and the Middle Bronze Age metalwork of southern Britain. Brown and Blin-Stoyle [134] studied British material from the Middle Bronze Age and Late Bronze

Age, analysing 209 and 229 objects from each period respectively. The results of the study revealed that the average tin composition for the entire sample was 11% [134, p. 190].

The use of metallographic techniques has permitted the exploration of the microstructure of archaeological metals, contributing to the understanding of palstave axe design and manufacture. Many Bronze Age axes and other implements were analysed by H. H. Coghlan over the course of several decades [116], [135], [136], [137]. These metallographic investigations illustrated the development of a skilled approach in the production of Bronze Age axes over the course of the period. As mentioned in section 2.2.1.2, Early Bronze Age axes were most likely poured into open moulds, which meant that considerable fine-tuning was needed to transform them into a satisfactory form. This is reflected in their microstructures, which show evidence of forging on both the blade and body. The axes were then annealed and probably received further hammering at the blade throughout their use to reform and strengthen the edge [116], [135], [136], [137], [138], [139]. This treatment would have been administered by the use of anvils and pounding stones, the presence of which has been reported at known metalworking sites [140, p. 103]. The use of a bi-valve mould during the casting of a palstave axe meant that after the sprue and any 'flashes' of metal were removed (by 'fettling'), the as-cast form was often very close to the desired shape of the tool [141, p. 427], [60, p. 71]. Consequently, the metallographic analysis suggests that these axes were not subjected to extensive forging, though some moderate hammering, in combination with annealing, is generally apparent at the blade [116], [135], [136], [137]. The majority received a final cold-hammering at the blade edge for the same reasons as cited for earlier specimens. Rowlands [60], [83], has asserted that visual evidence of a hammering is apparent on some Bronze Age palstave axe specimens of southern Britain, for example, crescent shape blades deformed by cold-working, bevelling lines, and light hammering marks on the blade. In their review of Bronze Age palstaves from the Netherlands, Butler and Steegstra [142] also commented that many axes showed 'pouches at the base of the sides of the cutting edge' and a 'J-formed blade', which could be synonymous with hammering [142, p. 165].

### 2.2.1.4    Hafting

Prehistoric palstave axes would have been attached securely to a handle, or haft. Axe hafts are generally considered to have been formed out of wood [143, p. 9], this relates to the dominance of haft finds of this material, and also the idea that bone or antler would not have been able to withstand the percussive force generated when using the axe to strike another material. There is

some evidence, that wood and bone may have interacted to create a composite type of haft [144]. However, the poor preservation of Bronze Age tool hafts, often leaves large gaps in the archaeological record [145, p. 44], [57, p. 40]. In most environments, none, or very little of the haft remains to be discovered and, therefore, only a limited amount information can be gathered and interpreted [146]. Underwater submergence, on the other hand, can benefit the survival of artefacts – organic material is safeguarded from deterioration by its concealment in sediment, producing an anaerobic environment in which the organisms responsible for degradation cannot survive. Some wooden hafts survive in sufficient measure for the species of tree to be identified. The most frequently occurring types appear to be ash (Fraxinus), oak (Quercus), and yew (Taxus baccata) [143, p. 7], [54, p. 136]. Ash seems to be the most common species of wood to be used for axe and spear hafts, this is largely a result of its combined strength and flexibility, reducing the severity of the shock which penetrates through the users arm during use and promotes increased durability [5, p. 124]. The suitability of ash as a haft material for Bronze Age axes has been tested in experimental work [5], [147]. Several investigations have also lead to the discovery of oak hafts; for instance, all three axes found at Flag Fen were of this material [148], as were multiple hafts uncovered at Llyn Fawr and Penwyllt [54]. An example of the use of yew for axe-hafting resides with Otzi the Chalcolithic traveller frozen within an Alpine glacier, though several others also exist [146, p. 88], [149, p. 4].

Although evidence is very scarce, it is highly probable that further precautions were implemented when attaching the axe blade to the haft. Bindings, made of animal skin or plant fibre, would have been wound around the septum of the axe and adjoining haft [145, p. 45]. The most commonly advocated material for this purpose is hide – this was easily accessible from both wild and domesticated animals, and did not require a difficult processing sequence, so that its manufacture was not restricted to experts [145, p. 52]. Raw hide also has an additional advantage – it shrinks, and the colloids adhere together when drying, which allows the tool and the haft to be held together very tightly, with very little opportunity for friction [145, p. 52]. Again, very few of these bindings survive deposition and subsequent environmental conditions, however, the axe found with Otzi is an illuminating example [149, p. 14]. Here, three or four narrow hide strips are slit at their ends and woven into one another, then a final strip was wrapped around the head-step of the haft to anchor the binding in place [146, p. 89]. Fixation agents, such as resin, tar, hide and blood may have been used to glue the haft to the metal blade. Coles [143, p. 9] has suggested that excessive use of such agents would not have been necessary as the force produced when using the implement would have been enough to keep the haft securely wedged into the septum of the palstave. It is also known that these adhesives fracture and disintegrate under high pressure. If

applied at all, it is likely, therefore, that these substances were mixed with beeswax to improve elasticity [145, p. 50]. The only evidence for the use of fixing agents on Bronze Age tools is also derived from Otzi – an investigation conducted on the substance residing between the blade and haft of the iceman's axe revealed that birch tar had been applied [146, p. 89], [150, p. 742]. Birch tar appears to have been a popular choice of glue throughout prehistory, and its presence has been revealed by compositional analysis on a number of stone tools [145, pp. 51, 52].

### 2.2.1.5   Use

In terms of the ideas that surround their functionality, palstave axes present a more complex historiography than other Bronze Age axes. This can be related, in part, to their prescribed name, which originates from the Icelandic, *paalstab*, meaning 'digging tool'. Connotations about the potential use of palstave axes in digging activities have stuck with the artefact throughout its academic evaluation. In his review of Bronze Age agricultural tools, Harding [151, p. 517] reflects on the idea that palstave axes may have been hafted one of two ways: 'traditional' and 'adze-wise'. The latter arrangement is described by Harding as having a "cutting edge at right-angles to the line of hafting", and would have been a more beneficial arrangement for digging [151, p. 518]. Next, Harding considers the tremendous numbers of bronze axes, and the apparent lack, in the archaeological record, of tools that would have been involved in agricultural processes in the Bronze Age, of which ground-breaking would have been a vital component. Following on from this argument, Harding proposes that palstave axes must have filled this void. After all, several cases have (supposedly) emerged, whereby ancient blade cutting scars, likened to the marks produced by a palstave, have been uncovered on the side of Bronze Age earthworks in archaeological investigations, for instance, at the Middle Bronze Age Angle Ditch excavation [152] and the Early/Middle Bronze Age shaft at Wilsford, Wiltshire [153]. One must question, however, if these marks can really be attributed specifically to palstave axes, and whether these interpretations reflect, more closely, the prevailing ideas about the function of the tool at the time.

Of course, palstave axes could have been used for a great diversity of purposes, for example, in food-processing, digging, mattocking, or fighting. As Barber states [14, p. 158], "[the] ideas about their possible uses is limited in part by our own assumptions" – meaning, modern cultural bias can cause the exclusion of viable functional options that may have actually been very relevant to past societies. However, the evidence, so far, does point towards wood-cutting as the primary function of the palstave axe. It is possible to infer, from the socio-economic and environmental

transformations of the Middle Bronze Age period, that considerable woodland clearances must have occurred. In a slight retraction of his former hypothesis about the number of palstave axes and their use as digging tools, Harding [23], and, later, Barber [14], have now recommended that the absence of other agricultural implements could suggest that they were actually made of wood. Hence, agricultural intensification would have required the production of many wooden tools, such as, ards, rakes, pitchforks, and shovels, in addition to wooden hilts and handles – which must have been whittled from timber chopped down by axes [23, p. 244]. Though it is not possible to say with complete certainty that palstave axes were used for woodland clearance and associated woodworking, use-wear analysis has demonstrated that the proceeding and succeeding axe typologies were used in wood-cutting activities [5], [6], [154]; considering then that palstave axes were the dominant axe type for approximately five hundred years, they must have assumed a similar role to cater to the needs of Bronze Age society. Bradley stresses the importance of these tools in the society of the Bronze Age when he asserts that:

*"[t]he axe may be considered the symbol of agricultural settlement as it provides the means of clearing the land and building houses"* - [62, p. 48].

As indicated by the above, the use of palstave axes in the construction and maintenance of settlements can also be readily assumed. Timber was the principal element of round houses; though later types were sometimes made in part by stone. In addition, from the Middle Bronze Age onwards, some sites of occupation were also enclosed by a low earthwork and palisade fence, or box rampart [23, p. 247]. Hence, there is much indirect evidence that points to the use of palstave axes in woodland clearance and in wood-working industries. One palstave axe has even been found 'in situ', as it were. At Woodwalton Fen, Cambridgeshire, a substantial buried forest has been uncovered, with many trunks and stubs to indicate the extent of the tree-felling activities [155, p. 167]. A palstave axe was found pecked into the buried trunk of an oak tree, like someone had placed it there and then forgotten to retrieve it [155, pp. 165, 166]. Secondly, as it stands, there is no known evidence for the hafting of Bronze Age axes as adzes, while two wooden palstave hafts have been discovered near Peterborough [156] and Langtoft, Lincolnshire [157], which were both designed to accommodate the palstave as an axe.

Many palstave axes have been discovered in what has been perceived to be, an unused state, which has prompted notions of limited use, and ideas that palstave axes could have been deliberately created as 'ingots' or for use in deposition [83], [13, p. 430]. Certainly, some of these objects, especially smaller varieties, may have actually been ingots, as research into the consistent weight of small types of palstave axe from the Smørumovre hoard, Denmark, has suggested [158].

However, the majority of the palstave axes present within the archaeological record of Britain are the larger, more robust varieties, that would have been capable of functional use [83], [114]. While there is compelling evidence to suggest that the majority of palstave axes would have had a functional purpose (as discussed above), it is pertinent to remember that the objects included in deposition cannot be considered to be representative of the norm. They are, instead, objects with distinguished value that were deliberately chosen for use in ceremonial practice, and hence may not have necessarily been working tools [76, p. 112]. The creation of palstaves for the intent purpose of deposition would, however, represent a large deviation from the life histories of other typologies [5], [6], [154]. Much of the significance bestowed on an artefact – especially everyday 'lived' objects, which obtain greater social meaning throughout engagement in social activities – is negotiated through its use [1, pp. 63–65]. Therefore, as Barber [14, p. 167] emphasises:

*"the secular and symbolic aspects of metal and metalwork were likely to have been closely entwined throughout the Bronze Age".*

It seems more likely that palstave axes would have been used, becoming engrained in special meaning by curation and the human-substrate relationships that this entailed. Eventually this exceptional history assumed paramount importance and they would have been removed from circulation [14, p. 167], [76, p. 112]. Yet, with no experimental work to establish the rate and form of wear on replica palstave axes, nor any use-wear analysis on ancient palstave axes, it is not possible to say that these objects they had a functional life at all. The lack of visible use could be related to other factors, which have so far remain unexplored. For example, palstave axes generally have an 'optimum' alloying mix of around 10% tin [116] and have been said to have exceptional balance, as well being efficient, durable cutting tools [135, p. 9], [159]. Hence, it could be that the absence of obvious deformations at the cutting-edge of palstave axes is a reflection of their superior mechanical properties, which make them more resilient to cyclic loading than other axe typologies.

As such, the present project, which is born out of the lack of use-wear analysis for Bronze Age palstave axes, will use the principles and concepts of materials science to conduct wear analysis of these objects to ascertain use-intensity. This will indicate just how prevalent functional use was in the lives of palstave axes [90, p. 545]. Such endeavours have already been undertaken in relation to the use-wear of archaeological assemblages [101], [160], [161], as well as prehistoric metalwork hoards. For example, O'Flaherty [9] concluded that longer and heavier halberds were much more likely to have less evidence of use, and they may have been created purely as deterrents. Similarly, Wall [162] discovered that Wessex daggers were usually subject to more wear than non-Wessex daggers, and that those from later phases were less damaged. Lastly, Roberts and Ottaway [5]

reported socketed axes from south-east Scotland were used much more heavily than those from eastern Yorkshire. Developing more detailed measures of use-intensity for palstave axes permits the same kind of interrogation as the studies listed above, but at much finer scales of inference; changing the debate from used/not-used, to the position within a spectrum of use-intensity. The higher the estimated use-intensity, the lengthier the functional biography before discard or recontextualisation.

### 2.2.1.6    Maintenance

Palstave axes would have required sharpening to maintain efficiency and this would have been a regular occurrence in the experiential repertoire of Bronze Age labourers [163, p. 98]. Experimental work has exemplified that bronze axes start to dull shortly after the beginning of use but actually remain efficient much past this point [159], [147]. Given the likely familiarity of Bronze Age people with the tools that they spent hours wielding and maintaining, it is not that hard to infer that individuals would have had an intuitive understanding of when an axe needed sharpening. Furthermore, archaeological evidence has illustrated that whetstones were carried around as part of a personal toolkit, permitting sharpening not only at the end of the working day, but whenever the optimum time for sharpening was determined by the user [146]. There is no guarantee that prehistoric people would have sharpened their axes only at the point where they reach minimum efficiency – it may have been a common practice to resharpen tools after every working day. If bronze was considered a special material with high value, then it is not hard to imagine the great care that may have gone into keeping objects, even routine tools, in pristine condition.

The resharpening of axes in the Bronze Age would have taken place by use of a collection of lithic tools, for example, grinding stones, whetstones, and polishing stones [140, p. 103]. Metalworking tools are often overlooked within the archaeological record; this is somewhat related to their deposition contexts – they are not often found in association with bronze artefacts, which can make them difficult to attribute to this industry – and also reflects that they have been afforded limited focus in the general discourse on Bronze Age material. Nonetheless, in his investigation of tools uncovered at Feudvar in the Carpathian Basin, Kienlin [164] was able to detect metal particles within the surface of the grinding stones – illustrating a reliable method to unequivocally connect such tools with the processing of metal. The metalworking locus discovered at the Late Bronze Age and Early Iron settlement of Timna (situated in the ancient Near East), has permitted the determination of grinding stones as unifacial loaf-shaped rocks of a medium coarseness [165, pp.

7, 8]. These stones most likely would have been used for fettling and creating a uniform surface. Whetstones and other polishing stone, by contrast, are generally finer and would have been small enough to be carried. An array of whetstones have been uncovered from the Early Bronze Age period and a collection of 21 samples was analysed by Woodward [81]; many of these samples showed evidence of wear and two even harboured traces of metal.

### 2.2.1.7    Recycling

Much metalwork was probably recycled and, thus, discoveries of palstave axes probably only constitute a small proportion of the objects that were consumed, and represent pieces that, for some reason or another, have not been included in recycling [166]. Recycling is generally difficult to detect as a result of the literal 'scrambling' of many useful compositional signatures within the material. While not entirely relevant to palstave axes, Bray and Pollard [167] were able to successfully detect recycling practices in EBA copper-arsenic-antimony-silver axes and other objects, suggesting the long period over which bronzes were subjected to recycling. The tennantite-tetrahedrite series makes the Ross Island mine, Co. Kerry, the only site currently recognized as being able to produce arsenic-silver-antimony, so many objects carrying this compound have been attributed to Ross Island. The objects that have had their manufacture dated to the period between 2000 and 1600 BC, when the mine was no longer active, have significant reductions in arsenic, antimony and silver levels – the authors deduced that these artefacts may have been formed using metal that was initially smelted around 500 years beforehand, with extensive recycling events between their first and final forms. In the same study, another 66 bronze artefacts from the same period were analysed, showing evidence of very low levels of silver (between 0.1 and 1%), with other elements seemingly absent (below 0.1%). There is no known ore source that would produce this composition so the authors suggest that when shifts in the chemical composition are taken into consideration, i.e., the loss of arsenic and antimony while the more noble silver remains, as a consequence of re-melting, it becomes clear that the artefacts are made from extensively recycled Ross Island metal. These studies have reinforced the belief that increased recycling practices emerged in the EBA as people began to widely recognize the mutability of metal.

## 2.2.1.8 Destruction and discard

It has already been suggested that palstave axes are ordinarily found in a 'complete' and 'undamaged' condition. Within his PhD thesis, which focuses on the patterns of destruction within Bronze Age metalwork from the south-west of England, Knight emphasises that palstave axes are regularly found in a 'complete' condition [13, p. 222]. He also recommends that the majority of damage exhibited on palstave axes can be defined as accidental [13, p. 430]. This was deduced by assessing areas of the palstave axe that may be susceptible to damage during use; the 'patterns of breakage'. Knight [13, p. 170] has suggested that the common areas of damage are the flanges, side-loop, and stopridge. Of course, damage in a similar place on many of the same type of object could suggest that there are certain rules governing its treatment, however, where fairly obvious design flaws can be envisaged, it is more likely to be related to the former. However, on a relatively minor amount of palstave axes, the breaks do occur in an unusual places, for example, across the body of the blade, or across the lower section of the blade. Knight proposes that this could reflect evidence of deliberate destruction, and where percussion marks surrounding the location of fracture were observed, this can be assumed with some certainty [13, p. 430]. Some suggestions have already been made as to the reason behind why bronze objects were deliberately destroyed (see section 2.1.3).

Similarly, the considerations around the motivations for deposition of bronze metalwork have already been discussed at length in the section mentioned above. Below presents a succinct review of the condition and treatment of palstave axes, in particular, during depositional practices. Looking to the catalogues of Bronze Age palstave axes [83], [114], [116], and the Portable Antiquities Scheme database, it is clear that the majority retained a fairly tidy cutting-edge despite any other damages. If this remains true upon further analysis, then there is strong case to suggest that palstave axes were preferred in a pristine condition for deposition, or were intentionally prepared for deposition by re-sharpening. The latter of these two outcomes would be very unusual in the context of Bronze Age metalwork, for which the presence of damage and use-wear on the blade of implements was acceptable, or even desirable [76, p. 139]. As Bradley suggests, re-sharpening means that they, "were made ready for a use that never happened", and could indicate that they were "destined for use in another world" [76, p. 139]. Palstave axes are variously discovered as isolated finds or as a part of larger assemblages. These may be deposits consisting of palstave axes only, but often other associated material is included, such as pottery, sherds, pins, flat axes, flanged axes, socketed axes, spearheads, rapiers or swords. Yates and Bradley's [168] investigation of the sites of one hundred well-provenanced hoards (many including palstaves) in the south-east of

England, revealed that the majority were situated beside streams, springs, river promontories, field boundaries and ancestral sites. Evidence from the south-west of England also points to the recurring localities of palstave deposits at sites of ancestral importance and areas overlooking water or wetlands [13, p. 319].

## 2.3   Relational narratives and life trajectories

This basic linear assessment presented above reflects an extensive and complex life history; still, it is very unlikely that most palstave axes experienced such a simplified sequence. The meanings ascribed to objects can be so drastically altered that they are considered to have gone through 'reincarnation' events, whereby the object may have, for all intents and purposes, already died, and is then re-born as something almost entirely new [90, p. 543]. This may have meant periods of relative inactivity in the utilitarian sphere, coupled with intense periods of use, as palstave axes changed hands and/or their purpose was redefined. The linearity of object lives cannot, therefore, be wholly assumed. In terms of the present investigation, the measure of the severity of wear and/or deformation can only tell us about the *total* intensity of functional use, and not individual stages of use or curation. Furthermore, sometimes the nature of the archaeological record makes it near impossible to extract all the relevant information for creating a comprehensive 'birth', 'life' and 'death' assessment. For example, corrosion can completely modify the appearance of the object, and some finds have no context history. In addition, there is no established method for extrapolating the 'time in circulation' (see [6] for an alternative opinion). Therefore, it is not possible to predict the timescale that activity was conducted over. Such comparisons would be invaluable for understanding whether objects transcended generational barriers [65, p. 242].

Joy [90] suggests that one way to partially resolve the problems mentioned above, is to develop 'relational biographies'. This advancement to the approach asserts that a linear, continual reconstruction is not essential, as the narrative can instead be considered as "connected jumps as the object becomes alive within certain clusters of social relationships and is inactive at other points in time and space" [90, p. 544]. By considering object biographies as relational, archaeologists are able to bring together all the available knowledge about an object without feeling that crucial information is missing; and, when one considers that most objects have multiple lives that simultaneously evolve to create multi-dimensional narratives, this approach can easily be used to create full biographies. Humans, for example, have a range of biographies, 'personal, professional, financial, political, psychological' – a look at the Wikipedia page for any notable person would

reinforce this – each of these has the purpose of telling a highly-specific story about the life of an individual [98, p. 488]. Likewise, objects have separate narratives that emphasise varying aspects of their lives, e.g., technical, economic, political, social, and spiritual [98, p. 488]. By examining the sum total of relationships forged in different spheres of the social web, relational biographies are able to form pervasive assessments about the engrained meanings of objects [90, p. 552]. Hence, this study will attempt to produce relational narratives of palstave axes by linking the severity of wear to the use-intensity of palstave axes, as well as compiling all the metallurgical, and contextual information that is available to try to reveal how these objects actively influenced Bronze Age society. For example, if the artefact technology suggests a lack of functionality, the visual inspection indicates deliberate damage, *and* the gauge of use-intensity demonstrates a low level of use, it may be appropriate to assume that the social and spiritual narratives of the object were far more important than technical [86, p. 5], [87, p. 2], [89, p. 6].

Though biographical analysis is usually 'confined to the scale of the individual object' to avoid generic interpretations about diverse material, the construction of 'life trajectories' may also be enlisted to compliment the construction of artefact-specific biographies and look for trends in the sample as a whole [90, p. 545]. These trajectories seek to simplify the stages in the life of a palstave axe to create versions that are easily cross-comparable. As Joy [90, p. 545] asserts, "by examining object groups it is possible to identify an 'idealized' life for a particular artefact type and spot those objects that deviate from the 'norm'". Or, rather, the life trajectories of the sample may reveal some commonalities between the narratives of different objects, while illuminating the vast amount of diversity that exists. Therefore, the construction of life trajectories in the present study is used to investigate the differing lives of palstave axes from the same hoards and across pooled deposits. This may highlight geographical, chronological, and typological trends in the treatment and curation of palstave axes. For example, a disparity in the use-intensity exhibited by palstave axes found in different geographical regions could suggest that these objects remained in circulation for longer in certain areas, before they were deposited [169, p. 90]. Equally, different levels of use-intensity in axes with a contrasting chronology could indicate a change in the curation of the objects over time. Moreover, the use of life trajectories helps to accentuate singular or groups of artefacts that have unusual narratives, so that their unique qualities are not ignored.

# 3   Metal use-wear analysis

The present chapter consists of a general overview and critique of past and present methodological approaches in the field of use-wear analysis, focusing mainly on the methods that have been conducted on Bronze Age axes, alongside work undertaken on other metal implements. The text discusses the methodological advances to the discipline of metal use-wear analysis from its conception in the 1950s, until the latest studies in the current decade. Subsequently, several gaps, which still pervade within the methodological strategy applied in the study of the wear manifested on metal artefacts, will be examined. This emphasises the necessity for more methodologically robust approaches and a wider scope, including the introduction of new experimental setups and techniques; so framing the methodological direction of this project.

## 3.1   The development of the field

Interest surrounding traces of use-wear detectable on archaeological artefacts emerged out of Semenov's [170] influential publication, *Prehistoric Technology*, in 1957. Within this work, the author systematically examined and recorded distinguishable marks related to use on the cutting blade of lithic tools with a 'low-power' microscope (<100 magnification), comparing them to observable striations on modern metal tools for clarification of function [86, p. 4], [171, p. 2]. These early attempts at use-wear analysis were later extended to include the determination of evidence of use on bone and metal artefacts [5, p. 120]. In addition, Semenov reconstructed prehistoric tools to further understand their manufacture, utilisation, productivity and effectiveness [172]. Since these initial efforts to develop a methodology for use-wear investigations, analysts have been preoccupied by the study of lithic, and increasingly, bone tools. This generated a rapid development of use-wear methodologies on each of these respective materials [173], [174], [175], [176], [177], [178], [179].

In contrast to the flourishing fields of lithic and bone wear analysis, the same level of attention was not initially applied to the analysis of wear on metal artefacts, which was often dismissed as unfeasible due to the complications added by manufacturing processes, recycling, sharpening, and corrosion [5, pp. 119, 120]. Nonetheless, some researchers were not discouraged by this premature condemnation of the field and by the late 1970s the earliest metal wear analysis was underway [180, p. 115]. In 1977, Penman [181] conducted metal wear analysis on over a thousand artefacts

pertaining to the Old Copper culture of North America – assessing the degree of blunting to the edges of the objects, the visible evidence of blows, and any indications of repair. From this, Penman concluded that very many of the artefacts could be considered as functional tools [182, p. 222]. Another early attempt at employing wear analysis on metal artefacts was implemented by Schauer [183], who characterised traces of use on Bronze Age spear-heads. Although these studies were constrained by simple, descriptive identification of use-wear, they still laid the foundations for the most basic methodology for analysing the evidence of wear on metal archaeological objects.

In a highly intuitive study, Kristiansen [184], [185], used macroscopic and low-power microscopic analysis to determine the extent of wear on Bronze Age swords within the threefold division of 'light', 'moderate', and 'heavy'. A similar method was subsequently applied by Wall [162, p. 116], who examined daggers from southern Britain for the presence of several surface features and then separated the specimens by the extent of wear observed into Kristiansen's categories of light wear, moderate wear, and heavy wear. This tripartite division of level of wear, and variants on the same theme, were adopted by the discipline and still remain the primary approach for documenting the amount of wear subjected to an artefact during use. At a similar time, Gordon [186] published his wear analysis of thirteen bronze tools from Machu Pichu. This used tribological principles, metallurgical investigation, and microscopic techniques to assess the evidence of post-production techniques and use on both the microstructure and surface of the implements. This study was very comprehensive in comparison to the preceding attempts, which were mostly conducted by non-specialists with little knowledge of either lithic wear analysis or materials science concepts [12, p. 79]. It could be argued that the appreciation of the underlying metallurgy of the material within Gordon's research has not since been paralleled in any other study of metal wear analysis. In the following decade, the field of metal use-wear research did not attract a great deal of interest. This was, perhaps, a consequence of the range of approaches that had been previously adopted, which did not leave a clear direction in which to advance the field. A central methodological framework was required to produce results within a consistent rubric and reinvigorate research.

## 3.2   Use-wear analysis of Bronze Age axes

In the latter part of the 1990s, the first truly systematic approach for analysing use-wear on metal artefacts was proposed by Kienlin and Ottaway [147] in their pioneering study, *Flanged axes of the North-Alpine region: an assessment of the possibilities of use-wear analysis on metal artefacts*. Their adopted method was: 1) actualistic experiments using 11 bronze flanged axe replicas with a range

of compositions and post-production processing to cut wood, in order to track the progression of wear; 2) producing dental casts of the replica axes and Bronze Age specimens; 3) inspecting the dental casts of the ancient axes for evidence of wear, such as, nicks, bluntness, asymmetry, scratches, by low-power microscopy, using the known deformations on the modern samples as a reference [147, pp. 271, 275]. The main objective of the experimental work was to observe how long the axes would last until they were severely worn and in need of sharpening. After this, the axes were not sharpened, so that the evidence of wear would not be destroyed, but instead, continued to be used in experimental trials until further use was impossible, so to produce the most extreme wear possible. The results of the reconstruction work demonstrated that pure copper axes blunted very quickly, and were prone to nicks and bending. The axes that had been cold-hammered lasted longer than those that had no intentional hardening; for the copper axes the durability improved by 30-50% and for tin axes the durability improved by 13-19%. Kienlin and Ottaway [147] explain that the types of wear observed on cold-hammered axes were similar to those seen on the pure copper axes, though this is not entirely obvious in the microscope images provided [147, p. 279]. The deformation phenomena were compared to those on prehistoric axes of type Salez and type Neyruz by microscope and were found to be comparable. The majority presented at least some blunting and nicks, and the authors were able to determine that 54% of the former type exhibited heavy damage, while this was as high as 72% in the latter [147, p. 284]. Hence this study illustrated that the functional application of the axes in woodworking activities was likely and that many had been used extensively. However, the most innovative aspects of the study are found in the reconstruction of experimental specimens. Where previous studies relied only on intuition to determine the nature of wear marks, the authors recognised that a catalogue of wear must be created with experimental work on replica objects to permit accurate analysis of the related artefacts.

While some scholars chose to disregard the call for experimental comparison [81], [187], the beginning of the 21st century largely saw widespread implementation of the methodological procedure suggested by Kienlin and Ottaway [147], and so commenced the application of experimental archaeology in metal use-wear studies on axes [12, p. 79]. Several efforts have been made to detail the traces of the woodworking on Bronze Age axes. Moyler [6] conducted a study on flat axes from Scotland, creating a programme of experimental work using five annealed and cold-hammered replica flat axes of varying composition (0%, 8%, and 10% tin-bronze) to fell trees in the New Forest. The author recorded the progression of bluntness, nicks, and use striations macroscopically on the axes over cycles of use and sharpening, and additionally, noted the development of asymmetry on the blades. Unfortunately, with the exception of a vague description

of the type of wear recorded on each axe, the author did not report the results of these experiments in full, citing the large number of variables as prohibitive of a comparative assessment between axes of differing metallurgical specifications. The prehistoric specimens (n = 278) were separated into three quantitative divisions; those that had received wear to the blade in the region of 0-10% were regarded to have had 'small use', those with blade wear between 10-20% were considered to have had 'medium use', and those with wear to the blade over 20% were thought to have had 'heavy use'. This categorisation of blade wear into percentile was partly based on the difference between the estimated original blade symmetry and the extant blade symmetry; and so, the 'blade wear', in this case, is actually a measure of material loss [6, p. 78]. Moyler [6] also made an assessment of the 'edge freshness' from the ornamental features on the axes – which was assumed to represent the length of circulation time – and, thus, some kind of gauge of 'intensity of use' versus 'overall life' could be formed (*Figure 8*) [6, p. 101]. The prehistoric axes appeared to be equally distributed across each ordered category, apart from that there were substantially more single finds in the 'small use, short circulation' group.
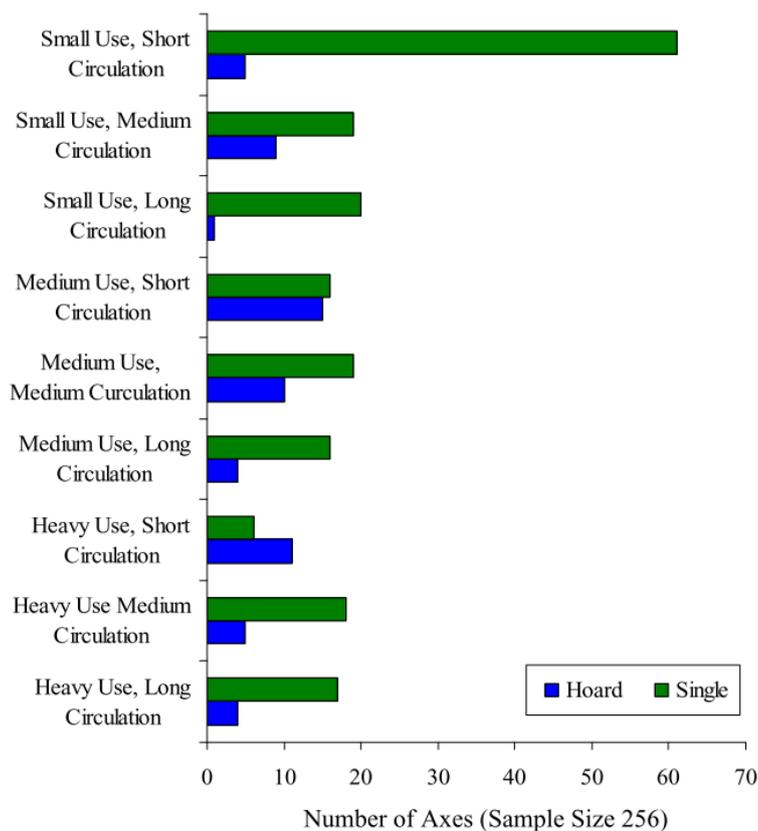


*Figure 8:* Bar chart categorising Flat axes from Yorkshire and Scotland by extent
of use and time in circulation (Source: courtesy of Shaun Moyler [6, p. 101]).

Continuing flat axe investigation, Crellin [154] recently published research on the examination of 38 axes from across Britain and Ireland. No experimental work was conducted, with the author drawing upon the repository of marks established by previous research using replicas in functional situations, e.g., [5], [2], [147], [188]. From this, the wear categories devised for blade deformation included: asymmetry of the blade, breaks to the blade, bluntness, flattening, and any evidence of bending. Furthermore, the investigation also involved an assessment of the axe butt for suggestions of wear, such as, rounding of the edges, striations, nicks, and asymmetry. The prehistoric axes were subjected to an analytical scheme that involved visual and photographic inspection, as well as microscopic documentation at magnifications from x8 to x40. Thirteen axes were considered to be only slightly blunt, and four very blunt [122, p. 10]. Measures of blade asymmetry were high, with nineteen axes demonstrating uneven wear [122, p. 10]. Moreover, twenty showed evidence of use-wear marks, and nine had breaks to the blade. Interestingly, a large proportion of the axes also exhibited rounding of the butt, and on some this was so pronounced that it culminated in asymmetry. Using the criteria above, encompassing both blade and butt wear, Crellin was able to discern that only two axes failed to show any evidence of use, while another had no blade present for analysis [122, p. 11]. Alongside her intriguing observations regarding the evidence for intentional deposition amongst these specimens, Crellin concluded that axes with many different life histories were deposited in symbolic circumstances [154, p. 15].

The only study focused on a later type of Bronze Age axe is Roberts and Ottaway's [5] analysis of the socketed axes of Bronze Age Yorkshire and Scotland. In this study, two replica socketed axes of 9% tin and 5% lead were constructed and used to strike wood; the traces that were forming on the surface were recorded by microscopy, photography and sketched diagrams at 15, 60, 120 and 240 minutes [5, p. 126]. Some of the production choices may have made the samples less representative; for example, it is well known that the blades of socketed axes were subjected to a final cold-hammering [116], but the replicas had none administered to them – the authors explained that this was in order to "minimize the number of experimental variables present" [5, p. 124]. The authors noted that while scratches were rapidly acquired, the blade remained sharp after considerable use and sharpening would have only been advantageous in the last hour of experimental work [5, p. 125]. Interestingly, there was no 'nick' formation like observed in the studies mentioned above, with the authors suggesting that these may only have been made by striking materials other than wood [5, p. 126]. Perhaps it is likely that in the case of high-tin, leaded alloys, the formation of nicks is not probable during a correct and standard chopping action onto wood. From a total of 54 prehistoric specimens, 31 were analysed for signs of micro deformation, while the remaining 23 were only analysed for evidence of macro deformation [5, p. 127]. The

results suggested many of the axes had been subjected to variable light use, though a noticeable proportion of the Scottish axes had indications of variable heavy use [5, p. 129]. The authors also commented that over 80% of the ancient axes had retained a robust cutting-edge, signifying that they were in a state where they could still be used [5, p. 136]. Thus, while the outcomes of the experiment suggest that the axes had been used to some extent, they were often discarded in a functional state.

## 3.3   Addressing lacunae

After evaluating the aforementioned studies, the key areas in need of methodological development in the metalwork wear-analysis of Bronze Age axes can be offered. None of the above studies included assessments of metallurgical properties of their samples beyond alloy composition, which limits not only vital information about how the objects were produced but does not give analysts all the information required to make valid judgments about wear (this will be expanded upon in Chapter 4). Similarly, the above studies have also suggested that actualistic testing cannot provide a highly-controlled experimental setup, which means answers about the influence of varying metallurgy remains elusive. The variables within these reconstruction tests need to be controlled more vigorously if the aim is to deduce the mechanics of wear. Furthermore, the identification of individual types of deformation phenomena remain ill-defined and presents only qualitative data. While low-power microscopy is regularly used, the adoption of high-power techniques could lead to breakthroughs in how certain wear formations propagate during use. Furthermore, as mentioned many times throughout this thesis already, there has been no investigation into how the specific manufacturing and morphologies pertaining to palstave axes may impact the way that deformation occurs. These issues, and any recent implementations within the methodological approach of metal use-wear analysis to address them, are examined in greater detail below.

### 3.3.1   Redefining the experimental

As the review conducted in section 3.2 has illustrated, experimental archaeology has had a longstanding relationship with metal use-wear analysis. Experimental archaeology is defined by Heeb and Ottaway [130, pp. 161, 162] as, "meticulously recorded experiments on and with materials and objects which were available at the time [of interest] for a better understanding of

methods of production and use". The terminology used in this definition implies a strong sense of scientific endeavour within experimental archaeology. This is a fair assessment of the outlook of the discipline today after rigorous attempts to create a distinction between 'experiential' (archaeological reconstruction to understand past human experience and perception) and 'experimental' (controlled tests with a clear objective) approaches. A clear division between these two approaches is necessary to ensure that so-called 'processes and function' experiments with replica artefacts, such as the type employed in metal use-wear analysis, can be conducted by thorough and systematic testing against a pre-determined hypothesis [189]. When falsified, certain parameters of the experiment can be changed to fit a new theory, and further testing can occur. Therefore, this system, while never proving outright that prehistoric people acted in a certain way, continuously narrows the possibilities of engagement between humans and materials [190, p. 18], [130, p. 162]. The most significant contribution to the reformulation of experimental archaeology was John Coles' [190, pp. 15–18] rules for experimental archaeology:

1. Experimental materials must have been accessible to the ancient society that are under investigation;

2. The manufacturing applied to said materials should also be within the supposed technical repertoire of the society;

3. The application of technology should not be permitted if it is likely to lead to the misconstruction of results, except where new analytical techniques have the capacity to enhance understanding;

4. Efforts should be made to ascertain the scope of the project before testing starts;

5. Experiments must be repetitive and follow a logical course of inference;

6. Researchers should have a legitimate uncertainty that the applied method will succeed and be ready to adapt the approach accordingly if this is the case. Even if the first attempt at experimentation produces a favourable outcome, other methods should still be considered and trialled;

7. Experimental archaeology cannot be considered to produce conclusive evidence that particular methods or processes were employed in the past;

8. A scientific approach to assumptions and uncertainties should be taken, so that the limits of the study are discussed openly and without misrepresentation.

While most of the guidelines described above should be strictly adhered to, the rule regarding the application of technology must be reconsidered as modern technological approaches with a significant potential for archaeological reconstruction work become available. In use-wear studies,

researchers should now make efforts to determine if their desired experimental outcome can be better reached by either actualistic or laboratory experimentation. The former of these two types of testing uses human participants, usually in an outdoor environment, to simulate the desired action(s) with the replica object. Experimental parameters, such as, the raw material, instrument manufacturing and post-casting treatment, the morphology of the replica, the weight of the replica, the type of action, the direction and angle of contact, and the total time used, are monitored (and regulated as much as is possible) during experimental trials [180]. However, as a consequence of the individual agency of the participants – who are not completely consistent in their movements and are liable to error – actualistic studies do not have a rigorously controlled format. This is not necessarily a problem – as emphasised by Bamforth [191, p. 101], if the aim of the research is to produce recognisable traces of use that can be compared to tools that were used by 'real people to accomplish real tasks in the past', then using real-life testing may be the only way forward. There is just no possibility, at least for now, that machines can be as convincing at documenting the unpredictability of human nature as people are. Thus, many of the tests with replica archaeological objects, conducted for the purpose of creating a corpus of marks to use as a comparison with those found on actual archaeological material, consist of actualistic experiments.

There is a lively debate in Bronze Age use-wear research on weapons (especially swords) over whether actualistic replications or simulated lab replications provide more reliable results for comparison to original Bronze Age metalwork. As Hermann et al. [192, p. 1041] suggest, laboratory tests using drop towers offer much better control over the variables of an experiment, in addition to an improved ability to document the mechanical properties of a weapon and the progression wear formation. As Molloy [193, p. 75] also mentions, mechanical impact testing may be crucial in providing the ability to investigate mechanical properties, like toughness, that are often ignored in current reconstruction experiments. However, as already mentioned above, mechanised testing does little to capture the complexity of human movement; this is of particular importance for swordsmanship, for which, the type of marks that are generated on the blade are considered a product of dynamic movement patterns cultivated through handler experience [192, p. 1041]. It would not make sense, therefore, to apply what Molloy [194, p. 118] terms as a 'whack it and see' approach to determine how marks on swords are accrued as this does not accurately reflect how the object is used in a combat setting. Instead, it is important for an experienced sword user to be able to create the setting for an accurate combat scenario by understanding likely movements and knowing how best to apply the weapon in terms of speed, force, blade geometry, and point of striking [196, p. 119].

On the other hand, if the objective of the research is to understand how, or at what rate, wear propagates on archaeological metals at a scientific level, then controlled laboratory experiments provide the best solution [191, p. 101]. In most cases this involves the manufacture of specifically-adapted mechanised rigs to simulate highly-specialised scenarios. This can be a laborious and daunting process, but the virtues of this method are clear. Firstly, it is possible to closely monitor the experimental variables (for example, the duration of work, force applied, and the executed action), so that the influence to the formation of wear under a certain parameter may be examined in isolation from the effects of other variables [180, p. 115], [12, p. 84]. This also makes the work easily repeatable. In addition, since human tiredness does not provide a limitation, this type of testing strategy may accelerate the analytical process; this means it may be possible to work with much larger data sets. Furthermore, all the experimental work can be contained within a series of laboratories that may reside in close spatial relation to one another, which is advantageous for the speed of data retrieval [195, p. 166]. Research using mechanised rigs has already been trialled by several authors over the last several decades. For example, Bridgford [7], [8], conducted experimental work on Bronze Age swords and spear-heads using a Monsanto Tensometer Balanced Impact Machine. O'Flaherty [196] simulated the use of a set of replica halberds in a Rosand high strain rate test facility. The true potential of such tests is still to be realised as the increasingly sophisticated technology of impact science allows for exciting new analytical possibilities. Hence, highly-controlled mechanised testing will be used to evaluate the use-wear of replica palstave axes included here-in.

### 3.3.2    Bringing structure to the foreground

Ascertaining the manufacturing process that formed Bronze Age artefacts is an integral part of artefact analysis, and crucial for use-wear investigations. In metal use-wear studies there has been a distinct lack of metallurgical analysis employed as part of the examination of both experimental replicas and ancient samples. Metals behave according to their composition, post-production processing, and use (see Chapter 4). Variations in these determine mechanical properties, such as elasticity, toughness, and hardness. Therefore, as the unique response of the material is integral to understanding the propagation of wear, metallographic investigation should be applied routinely during multiple stages of the experimental protocol [4, p. 175]. Analysis of the manifestation of wear on a material without obtaining sufficient understanding of its structural properties could be likened to trying to conduct a psychometric test on an individual for whom none of the underlying

personality traits have been ascertained; it is completely futile, since the very essence of what is being tested within the assessment is absent. Indeed, within their recent review paper, Dolfini & Crellin [12, p. 83] sensibly redefined the theoretical placement of the field of metal use-wear analysis at the junction between metallurgy, experimental archaeology, and use-wear analysis.

At the most basic level, the composition of the metal objects must be known and, in the case of experimental replicas, must be controlled. Techniques that allow the characterization of archaeological metals, for example, Energy-Dispersive X-ray (EDX), Inductively Coupled Plasma Mass Spectrometry (ICMPS), are widely available and have already been used to determine the chemical composition in a great variation of metal artefacts. As much previous experimentation has shown, [116], [141], [138], [139], [197], [198], [199], [200], [201], [202], [203], it is also possible to determine the approximate processes that formed metallic objects by examining arrangements in the microstructure by high-power microscope and hardness testing. Consequently, there is little justification for failing to consider the impact of manufacturing on the wear formation of metal artefacts or replicas. Nonetheless, the implementation of metallographic examination in metal use-wear studies has been haphazard at best. Many studies have completely failed to appreciate the relevance of the microstructure to their experimental scheme, some completed only the characterisation of past materials [8], [186], [204], or modern replicas [196], while next to none have provided comparisons between the two [205].

To elucidate, O'Flaherty et al. [196] [10] created a set of replica halberds that were then tested in reconstruction experiments. Hardness measurements of the halberds were taken and values from the bulk and cutting edge of one replica halberd corresponded well with measurements obtained from prehistoric specimens in work by Allen [116]. Bridgford [7], [8], conducted a comprehensive study of the metallurgy and wear of Bronze Age swords and spear-heads from the British Isles. Going a step further, Modlinger [204, p. 153] exercised an array of analytical techniques, for instance, Scanning Electron Microscopy, Electron Probe, X-ray fluorescence, X-ray, time of flight Neutron Diffraction, and 3D Computed Tomography to investigate the manufacture and usage of 50 Bronze Age swords from central Europe. The metallographic features that were examined consisted of: the composition; presence of eutectoid; the presence of the delta-phase; the maximum hardness on the edge of the blade; the percentage of deformation; and, the presence of slip lines [204, p. 157]. Anderson [205, p. 599] manufactured an extensive assemblage of replica spear-heads with consideration of the relevant typologies and manufacturing procedures of the Bronze Age. The hardness at the edge near the socket, the edge near the tip, and the midrib, was tested on 13 of the experimental spear-heads, against the hardness measurements recorded by

Tylecote [206] for prehistoric axes, swords, and spear-heads [205, p. 602]. Anderson [205, p. 599] then investigated the results of experimentation with these replicas against evidence for wear on 222 Late Bronze Age spear-heads found in northern Britain.

The interest in the metallography of ancient and replica specimens as suggested above, indicates a greater awareness of the potential contribution of materials science to metal use-wear analysis. This is not always the case, however, since a certain disregard for metallurgy and microstructure has been suggested, in particular, by the recent re-use of experimental reference collections that could be entirely dissimilar to the ancient artefacts being analysed. This is especially true where the production of replica bronze objects was reflective of the procedure in culturally-specific areas, but is then applied to geographically dissimilar prehistoric collections [2], [11], [207]. For example, in 2011, several projects were published that relied on prior experimental work by other authors for the interpretation of wear marks. For instance, Brandherm [11], used the experimental evidence produced by O'Flaherty [9], [10], as comparative data for assessing the wear marks on bronze halberds from Iberia. The corpus of wear marks that were recorded in the work of Bridgford were used again by York [208], in her analysis of 302 Bronze Age metal artefacts; a large proportion of these were spear-heads, swords, dirks, rapiers, and daggers that had been extracted from the non-tidal river Thames. Likewise, Dolfini [2], analysed nineteen axes, eight daggers, five halberds and an S-shaped knife from Chalcolithic Italy, with reference to the corpus of marks produced on experimental replicas by Kienlin & Ottaway [147] and O'Flaherty [10]. In his large-scale assessment of 154 spear-heads and 50 swords from the early Nordic Bronze Age, Horn [207] used the wear marks produced in experimental work by Anderson [205] and O'Flaherty et al. [196] as a comparison. Lastly, as touched upon in section 3.2, Crellin [154], in her study of 38 flat axes from across Britain and Ireland, used experimental data from earlier publications for comparison [5], [2], [147], [188].

Furthermore, with the exception of Kienlin & Ottaway [147] and Soriano-Llopis and Guiterrez [209], very few studies have attempted to document the progression of wear on replica artefacts with different alloy compositions and manufacturing during experimental work. The research conducted by Kienlin and Ottaway [147] has already been discussed a number of times, but nothing has yet been said of experimental work conducted by Soriano-Llopis and Guiterrez [209]. Within this study, nine replica Bronze Age flat axes with different tin composition (0%, 5%, and 15%) were produced and subjected to varying post-production processing. The axes were then examined for evidence of technological marks matching the categories, 'notch', 'cracks', 'burr', and 'grooves'. It should be noted that many of the replicas exhibited many casting defects and damage (cracking) from

processing due to excessive hammering periods of 20 minutes, which meant the material may have been more susceptible to degradation. The axes were then used in cutting activities for either 1 hour or 2 hour periods and use-traces were separated into one of the four aforementioned categories. Confusingly, the authors suggest that the compositional mix had the most substantial effect on the number of wear traces recorded [188, p. 120]. However, this is clearly an erroneous interpretation since axes of different composition within the same processing groups showed similar levels of wear, thus, the severity of wear appears to be much more dependent on the combination of post-production treatments. The axes that were subjected to annealing as their final processing treatment had the highest totals of use-wear traces, while those that were cold-hammered at their cutting-edge before use had the least number of wear marks recorded (the reason for this is explained in section 4.2). The results demonstrate that cracking is much more likely in high-tin specimens, although it is difficult to pick out any more specific trends in the type of wear observed. Since many variables already existed within the experimental materials, it may have been profitable to control the setup more tightly in order to bring out underlying trends in type of wear formation. With these comments in mind, the results presented by Soriano-Llopis and Guiterrez [209] should be considered with appropriate caution. Metal artefacts are far from uniform in their underlying characteristics and this clearly has a notable impact on how the material can be expected to respond under certain conditions. It is time to acknowledge this and to start employing suitable methods for testing such considerations; as such, the present study will make sure the composition and microstructure of both replica palstave axes and ancient palstave axes are accounted for.

### 3.3.3    Fluid terminologies and negligible empiricism

The characterisation of wear on the surface of archaeological specimens and replica artefacts has provided the principal approach to metal use wear studies for over half a century. Terminology, such as, 'nicks', 'notches', 'chips', 'bows', 'scores', 'tears', and 'flattening', have invariably been used to describe phenomena. This is, undoubtedly, a very subjective method of assessment for a number of reasons. In addition, different authors favour certain terms to describe particular phenomena and so, a 'notch' for once scholar, is another scholar's 'nick' [12]. This produces a clear discrepancy in the nomenclature assigned to varying types of wear mark. Such ambiguous terminology makes it difficult to compare and contrast the wear between papers produced by different researchers. Gutiérrez Sáez & Lerma [4] produced a catalogue of wear marks based on past experimental work. Each type of plastic deformation and surficial wear discussed within the paper was accompanied by a detailed description, the level of (low-power) magnification required to identify the feature, and

a photograph. The establishment of shared nomenclature is a crucial element of any developing field, allowing researchers to communicate in the same language and encouraging data assimilation to detect more large-scale trends. One might also suggest the potential adoption of 3D scanning and modelling as a regular feature of metal use-wear analysis, of which the results could be stored in online open-access databases (similar to the work currently undertaken by the Micropasts initiative in publishing 3D scans of archaeological objects online) [210]. This would allow immediate and continual reassessment of wear marks by a number of specialists, and act as a comprehensive training guide for those learning. Neural network analysis, which uses computer learning to automatically detect similar patterns, has been successful with lithic tools [211], [212]. Unfortunately, the variability of the wear marks that are observed on metal artefacts means that the topography of the objects does not lend itself well to detection via neural network analysis (there would be a very high level of 'redundant' information).

The difficulties presented above in regards to the identification of wear phenomena only scratch the surface, as it were, of a much bigger problem with employing quantitative approaches to use-wear analysis. In particular, only a handful of studies have so far attempted to incorporate empirical measurement into their assessment of the severity of wear. O'Flaherty [9], Bridgford [8], Horn [207] and Moyler [6] tried to assign arbitrary empirical values to the extent of surface wear, but this can only really be said to comprise a pseudo-quantitative method and even the authors express doubt over the usefulness of these subjective evaluations. As long as the assessment of wear on metal artefacts remains reliant on purely descriptive methods, there will always be a large margin of error in metal use-wear analysis. This, understandably, has implications for the resultant interpretative potential of the field. Qualitative assessment can only ever hope to generate vague statements about the type of action adopted when using weapons or tools, the likely opposing material, and the severity of wear.

However, the application of novel microscopic techniques, such as, interferometry, Alicona focus-variation microscopy, laser scanning confocal microscopy, and scale-sensitive fractal analysis may be possible for metal use-wear analysis. These can generate empirical measurements of surface roughness, which act as useful indicators for the unique contact outcomes between different materials. In the last decade, these techniques have been used to successfully differentiate the functionality of tools for a range of materials, for example, lithic [213], [214], [215], [216], [217], [218], [219], [220], [221], [222], [223], bone [91], [224], [225], and shell [226]. The first metal micro-wear study to be based on the idea of surface roughness is currently in progress by Rachel Crellin and Mark Purnell (in prep.) – the focus of this is Early Bronze Age flat axe-heads. The authors have

so far produced data from an initial set of cumulative experiments chopping ash trees, but have axe-heads ready to work on a far wider range of experiments (split, adzing, working dry and fresh wood, digging) (Rachel Crellin pers. comm). It is hoped that these experiments will eventually permit the successful categorisation of experimental Bronze Axes according to the specific texture parameters that were generated by material they were used to work. This surface roughness can then be statistically verified against ancient samples to produce matches of a high confidence level in relation to tool functionality and action. Likewise, methodical screening for measurements like surface hardness, as conducted here-in, has the potential to allow the quantitative modelling of deformation on archaeological objects (this will be discussed in further detail in section 4.2.1 and Chapter 5). This could help to provide accurate quantitative estimations of wear that can then be applied to real archaeological artefacts in comparative studies.

### 3.3.4    High-power microscopy

There has been no attempt to characterise the micro-wear features that form during testing with replica bronze objects by a high-power approach. Consequently, there is little appreciation of the types of feature that may exist on these specimens at the micro-level, such as, flaking, cracking, edge rounding [227, p. 65]. While corrosion may prevent this type of analysis on a significant proportion of Bronze Age artefacts, some are of a sufficient preservation that micro-wear analysis could be conducted. In fact, such an investigation would be particularly productive if undertaken on objects that appear to be in a good condition, as very minor traces, produced by minimal use periods, may be made observable [227, p. 65]. Some of the most fiercely debated issues in lithic and bone use-wear studies are starting to be resolved by high-power microscopic techniques. For example, the wear formation processes on stone sickles, which develop a type of gloss on their cutting blade during contact with plants, have been a controversial issue in the field of lithic use-wear analysis for a considerable time [171, p. 5]. Some scholars believed the phenomena to be one of purely abrasive action, while others fervently defended the interplay of the adhesive mechanism in what was named 'silica gel theory'. However, application of Scanning Electron Microscopy to lithic sickle blades by Olle & Verges [216] has now given reason for silica gel theory to be rejected on the basis that the sustained wear is mechanical and not adhesive.

Furthermore, combining a highly magnified *and* sequential sampling method may help to provide a better understanding of wear propagation – how surface deformation, polishment, and striations develop, which wear mechanisms are at play, and how their characteristics relate to type, or

duration of use. Olle & Verges [227] used SEM in sequential studies of lithic replicas to trace wear over period of attrition using a range of different magnifications. When advocating the ability of the technique to enhance the understanding of wear formation, the authors suggested that, "[sequential experiments] allow an entire process to be documented, rather than simply the final stages of it" [227, p. 65]. This is useful from a theoretical standpoint, for example, in elucidating how wear formation actually occurs – but could also allow analysts to detect how the severity of micro-wear is related to the degree of use. Hence, a high-power, sequential method was adopted as part of the use-wear analysis of replica palstave axes within the present study.

## 3.4   A developed approach

This section has detailed the current state of metal use-wear analysis, firstly, by explaining the methodological developments in the use-wear analysis of Bronze Age axes, and, subsequently, by clarifying areas for further methodological advancement. This has justified the necessity for a study that looks deeper into the material and from a materials science approach, so to examine the 'amount of use sustained'. Hence, this thesis is a response to the gaps that exist within the experimental protocol of metal use-wear analysis, and advocates the application of new directions and techniques by the creation of novel methodological frameworks for the analysis of palstave axes. Controlled experiments in mechanical rigs and sequential sampling were adopted so that the timescales under which certain marks emerge can be accurately determined, for instance, by using 'number of hits' instead of 'time of use', in addition to distinguishing and analysing features that are linked to material degradation rather than ones that appear due to miss hits or unusual opposition materials. These experiments provide much more meaningful results when comparing different alloying combinations and post-production processing, as the impact of interfering variables is minimised. This aids the interpretation of use-intensity from macroscopic wear phenomena, and allows novel quantitative indicators of deformation to be modelled precisely. Furthermore, there have been attempts to record wear at higher levels of magnification, which has allowed better understanding of the way degradation occurs at the micro-scale.

# 4    Tribological considerations

"*In order to get the 'right' sort of information from the experiments, one must choose to do the 'right' experiments. In order to do the 'right' experiments, one must have some preconceived notions of what actually goes on when moving surfaces interact*" – [228, p. 2].

The prior chapter examined the methods by which wear on Bronze Age metal artefacts has previously been characterised by analysists in the past. This chapter develops these ideas further by discussing how various scientific principles contribute to the wear of metals, accompanied by more specific discussions of the structure and material properties of ancient bronze. To understand the nature of wear and, ultimately, how it propagates on bronze archaeological specimens, the tribological system of the material must first be understood. This is because the contact conditions between two surfaces in relative motion are determined by the different structural or mechanical components that contribute to forming the system-related wear characteristics. It is the challenge of the field to understand the relationships between the underlying structure of a material, the mechanical properties, the surface chemistry, the presence of intentional or unintentional lubricant films, the type of contact, and the geometry of contact [228, pp. 1, 2], [229], [230, pp. 28, 29].

The following discussion examines how the structure and properties of bronze, condition its tribological response. As described in section 2.2.1.3, in the Middle Bronze Age, a fairly consistent method of production and fine-tuning seems to have been applied to palstave axes during manufacture; this was, smelting, alloying, casting, cycles of localised annealing and hammering, followed by a final cold-hammering [116], [135], [136], [137]. The implications of this manufacturing process on the underlying crystal structure of prehistoric copper-alloys are first examined. Next, the resulting mechanical properties from the production procedure are discussed. Following this, the wear mechanisms that are responsible for much plastic deformation and wear on the surface of Bronze Age palstave axes studied. Lastly, the chemical alterations, such as oxidation and corrosion, that take place at the surface of metals during contact with another surface or during static environmental conditions are examined. Due to the breadth of research, the comments are limited to those relating to bronze and archaeological contexts. There are, however, many excellent general reviews, [231], [232], [233], that could provide further insight into tribology.

## 4.1   Structural aspects

The properties of any substance are derived from the way individual atoms are joined to other nearby atoms in the same network [3, p. 40]. Between compatible atoms, bonds form, of which there are several constituent forces: an attractive force that reduces in size as atoms are pulled apart; a repulsive force that surges when atoms are pushed closely; and, the resultant force, that is, the total when the attractive and repulsive forces are added together [3, p. 40]. In metallic bonding, the valence electrons become delocalised from their atomic cores; the resulting shared 'electron cloud' provides both the glue between, and the necessary separation of, the atom cores [234, pp. 248, 249]. This method of sharing electrons also provides an explanation for why metals are such good conductors of heat and electricity. The primary constituent of bronze is the element copper (Cu), the atom of which has a nucleus consisting of 29 protons and 34-36 neutrons, encompassed by 29 electrons. Copper atoms bond with other atoms by metallic bonding and have only one unpaired atom in their outer orbital while all the lower orbitals are also fully-saturated; as a result, the metal structure that is formed is highly conductive and extremely stable, for instance, the melting point of pure copper is as high as 1083 °C [4], [235, p. 446].

The exact arrangement of atoms in metallic compounds is determined by the need to satisfy certain criteria. This includes the necessity for the atom to connect with the maximum number of suitable atoms and the requirement for the atom to be positioned where all the active forces between it and its neighbours equal a resultant force of zero, so that the atoms within the structure can be said to be at 'equilibrium separation distance' [3, p. 40], [234, pp. 248, 249]. These criteria can be satiated by the formation of layered lattice structures. Depending on the elemental composition of the atoms in a lattice, fourteen different arrangements can be assembled, these are commonly referred to as the Bravais Lattices. The atoms of copper are arranged into face-centred cubic lattices. This lattice formation is constructed when one plane of atoms, labelled 'A', is stacked upon another plane, labelled 'B', so that the atoms in the plane A fall into the interstices of the atoms in plane B, while the atoms in third plane alignment, labelled 'C', are positioned in the line of the remaining interstices left by both of the preceding layers [236, p. 5] [236, p. 5]. For face-centred cubic lattices, this pattern is thus repeated in the sequence 'ABCABCABC', as seen in *Figure 9*. These crystal structures form when the molten metal is solidified to a solid crystallized state, i.e., below its melting point. Metals that are made of two or more elements (alloys) will consist of different

states of equilibrium, which translate into 'phases', chemically distinct areas of crystal structure [237, p. 209].
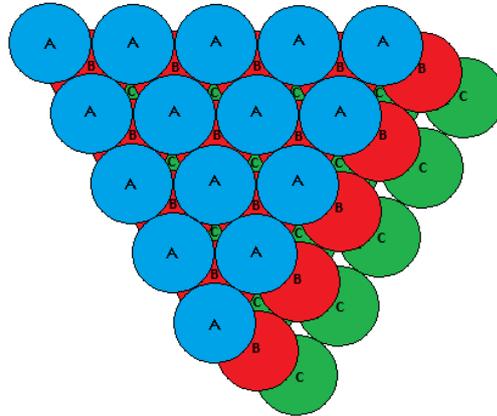


*Figure 9:* Stacking sequence of face-centred cubic lattices. A – first layer; B – second layer; C – third layer (Source: Author's own, based on [236, p. 6]).

As indicated in section 2.2.1.3, ancient copper was often subject to natural impurities, or deliberately alloyed with other metals. Impurities can produce distinct phases within the crystal structure of the copper-alloy if present in great enough levels and so, in turn, alter the physical properties of the metal very slightly. Moreover, copper was intentionally alloyed with tin, lead, and possibly arsenic, during the course of the Bronze Age in varying quantities and combinations to modify the mechanical properties and ease of casting. Needham et al. [238] examined the significance of a range of impurities, such as, tin, zinc, lead, arsenic, antimony, silver, nickel, bismuth, and cobalt in 350 implements (mainly axes) from several metalwork horizons in southern Britain during the Early Bronze Age. The quantity of these elements was shown to vary greatly within samples from different periods. Metalwork from the early 3rd millennium BC demonstrated high values of arsenic, with a high frequency of tools containing approximately 1% [238]. Although there is still some debate over the deliberateness of its addition, arsenic is the most significant impurity contained within the bronze material of the Early Bronze Age. It is possible that it was intentionally included to increase the ease of casting, while also improving the mechanical properties. Objects from the end of the same century included even higher values of arsenic (1-3%), with average measurements of antimony and lead around the 1% mark [238].

The later material in the assemblage analysed by Needham et al. [238] suggested the introduction of the "tin bronze economy" between c. 2200-2000 BC. During this time tin usually comprised 8-14% of the bronze material; this value then increased to 10-16% by the transition with the Middle Bronze Age [238, p. 392]. It is thought that, as a consequence of the local tin sources, the production

of tin-bronzes could have begun in Britain at this very early stage, and disseminated outwards across Europe. This is exemplified by the tin-bronze prototype daggers and axes originating from the early second millennium graves of south-west of England [28, p. 146], [71]. Needham's study also demonstrated the intentional incorporation of lead into the implements of the Late Bronze Age; values of which were often 4-7% of the total metal in most samples, but were found to reach values as high as 15% in some artefacts [134, p. 193]. Hence, this data suggests that the copper-tin alloy dominated the metalworking industries of Britain until the Late Bronze Age (c. 900 BC), when lead was preferentially added to the metal mix [71, pp. 30, 40], [25, p. 122].

The addition of tin to copper was the preeminent alloy choice throughout much of the Middle Bronze Age in Britain, when palstaves were the dominant form of axe. Consequently, tin-bronze forms the focus of the following discussion on the crystalline structure of ancient copper-alloys. Tin (Sn) is a silvery metal that forms a tetragonal crystal structure and has a low melting point of 232° C. When tin is added to molten copper, smelted, and then allowed to solidify, different phases of crystal may be produced within the microstructure of the alloy. Mixtures with less than 11% tin predominantly produce a homogenous alpha phase, where atoms of tin are directly substituted within the face-centred cubic lattice [132]. This generates crystals in the shape of dendritic arms [237]. When the tin content within the copper-alloy is increased the dendritic crystals are interspersed by darker patches of crystal, the 'αδ eutectoid'. In these locations, the tin atoms have not been fully incorporated into copper lattice structure as the maximum solid solubility of copper has been reached. Instead, they separate into another phase that has a higher proportion of tin than copper – and may not necessarily adhere to the fcc lattice structure (*Figure 10*) [237, p. 209].
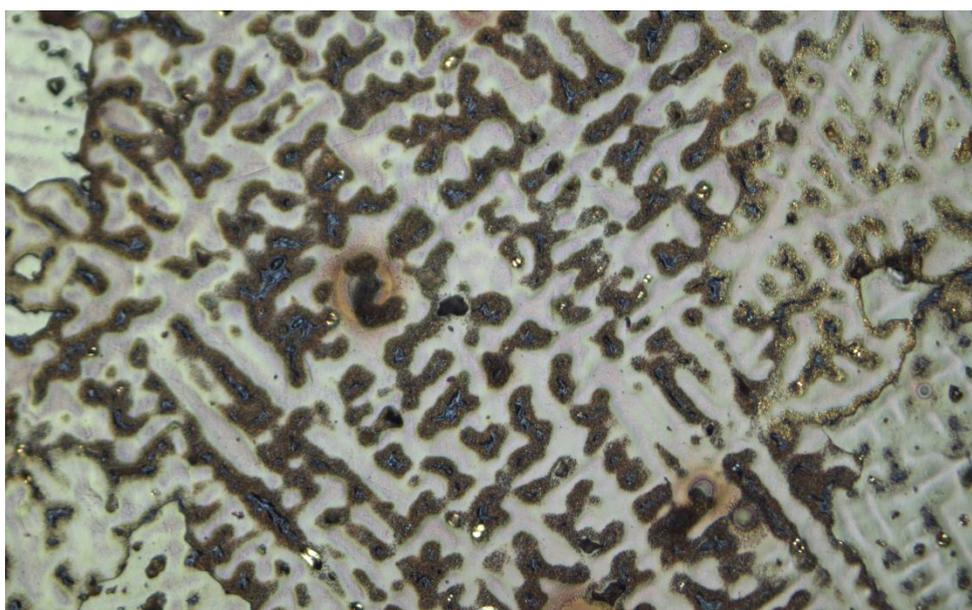


*Figure 10:* Dendritic coring of tin-bronze (Author's own).

The extent of the delta phase, or 'coring', within the microstructure is partly determined by the rate of cooling when the molten metal is poured into the mould to set. This is a result of the differing melting-points between alloying elements, which culminates in the solidification of the Sn-enriched inter-dendritic space before the Cu-enriched dendrites [116, p. 28], [106], [132, p. 49]. The casting of Bronze Age metal objects was achieved by using one of several types of mould: stone, bronze, clay, or sand [61, p. 99]. Experimental work has demonstrated that different mould materials may contribute to varying rates of cooling, and ergo, contrasting dendritic arm spacing (DAS). Ottaway & Wang [132] examined the DAS of replica 10% tin bronze flat axes, cast by three methods: bronze, sand, and clay. The results of the investigation concluded that bronze cast in bronze moulds have the smallest DAS values (9-18 μm), while the DAS of those cast in sand moulds is much greater (30-60 μm) and overlap considerably with the slightly larger DAS values for bronzes cast in clay moulds (40-80 μm) [132, p. 49]. More recently, Dungworth [201], observed the same phenomenon – very fine dendrite spacing when casting high-tin bronze in bronze moulds. It can be suggested, hence, that bronze cast in bronze moulds cools at a much faster rate and over a shorter solidification time. Furthermore, in comparison to other types of mould– which provide fairly comparable results – the microstructure generated when a high-tin bronze is cast using a bronze mould is substantially modified.

The microstructure of copper-alloys is often left with atomic faults after casting. Point defects are generated when an atom of a different size and contrasting bonding capabilities to the atoms that comprise the rest of the structure is incorporated within the material [234, p. 294]. For example, the direct substitution of tin atoms within the face-centred cubic lattice as mentioned above. Schottky and Frenkel-Defects are two other types of point defect, and are related to the existence of voids in the crystal lattice structure. Schottky defects describes the deviation of atoms from their proper position to the surface of the material, and Frenkel-Defects the movement of atoms to the interstitial sites between atoms [240, p. 7]. In addition, other faults, such as, line defects, and planar defects, also frequently occur within the microstructure. Line defects are concerned with dislocations within a line of atoms; this includes both edge and screw dislocations, as well as the many hybrids that exist in-between [241, pp. 295, 296]. Illustrations of the aforementioned defects are shown in *Figure 11.* Lastly, planar defects involve the appearance of stacking faults in the sequence of the planes (*Figure 12*), often producing crystal twins. Stacking faults can be created during initial crystallization, recrystallization (as provoked by further heating and cooling of the material), and during deformation [236, p. 21].
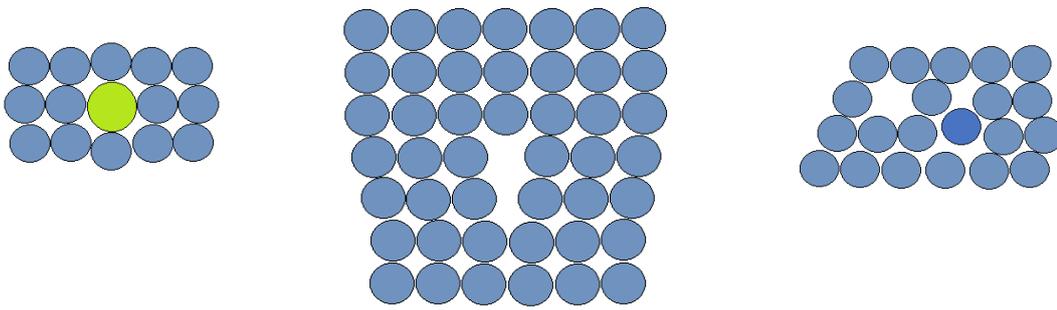
**Figure 11:** Illustrations depicting defects in a crystal lattice: (left) an atomic substitution, (middle) an edge dislocation, and (right) a Frenkel-Defect (Source: Author's own, based on [203, p. 7]).
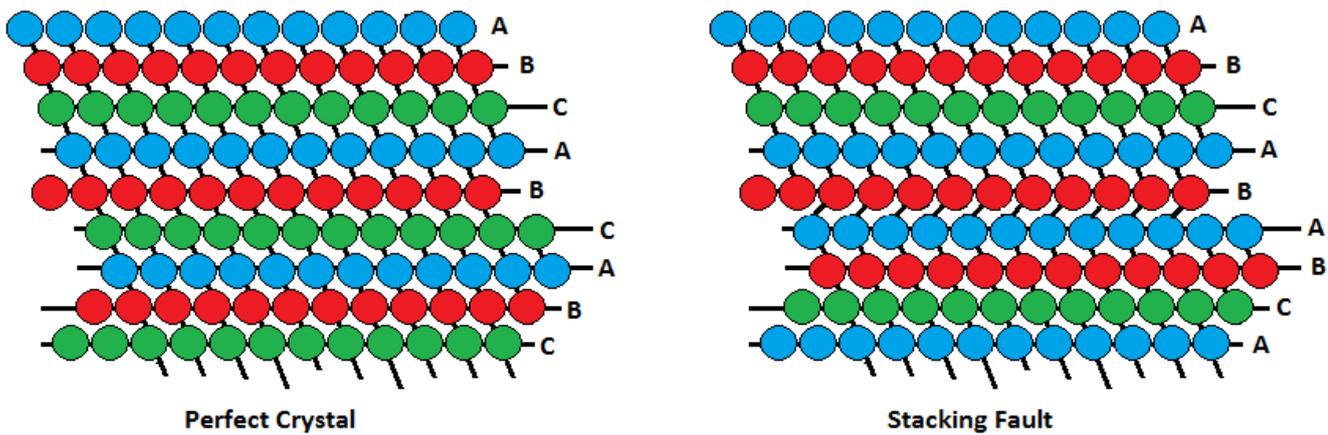


**Figure 12:** Illustration of a stacking fault in an FCC lattice structure (Source: Author's own, based on [199, p. 23]).

During manufacture, the hammering of the copper-alloy causes plastic deformation to occur on the surface of the crystal lattice, introducing slip lines into the structure [116, p. 28]. This fluidity in ductile materials is made possible by the sliding of atomic planes within the crystal lattice [236, p. 24]. Nonetheless, the movement of one entire plane of atoms over another is unlikely as the force needed to overcome the bonds of many atoms simultaneously is too great. More often, the slip propagates through the defects in the crystal lattice, since the force required to move several atoms at dislocation site is much less than the former option [3, p. 42]. In this scenario, the atoms migrate along the slip planes, moving through many atomic positions (*Figure 13*) [3, p. 42]. When the implement is annealed, however, these dislocations are removed. In fact, the entire structure may become fully recrystallized if the heating is at high temperatures (around 700°C), or dendritic

shading may remain if the temperature applied is low (around 500°C) [201, p. 151]. A worked microstructure that is subsequently annealed will contain annealing twins, crystals that have two parallel straight lines appearing across the grain. The form of recrystallized bronze is dependent on a number of contributing factors: the coarseness of the metal grain structure before processing, the amount of deformation, the temperate of the anneal, and the length of said thermal phases [242, p. 10]. Often when recrystallized copper is subjected to several cycles of cold-hammering and annealing, a final grain size of about 10μm, or even smaller, may be produced [201, p. 151]. If the metal is cold-hammered once again, strain lines will appear in the microstructure. When subjected to heavy cold-working these lines are obscured by the overall malformation of the structure as the crystal grains become increasingly bent and elongated in the direction of hammering [116, p. 28]. This process of microstructural alteration is illustrated in *Figure 14*.
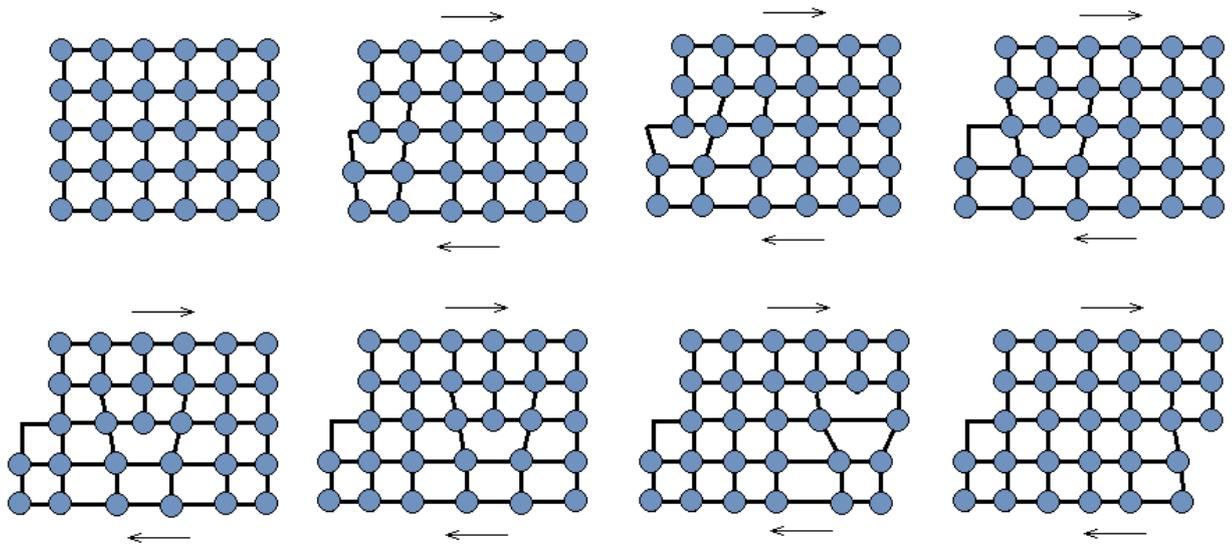


*Figure 13:* The progression of a dislocation as it moves through a crystal lattice (Source: Author's own, based on [159, p. 96]).
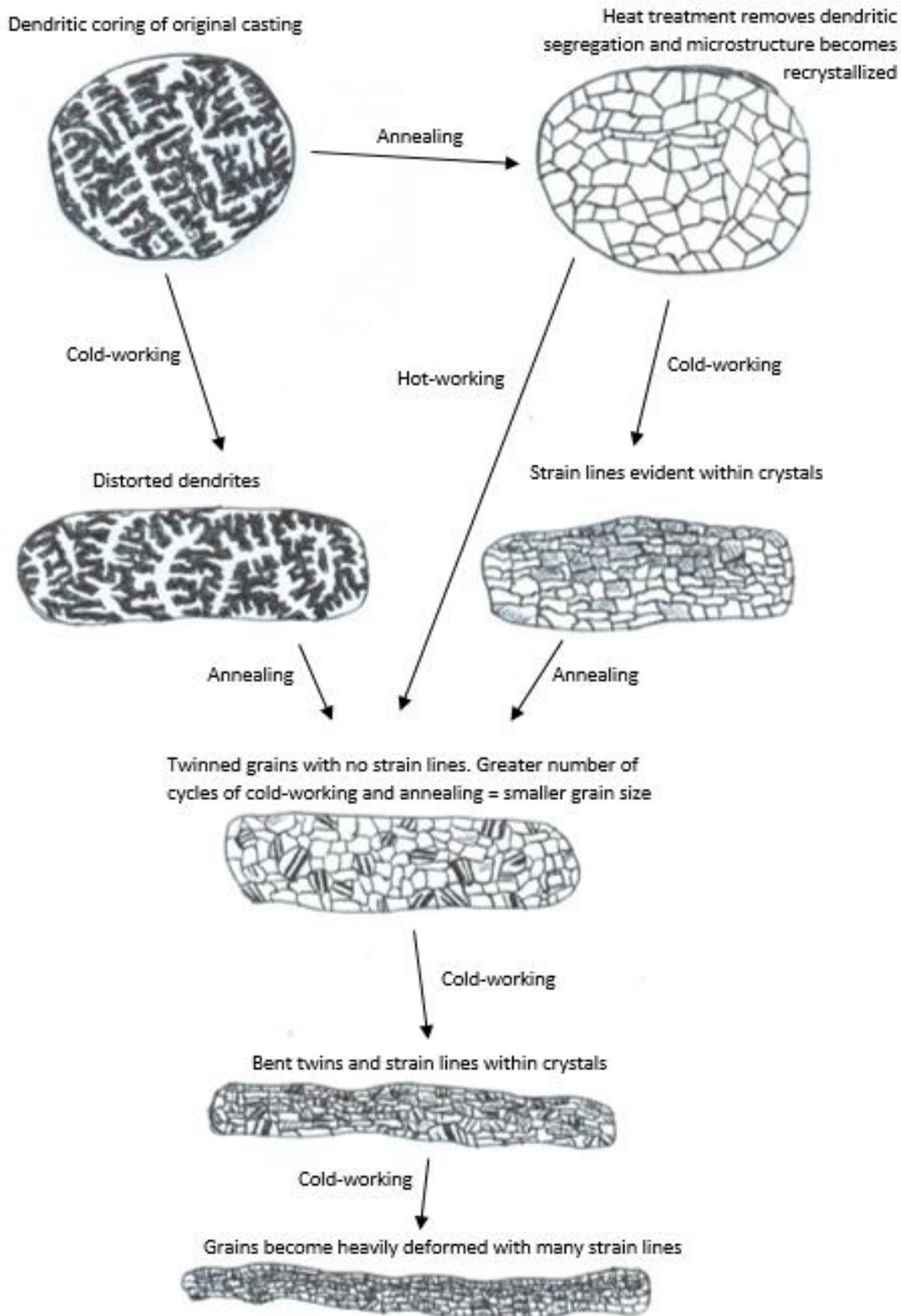
**Figure 14:** The microstructural changes that occur in tin-bronze during the stages of working likely in the Bronze Age (Source: Author's own, based on [275, p. 9]).

## 4.2  Mechanical properties

The underlying crystal lattice structure of a material has repercussions for how it behaves when force is applied. This comprises the 'mechanical properties' of a material, which include: its elastic ability; its hardness (resistance to plastic-flow), and associated work-hardening process at the area of contact; its strength, and its fracture toughness (resistance to brittle fracture) [230, p. 30]. The deformation of a crystalline lattice occurs when a tensile, compressive, or shear force is applied to the structure from contact with another solid structure. If only a small force is applied, then the response of the material will likely be an 'elastic deformation'. In these circumstances, a tensile force would pull atoms further apart from one another, inducing a slightly negative resultant force. A compressive force would push atoms closer together, producing a resultant force that is marginally positive. Finally, if a shear force was applied, the atoms would move in opposite directions. The atoms take care of the external force by deforming the crystal lattice structure in this way [3, p. 41]. Since the force is not great, the atoms do not move much away from the equilibrium separation distance and once the material is no longer under tension a 'restoring' force will allow the crystal lattice to return to its original structure [3, p. 41]. The response of a material to these forces can be calculated as a function of stress over strain, as in Young's Modulus:

$$E = \frac{stress}{strain} = \frac{F/A}{\Delta l/l\circ}$$

Where:

$E$ is the Young's modulus (modulus of elasticity)
$F$ is the force exerted on an object under tension;
$A$ is the actual cross-sectional area through which the force is applied;
$\Delta L$ is the amount by which the length of the object changes;
$L_0$ is the original length of the object.

However, this equation only remains true up to a certain value of force. If too much tension is applied onto the material it will reach its 'elastic limit', where the attractive forces between the bonds become unable to maintain the structure, and a new stage of deformation, called 'plastic flow' will begin [3, p. 41]. This type of deformation is permanent, once the atoms begin to 'flow' they will not be reformed to their original structure by restoring forces. When pressure is applied

to very brittle materials that cannot accommodate much plastic flow, the atoms cannot shift and the attractive force that preserves their bonds may be exceeded, at which point the material will fracture [3, p. 42]. In face-centred cubic lattice structures, like those comprising copper, there are four planes, all of which permit movement in three directions [234, p. 252]. Hence, there are twelve possible slip systems [235, p. 446]. This is the greatest number of possibilities for slip that exists within any metal structure. Pure copper, therefore, has a significant potential to experience slip and, as result, is much more inclined to deform rather than break [4, p. 174]. To that end, copper is often described as both malleable and ductile – this makes it ideal for fabricating copper wire for ornamental use. For the same reason, pure copper is also extremely soft, which makes it largely unsuitable as a practical implement.

The alloying of copper with other metals, in addition to lowering the melting point (improving the fluidity of the molten metal during casting so that more intricate designs can be manufactured), can also substantially decrease plasticity [4, pp. 172, 173], [71, pp. 39, 40]. The elevated hardness of bronze in comparison to unalloyed copper is on account of the changes to the microstructure of copper that occur when bronze is introduced. Firstly, the tin atoms that have been substituted into the crystal lattice change the regular distance between copper atoms, generating strain in the structure, and this introduces greater hardness. The presence of the αδ eutectoid phase has even greater implications for the plasticity of the copper alloy as these regions of harder crystals effectively immobilise many slip planes within the material. This means that the copper can no longer be deformed so easily – thus, the alloy becomes much harder. The most advantageous quantity of tin within a copper-alloy is approximately 10-12% [71, pp. 39, 40]. This produces a material that is of a sufficient hardness to be used to form weaponry or tools, but not so hard that it is liable to brittle fracture [4, p. 173]. A very high-tin bronze may be too susceptible to breakage to be useful in practical purposes.

A greater hardness of bronzes can also be achieved by the process of 'work-hardening'. As plastic deformation occurs, and dislocations progress through the crystal lattice, they begin to stack up at grain boundaries, inclusions and other obstructions. During this process the material becomes more difficult to deform, as the number of options for flexible movement are increasingly reduced and, thus, the hardness becomes elevated [201, p. 149]. Eventually plastic deformation comes to an end when dislocations are unable to travel any further and the material may fracture if further force is exerted upon it. The tensile stress-strain graph presented as *Figure 15* demonstrates the impact of work-hardening. The work-hardened copper sample is shown to be very resistant to deformation as the load increases. However, once it passes its elastic limit it cannot accommodate much more

plastic flow (or associated work-hardening), before it fractures. Conversely, pure copper that has been subjected to only annealing, is much more plastic than work-hardened copper and has a greater fracture toughness. As mentioned in section 4.1, when multiple cycles of annealing and hammering are completed, a very fine grain size may be produced. Grain boundary strength varies inversely to the square root of the grain size, otherwise known as Hall-Petch behaviour. This is a result of the immobilising power of grain boundaries; thus, more grains and, therefore, more grain boundaries, reduces the likelihood of large slip systems with the stacking fault energy required to cross into another grain [243]. In addition, the slip planes within individual grains do not often align well, which provides another barrier to movement. Hence, by decreasing the grain size the microstructure undergoes an increase in yield strength and will generally be slightly harder to deform. The combination of alloying, grain boundary strengthening, and work-hardening generated during manufacture can be used to produce palstave axes with a cutting-edge of optimum strength.
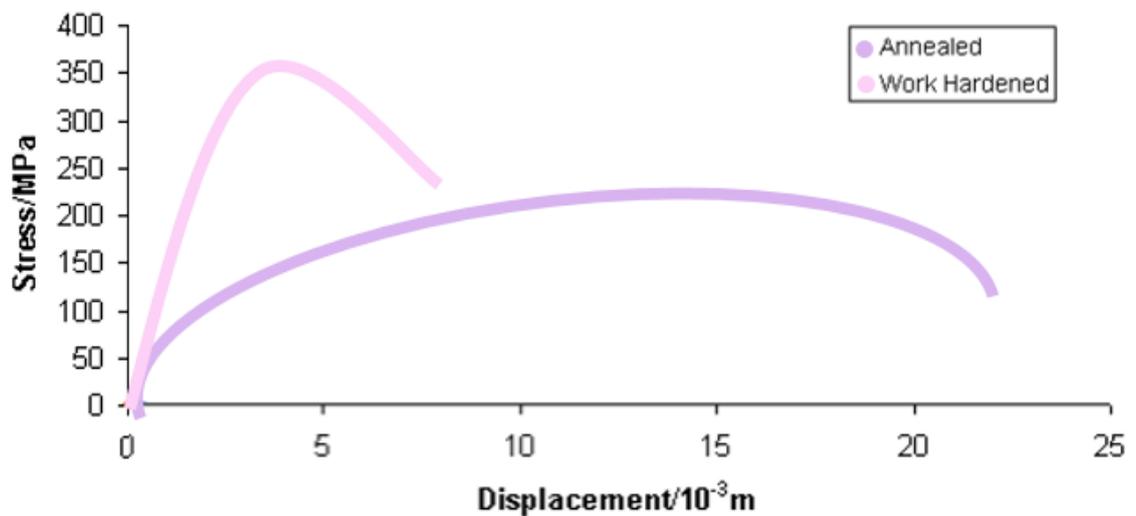


*Figure 15:* Stress-displacement curve for both annealed and work hardened copper (Source: Author's own, based on [244]).

With the exception of the cutting-edge, little evidence of fine-tuning has been found elsewhere on palstave axes [116], [135], [136], [137]. As a result, Knight [13, p. 171] has suggested that the cast nature of palstave flanges may make them more susceptible to breakage during use than hammered flanges, due to the 'simple' structural arrangement that is formed within the microstructure. One could elaborate further by saying that cast flanges with a low hardness would be more likely to suffer from bending, which could result cracks and breakage if continually fatigued or the material is distorted far enough out of position. Deformation of the flanges is likely to happen during hafting if the flanges are forcibly jammed into the haft to create a snug fit. The accidental breakage of the side-loop is also quite easy to imagine. The loop presents a fairly thin and

unsupported piece of material that would be subject to a great deal of force if the axe-head was to detach, per se, within the timber as the haft was pulled backwards. If the side-loop becomes brittle during use, but stays in-tact, it may still be preferentially attacked by intergranular corrosion. Knight [13, p. 170] also explains that a considerable number of palstave axes are found broken just above the stopridge, through the hafting plate and flanges. Drawing on this pattern, he proposes that the palstave may be liable to breakage in this area. This could be a feasible explanation, since this is one of two locations at which the haft directly abuts to the axe-head, and so, there is probably some transference of force within the system at this point. Perhaps then, this area does become work-hardened during use and becomes broken by accident, or is preferentially attacked by intergranular corrosion after deposition. In specimens where the hafting plate and flanges are of quite a substantial thickness, it is hard to imagine that use alone would be able to generate enough embrittlement for separation in this location to occur, however.


### 4.2.1    Investigation of the deliberate and unintentional work-hardening of archaeological bronzes

The phenomenon of work-hardening in archaeological bronzes has been subjected to a considerable amount of experimental investigation, mostly in relation to assessing the hardness progression amongst different alloy compositions. Marechal [245] pioneered the first of these experiments by comparing the work hardening of 8% arsenic bronze and 8% tin bronze by cold-rolling; he concluded that there was no mechanical advantage of tin-bronze over arsenic-bronze in relation to hardness. Building on this first look into the work hardening of arsenic-copper alloys, Budd and Ottaway [246] conducted research on seven different alloys, from 0.5 to 12 weight-percent arsenic, by systematic thickness reduction of the microstructure as a result of cold rolling; they determined that arsenic bronzes with 6.1% arsenic were too brittle to withstand further cold working at 63% reduction, and high-arsenic bronzes (8-11.7%) showed severe cracking at 31% reduction. Cold-rolling experiments do not, however, provide the most accurate way to simulate the deformation that would have been applied to most Bronze Age material. This was aptly proved by Lechtman's [247] work, which followed a similar method to the studies mentioned above, with the exception of the substitution of cold-rolling for cold-hammering. This research indicated that 5% and 7% weight-arsenic bronzes could be reduced to 87.5% of their original thickness and high-arsenic bronzes would only be too brittle to work further when their thickness was reduced by half.

The work-hardening of archaeologically-relevant bronzes has also been directly and quantitatively investigated by hardness testing, which involves simple indentation tests on polished and unetched mounted samples. There are several types of test that can be used to measure hardness, for example, Vickers, Knoop, Rockwell, and Brinell. During each test the indenter is loaded with a pre-determined mass and lowered onto the sample, applying a compressive force. The size of the impression is then measured and a hardness number can be calculated in relation to the load. In his seminal work *Prehistory of Metallurgy in the British Isles,* Tylecote [206], stated that his experimental work had shown that a 10% tin-bronze should have a hardness of 100 HV before hammering, and may be cold-worked to a maximum hardness of 230 HV. Lechtman [247] attempted to establish the maximum functional hardness of as-cast high-tin bronzes using cold-hammering and cold-hammering apparatus; she recorded that it was possible for a 10% tin-bronze to withstand an 80% reduction in thickness, producing hardness values upwards of 280HV (*Figure 16*). Ottaway & Wang [132] conducted hardness tests on bronze axes cast from each mould material. The results of these experiments demonstrated that bronze cast in bronze moulds are marginally harder – this is most likely related to the greater number of αδ eutectoids that are scattered through the sections of dendrite, which makes the metal more brittle [132, p. 55]. Ottaway and Wang [132] also undertook extensive experiments in the work-hardening of different recrystallized tin-bronze alloys in relation to their casting matrix. The results of cold-hammering a recrystallized 10% tin-bronze cast in a sand mould are also shown in the graph below (*Figure 16*). Like Lechtman's [247] study, as-cast 10% tin-bronze is shown to harden exponentially at first, followed by a much slower ascent as the material becomes harder to deform.
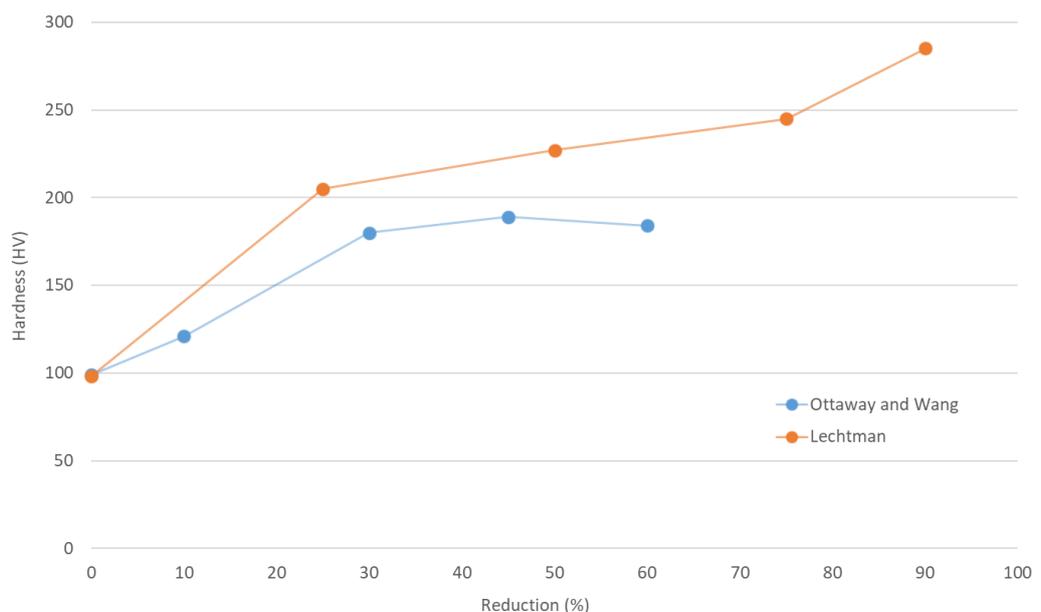


*Figure 16:* The hardness (HV) of 10%-tin bronze when reduced under mechanical action. It should be noted here, that no error bars are presented, as this data is based on single indents only (Source: Author's own, based on [132], [247]).

Integral to the investigation of Kienlin and Ottaway's, *Flanged axes of the North-Alpine region* [147], was the hardness testing of replica axes after varying degrees of mechanical processing in order to substantiate ideas about increased resilience and, thus, durability. But, the authors also stumbled upon the phenomena of unintentional work-hardening as a result of use. Specifically, two copper axes of the same composition and post-production processing were recreated, and while one was thereafter left alone, another was used in wood-cutting experiments. After this, hardness measurements were taken on both specimens. The first axe, in an unused form, showed hardness readings of 50-60 HV. Yet, hardness values of 90 HV were recorded at the cutting-edge of the second axe following functional simulation. The researchers were keen to recommend that, "the initial mechanical deformation during use had caused hardening of the cutting edge"; and, despite the lack of complete longitudinal data for the second axe (which would have produced results that were directly comparable), this was clearly a significant discovery [147, p. 274]. No other formal experimental work has since been documented on the subject. Though, several preeminent researchers in use-wear analysis, Andrea Dolfini (pers. comm) and Rachel Crellin (pers. comm), have also expressed their belief that unintentional work-hardening occurs at the cutting-edge of bronze age axes during use.

Extensive investigation of hardness mapping across the blade, and closer metallographic exploration, may highlight unique indicators of unintentional work-hardening versus deliberate cold-hammering. Gordon [186] analysed thirteen bronze tools from Machu Picchu in this way. He combined metallographic techniques, and hardness profiles – with measurements stretching from the tip of the blade to 20mm inwards – to assess the likelihood of plastic deformation generated by use [186, p. 322]. Results of one specimen showed a steep drop-off of hardness at sampling locations situated away from the tool blade, which most likely indicates an increase in hardness at the very periphery of the cutting edge due to work-hardening only. A gradual gradient of decline away from the blade was proposed to indicate cold-hammering. Although, Gordon eventually concluded that these tools were used for smashing up stones, the possibility of a similar mechanical alteration due to contact with timber (during a comparable action) is also probable [186, p. 311]. The author considered that the examination of the microstructure may itself provide a reliable gauge as to the severity of wear sustained by an object. He said this on the subject:

 *"It would be nearly impossible to use a bronze tool in any sort of heavy work without producing deformation markings in the microstructure; where the damage is more extensive, the resultant work hardening can be detected with microhardness measurements"* – [186, p. 320].

In addition to this revelation regarding the hardness changes in the blades of tools during use, Gordon reinforced that the occurrence of deformed and elongated sulphides in their

microstructures could be used to categorically isolate those axes that have been cold-hammered at some point in their existence. This approach rests on the idea that work-hardening alone is not able to deform sulphides. This deduction allowed the author to confidently assert that the objects he analysed were entirely free of deformation generated by cold-hammering.

## 4.3   Macromechanical response

This section considers the manifestation of wear on a material at the macroscopic level. Holmberg and Leyland [248], describe the macromechanical response of a material as, "the stresses and strains occurring, to the resulting total plastic and elastic deformations and to the wear particle formation process and its dynamics". It is important to consider at this point that a surface of a material is very rarely considered to be flat; as well as containing many defects, the atomic planes are most often skewed within the material matrix, so that a 'quasi-planar' surface is generated [231, p. 476]. Rather than a smooth plateau, the exterior of a material is really a series of 'peaks' and valleys' at all magnifications [231, p. 477]. Accordingly, when two substances are thrust together, the initial contact only arises at the highest 'peaks' on each surface. The affected area on these asperities usually only comprises <1% of the total surface area of a material [3, p. 40]. The limited area of contact between two solid surfaces in relative motion has considerable implications for the propagation of wear. Foremost, the existence of such tall 'peaks' is believed to inhibit 'close contact' between surfaces, which restricts the maximum degree of wear and friction that can occur [231, p. 476]. Yet, it is the changes that are produced as a result of the meeting of these asperities that give rise to all tribological processes. Thus, wear is really a function of the many interactions, mechanisms, and reactions "that distort the material around the points of contact" [3, p. 40].

The exact mechanism(s) by which the asperities on the surface of a material deform are both intricately related to the structure and properties of the material and the type of contact, such as, sliding, rolling, impact, fretting, and associated conditions that are formed. The types of wear mechanism that are likely to be relevant in the wear of Bronze Age palstave axes during wood-chopping are as follows: adhesive, abrasive, and fatigue [249, p. 316]. The specificities of the above mechanisms are assessed individually below. There has been little research [91], [216], [227] to illuminate the exact mechanics behind wear in archaeological scenarios; this is reflected in the absence of any discussion of ancient bronze in the discussion below. This is something that is addressed in the original research presented here-in. It is vital to consider that wear phenomena seldom occur separately to one another – often the material will respond in several different ways

over the course of time, or even simultaneously, due to varying contact types and conditions. There are a number of other wear responses that are less relevant for this research, for example, percussion, erosion, fretting, melting, and electrical-arc induced wear. These mechanisms are much less likely to take place within the tribological system produced when a palstave axe is used in a chopping action against wood.

## 4.3.1 Adhesive wear

Adhesive wear occurs when the surfaces of two solid structures meet in sliding contact [249, p. 316], [232, pp. 449, 450]. Given the chance, the majority of solids will adhere to some degree when in relative motion with one another due to atomic bonds that form between the two surfaces; however, contact is often avoided by intermediary lubricants, such as oxidation layers or artificial supplements to the contact interface [231, p. 577]. Despite this, lubricant films are susceptible to rupture, and when this happens, adhesion may cause the transfer of wear particles between the two materials. Although the net loss of material between the tribo-couple is normally low, the impact on each surface can be severely detrimental [231, p. 5]. It is quite likely that adhesion would have taken place when a palstave axe was used to chop wood, generating an increase in friction as the duration of use increased. In fact, adhesive wear rates can be extremely high and may generate sizable friction coefficients that are large enough to induce seizure of the material [231, p. 577]. This phenomenon may have led to the adoption of the 'side-loop' within later palstave axe typologies, which would have prevented the axe-head getting stuck in the cut.

Adhesive wear takes place only at the apices of asperities during the meeting of two surfaces [249, p. 316], [232, pp. 449, 450]. This means that materials with greater surface roughness are less easily affected by adhesive wear [250, p. 279]. During frictional contact, areas of adhesive bonding between touching peaks may develop, creating zones known as 'microwelds' [233, p. 83]. If these bonds are weak, then no wear is likely to occur when a shear sliding force is applied. However, if the interface has strong enough adhesive bonding to withstand relative sliding, then the material is subject to significant plastic deformation to the degree where a crack may form and a particle is most often detached from the softer surface and moved to the harder [250, pp. 278, 279], [233, p. 83]. The direction of this transfer is related to the plasticity of the material; surfaces with a higher hardness are more likely to be wear resistant [250, p. 279]. This means that the proportion of wear particles produced by the material with less relative hardness in any given contact greatly outnumber those generated by the harder material. Hence, within the tribo-couple of wood and

bronze, it would be much more likely for wood, as the softer material, to adhere to the metal surface. While not directly damaging the surface of the bronze, these plaques of wood could cause accelerated corrosion [251]. Fragments of the harder material are also deposited on the softer material, but in smaller numbers [250, p. 279]. The many defects that exist within the crystal lattice structure of tin-bronze make the loss of the harder material possible as they provide local areas of low mechanical strength. When these locations collide with asperities on the wood they may be dislodged and start to adhere to the softer material [232, p. 450].

Two variants of the adhesive wear mechanism have been widely documented (*Figure 17*). Firstly, if a tangential compressive shear force is applied to a contact zone with strong microwelds, the outcome may be the cultivation of slips within the crystal planes of one of the materials [250, p. 280]. This can create 'flake-like shear tongues' that are subsequently displaced from the surface of their origin and transplanted onto the exterior of the opposing structure  [250, p. 280]. Secondly, a shear sliding force may result in the plastic removal of consecutive layers of an asperity, so that a wedge-shaped feature is incrementally formed on the counter-surface over several loading cycles [232, p. 450]. With the continuation of sliding, the severed material that is formed in the above mechanisms is often transferred back and forth onto either surface in the contact, culminating in the generation of quite substantial wear particles [250, p. 280]. Although it might seem counterintuitive, given that the adhesive bonds were initially strong enough to rip the fragments from their original structure, these particles sometimes become completely detached from either surface [232, p. 450]. This signifies that the loose fragments have misplaced their ability to form durable bonds due to either chemical changes, such as oxidation, or fatigue processes that produce fracturing of the particle [232, p. 450]. These loose fragments can go onto contribute in abrasive wear, as explained below.

*Figure 17:* Illustration of the two principal processes of adhesive wear; a) adhesive transfer of a thin flake-like wear particle, and b) a wedge-like particle is formed on the opposing surface (Source: Author's own, based on [250, p. 280]).

### 4.3.2 Abrasive wear

Extended periods of frictional contact between solid structures and 'snags' (peaks on the exterior of counter-bodies or fragments that have become detached) with an equivalent or greater hardness, can generate abrasive wear [231, p. 525], [232, p. 459]. Materials like wood, that have a soft bulk, may form these problematic 'snags' under the pressure conditions of contact [231, p. 525], [250, p. 281]. Ductile materials, like copper, are susceptible to plastic deformation upon meeting with these hard topographic features on the opposing surface [232, p. 459]. As with

adhesive wear, the hardness of the material is also equivalent to its ability to withstand plastic deformation by these hard locations, and so the potential for abrasive wear can be considered to be inversely proportional to hardness. This means that palstave axes with a higher baseline hardness may not only be more resistant to significant deformation at the cutting-edge, but also abrasive wear. Many materials are deformed by even the slightest loads, so that when a repeated shear sliding force is applied to smooth ductile materials, corresponding grooves are observed on the surface of both structures that match the asperities on the opposing surface. These are more commonly known as, 'striations' within archaeological use-wear analysis [5]. When brittle materials with weak fracture toughness are exposed to the same resistance, cracking can contribute to brittle fracture [232, p. 459].

Two different modes of abrasive wear have been posited, which can be defined by the number of active agents in the contact (*Figure 18*). Two-body abrasive wear involves only the interaction of the two surfaces. For example, the exterior of both objects may contain hard asperities that act like sandpaper when the material is moved in relative motion one another, rubbing and abrading the opposite surface [231, p. 529]. Three-body abrasion is, instead, generated by the presence of a 'grit' caught in the interface between the two moving surfaces. These fragments may be formed by adhesive wear initially, and due to prolonged stress in the contact region, may be significantly harder than the relative areas of localised hardness on either surface [249, p. 330]. Clearly, they are also not fixed in one position, which means they are permitted to freely roll and slide, generating wear on either surface in motion, or even both at the same time [231, p. 529].
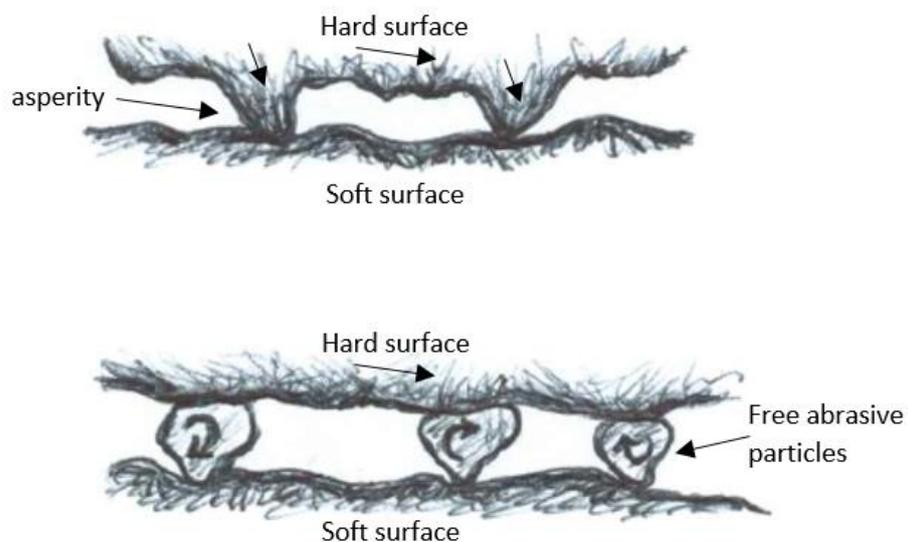


***Figure 18:*** Diagram capturing the processes of abrasive wear; a) two-body abrasion, and b) three-body abrasion (Source: Author's own, based on [232, p. 329]).

There are multiple variants to the mechanism of abrasive wear, reflecting the many contact types that can be applied to two surfaces and the individual mechanical response of the material. The most commonly observed wear mechanisms to affect ductile material like tin-bronze are: microcutting, wedge-formation, and ploughing (resulting in fatigue) [231, p. 526], [250, p. 284]. Microcutting comprises the abrasive wear that takes place at the contact interface of two flat ductile surfaces in relative motion (usually obtaining a low friction coefficient), when a sharp abrasive particle cuts into a surface with less resistance to plastic flow, producing a long 'ribbon-like' wear particle [231, p. 526], [250, p. 281]. Wedge-formation occurs when a fragment or hard asperity is pulled against a surface that has a high ratio of shear strength relative to the shear strength of the bulk material [232, p. 463]. This instigates the accumulation of wedge on the tip of the abrasive particle, which is fractured from the bulk and is then pulled along by the asperity, gaining size by adhesion with the underlying surface as it is moved. This generally produces a large friction coefficient [250, pp. 284, 285]. Ploughing transpires when a hard grooving asperity is ploughed across a ductile surface during sliding contact. In contrast to the mechanisms described earlier in this paragraph, ploughing does not produce a wear particle, only a shallow groove with deformed material displaced at the sides [250, p. 281]. However, if these ridges are flattened and reformed during subsequent loading cycles they may become fatigued and eventually fracture [232, pp. 462, 463].

### 4.3.3   Fatigue wear

Fatigue wear differs from adhesive and abrasive wear phenomena, as it does not reflect the initial interface deformation that occurs when two surfaces are in relative motion with one another, but the underlying structural strain. While fatigue of a material may occur in relation to other wear mechanisms, as mentioned above, it may also occur independently, even when lubricant films are sufficient and abrasive particles are not present [231, p. 5]. This is a result of the considerable stress that pervades through the surface film to the material below during contact types like impact, rolling, and sliding [232, pp. 474, 476]. However, the surface deformation sustained during other wear types is a, more-or-less, an immediate action, whereas, the weakening of the underlying structure of a material may take an extensive number of cycles before wear is detectable [232, pp. 342, 343], [250, p. 290]. When wear is induced after only a relatively few cycles of loading, the fatigue is called 'low-cycle'; when the opposite is observed and many cycles are needed before

damage is incurred, the fatigue is called 'high-cycle' [250, p. 290]. Nonetheless, both types of mechanism are considered to be mild forms of wear due to the delay in deterioration [231, p. 5].

The process of fatigue wear is closely related to the existence of defects and inhomogeneities within the crystal lattice structure of metals. When applied with prolonged cyclical stress during rubbing, plastic deformation may be gradually brought about in the subsurface structure of a material. The dislocations within a material can be provoked to slip along slip planes until they stack up at a point where they are no longer able to move. At this location, the material will be significantly harder, but with a low fracture toughness. Eventually, continued deformation at this site will lead to yield within the material in the form of micro-cracks [250, p. 292]. Evidence for the internal degradation of the microstructure will begin to appear on the surface of the material as pits, and further loading will exacerbate these weak areas, until cracks appear at the surface [250, p. 292]. Following more stress, these will propagate and form flake-like fragments that are removed from the surface; eventually entire areas of the material crack may off [233, p. 83]. This is unlikely to happen in low-tin bronzes, where the material is likely to deform rather than fracture. However, high-tin bronzes are much more brittle and repeated use could cause micro-cracking to form, which eventually leads to larger cracks and the loss of material at the cutting-edge.


## 4.4   Environmental attacks

While not a direct function of the tribological system, the corrosion of bronze as a consequence of local environmental conditions before or after deposition should be mentioned here, due to the implications it has for the identification of wear on archaeological material. The surface of a crystalline solid is often subject to chemical interactions with the environment and opposing contact materials. Like plastic deformation, this is largely a consequence of the defects present within the lattice structure. However, in this case, the important effect is the many weakly bonded atoms at the exterior interface of the crystal [231, p. 476]. In fact, if these dislocations did not occur within the lattice, it would sensible to assume that all metals would have been practically inert to other substrates [231, p. 476]. As metals go, bronze is quite resistant to corrosion. The close-packed lattice structure of copper prevents hydrogen ions and other unwanted contaminants from permeating through the microstructure to introduce degradation. However, when exposure is at the scale of millennia, like many Bronze Age artefacts, complete preservation is out of the ordinary.

The severity of corrosion on archaeological bronzes is dependent on many endogenous factors (the composition of the alloy, manufacturing techniques, the dimensions of the artefact) and exogenous factors (the elements in the soil, pH, humidity, porosity, etc.) [252, p. 2084], [253, pp. 762, 763]. In a non-aggressive deposition context, 'type I' corrosion is most likely. By this mechanism, an outer layer enriched in tin is formed, with an inner layer of cuprous oxide [253, p. 763]. This external layer does not cause the original surface of the material to change (there is no addition in surface volume), and it actually presents a barrier to more destructive corrosion processes (*Figure 19*) [252, p. 2094]. In more aggressive conditions, 'type II' corrosion is produced in the form of a three-layer structure: an outer layer made of cuprous (II) corrosion products; a middle layer of copper oxides; and an inner layer of high tin content [254, p. 11]. In this situation, the original surface of the artefact erupts outwards and many original features will be undistinguishable (*Figure 20*) [253, pp. 762, 763]. Most ancient bronze artefacts show evidence for both of these types of corrosion in distinct areas across their morphology.



*Figure 19:* An example of Type I corrosion on a Middle Bronze Age palstave axe (Source: Author's own, courtesy of Somerset Heritage Centre).

**Figure 20:** An example of Type II corrosion on a Middle Bronze Age palstave axe (Source: Author's own, courtesy of Dorset County Museum).

In terms of use-wear analysis on bronze artefacts, type I corrosion does not often adversely impact the investigation of wear. Type II corrosion, however, can mislead the identification of wear marks and completely obscure any evidence altogether. Moreover, areas of the microstructure that have been deformed by use are preferentially damaged by corrosion as there are more atomic dislocations sites at the surface of the material in these regions. Equally, when organic residues become embedded in the material matrix during use of the object, they generally promote areas of more intense corrosion [4, p. 184]. The simplest solution is to analyse parts of the artefact that are not corroded, or have only been affected by the less severe type of degradation. Where this is not possible, use-wear analysts must be prepared to determine traces of use amidst corrosive precipitates. In his wear analysis of 154 spear-heads and 50 swords from the early Nordic Bronze Age, Horn [207], discussed the difficulties that are introduced by corrosion at length, and suggested possible features for recognising wear even when corrosion has damaged the surface of the artefact. Sadly, these methods are not always successful. McClendon [255], for example, encountered the issue of corrosion when examining the polishing and striation formation of bronze replica sickles and prehistoric specimens. The reconstruction sickles that were created for harvesting vegetation in experimental tests demonstrated significant polishing on the cutting edge after use. However, corrosion precipitates obstructed any indication of a similar pattern of abrasion on the blades of the archaeological sickles [255, p. 84]. Cleaning or restoration treatments to reduce the impact of corrosion often remove or obscure any remaining manifestations of wear [4, p. 183], [209]. Though, in the last several years, Three-dimensional Computed Tomography X-ray has been proven as an effective way to visualise heavily corroded metal artefacts [256], [257], [258], virtually

stripping away the oxidation products which act to obscure the object within. The suitability of this technique for the visualisation of surficial use-wear is, however, still to be determined. Consequently, Dolfini and Crellin [12, p. 83] have named corrosion as the 'elephant in the room' of the field of metal use-wear analysis, as scholars have long evaded discussing its impact on the potential for investigating wear phenomena on metal artefacts.

## 4.5   A defined tribological system

As discussed in section 3.3.2, one of the major shortcomings with previous metalwork wear analysis is that researchers have not put ample consideration into defining the tribological system. To make sure the same mistakes were not made within this thesis, this chapter has addressed the materials science aspects that are important when investigating wear on Bronze Age palstave axes. The above text has illustrated how the structure of tin-bronze is altered by composition, processing, and use, which is very crucial for understanding the dynamics of the crystal structure under stress and also for accurately assessing the types of microstructure that are observed within the replica and ancient palstave axes presented here-in. Also discussed above was exactly how microstructural variation determines mechanical properties, such as elasticity, strength, toughness, and hardness. This has emphasised just how differently tin-bronze can behave when produced in particular ways, further validating the need for experimentation with replica palstave axes of varying composition and manufacturing. The types of wear mechanisms expected within the tribo-couple of wear and bronze have also been suggested. An appreciation of macromechanical action is vital for identifying how wear manifests on the surface of Bronze Age palstave axes. Finally, a few cautionary words were given about the obstructive nature of corrosion, which does somewhat limit the analytical potential of most metal use-wear studies.

# PART 2: EXPERIMENTAL WORK AND MATERIALS SCIENCE APPROACH

## 5 Methods and Data

The current chapter presents a methodological narrative and data overview for the experimental work conducted on replica bronze palstave axes. The methodological approach has involved the creation of ten replicas with different compositions and post-production processing, which were subsequently examined by Energy Dispersive X-ray spectroscopy and metallography to check the correct manufacturing specifications had been achieved. The replicas were subjected to mechanised testing in a drop tower at impact energies that reflect the range of human arm-propulsion. Sequential analysis (by Vickers microhardness, Scanning Electron Microscopy, and digital microscopy) was used to record and characterise the progression, form, and properties of the surface-level wear that developed during use and how these features interacted with signatures left by maintenance activities. The frequency and morphology of macroscopic failures at the cutting-edge, named 'major deformation phenomena', were also recorded sequentially by photography and macroscopy. The details of the material fabrication (section 5.1), experimental setup (section 5.2), and analytical techniques (section 5.3) are discussed in the section below.

### 5.1   Materials

To design a representative replica for archaeological reconstruction experiments, a good understanding of the context of the object is required from both a materials science and archaeological standpoint. Ultimately, it is not possible to know the exact decisions and techniques that went into the production of a Bronze Age palstave axe. That said, some factors that pertain to the manufacture of these objects, for example, type, composition, casting, processing, and sharpening, can be identified and considered in the pursuit of a relatively representative axe design. In addition, there was often a trade-off between the adoption of authentic and modern methods during their creation. All reasonable efforts were made to produce replicas in the most authentic way, however, to ensure the right material specifications were achieved modern techniques were

often used. The following sections will, therefore, outline the approach, specifications, and limitations relating to the construction of the experimental specimens.

### 5.1.1   Type

Replica palstave axes and smaller blade-only experimental specimens (the need for which will be discussed in section 5.2.3) were reproduced at Butser Ancient Farm by resident bronzesmith, Jim Clift. The axe used as a pattern for casting the replica axes and blades was an un-providenced low-flanged palstave type that was uncovered in field in the Meon Valley, Hampshire, by a farmer overseeing his agricultural work. As seen in *Figure 21*, the palstave axe used to construct experimental specimens has the typical characteristics of a low-flanged palstave, including a maximum height at the stopridge, a broad-blade that is slightly expanded, a sunken shield motif filled with multiple ribs, and ribs above the stop, on the septum floor. The axe does not have a side-loop. This axe is representative of a type of palstave axe that may have been used in Britain in the midst of the Middle Bronze Age, which makes it suitable for the present work.



*Figure 21:* The original axe from which the casting pattern was constructed from (Source: courtesy of James Clift).

### 5.1.2   Composition

As already shown in Chapter 4, changes in composition and, therefore, the internal microstructure, can affect the manifestation of deformation and the progression of wear. Consequently, the composition of the replica axes and blades was controlled tightly. *Table 1* presents the manufacturing data for each experimental specimen. The alloy composition of Axes 1-4 and Blades

1-4 (90% copper and 10%) tin was based on the compositional data produced by Coghlan [116], [135], [137] for the twenty-eight palstave axes from across Britain and Ireland that form a part of the sample of the present study. Based on the data presented in [116], [135], [137], the average tin content for the Coghlan palstave axes is 9.7%. Hence, the use of 10% tin-bronze in the production of these experimental specimens was used to recreate a microstructure that was representative of the Coghlan palstave axes. The alloy composition of Blades 5 and 6 (86% copper and 14% tin) was based on the compositional data produced by Peter Northover for the 112 palstave axes from the south-west of England that contribute to a large proportion of the sample in the present study. The average tin composition of the south-west palstave axes was calculated as 13.07%. However, after examining the histogram presented below (*Figure 22*), a tin contribution of 14% was deemed appropriate, as this would capture the metallurgy of a greater number of axes around the 13-15% marker. This decision was made on the assumption that a difference of ~1-2%, below or above the target alloy, would only produce only small variations in mechanical properties. Hence, the use of 14% tin-bronze in the production of these experimental specimens recreated a microstructure that was representative of the majority of higher-tin south-west palstave axes.

| ID | Form | Composition | Processing | Sharpening |
|---|---|---|---|---|
| **Axe 1** | Full axe | 90% Cu, 10% Sn | As-cast | Engineering |
| **Axe 2** | Full axe | 90% Cu, 10% Sn | As-cast, cold-hammered | Engineering |
| **Axe 3** | Full axe | 90% Cu, 10% Sn | Cold-hammered, annealed | Engineering |
| **Axe 4** | Full axe | 90% Cu, 10% Sn | Cold-hammered, annealed | Engineering |
| **Blade 1** | Blade only | 90% Cu, 10% Sn | Cold-hammered and annealed x2 | Authentic |
| **Blade 2** | Blade only | 90% Cu, 10% Sn | Cold-hammered and annealed x2, lightly cold-hammered | Authentic |
| **Blade 3** | Blade only | 90% Cu, 10% Sn | Cold-hammered and annealed x2, lightly cold-hammered | Authentic |
| **Blade 4** | Blade only | 90% Cu, 10% Sn | As-cast | Authentic |
| **Blade 5** | Blade only | 86% Cu, 14% Sn | Cold-hammered and annealed x2 | Authentic |
| **Blade 6** | Blade only | 86% Cu, 14% Sn | Cold-hammered and annealed x2, lightly cold-hammered | Authentic |

*Table 1:* The composition and manufacturing specifications of each experimental specimen within the study.
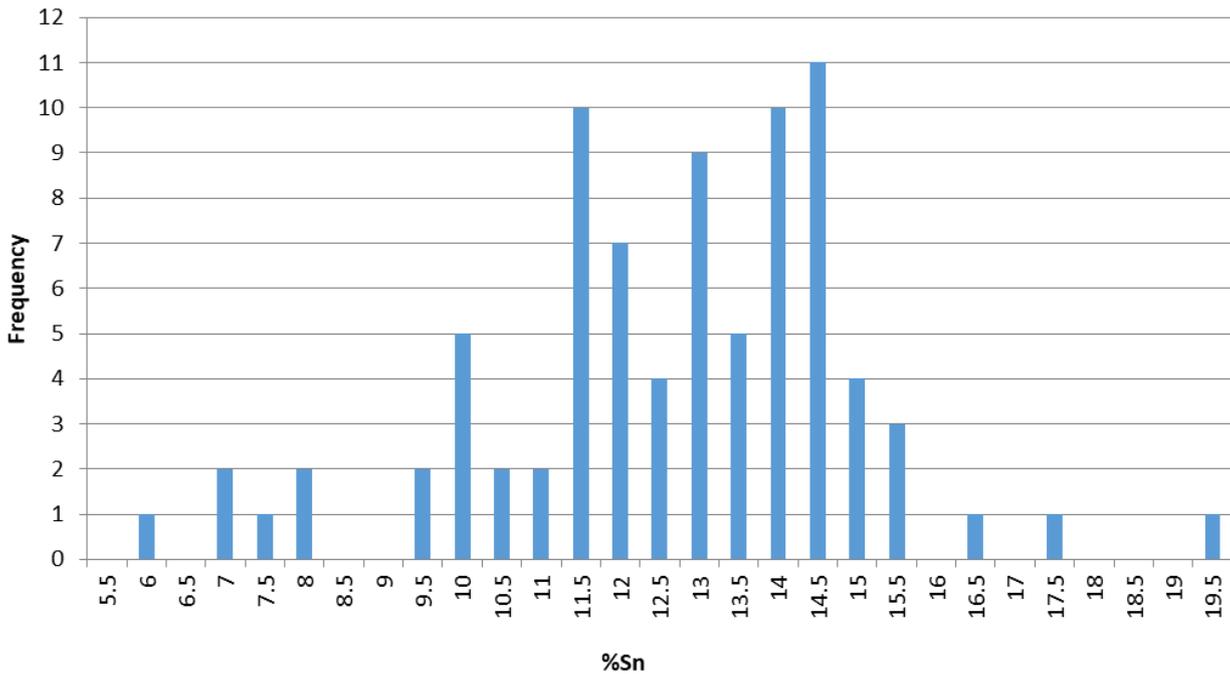
**Figure 22:** Tin composition of the palstave axes from the south-west of England (Source: courtesy of Peter Northover).

It is clear that impurities existed within the matrix of Middle Bronze Age palstaves. For instance, both the Coghlan [116], [135], [137], and south-west palstave axes (both discussed in more detail within section 6.1), and a sample of palstave axes analysed by Brown and Blin-Stoyle [134], typically exhibited minor amounts of lead and arsenic (>1%), in addition to quite regular nickel values of 0.4%. Since, in most cases, the impurities within these palstave axes were recorded at low levels and, thus, would have had very little impact on the microstructure or associated properties of the object, it was decided that impurities would not be included within the alloy composition of the experimental specimens. Hence, the raw materials that were used to create the experimental specimens were pure copper wire and 99C tin solder (99% tin and 1% copper). These were chosen over copper ore and the use of tin ingots due to their ease of use, cost, and availability. For Axes 1-4 and Blades 1-4, a total of 500.00g of tin and copper wire were weighed for each specimen using a scale displaying two decimal places, at the chosen composition of 90% copper and 10% tin, this equated to 449.50g of copper wire and 50.50g of tin solder. For Blades 5 and 6, a total of 500.00g of tin and copper wire were weighed for each specimen, at the chosen composition of 86% copper and 14% tin, this equated to 429.30g of copper wire and 70.70g of tin solder.

### 5.1.3  Casting

The experimental specimens were cast using a sand mould (the archaeological evidence for the use of this method was discussed in section 2.2.1.3). The full axe replicas were 150mm long with a blade width of 65mm and a maximum thickness of 30mm at the stopridge. For the blade only replicas, the blade width was 65mm (dimensions of the block used to attach each specimen to the instrument striker can be found in section 5.2.1). The sand moulds were created by the use of a hinged metal flask and petrobond sand (*Figure 23*). The dimensions of the metal flask were approximately 230mm x 120mm x 100mm (LxWxD). Although there may be less direct evidence for the production of palstave axes using sand-casting, rather than other methods, this procedure was chosen as it consistently produces good quality of surface finish and, thus, a high success rate. To create the mould, the bottom half of the frame was filled with sand and compacted. Next, a pattern was placed onto the sand in the centre of the frame and the top half of the frame was filled with sand and compacted around the pattern. The flask was then opened and the pattern removed. After each casting, the sand was removed from the flask and then allowed to cool before reuse. The materials for each specimen were placed in a ceramic crucible. The crucible containing the tin and copper was placed in a modern furnace (constructed of firebricks and ceramic fibre). A burner was inserted into an opening in the furnace, this was connected to a canister of propane gas by a rubber tube. The mould was positioned next to the furnace with the entrance to the sprue upwards. The burner was ignited and the crucible was heated to a temperature of over $1350^\circ$C (upper limit of laser thermometer temperature gun) until the metal inside was completely molten (approximately 10-15 minutes). As already discussed, Bronze Age metalsmiths most likely constructed a clay lined pit sunken within the earth [126, p. 281]. This method was not used due to the difficulty in achieving an adequate melting temperature, leading to inconsistent casting success, and the relative length of production time. Immediately after removing from the heat, the molten bronze was poured into the mould through the sprue (this took no more than 10 seconds) (*Figure 24*). Pouring was carried out in a controlled manner but without specific consideration for the entrainment of air within the cast item. After 3-4 minutes the flask was opened and the axe was removed and was allowed to cool down without quenching. While an experienced bronzesmith completed all casting, in order that casting quality was kept as consistent as possible, it is very unlikely that the skill level of even the most experienced bronzesmiths of the modern era are equivalent to those of the Bronze Age. The quality of the casts created herein, therefore, are no doubt inferior to ancient axes.

**Figure 23:** The pattern has been removed from the flask and a mould has been created in the sand (Source: Author's own).



**Figure 24:** The crucible and molten metal are poured into the mould by Jim Clift (Source: Author's own).

The casting methodology is likely to have had an impact on the microstructure and porosity of the replicas in several ways. Firstly, the use of a sand mould and the lack of quenching is likely to produce coarse dendrites (DAS of 30-60 µm) as the cooling rate will have been slow [132, p. 49]. As already mentioned, the pouring of the cast was not optimised to reduce entrainment of air, thus, there was considerable potential for the introduction of porosity into the material matrix.

## 5.1.4  Processing techniques

The axes were finished, firstly, by using an angle grinder to fettle away any flashing along the seams of the cast. Afterwards, a more detailed fettling was achieved by using flat and half-round metal files. Most axes and blades were then subjected to some kind of further post-production processing (a summary is presented above in *Table 1*), in order that development of wear could be recorded on axes exhibiting a range of microstructures. Although the predominant processing applied during the manufacture of palstave axes is thought to have been the hammer-anneal-hammer combination, the choice to experiment with axes in an as-cast and hammer-anneal form reflects the desire to obtain an understanding of the response of the material across a full range of metallurgical specifications. Experimental specimens with none, or part processing are, firstly, necessary as a comparative tool for fully-processed experimental specimens and, secondly, are representative of real palstave microstructures (albeit in smaller numbers) [116].

Annealing was not conducted in an authentic manner, however, as the use of modern methods was necessary to make sure that the microstructure was 'reset' to an adequate degree. This required ensuring that the axes were annealed at the right temperature, for the specified time. The length and temperature of the anneal was determined by the following equation devised by Dungworth [242], which describes the relationship between hardness, time and temperature of a 1.2% tin bronze alloy:

$$Hv_t = Hv_0 - (Hv_0 - Hv_\infty) \times \left( \frac{t^{(0.00997T-2.766)}}{(1419e^{(-0.0058T)}) + t^{(0.00997T-2.766)}} \right)$$

*Where,*
*$Hv_t$ is the hardness after time t,*
*$Hv_0$ is the hardness before any annealing,*
*$Hv_\infty$ is the hardness after infinite annealing (hardness before cold-working),*
*t is the time measured in minutes,*
*T is the temperature ($^o$C)*

According to the equation proposed by Dungworth [242], a 10 minute anneal at 600°C would culminate in an approximate hardness of 100 HV if the hardness of the experimental specimens before annealing was under 200 HV (which hardness measurements taken after the hammer-hardening of Axe 2 showed to be likely). Thus, Axes 1 and 2 were subject to annealing by blow torch for 10 minutes until the blade reached a 'cherry-red' colour, which indicates a temperature of approximately 650-750°C [259, p. 110]. Although this amount of annealing was shown to decrease hardness to the baseline level [206], inspection of the microstructure by metallography indicated that the grains had not been recrystallized and remained in a dendritic form (see section 6.1). Therefore, the decision was taken to anneal Axes 3 and 4 in a furnace for 10 minutes at 600°C. Nonetheless, this method still did not ensure the recrystallization of the microstructure. Since Dungworth's equation was based on a 1.2% tin bronze alloy, it may not accurately represent the rate of diffusion within a 10% tin-bronze during annealing. The higher concentrations of tin within the experimental specimens produced herein may mean that they require longer annealing times to allow for diffusion of the microstructure from dendritic to recrystallized alpha phase bronze. Hence, the annealing time for Blades 1-3, 5 and 6 was increased to 20 minutes and the temperature to 650°C, and was administered two times, with hammering in-between. The decision to cold-hammer Axe 2 and Blades 2, 3, and 6 after annealing, reflects the type of processing that may have been upheld by prehistoric practitioners to secure the durability of the blade. Cold-hammering consisted of hitting the blade with a ball-point hammer; 64 light strokes on each side and 12 along the top of the blade.

### 5.1.5    Maintenance

The initial sharpening, as well as subsequent re-sharpening events, was administered by either 'engineering' or 'authentic' methods. 'Engineering' methods, which were first used due to the ease of  application over authentic methods, consisted of using a flat metal file in a back and forward motion until a reasonably acute angle was formed at the edge; this was followed by a dampened silicon carbide whetstone in a circular motion. After using engineering methods to sharpen Axes 1-4, and observing the clear increase in hardness along the blade introduced by this treatment (see section 6.2), it was considered appropriate to test authentic methods and compare the result in terms of hardness. 'Authentic' methods consisted of using a limestone grinding stone in a circular motion until a reasonably acute angle was formed at the edge, followed by a sandstone whetstone

in a circular motion.  In order to conduct these investigations, two 10% tin-bronze blocks with the dimensions 5cm x 2.5cm x 2cm were cast by Jim Clift. One block was labelled 'A' and the other 'B', while corresponding long side faces on each block were labelled 1-4. On the '1' and '3' sides of both blocks (four sides in total), engineering methods were applied. This included 30 minutes of sharpening with an engineering file, and 15 minutes of finishing with a silicon carbide whetstone. On the '2' and '4' sides of both blocks (four sides in total), authentic methods were applied. This included 30 minutes of sharpening with a limestone grinding stone (*Figure 25*), and 15 minutes of finishing with a sandstone whetstone (*Figure 26*). After sharpening was complete, hardness testing was systematically conducted by making five measurements at five sample locations (spaced 0.5cm apart), forming a transect down the centre of the face of each side (the methodological considerations applied to this technique are discussed in 5.3.2). The average measurement for each side are presented in the tables below (*Table 3* and *Table 2*) and the following graph (*Figure 27*).



*Figure 25:* Sharpening a block with the limestone grinding stone (Source: Author's own).

*Figure 26:* Sharpening a block with the sandstone whetstone (Source: Author's own).

| Block A | Pre-sharp average | st.dev | Post-sharp average | st.dev |
|---------|-------------------|--------|--------------------|--------|
| 1 | 102.07 | ±9.92 | 154.33 | ±24.66 |
| 2 | 108.97 | ±11.28 | 189.78 | ±29.08 |
| 3 | 103.68 | ±13.49 | 169.96 | ±27.53 |
| 4 | 100.53 | ±15.93 | 177.48 | ±18.21 |

*Table 3:* The mean hardness of Block A.

| Block B | Pre-sharp average | st.dev | Post-sharp average | st.dev |
|---------|-------------------|--------|--------------------|--------|
| 1 | 104.83 | ±22.63 | 161.82 | ±23.1 |
| 2 | 104.41 | ±12.93 | 197.56 | ±27.44 |
| 3 | 108.13 | ±10.26 | 165.09 | ±24.98 |
| 4 | 102.88 | ±12.93 | 172.21 | ±34.48 |

*Table 2:* The mean hardness of Block B.
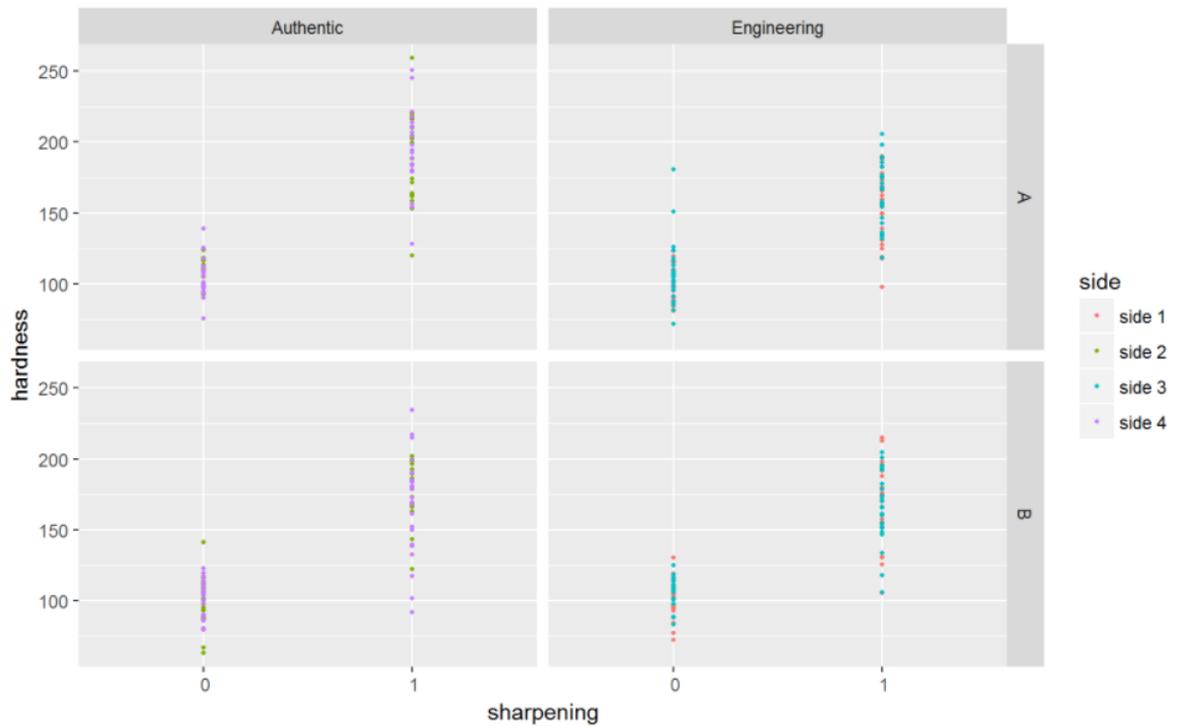
***Figure 27:*** Graph illustrating the difference in hardness values recorded after 'Authentic' and 'Engineering' sharpening methods on Blocks A and B.

The hardness results above have demonstrated that in all cases sharpening increases the hardness of the copper-alloy surface. The average initial hardness of these 10% tin-bronze blocks generally sits just over 100 HV for all sides. After sharpening, the sides that have been subjected to 'engineering' methods have an average hardness of between 154 HV and 169 HV. In contrast, the sides that have been subjected to 'authentic' methods have an average hardness of between 172 HV and 197 HV. The greater hardness increase in the sides sharpened by authentic methods is exemplified in *Figure 27*. It is likely that a greater hardness is introduced by authentic sharpening methods due to the higher pressure applied when using 'authentic' tools. As a result of the differences in material modification presented by the 'Engineering' and 'Authentic' sharpening methods, it was made clear that using modern methods was moving the microstructure of the palstave axes further away from that of ancient palstave axes, and it was decided that subsequent specimens should be sharpened with authentic methods.

## 5.2   The experimental rig

In the same way that the validity of chosen specifications for axe manufacture must be evaluated, the decision-making process and assumptions within the design of the experimental rig must also

be stipulated and addressed as part of a rigorous scientific method. It goes without saying that most scientific studies cannot be considered to be truly representative of real life scenarios. Most research is, instead, a close-fitting simulation of the variables underpinning the hypothesis. To make the most of finite time and resources it is often necessary to assume certain aspects of these variables – this information can be ascertained from the previous work of other researchers, estimated by mathematics, or deduced from the knowledge of certain well-founded principles. This element of inference within the methodology suggests that decided parameters may not be entirely accurate; in fact, they may provide sources of uncertainty in the results. To verify the validity of the conclusions made in any scientific study it is, therefore, an integral part of the scientific method to retain complete transparency in the delivery of the specifications, assumptions, and limitations.

## 5.2.1   The impact tower

The experimental rig comprised of a CEAST 9350 impact tower (Instron); an instrument that drops a specimen into an opposition material situated in the impact chamber below (*Figure 28*). The impact tester was chosen because it permits the energy, velocity, and force, at which the specimen is dropped into the opposition material, to be specified. The instrument also measures the actual velocity (as a flag on the instrumented striker passes through a photocell on the main frame), the actual force and the time taken until impact (the instrumented striker contains a strain gauge) of each test. This data is recorded by a DAS 64K data acquisition and analysis system (Instron), which relays the information to VisualIMPACT software (Instron). This computer software presents the data for velocity, force, and also impact depth (calculated by a double integration equation using force) in both numerical and graphical forms. By conducting tests using the CEAST 9350, several compromises were made in relation to the motion and attachment of the experimental specimens that could create some inauthenticity when compared to human action. For example, while the executed action is a downwards drop producing similar shear/compressive stress onto the axe-head as authentic tests would, it cannot reflect the same motion generated during an human arm-swing. This may have the undesired effect of re-directing stress from the blade corners (the area that makes contact first in an axe-swing), to the centre, introducing fewer failures in the aforementioned areas and, thus, potentially leading to an underrepresentation in the progression of asymmetry within the experimental samples. There is little that can be done to reduce the likelihood of this issue, however, the interpretation of the cutting-edge of each experimental specimen should be made with this in mind.

Furthermore, the reported methods for securely attaching the axes and blades to the instrument striker deviates significantly from the way Bronze Age axes would have been clamped into place for use (see section 2.2.1.4). This departure from prehistoric tradition is a consequence of the limitations of the experimental rig; a full haft would render attachment to the device unattainable, and other materials are needed to slot through the septum of the axe as a safety requirement. Ordinarily, the impact tower has predetermined inserts that screw into the instrument striker. Hence, it was necessary to design a method for attaching the experimental specimens in the same way. For testing with Axes 1-4, a modified insert was designed by Stephen Monaghan so that the axes could be clamped securely to the instrumented striker. To comply with the 85 mm diameter of the entrance to the impact chamber, the clamp system was made a hexagonal shape (reducing the radius of its outside edge). The clamp was comprised of steel in order to ensure fracture toughness, yield strength, and fatigue strength during thousands of impact cycles. At the base of the clamp a large rectangular block that harbours a M10x1.25 hexicoil hole that used to attach to the insert to the drop tower. The two prongs that emanate from the base also contain two holes (*Figure 29*); to secure the axes within the clamp, two nylon rods are positioned through the corresponding holes on either side, passing through matching holes in the septum of the palstave (*Figure 30*). These nylon rods often snapped after around 100-200 tests, which significantly slowed down progress, so for Axes 3 and 4, steel rods were instead inserted through the palstave septum and fastened tightly to the clamp with steel nuts. To avoid metal-on-metal contact, oak panels (chiselled by hand) were inserted at the haft-end of the axe and either side of the flanges. This also ensured the tight-fit of the axe within the central axis. Unfortunately, using steel rods also proved problematic as the thread was progressively worn during impact testing so that the nuts regularly became adhered to the rod and were very difficult to remove.

As the above text suggests, securing a full axe-head to the instrument striker was problematic from a testing standpoint (detachment of the specimen from the clamp was often frustrating and lengthy), and the full replica axe-heads were cumbersome to analyse. Thus, the introduction of the blade-only specimens made the testing process much more time and labour effective. The blades were designed so that no clamp was required for attachment to the instrument striker. A M10x1.25 hexicoil screw thread was inserted into the block part of each Blade to make their attachment to the instrument striker possible (*Figure 31*).
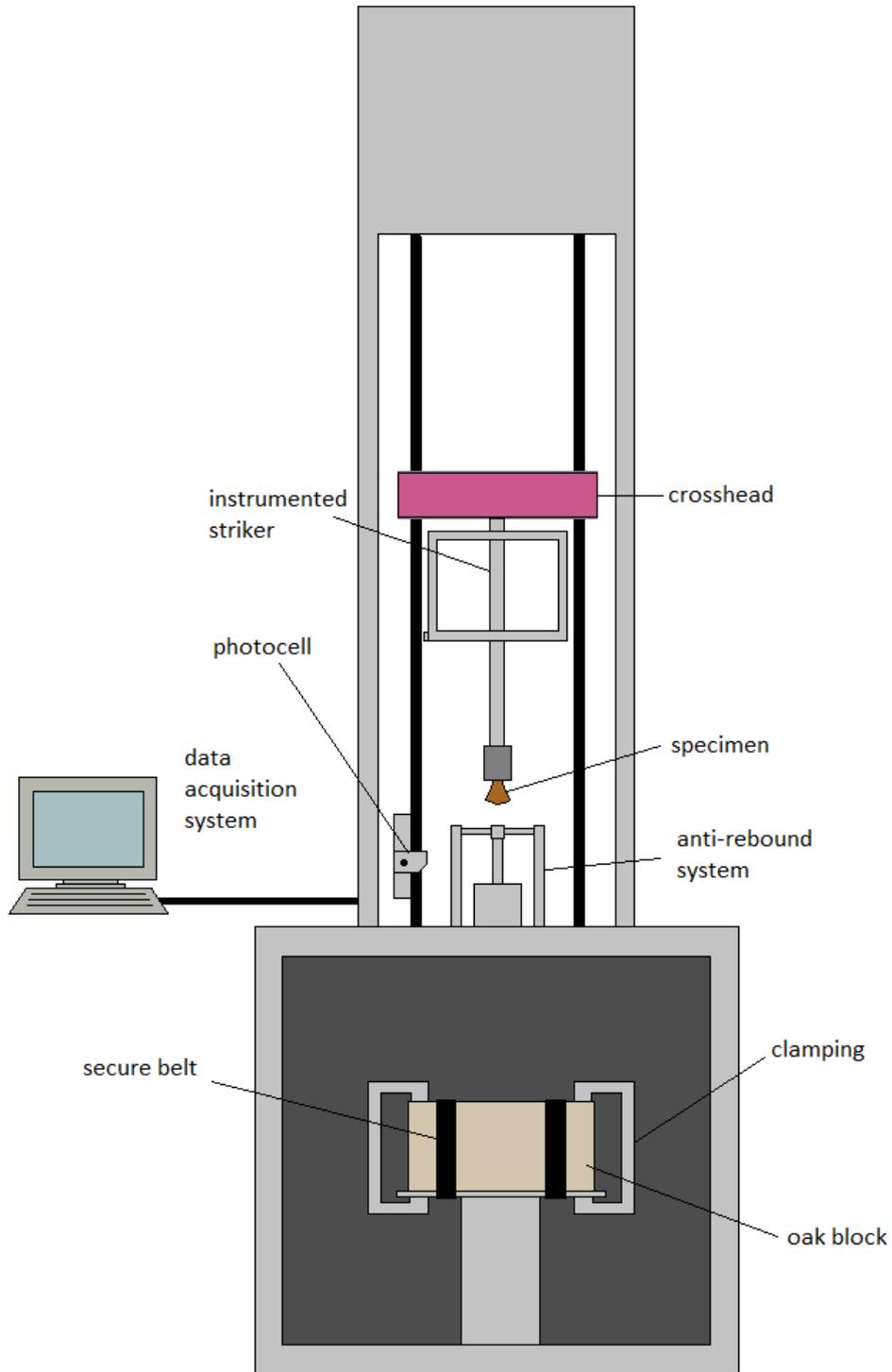
***Figure 28***: The modified CEAST impact tower that comprised the experimental rig, not to scale (Source: Author's own).
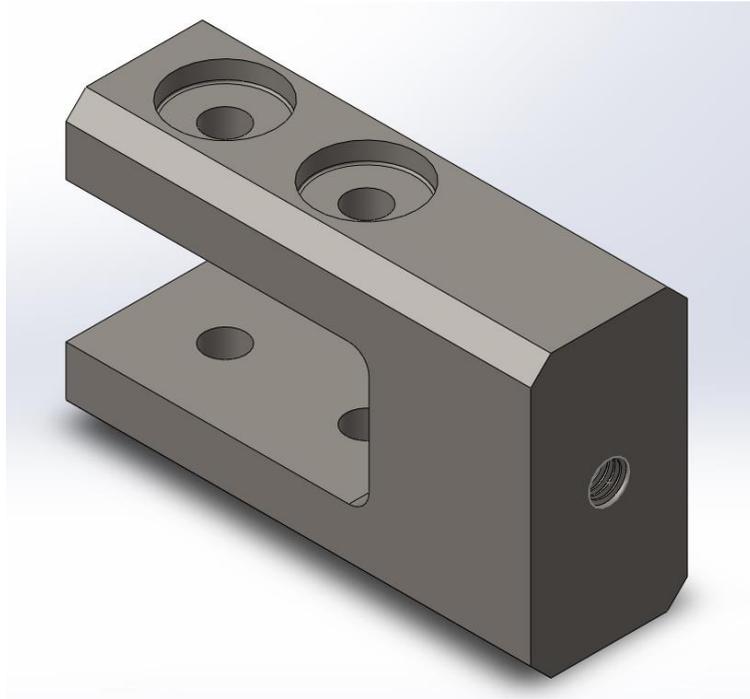
*Figure 29:* Illustration of the clamp to demonstrate the two holes on each prong in which nylon rods may be inserted (Source: courtesy of Stephen Monaghan, SOLIDWORKS).
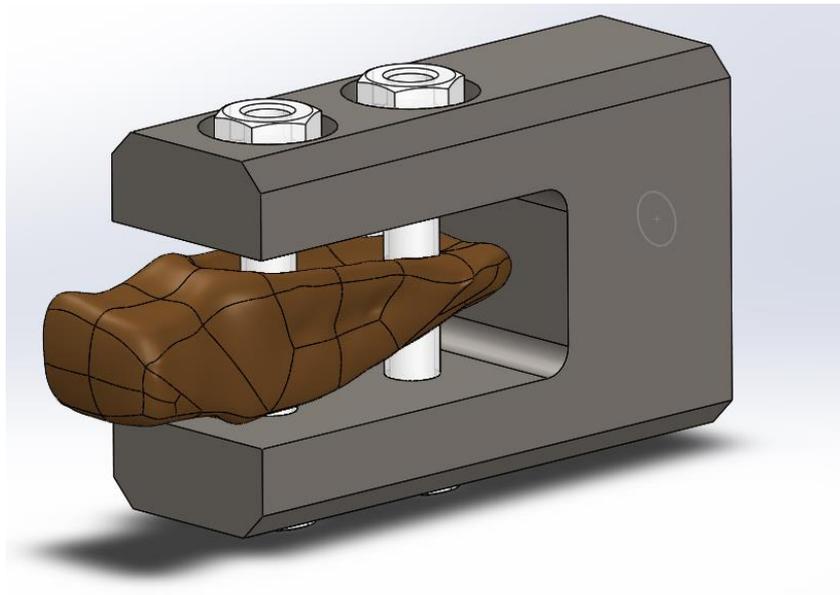


*Figure 30:* Illustration of the septum of a palstave axe secured into place within the clamp system (Source: courtesy of Stephen Monaghan, SOLIDWORKS).
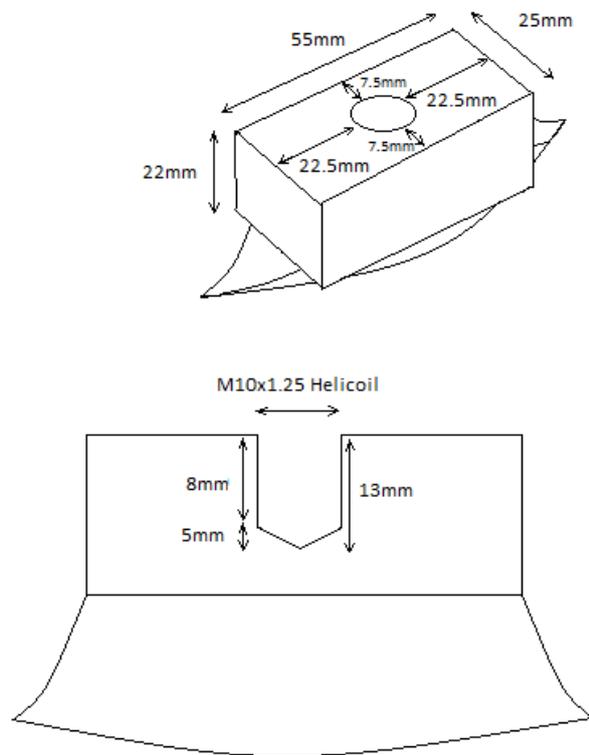
*Figure 31:* Diagram demonstrating the design of Bladelets 1-3, which incorporate a screw thread in the block shown so that direct attachment to the instrument striker is possible (Source: Author's own).

## 5.2.2   Testing parameters

In order to determine the testing parameters, actualistic experimentation with a hafted axe was undertaken to estimate the kinetic energy of an axe before impacting a target. Given the lack of evidence for prehistoric hafts for palstave axes (see section 2.2.1.4), the hafted axe, produced by Jim Clift, was constructed in the style of the 75cm in-tact socketed axe haft discovered at Must Farm in 2016 (*Figure 32*). This is considered to be one of the best preserved specimens found to date, and is representative of other hafts finds in Britain and beyond. For example, the length of the complete haft found at Must Farm as 73cm, the length of Otzi's haft is 76cm, and palstave haft found at Flag Fen is also about 74cm [146], [148]. The type of wood comprising the Must Farm axe has not yet been established, so the choice of oak for the replica haft was based upon the wood analysis of the Flag Fen hafts [148]. After talking to re-enactment specialists at Buster Farm, it was determined that a low, gravity swing can be assumed to be an accurate representation of the

'Bronze Age axe swing'. In this type of swing, little extra force is applied by the arms, while the mass of the whole haft and axe-head play a bigger part.



**Figure 32:** Replica Bronze Age axe used to calculate the energy of an axe-swing (Source: courtesy of Jim Clift).

To assess the Kinetic Energy transferred to the palstave axe, the velocity at impact must be assessed. A simple, yet efficient method, involving the use of a high-speed camera, was devised to collect this data. A block of wood was secured to a palette, with a ruler attached vertically behind. The high-speed camera, an IM10 Motion Pro X3, was set up approximately 2 metres away from the wooden block (*Figure 33*). In order to try to make the data as reliable as possible, five participants were recruited. They were asked to stand side-on from the impact zone and swing the axe just in front of the ruler. The participants were asked to perform a low, gravity swing. After some practice time, three impacts by each participant were recorded on the high-speed camera. The chosen film speed was 300 fps, which though not overly 'high-speed', permitted the camera to store a 1.6 second clip, which was long enough to record the frames capturing the axe entering the screen through to hitting the wooden block. These clips were stored for later analysis, whereby the distance travelled by the axe was measured on the ruler behind between frames 4-7 (depending on how easy it was to read the markers on the ruler) (*Figure 34*). Each frame was, of course, equal to 0.003 seconds. Using this information, following equation for the determination of velocity was used to calculate the velocity at impact of each axe-swing:

$$v = \frac{x_f - x_i}{t} = \frac{\Delta x}{t}$$

*Where,*
*v is the velocity (m/s),*
*$x_f$ the final position (m),*

$x_i$ the initial position (m),

$t$ the time in which the change occurs (s),

$\Delta x$ the short form for 'the change in' position (m).



***Figure 33:*** Experimental setup for calculating the energy of an axe-swing (Source: Author's own).
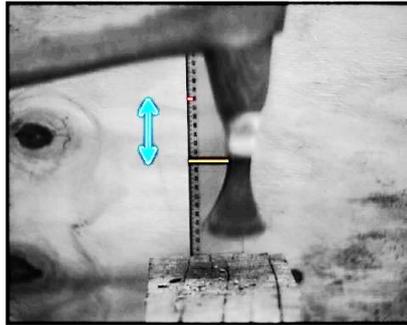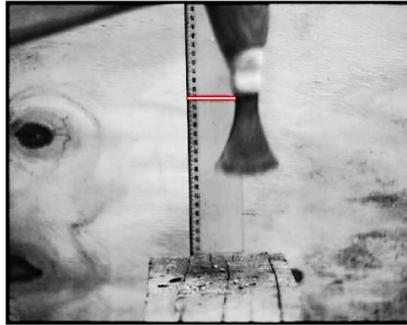
**Figure 34:** Photo series illustrating how the distance travelled by the axe was measured by the use of the ruler in the background of the images (Source: Author's own).

101

The calculation of velocity could then be used to establish the Kinetic Energy using the equation quoted below, with the known mass of the axe and haft at 1.2kg:

$$E_{impact} = \frac{1}{2}mV^2_{impact}$$

The results of the experiment are presented in the table below (*Table 4*).

| Participant | Replicate | Δx (m) | t (s) | Velocity (m/s) | Energy (J) |
|---|---|---|---|---|---|
| 1 | 1 | 0.09 | 0.017 | 5.41 | 17.53 |
| | 2 | 0.09 | 0.017 | 5.41 | 17.53 |
| | 3 | 0.07 | 0.013 | 5.26 | 16.57 |
| 2 | 1 | 0.07 | 0.020 | 3.50 | 7.36 |
| | 2 | 0.06 | 0.013 | 4.50 | 12.17 |
| | 3 | 0.08 | 0.020 | 4.00 | 9.62 |
| 3 | 1 | 0.08 | 0.017 | 4.80 | 13.85 |
| | 2 | 0.07 | 0.013 | 5.26 | 16.57 |
| | 3 | 0.11 | 0.023 | 4.72 | 13.36 |
| 4 | 1 | 0.07 | 0.017 | 4.20 | 10.61 |
| | 2 | 0.09 | 0.017 | 5.41 | 17.53 |
| | 3 | 0.11 | 0.013 | 8.26 | 40.92 |
| 5 | 1 | 0.10 | 0.017 | 5.71 | 19.53 |
| | 2 | 0.08 | 0.013 | 6.01 | 21.64 |
| | 3 | 0.12 | 0.013 | 8.63 | 44.72 |

*Table 4:* The distance and time data processed from the high-speed camera footage, and the associated velocity and energy data that can be derived from this.

The results demonstrated that the estimated average kinetic energy across the tests was 14.9±4.2J. It should be noted that two tests have been excluded from the calculation of the mean due to the high energy exhibited in the axe-swing (Participant 4, replicate 3 and Participant 5, replicate 3), which indicates that the low, gravity swing was not adhered to. An axe-swing energy of 15J was adopted for testing across all Axes 1, 3, 4 and Blades 1-6. Some testing was also conducted with a higher energy inputs, at 30J and 45J to trial the acceleration of wear. A graphical summary of the energy specifications applied during the testing of each specimen is shown below (*Figure 35).* It should be noted that, ideally, testing with different energy parameters would have been accomplished using individual test specimens, in order to eradicate the impact of previous experimentation on the microstructure of the cutting-edge. Instead, each Blade had already been subjected to considerable testing with other energy parameters that may have made the specimens more susceptible to blade failure and so, the number of impact tests they endured before exhibiting a major deformation at the cutting-edge may be underestimated.
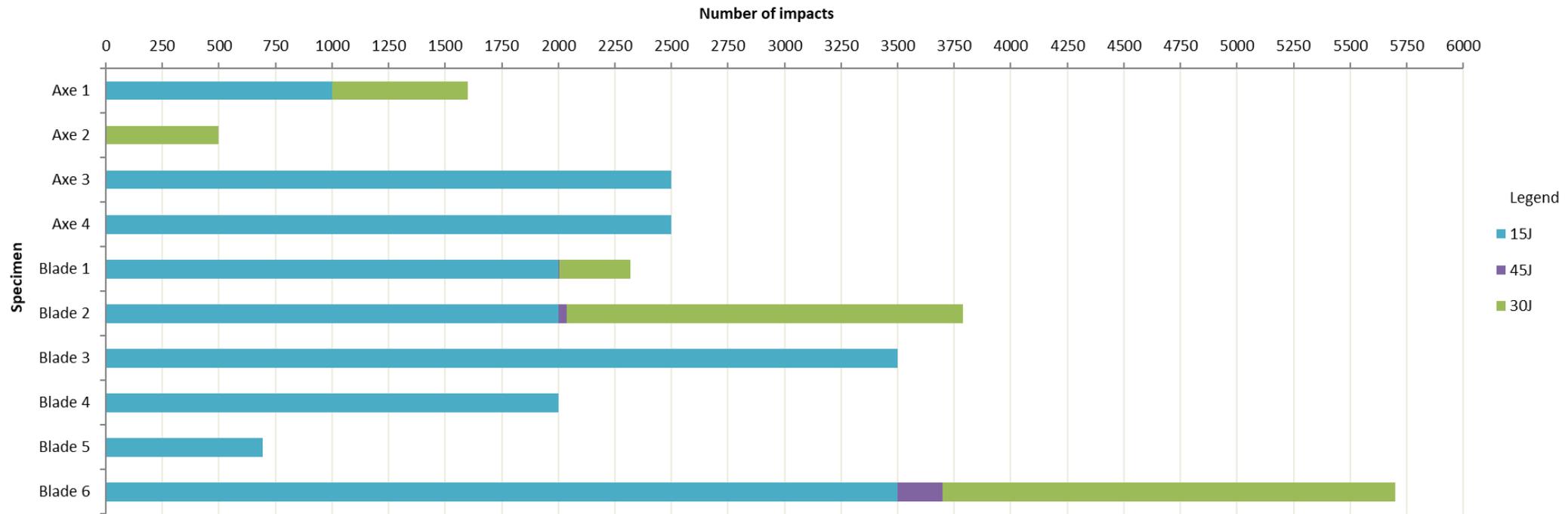
***Figure 35:*** The energy specifications applied to each specimen over the duration of impact testing.

### 5.2.3    Opposition material

The experimental specimens were dropped into blocks of *Quercus robur* (English oak) during the experimental procedure. As already discussed in section 2.2.1.5, wood may have been one of only several materials that axes were used to cut. However, their use as woodworking tools is by far the most substantiated at this time, for example, by the extensive forest clearance and woodworking activity of the MBA, and the results of the use-wear analysis on bronze axes that has so far been conducted [5], [6], [154]. The selection of oak as the opposition material is related to an observed decline in the number of oak trees in Britain during the Bronze Age period. Pollen extracted from cores taken from the Somerset Levels, for example, show that oak pollen comprised over 40% of the total composition of the sample at depths that correspond to approximately 3000 BC [260, p. 88]. This demonstrates that the level of oak coverage in this area was considerable. In the succeeding two millennia, however, the pollen analysis indicates that the number of oak trees must have diminished significantly, before increasing again around the transition to the Iron Age [261, p. 842]. This fluctuation has been observed across other areas of Britain, and most likely indicates the steady growth of woodworking industries. Oak produces particularly hard and durable timber that is ideal for construction projects, and there is evidence for the use of oak as a structural feature of round houses in Sussex [262] and Stirlingshire [263]. The density of Alder in southern Britain was also high during this period, however, this material was not so favourable for use in construction [260, p. 95].

The surface of impact was controlled tightly during the experimental procedure. Wood is an 'orthotropic' material, which means it has distinctive mechanical properties along three mutually perpendicular axes: longitudinal, radial, and tangential (*Figure 36*). The longitudinal axis is parallel to the grain; the radial axis is perpendicular to the growth rings in the radial direction; and the tangential axis is perpendicular to the grain but tangent to the growth rings [264, pp. 1, 2]. The hardness of wood varies greatly across these different axes. The longitudinal axis is fairly resistant to indentation as the wood fibres can support a substantial load in compression. In comparison, values of 'side hardness', comprising measurements taken at the radial and tangential directions of the grain, are usually much less, as the fibres are more susceptible to compressional forces. Despite the greater hardness, it is actually much easier to split the structure parallel to the fibre direction (longitudinally) when cutting timber with a sharp implement; this is a result of fracture induced along grain boundaries. To simulate chopping a tree trunk, the experimental axes were used to cut the sides of the oak block across the grain. Thus, while the material is less resistant to compressive forces at this orientation of impact, it is not predisposed to fracturing. This decision avoided the

splitting of the wood, which would endanger the sample becoming in contact with the specimen platform and increase the number of oak blocks that would need to be used in experimentation considerably. Oak produces a relatively hard timber, and a slower rate of material deterioration would likely be observed if the axe was used to chopped softer species of tree, such as Alder.
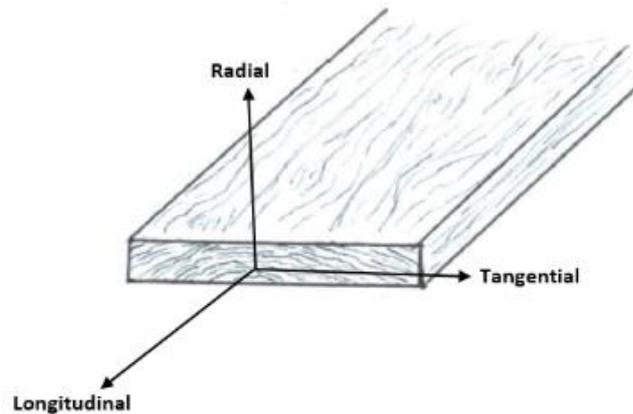


*Figure 36*: The three axes of grain direction in wood (Source: Author's own, based on [170, p. 2].

The age of the oak blocks was kept consistent throughout experimentation as a means of controlling the moisture content of the timber. The water that exists within wood alters how compact the material is, so much so that the density of wood is measured in 'specific gravity', which is derived from the water content of oven dry wood at predetermined temperatures [265, p. 11]. The specific gravity of wood affects the coefficient of friction, and thus, the ease of working of the timber. The amount of friction experienced when cutting oven dry wood is much less than when trying to chop green wood, unless the surface of the wood is fully covered with water [264, p. 22]. Hence, in general, the lower the specific gravity, the easier it is to cut the wood with a sharp implement. The oak blocks that were acquired for use in the experiment were all from the same source; the supplier (Comley Reclaim, Wrecclesham) explained that this batch had been chopped down between 4 and 5 years ago and stored in a dry warehouse.

The wooden blocks were loosely secured in place by fabric straps each side of the impact zone. To secure the opposition material further, clamps that tightly fasten the oak to the specimen platform were placed either side of the block. Preliminary work illustrated that approximately three impact locations (where the wood was cut) at 5cm apart could fit onto each side of the oak block and so this arrangement was adopted. Each of these locations of impact were subjected to only 50 impact tests (or cycles) so that the axe did not chop too deeply into the block and get stuck, generating a fault within the impact striker of the drop-tower.

### 5.2.4    Detection of sharpening intervals

The identification of sharpening intervals was an integral part of the study, which aimed to examine the interaction between use-wear and maintenance marks. The drop tower system was meant to be able to calculate the total displacement (mm) of the opposition material during each impact. Hence, it was originally thought that the depth of the impact location during testing may give a reliable indicator as to when sharpening should take place, since a reduced cutting ability should be reflected by diminishing displacement of the wood. Unfortunately, many issues were encountered with the recording of displacement readings by the instrument (there were many random values and often an inclining trend), so that these could not be used to evaluate an appropriate time for sharpening. Another approach that was trialled, with Axe 1, was to measure the depth of the incision after testing had been completed (50 drop tests per incision). However, no noticeable difference was recorded over the course of testing, with the total depth of each incision measuring at approximately 15-20mm. Instead of monitoring the sharpness of the cutting-edge as suggested above, the specimens were only sharpened when a significant deformation was formed upon the blade. Although this method presented the only certain means to establish when the sharpening of an axe should occur, sharpening the blade of a palstave axe due to deformation can only really reflect the very minimum amount of sharpening that an axe would have been subjected to in order to retain functionality (see section 2.2.1.6 for further considerations relating to this).

## 5.3    Analytical techniques

During mechanised experiments, as detailed in the section above, sequential analysis was undertaken in order to examine the surface wear, mechanical properites, and microstructural components of replica palstave axes. Different techniques, and the intervals at which they were conducted, were trialled over the course of the experimental phase of the project, thus forming an iterative metholodgy that was refined over the course of experimentation. The initial approach, exemplified by Axe 1 and 2, involved coinciding the failure event and, subsequent re-sharpening, with the analytical sampling (macroscope imaging and systematic hardness testing). However, it became clear that blade failure events were too inconsistent to provide regular intervals for analysis and, thus, predetermined intervals were introduced for subsequent testing. As such, Axes 3 and 4 were sampled at 250 and 500 impacts respectively, to establish how fine the sampling intervals

must be to provide adequate coverage of material changes. It was, thereafter, decided that sampling intervals at every 250 impacts was necessary. The reduced-size of the blades meant that Scanning Electron Microscopy and digital microscopy could be introduced to the experimental rubric. The analytical techniques and their associated acquisition intervals applied to each experimental specimen are summarised in the table below (*Table 5*). The background of each analytical technique, and the specific sampling strategy employed, are explored in the following sections.

| Specimen | EDX | Acquisition intervals | Micro-hardness | Acquisition intervals | Macro-scope | Acquisition intervals | Digital Micro- | Acquisition intervals | SEM | Acquisition intervals | Metallo-graphy | Acquisition intervals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Axe1 | Yes | Before testing | Yes | After initial sharpening, end of test (only random sampling) | Yes | After initial sharpening, before subsequent sharpening events | No | n/a | No | n/a | Yes | End of testing |
| Axe2 | Yes | Before testing | Yes | After initial sharpening, end of test | Yes | After initial sharpening, before subsequent sharpening events | No | n/a | No | n/a | Yes | End of testing |
| Axe3 | Yes | Before testing | Yes | Before and after all sharpening events, every 250 impacts | Yes | After initial sharpening, before subsequent sharpening events | No | n/a | No | n/a | Yes | End of testing |
| Axe4 | Yes | Before testing | Yes | Before and after all sharpening events, every 500 impacts | Yes | After initial sharpening, before subsequent sharpening events | No | n/a | No | n/a | Yes | End of testing |
| Blade1 | Yes | Before testing | Yes | Before and after all sharpening events, every 250 impacts | Yes | After failure events | No | n/a | Yes | Before and after all sharpening events, every 250 impacts | n/a | End of testing |
| Blade2 | Yes | Before testing | Yes | Before and after all sharpening events, every 250 impacts | Yes | After failure events | No | n/a | Yes | Before and after all sharpening events, every 250 impacts | n/a | End of testing |
| Blade2 | Yes | Before testing | Yes | Before and after all sharpening events, every 250 impacts | Yes | After failure events | Yes | Before and after all sharpening events, every 250 impacts | No | n/a | n/a | End of testing |
| Blade 4 | Yes | Before testing | No | n/a | Yes | After failure events | Yes | Before and after all sharpening events, every 250 impacts | No | n/a | Yes | End of testing |
| Blade 5 | Yes | Before testing | No | n/a | Yes | After failure events | Yes | Before and after all sharpening events, every 250 impacts | No | n/a | Yes | End of testing |
| Blade 6 | Yes | Before testing | No | n/a | Yes | After failure events | Yes | Before and after all sharpening events, every 250 impacts | No | n/a | Yes | End of testing |

**Table 5:** Analytical scheme that was employed for each experimental specimen.

### 5.3.1   Energy-dispersive X-ray spectroscopy

It was vital to assess the composition of the experimental specimens to check that the alloying specifications had been successfully achieved. An extra probe was inserted within the Scanning Electron Microscope (described fully in section 5.3.3) so that the instrument could record signals from Characteristic X-rays that are produced when the electrons within the sample are excited. This type of analysis is called EDX and it permits quantitative information about the concentration of certain types of elements to be obtained. All of the experimental specimens in the present paper had their chemical composition characterized by this method before use in tests. In order to conduct these tests, a small sample was taken from the sprue of each casting. Each specimen was attached to the specimen holder by conductive tape. The vacuum pressure used throughout all spectrum acquisition was <9x $10^{-4}$, the voltage was 15kV, and the probe current was set to 14. Spectra were obtained over three random locations using the area function. Since measurements were made on very small sample locations across a structure that was not entirely homogeneous, some amount of inaccuracy and variability was expected within the measurements.

### 5.3.2   Vickers microhardness

Surface microhardness indentation was used to investigate the changing mechanical properties of the replica axes as they were progressively used. Sequential hardness mapping may be used to produce a mathematical model that, upon comparing the corresponding data from prehistoric palstave axes, permits a quantitative prediction of the number of impacts. Vickers microhardness, as used in the present study, refers to use of a smaller indenter with lighter loads (100 gf to 1 kgf) than normal Vickers hardness tests; the latter of which would have produced large indents that would have been obstructive for the examination of surface wear. The method for taking microhardness measurements was as follows:

- The axe or Blade was secured in place with an in-built clamp system of the microhardness tester.
- Measurements were taken by first selecting a suitable area for indentation using the x40 magnification microscope objective.
- Once the sample area was chosen, the turret mechanism was rotated so that the indenter (a square-based pyramid) was hovering over the correct location.
- After pressing 'start', a load of 500 gf was lowered onto the specimen for 15 seconds.

- Following the cessation of the indentation period, the turret was rotated again so that the x40 microscope objective was overhead.
- The length of each diagonal (d) was measured in microns using a micrometre eyepiece with a digital measurement feature.
- The average diagonal length was ascertained and converted into millimetres, then used to calculate the Vickers Hardness Number, according to this equation:

$$HV = \frac{2F sin\frac{136°}{2}}{d^2}$$

From this equation we can derive this:

$$HV = 1.845\frac{F}{d^2} approximately$$

The usual procedure for hardness testing involves cutting, mounting, grinding, and polishing the chosen sample(s). This approach is generally adopted to ensure that the surface of the sample is not rough and is plane-parallel. These considerations are important for microhardness testing as tilting of the specimen produces asymmetrical indentations that do not represent measurements of an optimum accuracy. Specifically, for every 2° of tilt, 1% of error in the recorded hardness is introduced. As a working control, American Society for Testing and Materials (ASTM E834) suggest in their standard for the procedure, that the difference between the two diagnonals d1, and d2, should not deviate from the mean value by more than 5%. Equally, when the surface roughness of a sample is high, it can be difficult to accurately read the corners of the indent. It should be mentioned here that the ASTM E834 guideline is for engineering purposes, whereas the study presented here-in is an archaeology experiment. Hence, while all reasonable efforts were made to follow to adhere to the guidelines, some modifications to the standard protocol for hardness testing were necessary in order to meet the differing requirements of an archaeological experiment. In order to conduct sequential tests, the replica axes could not be cut during the course of the experimentation. The measurements were, instead, taken on the unprepared surface of the axes. Although efforts were taken to make sure the surface was parallel to the indenter, the surface of the axe is inherently curved, so many measurements exhibited some form of vertical distortion. This problem was especially pronounced at measurements taken at the Blade, due to the acute angle of the cutting tip. Some measurements also exhibited some degree of horizontal distortion due to the largely natural state of the material surface, which was very rough. It is suggested in the ASTM guideline, that the highest load possible should be selected for most experiments, which, in

this case, would have been 1 kfg. However, a load of 500 fg was preferred, as this was the highest load available that still produced indents that could be placed on the minimally-sized smooth plateaus that interspersed a largely rough surface at Positions 3 and 4. Using a load of 500 fg meant that indents were generally sized between 50 and 120 μm, which, even in the case of coarse dendritic structures, is comparable or greater than the size of individual dendrite arms. As a result, the measurement site must have often encompassed a range of material phases, producing an aggregate measurement. The indent size may have been subject to variation depending on the quantity of delta eutectoid present at the measurement location. The ASTM standard also specifies that the surface of the sample should have all contaminants, for example, oil, grease, scale and dirt, removed before testing. This is necessary to avoid the underestimation of hardness that may result from the presence of a thin lubricating film, which reduces the coefficient of friction and produces marginally larger indents. All replicas were washed with water by hand before hardness testing so that any large flakes of oak that adhered to the blade were removed.

The measurement of surface microhardness was initiated with the testing of Axes 1 and 2. This analysis was performed in order to test the planned methodological process, and to generate a proof of concept for further investigation. A manual Matsuzawa Seiki Co. Ltd microhardness tester was used to take the preliminary hardness measurements on Axe 1. Some random spot samples on the blade of Axe 1 were taken using the manual microhardness tester after 1000 tests at 15J, as a proof of concept for the increase in surface hardness due to use. The manual microhardness tester was also used to take the preliminary hardness measurements on Axe 2. Fifteen sampling points were marked on the axe with permanent pen at several positions along the axe-head: Position 0, or the 'Blade', was the cutting edge itself (or as close as practically possible, which in reality was often around 1mm from the actual cutting edge); Position 1 was 0.5cm from the cutting edge; Position 2 was 1cm further up the cheek than the previous sampling location; and Positions 3 and 4, which acted as experimental controls, were each situated a 1cm further up the cheek of the axe than the previous sampling location (*Figure 37*). Three measurements were taken at each sampling point per sampling phase, for the purpose of calculating average hardness – this, therefore, equated to 45 measurements in total. The same systematic approach was taken when Axe 2 was analysed after 500 tests at 30J; however, these measurements were taken using a digital Future Tech FM-300 microhardness tester. Due to the unreliability of the manual microhardness tester, which was old, did not have an in-built clamp, and had not been calibrated in several years, it was concluded that all future microhardness evaluation should be conducted with the digital microhardness tester. Furthermore, it was decided systematic hardness measurements would be taken before and after sharpening so that the relationship between hardness and sharpening could be examined further.
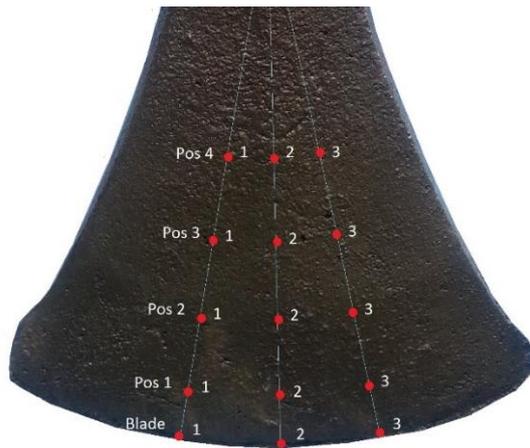
**Figure 37:** The hardness sampling locations on Axes 2-4 (source: Author's own).

Thus, for Axe 3, three measurements were recorded on the axe-head before and after every sharpening event, and after every 250 tests. For Axe 4, the same hardness map was designed on the axe-head, but five measurements were taken at each sampling point per sampling phase to increase the reliability of the average hardness – this equated to 75 measurements in total per sampling phase. Measurements were recorded on the axe-head before and after each sharpening event, and after every 500 tests. Sampling considerations that could have affected the accuracy of these measurements are as follows. The ASTM E834 guideline suggests that indents should be recorded across all types of structural material (or in this case, surface features), so that the entire nature of the material can be characterised. It is also specified that indents should be spaced at a reasonable distance apart (usually at least 3 diagonal widths) in order that local hardening around the site of one indent does not influence other nearby measurements. For Axes 1 and 2, as well as Axes 3 and 4, indentations were often placed on the same type of surface feature and were sometimes bunched close together – this may have culminated in the overestimation of material hardness. This issue is particularly pronounced at Position 2 (and could be a contributing to elevated hardness at Position 0 and Position 1), as the problems presented by the surface curvature and/or roughness meant that indents were usually placed on small 'islands', where appropriate surface conditions prevailed. Hence, indents were often in a close proximity to each other. On the other hand, the relatively parallel and smooth surfaces at Position 3 and 4 meant there was no difficulty in finding suitable locations for indentation and measurements could be placed easily. The bunching together of indents across Positions 0-2 was corrected when tests were conducted on Blades 1 and 2 so that the method would adhere more closely to the guidelines. Special care was taken to perform measurements in 5 random locations encircling the sampling point, in order to try to

recreate a more representative picture of the hardness changes throughout the entirety of the material. In addition, indents made on these specimens were spaced at a reasonable distance apart (the equivalent width of five indents).

Unlike the fairly sporadic data collected for Axes 1 and 2, the sequential data produced during testing with Axes 3 and 4 lent itself to further statistical analysis in the form of mixed effects models – a type of linear regression that provides correct estimates of fixed effects in the presence of the correlated errors that arise from a data hierarchy [266, p. 378]. Hence, the application of this type of modelling has seen much use in biological and clinical studies, especially when working with longitudinal data (sequential results obtained from the same sample area over an extended number of tests). More recently, the method has also been applied to more archaeologically-relevant investigations [267], [268], [269], [270]. Since the surface hardness data produced here-in represents longitudinal data that may also be subject to issues of data hierarchy, the decision was made to use mixed effects models to reveal real data trends. All statistical analysis was completed using RStudio [271] and the statistical package lme4 [272], and was performed by Daniel Andrews. It should be mentioned here that any measurements that were less than 80HV, or more than 300HV were excluded from statistical manipulation on the grounds of being outside the likely range of hardness for a 10%-tin bronze. No linear mixed effects models were produced for the surface hardness data pertaining to Blades 1 or 2. This is because the use of surface hardness evaluation was deemed unsuitable for transferral to prehistoric palstave axes by this point in the project timeline (see section 6.2), so complex statistical analysis was not deemed necessary. Surface hardness measurements on Blades 1 and 2 were only made at the 'Blade' (five per sample location) every 250 tests, with five further 'baseline' measurements made 1cm up the blade (as a control) at each sampling interval.

### 5.3.3    Scanning Electron Microscopy

High-power microscopy (SEM) was adopted to track surface features, such as, wear marks, edge-reduction, and cracking, indicating the nature of the wear formation processes at play. Hence, it was hoped that the SEM data would provide further understanding about the micro-scale response of palstave axes during testing with known parameters, and help to determine the suitability of this technique for future metal use-wear investigations. The SEM uses a focused beam of accelerated electrons to provoke interactions from the atoms within the sample, some of which can be detected by the instrument. Secondary electrons (SE), which only originate a few nanometres below the

surface of the specimen, are ejected by inelastic scattering interactions with beam electrons – providing topographic data at a high resolution. In the current research, SEM imaging was performed using a JEOL JSM-6500F instrument and JSM6500 software. The Blades did not need to undergo any kind of coating as copper is highly conductive. Large flakes of oak were dislodged from the cutting-edge of each test specimen when they were washed by hand with water before analysis but since they were not cleaned with an ultrasonic bath, many microscopic particles of oak remained. Each specimen was attached to the specimen holder by conductive tape. The vacuum pressure used throughout all imaging was <9x $10^{-4}$ Torr, the voltage was 15kV, and the probe current was set to 11. Images were taken at pre-determined points of interest at the blade edge (SL 1, SL 2, and SL 3) before and after every sharpening event, and at each interval of 250 tests (*Figure 38*). Images were taken at magnifications of x25, x50, x100, x250, x500, and x1000, to monitor wider changes to the surface of the cutting-edge and inspect the wear mechanisms at play in close detail.
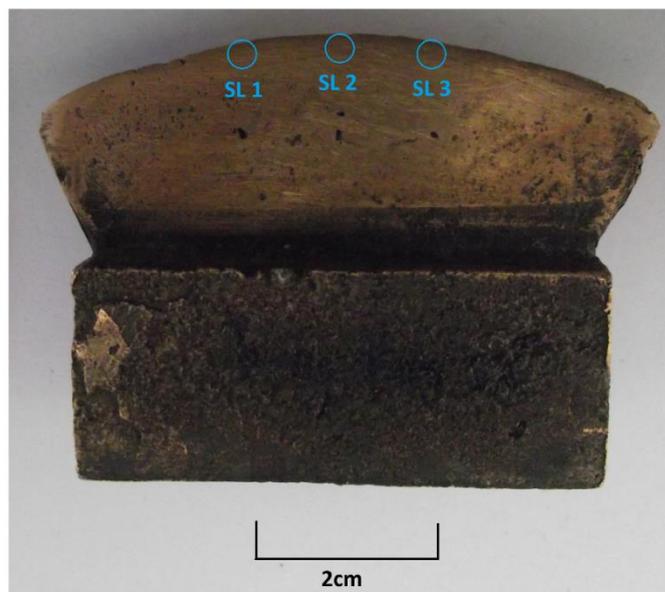


*Figure 38:* The positioning of the three sample locations: SL 1, SL 2, and SL 3, on the blade of each Blade (source: Author's own).

Issues of alignment were prevalent throughout many of the SEM analytical intervals. For example, not all of the earliest images depicting the blade before sharpening match up exactly with the later images as a result of the destruction of the distinguishable features after sharpening. Equally, at high magnifications, it was very difficult to find the same sample location again within the time constraints of the SEM booking. It was not uncommon to have to capture a different area, if the original location did not reveal itself. There were also some problems with focusing on a sample that was not plane-parallel. At low magnifications, the corners of the image were often out of focus

– the working distance of 40mm was opted at x25 magnification in order to minimise this effect, but it still remains pronounced on some images. As the cutting edge became less acute, it was difficult to focus on the entire sample location. The area closer to the cutting-edge was always focused preferentially, leading to some considerable blurriness in the lower half of many images. Furthermore, often there were large pieces of organic matter wedged within crevices on the axe surface, or contaminants such as small hairs. This reduced the quality of the image (as SEM is unable to scan organic matter successfully) and occasionally, when the surface was completely obscured, an area away from contaminants was captured instead. This meant that the state of the surface was at least documented, albeit not in the original sample location, which reduced the consistency of the sequential aspect of the study.

In terms of application potential for prehistoric axes, this method provides the opportunity to image specimens with a very high resolution, which would certainly make the determination of use-intensity more accurate. However, the size of the specimen chamber limits the sample selection only to blade fragments, or small sections cut from the cutting-edge (which can be difficult to come by); hence, the practicality of this technique for routine analysis is perhaps questionable. In fact, this method has not been included within the arsenal of analytical tools used by the author during subsequent analysis with MBA palstave axes since the sample was predominantly complete specimens that were examined within the museums in which they were curated.

### 5.3.4 Digital microscopy

With the understanding that SEM imaging must assume more of an explanatory role in terms of accounting for the response of the material, rather than providing a suitable referential tool for use-wear analysis, sequential analysis was also conducted using digital microscopy. This technique was employed in order to reveal the rate at which microscopic striations appear at the cutting-edge. Given that the cutting-edge of prehistoric palstave axes will fit somewhere along a spectrum of wear, this data may be a useful comparative tool when assessing these objects for evidence of their use-intensity. Digital microscopy is a low-power imaging technique that is particularly useful for examining archaeological objects since it has no fixed platform, which means that it can easily be transported to in-situ locations, and there is freedom to place the objects in the most optimum positioning for imaging. Another advantage of digital microscopy in comparison to SEM, is that the samples do not need a great deal of cleaning to be imaged, and any organic residues left on the

surface do not obscure the features greatly. One area, however, where digital microscopy cannot match up to SEM imaging (as well as the obvious disparity in resolution), was in the depth of focus.

A Dino Lite 2.0 microscope was used in conjunction with the associated Dino Capture 2.0 software. The Blades were cleaned with water and soap by hand, then rinsed in ethanol, and dried with a hairdryer, before analysis was undertaken. Sampling was conducted before and after the initial sharpening, as well as any other sharpening events (when the blade failed), and at intervals of every 250 tests, at the three sample locations that were identified in *Figure 38*. Images were taken at x25 and x50 magnification using the 'edge of field' feature to create a range of focal layers that were stitched together automatically by the software. Since the samples were not plane-parallel and it was difficult to focus on the entire sample location, the area closer to the cutting-edge was focused upon preferentially, which, ultimately, lead to some considerable blurriness in the lower half of many images. Slight variations in the image exposure, as well as the limited resolution of the technique, sometimes made changes to the density of use-striations quite difficult to detect.

### 5.3.5   Photographs and macroscopy

The frequency and form of blade failure at the cutting-edge of the experimental specimens was recorded by photography and macroscopy; this was a vital part of documenting the durability of palstave axes with different post-production processing at impact energies that reflect the range of human arm-propulsion. Documentation of blade failure may be used to inform the use-wear analysis of prehistoric palstave axes by indicating the likelihood of blade failure for artefacts with specific metallurgical properties, as well as the distinction of intensity-related marks from those that were formed due to contact with an unusual opposition material, or accidental damage. Photographs of deformations at the cutting-edge were taken using a Fujifilm FinePix F20LE and Fujifilm FinePix S1900 digital cameras – the former was used for Axes 1-4, and the latter for the images taken of Blades 1-6, as the quality was preferred. Macroscope images were captured at locations where prominent features could be discerned using a WILDMAKROSKOP at x2 magnification, allowing a more detailed inspection of the area of deformation.

### 5.3.6    Metallography

Metallography is the examination of polished sections of metals using optical or electron microscopy for the purpose of visualising the microstructure of the sample. Once the experimental specimens had been subjected to testing, they underwent preparation for metallography and their microstructure was examined under an optical microscope to check that manufacturing had been conducted successfully. The first step of the procedure involved cutting samples from the cutting-edge of the specimens with a Minitom cutting wheel. The samples were taken from the blade so that each sample was a triangular cross-section of the blade tip. After removal from each axe, the samples were lightly buffed and cleaned with water. They were subsequently cold-mounted using an epoxy resin to avoid any microstructural homogenisation that may have resulted from hot-press mounting. The samples were then washed again with water by hand. Fine-grained silicon carbide sand paper was used to grind the samples. For Axes 1 and 2, polishing was conducted using 6 μm diamond paste on a 6 μm cotton disk, and 1 μm diamond paste on a 1 μm cotton disk. This method was found to be unsatisfactory after many scratches were left on the sample after significant polishing. Hence, with Axes 3 and 4, a 6 μm diamond suspension on a Buehler Texmet cloth were used and, subsequently, a 1 μm diamond suspension on a Buehler MasterTex cloth were used to polish the samples. An acidified ferric chloride solution (100ml of ethanol, 20ml of HCL, and 5g of Iron(III)-chloride) was used to etch the samples over several light applications. A great number of images of the unetched and etched polished surface of each sample were recorded and those that best reflected the typical features of each specimen were included in the results.

# 6    Results and Discussion of Experimental Work

The present chapter demonstrates the results that have been collected during the experimental phase of the present study. The following text will cover various aspects of the hierarchical tribological system of replica bronze palstave axes suggested in Chapter 4, which frames the areas that have been examined during experimentation. As proposed frequently throughout this thesis, a comprehensive assessment of wear should always start with the composition and microstructure of the objects in question. As such, section 6.1 discusses the underlying structures of each experimental specimen. This is followed, in section 6.2, by an examination of the results relating to the mechanical properties of palstave axes. Looking towards the development of surface alteration during use, sections 6.3 and 6.4 discuss, respectively, the form of the surface wear on palstave axes, and the rate by which wear progresses. Lastly, section 6.5 focuses on the frequency and morphology of catastrophic deformations at the cutting-edge, and other associated aspects of macro-scale wear; for instance, blade sharpness and blade asymmetry, which are altered over the course of cycles of use and maintenance.

## 6.1    Composition and microstructure of the replicas

All of the experimental specimens in the present paper had their chemical composition characterized by Energy-Dispersive X-ray (EDX) before use in tests. *Table 6* presents the tin composition of the experimental specimens as determined by EDX. The data demonstrates that most of the measurements made across all samples indicated tin content close to the required level. It seems likely that slightly higher than expected readings may have been produced on occasion (see Blade 5, replicate 3 and Blade 6, replicate 2) by the sampling of particularly enriched areas of tin. All measurements on Axe 4 were higher than expected. As a consequence, the mean tin composition for Axe 4 was found to be 11.39%. This may mean that this replica had a tin content closer to 11%. However, as explained in 5.3.1, obtaining completely accurate measurements using this method is unlikely. The application of this technique was mostly to check that nothing had gone wildly wrong during manufacture; hence, these measurements were deemed to sufficiently reflect the desired tin composition of each specimen.

| Specimen | %tin by weight Measurement | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| *Axe 1* | 9.71 | 9.91 | 10.33 |
| *Axe 2* | 9.49 | 9.47 | 9.59 |
| *Axe 3* | 9.61 | 9.68 | 9.85 |
| *Axe 4* | 10.96 | 11.31 | 11.91 |
| *Blade 1* | 9.32 | 9.3 | 10.36 |
| *Blade 2* | 10.56 | 9.27 | 9.84 |
| *Blade 3* | 9.89 | 9.94 | 8.93 |
| *Blade 4* | 9.90 | 9.70 | 10.76 |
| *Blade 5* | 13.41 | 13.92 | 15.49 |
| *Blade 6* | 13.99 | 15.19 | 13.88 |

*Table 6:* The EDX results for each specimen, presenting the %tin recorded during each measurement attempt.

The quality of casting, indicated by the extent of porosity observed, varied across the experimental specimens. It is important to comment on this, as these faults within the crystal grain structure could have implications for the response of the material during testing. The microstructures of Axe 1 (*Figure 39*), Axe 2 (*Figure 40*), Axe 4 (*Figure 42*), Blade 1 (*Figure 43*), Blade 2 (*Figure 44*) and Blade 6 (*Figure 48*) all exhibit only a small number of pores of a minimal size and were, therefore, likely to be mechanically robust upon testing. Similarly, the samples taken from the cutting-edge of Blade 3 were fairly absent of pores, except the large cavity depicted in *Figure 45*. Since this was located right in the middle of the blade tip, it is unlikely that it greatly weakened the microstructure. In contrast, Axe 3 (*Figure 41*), Axe 4 (*Figure 42*), Blade 4 (*Figure 46*), and Blade 5 (*Figure 47*) demonstrated a considerable network of small or moderately-sized pores. Thus, this means that there were more points within these specimens where stress may become concentrated and this could produce deleterious consequences for blade durability.
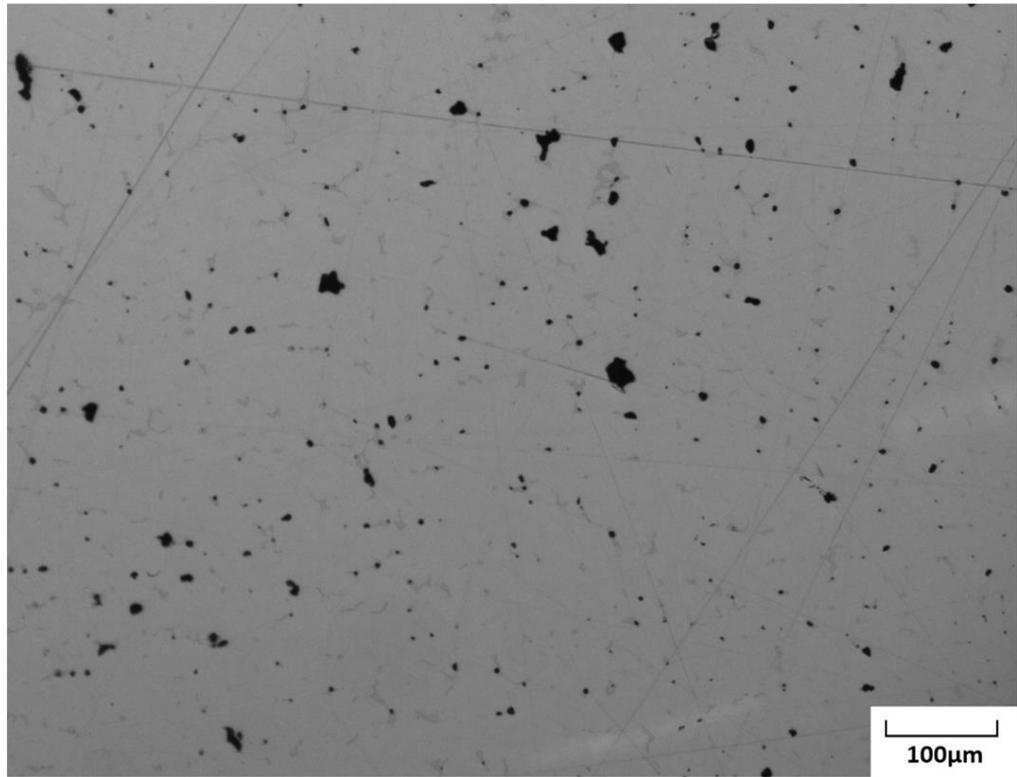
**Figure 39:** Metallograph of Axe 1, un-etched (x5) (Source: Author's own).
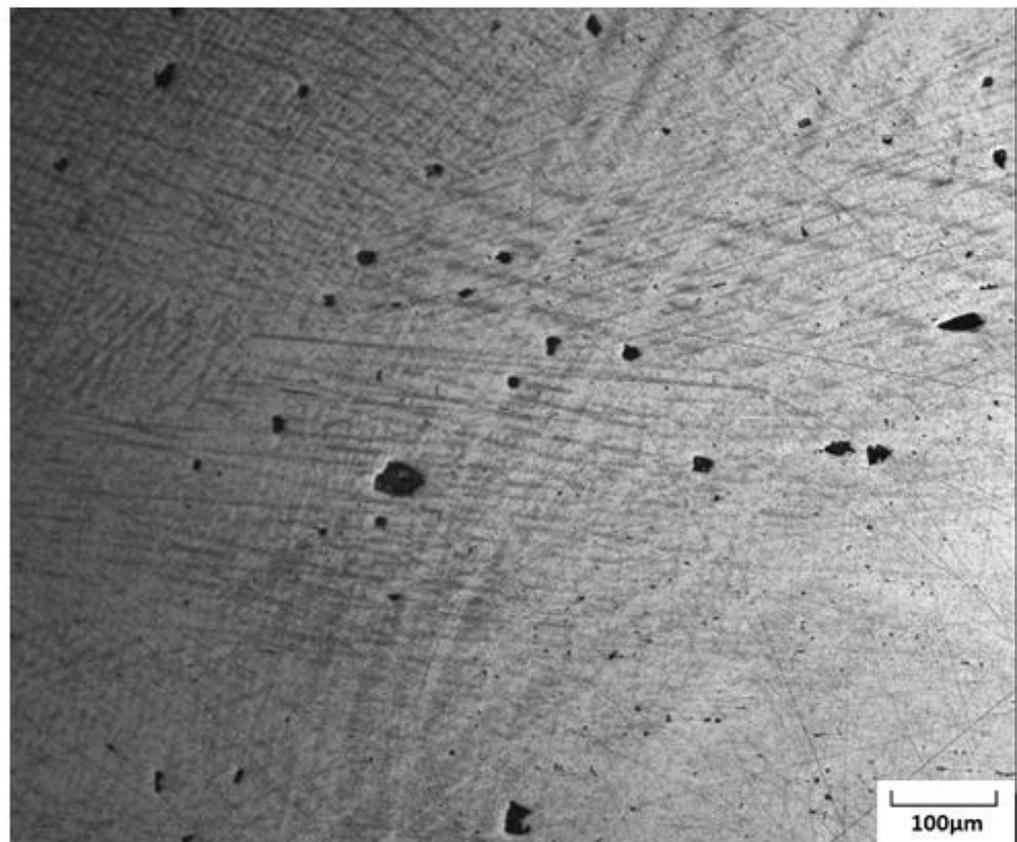


**Figure 40:** Metallograph of Axe 2, un-etched (x5) (Source: Author's own).
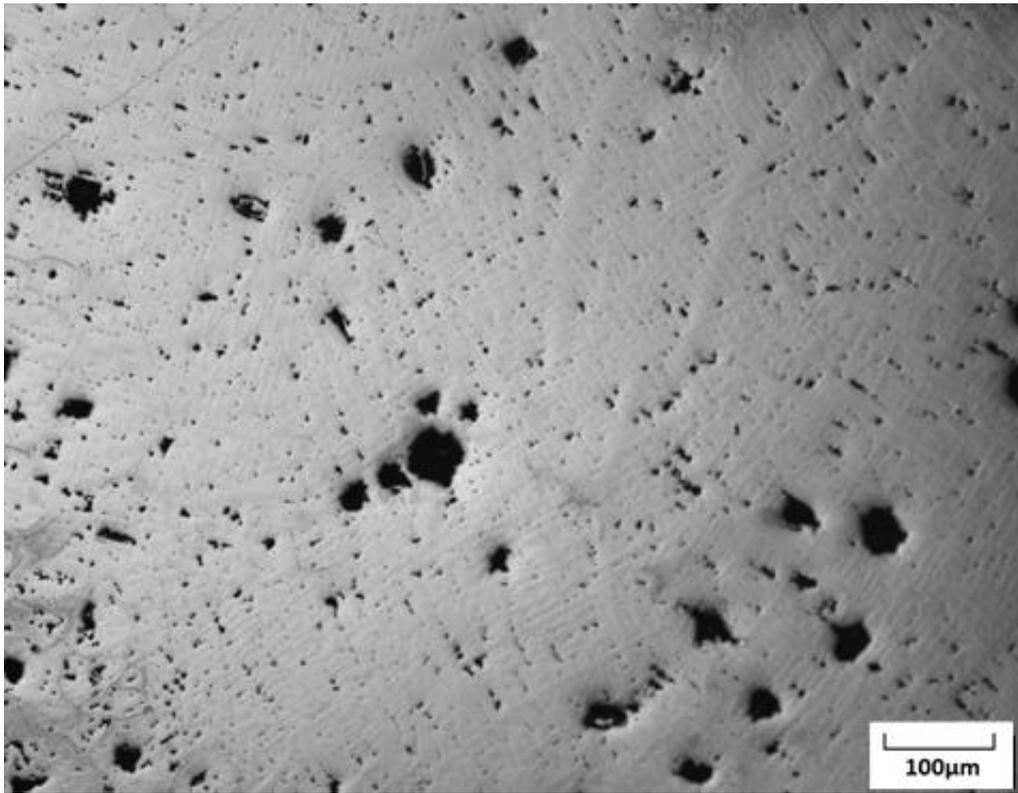
*Figure 41:* Metallograph of Axe 3, un-etched (x5) (Source: Author's own).
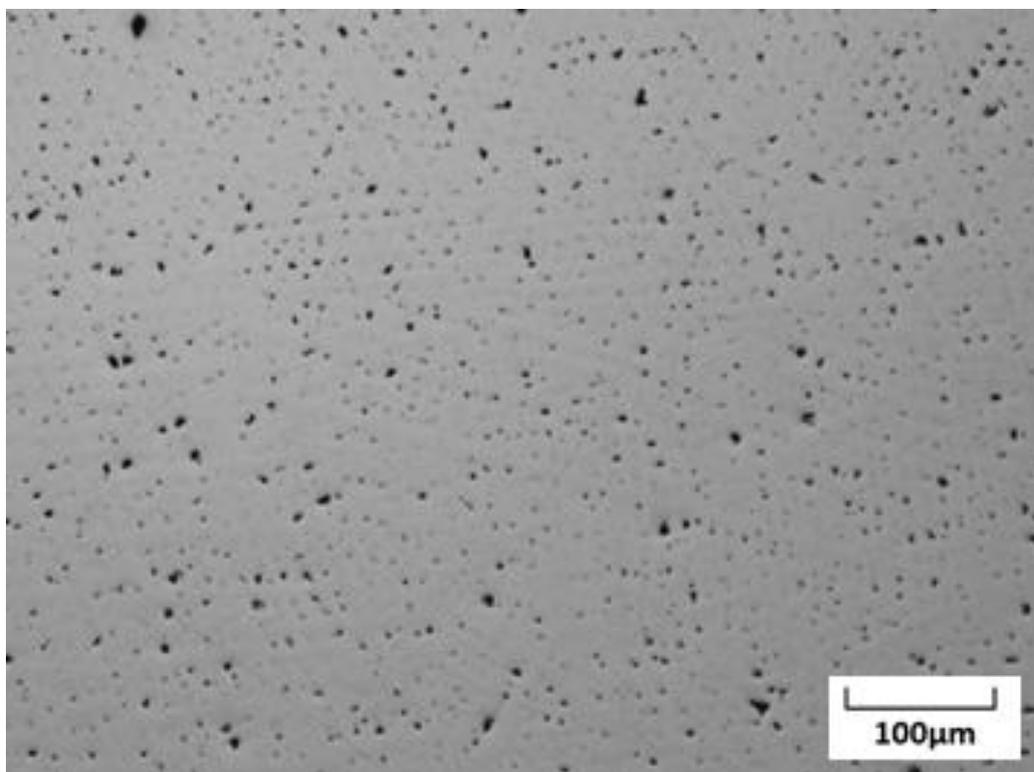


*Figure 42:* Metallograph of Axe 4, un-etched (x5) (Source: Author's own).
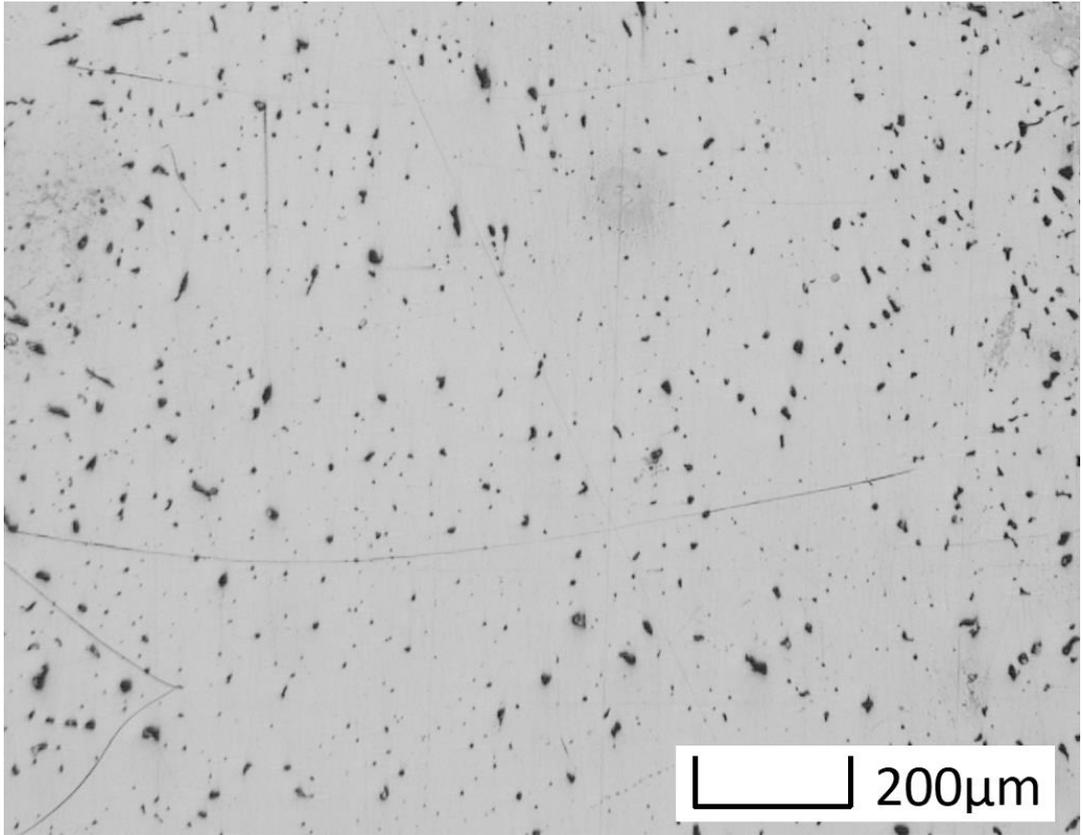
**Figure 43:** Metallograph of Blade 1, un-etched (x5) (Source: Author's own).
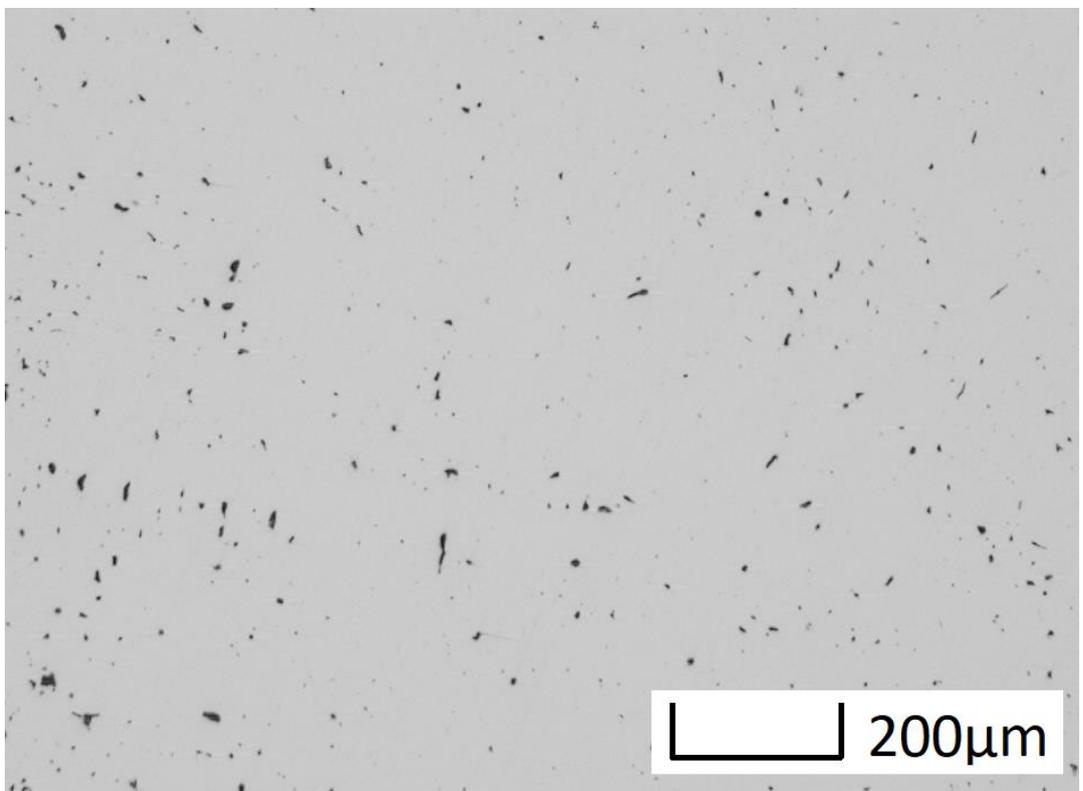


**Figure 44:** Metallograph of Blade 2, un-etched (x5) (Source: Author's own).

123
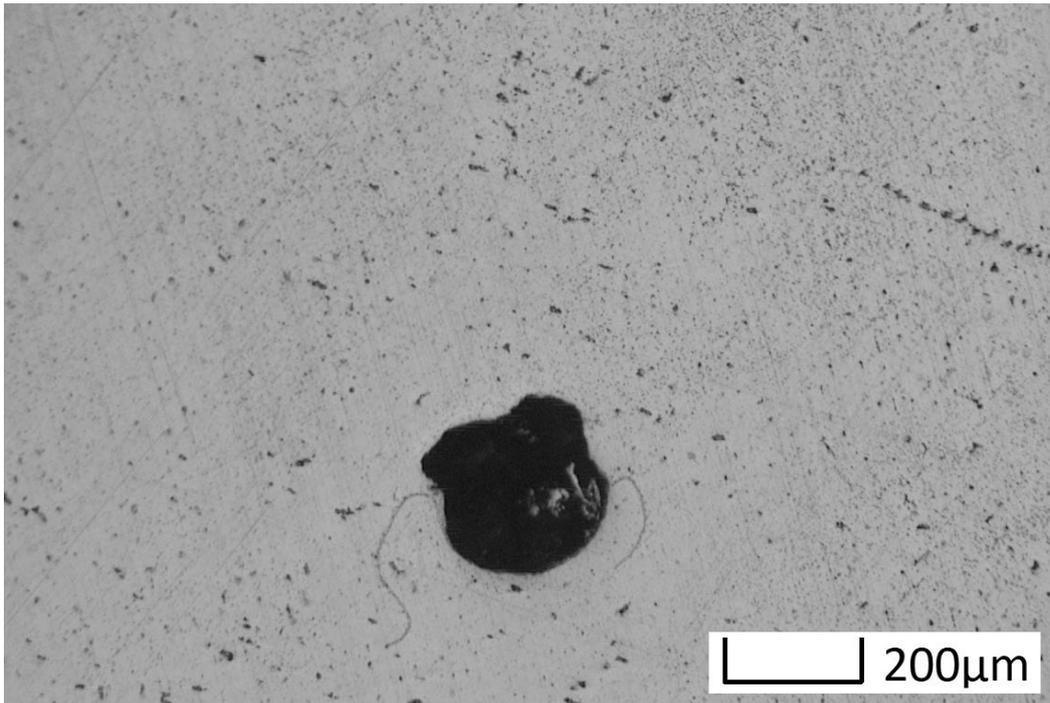
*Figure 45:* Metallograph of Blade 3, un-etched (x5) (Source: Author's own).
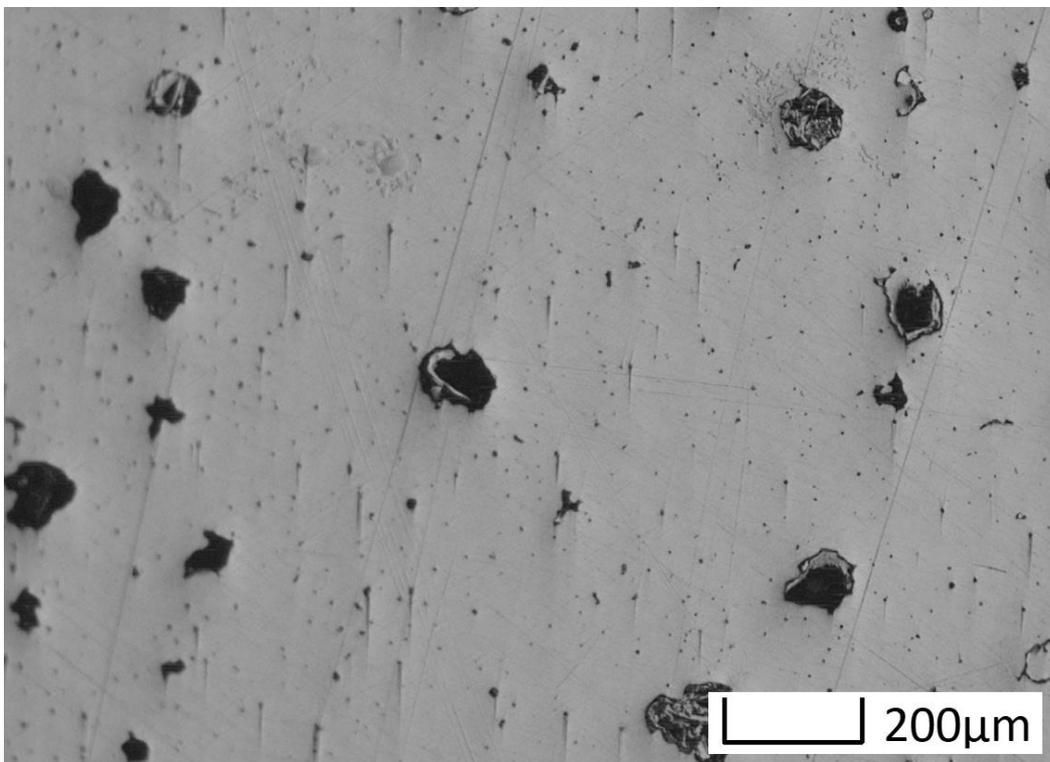


*Figure 46:* Metallograph of Blade 4, un-etched (x5) (Source: Author's own).
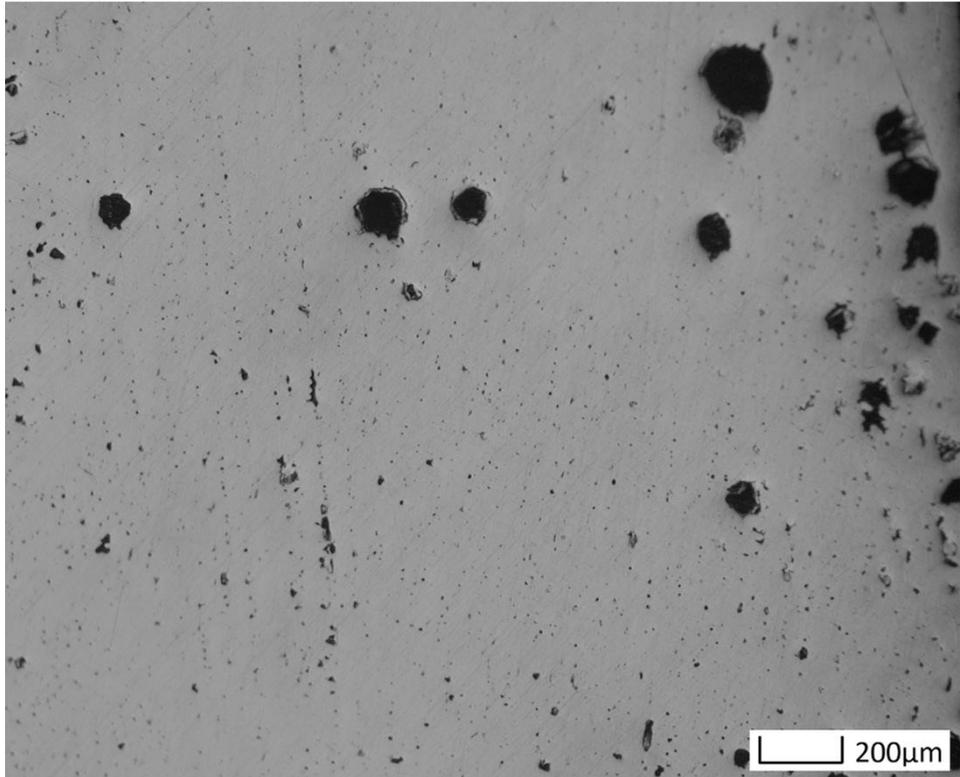
**Figure 47:** Metallograph of Blade 5, un-etched (x5) (Source: Author's own).
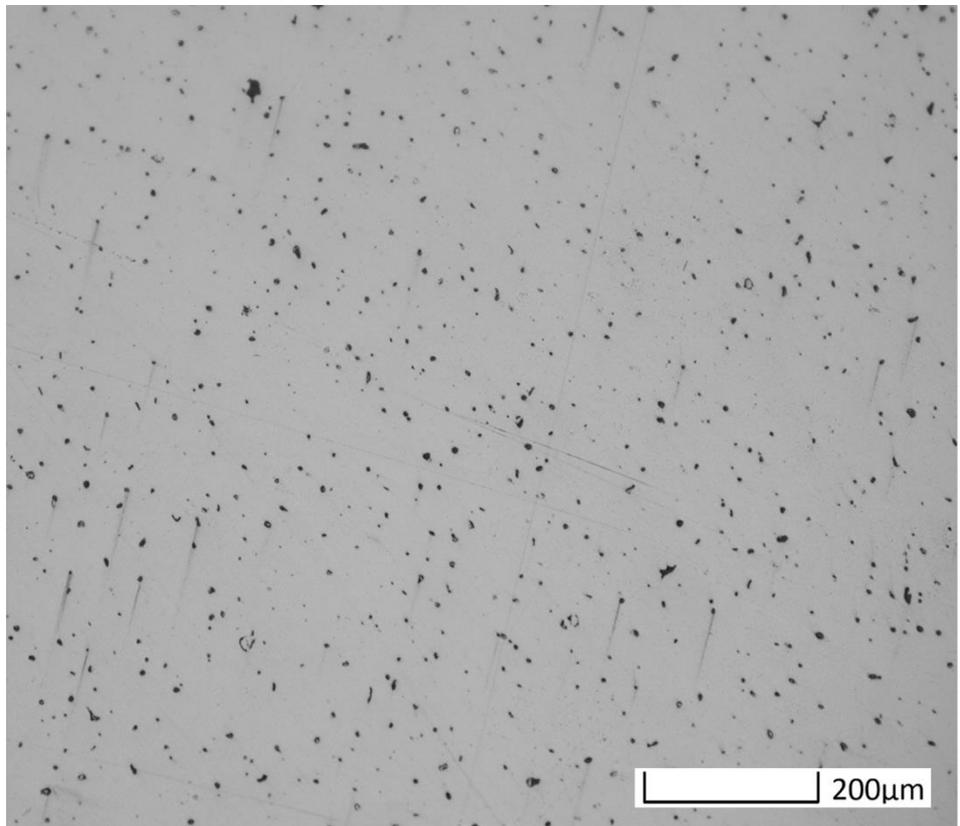


**Figure 48:** Metallograph of Blade 6, un-etched (x10) (Source: Author's own).

The microstructure of each experimental specimen is presented below. The importance of the internal structure of a palstave axe in terms of modifying its wear response has been explained in detail in sections 4.1 and 4.2. In accordance with their manufacturing specifications, Axes 1 (*Figure 49*) and 2 (*Figure 50*) both presented dendritic microstructures. The bending and distortion of dendrites due to blade failure can also be observed in *Figure 50*. The microstructures of the experimental specimens were not always as expected. Axe 3 and 4 were both annealed (see *Table 1*) to create a recrystallized microstructure. It appears that the temperature and/or time of annealing applied to these two experimental specimens was not sufficient enough to generate recrystallization. For example, *Figure 51* demonstrates the coarse dendritic structure exhibited by Axe 3. Similarly, *Figure 52*, suggests the dendritic microstructure of Axe 4. The lack of recrystallization within the blades of these experimental specimens has undoubtedly made them less strong and more susceptible to deformation; as such, they must be considered to comprise similar mechanical properties to Axes 1 and 2. As expected, the microstructure of Blade 4 (which was left in an as-cast state) was in a dendritic form (*Figure 53*).
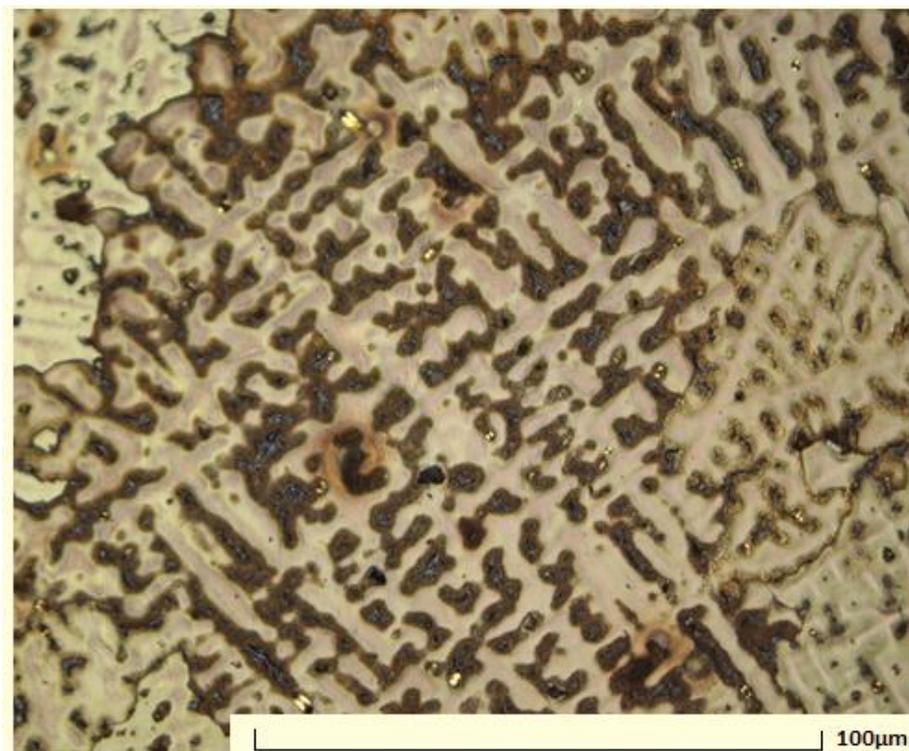


**Figure 49:** Metallograph of Axe 1, etched (x20) (Source: Author's own).

**Figure 50:** Metallograph of Axe 2, etched (x5) (Source: Author's own).
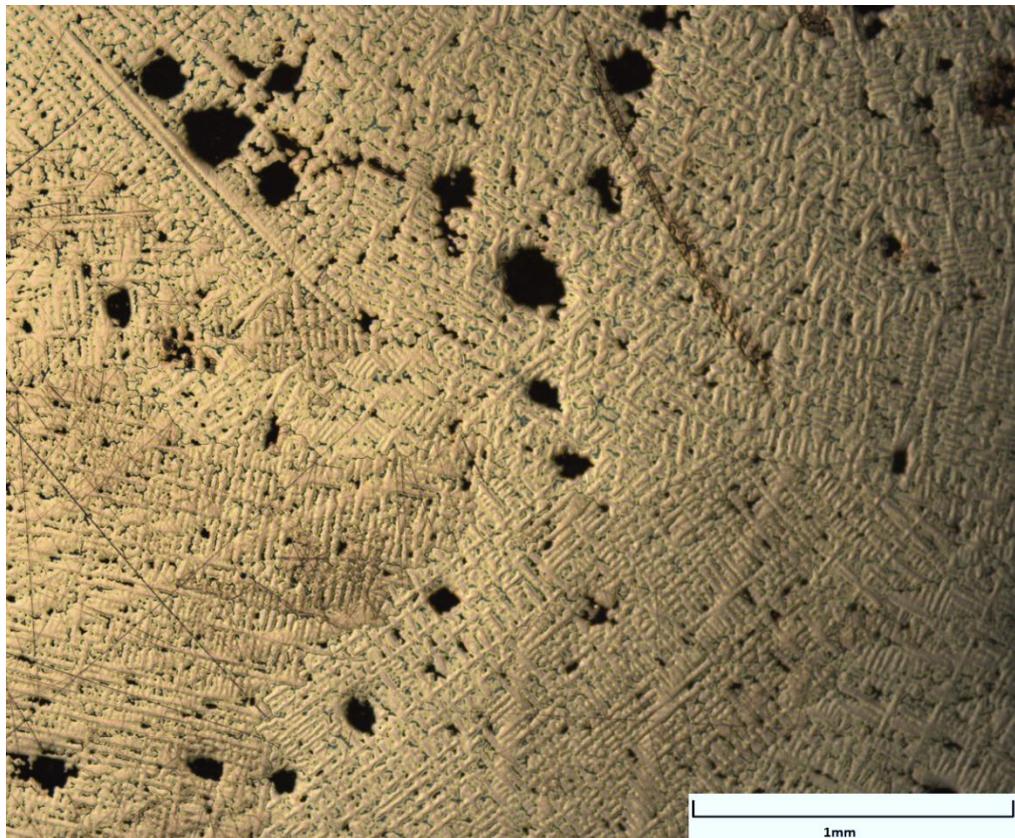


**Figure 51:** Metallograph of Axe 3, etched (x5) (Source: Author's own).
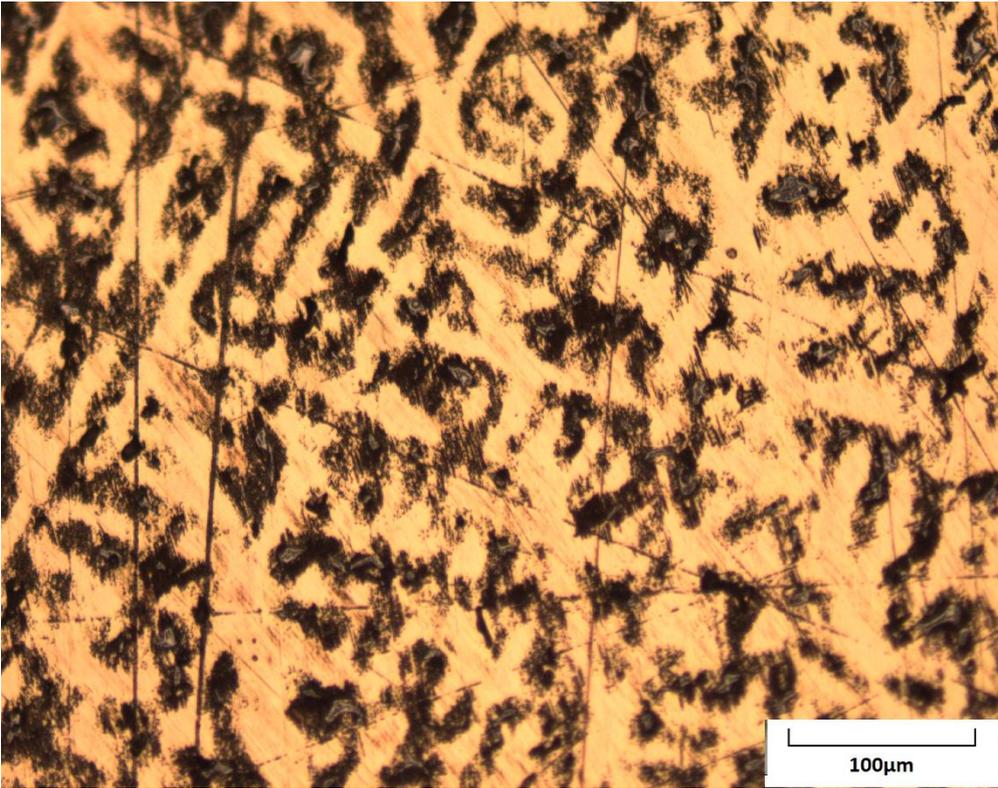
**Figure 52:** Metallograph of Axe 4, etched (x20) (Source: Author's own).
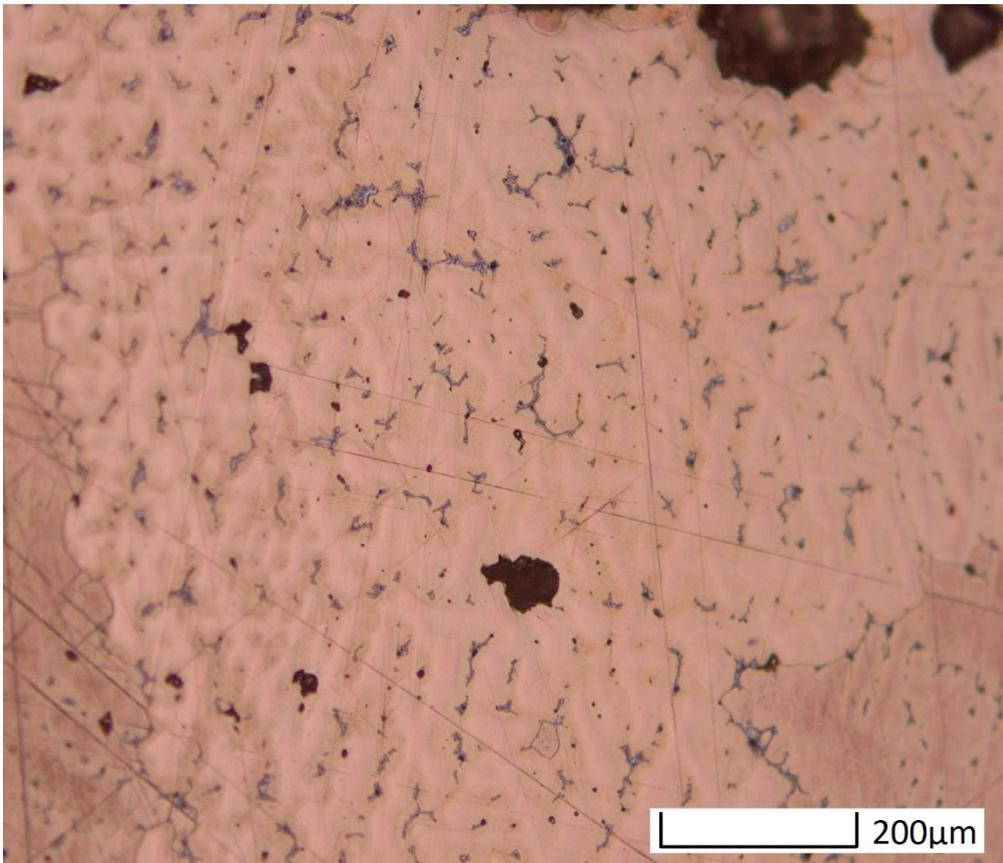


*Figure 53:* Metallograph of Blade 4, etched (x10) (Source: Author's own).

Blades 1, 2, 3, 5 and 6 were also annealed, and each of their respective microstructures (shown in *Figure 54*, *Figure 55*, *Figure 56*, *Figure 57*, and *Figure 58*) demonstrated recrystallization close to the exterior of the sample. The crystal grains within each sample contained annealing twins, and many exhibited strain lines. Considering that Blade 1 and 5 were not hammered, the presence of strain lines is particularly interesting, as it suggests that significant deformation was occurring at the surface of the blade. Across all specimens, the bulk of the material remained in a dendritic form. Again, it appears that the temperature and/or time of annealing applied to each axe was not sufficient enough to generate complete recrystallization of the entire microstructure. Although the processing of these experimental specimens has not achieved the desired microstructure, it is likely that the recrystallized areas may improve the strength of the blade tip and provide a mechanical advantage over the as-cast replicas presented above. It should be noted, however, that this will be somewhat less than what it would have been if they were fully recrystallized. However, metallographic analyses of Bronze Age objects [116], [135], [136], [137] have suggested the occurrence of partially recrystallization microstructures within palstave axes, reinforcing the sustained microstructural similarity of the experimental specimens despite this unexpected outcome.
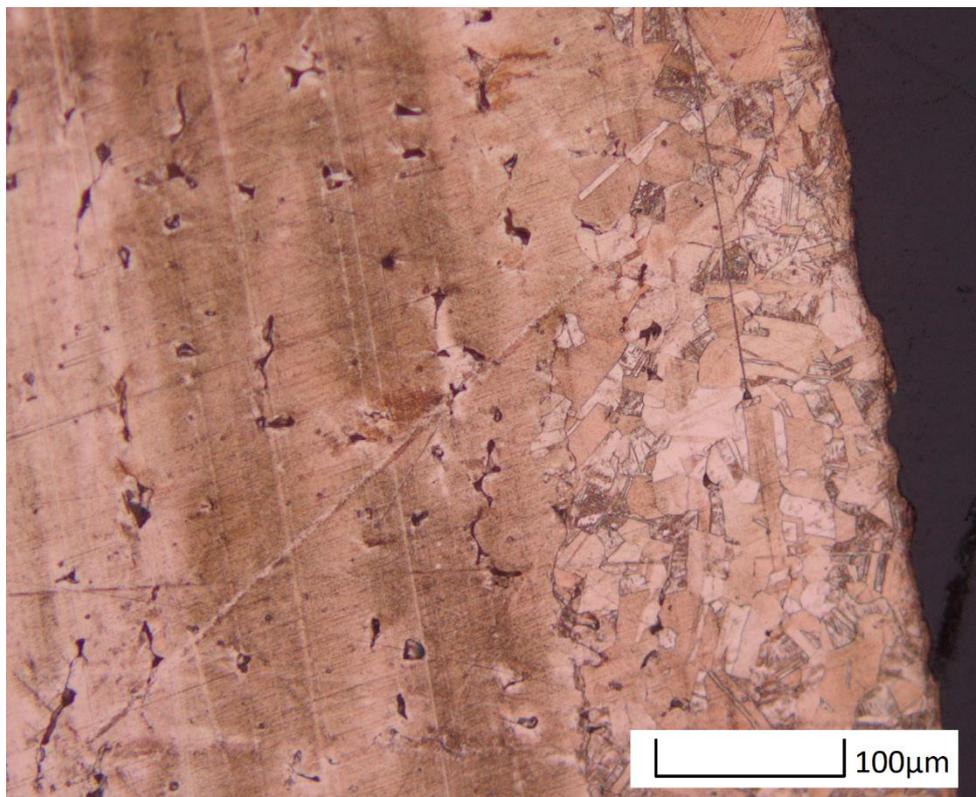


**Figure 54:** Metallograph of Blade 1, etched (x20) (Source: Author's own).
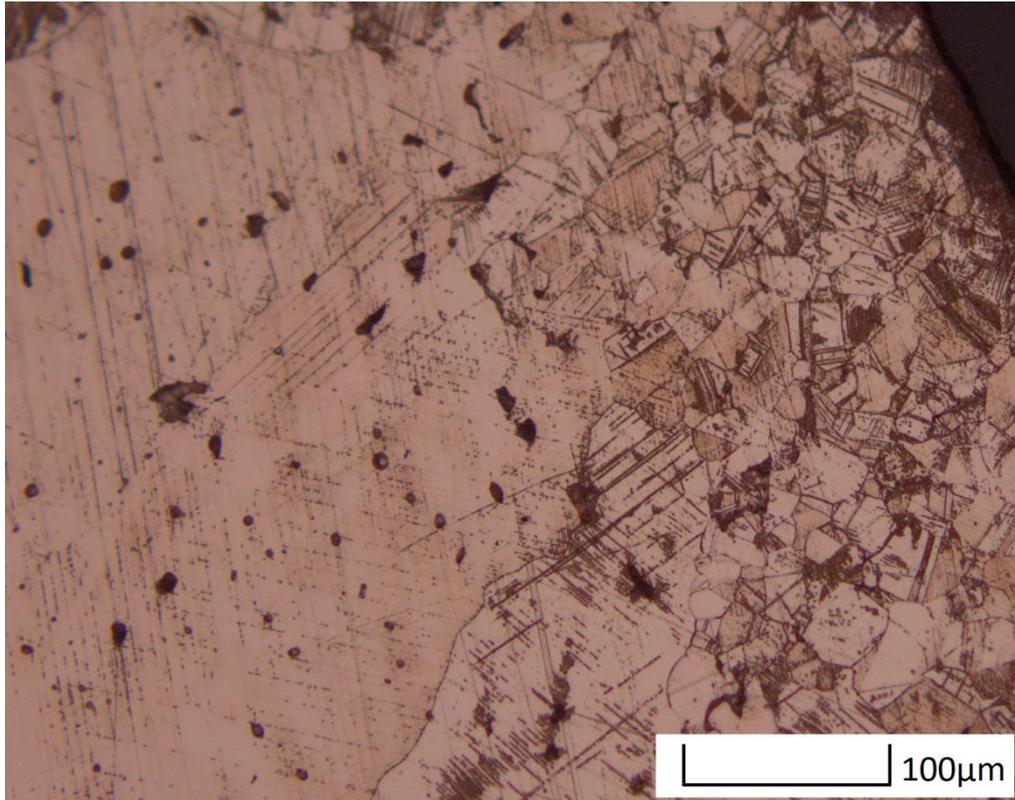
*Figure 55:* Metallograph of Blade 2, etched (x20) (Source: Author's own).
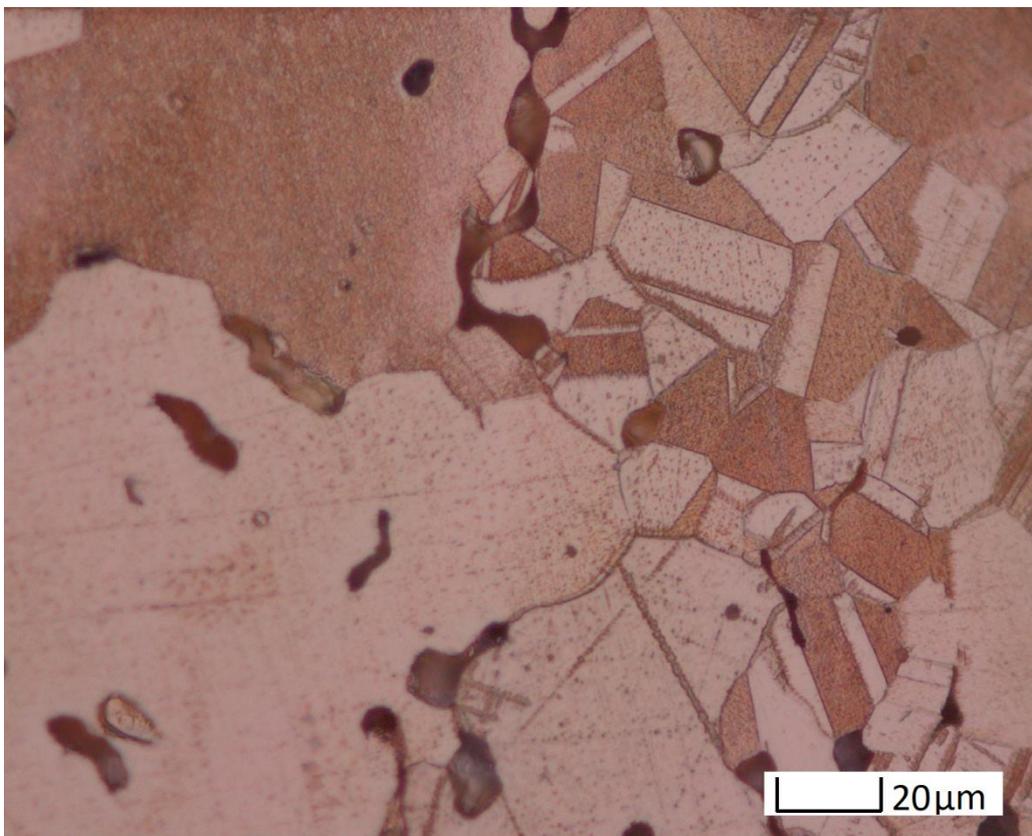


*Figure 56:* Metallograph of Blade 3, etched (x50) (Source: Author's own).
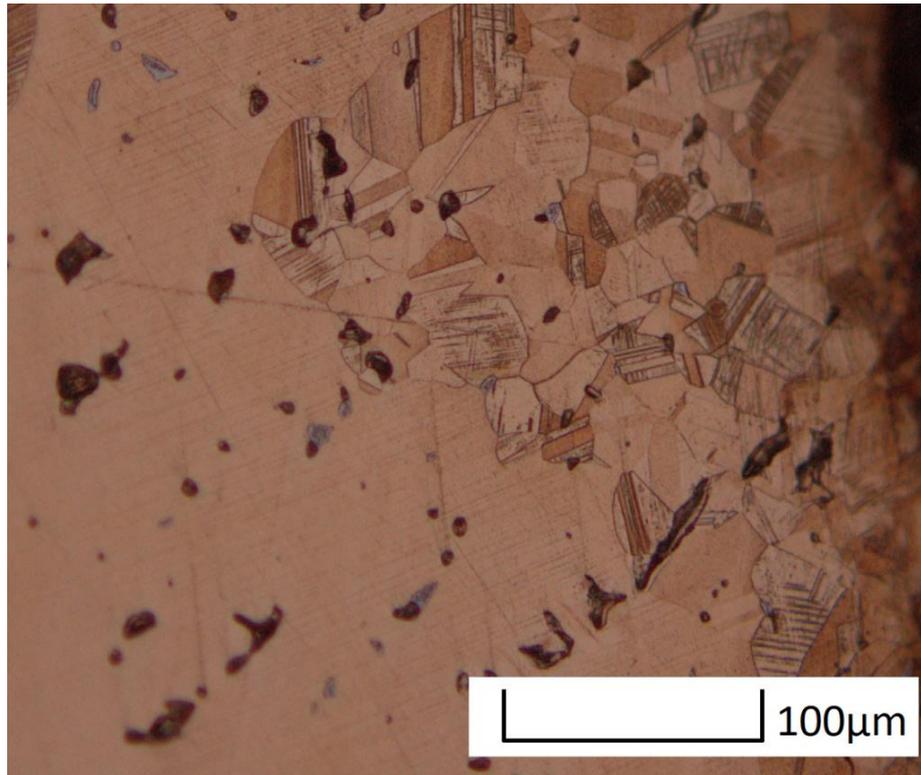
**Figure 57:** Metallograph of Blade 5, etched (x20) (Source: Author's own).
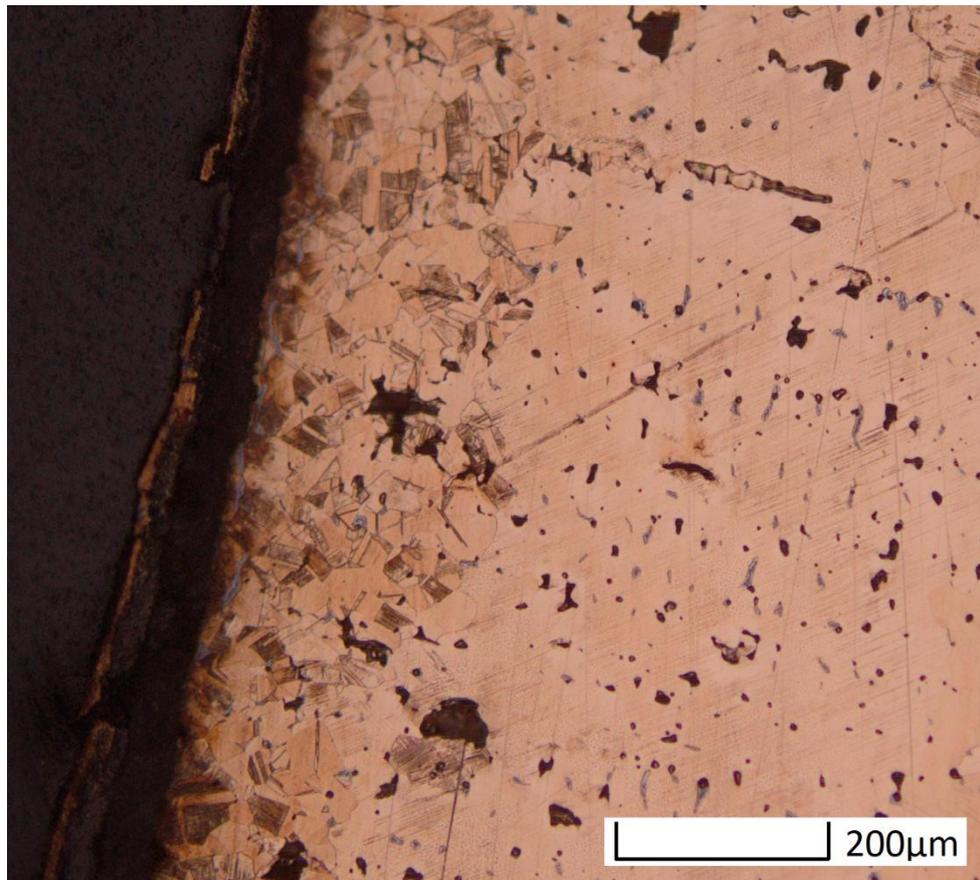


**Figure 58:** Metallograph of Blade 6, etched (x10) (Source: Author's own).

## 6.2    Properties of the surface-level wear

To better understand the mechanical changes induced at the cutting-edge of the replica palstave axes during maintenance and use, the surface hardness of Axes 1-4, and Blades 1 and 2 was investigated closely. It should be noted that only averaged microhardness measurements are reported here, with the full breakdown of data included in Appendix A. For the sake of discussing the progression of hardness in a logical order, the opening stage of hardness modification, i.e., sharpening, will first be addressed. As *Table 7* and *Table 8* suggest, although Axe 2 received a cold-hammering treatment, the blades of both Axe 1 and Axe 2 had an average hardness elevated well over 100 Hv (the assumed baseline for 10% tin-bronze [206]), with the blade of Axe 2 only ever so slightly harder than that of Axe 1. This could, in part, be a result of the slightly higher initial hardness of Axe 1, as indicated by the elevated hardness at Position 3 and 4. But, clearly a common denominator has permitted such a similar pattern of hardness along the three positions closest to the blade; and, this must be surface deformation generated by sharpening. It is intriguing that the effects of sharpening appeared to be greatest at Position 2, which lies at the pinnacle of the blade bevel, and are less marked at Position 1, and even less so at the Blade (*Figure 59*). This is, perhaps, a consequence of the action that was used during sharpening, which aimed to keep the file/whetstone flat to the blade, to make sure a second 'stumpy' bevel was not formed. This action most likely caught the highest point of the bevel, and generated more surface hardness.

| | Post-sharpening |
|---|---|
| Blade | 129±23 |
| Pos 1 | 142±49 |
| Pos 2 | 173±18 |
| Pos 3 | 116±39 |
| Pos 4 | 100±15 |

**Table 7:** The average values for hardness (HV) (and associated standard deviations) measured across the blade and cheek Axe 1 after sharpening.

|  | Post-sharpening | Post-500 tests at 30J |
|---|---|---|
| Blade | 142±62 | 254±58 |
| Pos 1 | 150±65 | 194±15 |
| Pos 2 | 154±55 | 162±21 |
| Pos 3 | 93±21 | 123±16 |
| Pos 4 | 89±10 | 92±11 |

**Table 8:** Table compiling the average values for hardness (HV) (and associated standard deviations) measured across the blade and cheek Axe 2 after sharpening and after 500 tests at 30J.
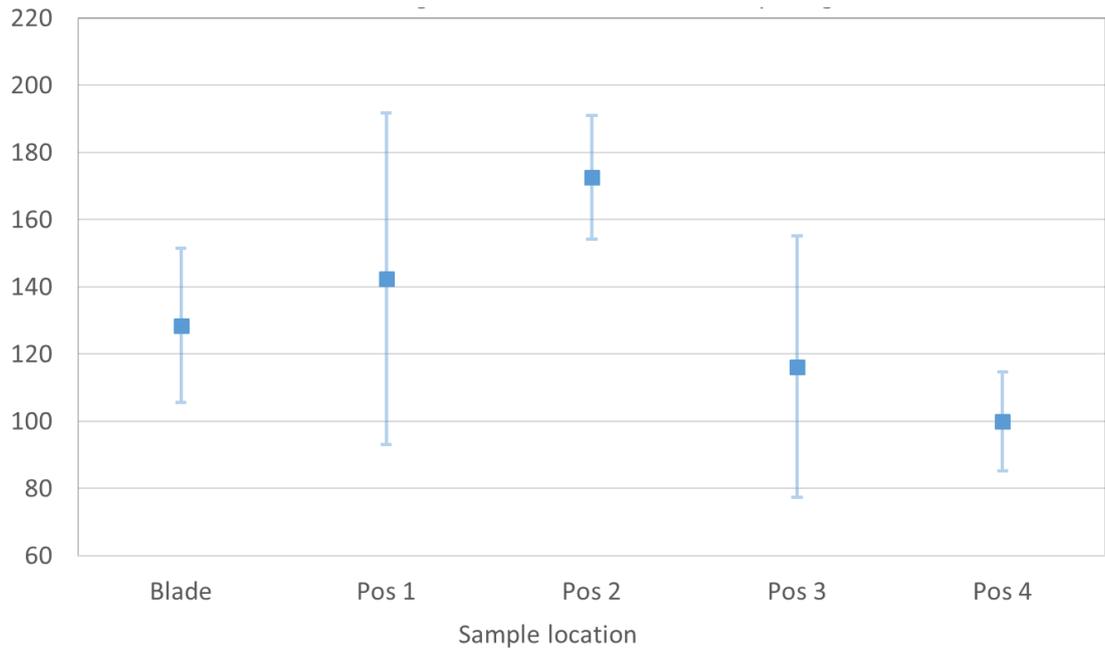


**Figure 59:** Graph presenting the average values for hardness (HV) (and associated standard deviations) measured across the blade and cheek of Axe 1 after sharpening.

Several random measurements were also made at the blade of Axe 1 after 1000 tests on the drop tower at 15J; the calculated Vickers hardness numbers at these points were, 154.4, 185.9, 226.3. These measurements demonstrate an increase in hardness over the course of the impact testing. While two different machines were used to obtain the hardness measurements for Axe 2 (perhaps

introducing some issues of incongruity within the results), the same can be said about the hardness measurements taken after 500 tests at 30J. *Figure 60* clearly exemplifies a considerable increase in hardness at the sampling locations along the blade edge of Axe 2, with an average increase in hardness of 112 HV. The hardness does not appear to have increased greatly in the horizontal sampling locations at Position 2 or 4. Some increase is exhibited in the areas sampled as part of Position 3, though the change may not be as profuse as is presented in the graph, since some of the initial measurements made with the manual microhardness tester are suspiciously low.
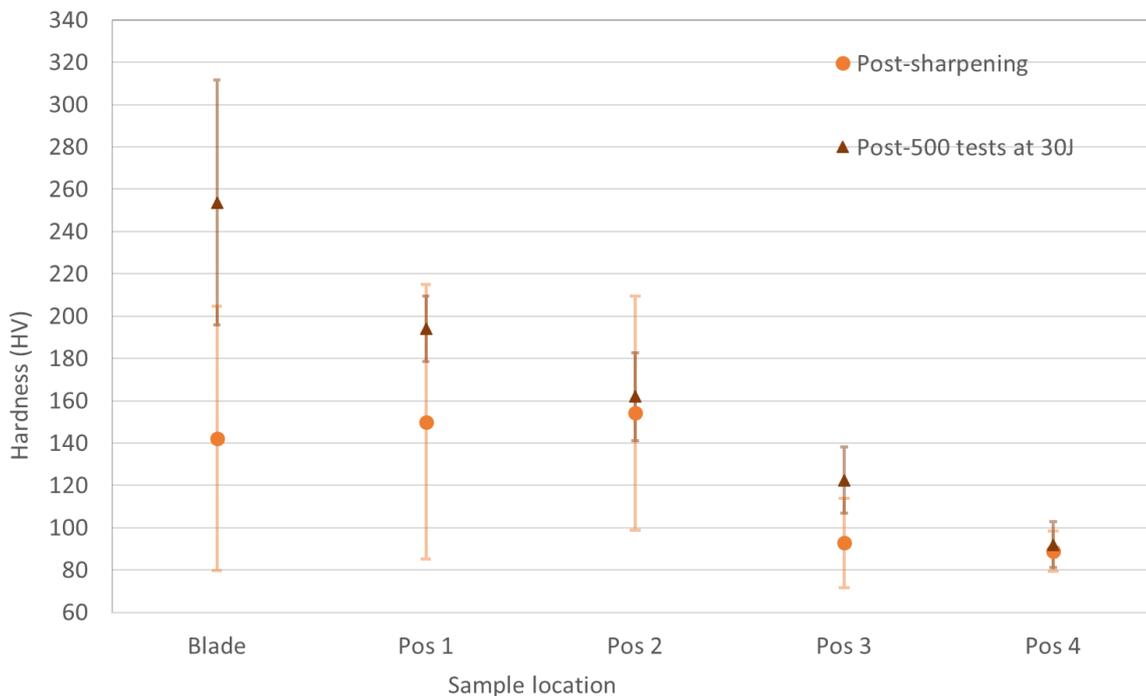


**Figure 60:** Graph presenting the average values for hardness (HV) (and associated standard deviations) measured across the blade and cheek of Axe 2 after sharpening and after 500 tests at 30J.

Hardness mapping was successfully conducted on both Axe 3 and 4 at set intervals, and interspersed sharpening events, producing complete datasets that can be easily compared. *Table 9* and *Table 10* present the mean hardness results across Axe 3 and 4 respectively, while *Figure 61*, *Figure 62*, *Figure 63*, *Figure 64*, and *Figure 65*, demonstrate this data graphically for each Position.

|  | **Blade** | **Pos 1** | **Pos 2** | **Pos 3** | **Pos 4** |
|---|---|---|---|---|---|
| *0 pre-sharpen* | 107±10 | 106±19 | 110±17 | 115±17 | 104±13 |
| *0 past-sharpen* | 159±29 | 137±19 | 170±21 | 144±21 | 110±11 |
| *250* | 161±26 | 148±24 | 171±19 | 135±16 | 121±13 |
| *500* | 167±22 | 156±24 | 176±17 | 136±12 | 134±10 |
| *600 pre-sharpen* | 188±19 | 158±10 | 182±24 | 147±17 | 130±10 |
| *600 post-sharpen* | 191±9 | 179±29 | 182±17 | 137±12 | 132±15 |
| *750* | 189±14 | 159±27 | 181±21 | 140±24 | 129±16 |
| *1000* | 184±24 | 155±17 | 183±28 | 135±21 | 122±12 |
| *1150 pre-sharpen* | 198±21 | 164±21 | 179±18 | 132±19 | 126±16 |
| *1150 post-sharpen* | 212±18 | 168±31 | 192±34 | 138±18 | 133±33 |
| *1250* | 206±20 | 177±24 | 198±27 | 126±11 | 122±16 |
| *1500* | 207±41 | 179±26 | 193±19 | 137±17 | 121±16 |
| *1750* | 215±45 | 186±30 | 211±27 | 134±15 | 116±17 |
| *2000* | 209±23 | 186±28 | 202±55 | 132±21 | 121±13 |
| *2250* | 201±17 | 179±25 | 190±25 | 131±18 | 125±14 |
| *2500* | 205±20 | 189±31 | 188±36 | 130±12 | 126±7 |

***Table 9:*** Table of mean hardness (HV) for each Position across Axe 3 over the course of impact testing.

|              | Blade   | Pos 1   | Pos 2   | Pos 3   | Pos 4   |
|--------------|---------|---------|---------|---------|---------|
| *0 pre-sharpen*    | 121±17 | 116±20 | 113±12 | 111±12 | 107±13 |
| *0 post-sharpen*   | 160±21 | 172±26 | 181±25 | 139±25 | 122±25 |
| *200 pre-sharpen*  | 158±16 | 171±24 | 186±26 | 138±28 | 124±19 |
| *200 post-sharpen* | 167±32 | 168±31 | 178±28 | 136±36 | 129±28 |
| *500 pre-sharpen*  | 178±35 | 175±25 | 179±36 | 132±17 | 119±15 |
| *500 post-sharpen* | 179±15 | 156±25 | 168±42 | 134±24 | 113±16 |
| *1000* | 184±31 | 179±33 | 184±33 | 133±36 | 125±17 |
| *1500* | 197±30 | 179±44 | 187±28 | 133±22 | 121±16 |
| *2000* | 204±28 | 171±21 | 189±22 | 129±28 | 119±20 |
| *2500* | 201±11 | 182±21 | 187±31 | 132±15 | 119±13 |

***Table 10:*** Table of mean hardness (HV) for each Position across Axe 4 over the course of impact testing.
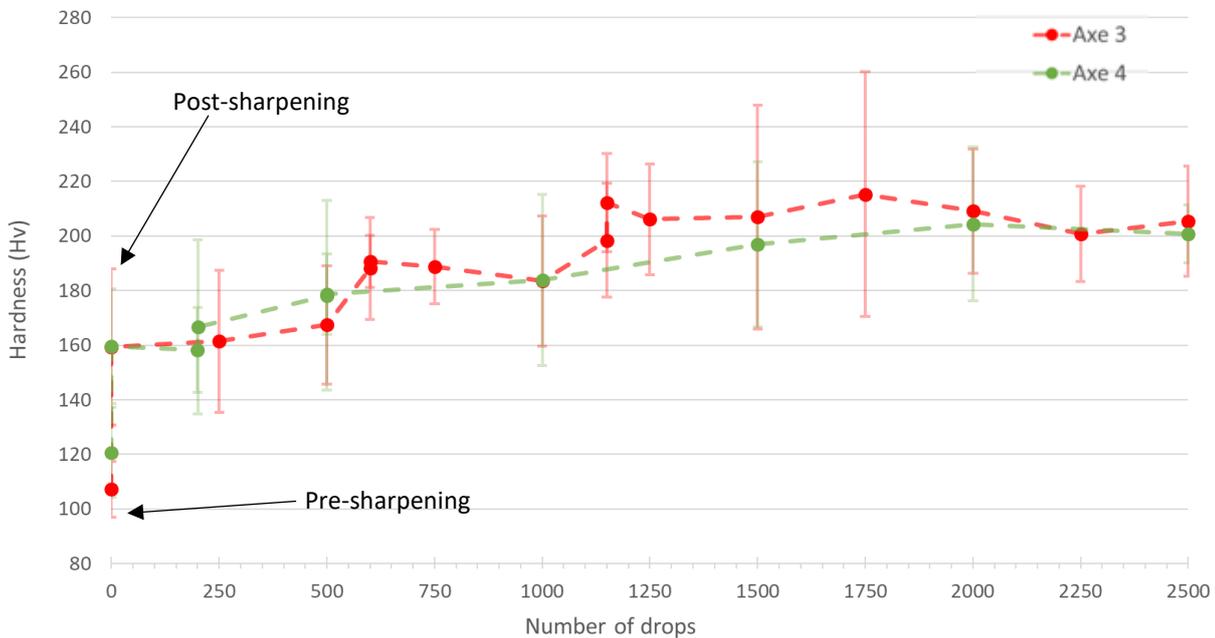


***Figure 61:*** The mean hardness and standard deviations of the hardness measurements recorded across the cutting-edge of both Axes 3 and 4.
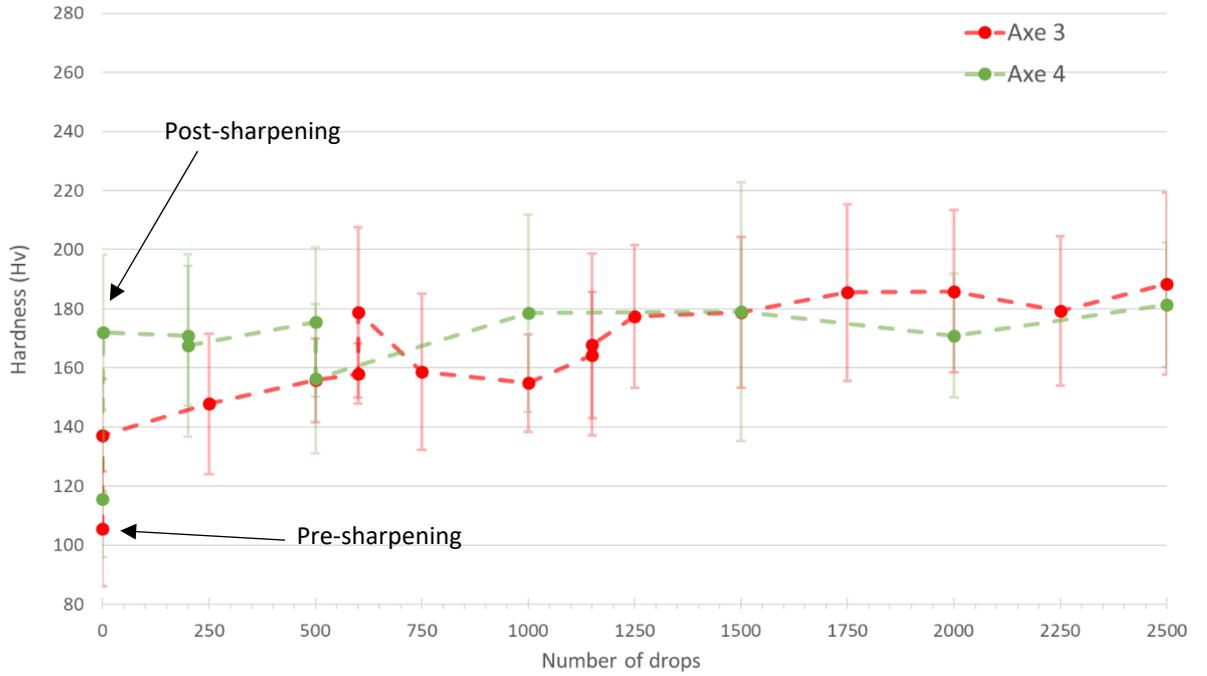
***Figure 62:*** The mean hardness and standard deviations of the hardness measurements recorded across Position 1 of both Axes 3 and 4.
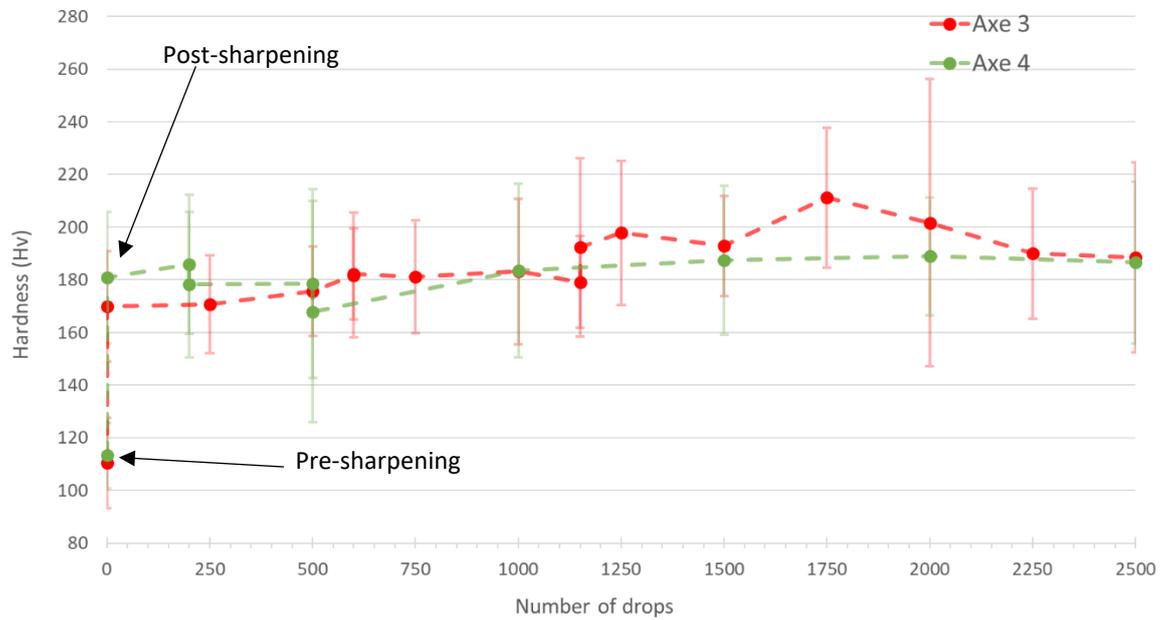


***Figure 63:*** The mean hardness and standard deviations of the hardness measurements recorded across Position 2 of both Axes 3 and 4.
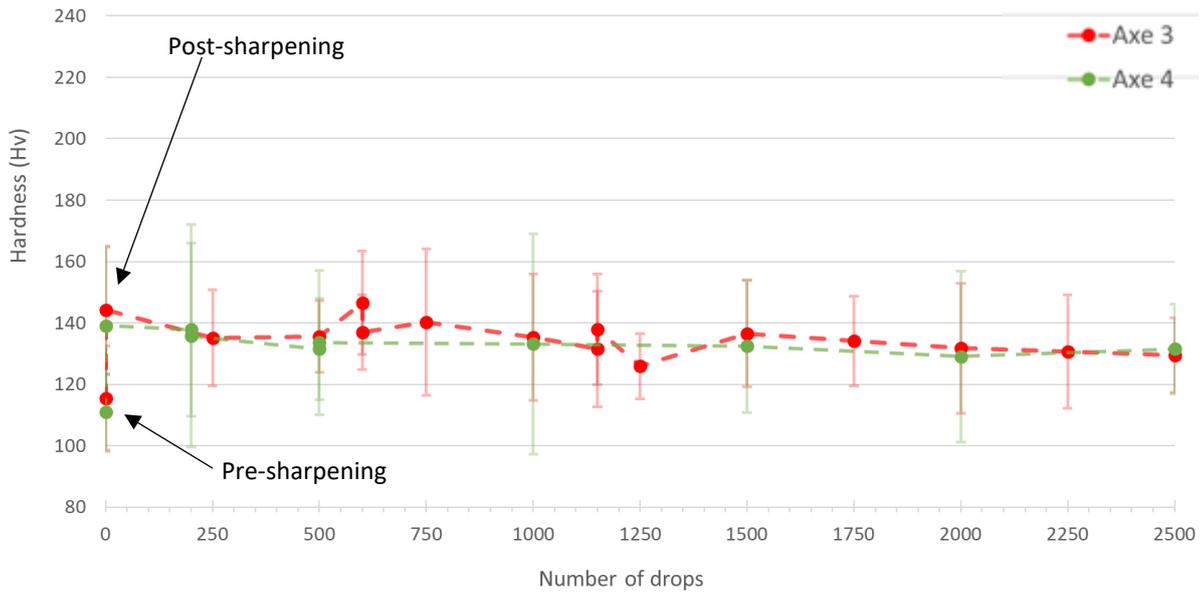
**Figure 64:** The mean hardness and standard deviations of the hardness measurements recorded across Position 3 of both Axes 3 and 4.
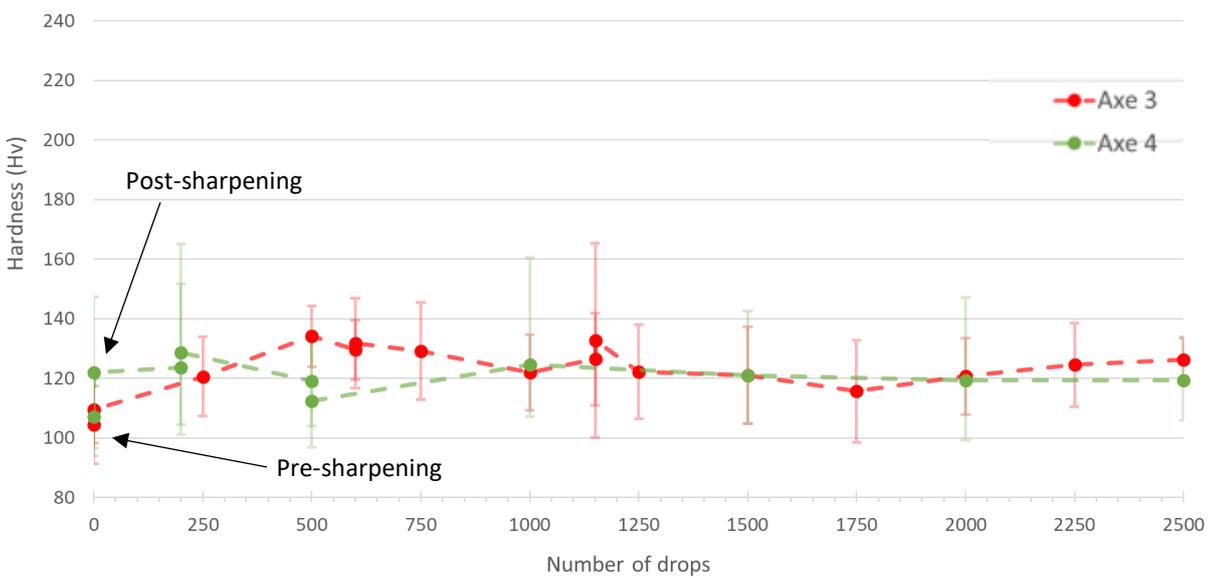


**Figure 65:** The mean hardness and standard deviations of the hardness measurements recorded across Position 4 of both Axes 3 and 4.

Like the results for Axe 1 and 2, the averaged hardness measurements for Axe 3 and 4 show a great elevation in hardness after the initial sharpening, particularly at the sampling locations along the Blade (Position 0), Position 1, and Position 2 (*Figure 61*, *Figure 62*, and *Figure 63*). The mean hardness increase at the Blade of Axe 3 after the first sharpening phase was 52 HV, and at Position 2 was 60 HV, while that of Position 1 was markedly lower (32 HV). In the case of Axe 4, the mean

hardness increase at the Blade of Axe 4 after the first sharpening phase was only 39 HV, while it was 56 HV at Position 1 and 68 HV across Position 2. Thus, the results for the Blade and Position 1 are not completely comparable between Axes 3 and 4. This is perhaps the result of the differential pressures placed on the axe during sharpening, since this process was done by hand and so could not be easily controlled. The hardness across Positions 3 on both axes was raised slightly as some indents were placed on areas that had been affected by sharpening, while little difference was recorded across Position 4.

In contrast to the results presented above, subsequent sharpening phases, of which there were two for each axe, had little effect on the hardness of the axe-heads. For example, the second sharpening event had only a very minor effect across the Blade of Axe 3, whereas the third sharpening induced a mean increase in hardness of only 14 HV. The material at Position 1 on Axe 3 seems to undergo some hardening (an increase in mean hardness of 21 HV) at the second sharpening phase. This is most likely a consequence of the low hardness of the position at this point (a mean hardness of only 158±10 HV), which made the material easier to deform and, therefore, more susceptible to rapid hardening. The third sharpening phase for Axe 3 at 1150 tests apparently induced very little change in hardness across Position 1. No change was recorded across Position 2 on Axe 3 after the second sharpening phase, and considering the high hardness of these areas prior to maintenance, this was to be expected. Conversely, as shown in *Figure 63*, the third sharpening phase appears to have brought about some hardening (an increase in mean hardness of 13 HV) across Position 2 – the reasons for which, given the rest of the data, are difficult to explain. The data for Axe 4 suggests that only negligible increases in hardness were induced across the Blade by subsequent sharpening events. The measurements taken at Positions 1 and 2 on Axe 4 post-sharpening, all demonstrate reduced hardness than those taken prior to sharpening. While, the scale of decrease is rather minor at 200 tests, the data collected at 500 tests indicates a greater change that largely contradicts the rest of the measurements. The hardness of Positions 3 and 4 on both axes does not seem to have been influenced by further sharpening.

To investigate the elevation of surface hardness at the cutting-edge of palstave axes due to sharpening and use, RStudio [271] and the statistical package lme4 [272] were used to perform a linear mixed effects analysis of the relationship between hardness and sharpening for each axe. When stipulating the fixed effects in the model referred to above, a term for the change in hardness before and after sharpening at each position and sharpening interval was included. The random effect entered into the model was the interaction between the sample location at each position

and the number of drops, since it is expected that the hardness measurements taken at each sampling location may show some inter-relation throughout the course of the experiment.

The estimates generated as part of the model show that sharpening affected the hardness of Axe 3 most drastically in the first sharpening, increasing the Blade by 53±10 HV (all estimates are accompanied by the related measure of standard error), Position 1 by 31±10 HV, Position 2 by 60±10 HV, Position 3 by 29±10 HV, and Position 4 by 6±10 HV. The following sharpening only appears to have a significant impact on Position 1, which increased by 21±10 HV, while hardness changes across the rest of the axe-head are negligible. The final sharpening raised the hardness of the Blade by 19±9 HV and Position 2 by 13±10 HV, while hardness changes across the rest of the axe-head are minimal. The estimates generated as part of the model show that sharpening also affected the hardness of Axe 4 most drastically in the first sharpening, increasing the Blade by 39±9 HV, Position 1 by 58±10 HV, Position 2 by 68±9 HV, Position 3 by 29±9 HV, and Position 4 by 15±9 HV. The following two sharpening events only appears to have had very little impact on the hardness of each position across the axe-head. Contrary to how the significance of this type of analysis is usually reported in academic journals, there is no infallible way to currently derive p values from linear mixed-effects models. The best way to express the differences captured within the model estimates, therefore, is through the depiction of confidence intervals (this is strongly advocated by the creator of the lme4 package). The confidence intervals for the effect of sharpening on the hardness of Axes 3 and 4 at all five positions after each sharpening event is displayed below (*Figure 66*). They demonstrate that the initial sharpening event has a significant effect on hardness at the Blade, as well as Positions 1-3 and that – with the exception of Axe 3, Position 1, after the second sharpening and Axe 3, Blade, after the final sharpening – there is no significant increase in hardness due to later sharpening events.
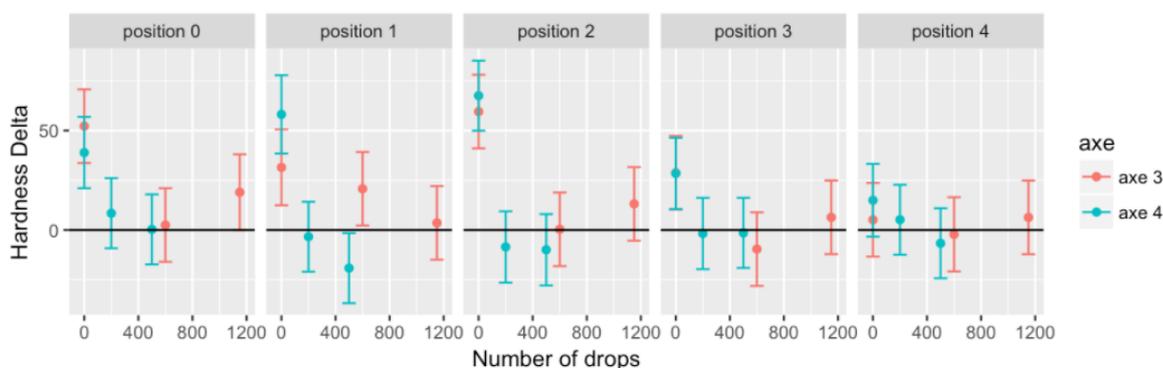


***Figure 66***: Point estimates and confidence intervals (shown at the 95% level) produced by the model estimates for sharpening effect on Axes 3 and 4 [271].

Now, with a better understanding of the role of sharpening in elevating the surface hardness of the replica palstave axes, it is possible to properly evaluate the rest of the sequential hardness data. The data shows that a rather rapid hardening effect was experienced at the Blade of both axes at first; by 1000 impacts the sample locations across Axe 3 exhibited a mean hardness of 184±24 HV and, Axe 4, a mean hardness of 184±31 HV. After this, the surface hardness across the Blade of Axe 3 appears to have been quickly elevated to over 200 HV (by the second analyses at 1150 impact tests), and fluctuated between this value and 215 HV for the remainder of the testing. Conversely to the data produced by Axe 3, by 1500 impact tests the average hardness measured across the Blade of Axe 4 was still just under 200 HV, a value over this threshold was only obtained at 2000 impact tests. Thus, it appears as though the rate of hardening between 180 and 200 HV was slightly slower for Axe 4. It should be noted, however, that the larger analysis intervals applied to Axe 4 gave less opportunity to record measurement scatter (which, looking at the Axe 3 data, is fairly severe) and if data acquisition had been conducted more frequently, it is quite possible that a faster rate of change may have emerged. As a result of this 'scatter', it is also not possible to accurately estimate the total amount of use-hardening experienced across the blade of each axe, though this appears to be in the range of 45-55 HV for Axe 3 and 40-45 HV for Axe 4. It should also be noted that the thinner, less constrained material at the cutting-edge may have resulted in an under-valuation of the hardness at this location.

Looking further up the axe-head, onto Position 1, the results between Axes 3 and 4 quickly become less analogous (*Figure 62*). As mentioned earlier in the text, Axe 3, Position 1, had an unusually low starting hardness after the initial sharpening (mean = 137±19 HV). As a result, the position appears to have been easily deformed and hardened at first (an average increase of around 40 HV between 0 and 1250 drops) and then more slowly (an average increase of 10 HV) for the remainder of the experiment. In contrast, Axe 4, Position 1, already had a starting hardness of 172±26 HV after the initial sharpening and only increased by an average of 9 HV across the whole experiment. Hence, while the results present a very different total amount of hardening experienced across the sampling locations at Position 1 between Axes 3 and 4, the observed contrast is slightly misleading. To reiterate, this is due to the substantial difference in starting hardness after initial sharpening between the two axes, the increases in hardness at Axe 3, Position 1, due to the second sharpening (as discussed earlier), and the nature of work-hardening in bronze (greater increases when softer). What can be concluded, is that the impact tests were unable to induce substantial increases in hardness above c. 170 HV at Position 1 on both replica axes during only 2500 impact tests.

A similarly complex picture is presented by the contrasting results of each axe at Position 2 (*Figure 63*). For instance, the mean hardness data from Axe 4 begins at approximately 180 HV and continues to oscillate around this value fairly consistently while the comparative data from Axe 3 shows substantial increases in average hardness. The greatest apparent increases in hardness across Axe 3, Position 2, appears to have commenced after the third sharpening at 1150 drops, and continued until 2000 drops – with 211±27 recorded as the highest mean hardness. Although it remains unclear why areas of the material that are largely remote from the major zones of impact might experience such great changes in hardness, this mostly likely relates to the issues of sampling strategy, for example, the clustering of measurements, which were discussed in section 5.3.2. The final two measurement intervals for Axe 3 produced average hardness values for Position 2 that were much more conservative – indicating that the sampling strategy was most likely responsible for the unexpected increases recorded earlier in the testing. The results produced for the two control Positions, 3 and 4, were very comparable across nearly all measurement intervals (*Figure 64* and *Figure 65*). The average hardness values recorded at Axe 3, Position 3, fluctuated between 130 HV and 140 HV, approximately. In close likeness, the average hardness values recorded at Axe 4, Position 3, fluctuated between 129 HV and 139 HV. The average hardness values recorded at Axe 3, Position 4, fluctuated between 120 HV and 130 HV, approximately. Similarly, the average hardness values recorded at Axe 4, Position 4, fluctuated between 119 HV and 128 HV. These results demonstrate that, though individual hardness indents are vulnerable to material differences (reflected in the considerable standard deviations presented across most of the results), when averaged, the baseline variability of hardness is only around 10 HV.

Two further linear mixed effects models were generated in RStudio [271] using lme4 [272] statistical package, investigating the gradient of hardness change at each position over the number of drops in each axe. When stipulating the fixed effects, a term for removing the impact of the initial sharpening event from was included in order to highlight the elevation in surface hardness from use only. The random effect entered into the model was the interaction between the sample location at each position and the number of drops. *Figure 67* separates the gradients described for Axe 3 by sample location across each Position. For Axe 3, the estimates generated as part of the model demonstrate positive gradients ranging between 0.019±0.0036 and 0.023±0.0038 for the sampling locations on the Blade (Position 0). Similarly, positive gradients between 0.016±0.0036 and 0.019±0.0036 were estimated for the sampling locations on the Position 1. The estimations for Position 2 were not so comparative, with sample location 1, presenting a minor gradient of 0.00079±0.0036, and the two other positions, gradients of 0.015±0.0036 and 0.018±0.0036. The model estimates for the sampling locations across Position 3 demonstrated negative gradients

ranging between -0.0077±0.0036 and -0.0026±0.0036. While further negligible gradients were generated by the Position 4 data (0.0067±0.0031 to 0.0029±0.0031). A visual representation of the gradients described for Axe 4 can be seen in *Figure 68.* For Axe 4, the estimates generated as part of the model demonstrate positive gradients ranging between 0.018±0.0037 and 0.021±0.0037 for the sample locations at the Blade (Position 0). Positive gradients between 0.006 ±0.0037 and 0.0022 ±0.0037 were estimated for the sample locations at the Position 1. The model estimates for Position 2 presented positive gradients between 0.009 ±0.0037 and 0.0013 ±0.0037. The model estimates for the sampling locations across Position 3 and Position 4 demonstrated both positive and negative gradients ranging between 0.0023 ±0.0037 to -0.0052 ±0.0037, and 0.0045 ±0.0034 to -0.001 ±0.0034, respectively*.* Point estimates and confidence intervals for the 'gradient of hardness increase' and the 'number of drops' were produced from the model estimates (*Figure 69*).
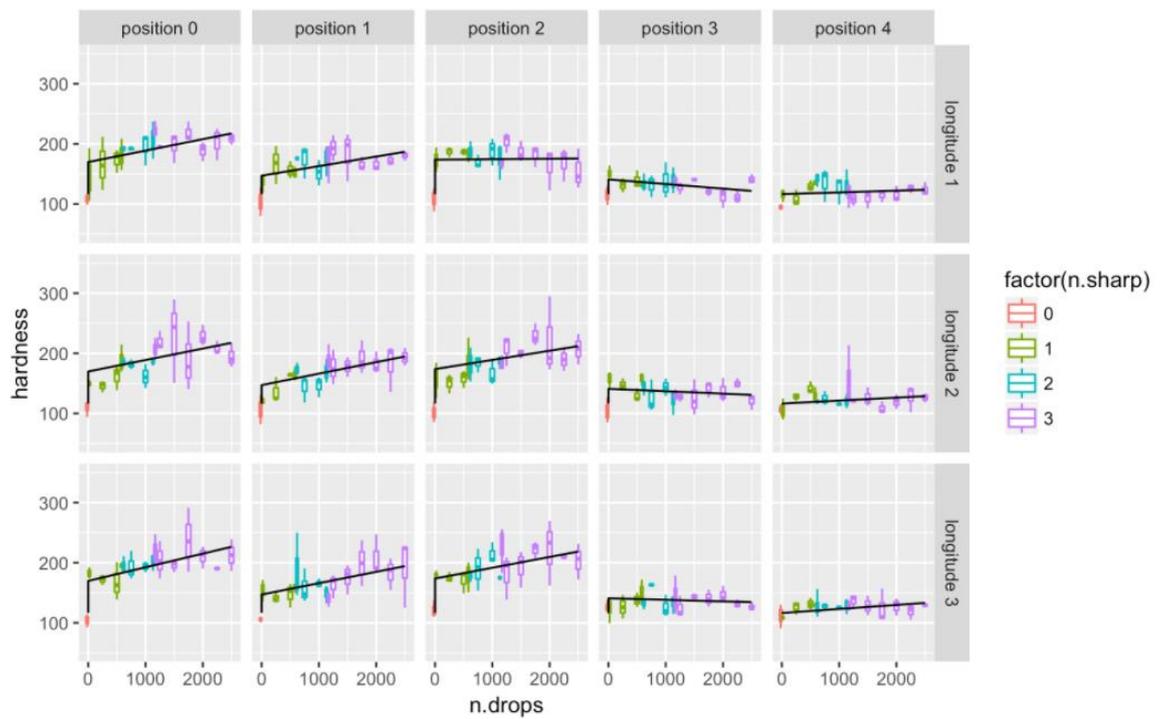


***Figure 67:*** Graph illustrating the model estimates and data trend lines produced from the linear mixed effects model for Axe 3 [208].
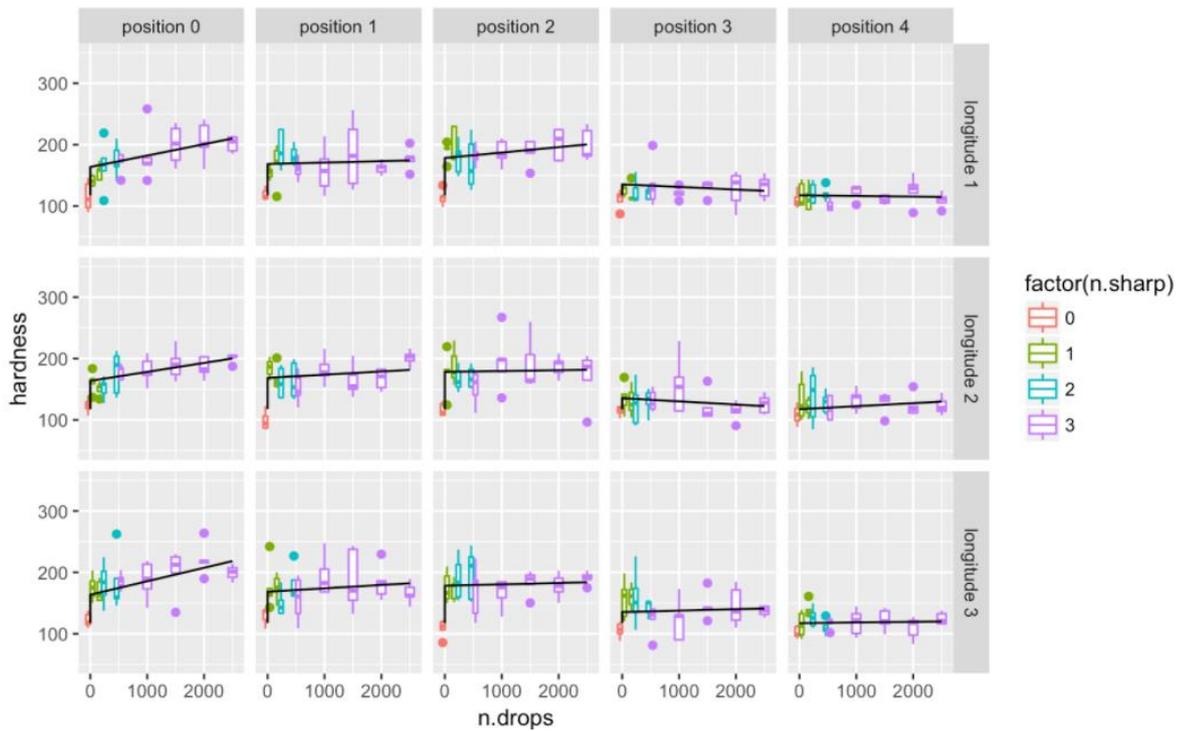
**Figure 68:** Graph illustrating the model estimates and data trend lines produced from the linear mixed effects model for Axe 4 [208].
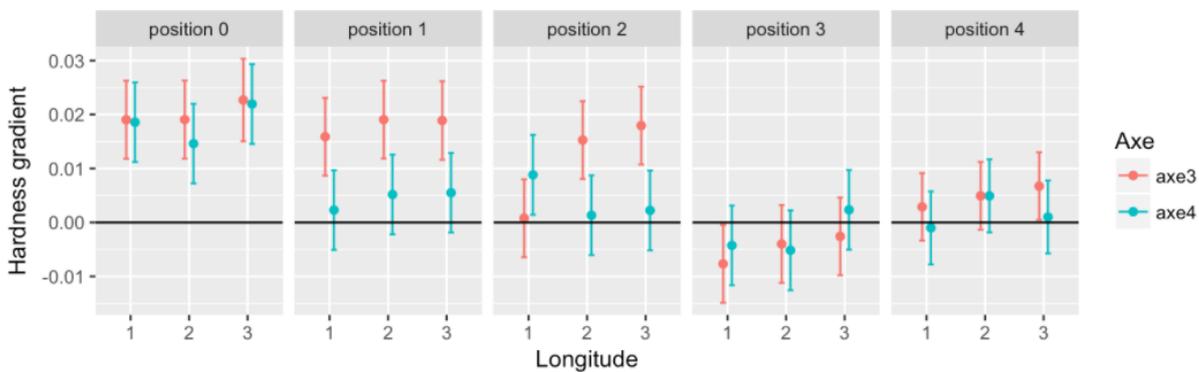


**Figure 69:** Point estimates and confidence intervals (shown at the 95% level) produced from the model estimates for the linear mixed effects models investigating hardness against no. of drops [208].

As seen in *Figure 67* and *Figure 68*, the model estimates of the linear mixed effects analysis for the sample locations along the Blade (Position 0) have produced positive gradients for both Axes 3 and 4. The impact of the low starting hardness at the sample locations across Axe 3, Position 1, is clearly exhibited by the gradients produced by the model estimates of the linear mixed effects analysis – which, as a result, all demonstrate positive gradients that are significant at the 95% confidence level (*Figure 69*). In contrast, the gradients produced by the model estimates of the linear mixed effects analysis for the sample locations across Position 1 on Axe 4, are only weakly positive and are not

significant at the 95% confidence interval (*Figure 69*). For Axe 4, Position 2, only sample location 1 has a marginally significant positive gradient produced by the model estimates of the linear mixed effects analysis. Whereas, for Axe 3, Position 2, strongly positive gradients were only produced for sample locations 2 and 3. The model estimates of the linear mixed effects analysis produced weakly negative gradients for the majority of the sample locations across Position 3 for both axes (*Figure 67* and *Figure 68*). The model estimates of the linear mixed effects analysis produced a mixture of weak positive and negative gradients for the sample locations across Position 4 for both axes. (*Figure 67* and *Figure 68*).

Given the discussion pertaining to the hardness results given above, it is possible to say with some confidence that the surface of the replica palstave axes closest to the blade edge undergoes a hardening effect during use. This appeared to be very encouraging in terms of establishing data for the surface hardness measurements recorded on ancient specimens to be compared against. The next logical step, therefore, was to test the method on a prehistoric axe. A Bronze Age palstave axe (a very well-preserved unprovenanced 'Side-Flanged' palstave found by a metal detectorist) was used to trial the application of surface hardness testing to a prehistoric bronze axe. Unfortunately, upon loading, the indenter broke through the oxidised surface of the axe and onto a corrosive layer beneath, in which the indents were completely engulfed. Not only was it not possible to measure the indent, but the material matrix had clearly been completely compromised and any values that could be extracted would not reflect the original hardness of the surface. The microscope images below, *Figure 70* and *Figure 71*, illustrate the asperous cavities that were produced in the surface of the prehistoric axe by indenting. Considering that this palstave axe was a very well-preserved specimen, it seems unlikely that surface hardness testing as a proxy for use-intensity is a viable option to pursue for the analysis of ancient palstave axes.

*Figure 70:* Microscopic image of one of microhardness indents placed on the surface of the prehistoric axe (x10 magnification).



*Figure 71*: Microscopic image of one of microhardness indents placed on the surface of the prehistoric axe (x10 magnification).

The surface hardness of Blades 1 and 2 was successfully recorded over numerous intervals; however, in accordance with the devaluation of hardness testing for this study, measurements were made only at the Blade and in the control area, named 'Baseline'. Like the previous results with Axes 1-4, the averaged hardness measurements at the blade show a great elevation in hardness after the initial sharpening (*Table 11*). The mean hardness increase at the cutting-edge of Blade 1 after the first sharpening phase was 71 HV, which is slightly higher than the values recorded for previous specimens, but in-line with the findings for the increased hardening effect of actualistic sharpening methods (see *Figure 27*). The average hardness across the Baseline zone on Blade 1 was raised considerably (47 HV) as most of the indents were placed on areas that had been affected by sharpening. The results presented for Blade 2 are in a slightly different format, as this specimen was also hammer-hardened before sharpening. Thus, the mean hardness increase at the Blade of Blade 2 after hardening was 28 HV, with an additional increase of 46 HV after sharpening – equating to a total increase of 74 HV (*Table 11*). The average hardness across the Baseline zone on Blade 1 was raised by 7 HV after the hammer-hardening, and another 60 HV by sharpening. The Blades were not subject to any further sharpening events.

As seen in *Table 11*, the mean hardness recorded along the Blade displays an inclining trend for both Blades 1 and 2. The data shows that a particularly rapid hardening effect was experienced by Blade 1 at the beginning of testing; by only 750 impact tests the sample locations across Blade exhibited a mean hardness of 200±24 HV and fluctuated around this value for the remainder of the testing (*Figure 72*). The surface hardening encountered by Blade 2 was more gradual – at 500 impact tests the mean hardness was already at 183±25 HV, but it was not until 1250 impact tests when the measured values were close to 200 HV when averaged. Since Blade 2 was administered with hammer-hardening before simulated use in the rig, the rate of hardening was slower because the material was already more resilient to deformation at the beginning of testing. As suggested by *Table 12*, the results produced at the control position on each specimen indicate that the average hardness values recorded on Blade 1 fluctuated between 135 HV and 150 HV, while they were in the range of 150 HV and 166 HV for Blade 2 (*Figure 73*). Thus, the range of baseline hardness measurements is somewhat wider than for previous experiments, which can be explained by the short distance between the 'baseline' zone and the blade edge, which made it more susceptible to the effects introduced by manufacturing and maintenance practices. Correspondingly, the measurements recorded on Blade 2 were of a slightly higher hardness – this is most definitely related to the hammer-hardening that the cutting-edge was subjected to.

|  | Blade | Baseline |
|---|---|---|
| *0 pre-sharp* | 95±7 | 98±9 |
| *0 post-sharp* | 166±20 | 144±10 |
| *250* | 178±18 | 140±17 |
| *500* | 191±25 | 147±8 |
| *750* | 200±24 | 143±13 |
| *1000* | 193±21 | 136±3 |
| *1250* | 202±16 | 149±9 |
| *1500* | 210±21 | 140±13 |
| *1750* | 203±13 | 136±28 |
| *2000* | 212±23 | 148±23 |

*Table 11:* Table of mean hardness (HV) for both positions across Blade 1 over the course of impact testing.

|  | Blade | Baseline |
|---|---|---|
| *0 - pre-sharp* | 94±8 | 100±5 |
| *0 - hardened* | 122±23 | 106±10 |
| *0 - post-sharp* | 168±14 | 167±42 |
| *250* | 171±18 | 156±19 |
| *500* | 183±25 | 153±21 |
| *750* | 182±28 | 158±7 |
| *1000* | 188±17 | 150±30 |
| *1250* | 199±21 | 151±9 |
| *1500* | 203±23 | 167±24 |
| *1750* | 205±13 | 158±30 |
| *2000* | 204±26 | 155±18 |

*Table 12:* Table of mean hardness (HV) for both positions across Blade 2 over the course of impact testing.
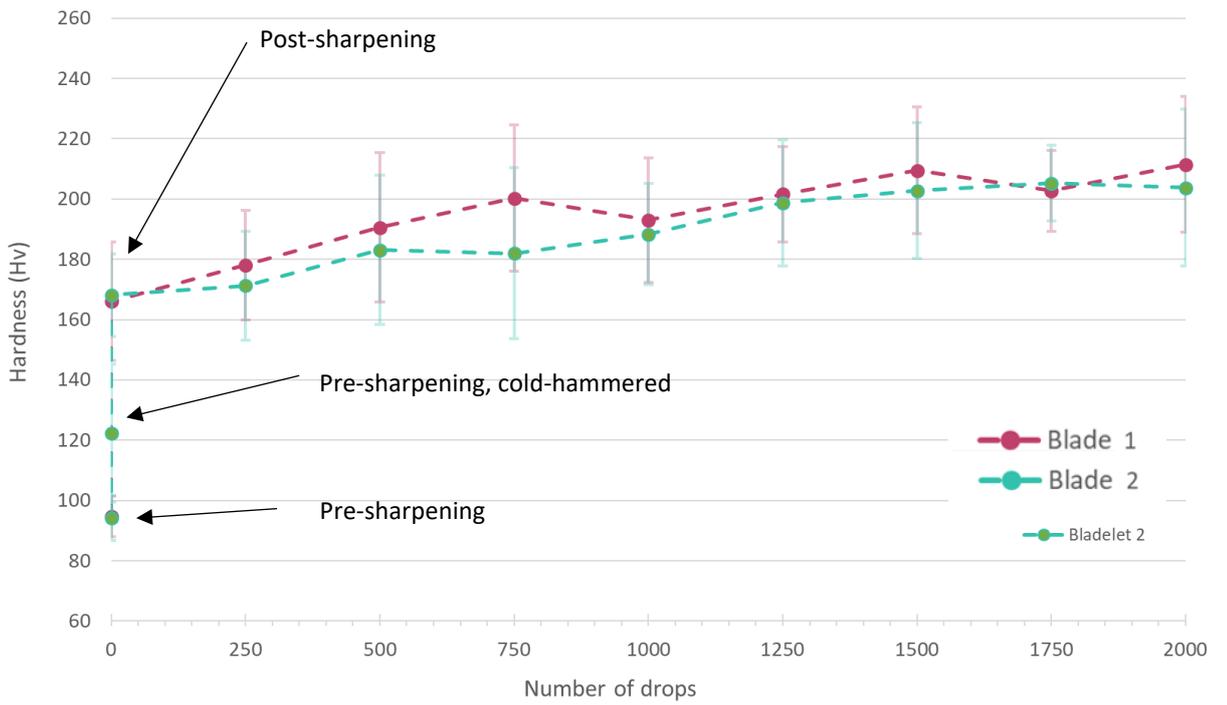
*Figure 72:* The mean hardness and associated standard deviations of the hardness measurements recorded across the Blade of both Blades 1 and 2.
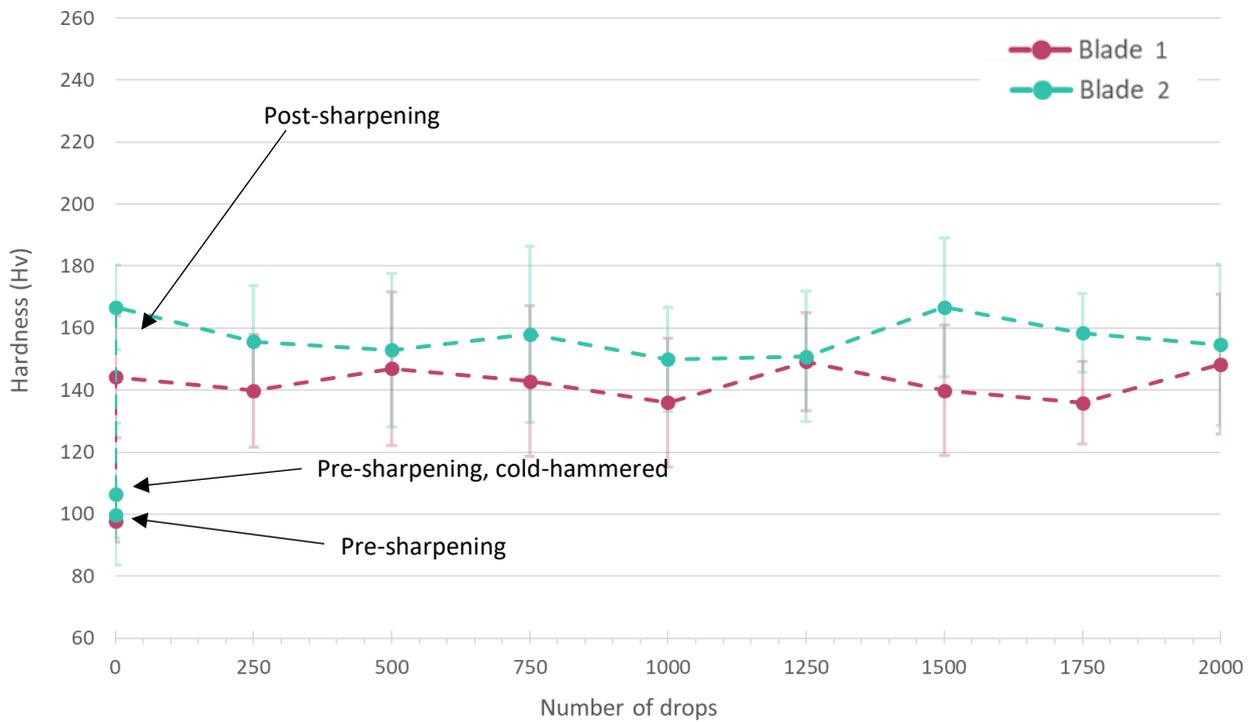


*Figure 73:* The mean hardness and associated standard deviations of the hardness measurements recorded across the 'Baseline area' of both Blades 1 and 2.

149

Combined with the results from Axes 3 and 4, a general picture of the surface hardness increase at the blade over number of drop tests can be formed (*Figure 74*). Firstly, the results demonstrate a more rapid hardening effect prior to 200 HV, with a slower hardening once this threshold had been reached. Previous experimental work [247] has suggested that 200 HV is a pivotal hardness value for 10% tin-bronzes, after which the material is much more difficult to deform – thus, a plateau in hardness of this kind is to be expected and it is possible that much more exhaustive testing would be needed to generate further hardness elevation. A similar phenomenon has also been observed with Cu-Al alloys, which have been shown to experience a period of rapid hardening up to a true axial strain of about 0.1 but thereafter do not continue to deform until a strain of 0.2 is reached [273]. Secondly, the results of both Ottaway and Wang [132] and Lechtman [247], demonstrate that a hardness of ~200 HV equates to around 30% reduction; this suggests that the experimental specimens presented herein had also experienced such a reduction but by *use* only. Lastly, it is interesting to note that the rate of hardening of the cutting-edge of both dendritic and recrystallized microstructures is comparable (given the standard deviation of the measurement values). Had Blades 1 and 2 been fully recrystallized (more than just the very surface), then the more homogeneous nature of this structure may have resulted in reduced variability of measurements and the opportunity for further comparison of the two microstructures. Regardless, it is clear that both microstructures can be hardened by similar mechanisms, with grain size and amount of work hardening likely generating minor differences.
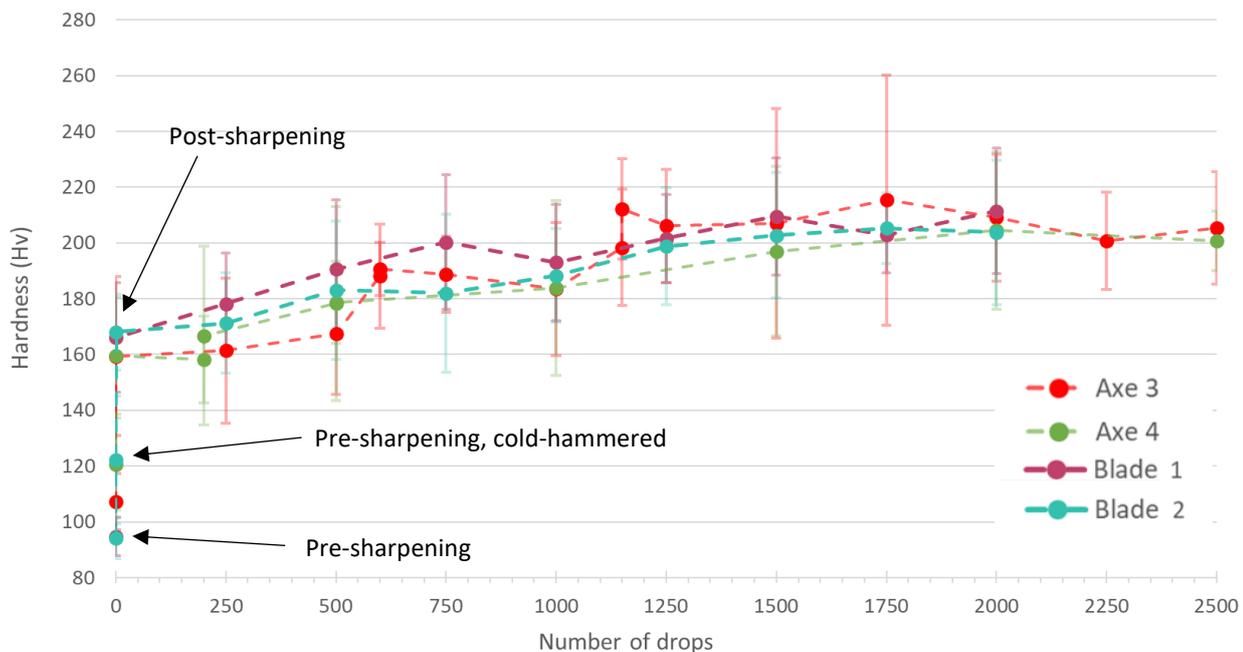


**Figure 74**: The graph presents the average hardness and associated standard deviations recorded across the blade tip of Axes 3 and 4, as well as Blades 1 and 2.

## 6.3   Form of the surface-level wear

The results presented above have demonstrated that incremental changes are occurring in the material properties of the surface of replica palstave axes during use. It was the aim of the SEM imaging to permit the visualisation of this ongoing surface wear at the microscopic level. The following text draws upon the SEM data to examine the reduction of the cutting-edge, the manifestation of wear mechanisms and the corresponding marks or deposits on the surface, as well as areas of cracking. A selection of the most interesting images captured using the SEM are presented here, but an additional number of supporting figures can be found in Appendix A. As illustrated in *Figure 75*, *Figure 76*, *Figure 78*, *Figure 81*, and *Figure 82*, the cutting-edge presented smooth irregularities prior to sharpening; these were most likely introduced due to the imprecise nature of the casting process. After sharpening, the cutting-edge is quite significantly reduced, and appears to be well levelled at lower levels of magnification. However, upon further magnification, the cutting-edge appears to be often prone to jagged areas, and, as a result, is altered towards a much rougher condition (*Figure 78*, *Figure 80*, and *Figure 82*). As expected from the area sustaining the most of the impact force, the cutting-edge presented clear transformations from an early stage of impact testing. Rapid deterioration, in the form of flattening of the cutting-edge, as well as the introduction of asperous cavities, was documented across both experimental specimens. As *Figure 76* and *Figure 77* demonstrate, the uneven appearance of the blade edge produced by sharpening was, in some places, very much reduced by 1000 impacts; the material was clearly deformed and flattened by repeated loading. In other areas substantial cavity formation at the very apex of the blade tip was exhibited. *Figure 80* highlights, for instance, a sunken area of material on the cutting-edge of Blade 1. Here, the hard exterior of the apex of the blade tip has given away, permitting the softer internal material to be deformed at a quicker rate.

The prevalence of adhesion on the surface of each blade is easily recognisable in the images mentioned above. Oak, as the softer material, has been removed from its original matrix and transplanted on the surface of both replicas. At the earlier sampling intervals, oak particles were most commonly seen trapped within small voids in the surface that were introduced during casting. However, by the 1750-2000 impact tests, tiny particles of oak had begun to stubbornly adhere to the surface, to the point where they frequently obscured the metal below (*Figure 78* and *Figure 79*). The cavities observed at the blade tip were also completely plastered with particles of oak by 2000 impact tests (*Figure 80*). While these particles do not directly indicate the degradation of the cutting-edge, when left on the metal surface for an extended period of time, they could induce corrosion at the surface that may lead to an accelerated decline in structural integrity.
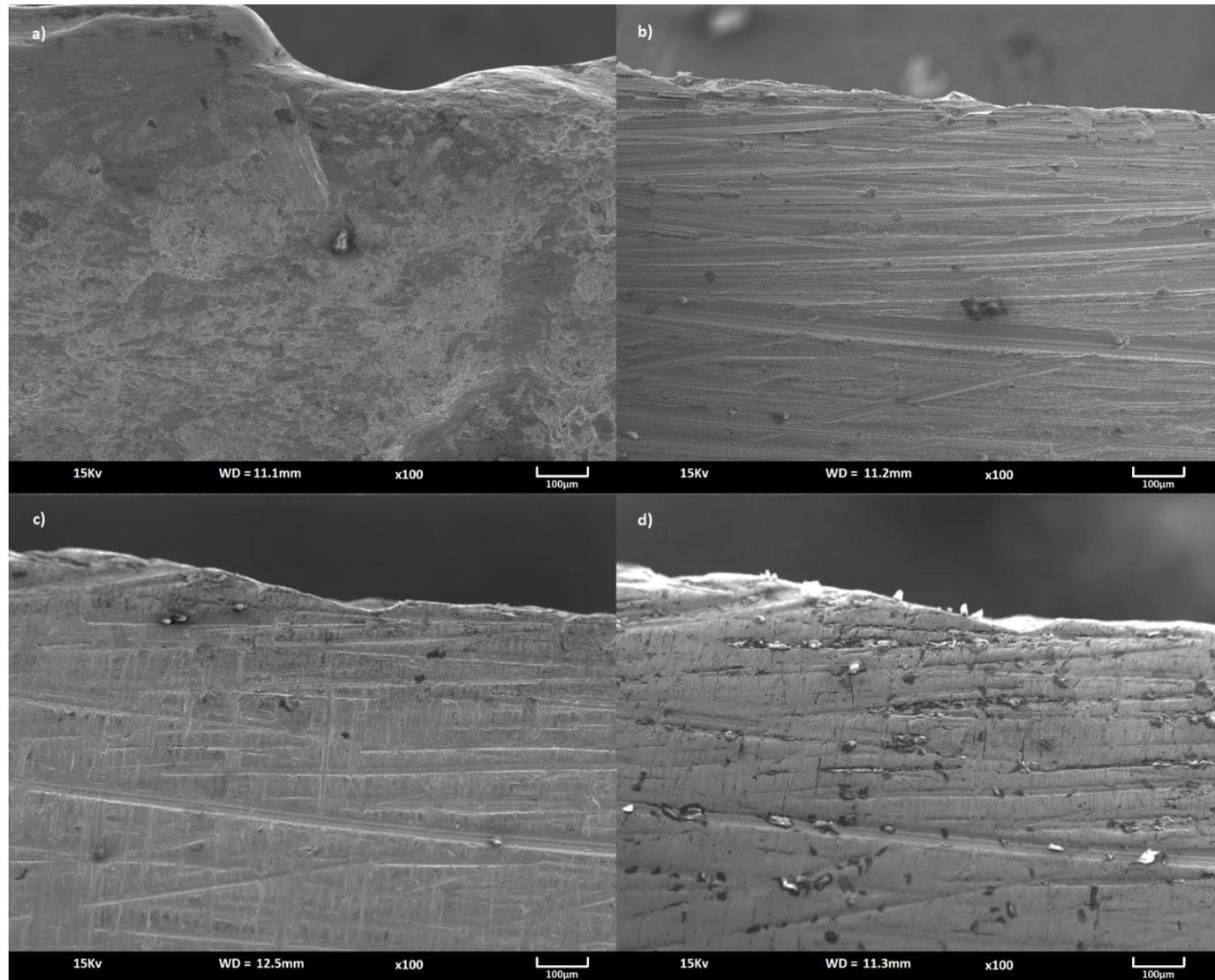
***Figure 75:*** Blade 2, SL 2, at x100 magnification: a) before sharpening; b) after sharpening; c) after 1500 impact tests; and, d) after 2000 impact tests (source: Author's own).
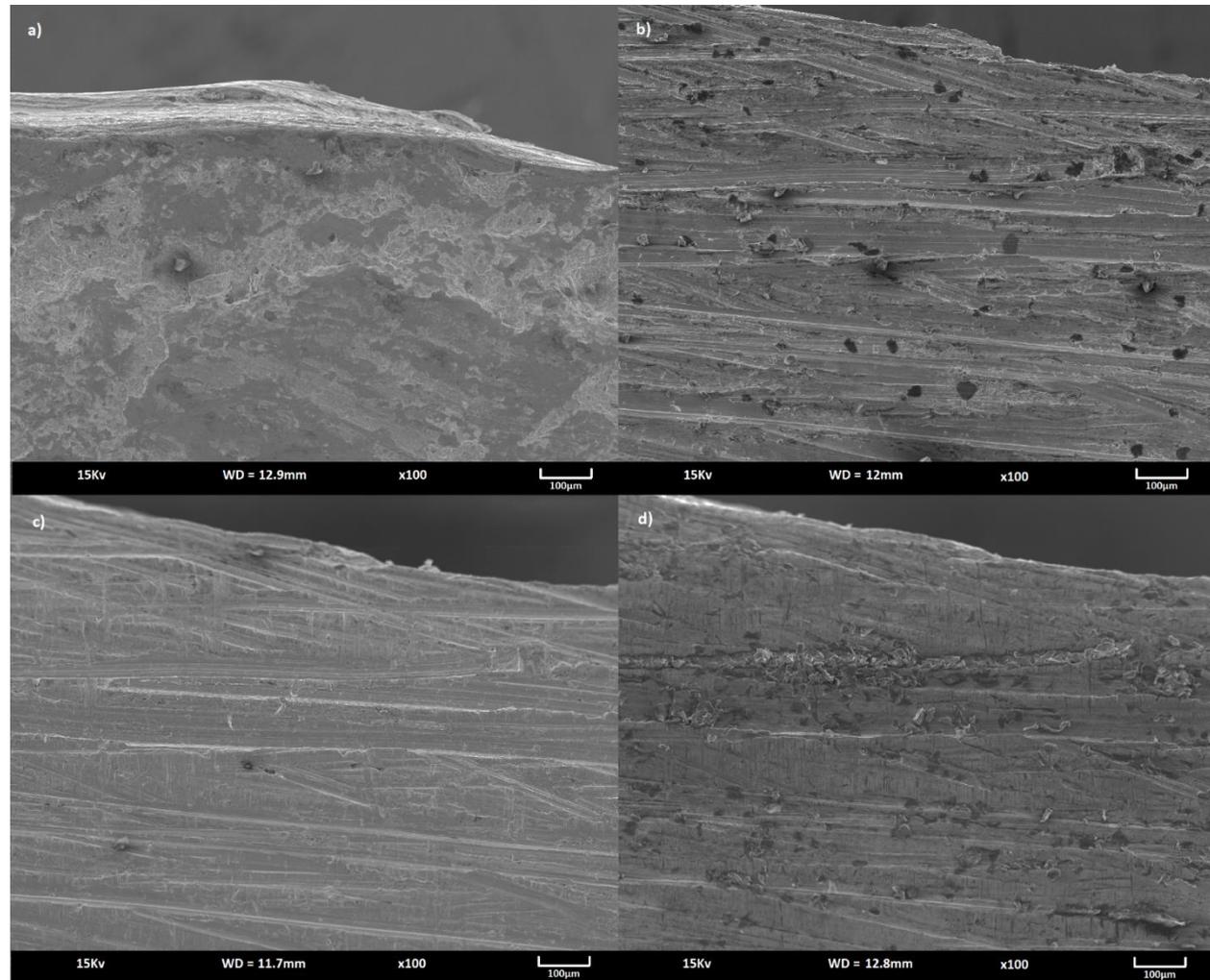
**Figure 76:** Blade 1, SL 2, at x100 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests (source: Author's own).
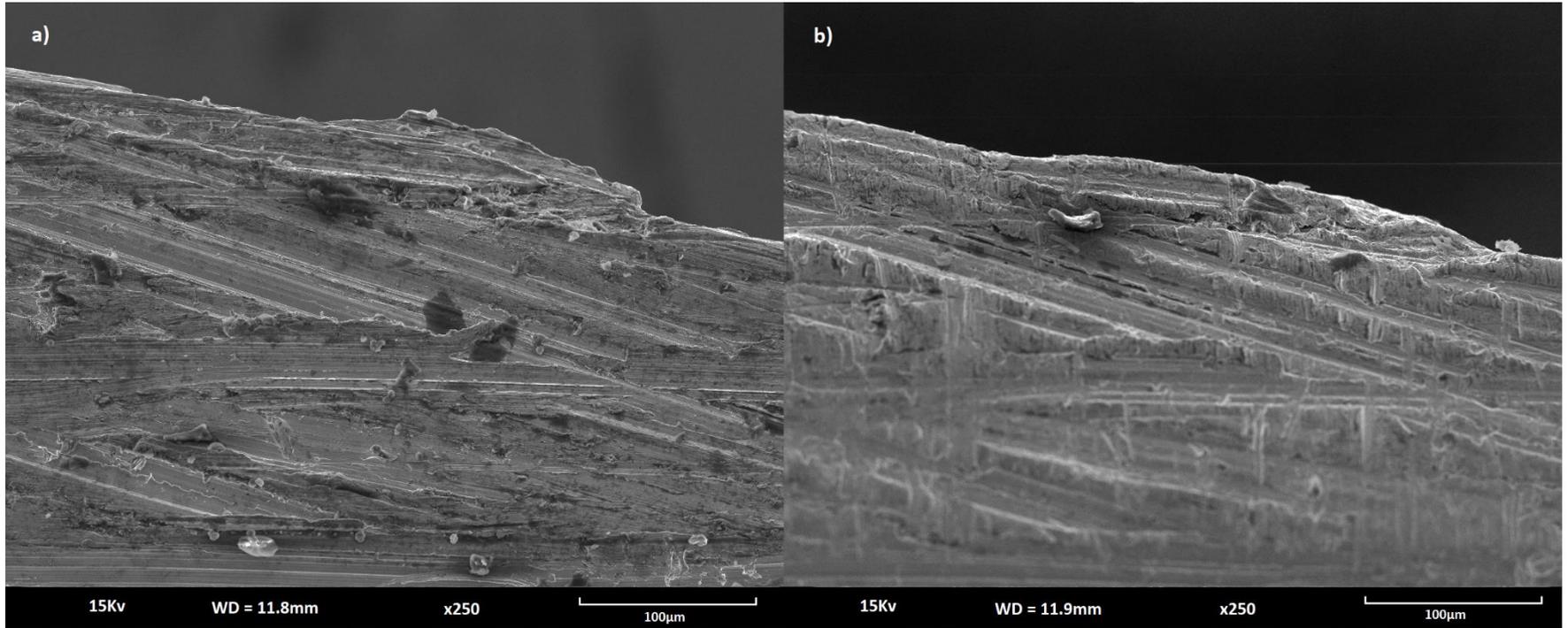
*Figure 77:* Blade 1 SL 2, x250 magnification: a) after sharpening; and, b) after 1000 impact tests (source: Author's own).
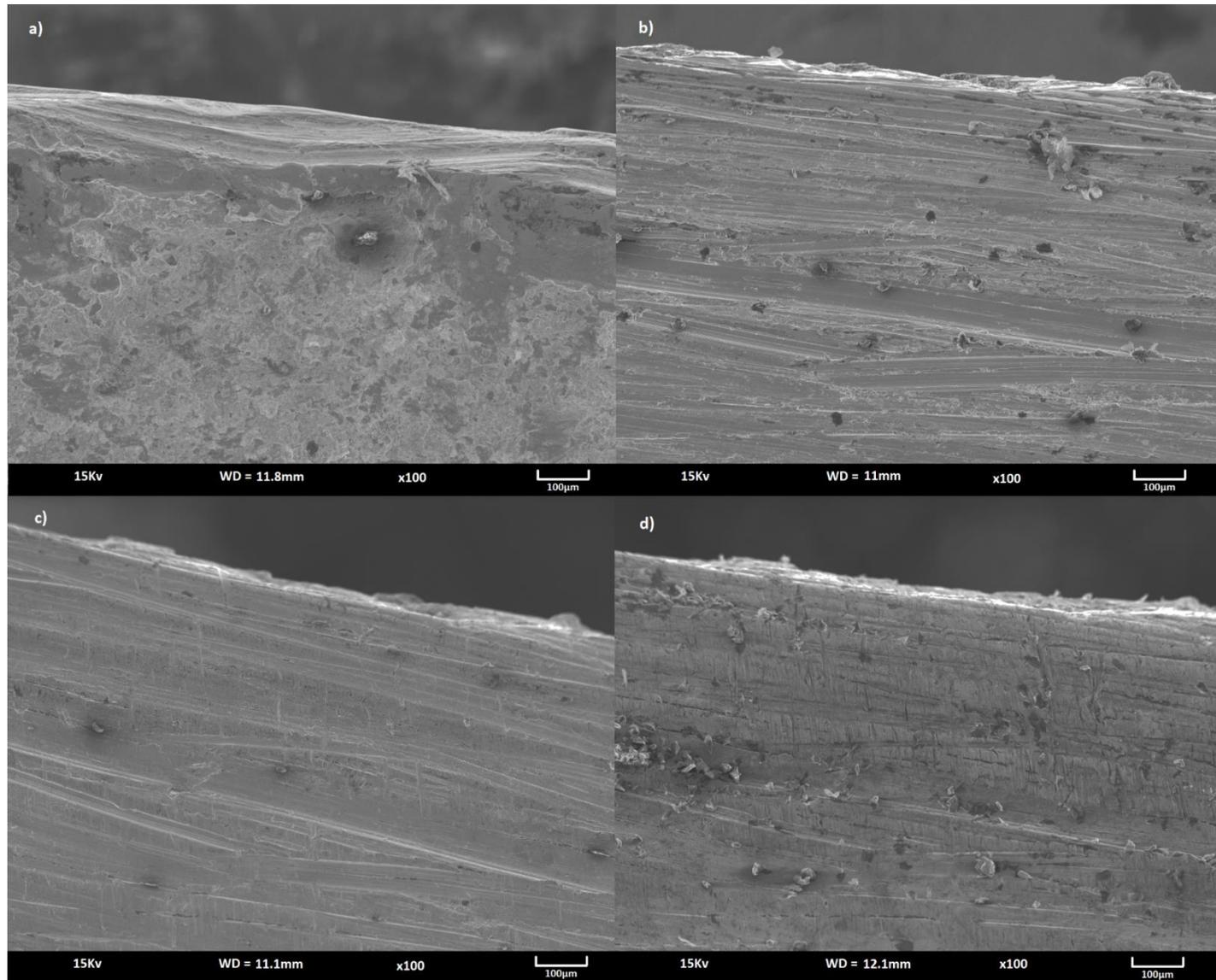
***Figure 78:*** Blade 1, SL 3, at x100 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests (source: Author's own).
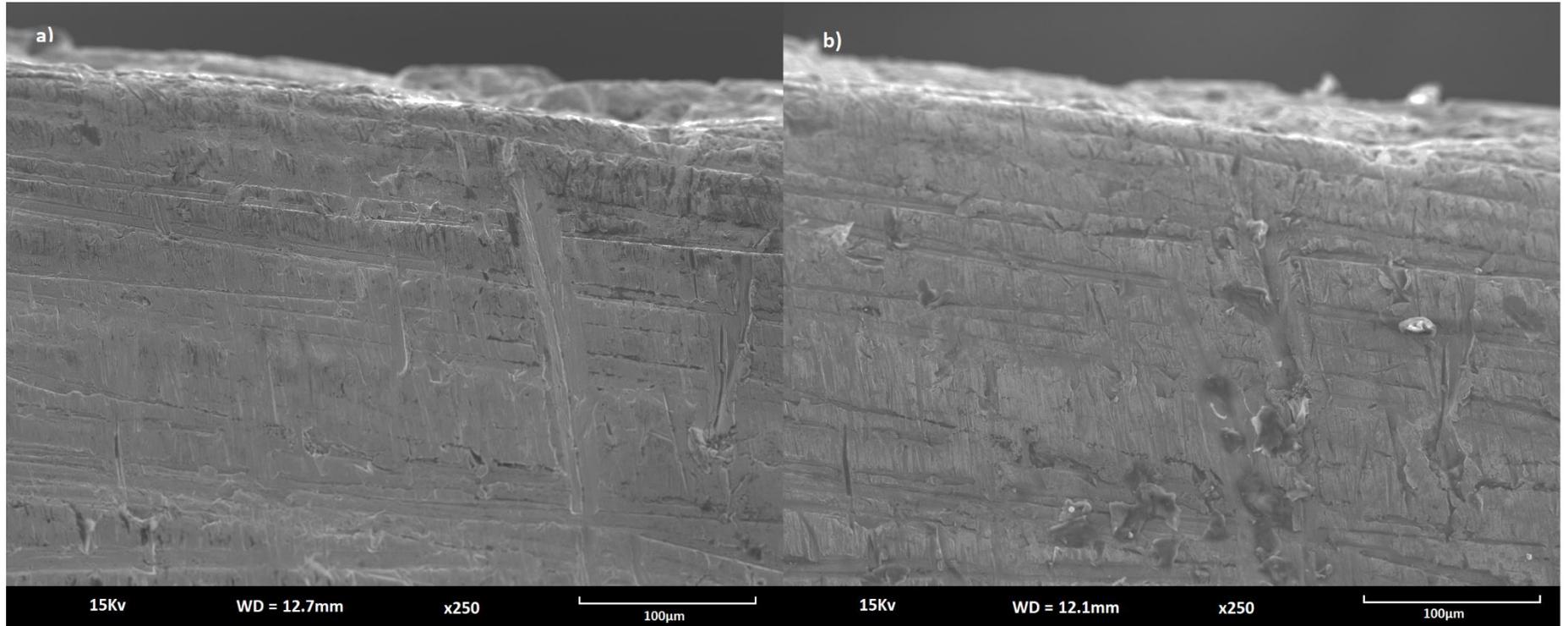
*Figure 79:* Blade 1, SL 3, x250 magnification: a) after 1750 impacts; and, b) after 2000 impacts (source: Author's own).
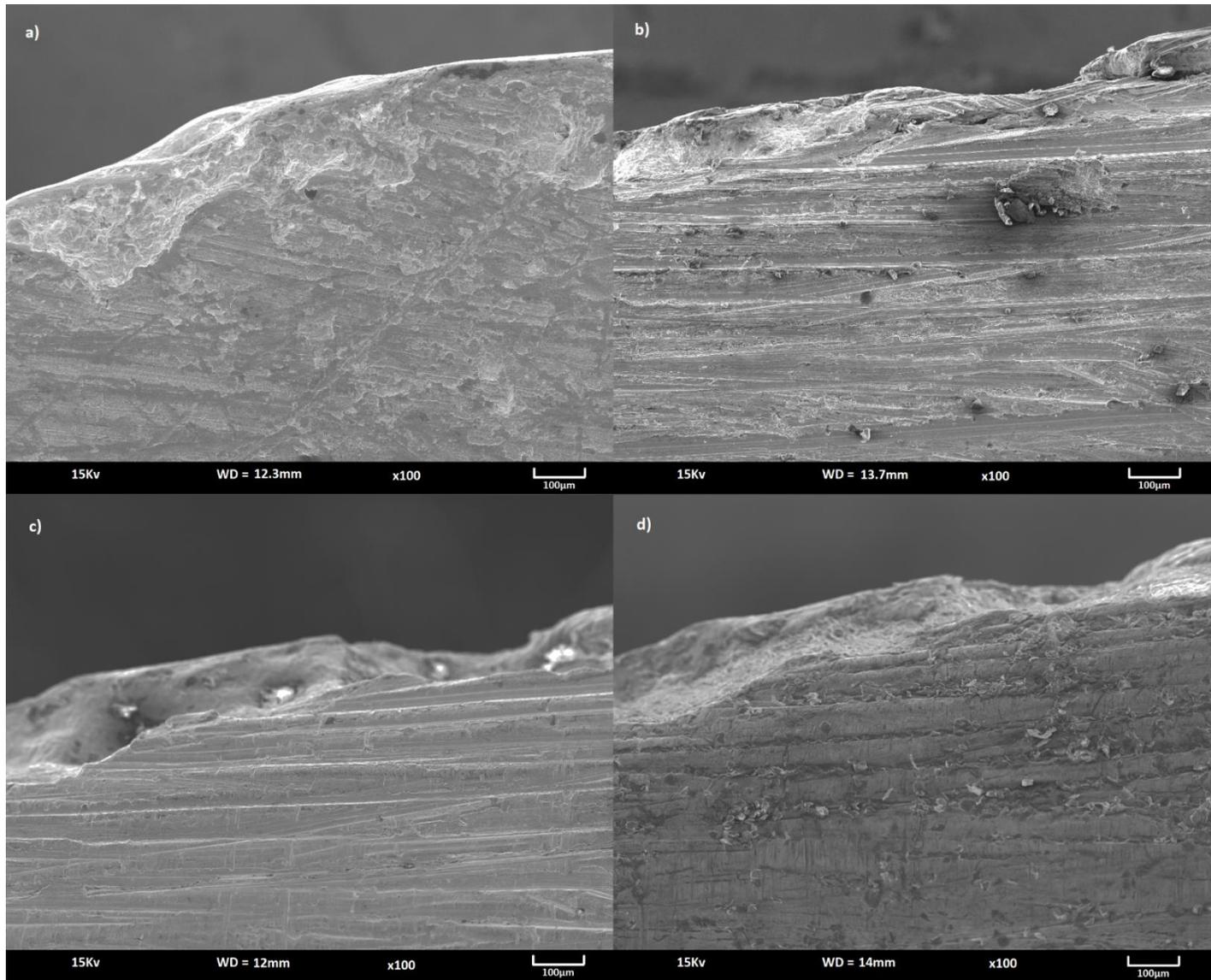
*Figure 80:* Blade 1, SL 1, at x100 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests  (source: Author's own).

While evidence of adhesion is present on both experimental samples, it is clear that abrasive action generates most of the deleterious changes observable at the surface of the metal. At all magnifications, it is evident that sharpening has erased the mottled surface produced by casting and has generated clear horizontal striations parallel to the cutting-edge. At x100 magnification, use-striations perpendicular to the blade edge were already noticeable by the first analytical interval at 250 impacts; these become increasingly prevalent throughout the subsequent impact tests (*Figure 81* and *Figure 82*). At x500 magnification, the local impact of these use-striations can be observed, and there is considerable displacement of material by abrasive action (*Figure 83*). *Figure 84* indicates that the striations left by sharpening have a significant part to play in the subsequent wear of the material. The elevated areas of material produced by sharpening are progressively deformed by use-striations into 'lips' that extend over the large grooves also generated by sharpening (*Figure 84*). If the area is formed of a ductile region of metal, the lips may be flattened and reformed progressively over cyclic loading or, if they are brittle areas, they become continually fatigued until they break off. As such, at x1000 magnification, sharpening striations are shown to exhibit an extremely reduced prominence (*Figure 85*) as the axe is impacted.

The emergence of micro-cracking at the surface of the material was also documented in places. *Figure 86*, for instance, illustrates the development of pitting as a result of micro-cracking. Evidence of cracking at the material surface of the Blades was variably found. A major area of cracking was identified at Blade 2 early on in the testing (*Figure 87*). However, it is probable that the crack opened up during manufacture (when the hammer-hardening was applied), but instead of growing larger, the crack seems to have been forced back together through repeated impacts.
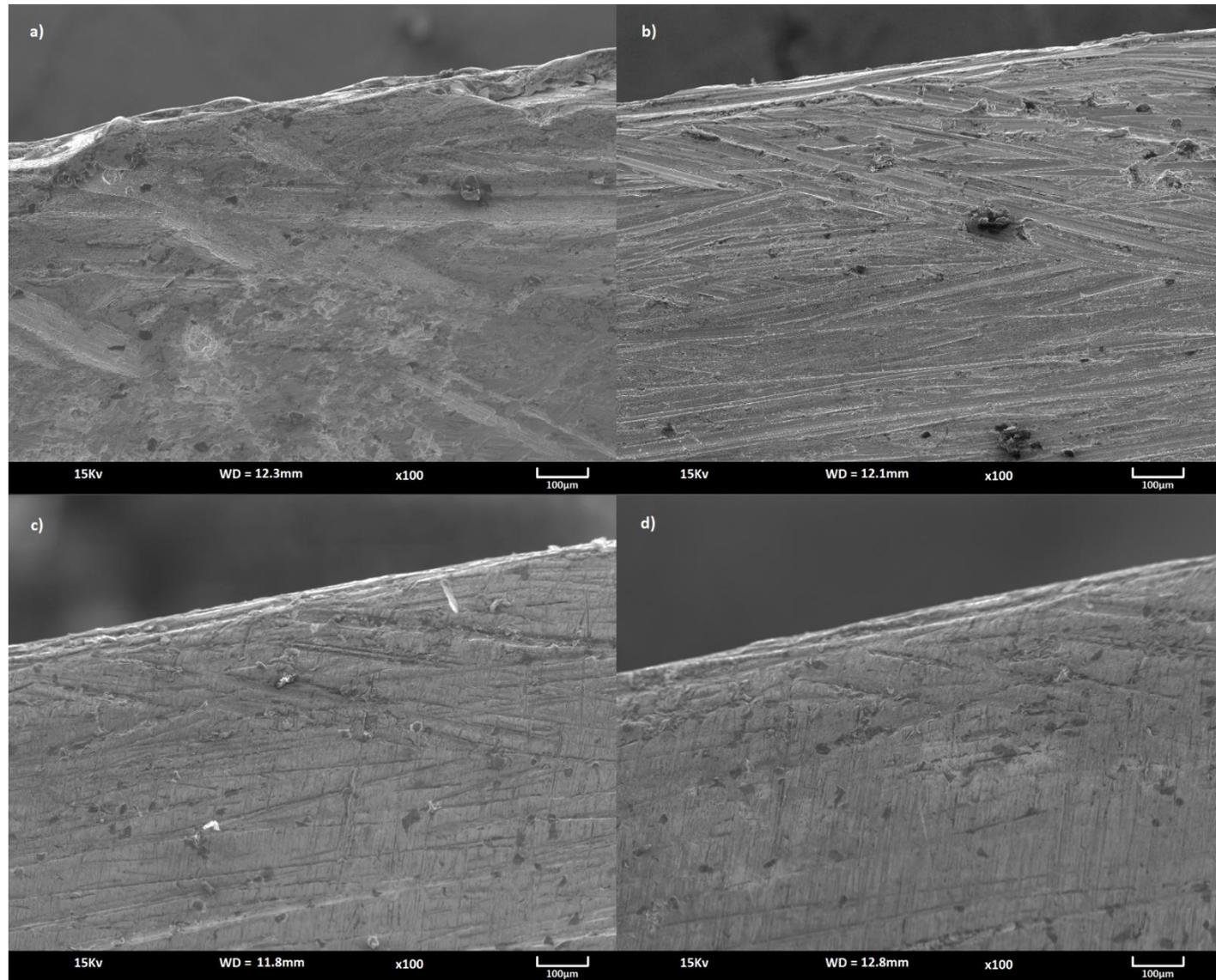
***Figure 81:*** Blade 2, SL 1, at x100 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests (source: Author's own).
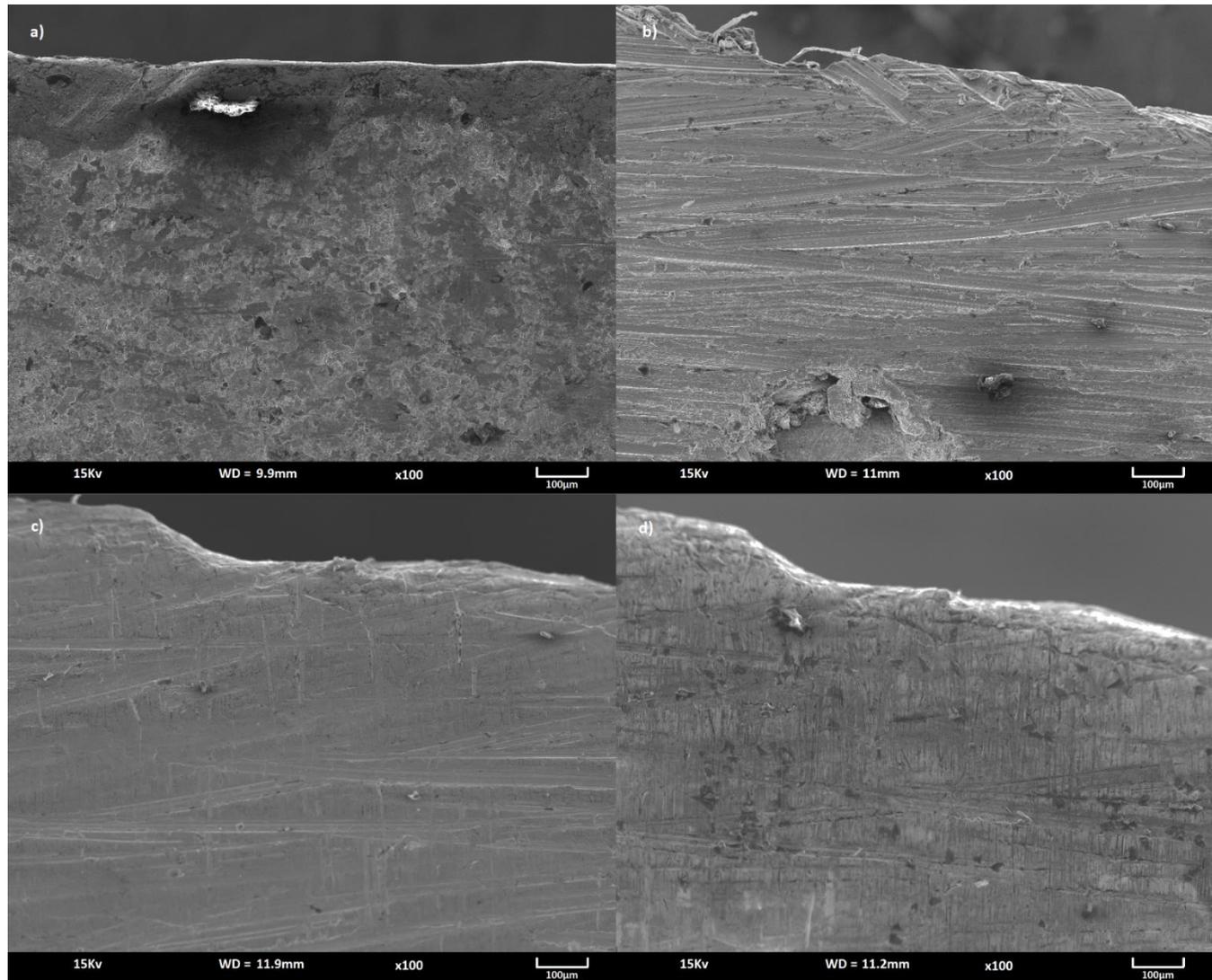
*Figure 82:* Blade 2, SL 3, at x100 magnification: a) before sharpening; b) after sharpening; c) after 750 impact tests; and, d) after 2000 impact tests (source: Author's own).

15Kv          WD = 13mm          x500          10μm
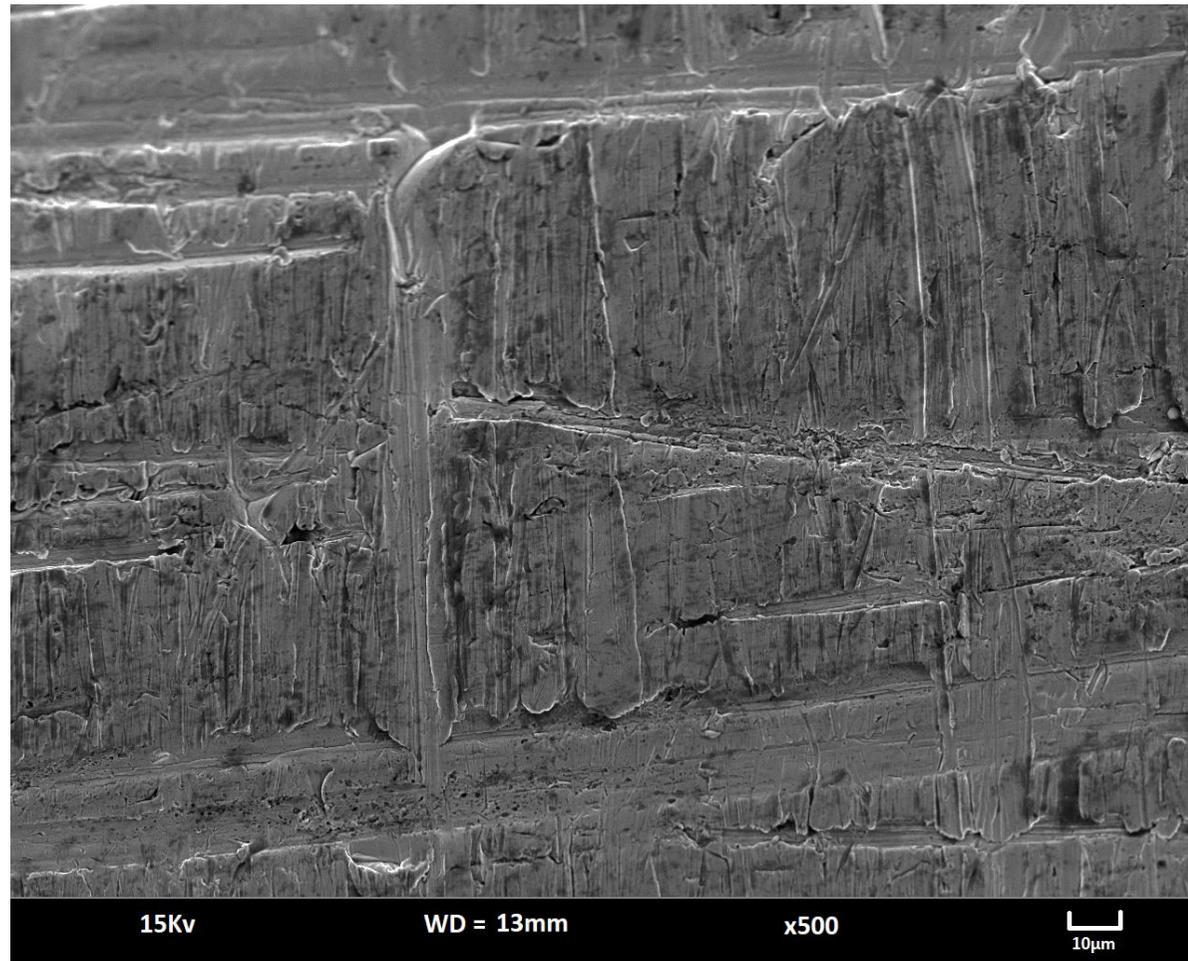
*Figure 83:* Blade 1, SL 1, x500 magnification, after 1750 impacts (source: Author's own).
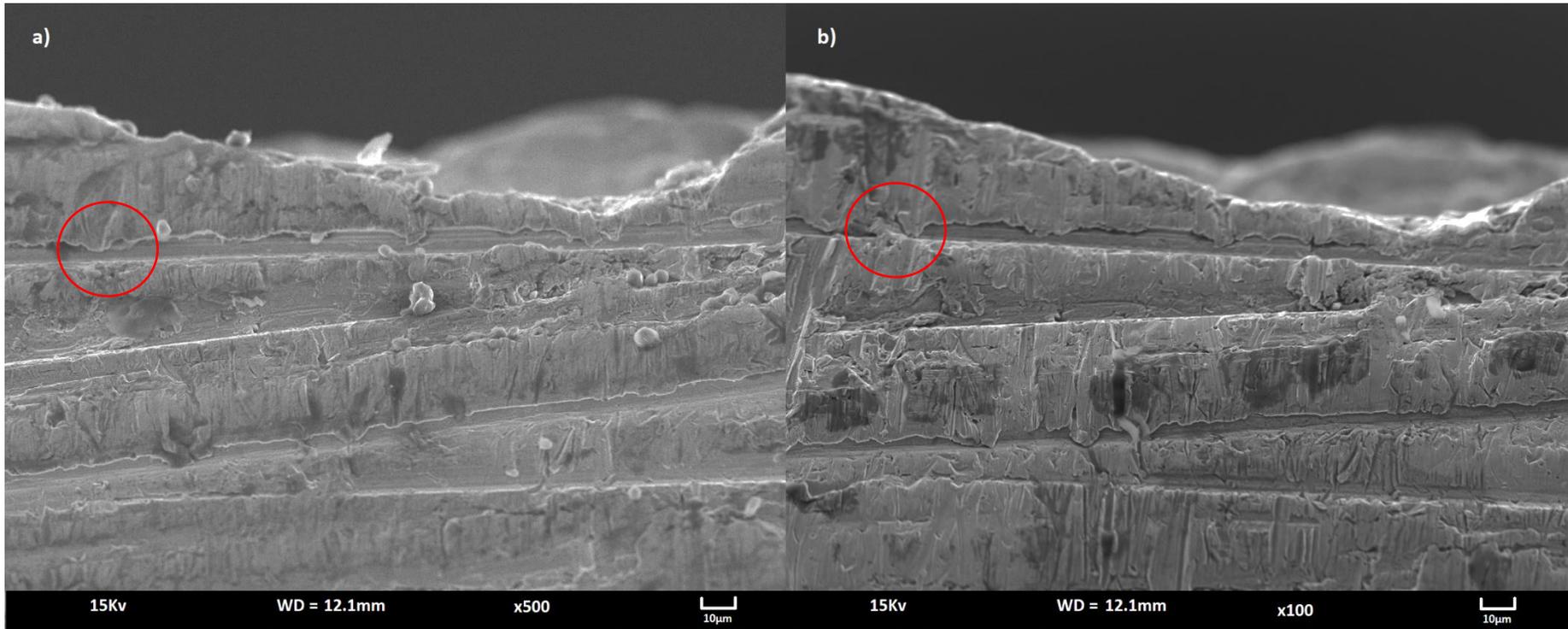
*Figure 84:* Blade 2, SL 2, x500 magnification: a) after 750 impacts; and, b) after 1750 impacts  (source: Author's own).
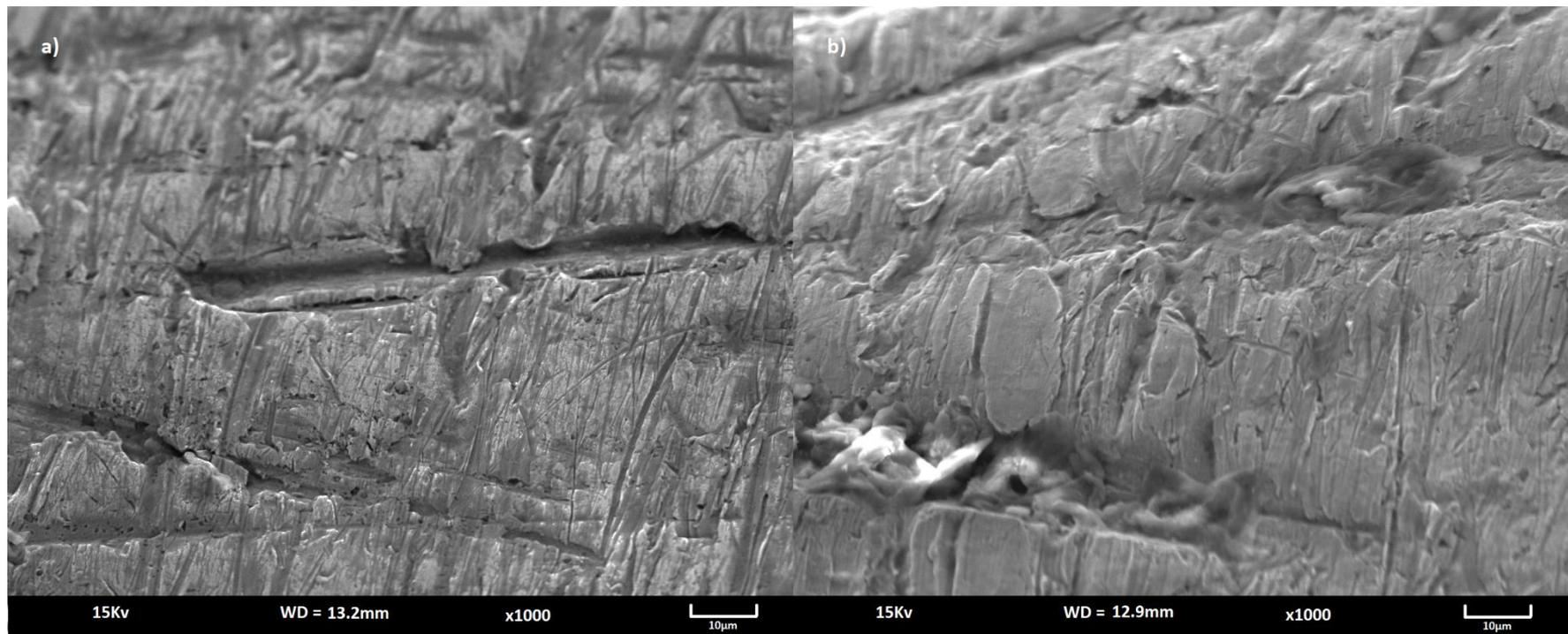
*Figure 85:* Blade 2, SL 1, x1000 magnification: a) after 1000 impact tests; and, b) after 2000 impact tests (source: Author's own).
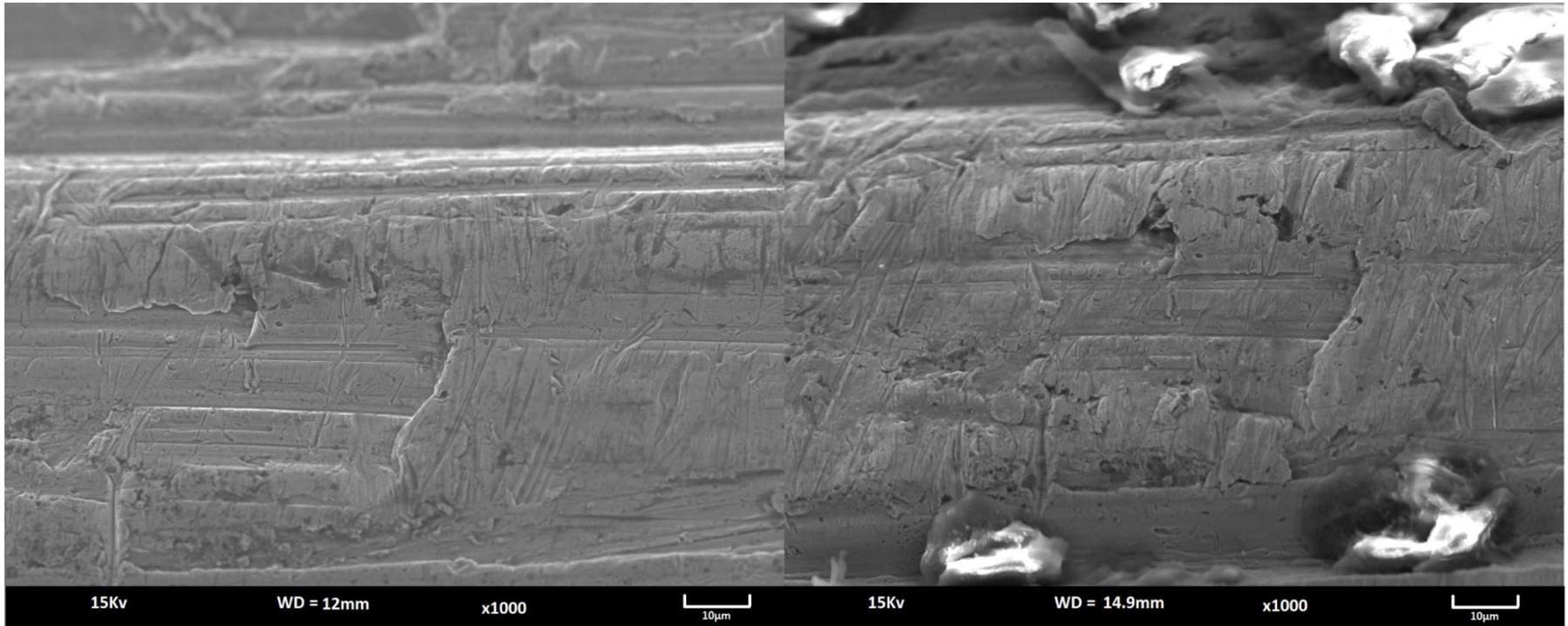
*Figure 86:* Blade 1, SL 1, x1000 magnification: a) after 1000 impact tests; and, b) after 1500 impact tests (source: Author's own).
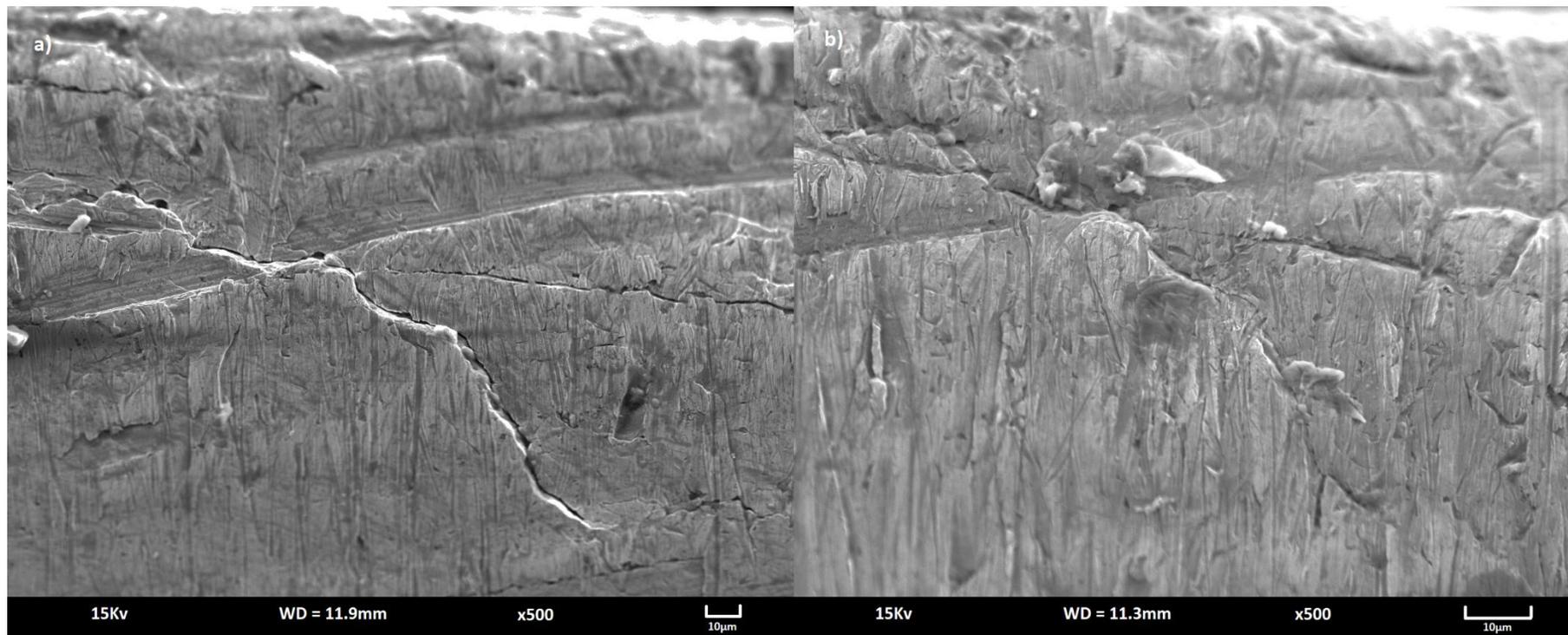
*Figure 87:* Blade 2, SL 3, x500 magnification: a) after 750 impact tests; and, b) after 2000 impacts tests (source: Author's own).

## 6.4   Development of the surface-level wear

The observed rate of progression of abrasive striations at low-power magnifications was documented due to the direct relevance for the microscopic investigation of ancient palstave axes. A selection of the most interesting images captured using digital microscopy are presented here, but an additional number of supporting figures can be found in Appendix A. Interestingly, a slightly differing rate was observed across replica axes with varying composition and post-production processing. On consideration of the relationship between mechanical properties and resistance to abrasion, which was discussed in section 4.2, this is not overly surprising. To recap, it is likely that materials with a greater hardness and yield strength are less susceptible to abrasive wear – this is something that has never really been considered before when assessing the development of striations on archaeological metals. Another factor that is very important for the progression of wear severity is the interaction between the abrasive marks and sharpening events, which often act to erase visible wear. The following text will review the results for each type of microstructure separately discussing how the rate of development is influenced by both underlying properties and frequency of maintenance intervention. This data is thereafter summarised into a referential scheme that may be used to estimate the use-intensity from the severity of wear observed on prehistoric palstave axes.

Looking first at the 10% tin-bronze as-cast experimental specimen (Blade 4) – at x50 magnification, use-striations were already clearly distinguishable at the cutting-edge by 250 impact tests. At x25 magnification, the first sign of abrasive wear became apparent at 500 impact tests. The visible reduction of deep sharpening marks (which are an easy feature to trace due to their dark appearance) occurred very rapidly, and there was a considerable loss of definition at both levels of magnification after 1000 impact tests (*Figure 88*, *Figure 89*, and *Figure 90*). Although the surface became 'severely worn' quickly, for example, demonstrating a high density of use-striations that essentially removed evidence of prior sharpening, axes with this microstructure are more likely to experience failure (this is be discussed in more detail in section 6.5) and so were resharpened more regularly. This, of course, meant the removal of use-striations as seen in *Figure 90*, when Blade 4 was sharpened after 1050 impact tests. Hence, the cycle of wear severity, and associated use-intensity, could be said to be relatively short in duration but presenting fast degradation of the cutting-edge.
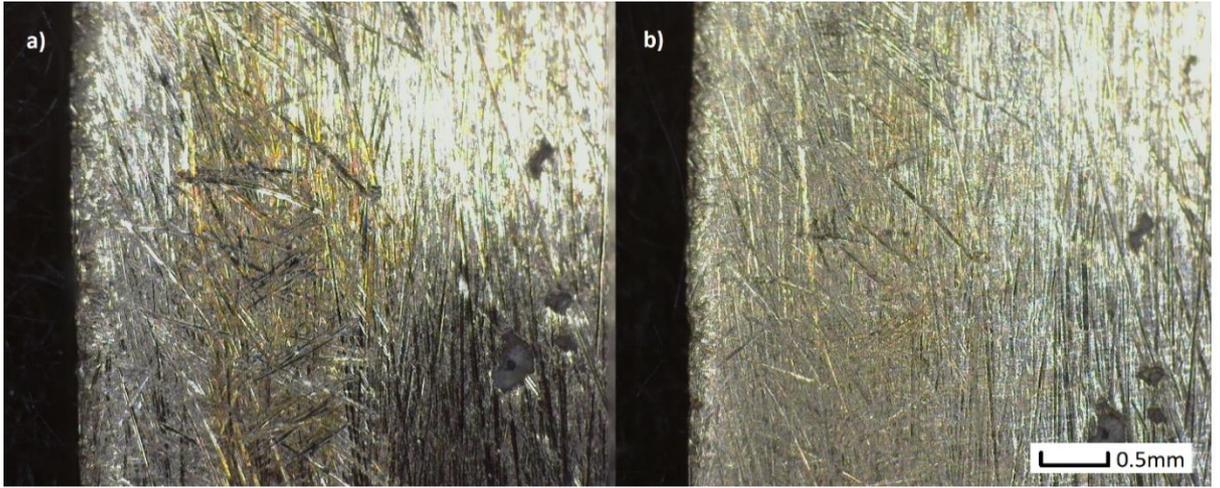
***Figure 88:*** Digital microscope images of Blade 4, SL 3, at x50 magnification, where: a) post-sharpening at 58 impacts; b) 1000 impacts (source: Author's own).
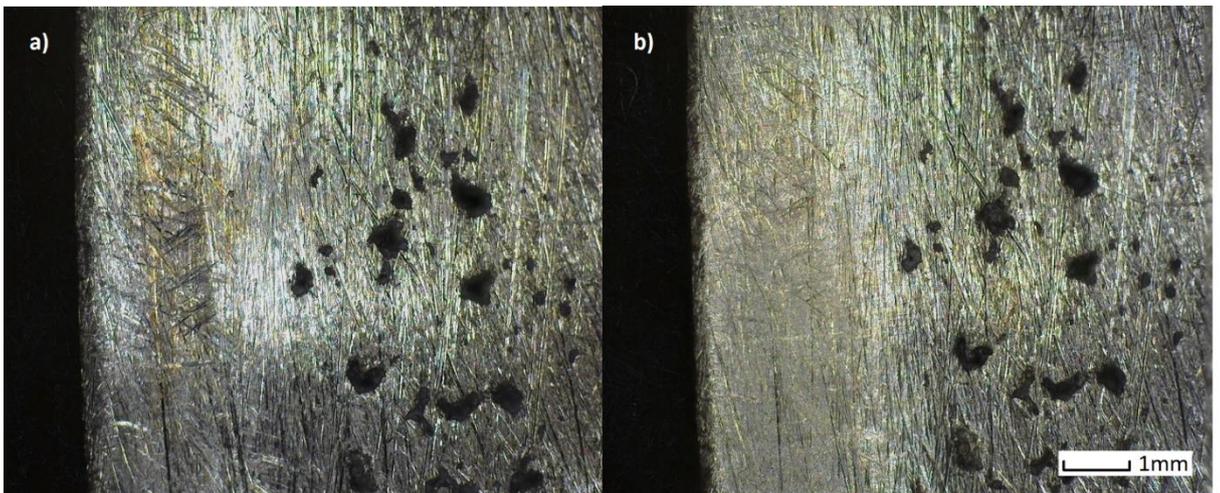


***Figure 89:*** Digital microscope images of Blade 4, SL 3, at x25 magnification, where: a) post-sharpening at 58 impacts; b) 1000 impacts (source: Author's own).
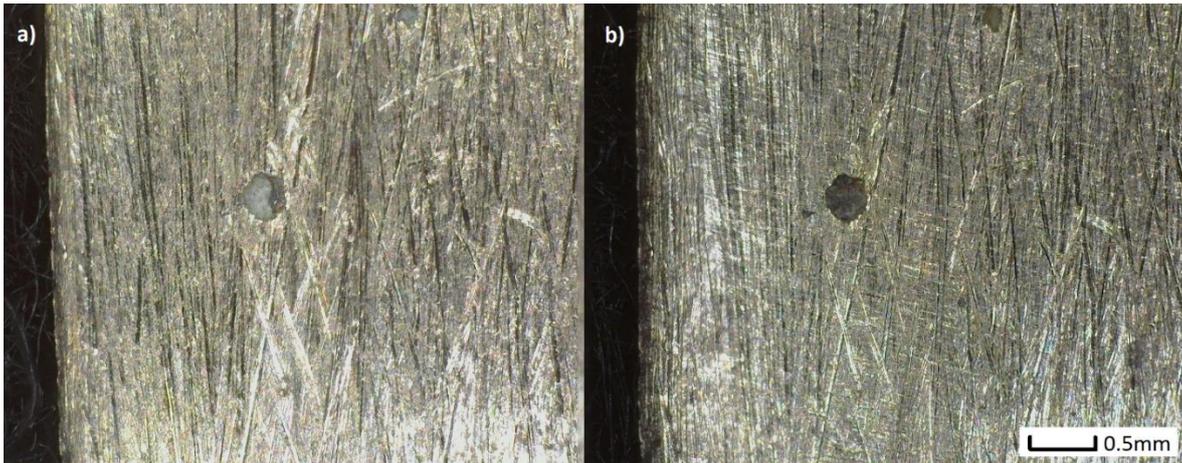
*Figure 90:* Digital microscope images of Blade 4, SL 1, at x50 magnification, where: a) post-sharpening at 1050 impacts; b) 2000 impacts (source: Author's own).

Similar to the results documented on the cutting-edge of Blades 1 and 2 with the SEM, the 10% tin-bronze experimental specimen that had been subjected to the anneal-hammer-anneal processing (Blade 3) already demonstrated a smattering of use-striations at the cutting-edge by 250 impact tests. The rate at which these manifested across the blade in subsequent testing was slower than observed for Blade 4. For example, at x50 magnification (see *Figure 91*, *Figure 92*, and *Figure 93*) the impact of wear on the surface of the cutting-edge by 1000 impact tests appears to be somewhat less and the darker troughs left by sharpening are still prominent. Furthermore, use-striations are barely even visible at 1000 impact tests at x25 magnification (*Figure 94* and *Figure 95*). Since hardness testing has already indicated that the increase in surface hardness (and therefore the amount of deformation occurring) between an as-cast 10% tin-bronze and a partially recrystallized 10% tin-bronze is very similar, the delayed progression of wear severity on Blade 3 is slightly unexpected. However, the sliding contact produced when the blade cuts through the opposition material may have meant that stress was mainly distributed along the recrystallized areas at the surface of the material (recruiting enhanced strength through a greater thickness of small crystals). Rather, the compressional load introduced by the microhardness indenter would have been directed inwards where only a small layer of crystals was present before the microstructure became dendritic. Or, perhaps, the hardness of the as-cast 10% tin-bronzes really was over-estimated, as already posited. Blade 3 was not subjected to any further sharpening events after the initial sharpening, the reasons for which are discussed in section 6.5. As a result, the progression of surface wear was documented over 3000 impact tests. As the images pertaining to Blade 3 suggests, the surface at the cutting-edge only became more overtly worn between 2000 and 3000 impact

tests. Once again reinforcing the much more gradual accumulation of use-striations on this replica with a partially recrystallized microstructure.



***Figure 91:*** Digital microscope images of Blade 3, SL 1, at x50 magnification, where: a) post-sharpening; b) 1000 impacts; c) 2000 impacts; d) 3000 impacts (source: Author's own).
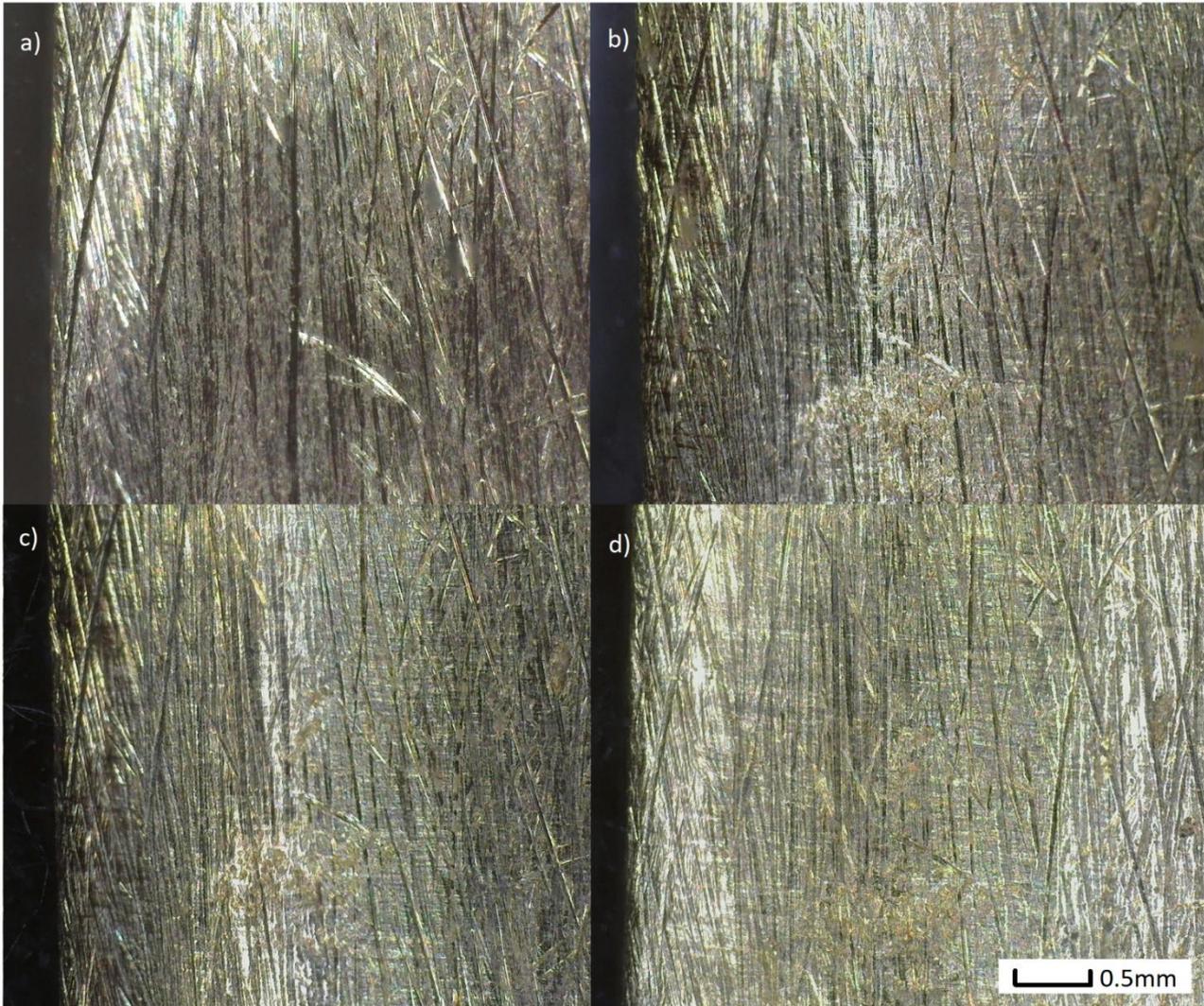
**Figure 92**: Digital microscope images of Bladelet 3, SL 2, at x50 magnification, where: a) post-sharpening; b) 1000 impacts; c) 2000 impacts; d) 3000 impacts (source: Author's own).
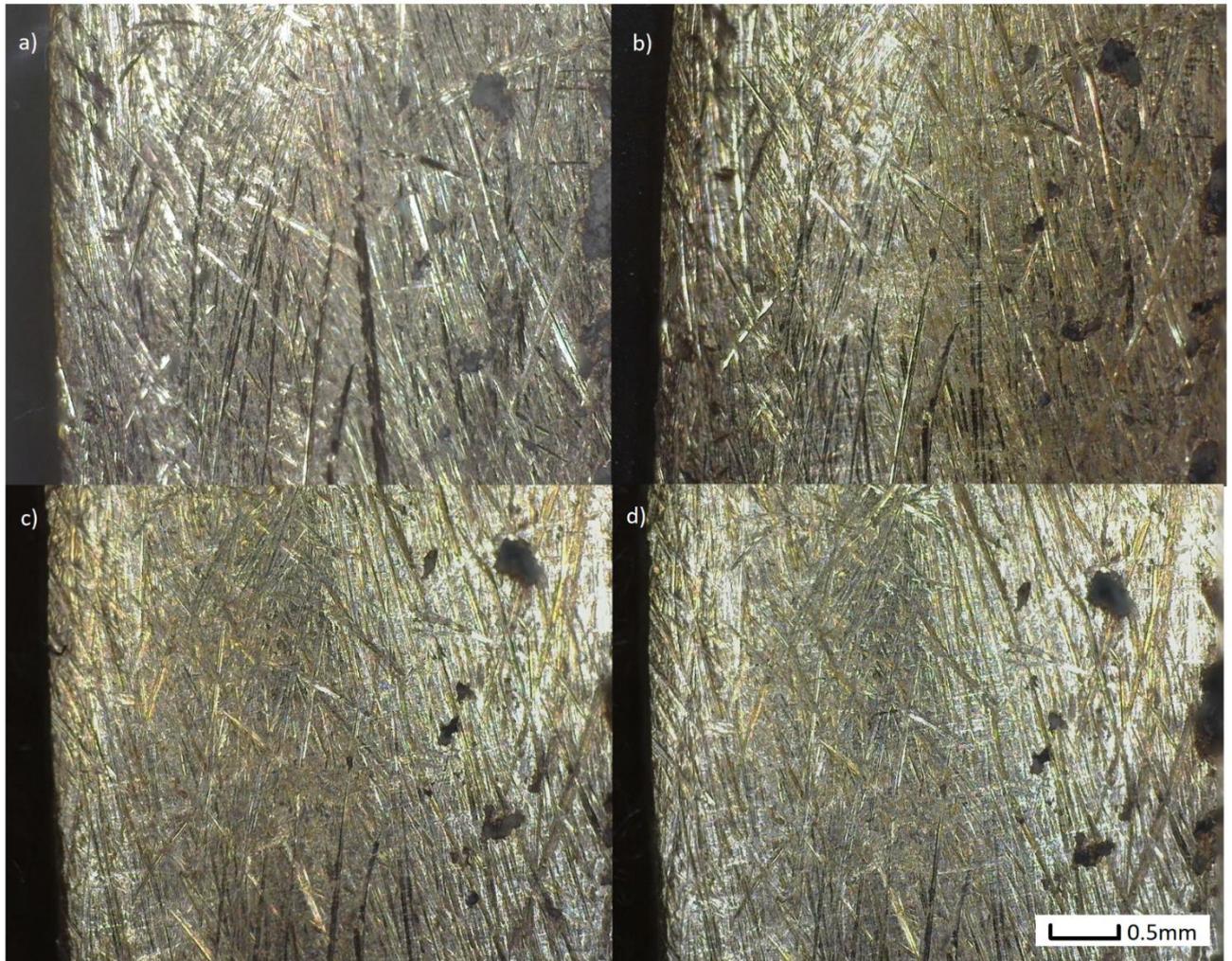
*Figure 93:* Digital microscope images of Bladelet 3, SL 3, at x50 magnification, where: a) post-sharpening; b) 1000 impacts; c) 2000 impacts; d) 3000 impacts (source: Author's own).
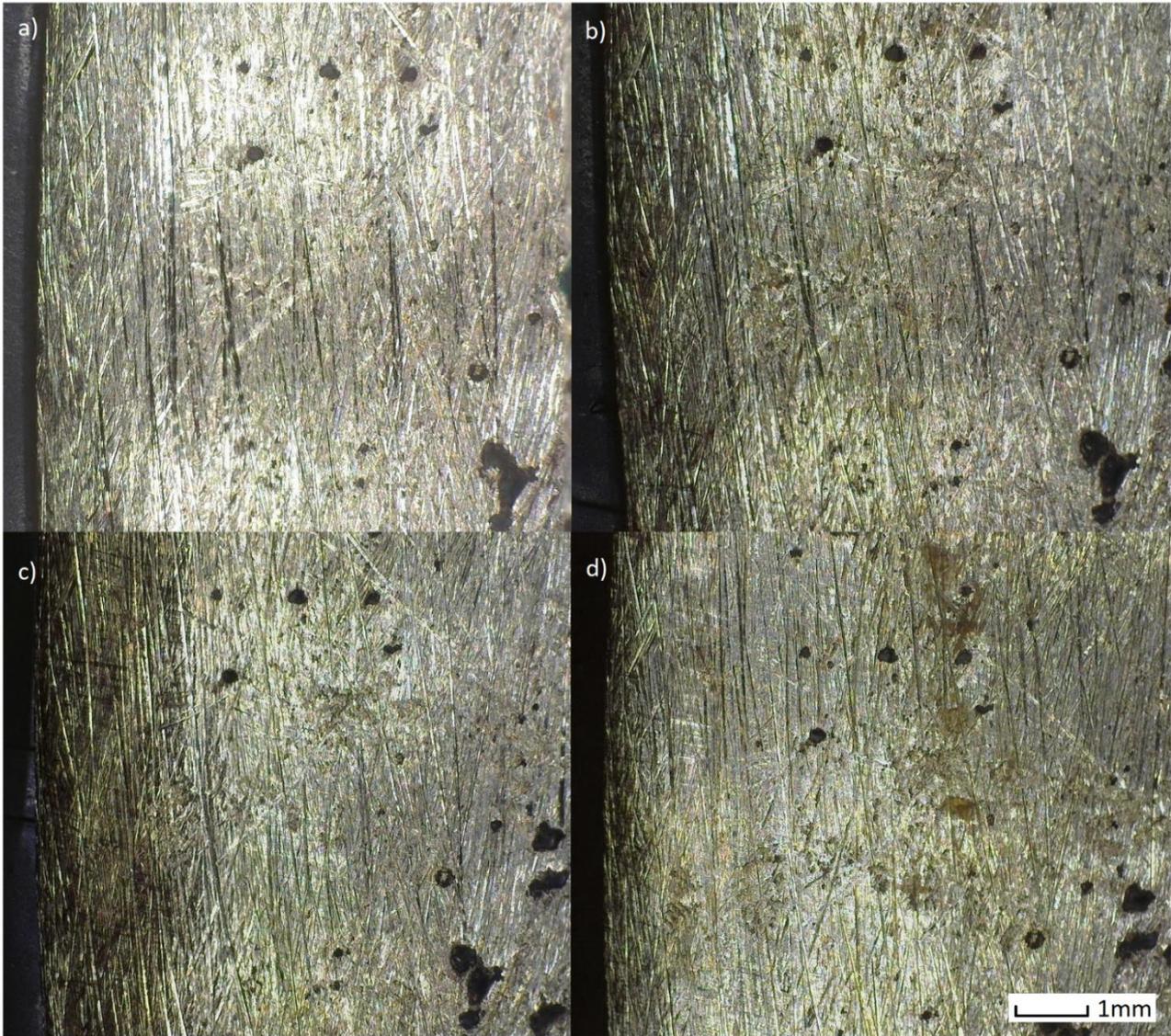
**Figure 94:** Digital microscope images of Blade 3, SL 1, at x25 magnification, where: a) post-sharpening; b) 1000 impacts; c) 2000 impacts; d) 3000 impacts (source: Author's own).
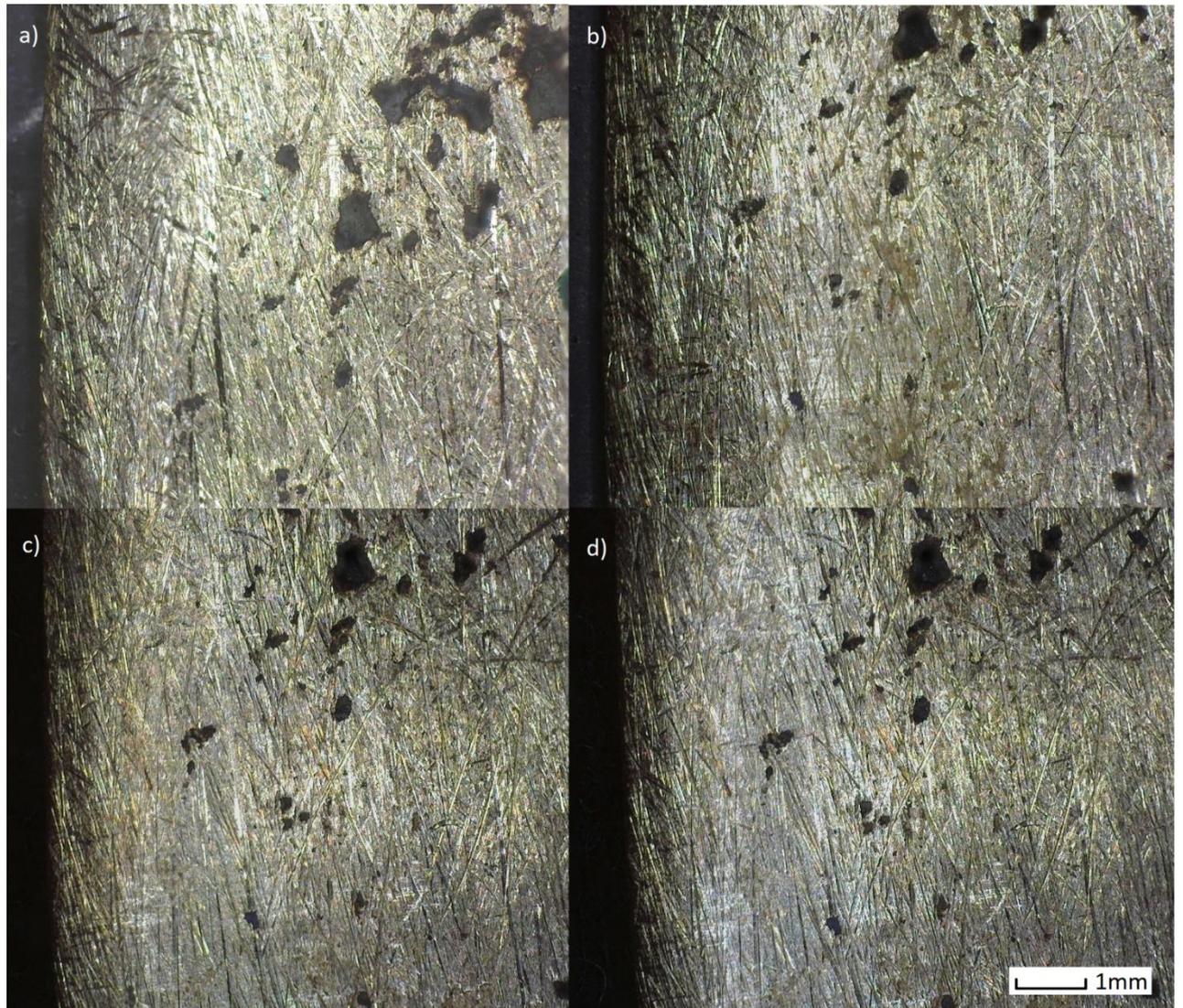
***Figure 95:*** Digital microscope images of Blade 3, SL 3, at x25 magnification, where: a) post-sharpening; b) 1000 impacts; c) 2000 impacts; d) 3000 impacts (source: Author's own).

The two 14% tin-bronze experimental specimens with partially recrystallized microstructures (Blades 5 and 6) demonstrate the least amount of change to the surface of the cutting-edge throughout testing. Very few use-striations were visible at x50 magnification after 500 impact tests, with only a minor covering at 1000 tests. The microstructure of these replicas would have had a higher baseline hardness and, therefore, is more resistant to abrasion from the start of testing and, of course, the surface would have also benefitted from grain boundary strengthening like Blade 3. *Figure 96* and *Figure 97* indicate that very few use-striations developed in the early stages of testing. It is also clear that there is little difference in the accumulation of surface wear between the replica that had been subjected to a final cold-hammering (Blade 6) and not cold-hammered (Blade 5), but this is not surprising. As section 6.2 illustrated, the surface hardness is actually quite similar

between samples with cold-hammering and those without, suggesting a similar rate of surface deformation. Experimental replicas with 14% tin-bronze were liable to further sharpening events in the early stages of testing due to existing casting flaws and embrittlement (more on this in section 6.5 below); after failing at 1000 tests, Blade 6 was subjected to a further 2500 impact tests without any sharpening intervals. As *Figure 98* and Figure 99 suggest, the impact of abrasive wear was substantially less on this replica after 2000 impact tests post-sharpening (3000 total impacts tests) than documented on those discussed above. In fact, most sharpening striations are still clear by 3500 impact tests. An exact timeline of the progression of use-striations on replica palstave axes at x50 magnification with each of the types of microstructure discussed throughout this section is presented in *Table 13* below.
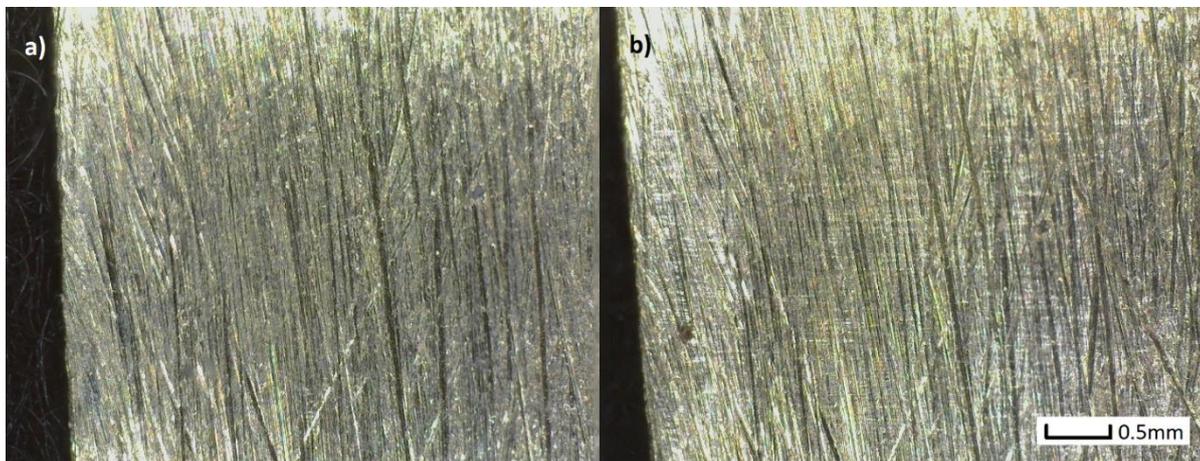


**Figure 96:** Digital microscope images of Blade 5, SL 2, at x50 magnification, where: a) post-sharpening at 50 impacts; b) 695 impacts (source: Author's own).
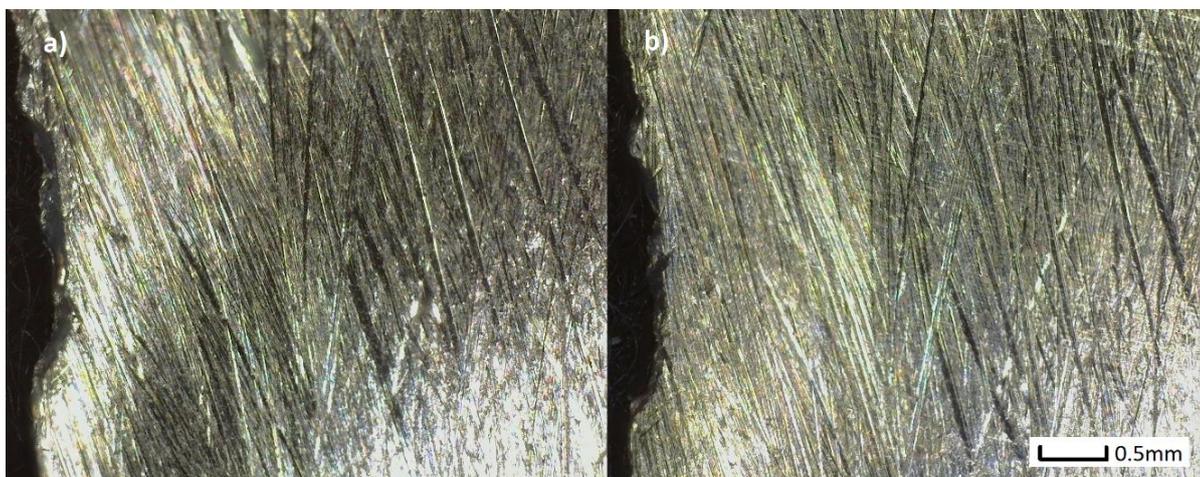


**Figure 97:** Digital microscope images of Blade 6, SL 1, at x50 magnification, where: a) post-sharpening; b) 1000 impacts (source: Author's own).
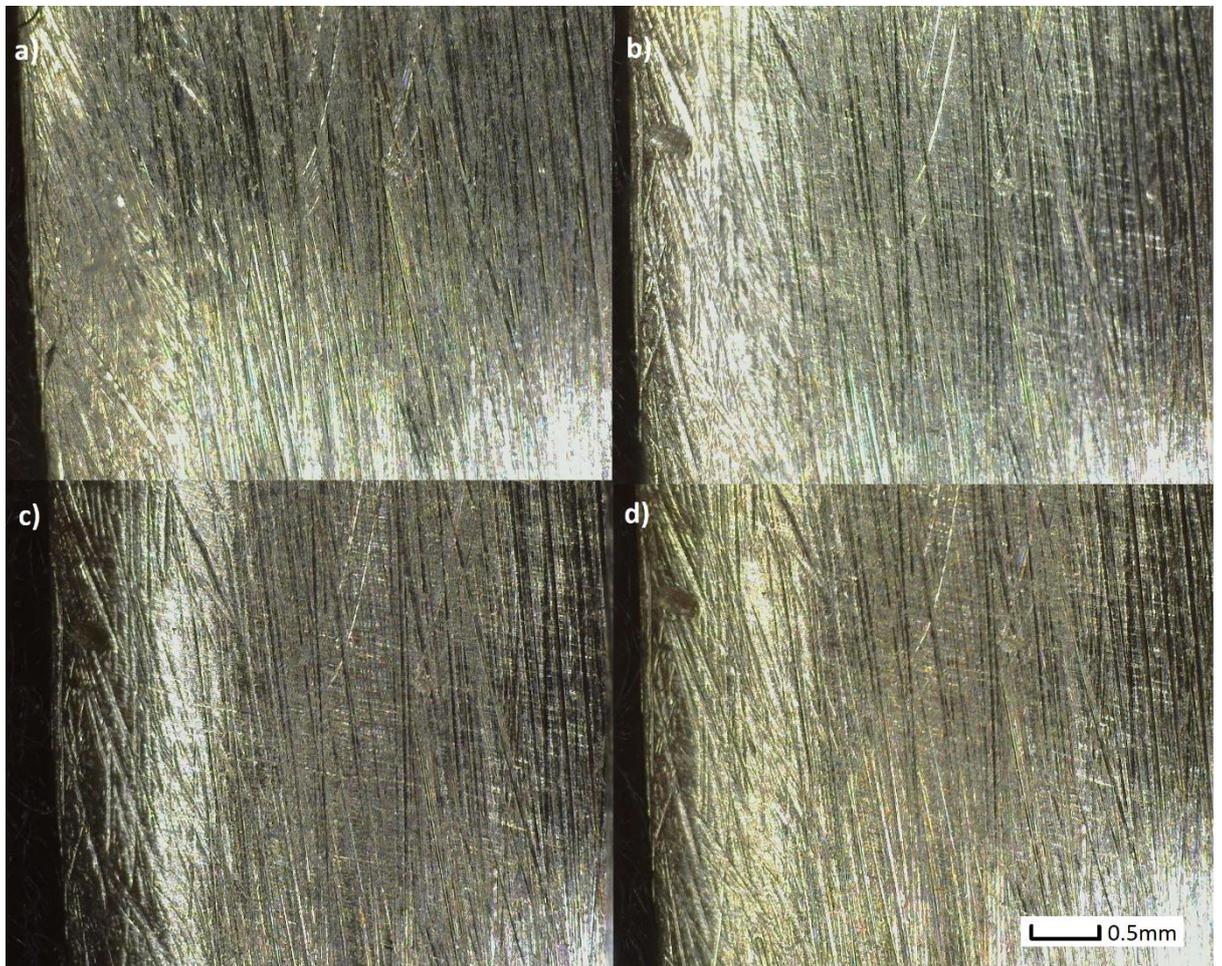
***Figure 98:*** Digital microscope images of Blade 6, SL 1, at x50 magnification, where: a) post-sharpening at 1000 impacts; b) 2000 impacts; c) 3000 impacts; d) 3500 impacts  (source: Author's own).
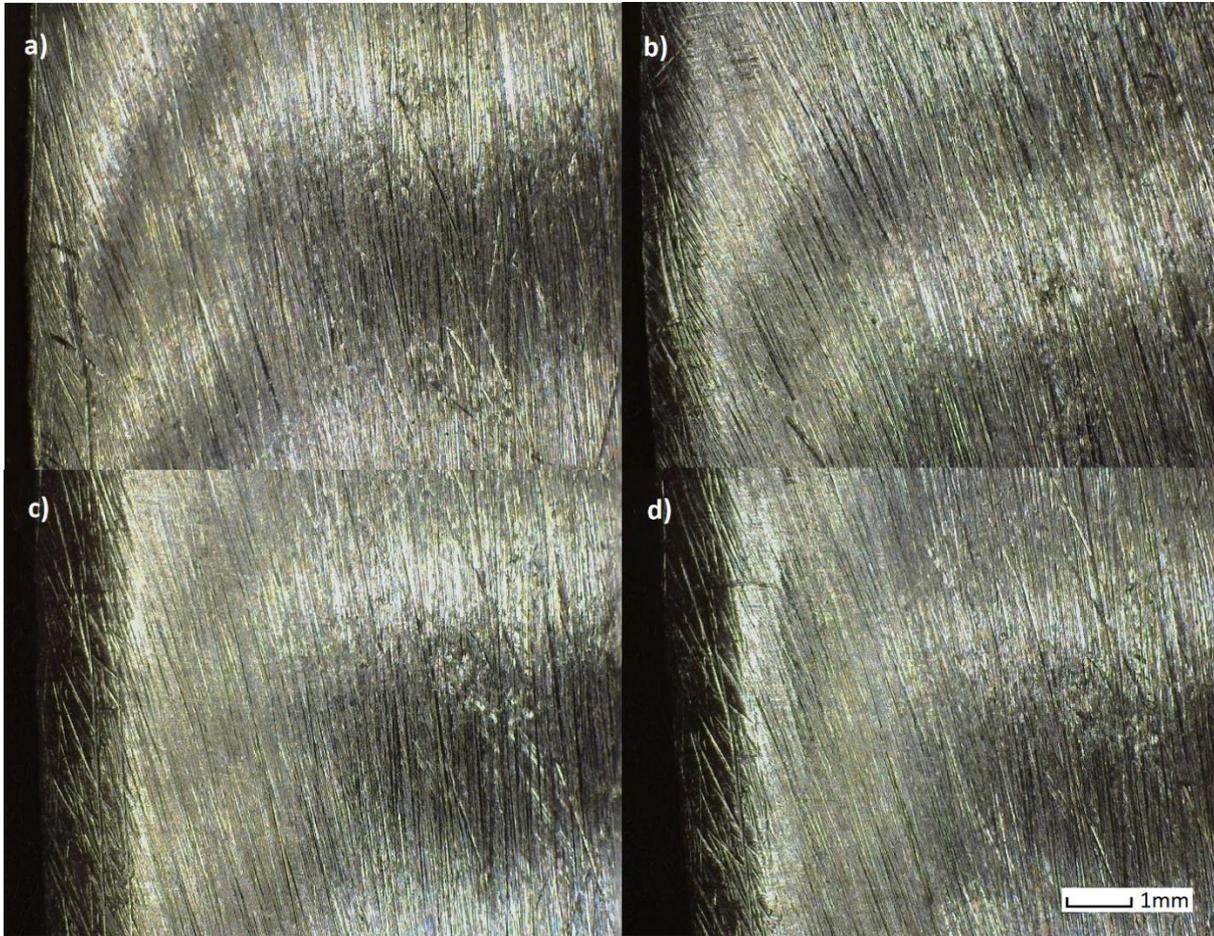
**Figure 99:** Digital microscope images of Blade 6, SL 2, at x25 magnification, where: a) post-sharpening at 1000 impacts; b) 2000 impacts; c) 3000 impacts; d) 3500 impacts  (source: Author's own).

| Intensity of use | Micro-level identifiers of use-intensity at x50 magnification | | | |
| --- | --- | --- | --- | --- |
| | ~10% tin-bronze axes | | | ~14% tin-bronze axes |
| | As-cast, sharpened | Cold hammered, annealed, sharpened | Cold hammered, annealed, final hammering, sharpened | Cold hammered, annealed, final hammering, sharpened |
| No use | Deep sharpening striations parallel to the blade edge. | Deep sharpening striations parallel to the blade edge. | Deep sharpening striations parallel to the blade edge. | Deep sharpening striations parallel to the blade edge. |
| 0 – 500 impacts | Sharpening striations parallel to the blade edge, a considerable number of use-striations (perpendicular to the blade) may be apparent. | Deep sharpening striations parallel to the blade edge, one or two faint use-striations (perpendicular to the blade) may be apparent. | Deep sharpening striations parallel to the blade edge, one or two faint use-striations (perpendicular to the blade) may be | Deep sharpening striations parallel to the blade edge, one or two faint use-striations (perpendicular to the blade) may be apparent. |
| 500 – 1000 impacts | Use-striations (perpendicular to the blade) may have started to obscure, or may completely obscure, most evidence of sharpening striations. | Deep sharpening striations parallel to the blade edge, use-striations (perpendicular to the blade) are sparse but unmistakable. | Deep sharpening striations parallel to the blade edge, use-striations (perpendicular to the blade) are sparse but unmistakable. | Deep sharpening striations parallel to the blade edge, one or two faint use-striations (perpendicular to the blade) may be apparent. |
| 1000-1500 impacts | Since it is likely that the blade will have failed and have been sharpened, it is not possible to detect the number of impacts past this point. | Deep sharpening striations parallel to the blade edge, use-striations (perpendicular to the blade) are frequently observed. | Deep sharpening striations parallel to the blade edge, use-striations (perpendicular to the blade) are frequently observed. | Deep sharpening striations parallel to the blade edge, use-striations (perpendicular to the blade) are sparse but unmistakable. |
| 1500-2000 impacts | n/a | Sharpening striations (parallel to the blade edge) are clear but have reduced depth in some areas, use-striations (perpendicular to the blade) cover much of the blade surface. | Sharpening striations (parallel to the blade edge) are clear but have reduced depth in some areas, use-striations (perpendicular to the blade) cover much of the blade surface. | Deep sharpening striations parallel to the blade edge, use-striations (perpendicular to the blade) are frequently observed. |
| 2000-3000 | n/a | Sharpening striations (parallel to the blade) are still apparent but no longer appear dark, use-striations (perpendicular to the blade) cover much of the blade surface. | Sharpening striations (parallel to the blade) are still apparent but no longer appear dark, use-striations (perpendicular to the blade) cover much of the blade surface. | Sharpening striations (parallel to the blade edge) are clear but have reduced depth in some areas, use-striations (perpendicular to the blade) cover much of the blade surface. |
| 3000-4000 | n/a | n/a | n/a | Sharpening striations (parallel to the blade) are still apparent but have a reduced depth in most areas, use-striations (perpendicular to the blade) cover much of the blade surface. |

*Table 13:* The likely timelines of the development of use-striations on the surface of the cutting-edge of palstave axes with varying composition and microstructures, while taking the frequency of sharpening into account.

## 6.5   Frequency and morphology of blade failure

Much has been determined about the relative resistance of replica palstave axes with different alloy compositions and post-production processing to blade failure during the experimental testing presented here-in. It makes most sense, of course, to discuss the response of specimens with a similar composition and microstructure alongside one another, and so with reference to section 6.1, Axes 3 and 4 shall be considered as-cast despite having received (a failed) annealing treatment and will grouped with Axe 1 and Blade 4. Testing was completed with Axes 3 and 4 up to 2500 impact tests, in which time each specimen exhibited the formation of two macro-scale deformation marks. Axe 3 succumbed to blade failure at 600 (*Figure 100* and *Figure 101*) and 1150 impact tests (*Figure 102* and *Figure 103*), whilst Axe 4 was weakened more quickly, the blade buckling at 200 (*Figure 104* and *Figure 105*) and 500 impact tests (*Figure 106* and *Figure 107*). The testing with Blade 4 followed a similar pattern; the cutting-edge failed at 59 (*Figure 108* and *Figure 109*) and 1050 impacts (*Figure 110* and *Figure 111*). It is interesting to note that all significant blade deformations occurred within the first half of the testing duration. This may suggest a surprising benefit of the considerable surface hardness elevation experienced across the surface of the cutting-edge during use, in so much as, this deformation resistant layer may work to reduce the susceptibility of the blade to bending. Thus, the cutting-edge may become noticeably more resistant to deformation over the course of testing. As discussed in 6.2, the metal appeared to reach a plateau in hardness, at which point any further elevation was much more difficult to induce. Interestingly, macro-scale deformations rarely occurred after this degree of surface hardness had been obtained.

In contrast to the results presented above, Axe 1 failed to exhibit any major blade deformation after 1000 impact tests at 15J, and even after another 600 tests at 30J, no failure could be induced. Though it is unclear as to why Axe 1 was able to withstand blade failure after considerable testing, the quality of the casting may go some way to explain the different levels of material response between these three axes. For example, the samples taken from Axe 1 for metallography show minor porosity (*Figure 39*), while those from Axes 3 and 4 demonstrated moderate porosity (*Figure 41* and *Figure 42*). Likewise, the difference in resistance to deformation between Axes 3 and 4 was probably a result of minor variation in their composition and casting quality. Axe 2, which was cold-hammered to increase durability, withstood 500 tests at 30J before a large deformation had manifested on the blade edge (*Figure 112* and *Figure 113*); thus, this experimental specimen illustrated a far greater resilience to deformation than those that had not been cold-hammered.

**Figure 100:** Photograph of the blade of Axe 3 post-600 tests, illustrating the large deformation at the cutting edge (source: Author's own).
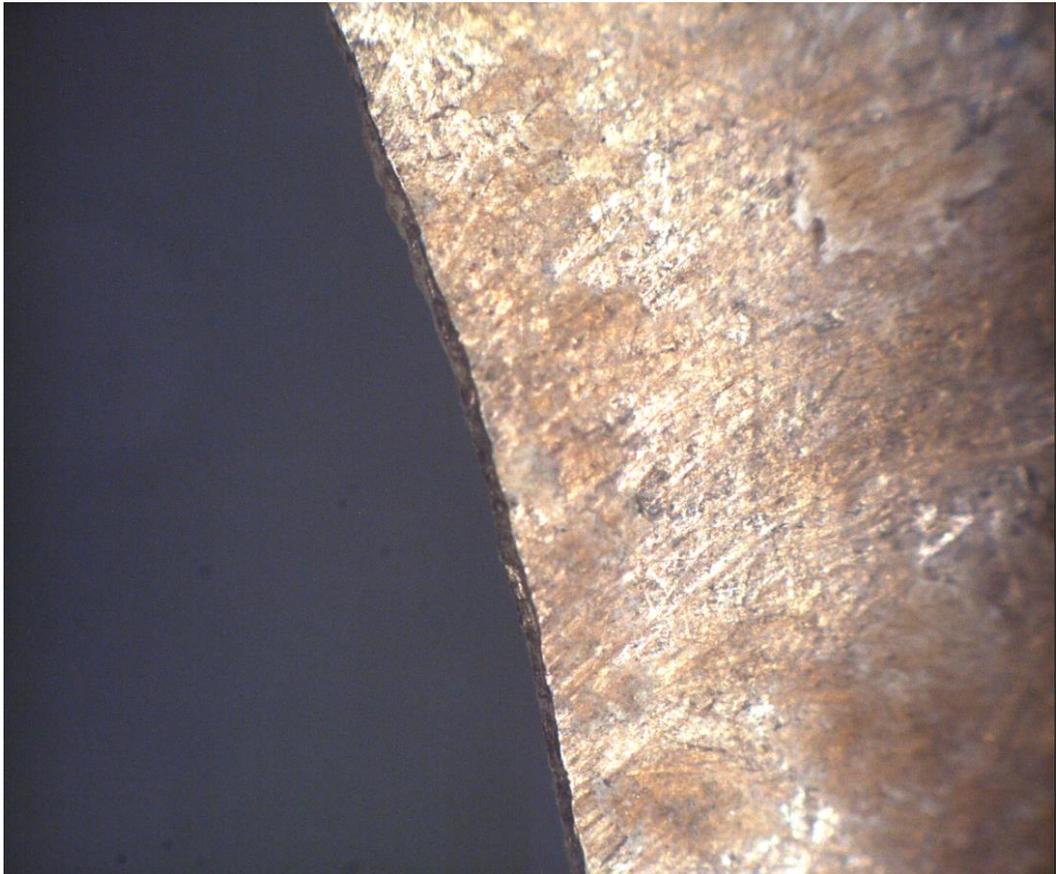


**Figure 101:** Macroscope (x2) image of the blade of Axe 3 post-600 tests, illustrating the large deformation at the cutting edge (source: Author's own).

*Figure 102:* Photograph of the blade of Axe 3 post-1150 tests, illustrating the large deformation at the cutting edge (source: Author's own)..



*Figure 103:* Macroscope (x2) image of the blade of Axe 3 post-1150 tests, illustrating the large deformation at the cutting edge (source: Author's own).

180

**Figure 104:** Photograph of the blade of Axe 4 post-200 tests, illustrating the large deformation at the cutting edge (source: Author's own).
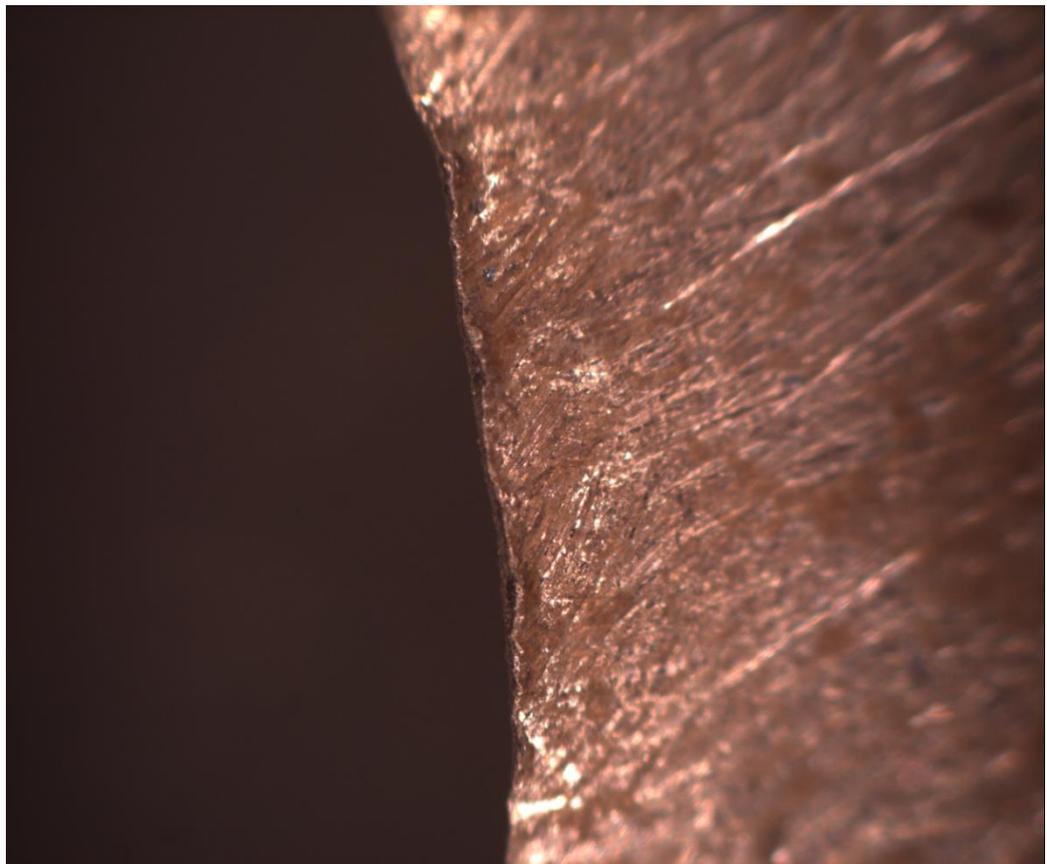


**Figure 105:** Macroscope (x2) image of the blade of Axe 4 post-200 tests, illustrating the large deformation at the cutting edge (source: Author's own).

**Figure 106:** Photograph of the blade of Axe 4 post-500 tests, illustrating the large deformation at the cutting edge (source: Author's own).
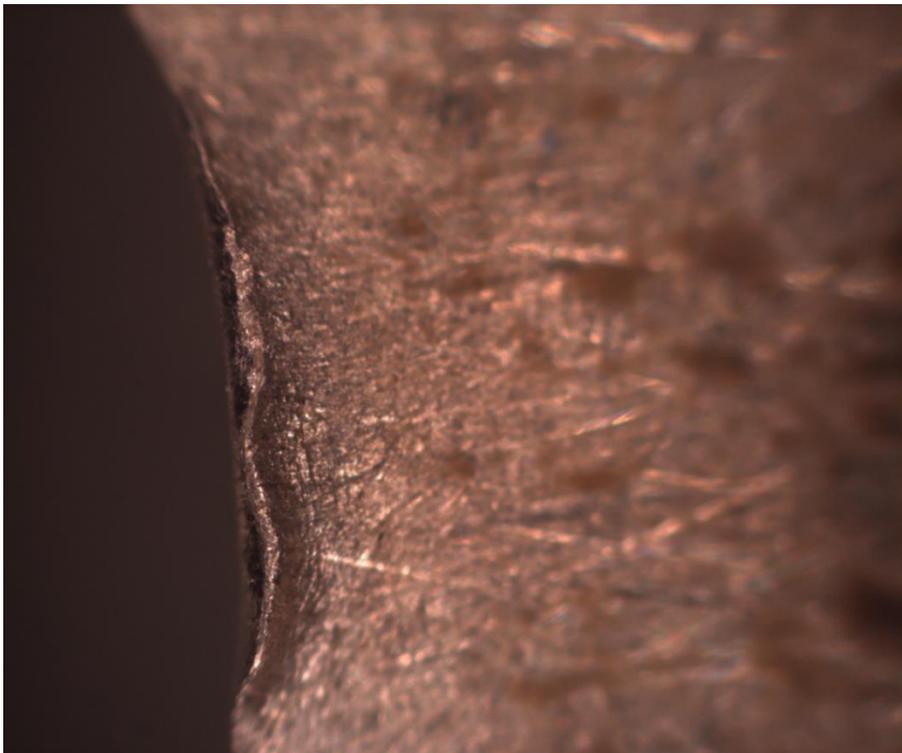


**Figure 107:** Macroscope (x2) image of the blade of Axe 4 post-500 tests, illustrating the large deformation at the cutting edge (source: Author's own).

**Figure 108:** Photograph of failure of the cutting-edge of Blade 4 after 59 impacts (source: Author's own).



**Figure 109:** Macroscope (x2) image of the blade of Blade 4 after 59 tests, illustrating the bending of the blade at the cutting-edge  (source: Author's own).

*Figure 110:* Image of the bending at the cutting-edge of Blade 4 after 1050 impacts  (source: Author's own).
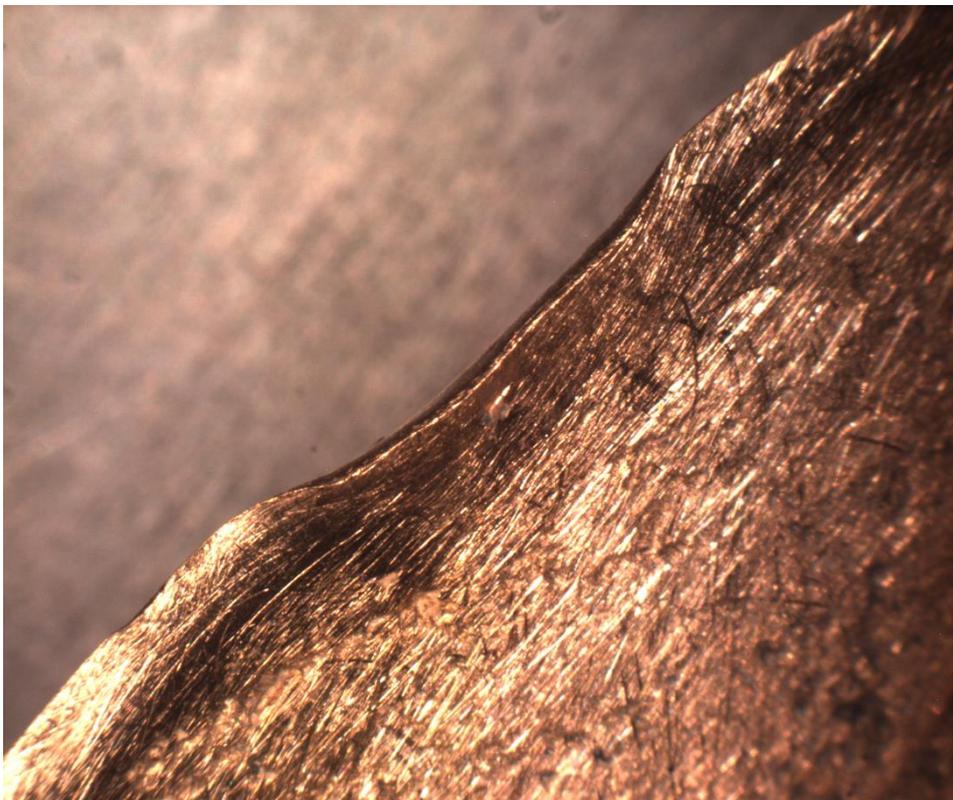


*Figure 111:* Macroscope (x2) image of the blade of Blade 4 after 1050 tests, illustrating the bending of the blade at the cutting-edge (source: Author's own).

**Figure 112:** Photograph of the blade of Axe 2 post-500 tests at 30J, illustrating the large deformation at the cutting edge (source: Author's own).
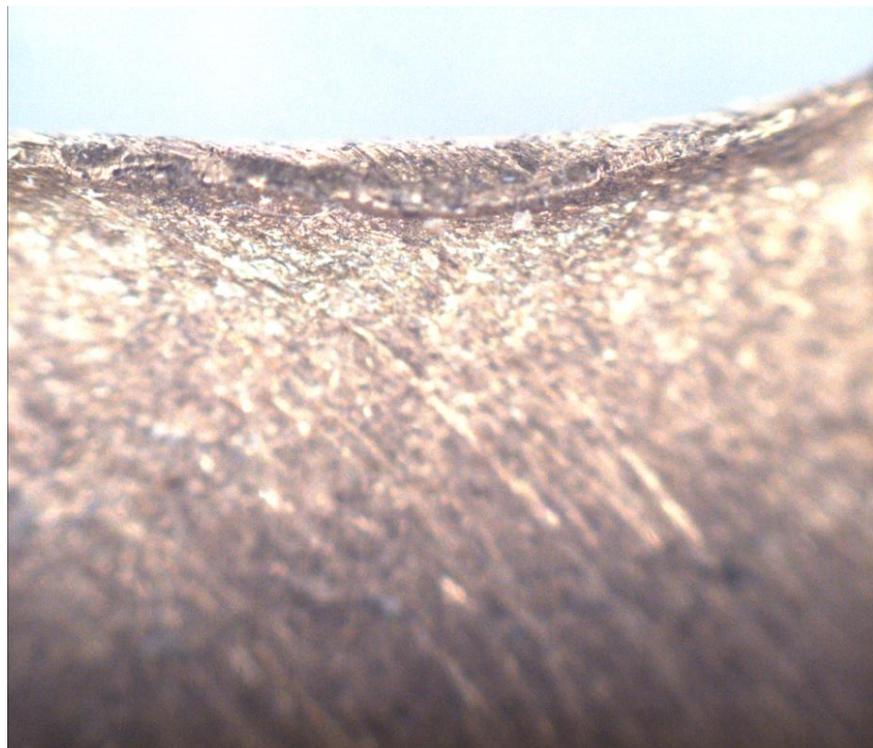


**Figure 113:** Macroscope (x2) image of the blade of Axe 2 post-500 tests at 30J, illustrating the large deformation at the cutting edge (source: Author's own).

Blades 1-3 did not succumb to a blade failure throughout testing at 15J. This is not to say that the cutting-edge of the Blades did not show any signs of minor deformation. Blade 1, for instance, had developed an insignificant bilateral deformation by 1500 tests (*Figure 114* and *Figure 115*), which looked remarkably similar to the earliest semblance of deformation experienced by Axes 3 and 4, at 600 and 200 tests. As *Figure 116*, *Figure 117*, and *Figure 118* suggest, an area on the cutting-edge of Blade 2 also appeared to be slightly bent by around 1500 tests – in this case, the deformation could be likened to a unilateral bending of the cutting-edge, such as the one that appeared on Axe 4 at 500 tests, but in an early stage of development. Blade 3 also developed a similar minor deformation at 1750 impacts (*Figure 119*). Hence, it is not that these specimens are completely devoid of deformation, but that the timescale for the progression of wear has been significantly elongated. The trend in early failure of dendritic axes/blades was the same, despite differences in fixturing during impact testing – this suggests that while the latter approach deviated away from testing with full axe-heads (a method with high expected compliance), no significant source of error was introduced by the blades being screwed directly into a tup made of steel. The same can also be said about the adoption of authentic sharpening methods for Blades 1-6. A suitable explanation for this is that the partially recrystallized microstructure of these specimens have obtained superior resistance to major deformation under sliding compression tests. It should also be noted, however, that the casting quality of Blades 1-3 was somewhat better than Blade 4 and Axe 3 (although not Axe 4). Hence, it is likely a combination of the enhanced strength and the reduced potential for slip within the partially recrystallized microstructures which have prevented macro-scale deformation.



*Figure 114:* Photograph of one corner of the cutting-edge of Blade 1 after 1500 impacts (source: Author's own).
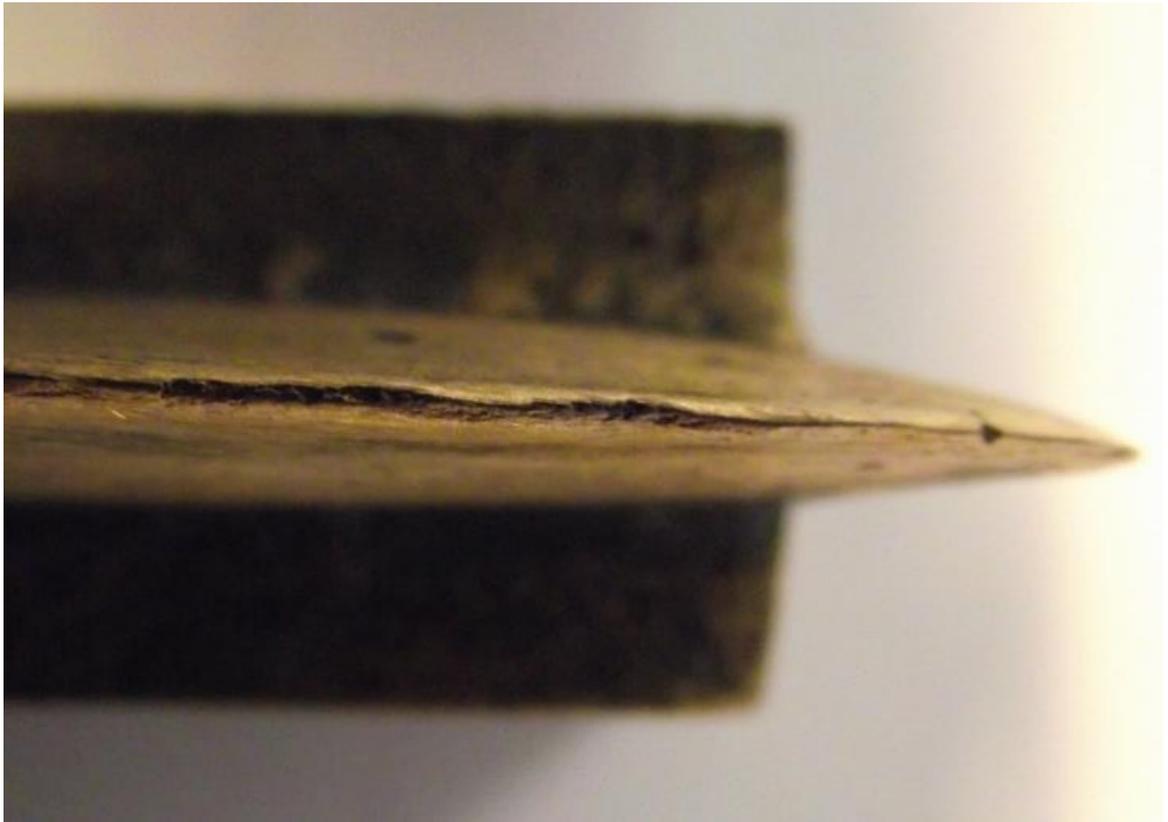
***Figure 115:*** Photograph of one corner of the cutting-edge of Blade 1 after 1750 impacts (source: Author's own).



***Figure 116:*** Photograph of bending at cutting-edge of Blade 2 after 1500 impacts (source: Author's own).
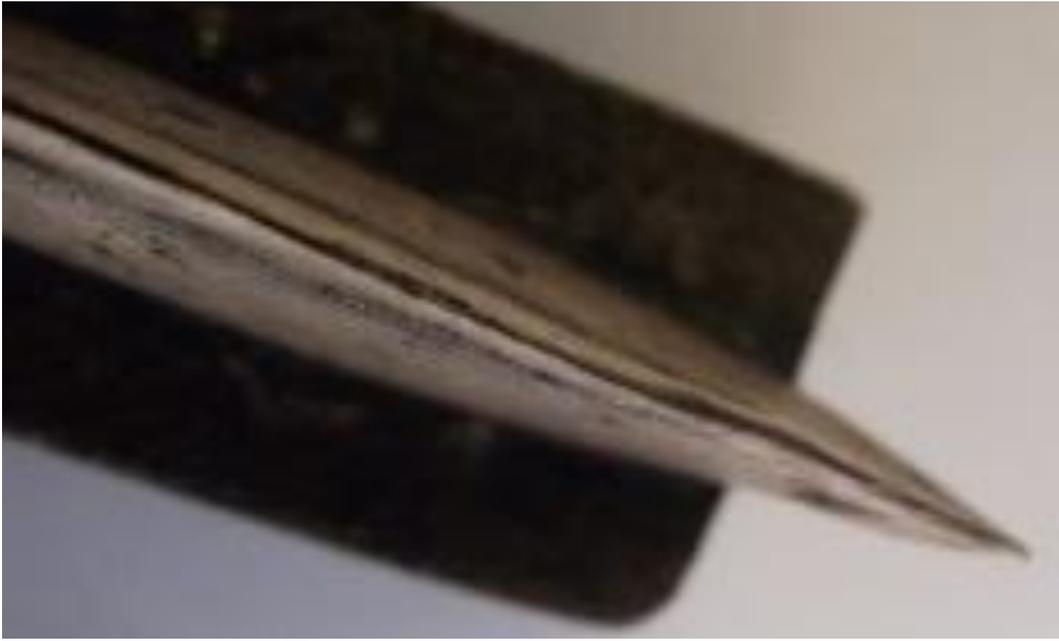
*Figure 117:* Photograph of the bending at cutting-edge of Blade 2 after 1750 impacts (source: Author's own).



*Figure 118:* Photograph of the bending at cutting-edge of Blade 2 after 2000 impacts (source: Author's own).
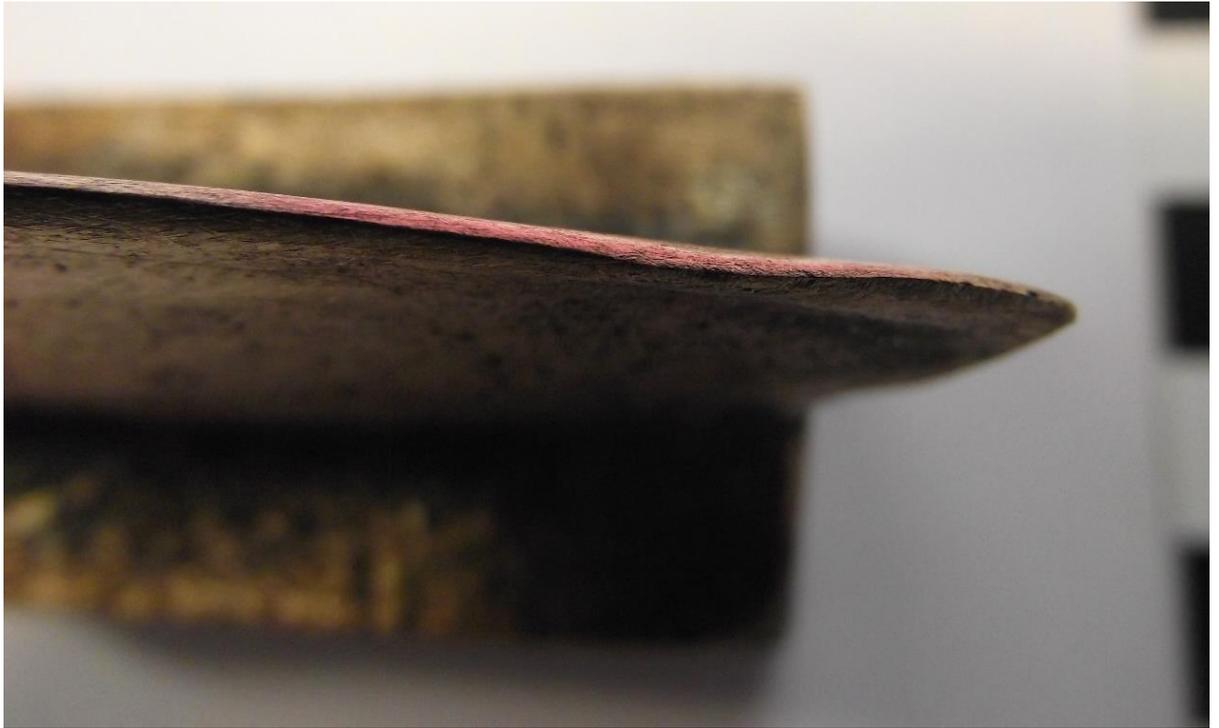
*Figure 119:* Photograph of one corner of the cutting-edge of Blade 3 after 1750 impacts (source: Author's own).

Interestingly, the 14% tin-bronze partially recrystallized experimental specimens present quite different results the 10% tin-bronze partially recrystallized replica palstave axes. Blade 5 experienced a unilateral deformation at 50 tests (*Figure 120* and *Figure 121*), and then, as *Figure 123* and *Figure 124* suggest, a catastrophic failure at 695 tests (this was so severe that it could not be repaired by re-sharpening and so testing was ceased). Both of these can be largely attributed to poor casting quality of this blade, which had visible structural issues (cracking and a casting defect) at both of the areas where the blade failed (*Figure 122*). The occurrence of cracking in high tin-bronzes after processing has been noted in a previous study [188], and is most likely the result of the high initial hardness of the material, which makes it susceptible to brittle fracture during maintenance. The second 14% tin-bronze specimen, Blade 6 (annealed and cold-hammered to finish) experienced a failure at 1000 tests. The morphology of this deformation was very different than other failures, as it was a fracture rather than a deformation (*Figure 125* and *Figure 126*). It seems very likely the area of the cutting-edge that became fractured was an area that had a high concentration of tin and therefore was liable to localised embrittlement during testing. The specimen succumbed to no further failures for the remainder of testing at 15J.
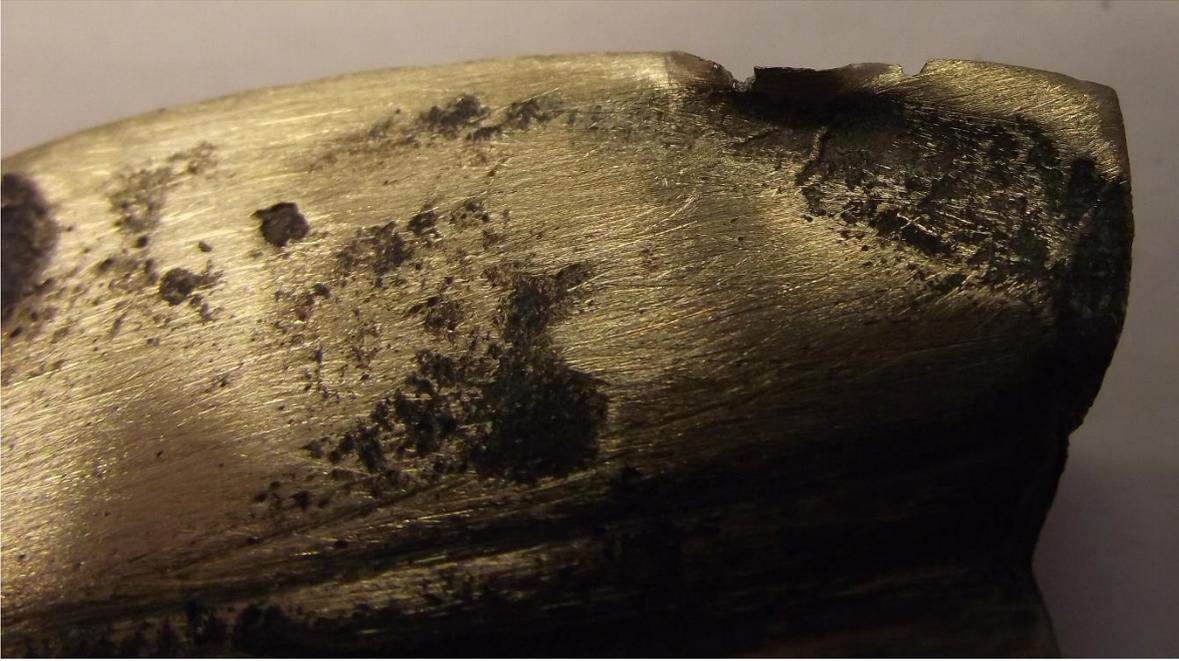
*Figure 120:* Image of the failure at the cutting-edge of B5 after 50 impacts (source: Author's own).
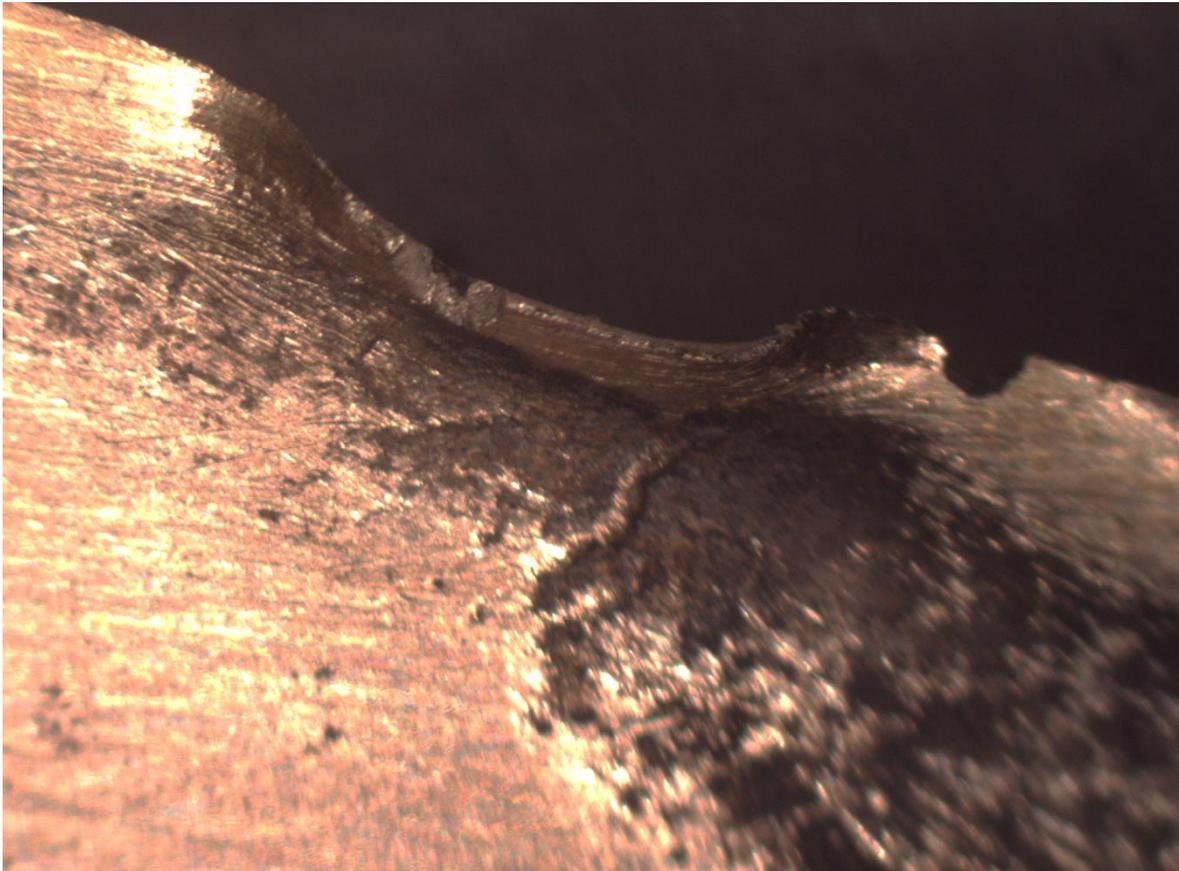


*Figure 121:* Macroscope (x2) image of the failure at the cutting-edge of B5 after 50 impacts (source: Author's own).

*Figure 122:* Profile of the blade of B5 after sharpening prior to testing, a small nick in the cutting-edge and a large casting defect are depicted in the red circles (source: Author's own).



*Figure 123:* Image of the failure at the cutting-edge of B5 after 495 impacts (source: Author's own).
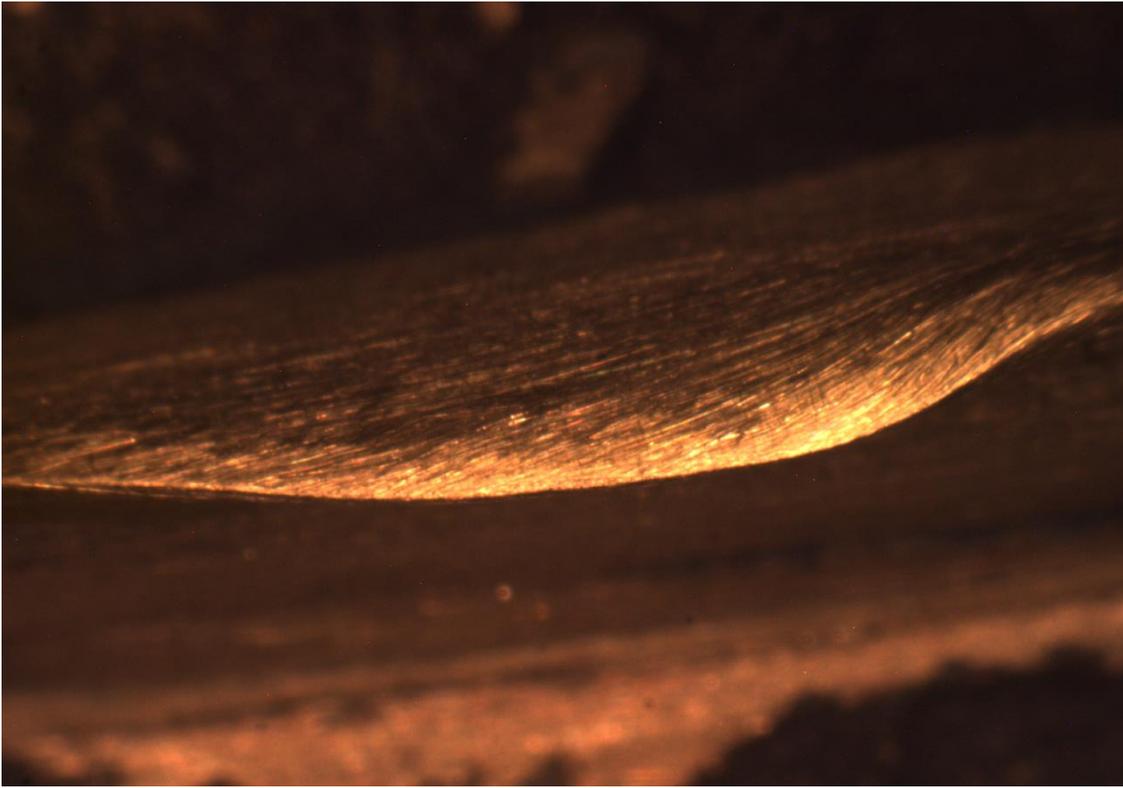
*Figure 124:* Macroscope (x2) image of the failure at the cutting-edge of B5 after 495 impacts (source: Author's own).



*Figure 125:* Image of the failure at the cutting-edge of B6 after 1000 impacts (source: Author's own).
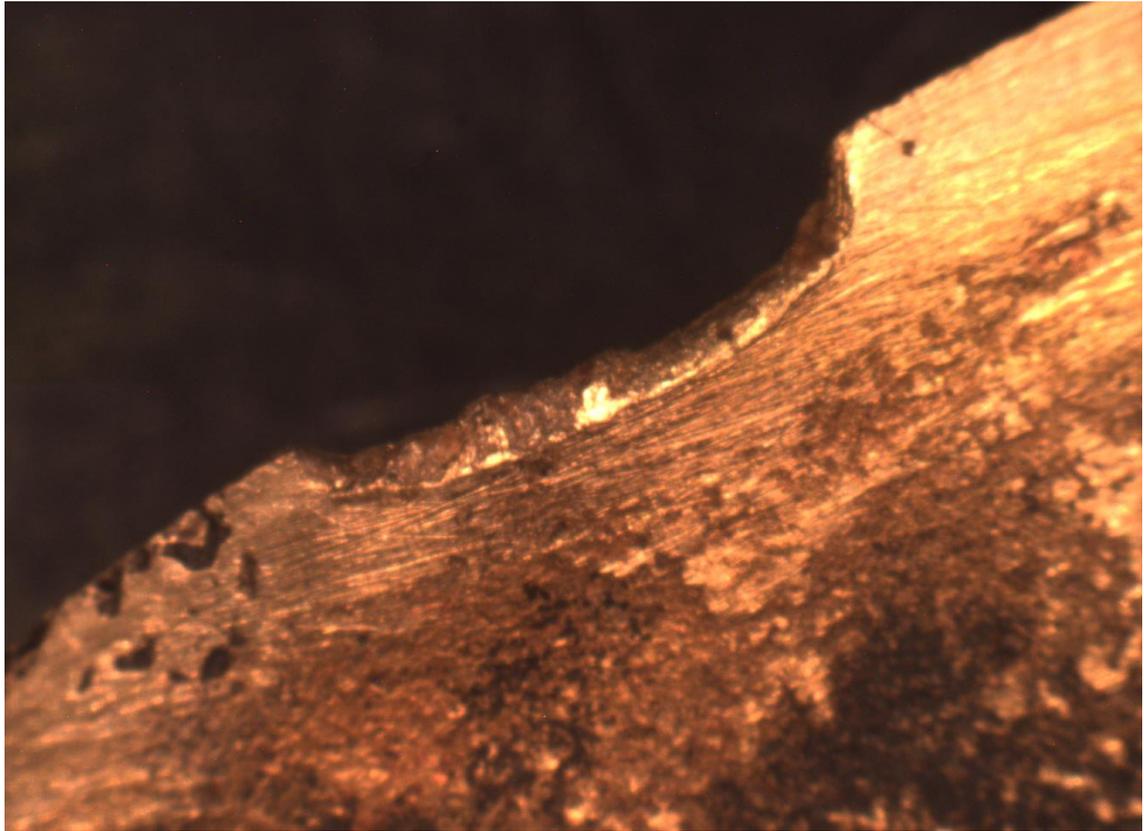
*Figure 126:* Image of the failure at the cutting-edge of B6 after 1000 impacts (source: Author's own).

After examining the response of the material when dropped with an energy of 15J, Blades 1, 2, and 6 were then subjected to impact testing at 45J and 30J to investigate how long the cutting-edge would withstand failure at a higher energy level. At 45J, Blade 1 sustained only 6 tests before a major deformation formed at the cutting-edge (*Figure 127* and *Figure 128*), while the cutting-edge of Blade 2 failed after 38 tests (*Figure 129* and *Figure 130*). Interestingly, Blade 6 was able to withstand 200 tests at 45J before a bend occurred in the cutting-edge (*Figure 131*); a substantial increase in resilience compared to the 10% tin-bronze specimens. A similar pattern emerged when testing with the 30J parameter – a significant contortion was observed on Blade 1 at 314 impact tests (*Figure 132*), while a deformation with the same morphology occurred on Blade 2 at 1750 impact tests (*Figure 133*). The cutting-edge of Blade 6 endured 3000 impact tests until failing (*Figure 134*).

**Figure 127:** Photograph of the entire cutting-edge of Blade 1 after 6 impacts at 45J (source: Author's own).



**Figure 128:** Macroscope (x2) image of the blade of Blade 1 after 6 tests at 45J, illustrating the bending of the blade at the cutting-edge (source: Author's own).

***Figure 129:*** Photograph of the entire cutting-edge of Blade 2 after 38 impacts at 45J (source: Author's own).
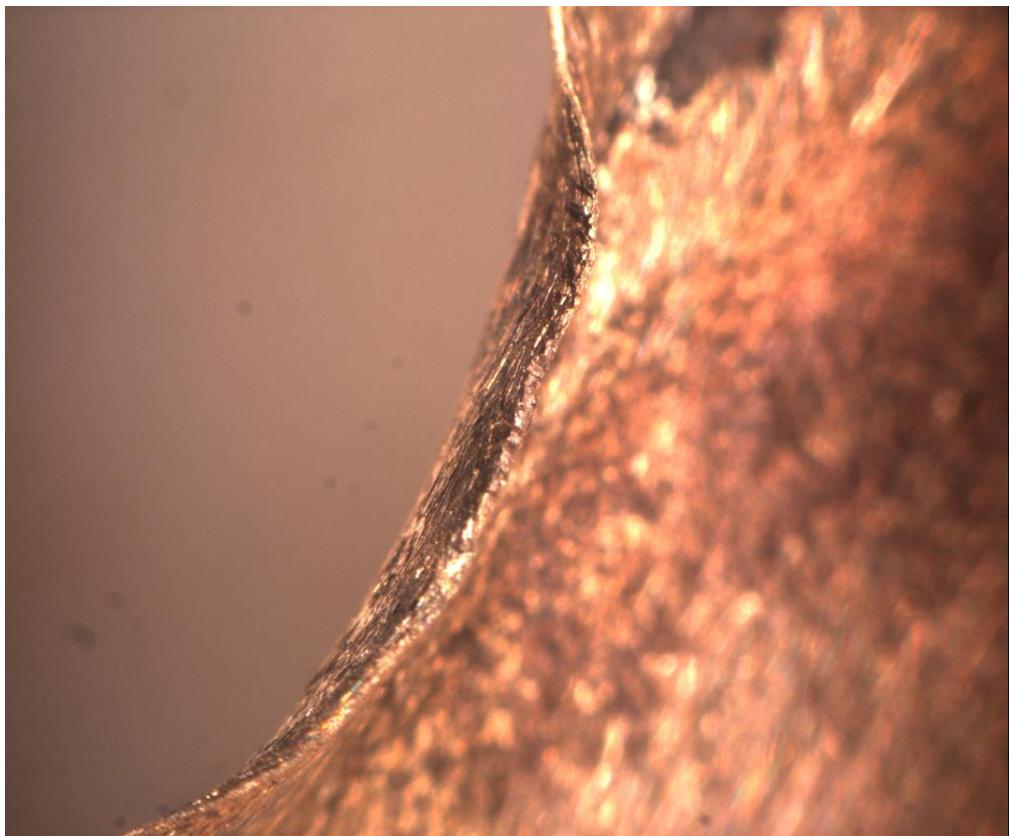


***Figure 130:*** Macroscope (x2) image of the blade of Blade 2 after 38 tests at 45J, illustrating the bending of the blade at the cutting-edge (source: Author's own).

**Figure 131:** Image of the failure of the cutting edge on B6 after 200 impacts at 45J (source: Author's own).



**Figure 132:** Photograph of the entire cutting-edge of Blade 1 after 314 tests at 30J (source: Author's own).

*Figure 133:* Photograph of the entire cutting-edge of Blade 2 after 1750 impacts at 30J (source: Author's own).



*Figure 134:* Image of the failure of the cutting edge on B6 after 3000 impacts at 30J (source: Author's own).

Following the delivery of the results relating to the frequency and morphology of blade failure above, further interpretations can be offered about the susceptibility to deformation of palstave axes with varying alloying mixtures and post-production processing. As has been previously suggested in the literature [147] [138], as-cast palstave axes are much more likely to present frequent blade failures. Palstave axes that contain roughly 10% tin, and that were also subjected to several cycles of cold-hammering and annealing to generate recrystallization and work-hardening,

however, are much more resilient to major deformation and in optimum circumstances may not yield even after exhaustive use. There are likely differences in deformation and failure modes between dendritic and recrystallized bronze, for example, mechanical interactions at phase boundaries, harder delta phases and other potential precipitates. Defining these in more detail is outside the bounds of this thesis. While the study has tried to eliminate the influence of interfering variables as much as possible, it was difficult to control the casting quality of the replicas and this may have also impacted on the resilience of the cutting-edge to deformation. Therefore, further work with replica palstave axes of a closer casting quality is necessary to test the observations made above. Equally, experimentation with fully recrystallized microstructures would likely suggest even greater mechanical advantages.

The data produced by Blades 1 and 2 suggests that axes which have been subjected a final cold-hammering are much more resilient against the significant material stress induced by high-energy impacts. Thus, hammer-hardening could be considered to be a safeguard against accidental high-energy hits that would, otherwise, generate bending of the cutting-edge after only a few impacts. In general, the data produced by Blades 5 and 6 presents a more convoluted picture, and further experimentation is required to reveal reliable assertions. However, it can be said with some confidence that axes containing this composition of tin can be much more resistant to failure at higher energy levels. In contrast, axes with a higher tin composition are also more susceptible to defects generated during manufacturing, which are likely to permit catastrophic failure of the cutting-edge after minimal use. Lastly, it seems that axes with around 14% tin-bronze are unlikely to present bending of the cutting-edge at lower impact energies but, instead, might exhibit blade fracture where certain areas have undergone significant embrittlement.

The major failures referred to throughout the text above developed relatively quickly, for instance, generally within the space of 50 impact tests, indicating that once a weakness had been encountered, the degradation of the material was exacerbated fairly rapidly. In addition, the cutting-edge of the axes remained remarkably sharp even after hundreds of impact cycles. The lack of major deformations during testing at 15J with Blades 1-3 had a knock on effect for the implementation of sharpening events. Without a clear indication of when the specimens should be resharpened, the Blades remained in the condition that they reached after the initial sharpening throughout the entirety of testing. Although certainly blunting a little, and looking a bit battered, the blade of each specimen retained a relatively sharp cutting-edge that was definitely still functional at the end of 2000-3000 tests, as suggested by *Figure 135* and *Figure 136*. However, the cutting-edge of Blade 6 (*Figure 137)*, which underwent 3500 tests at 15J definitely fell in the realm

of 'blunt' upon the cessation of testing. As such, this data can be used, already, to inform ideas about the deposition state of Bronze Age palstave axes – it seems probable that axes retained a largely 'pristine' blade during the majority of their use in wood-cutting activities, and that periods where a significant deformation was present were short and became increasingly infrequent as the axe was used (possibly due to the interaction with surface hardness discussed above). Of course, it cannot wholly be assumed that a prehistoric axe would have been resharpened imminently after failure, but if the functionality of the blade was a high priority, then this seems likely.



*Figure 135:* Photograph of the entire cutting-edge of Blade 1 after 2000 impacts (source: Author's own).
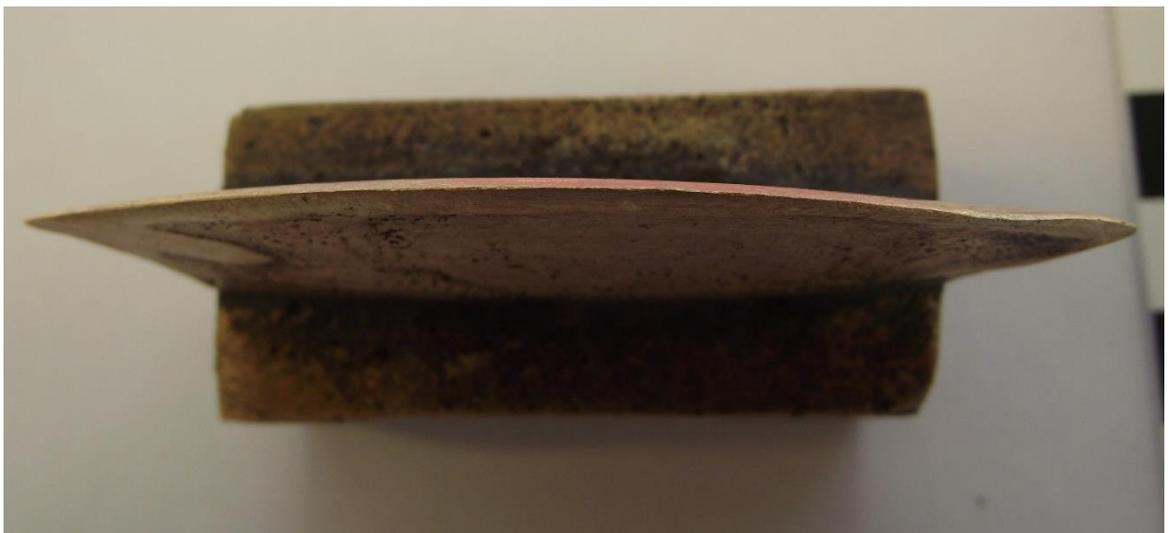


*Figure 136:* Photograph of the entire cutting-edge of Blade 3 after 3000 impacts (source: Author's own).

**Figure 137:** Image of the cutting-edge of B6 after 3500 impacts (source: Author's own).

The location of deformations, and the sharpening that followed, considerably impacted on the shape of the blade after failure. After sharpening to remove the deformation, the area where failure had been appeared to be noticeably reduced in size and the blade became slightly shorter or asymmetrical as a result. Often the deformations repeatedly occurred in the same corner of the blade, for instance, in the case of Blade 4 (*Figure 138* and *Figure 139*), which was moderately asymmetrical after experiencing a second blade failure (and sharpening) at 1050 impact tests (*Figure 140*). Since the present discussion has provided a very clear idea about the frequency of blade failures at the cutting-edge of palstave axes, and asymmetry may be a direct result of such failures, the amount of asymmetry demonstrated on ancient Bronze Age palstave axes may provide a useful gauge for estimating the use-intensity. *Table 14* summarises the frequency of blade failure, and associated progression of asymmetry and other macro-scale identifiers, for palstave axes with differing compositions and post-production processing. It should be noted that estimations of overall use-intensity based on asymmetry can only really suggest the minimum number of deformation at the cutting-edge and, therefore, use and maintenance cycles, since deformations could occur at opposite sides of the blade, effectively generating a levelling effect upon the resharpening of the blade.

It is difficult to estimate from the results produced here-in, exactly how long a palstave with full processing would last before requiring replacement. This is a result of the relatively limited tests applied to each specimen and the inability to produce deformation on specimens with partially recrystallized microstructures. It is likely that axes with full recrystallization would have been even

less likely to deform. That being said, the previously posited 5% in reduction for each axe per year (made in [274, p. 163] when considering the rate of metal consumption within the Danish Bronze Age) seems, to this author, like a conservative estimate indeed. Based on sporadic measurements made during experimentation made here-in, it is likely that approximately 0.3-0.6g of material is lost per sharpening interval. For a 400g axe (which better reflects the average weight of British palstave axes), only around four or five sharpening events would have to take place per year before 5% reduction was reached. Given that these axes were most likely in persistent use (with daily 'hits' possibly reaching into the thousands), were susceptible to deformation when subjected to higher energy impacts, and were likely sharpened more frequently than just at the point where it was necessary to restore basic functionality, a greater number of sharpening events per year is likely. When the growth of household construction in the MBA is considered alongside the potential for seven axes per house (as found at Must Farm [67, p. 46]), it is likely that the annual imports of metal into Britain must have been very high, at least from 1600 BC onwards when the reliance on Great Orme diminished.



**Figure 138:** Profile of the blade of B4 after failure at 59 impacts (source: Author's own).

**Figure 139:** Profile of the blade of B4 after failure at 1050 impacts (source: Author's own).



**Figure 140:** Profile of the blade of B4 after sharpening at 1050 impacts (source: Author's own).

The morphology of the majority of the deformations that were generated at the cutting-edge of the experimental specimens was very consistent. The form could be likened to 'bending' of the blade tip, or a 'leading edge curl'. In several cases the cutting-edge only curled in one direction, but sometimes the material was so weakened that the blade was contorted bilaterally. It is well known that areas that have been subjected to significant plastic deformation are much more liable to intergranular corrosion [8], [137]. Thus, it may be posited here, that for archaeological axes, corrosion, or even incomplete resharpening, could very well have culminated in the partial loss of this area. Consequently, as well as searching for evidence of bending, it is likely that the same kind of deformation may appear as a minor depression at the cutting-edge. The only deformations that did not adhere to the bending described above were those that were formed on Blade 1, Blade 2, and Blade 6 after testing at 30J. In all of these instances a much larger portion of the cutting-edge was contorted. These, more devastating, deformations were likely a result of the exhaustive testing that had been applied to these specimens over the course of testing at 15J, 45J, and then 30J – the whole blade must have been undoubtedly weakened. If a similar catastrophic contortion is presented by ancient palstave axes, it should be assumed that these objects have been subjected to extremely hard work at higher impact energies than common for tree-felling and wood-chopping.

| | Macro-level identifiers of use-intensity | | | |
|---|---|---|---|---|
| | ~10% tin-bronze axes | | | ~14% tin-bronze |
| Intensity of use | As-cast, sharpened | Cold hammered, annealed, sharpened | Cold hammered, annealed, final hammering, sharpened | Cold hammered, annealed, final hammering, sharpened |
| No use | The axe appears to have a smooth finish in areas where corrosion is absent. | The axe appears to have a smooth finish in areas where corrosion is absent. There may be a pronounced bevel. | The axe appears to have a smooth finish in areas where corrosion is absent. There may be a pronounced bevel. | The axe appears to have a smooth finish in areas where corrosion is not obstructive to the assessment. There may be a pronounced bevel. |
| 0 – 500 impacts | The blade may have experienced a further major failure. Moderate asymmetry, the blade will be sharp. | No asymmetry, the blade will still be sharp. | No asymmetry, the blade will still be sharp. | No asymmetry, the blade will still be sharp. |
| 500 – 1000 impacts | The blade may have experienced a further major failure. Minor or moderate asymmetry, the blade will be sharp. | No asymmetry, the blade will still be sharp. | No asymmetry, the blade will still be sharp. | The blade may have experienced a major failure; hence, this will be apparent as a depression, or the blade will have very slight asymmetry due to sharpening. The blade will be sharp. |
| 1000-1500 impacts | Moderate asymmetry, sharp blade. | No asymmetry, sharp blade. | No asymmetry, sharp blade. | Very slight asymmetry, sharp blade. |
| 1500-2000 impacts | Moderate asymmetry, sharp blade. | No asymmetry, sharp blade. | No asymmetry, sharp blade. | Very slight asymmetry, sharp blade. |
| 2000-3000 impacts | Likely that the blade will experience further failures, leading to severe asymmetry and a sharp blade. | No asymmetry, medium blade sharpness. | No asymmetry, medium blade sharpness blade. | Very slight asymmetry, sharp blade. |
| 3000-4000 impacts | n/a | n/a | n/a | Blade may be sharpened due to blunting. Very slight asymmetry is possible. |

*Table 14:* The likely timelines of the development of macro-scale identifiers at the cutting-edge of palstave axes with varying composition and microstructures, while taking the frequency of sharpening into account.

# PART 3: ADDRESSING ARCHAEOLOGICAL QUESTIONS

## 7 Methods and Data

The experimental work has provided directly comparable analytical methods, referential schemes, and other relevant supporting data to help elucidate the use-intensity of Bronze Age palstave axes. It has been the dedicated purpose of the third part of this thesis to use the experimental insight offered in Chapter 6 to investigate the amount of use experienced by ancient palstave axes, and determine how this fits into their overall life narratives.

The selected sample of prehistoric palstave axes was based on the availability of pre-existing metallographic mounts. A collection of eighty-six palstave axes which were sampled, mounted, and chemically characterized by Peter Northover (Archaeometallurgist, Oxford Materials Characterisation Service) in the 1970s/1980s as part of his analysis on Bronze Age objects from the south-west of England, were kindly offered for study. The existing chemical characterization and metallographic data pertaining to twenty-six samples, which was recorded by H.H. Coghlan in several papers [116], [135], [137] was also reviewed. This data was then combined with the use-wear analysis of each artefact. Using this integrated approach, the metallurgical analysis of each palstave axe is used to explain the biographical possibilities of the object at its 'birth', and suggest mechanical differences that will alter the wear-related characteristics throughout its use. The measure of use-intensity has been used to ascertain the extent to which an axe was utilised in fulfilling utilitarian tasks and, therefore, reveal the presence, or absence, of human-substrate interactions that were formed on a functional basis. Combined with other biographical indicators, for example, the final condition, damage, burial context, a comprehensive picture of the individual narrative of each palstave axe has been established, highlighting unique artefacts that represent highly distinctive life narratives. Thus, conjuring up new questions about the many ways in which these objects acted as both an extension of, and an agent to, societal construction in the Middle Bronze Age in Britain. When the data from each axe is compared, broader trends should become apparent, such as the common life trajectories of palstave axes belonging to different geographical, typological and contextual groups.

Drawing upon the sequence of life stages introduced in section 2.2.1, and with reference (where relevant) to the many insights gained during the experimental work, the present section offers the methodological approach used to evaluate the type, chemical composition, microstructure, wear,

damage, and deposition characteristics of the archaeological dataset. The nature of the dataset for each characteristic is described so that certain qualities such as, sample composition, sample attributes, and sample completeness can be assessed. Attempts were made to document the characteristics pertaining to each palstave axe in as much detail as possible so that the compilation of relational narratives could draw upon comprehensive records. As already mentioned in section 2.3, the second output for the analysis of ancient palstave axes is the construction of life trajectories, which represent a simplification of the biographical data of each object into easily comparable categories. The justification for the creation of these categories is also presented in the text below.

## 7.1 Assessment of axe type

In-situ examination of each palstave axe was conducted at museums across the south and south-west of England, including: The Ashmolean Museum (Oxford), The Bristol Museum and Art Gallery, The Dorset County Museum (Dorchester), The Newbury Museum, The Pitt Rivers Museum (Oxford), the Royal Albert Memorial Museum (Exeter), the Somerset Museum (Taunton), and the Royal Cornwall Museum (Truro). Objects were photographed using a Fujifilm FinePix S1900 digital camera, drawn, and described. The basic morphological data recorded for each palstave axe included measurements of length, width of blade, width of butt, thickness of butt, thickness of blade, and weight. The typological classification system of Schmidt and Burgess [86] was adopted for identification of type as it provides a fairly complete typological sequence that still holds true despite the new material that has been recovered in the last several decades. While the allocation of specific variant classification, as variably suggested by Rowlands [83] and Schmidt and Burgess [86], has generally not been undertaken due to the poorly-defined nature of these categories, South-western palstaves of variant Crediton have been acknowledged here-in due to the clear diagnostic features of this type and their relevance for the study location.

*Table 15* presents a summary of the data relating to the typological make-up of the full sample. The complete dataset can be found listed in Appendix B. The typological composition of the sample spans a relatively full spread of types of palstave axe available during the Middle Bronze Age. The data shows that the sample is weighted towards axes dating to the core of the MBA, for example, Group III palstaves and south-western palstaves, with these categories comprising just over half the sample. Conversely, the sample consists of only twenty-eight axes dating to the beginning of the MBA, for example, Group I and Group II palstaves; also included within this are four flanged axes,

which, while not technically palstave axes, date roughly to the transition between the EBA and the MBA. The remaining 20% of the palstave axes in the sample belong to type categories that date to the latter stages of the MBA, for instance, Transitional, Double-looped and Narrow-bladed palstaves. The fewer number of later palstaves reflects a general trend of the lower prevalence of these types within Britain in comparison to those that proceeded them [86].

| Axe type | No. of axes |
|---|---|
| Flanged axe | 4 |
| Irish palstave | 1 |
| Group I | 15 |
| Group II | 9 |
| Group III | 24 |
| Group IV | 1 |
| South-western | 17 |
| South-western variant Crediton | 11 |
| Transitional | 15 |
| Narrow-bladed | 2 |
| Double-looped | 3 |

**Table 15**: The number of axes within each category of axe type.

*Figure 141* presents a graphical display of the composition of axe types within the south-west sample, while *Figure 142* shows the comparable data for the Coghlan sample. Both samples have a similar proportion of Group III palstaves – the typology which is considered to be most consistently represented across Britain. However, the south-west sample has far fewer Flanged axes and Group II palstave axes compared to the Coghlan sample. The different number of Flanged axes is easily explained by sample selection, since Coghlan appears to have more readily included these transitional variants in his analysis than Northover. In terms of the Group II palstaves, Rowlands suggests that the find locations of Group II palstaves are mostly concentrated around the south-east, Thames Estuary and east of England. Unsurprisingly, the south-west sample has a large number of South-western palstaves, and the associated Crediton variant, which comprise 31% and 12% of the sample, respectively. Compared to the south-west sample, the range of types in the Coghlan sample is less and omits the South-western (though not variant Crediton) palstaves and Double-looped types entirely. This may be related to the smaller number of palstave axes (n = 24) within the Coghlan sample, which possibly does represent the full amount of variation within the population.
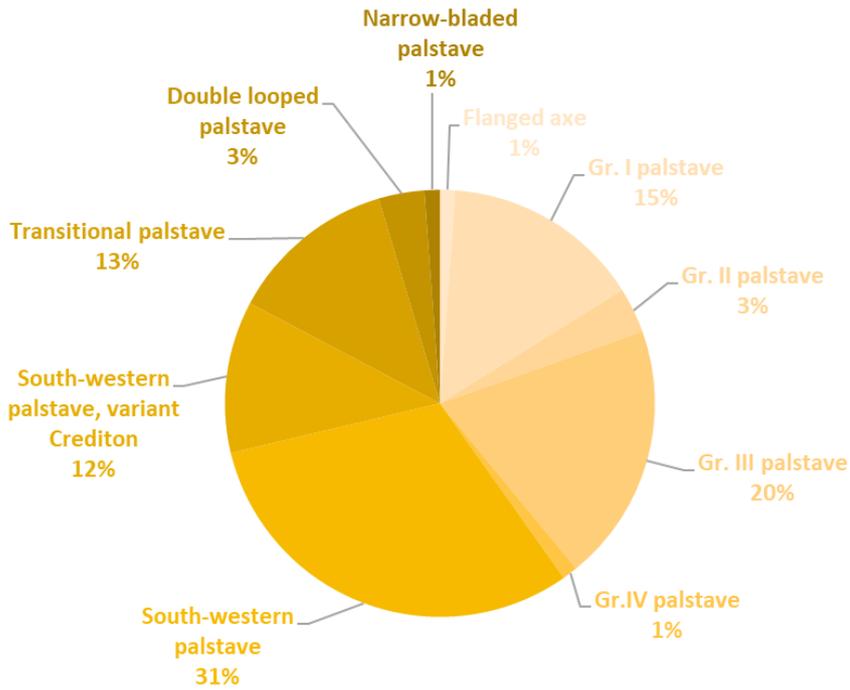
*Figure 141:* Pie chart suggesting the typological composition of the south-west sample.
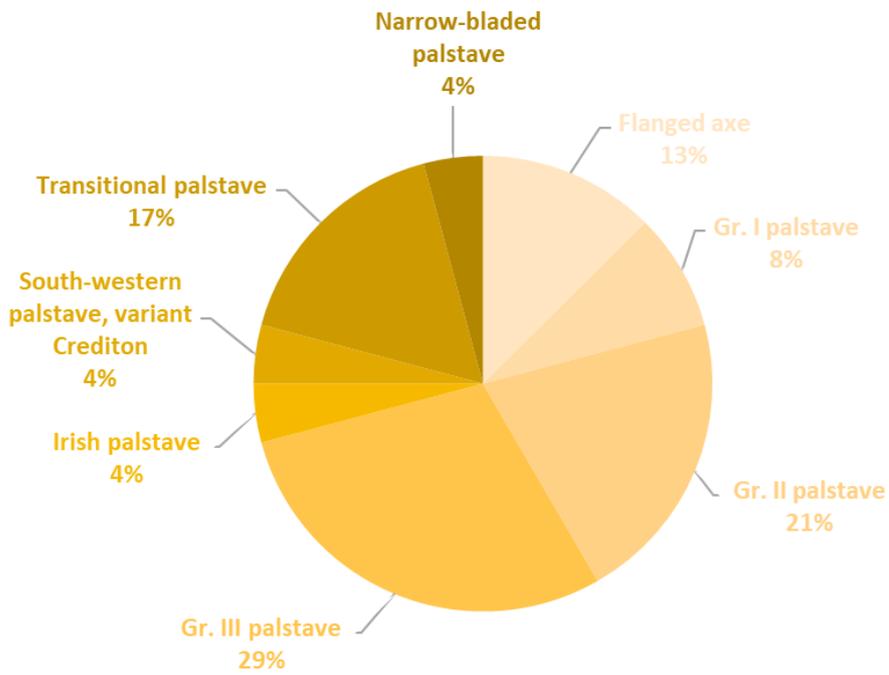


*Figure 142:* Pie chart suggesting the typological composition of the Coghlan sample.

208

## 7.2   Chemical considerations

Northover conducted the chemical characterization of the south-west sample using Electron probe microanalysis (EPMA) with energy-dispersive spectrometry. No details are given by Coghlan about the type of chemical analysis that was undertaken in order to elucidate the elemental composition of the palstave axes included in his analyses. In order for tin content to be discussed easily within the life trajectory analysis, quantitative categories relating to tin percentage were assigned to each axe. These categories were determined by numerical methods; the Coghlan and south-west composition data was pooled and then a box plot was made to split the data into quartiles (*Figure 143*). Thus, the axes that fall between the range of 1-10.8% tin fall into the 'Low tin' category, those that have a range between 10.9-12.6% are in the 'Medium-low tin' category, the axes that have a tin value between 12.7-14.1% fall in the 'Medium-high tin' category, and those that have a tin value between 14.2-20% are included in the 'High tin' category. The plot demonstrates that while there is a large range in the tin content of the palstave axes, 50% of the combined sample sits between 10.9-14.1% tin content.
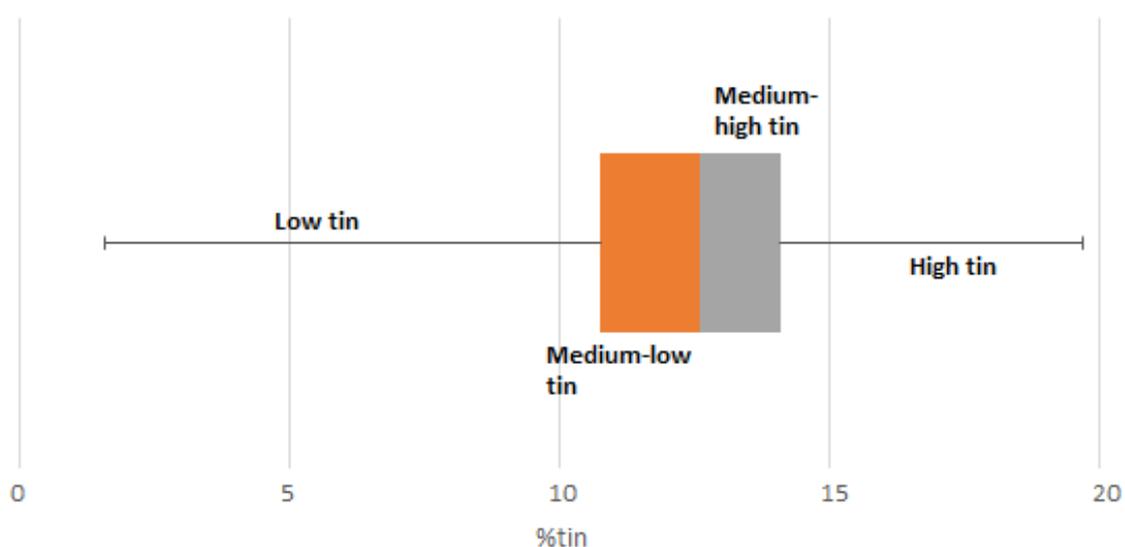


*Figure 143:* Box plot demonstrating the distribution of tin percentage within the full sample.

## 7.3   Microstructural evaluation

The mounts made available by Peter Northover were accessed via his private collection and taken to the Materials Laboratories at the University of Southampton for preparation. Eight mounted samples were found to be absent and could not be subjected to metallography, seven were only drilled samples, and a further two were not in a good enough state of preservation for an accurate evaluation to be made. The metallographic drawings, descriptions, and chemical composition data pertaining to a further twenty-six palstave axes, published by H.H. Coghlan in several papers published in 1970 [135], [137], was used to infer the microstructural properties of these objects.

The methodological approach adopted by both Peter Northover and H.H. Coghlan for the extraction of samples for metallographic analysis was fairly similar. The samples obtained by both analysts were small segments extracted from the cutting-edge of each axe, though it should be noted that a much greater amount of material was removed on the axes sampled by Coghlan. They were cold-mounted using an epoxy resin to avoid any microstructural homogenisation that may have resulted from hot-press mounting. The samples that were not re-analysed and, therefore, were prepared by Coghlan, were polished using a 6 μm diamond paste on a 6 μm cotton disk, and 1 μm diamond paste on a 1 μm cotton disk. An acidified ferric chloride solution was used to etch the samples. In keeping with the method described above, the samples that were available for re-analysis were prepared using a similar method, which also happens to be the approach preferred by Scott [275]. To begin, the mounts were ground using a fine-grained silicon carbide paper. Each sample was then polished using a 6 μm diamond suspension on a Buehler Texmet cloth and, subsequently, a 1 μm diamond suspension on a Buehler MasterTex cloth. Finally, an acidified ferric chloride solution (100ml of ethanol, 20ml of HCL, and 5g of Iron(III)-chloride) was used to etch the samples over several light applications.

The metallographic assessment incorporated a number of microstructural variables as stipulated below. Firstly, in order to give some comparable gauge of the casting quality of each axe, the severity of porosity – investigated during the initial microscopic assessment of the unetched metallographic mounts – was simplified into three categories. These are as follows, with an explanation of their determination criteria: 'Minor porosity', (very few small pores can be observed); 'Moderate porosity', (regular pores of a small size can be observed); 'Severe porosity' (numerous pores that may be of a considerable size can be observed). While the criteria for these categories does take into account the number of pores that can be observed within the sample, the delegation of samples into certain categories could, perhaps, have been made more robust by

measuring the exact size of pores, rather than using visual perception only. Also, it should be said that since only one sample was extracted from each 'south-west' palstave axe by Northover, and as these were often small and slightly deteriorated, the evaluation of porosity may not be fully representative of the general casting quality of the axe. Instead, Coghlan generally sampled the axes in multiple locations and the sample size was much larger, giving a good idea of the prevalence of porosity throughout the entirety of the cast.

Following this, the type of microstructure (for example, recrystallized, partially recrystallized, or dendritic) of each sample was recorded. As mentioned frequently throughout this thesis, the type of microstructure often alludes to the way that the object was manufactured. In addition, an appreciation of the underlying microstructure is vital for determining how the object might respond to mechanical stress during use. The presence of annealing twins within recrystallized microstructures was also recorded, as this feature suggests that the axe had been hammered prior to annealing. Lastly, evidence of strain-lines and crystal grain distortion, which suggest final cold-hammering of the axe blade, was recorded. The pervasiveness of this feature was also noted and used to deduce the extent of the final hammering treatment; for example, a few strain-lines were present towards of the exterior was considered suggestive of a light cold-hammering, but heavy distortion of the sample indicated a strong final hammering. For the construction of easily comparable life trajectories, the overall degree of processing received by each axe was simplified into several categories. Firstly, axes that were manufactured according to the hammer-anneal-hammer sequence (recrystallized, annealing-twins, and strain-banding) were labelled as having 'full' processing. Secondly, axes that were manufactured by differing methods, for example, did not receive a final hammering (no strain-banding), were labelled as having 'partial' processing. All axes that presented a dendritic microstructure were labelled as 'as-cast'.

## 7.4   Metalwork wear analysis

The metalwork wear-analysis was performed in-situ at the aforementioned museums. The first step in the assessment of metal wear was determining the suitability of the object for analysis. The pie chart that comprises *Figure 144*, indicates the proportion of the combined sample (Coghlan and south-west palstave axes together) that could be analysed using micro- and macro- analysis. The condition of the sample in terms of preservation was, generally, quite poor. Many of the palstave axes within the sample were discovered over one hundred years ago. Hence, these axes begun their time in curation when attitudes to archaeological objects were very different. While conservators

are now concerned about preserving the maximum amount of information from the artefact, in the past, antiquarians wanted the objects to be reinstated to their former appearance. This means that objects were often re-ground to remove corrosion, or heavily waxed. Equally, the corrosion exhibited on these samples was probably more severe since many of them were found on acidic soils moorland soils in the south-west of England. Hence, while the identification of micro-level wear was possible on 45 palstave axes, the remaining 57 were not suitable for this type of analysis; this was a result of, the absence of the cutting-edge (4.3%), past conservation methods like varnishing (5.4%), modern cleaning/regrinding (20.7%), and corrosion (25%). Nonetheless, macro-level use-wear analysis was possible for 91% of the sample – the only specimens that were not suitable for analysis were those where the blade had completely broken off.
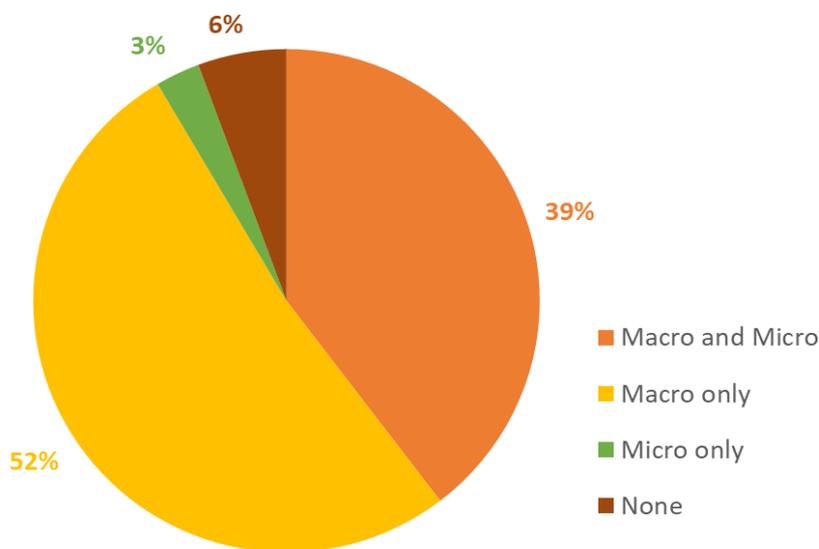


*Figure 144:* Pie chart displaying the suitability of the complete sample for different types of analysis.

The methodological approach for the metal wear analysis included here-in was based upon the procedure demonstrated by Crellin [154], and closely related to the approaches taken during the experimental phase of research. Objects were examined by a portable digital microscope (DinoLite 2.0) at magnifications of ×25 to ×50, and by visual inspection, with the use of a Fujifilm FinePix S1900 digital camera to document areas of interest. All wear marks were recorded, on illustrations and in a datasheet. The data categories selected for analysis closely resembled those used by Crellin [154]. The categories related to features generated by manufacturing processes are described below. Each object was examined for the presence of casting seams to indicate the type of mould that was used. Any marks or cracking left by hammering were recorded to further ballast the

metallographic data. Each object was scrutinised for evidence of trapped gases and casting defects that may further indicate the quality of the cast. Next, the object was analysed for evidence of incomplete polishing to suggest palstave axes that had not been prepared for use. Similarly, the blade was inspected for evidence of striations parallel to the blade, which, as determined in the experimental work in sections 6.3 and 6.4, is indicative of sharpening.

The data categories adopted to capture a comprehensive picture of use-wear are described below. The cutting-edge of each palstave axe was scrutinized for any obvious areas of deformation, such as bending and nicks, which were then documented. As already mentioned in section 6.5, any areas of shallow depression at the cutting-edge could be previous sites of contortion that have been corroded or partially sharpened away, and for this reason, they were also recorded. The blade was examined for striations perpendicular to the blade, which as the experimental work demonstrated, are most likely a result of use. Where possible, the scheme developed for tracking the progression of use-striations at the cutting-edge (

*Table 13*) was used to estimate the amount of use that the object had been subjected to since it was last sharpened. As suggested above, the use-wear data categories recorded for each palstave axe were based upon those suggested by Crellin [154] and, as such, the analysis incorporated the investigation of the butt of the axe as well as the cutting-edge. This involved examining the septum of each palstave axe to investigate if any wear was produced by the hafting arrangement during use. Although no experiments were conducted to document the progression of hafting striations, it is likely that only a considerable amount of use would be able to produce striations in the septum of the butt. As such, hafting striations were considered valid evidence when determining whether an object was used or not. Nonetheless, the identification of hafting striations was based on the intuition of the analyst and, as a result, there is likely to be some inaccuracies within the reporting of this feature. Rounding of the edges of the butt and asymmetry of the butt were also recorded during analysis. However, due to unknown interactions with processing and maintenance practices, these types of wear were not taken into account when determining whether the object was used or not.

It was necessary for simplified labels to be assigned to some use-wear characteristics (namely blade sharpness and asymmetry). The allocation of blade sharpness was largely determined by the 'Thickness of blade (mm)' measurements made with a caliper, and also by visual and sensorial inspection (the feel of the cutting-edge across the thumb) during handling. A 0-1mm thickness of the blade was considered to be 'Sharp', a 1-2mm thickness of the blade corresponded to 'Medium sharpness', and a blade thickness of >2mm corresponded to 'Blunt'. The assessment of blade

asymmetry is presented below; this measure was used to determine the overall use-intensity experienced by each axe. The decision was made not to use the calculations proposed by Moyler [6] to create quantitative data to measure asymmetry; without proper modelling of the rate of total material loss at the cutting-edge over sustained use and sharpening, these calculations would have been essentially meaningless, and arbitrary labels would still be necessary. Instead, the scheme developed for tracking the progression of macro-scale use-intensity features at the cutting-edge (*Table 14*) was used to estimate the number of cycles of use and sharpening each palstave axe had received. Hence, the blade was labelled as 'Symmetrical' if no material loss could be discerned – accordingly, based on this factor and others, e.g., if the axe has not been finished, and if there was no evidence of hafting striations, the utilitarian use-history of the artefact was considered to be 'None'. The blade was labelled as having 'Slight asymmetry' if some material loss from one corner of the blade could be observed, but was only just noticeable, indicating the blade had failed and been resharpened at least once, indicating 'Minimal' use-intensity. The blade was labelled as having 'Moderate asymmetry' if it was clearly skewed by at least several blade failure events and resharpening attempts – axes of this kind were assumed to have sustained a 'Considerable' use-intensity. The blade was labelled as having 'Severe asymmetry' if the blade was completely lopsided due to an 'Extensive' number of use, failure, and sharpening cycles.

## 7.5   Classification of damage

The methodological approach for the determination of damage was based upon the principles and procedures suggested by Knight [13] for the examination of damage on palstave axes. Objects were examined by visual inspection and multiple photographs were taken of each axe using a Fujifilm FinePix S1900 digital camera. All areas of damage were recorded on illustrations and in a datasheet. A singular data category, 'areas of  breakage', was used to encourage a full descriptive evaluation of the entire object, rather than confining the scale of analysis to only the blade and butt [cf. 122]. In order to highlight palstave axes that were given special treatment before discard, it was vital to distinguish the types of damage that were not intentional – for instance, those that were generated during use, or occurred due to existing casting flaws – from palstave axes that exhibit areas of damage that signify purposeful destruction.

The deduction regarding the type of damage sustained was determined by a close examination of the breakage. The visual inspection of the zone of breakage first involved an assessment of the patination and corrosion. If the patination and corrosion were not consistent with the overall

condition of the axe, the break was considered to have occurred 'Post-deposition'. If the colour of patination and severity of corrosion was found to be similar to the overall condition of the axe, the break was considered to be ancient. The likely 'patterns of breakage' for palstave axes have already been discussed in detail within sections 2.2.1.8 and 4.2. Hence, when breakages were found within the flanges, side-loop, or stopridge, they were generally considered to be 'Accidental', unless otherwise specified. As a result of flaws that were introduced during the initial cast, it is possible that breakage may have occurred both in areas that have no kind of predisposition due to design. Thus, if the overall casting quality was known to be poor, and during the visual inspection, casting flaws were noticeable within the zone of breakage, it was assumed that the material was particularly weak in this location and damage was labelled as 'Accidental'. If breaks occurred in unusual places, for example, across the body of the blade, or across the lower section of the blade, and there was no evidence of casting flaws or trapped gases, the fracture was labelled as 'Deliberate'. It was possible to define a break as intentional with some certainty if there were blow marks surrounding the location of fracture.

## 7.6 Deposition context

It was possible to find published bibliographic information for all the palstave axes in this study; this information was mostly drawn from Coghlan [116], Coghlan [137], Rowlands [83], and Pearce [84]. Many of the palstave axes within the sample were discovered in the 19th or early 20th century, during excavations, or by chance discovery. The data categories relating to the deposition context included: the find location, to geographically pinpoint the place the item was deposited; the type of terrain at the find location, indicating the preferred environments for deposition; and, the associations of the deposit (for example, whether the find was isolated or a group), which suggests the interrelatedness of the objects within the sample. The south-west sample was confined to palstave axes discovered within the counties of Cornwall, Devon, Dorset, Somerset, and Oxfordshire. The selection of these objects by Northover was random. A good number of the artefacts, especially from the south-west sample, could be provenanced to a local level. The sampling strategy adopted by Coghlan was not specified any of the relevant publications [116], [135], [137], however, it is likely that he analysed all of the palstave axes that were held at the Pitt Rivers and the Newbury Museum at the time of his research project. The Coghlan palstave axes are generally not local finds to each respective museum, and they do not belong to any particular geographical or culturally-specific area. Thus, there is a clear difference in the contexts of the two

samples; those from the south-west of England are closely related by their membership to this area, whereas the Coghlan axes are a highly uncorrelated sample, containing artefacts from diverse cultural backgrounds. Just under a quarter of the full sample can be considered as having completely unknown associations and an uncertain environmental context – sixteen of these objects were part of the Coghlan sample, many of which had very limited bibliographic information found in relation to them.

# 8 Results and Discussion of the Archaeological Analysis

This chapter presents the results obtained during the archaeological investigation of ancient palstave axes from Britain and Ireland. This does not commence with a synthesised discussion of the individual narratives. Instead, it was seen necessary to first contextualise the intricacies of the biographies by trying to pick out general patterns in the data. As such, section 8.1 focuses on relaying the results obtained for each stage of life of the palstave axes analysed here-in, while establishing how similar or different this data is across the two samples. Following this evaluation, section 8.2 draws together the commonalities seen within the lives of palstave axes to suggest some typical ways in which palstave axes may have interacted with humans, or vice versa, and how this dynamic influenced Bronze Age society. Nonetheless, generalisations of this kind undoubtedly miss the dynamic interplay conferred by the individual stories of objects. Hence, the subsequent section (8.3), presents the data in a form that reveals the high variability in the life trajectories of palstave axes of the same type, and suggests just how individualistic their lives were. As mentioned throughout the above text, the primary output for this study was the production of individual narratives for each palstave axe (see Appendix B). These datasheets combine all of the known characteristics of the object that were obtained during analysis (with images to substantiate any observations); the sequence of data was thereafter transformed into an account of the life of the object using the methods for data interpretation set up above. This summary of the detailed biographies of the palstave axes (section 8.4), works to highlight objects that have had an extremely unique life, suggesting unusual and understated ways in which the relationships between people and palstave axes unfolded. Lastly, section 8.5, conveys the vast variation in life story that exists between objects belonging to the same assemblage.

## 8.1 Unpicking the lives of palstave axes from Bronze Age Britain: a comparison between the Coghlan and south-west samples

This section addresses each element in the sequence of life of the palstave axes in-turn, reporting the results of certain data categories and drawing out differences in the data between the south-west and Coghlan samples. It should be reiterated that the latter of these two groups does not reflect a specific geographical area, and consists of axes found all over Britain. It cannot be assumed to represent a control group, since the data could be unknowingly skewed in any direction. Equally, the south-west sample is represented by seventy-eight palstave axes, while the Coghlan sample

comprised only twenty-four. Regardless of these issues, the comparison presented here-in should still be able to provide a sufficient understanding of whether the data generated from the south-west axes differs from palstave axes found in other locations. As well as summarising data from the original sampling categories (the raw data is presented in Appendix B), seven simplified categories relating to key biographical stages in the life of a palstave axe were constructed to create easily comparable life profiles of each object. These variables, which have been individually discussed and justified in Chapter 7, are as follows: Tin content, Processing, Use-intensity, Final condition, Damage, Find terrain, and Find associations.

### 8.1.1   Composition

The results produced from the composition data indicate that there is a concentration of palstave axes containing between 10 and 14% tin. The palstave axes of the south-west sample, on average, have a greater tin content than those within the Coghlan sample. To be specific, the south-west sample, has a range of tin percentage from 6.44% to 19.7%, and a median average of 13.26%. In contrast, the Coghlan sample has a range of tin percentage from 1.3% to 13.8%, and a median average of 10.1%. As discussed at multiple points during this thesis, the common range of tin content within Bronze Age palstaves is 10-14%; however, the average value for the Coghlan samples sits right at the bottom of this range, and contains several palstave axes with really low tin contents. In contrast, the average value for the south-west samples sits at the top of this range, with (as demonstrated by *Figure 145*) certain palstave axes, for example, DOR-1884.9.22 (16.94% tin), DOR-1884.9.3 (17.82% tin), and RAMM-593/2005 (19.7% tin), reaching well above it.
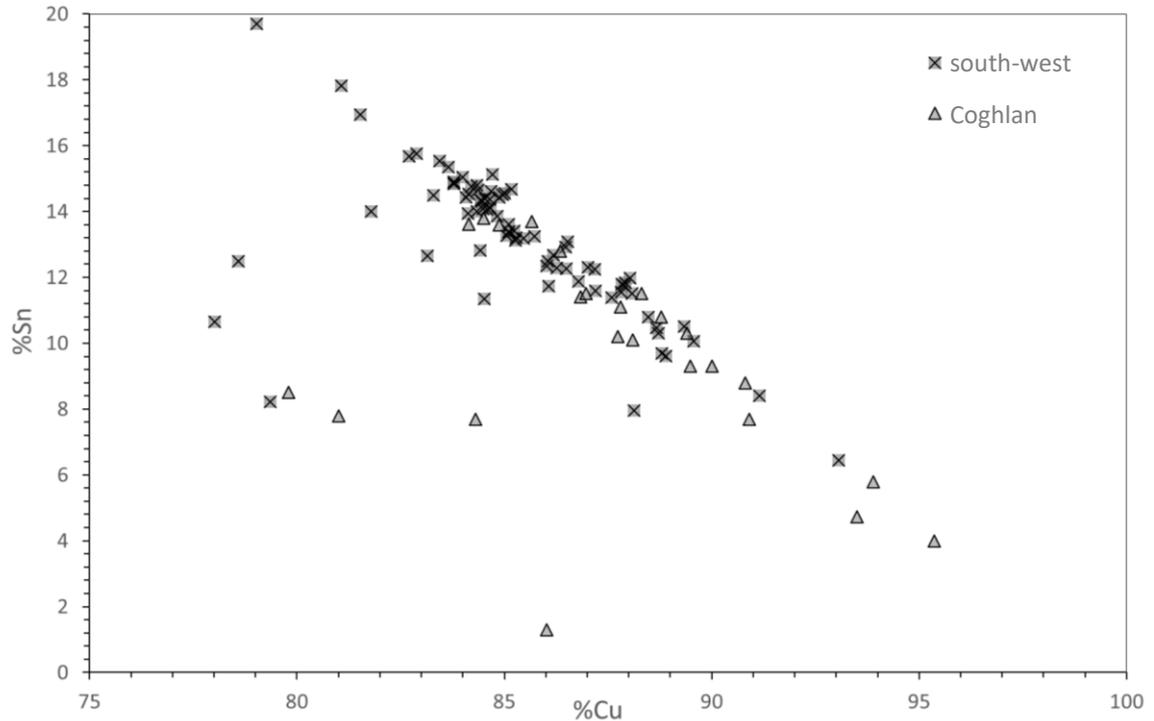
**Figure 145:** Percentage copper and tin in each palstave axe within both datasets [116], [135], [137].

As *Figure 146* suggests, the south-west has many more palstave axes (35% of the sample) with a high tin content than the Coghlan sample (no axes with above 14.2% tin). Equally the south-west sample has far fewer palstave axes containing a low tin content (deemed as <10.8% tin here-in), whereas artefacts with this level of tin make up almost two thirds of the Coghlan sample. Some suggestions can be made as to why greater amounts of tin were added to palstave axes in the south-west; firstly, it could be related to the rich tin resources in Cornwall and Devon that meant that ore was more readily available; secondly, it could mean that the mechanical properties were often a secondary concern to other features, such as colour, or visual distinctiveness; or perhaps, the metallurgists of the south-west had intentionally increased tin content for a greater durability against the hard timbers (Quercus and Betula) that were heavily distributed across the region [260].
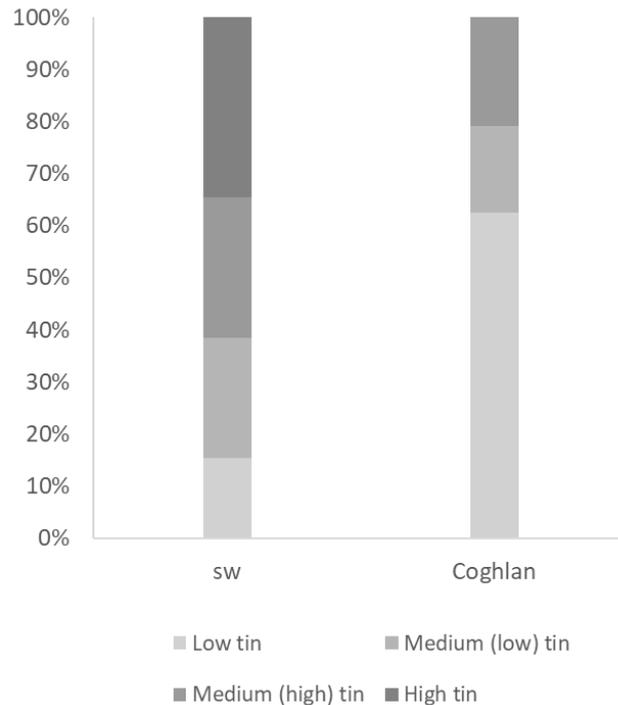
*Figure 146:* The proportion of palstave axes within each tin content for both the south-west and Coghlan datasets [116], [135], [137].

As seen in *Figure 145*, most of the palstave axes demonstrate a well-fitting negative relationship between copper and tin content (as copper content decreases, tin content increases) suggesting that only a few contain a significant amount of impurities or deliberate additions of other minerals. On analysis of the data for arsenic content, calculations of median average (chosen to eliminate the impact of outliers) suggest that the south-west sample contained only 0.35%, while the Coghlan sample contained a slightly higher value of 0.61%. Similarly, the median averages for lead content indicate that the south-west sample contained only 0.15%, while the Coghlan sample contained a slightly higher value of 0.59%. Palstave axes with notable additions of lead from the south-west sample fall within typologies with a later chronology, i.e., DCM-1902.1.3 and MoS-75.AA.4 (both Transitional) and MoS-63B (Narrow-bladed), conforming to the, generally accepted, idea that lead was introduced into Bronze Age metalwork at the end of the MBA. Conversely, palstave axes containing a large amount of lead within the Coghlan sample are earlier variants, i.e., WBM-OA324 (Gr.I palstave) and PR-1884.119.113 (south western palstave, variant Crediton), within which, it is generally quite unusual to find such significant inclusions. Another metal that is commonly found within the south-west sample is nickel, which contributes an average value of 0.36% within the metal composition of the south-west axes. This is consistent with the nickel content within the Coghlan sample, which was found to be 0.37%. Other elements that variably and inconsequentially

feature within the make-up of the palstave axes from both samples were, cobalt, antimony, silver, gold and zinc.

## 8.1.2    Casting

In terms of the casting characteristics that were documented for each of the palstave axes, it appears that only a quarter of the sample did not exhibit casting seams; this suggests that the majority of the axes were almost definitely cast using a bivalve mould. The adoption of bivalve moulds was likely necessary in order to create the deep septum and intricate features such as loops. In terms of the overall casting quality of the sample (*Table 16*), just under half the sample contained no signs of porosity, indicating that a highly-skilled craftsperson was responsible for their creation. Porosity of the metal and trapped gases upon the surface of the sample were identified in 17% of the sample, with another 20% of palstave axes presenting porosity but no trapped gases, and a further 17% exhibiting only trapped gases but no porosity. This demonstrates that the presence of trapped gases on the surface of the sample cannot be used to assume that the internal casting quality is poor, and vice versa. Only six of the palstave axes that were examined presented any noticeable casting defects.

| *Degree of porosity observed* | No. of palstave axes |
|---|---|
| *Unknown* | 18 |
| *No porosity* | 46 |
| *Micro-porosity* | 7 |
| *Mild porosity* | 17 |
| *Moderate porosity* | 9 |
| *Severe porosity* | 5 |

**Table 16:** Qualitative condition descriptions of the degree of porosity observed for the full sample (south-west and Coghlan combined) [116], [135], [137].

## 8.1.3    Processing

The bulk (71%) of the palstave axes exhibited a recrystallized, twinned, microstructure, suggesting that they had been produced by a process of hammering and annealing (*Table 17*). Within this group of recrystallized, twinned palstave axes, only one in ten did not demonstrate evidence of strain-lines within their microstructure and, thus, did not receive a final hammering (*Table 18*). It should be noted that evidence of hammering upon the surface of the axe was rarely observed despite the clear occurrence of such practices across the sample as seen in the microstructure. This result has

an obvious explanation: much less shaping work is required when using bivalve moulds, hence leaving less conspicuous markings. A small proportion (15%) of palstave axes demonstrated a dendritic microstructure, which indicates that they were largely left in an as-cast form (*Table 17*). Only nine palstave axes presented an unfinished surface (though, as already suggested, a considerable amount of the total sample could not be analysed by microscopy) – interestingly, while three of these were axes with a dendritic microstructure, the remaining six had been, otherwise, fully processed (*Table 19*). Finally, as presented in *Table 20*, just over half of the palstave axes that had their blade examined by microscopy demonstrated evidence for sharpening, indicating that attempts were made to ready the cutting-edge for use or display on at least one occasion, and in some circumstances this provided the final treatment of the axe prior to discard.

| *Observed microstructure* | No. of palstave axes |
|---|---|
| *Unknown* | 12 |
| *Dendritic* | 15 |
| *Recrystallized* | 75 |

**Table 17:** Assessment of the microstructure of the full sample (Coghlan and south-west axes combined) [116], [135], [137].

| *Evidence of strain-banding* | No. of palstave axes |
|---|---|
| *Unknown* | 27 |
| *No* | 8 |
| *Yes* | 67 |

**Table 18:** Assessment of the presence of strain-banding within the microstructures of the palstave axes (combined sample) [116], [135], [137].

| *Incomplete finishing* | No. of palstave axes |
|---|---|
| *Unknown* | 69 |
| *No* | 24 |
| *Yes* | 9 |

**Table 19:** Assessment of the state of surface finish of the palstave axes (combined sample).

| *Sharpening striations* | No. of palstave axes |
|---|---|
| *Unknown* | 69 |
| *No* | 16 |
| *Yes* | 17 |

**Table 20:** Evidence of sharpening striations on the palstave axes (combined sample).

As shown in *Table 21* and *Figure 147*, the south-west sample contains a much larger number of as-cast axes, which could suggest that more palstave axes from this area were not always destined for use in woodworking activities. On the other hand, the Coghlan sample has a larger proportion of axes that were not processed fully compared to the south-west sample. This could suggest that the skill level of bronzesmiths and, therefore, the quality in the production of Bronze metalwork, was more consistent in the south-west than elsewhere in the country. If one assumes that the south-west was, at some point, most likely a hub for the production of bronze (during the height of tin extraction at least), it is not hard to imagine that it would have produced, and attracted, some craftspeople who were true artisans of their trade.

| *Processing* | south-west | Coghlan | Total |
|---|---|---|---|
| *Unknown* | 13 | 0 | 13 |
| *As-cast* | 13 | 2 | 15 |
| *Partial* | 4 | 7 | 11 |
| *Full* | 48 | 15 | 63 |

**Table 21:** Comparison of the degree of processing of palstave axes from each sample [116], [135], [137].
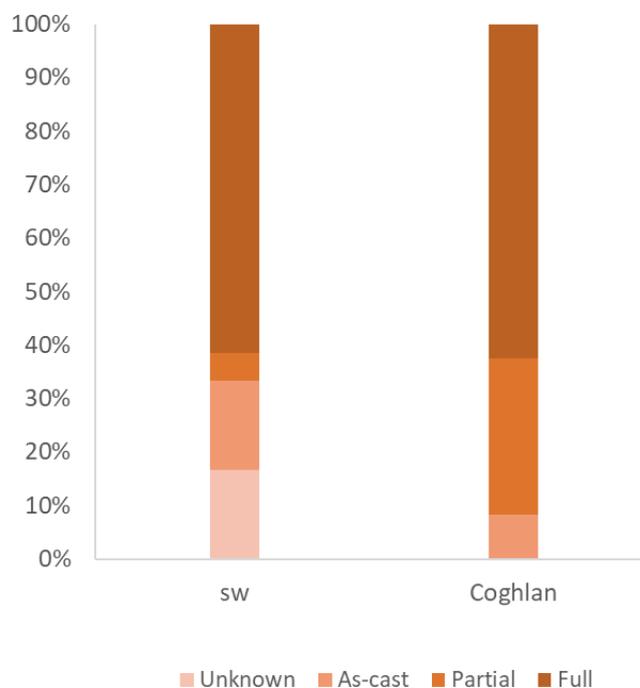


**Figure 147:** The proportion of palstave axes within each processing category for both the south-west and Coghlan datasets [116], [135], [137].

## 8.1.4   Use

The visual assessment of use-wear on the sample of palstave axes demonstrated that evidence of asymmetry was present on just under half of the axes deemed suitable for analysis, with the majority of these exhibiting only a slight amount of material loss from one blade tip (*Table 22*). Palstave axes that were more overtly asymmetrical were much fewer in number, illustrating an apparent predilection for axes that showed little sign of obvious use within deposition practices. In accordance with this observation, indications of depression or contortion at the cutting-edge were presented on only 16% of the sample, while 79% were free of any features that resembled, or may have once resembled, an area of bending (*Table 23*). Lastly, the data collected on the sharpness of the cutting-edge (*Table 24*) suggested that the sample was split fairly equally between the three aforementioned categories ('Sharp', 'Medium', and 'Blunt'), though it quickly became apparent that this data could not be used to reliably suggest whether an axe had been used, since the original sharpness of the cutting-edge of each artefact was unknown.

| Evidence of asymmetry | No. of palstave axes |
|---|---|
| Unknown | 9 |
| None | 44 |
| Slight | 34 |
| Moderate | 7 |
| Severe | 4 |

**Table 22:** Assessment of the degree of asymmetry presented on the blade of the palstave axes (full sample).

| Depression or bending | No. of palstave axes |
|---|---|
| Unknown | 7 |
| No | 79 |
| Yes | 16 |

**Table 23:** Evidence of major deformations on the cutting-edge of the palstave axes (full sample).

| Blade sharpness | No. of palstave axes |
|---|---|
| Unknown | 8 |
| Blunt | 30 |
| Medium | 31 |
| Sharp | 33 |

**Table 24:** Assessment of the degree of sharpness presented by the Blade of the palstave axes (full sample).

In terms of the micro-scale analysis, use-striations were found on a third of the palstave axes that were suitable for analysis (*Table 25*). The limited observation of this feature is partly related to the prevalence of other surface features. For example, 27% of the palstaves axes examined by microscopy were unfinished and 52% were found with sharpening marks – although use-striations and sharpening striations are not necessarily mutually exclusive as the former may overlay the latter when the axe has been used subsequent to sharpening. Moreover, experimental work demonstrated that faint use-striations could be only be detected after only 750-1000 impacts on 14% tin-bronze replica palstave axes, and it may be that only severely worn surfaces retain any evidence of these impressions after corrosion processes have been at work on the ancient palstave axes. This seems to be the case with the use-striations observed here-in, which more often than not appeared without the presence of sharpening striations. This indicates a very extended period of use prior to deposition that eradicated any sharpening marks and left indentations that were deep enough to survive a degree of chemical alteration post-deposition. Hafting striations were recognised on an additional nineteen artefacts, which equated to 57% of palstave axes with a surface within the septum that was preserved enough for analysis (*Table 26*). Hence, marks left from hafting appear to have been slightly better retained within the surface. An interesting difference between the Coghlan and south-west dataset regarding evidence of use is that no axes in the former group were buried with a failure at the cutting-edge, while a small number of the latter group were (*Figure 148*). This disparity may just be a result of the smaller sample number of the Coghlan axes, or it could be reflective of the relatively high tin-content of the south-west axes, which may have predisposed them to failure. Moreover, there may have been certain rules governing the selection of palstave axes with particular qualities for deposition (this will be addressed later).

| *Use-striations* | No. of palstave axes |
|---|---|
| *Unknown* | 69 |
| *No* | 22 |
| *Yes* | 11 |

*Table 25:* Evidence of use striations on the palstave axes (full sample).

| *Hafting striations* | No. of palstave axes |
|---|---|
| *Unknown* | 51 |
| *No* | 22 |
| *Yes* | 29 |

*Table 26:* Evidence of hafting striations on the palstave axes (full sample).

When the results presented above are extrapolated to produce use-intensity estimates (using asymmetry as the determining attribute as discussed in section 7.4), it appears that the south-west and Coghlan datasets are very comparable (and *Figure 149*). The data presented below suggests that around 30% of the palstave axes that exhibited evidence of use were only used very minimally, while relatively few could be described as demonstrating signs of extensive use, and ~16% fell somewhere in between these two categories (moderate use). The only major differences between the use-intensity data presented by the two samples is that more of the Coghlan sample, proportionally, have an unknown use-intensity, and there are fewer axes with no use in the Coghlan group than the south-west group. This may suggest that palstave axes from the south-west were less likely to have been used for wood-chopping activities before their identities assumed a symbolic or ceremonial meaning than in the wider population.
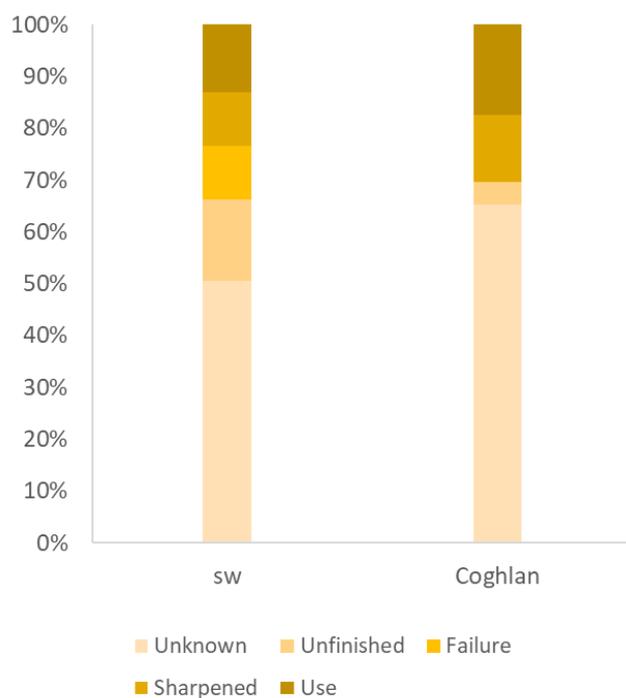


**Figure 148:** The proportion of axes within each final condition category for both the south-west and Coghlan datasets.

| Use-intensity | south-west | Coghlan | total |
|---|---|---|---|
| *Unknown* | 25 | 10 | 35 |
| *None* | 13 | 2 | 15 |
| *Minimal* | 25 | 7 | 32 |
| *Considerable* | 12 | 4 | 16 |
| *Extensive* | 3 | 1 | 4 |

**Table 27:** The estimated use-intensity of the palstave axes in each dataset, and as a total of the combined sample.

226
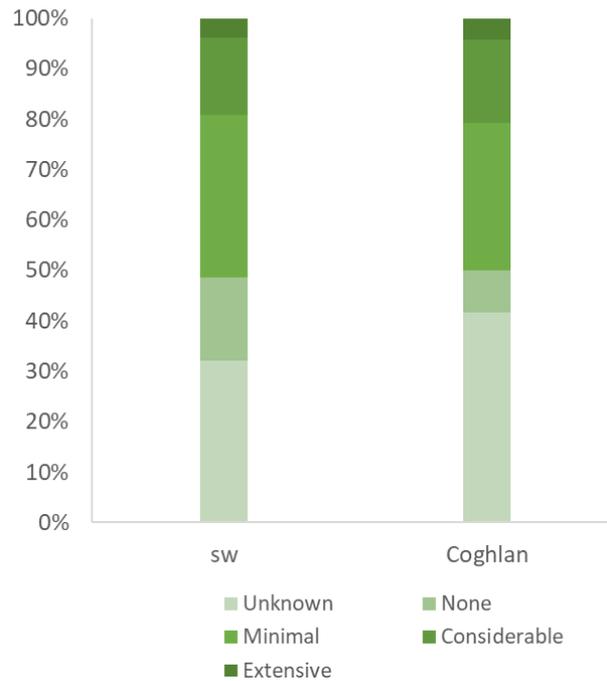
*Figure 149:* The proportion of palstave axes within each use-intensity category for both the south-west and Coghlan datasets.

### 8.1.5 Damage

Like the estimation of use-intensity presented above, the data regarding the assessment of damage for both the south-west and Coghlan samples is very similar. The data presented in *Table 28* and *Figure 150* suggests that approximately half of the palstave axes in each sample exhibited no signs of damage. The percentage of palstave axes found with post-depositional damage was very close between the south-west and Coghlan samples, at 14.1% and 12%, respectively. Similarly, 25.6% of palstave axes within the south-west sample were found with signs of accidental damage, while 20.8% of the Coghlan sample were likely broken by accident in antiquity. It was clearly quite common for palstave axes to be broken during use; as well as broken side loops, damage was especially prevalent on the flanges, which often were often warped or cracked, possibly reflecting deterioration due to the stress induced by hafting processes. The number of palstave axes that had obvious indications of deliberate damage was relatively low for both samples, with a marginally higher proportion in the Coghlan sample. This topic will be continued in more detail in section 8.2.

| Damage | south-west | Coghlan | Total |
|---|---|---|---|
| None | 41 | 13 | 54 |
| Post-depositional | 11 | 3 | 14 |
| Accidental | 20 | 5 | 25 |
| Deliberate | 6 | 3 | 9 |

**Table 28:** Comparison between the south-west and Coghlan samples for the primary type of damage present on each palstave axe.
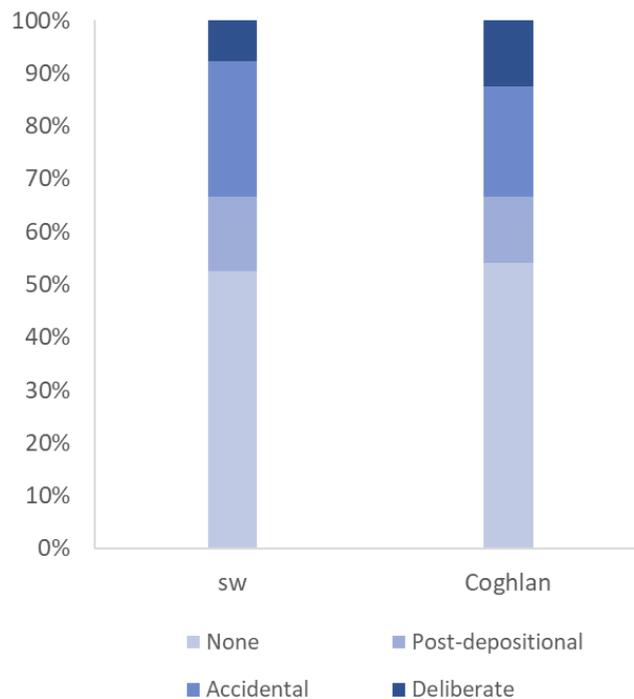


**Figure 150:** The proportion of palstave axes within each damage category for the south-west and Coghlan datasets.

## 8.1.6   Deposition

It is difficult to derive many meaningful trends within the data relating to deposition circumstances due to the limited availability of information relating to the find context and content of a large number of artefacts. On examination of *Table 29* and *Figure 151*, however, the data does suggest that a larger proportion of south-west axes were found in dryland locations than wetland environments. This perhaps suggests that palstave axes from the south-west were more symbolically connected with the earth, rather than water; however, this dearth of wetland palstave axes could be related to the problematic recovery of submerged finds, which are not easy to detect and oft become scattered by dredging or the movement of water. The opposite can be said of the Coghlan data, which may indicate a preponderance for wetlands contexts for the deposition of palstave axes. This could indicate that the deposition practices pertaining to palstave axes in the

south-west were slightly different; if one combines the observations made in regards to damage above, it could be suggested that south-west axes were potentially less likely to be deliberately damaged and thrown into wetland environments than axes from the rest of the British isles. Ultimately, however, a degree of caution must accompany this statement as the data relating to the depository circumstances of the Coghlan sample is so limited and no doubt somewhat unrepresentative. As *Table 30* and *Figure 152* emphasise, there is also a large number of palstave axes within the Coghlan dataset that cannot be assigned to an associations category, though within those that can, more seem to have been group finds. By comparison, the south-west data has a lot less unknowns regarding the associations of each artefact. Disregarding the eight axes within the south-west sample that could not be evaluated, the remaining data is split almost exactly between single and group finds. However, similar to the concerns raised about wetland finds, it is probably quite likely that the number of groups finds is underrepresented due to incomplete sampling in the antiquarian period of archaeology, in which many of these artefacts were discovered.

| *Terrain* | south-west | Coghlan | Total |
|---|---|---|---|
| *Unknown* | 43 | 18 | 61 |
| *Dryland* | 30 | 2 | 32 |
| *Wetland* | 5 | 4 | 9 |

**Table 29:** Comparison of the data between the south-west and Coghlan samples for the find terrain of each palstave axe.
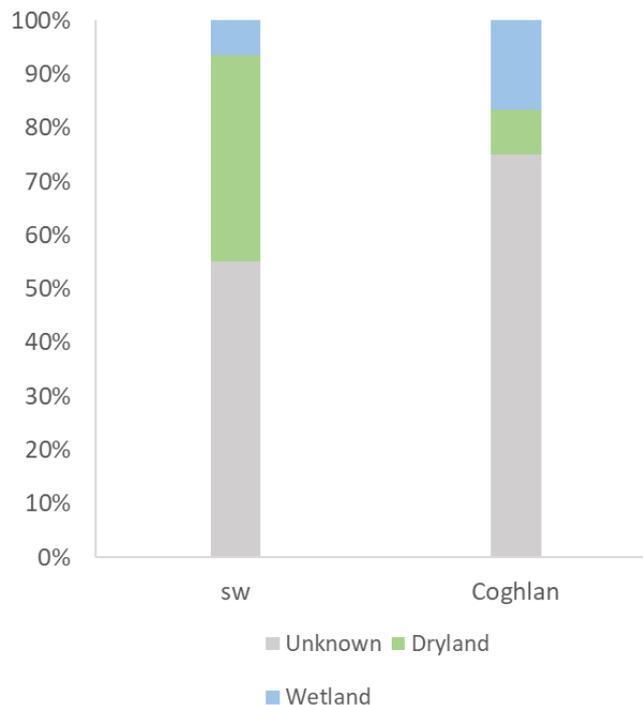


**Figure 151:** A comparison between the two samples of the proportion of palstave axes in each of the categories relating to terrain.

| Associations | south-west | Coghlan | Total |
|---|---|---|---|
| Unknown | 9 | 18 | 27 |
| Single | 34 | 2 | 36 |
| Group | 35 | 4 | 39 |

**Table 30:** Comparison of the data between the south-west and Coghlan samples for the find associations of each palstave axe.
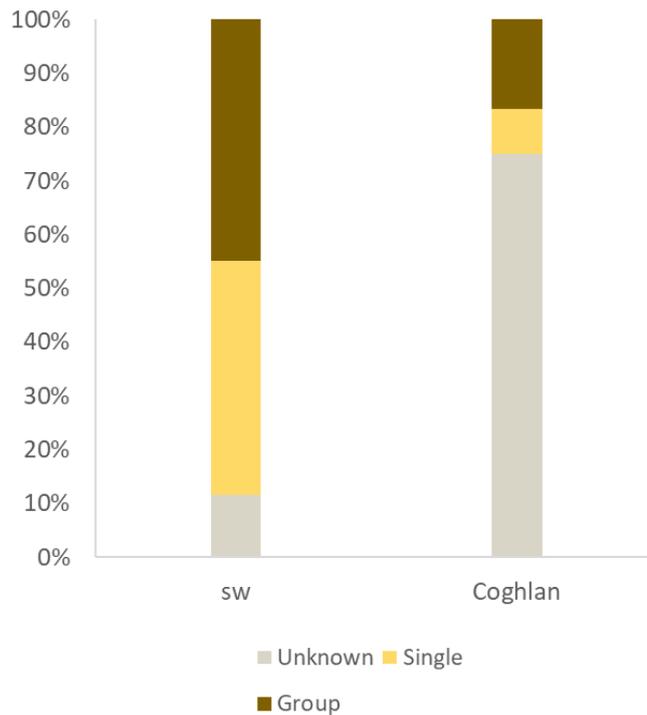


**Figure 152:** A comparison between the two samples of the proportion of palstave axes in each of the categories relating to find associations.

## 8.2 Commonalities in biography: confronting old assumptions and welcoming new insights

The above section has emphasised the areas in which the Coghlan and south-west datasets differ, and has suggested some regionally specific trends; for example, the higher tin content and the predominance of dryland find contexts within the south-west sample. While acknowledging that variation does exist between the two samples, there were many areas where the data from the two samples was similar. The congruency of the results between the two samples in relation to manufacturing procedure, use-wear, and damage, was highlighted in particular. The purpose of this

section is to further interpret the commonalities within the lives of these palstave axes, using this insight to support or challenge established arguments, and inform new ideas about the past sociality of Bronze Age Britain.

The results produced from the composition data (*Figure 143*) indicate that there is a concentration of palstave axes containing between 10 and 14% tin, which supports existing analysis regarding the average addition of tin to MBA bronze objects [238, p. 392]. Given the experimental work here-in, as well as other studies that have included experiments with replicas with a range of tin compositions [147], [209], it is well appreciated that this level of tin produces the most optimum mechanical properties for functional application of the tool. This suggests, therefore, that a considerable proportion of palstave axes within this study were produced with the biographical potential for use. It does not necessarily mean that the addition of this amount of tin was always entirely controlled and deliberate, however, as the palstave axes could have been cast from recycled material that contained this mixture of metal. Nonetheless, it suggests that the 'bronze standard' was close to 10-14%.

As demonstrated in *Figure 153*, the observations produced from the metallographic data demonstrate that the majority of palstave axes within the sample were created with 'Full' processing and so had the biographical potential to be used as a working axe. A recrystallized, twinned, microstructure has demonstrated superior resistance to deformation throughout the experimental work – a benefit that BA bronze smiths were certainly aware of, and which would have influenced decision-making when manufacturing tools intended for use. Equally, many palstave axes had been subjected to a final hammering; a treatment that has been shown to substantially increase the durability of the blade, and safeguard it against the extremely damaging effects of high-energy hits, within the experimental work presented above. Again, this suggests that the mechanical advantage of this treatment was well recognized by Bronze Age bronze workers, who administered it to tools and weapons that were likely to experience functional application [116], [135], [136], [137], [138], [139]. Interestingly, some axes were left in an as-cast state, which probably means that they were never intended for use. As such, while the prevailing idea that the production of BA palstave axes was completed according to a fairly standard procedure of hammer-anneal-hammer remains, it was not applied consistently across all palstave axes.
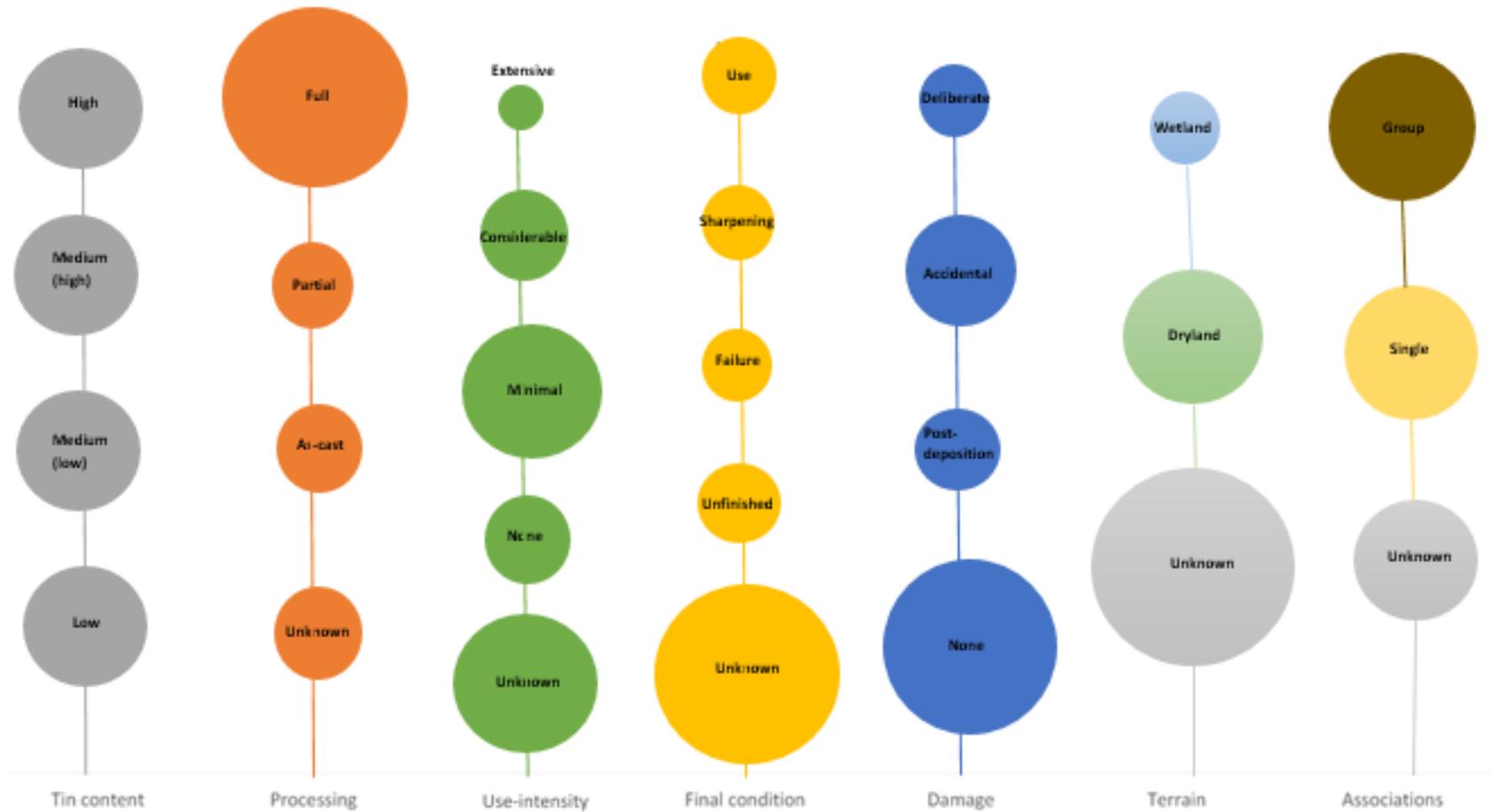
***Figure 153:*** A balloon plot created with the combined data from both south-west and Coghlan samples; whereby, each string of balloons represents a 'simplified' life trajectory category, and each balloon approximately indicates the number of palstave axes (not to scale) in each variable within these.

Out of the axes that could be analysed by some form of use-wear analysis (n = 70), a total of fifty-six axes were found to present some evidence of use, while it was only possible to confidently determine fourteen that were without any signs of use. As already mentioned, many palstave axes have, in the past, been perceived to have been in an unused state, which has prompted notions of limited use, and ideas that many of these objects could have been deliberately created as 'offerings' [13, p. 430], [83]. The data produced here-in suggests that these deeply-engrained assumptions are mostly erroneous. The similar data between the two datasets gives confidence to the idea that palstave axes with minimal use frequently appear in metalwork assemblages across Britain (*Figure 149*). Interestingly, this also provides further evidence against functionalist interpretations of metalwork hoards as collections of tools for recycling, which surely would have resulted in a collection of severely-worn blades; or, as the hidden belongings of a metalsmith, suggested by palstave axes that lacked evidence of use entirely. Clearly, possessing a use-history in some form was, for the most part, an important requirement for palstave axes that were removed from circulation and used in deposition practices (*Figure 153*).

The frequency of palstave axes with minimal use suggests that it was common for palstave axes to be used, but that there may have preference for the blade to remain in a largely pristine-looking condition when deposited. Although the limited prevalence of palstave axes with evidence of deformation at the cutting-edge within the sample may reflect the infrequency of failure events experienced by well-manufactured axes (as suggested in section 6.5), it also alludes to the preference for recycling of tools with catastrophic failures, over selection for deposition. This, again, emphasises that palstave axes with relatively well-retained cutting-edges were preferred. Given this supposition, it is no surprise that a fair proportion of the sample was subjected to a sharpening before interment in the ground (*Figure 153*). Perhaps, as Bradley has suggested, a sharp cutting-edge was seen to be important requirement as the palstave axes were intended for use in another world [76, p. 139]. In contrast with this idea, on several occasions the cutting-edge was in a blunt condition, yet sharpening-striations can still be detected – demonstrating that this treatment was purely cosmetic and not to create a functional edge.

Following on from this, a clear pattern towards 'completeness' is also demonstrated by the lack of damage observed on the ancient palstave axes. It was only possible to confidently determine nine axes that were deliberately damaged, while fifty-four displayed no evidence of damage at all (*Figure 153*). As already stated, unlike other bronze material that was routinely destroyed before deposition, existing investigations involving palstave axes have shown that intentional breakage is uncommon [13], [83], [114], [116]. It appears that the rules that governed the deposition of other

bronze metalwork, and emphasised the need for fragmentation, may not have applied to palstave axes. A functionalist perspective on the deliberate damage of metalwork prior to deposition may argue that it was seen as unnecessary to disable utilitarian tools in the way that weaponry was disposed of in order to obstruct enemy acquisition [28, p. 206]. Alternatively, the unusual treatment of palstave axes in comparison to other Bronze Age metalwork may have been closely related to their important role in facilitating the emergence of landscapes that were heavily dominated by agriculture [20, p. 431], [21, p. 289]. It should also be remembered that, unlike many bronze weapons and ornaments, the axe-head in its various forms presents a lengthy history within human society and there were likely enduring symbolic associations between man and axe, of which, deliberate destruction may have never been a significant aspect. The data indicates that it is quite typical for palstave axes included within deposition to have signs of accidental damage, for example, fracture through the flanges, side-loop, or stopridge. The occurrence of accidental damage within the sample may reflect the frequency of breakage of palstave axes during use; suggesting that flanges and side-loops, in particular, are fragile and break regularly. Or, axes with these types of breakage were actively chosen for deposition, since they still retained a well-proportioned cutting-edge, but were, otherwise, no longer in the best shape for use. Interestingly, these minor deformities seem to have been acceptable when selecting axes for deposition, while obvious alteration to the cutting-edge was generally not.

## 8.3   Life trajectory profiles as a way to visualise the 'full story' of the lives of palstave axes of different types

While the above discussion attempts to propose commonalities in the life trajectory of Middle Bronze Age palstave axe, it is vital to remember that the artefacts analysed within this study had highly variable and individualistic lives that were much more nuanced than generalisations like the ones made above suggest. When the lives of palstave axes are visualised fully by creating life trajectory profiles (graphs that indicate the individual life path taken by each object), it is evident that many objects do not conform to the commonalities set out above. Instead, the highly individual life trajectories of these axes create a vast amount of variation within the sample. When broken down into axe type, the full breadth of diversity in life trajectory becomes increasingly apparent. Hence, the present section will present the life trajectory profiles of each palstave axe, separated by axe type. The original decision to divide the palstave axes by axe type was made because it permits a chronological assessment of the objects, highlighting changes in the treatment of these

objects over time. It also allows the culturally-linked types, for instance, the South-western and South-western variant Crediton to be considered together, rather than imposing arbitrary geographical separation (since areas of common social practice in the Bronze Age were likely not bound within modern counties) based on find location. However, more than anything, the surrounding discussion is able to display the variation that exists within the lives of these objects, reinforcing both the aforementioned trends where applicable, but also placing a spotlight on the axes that do not conform to said patterns.

Starting with the earlier typologies (Group I and Group II), it appears that the tin content within Group I palstave axes was quite variable with a slightly higher frequency of axes in the 'Medium-low' category (10.9-12.6%) (*Figure 154*). All the palstave axes that were analysed illustrated evidence of a fully processed microstructure. Four axes had use-intensities that could be considered 'considerable', and four had 'minimal' use-intensities. There is a particularly fascinating sub-group of three axes that were fully processed, but were then not used or finished. One of these three axes was also deliberately broken, which is a departure from the majority of palstave axes of this type that demonstrated no evidence of damage of any kind. No Group I axes were left with deformations or use-striations at the cutting-edge, but four were sharpened prior to deposition. This could indicate that these axes were prepared for their use in ceremonial practices. In general, however, the data is fairly split across the damage categories, though it seems most common for this type of axe to have no damage at all. Finally, there was more single finds (six) than group finds (four), a trend of which was also echoed by the Flanged axes (*Figure 155*).

While some Group II palstaves fell into the 'Medium-high' and 'High' categories for tin content, there is a clear concentration of artefacts in the 'Low' class (*Figure 156*). The processing of the Group II axes was fairly mixed; however, five out of the eight axes that had available microstructural data fell into the 'Full' processing category. There are a number of axes presenting evidence of use in this group, with four axes exhibiting considerable use-intensities, and two with minimal use-intensities. When this observation is combined with those generated in the paragraph above, it appears that earlier palstave typologies (dating c.1500-1250) may be more likely to have been subjected to 'considerable' use-intensities. There are also two axes (one of which was fully processed and one which was as-cast) that were not finished or used. Again, the data is fairly split across the damage categories but it seems most common for this type of axe to have no damage at all. Like the Group I palstave axes and Flanged axes, there is a tendency towards single finds, rather than group finds.
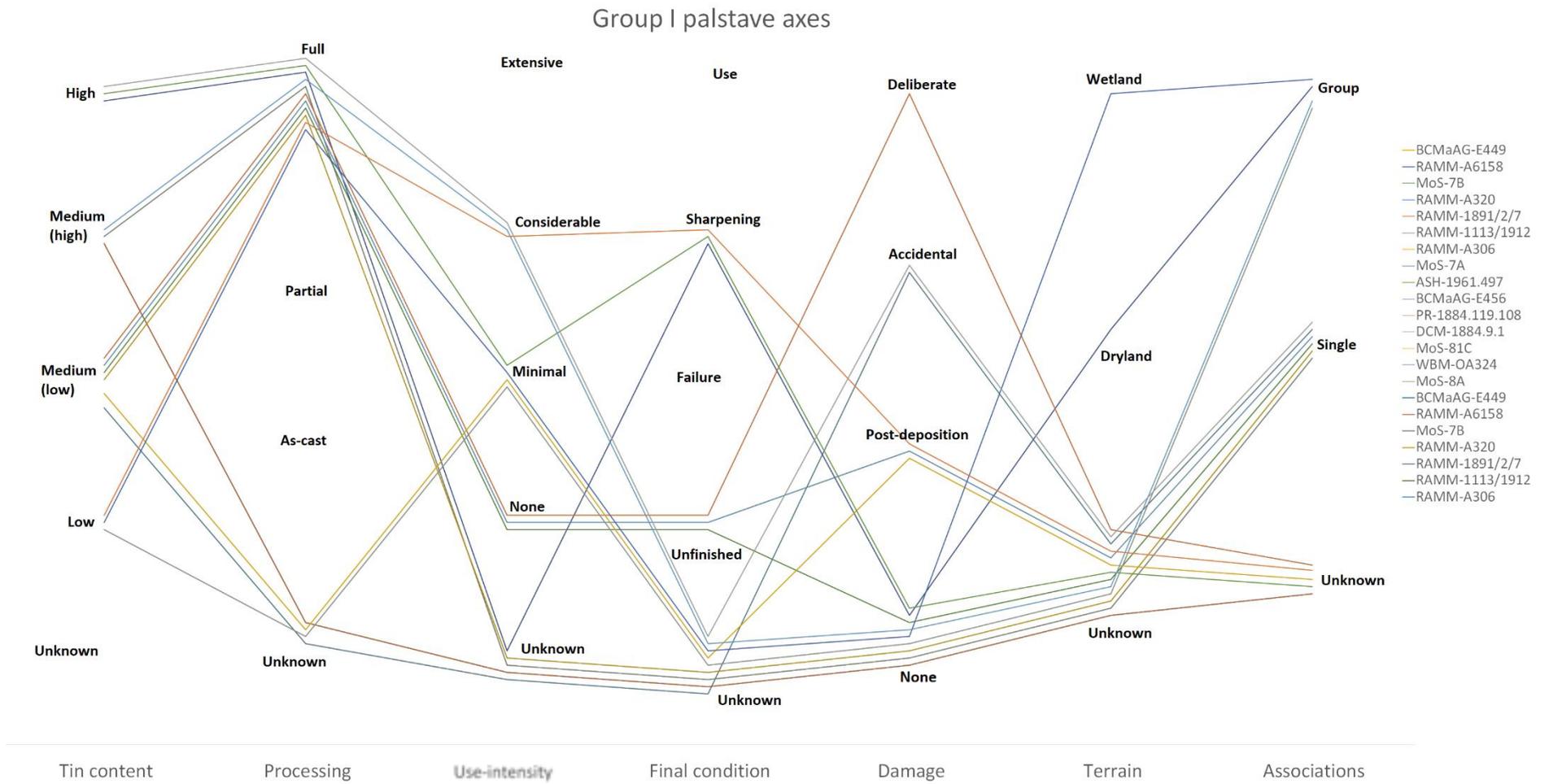
***Figure 154:*** Life trajectory profiles for the Group I palstave axes.
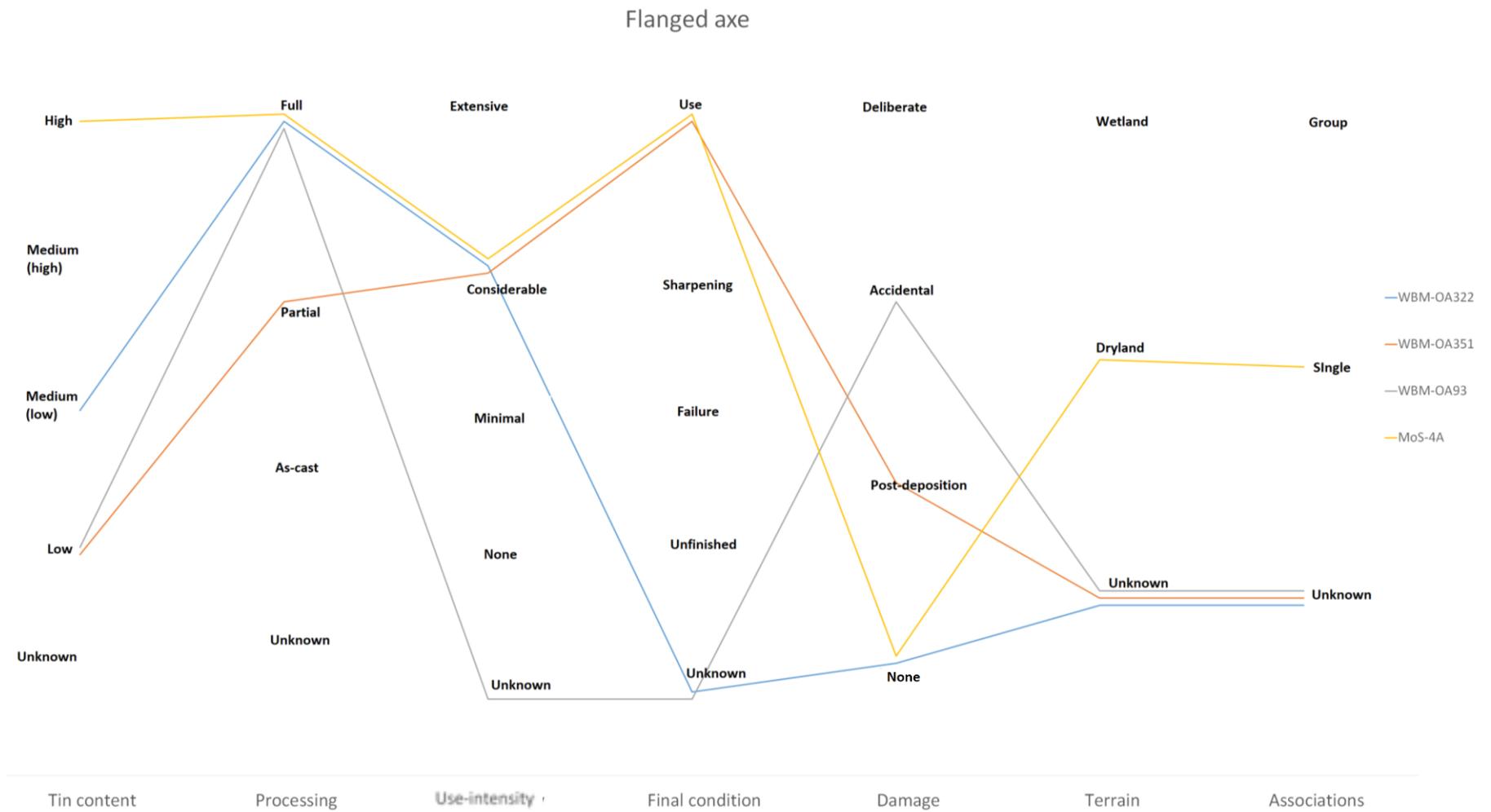
*Figure 155:* Life trajectory profiles for the flanged axes.
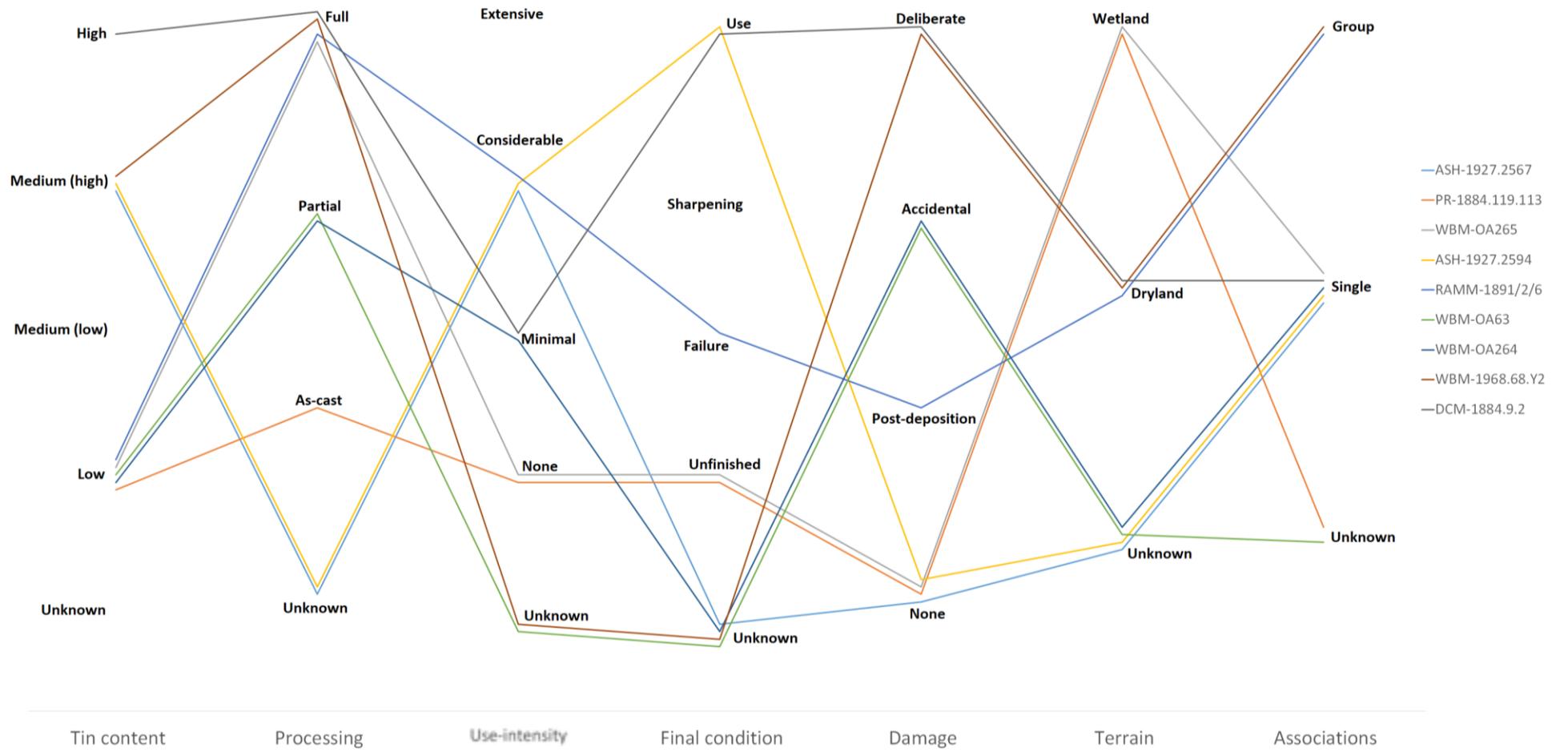
***Figure 156:*** Life trajectory profiles for the Group II palstave axes.

Though the data regarding tin content for Group III is spread across all classes, many of the palstave axes within this type fall into the 'High' tin class, with another appreciable proportion within the 'Low' tin class (*Figure 157*). The majority of palstave axes were produced according the standard manufacturing procedure, although there is certainly a clear concentration of axes within the partial processing category. This may indicate that the casting quality of Group III palstave axes was more variable than for other types. There is also one as-cast axe, which forms a subgroup with two other palstaves (both with 'Full' processing) that were not finished or used. There were more palstave axes in Group III with minimal use-intensities (nine), than considerable (two), or extensive (four). There appears to be a range in the final treatment of palstave axes of this type. Most axes within Group III presented either accidental, or no damage. The high number of palstave axes that have been damaged accidentally could, again, indicate that casting of artefacts of this type was less high quality. Like the proceeding palstave typologies, there are less Group III axes deposited as group finds than as single finds – though the margin between these two categories appears to have narrowed. Very little can be gleaned from the life trajectory profiles for the Group IV palstave, but the graph has been included for the sake of completeness (*Figure 158*).

Unsurprisingly, the largest proportion of South-west axes fall within the 'High' and 'Medium-high' tin classes (*Figure 159*). Many of the palstave axes belonging to this type that were analysed by metallography presented a fully processed microstructure. However, there is a subgroup of four as-cast axes, three of which that went on to have use-intensities. Interestingly, all artefacts examined by use-wear analysis showed some evidence of use. Similar to the Group III palstave axes, more tools exhibited a 'Minimal' use-intensity (eight), than 'Considerable' (four), while none could be considered to have 'Extensive' use or no use at all. There appears to be a range in the final treatment of palstave axes of this type, though there are no axes that have been left unfinished. It appears that most South-western palstave axes were used regardless of their processing. Many axes within the South-western typology presented accidental damage, and almost an equal amount were deposited as group and single finds. The South western variant Crediton palstave axes were well separated between different tin content classes (*Figure 160*). Many of the axes within this typology had a fully processed microstructure, though there were also four as-cast axes, three of which went on to be used, another with no use, and two with unknown use-intensities. While most palstave axes within this typology had an unknown use-intensity, the axe mentioned above, as well as three others presented evidence of 'Minimal' use. Interestingly, these axes were much less likely to have accidental or post-depositional damage (probably because they were so robust). Two palstave axes of this type were, however, deliberately broken. South-western variant Crediton palstave axes were closely divided between the group and single finds categories.
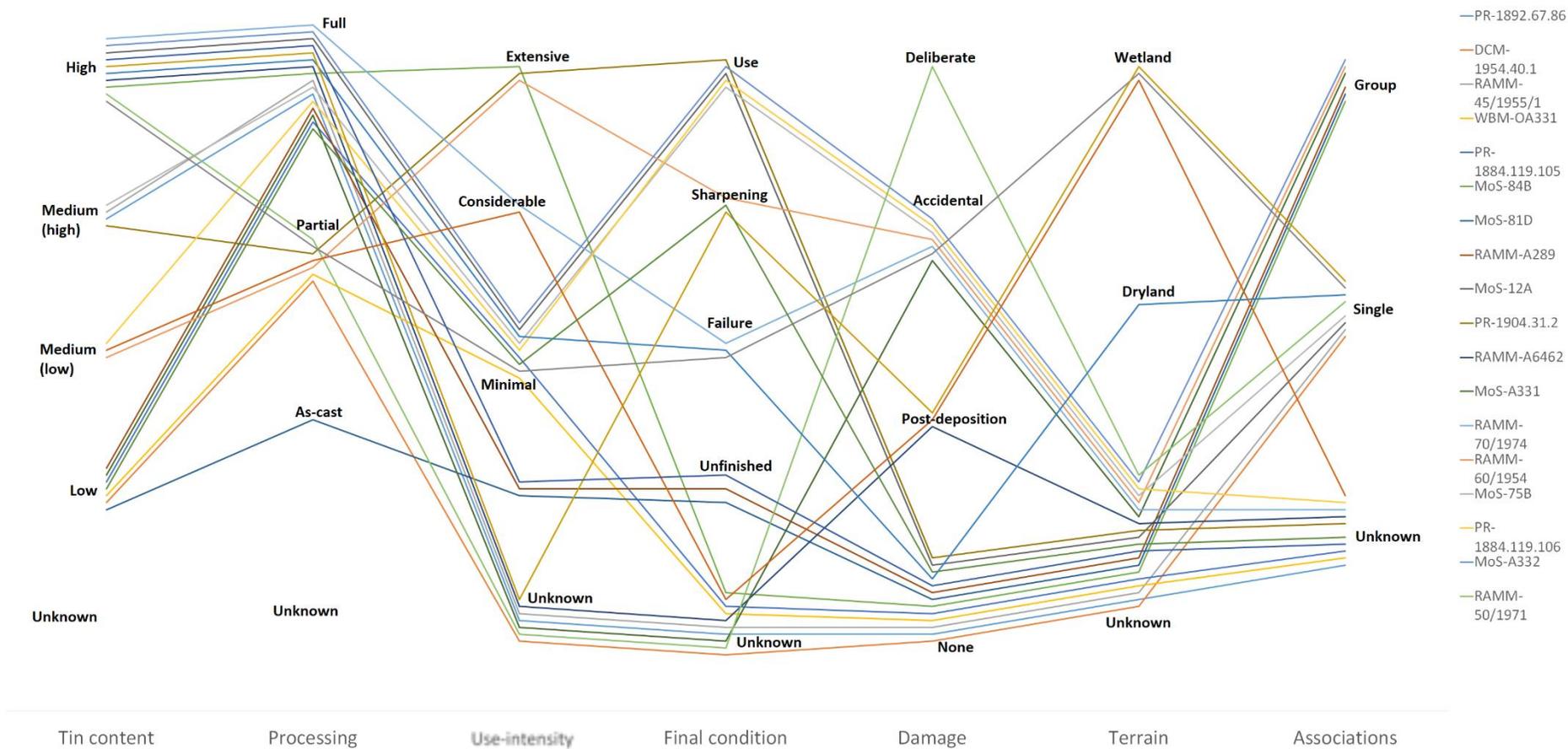
**Figure 157:** Life trajectory profiles for the Group III palstave axes.

# Gr.IV palstaves



| Tin% | Processing | Use-intensity | Final condition | Damage | Terrain | Associations |
|------|-----------|---------------|-----------------|--------|---------|--------------|
| High tin | Optimum | Extensive | Use | Deliberate | Wetland | Group |
| Standard (high) tin | Not optimum | Considerable | Sharpening | Accidental | | Single |
| Standard (low) tin | As-cast | Minimal | Failure | | Dryland | |
| Low tin | | None | Unfinished | Post-depositional | Unknown | Unknown |
| Unknown | Unknown | Unknown | Unknown | None | | |

MoS-14A

***Figure 158:*** Life trajectory diagram for the Group IV palstave axe.

South-western palstave axes
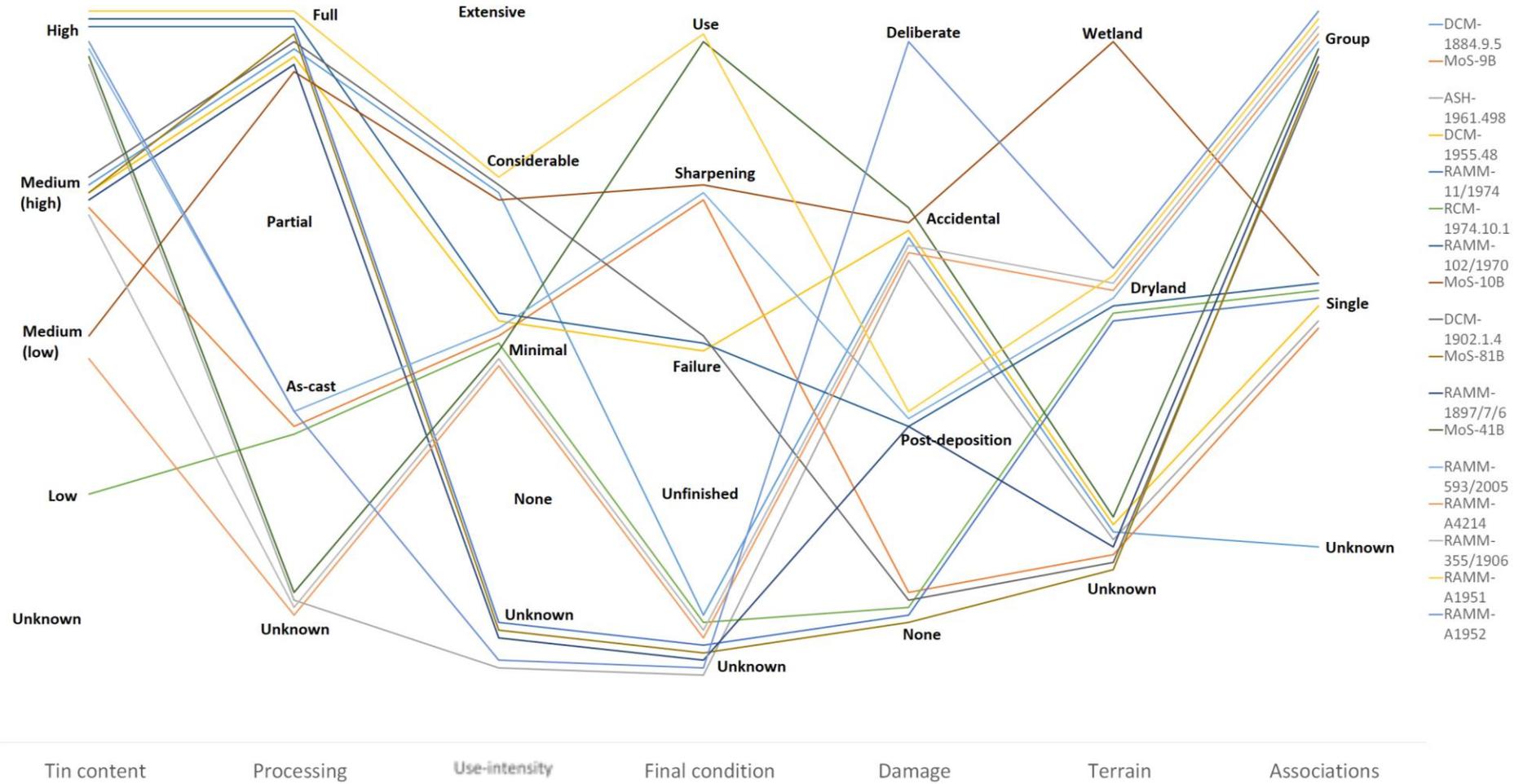
*Figure 159:* Life trajectory profiles for the south-western palstave axes.
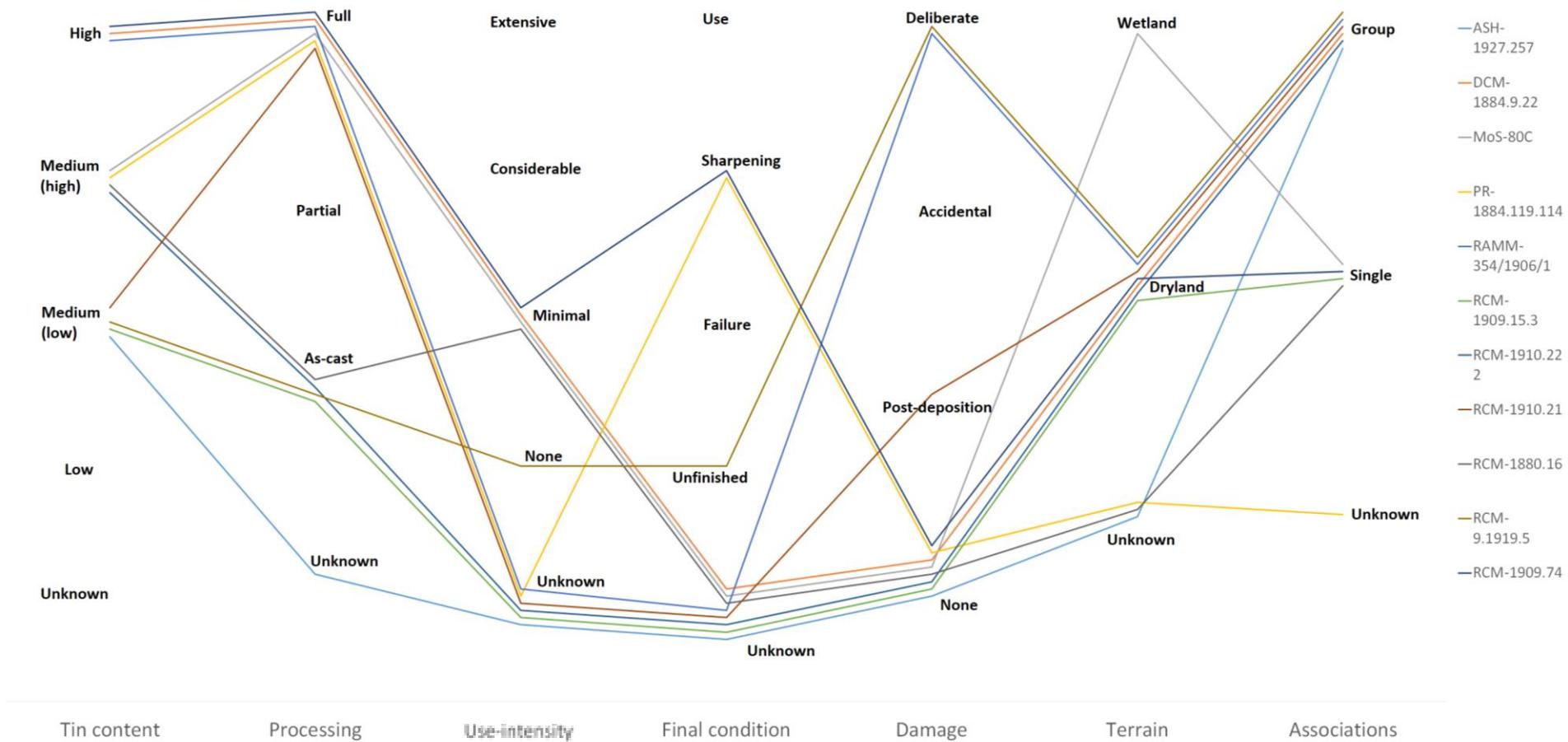
**Figure 160:** Life trajectory profiles for the south-western, variant Crediton, palstave axes.

243

The Transitional palstave axes are the only late MBA axe type with a large enough sample number in order for any patterns to be properly examined. These palstave axes were well separated between different tin content classes, though few were found in the 'High' tin class (*Figure 161*). The majority of the palstave axes were produced according the standard manufacturing procedure, though there were also five as-cast axes, four of which were not finished or used. As with Group III and south-western palstaves, there appears to be a concentration of palstave axes with 'Minimal' use, though one exhibited evidence of 'Considerable' use. Most axes present no damage at all, though there is a small concentration of axes within the 'Accidental' category. But, relatively speaking, this is far fewer than for other palstave types. Again, this is most likely related to developments in the design of the palstave axe, such as more robust flanges and wider septums. While the number of middle MBA types that were deposited either as group or as single finds was generally fairly even, there are more Transitional palstave axes deposited as group finds than as single finds. Hence, a transition from the deposition of earlier palstave axe types as single finds, to the more frequent deposition of middle and later types in group finds can be well observed. It is well known that Early Bronze Age flat axes were more likely found as isolated finds [154], [227, pp. 1–2], so this pattern clearly reflects a proliferation of hoarding practices throughout the Middle Bronze Age. Very little can be gleaned from the life trajectory profiles for the Narrow-bladed (*Figure 162*) and Double-looped palstave types (*Figure 163*), so the graphs presented below are included for the sake of completeness.
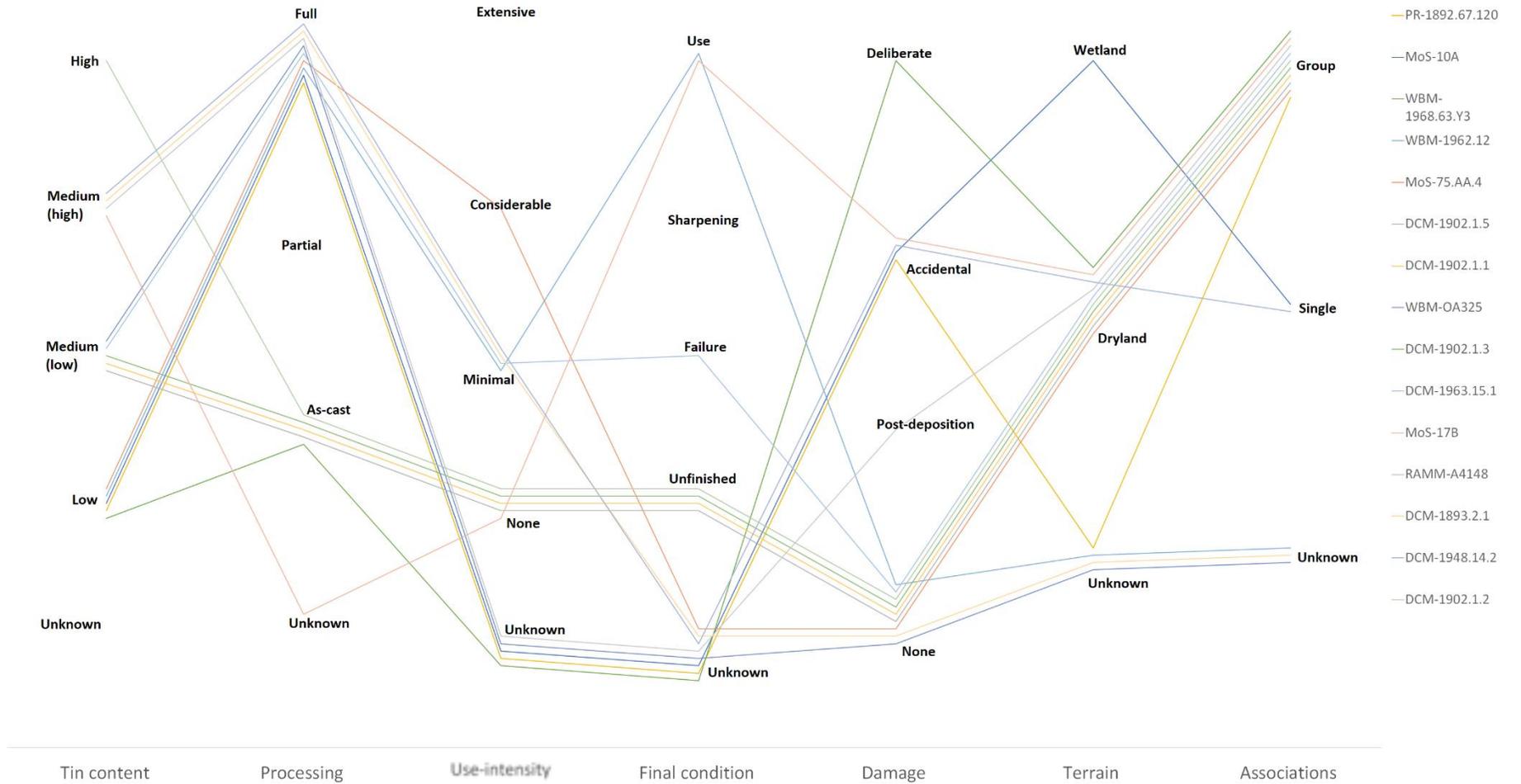
**Figure 161:** Life trajectory profiles for the Transitional palstave axes.

**Double-looped palstaves**
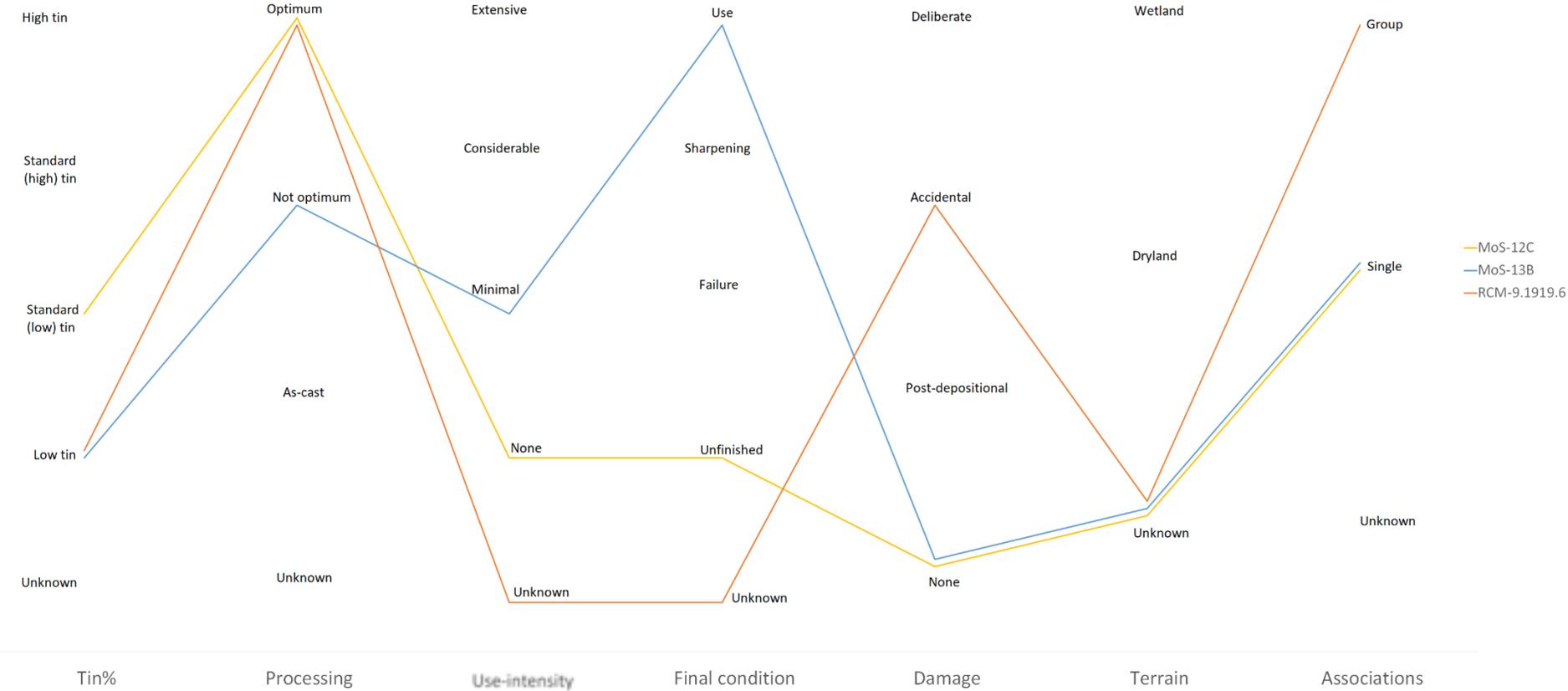
*Figure 162:* Life trajectory profiles for the Double-looped palstave axes.

**Narrow-bladed palstaves**

***Figure 163:*** Life trajectory profiles for the Narrow-bladed palstave axes.

## 8.4   Individual narratives: emphasising outliers and unique objects

The life trajectory profiles, while going some way to suggest the unique life path of each palstave axe, are a simplification of the individuality presented by the biographies of palstave axes. The full narratives pertaining to each of these objects tell a much more dynamic, richer story, that encompasses many human/material interactions. Due to the constraints of the word count of this thesis, the individual narratives compiled for each object can be found in Appendix B. This section will draw on these narratives, closely inspecting particularly interesting palstave axes (including those highlighted in the previous section) that demonstrate highly individualistic lives and attempt to posit the significance of these special objects within the current understanding of Bronze Age society. After all, none of these objects can be considered to be representative of a 'normal' palstave axes. They are, instead, objects with distinguished value that were not put forward for recycling, but were deliberately removed from circulation for a reason that is now unknown to us.

There was a small contingent of palstave axes were left in an as-cast state, and were not finished, sharpened, or used. Four of the palstave axes (DCM-1902.1.1, DCM-1902.1.2, DCM-1902.1.3 and DCM-1902.1.5) that were as-cast (*Figure 164*) and unfinished, were all from the same hoard, and consist of two very similar pairs of Transitional palstaves – DCM-1902.1.1 and DCM-1902.1.2 without a loop, DCM-1902.1.3 and DCM-1902.1.5 with a loop. In the past, a hoard that consisted of many copies of the same item, especially in an unfinished condition like this, would have been suggested to have been the property of a trader [64, p. 123]. As discussed in detail in section 2.1.3, ideas like this have since been largely refuted, as deposition practices are generally considered to have been purposeful and formal; this assemblage, therefore, could represent a highly distinctive type of hoard, whereby palstave axes were created for the sole objective of deposition. This idea is reinforced by the narrative of PR-1884.119.113, a palstave axe that is a shoddily cast, crooked, and still retains flashing (*Figure 165*); if this object was meant to be a functional axe it could have been easily re-melted and re-poured, so it seems that it may have been hastily constructed for ceremonial practices. Of course, it is possible that this axe was put forward for deposition due to its deficiencies, however, the lack of defective objects within the sample suggests that they were rarely treated in this way. The arguments suggested above become even more intriguing when the narrative of RCM-1919.9.5 is considered. This unfinished palstave axe (*Figure 166*) is also a crooked casting, which was deliberately broken and placed within a multi-period hoard (Late Bronze Age socketed axes were present). It could be possible that this object was cast after the cessation of the MBA to complete this specialist '*in memoriam*' hoard. This theory is substantiated by the narrative

of MoS-81D, another unfinished axe that was also discovered as part of a multi-period hoard (a flat axe and socketed axe were included). The narratives of palstave axes that were fully manufactured, but were not then finished, sharpened, or used (Mos-7A, MoS-12C, RAMM-1113/1912, RAMM-A289, RAMM-A306, RAMM-130/1979, and WBM-OA265), seem to represent an entirely different and perplexing behaviour – they were mostly all (with the exception of Mos-7A and RAMM-130/1979, which have an unknown context) isolated finds.
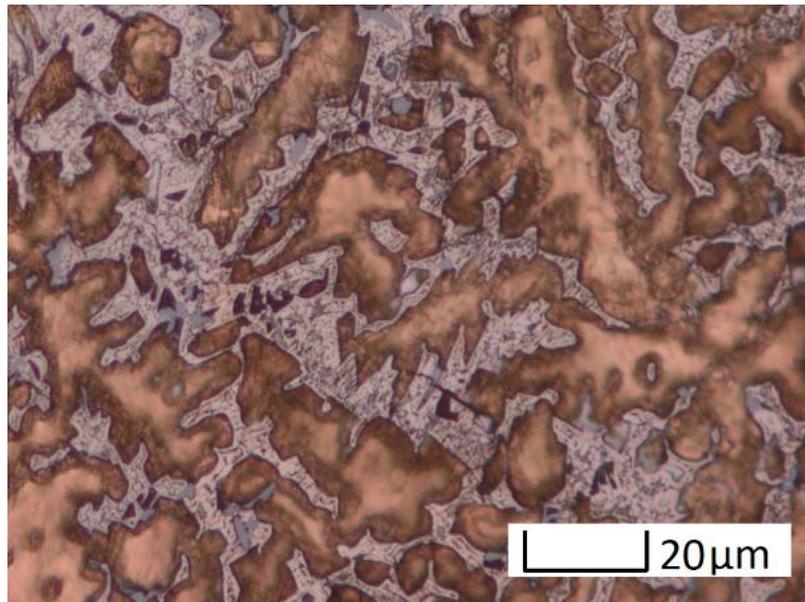


*Figure 164:* Metallograph of palstave axe DCM-1902.1.2 (source: author's own, courtesy of Dorset County Museum).



*Figure 165:* Photograph of palstave axe PR-1884.119.113. The damage to the blade was incurred during the extraction of the metallographic sample (source: © Pitt Rivers Museum, University of Oxford).
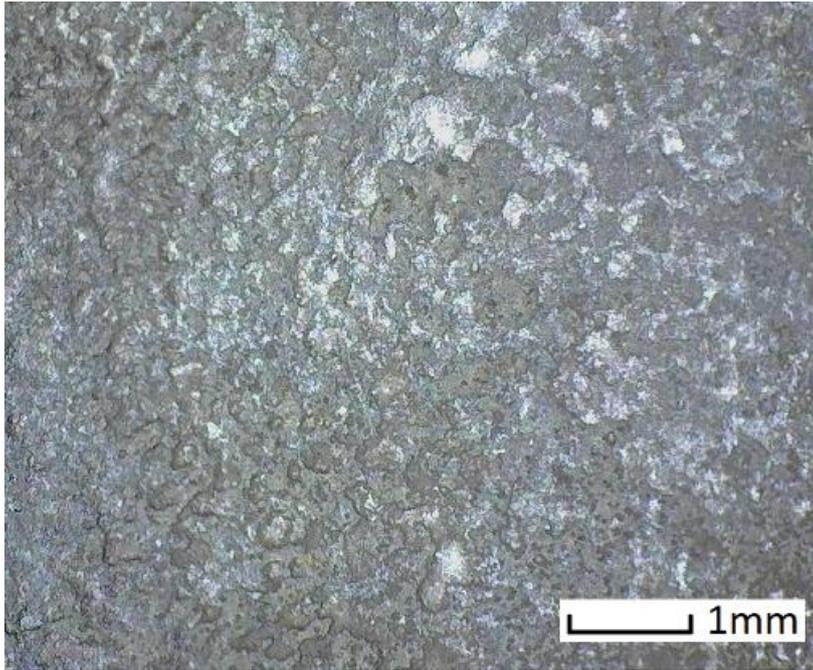
***Figure 166:*** Micrograph of the unfinished surface of palstave axe DCM-1919.9.5 (source: author's own, courtesy of Dorset County Museum).

The second unusual sub-category of palstave axes consists of those that were left in an as-cast state and were still used (RCM-1974.10.1, RCM-1880.16, MoS-9B, and RAMM-593/2005). Given the structural inferiority of these palstave axes compared to those that had been fully processed, it seems unlikely that they would be used as functional tools – but these objects do not conform to this expectation. RCM-1974.10.1, RCM-1880.16 and MoS-9B (*Figure 167*) experienced at least one cycle of use (the blade of each has evidence of slight asymmetry), which probably ended in failure fairly quickly, with the latter of these artefacts demonstrating physical evidence of this final act of sharpening prior to deposition. It may be that these axes were assumed to have been manufactured properly, and were then used, before quickly failing and being decommissioned. The narrative of RAMM-593/2005 is slightly different; the combination of use-wear traits presented by this palstave axe suggests the cutting-edge was not properly prepared, subjected to very minimal use (no evidence of blade asymmetry but use-striations were present), failed (*Figure 168*), and then was tidied up by sharpening. While it is possible that this palstave axe was nonchalantly used whilst in a completely unfinished condition, it is also a possibility that the object was subjected to use specifically to imbue it with a use-history before deposition.

**Figure 167:** Photograph of the blade of palstave axe MoS-9B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 168:** Photograph of the blade of palstave axe RAMM-593.2005 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

Based on the types of deformation that occurred during the experimental work (bending of the cutting-edge, which may culminate in depressions following sharpening, or after millennia of corrosive processes), there are a number of axes (WBM-OA351, PR-1892.67.86, MoS-41B, and Mos-14A) that demonstrate marks (nicks and notching) that may not be related to striking materials other than wood (*Figure 169*). The formation of 'nicks' under these conditions has also been suggested by Roberts and Ottaway in their study of leaded tin-bronze socketed axes [5, p. 126]. WBM-OA351 and MoS-41B (*Figure 170*) also present very pronounced use-striations alongside the nicks, which suggests periods of sliding contact between the surface of the axe and a material with a greater hardness than wood. Thus, it is possible that these palstave axes were used for a different purpose, for example, in food-processing, digging, mattocking, or fighting. It is interesting that they have been included within deposition practice, given the severe blemishing of the cutting-edge, which seems to have generally been an undesirable feature, as already discussed. While little is known about the deposition circumstances of WBM-OA351 and PR-1892.67.86, the two other aforementioned palstave axes were both found with impressive associated material. MoS-41B was found with a substantial hoard, which included ornaments, and perhaps was specially selected as an addition to this hoard due to its unique character. Moreover, Mos-14A is said to have been discovered with a human skeleton (now lost). If this is true, it could be possible that this object was a multi-purpose tool that held particular significance to this individual.



*Figure 169:* Photograph of the blade of palstave axe MoS-41B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Figure 170:** Micrograph of the use-striations observed on the cutting-edge of palstave axe MoS-41B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

The last subgroup that should be mentioned are the palstave axes that were found with evidence of intentional damage (RAMM-354/1906, RAMM-1952, RAMM-50/1971, DCM-1884.9.2, PR-1884.119.136, MoS-7A, WBM-1968.68.Y2, and WBM-1968.63.Y3). There appears to be a slight tendency for these palstave axes to exhibit as-cast or partially manufactured microstructures. RCM-9.1919.5, which has already been mentioned above, RAMM-1952, and WBM-1968.63.Y3, are all as-cast, while WBM-1968.68.Y2 was only partially annealed, and RAMM-50/1971 was not finished with a final hammering. Whether these palstave axes were subjected to use before their destruction is impossible to tell (with the exception of RCM-9.1919.5), due to their fragmentary condition – but, it could be possible that they were purposefully created for the practices associated with deposition (as has been posited for other palstave axes that have not been fully processed). Like RCM-9.1919.5, both WBM-1968.68.Y2 and WBM-1968.63.Y3 were from a multi-period hoard, which certainly makes this argument interesting. In contrast, RAMM-354/1906, DCM-1884.9.2, and PR-1884.119.136 all had fully processed microstructures and demonstrated evidence of use. The type of breakage observed was quite diverse: RAMM-354/1906, DCM-1884.9.2, WBM-1968.68.Y3 (*Figure 171*) and RAMM-50/1971 (*Figure 172*), all exhibited a removal to some part of the blade, as

did PR-1884.119.136, alongside damage to the butt; MoS-7A had also lost a section of the butt; RCM-9.1919.5 was broken across the body and refitted, with WBM-1968.68.Y2 and RAMM-1952 exhibiting the same type of breakage, but displaying no refitting.



*Figure 171:* Photograph of the blade of palstave axe WBM-1968.63.Y3 (source: author's own, courtesy of West Berkshire Museum).



*Figure 172:* Photograph of palstave axe WBM-50/1971 (source: author's own, courtesy of West Berkshire Museum).

## 8.5 Contrast as a requirement: the value of object individualism in deposition practices

So far this text has examined the data as a whole, investigated patterns between the two sample groups and within axe types, as well as highlighting the groups that represent the outliers and oddities. One aspect that has not been investigated yet is the unique biographies of palstave axes that were found together within the same hoard. We may never comprehend the true value of these objects, nor understand what was really meant by the activity of hoarding, but the selection and joining together of objects with either similar, or differing, characteristics and narratives to one another, provides fascinating insight into the decision-making processes associated with deposition practices. Unfortunately, very few complete assemblages were analysed here-in due to the predetermined nature of sampling, but where objects from the same assemblage have been examined, differing selection practices have been exposed.

Firstly, there are a number of hoards that contain palstaves with a very similar narrative, some of which have already been mentioned in the proceeding section. To start with then, within the multi-period hoard in Yattendon, Berkshire, WBM-1968.68.Y2 and WBM-1968.68.Y3 present very close narratives; though, the former is a Group II palstave axe and the latter, a Transitional palstave, the contrasting chronologies of which, perhaps, determined their selection. They both share similar metallurgical characteristics and were both subjected to significant damage. Similarly, the South Petherton Hoard (Somerset) includes three palstave axes, MoS-A331, MoS-A332 and MoS-13B, that present narratives that are very alike. MoS-A331, and MoS-A332 are both Group III axes, and both received full processing, while MoS-13B is a Double-looped palstave, with a similar microstructure (though lower tin content and less cold-hammering). All three of these axes demonstrate evidence of functional application, though the use-intensity of MoS-A331 is more substantial, and the object had been damaged before deposition. The hoard uncovered on Dewlish Hill, Dorset, consisted of a number of palstave axes (DCM-1902.1.1, DCM-1902.1.2, DCM-1902.1.3, and DCM-1902.1.5) with very comparable narratives, however, it also included another axe that was analysed as part of the present study, DCM-1902.1.4. This palstave axe presents a highly divergent narrative to the rest of the artefacts in the hoard; for instance, it is a south-western palstave axe, that was fully manufactured and demonstrated a moderately asymmetrical cutting-edge, suggestive of a significant use-history. Unlike the 'new' appearance of the rest of the palstave axes in this assemblage, DCM-1902.1.4 also had an area of bending at the cutting-edge which had not been erased by sharpening (*Figure 173*). The deliberate placement of an axe that, so overtly, manifests a

rich use-history, with four axes that could have been cast purely for depositional practices, is an intriguing juxtaposition.
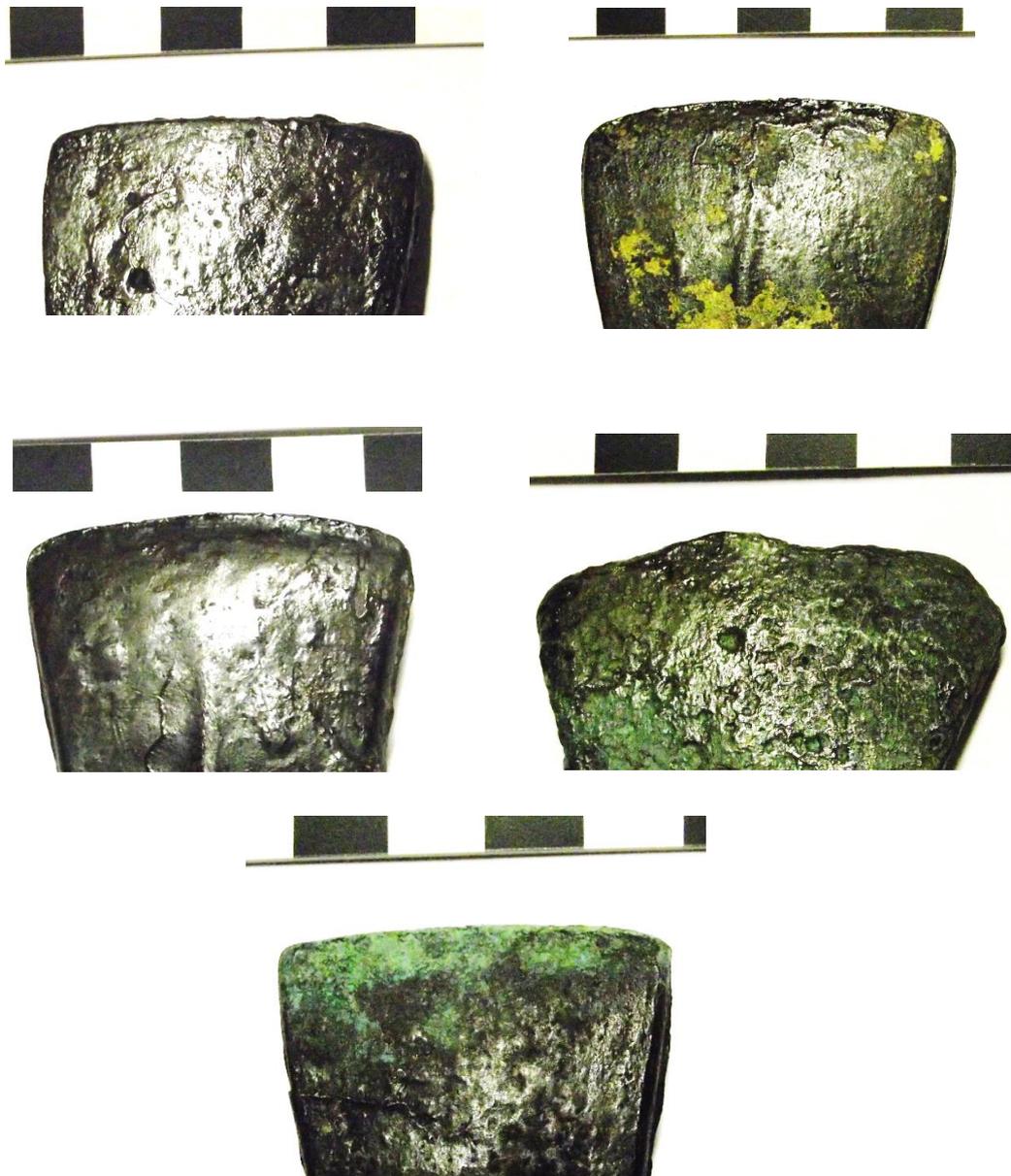


*Figure 173:* The appearance of the blade of the axes from the hoard found at Dewlish Hill, Dorset. Top left: DCM-1901.1.1. Top right: DCM-1901.1.2. Middle left: DCM-1901.1.3. Middle right: DCM-1901.1.4. Bottom: DCM-1901.1.5  (source: author's own, courtesy of Dorset County Museum).

There are several other hoards that contain palstaves that have narratives with a mixture of similarities and differences. For example, three of the palstave axes (RAMM-593/2005, RAMM-A1951 and RAMM-A1952) that were found within the Colyton Hoard, in Devon, present a blend of

characteristics. All three of these palstave axes are South-western types, and contain very high levels of tin (14-19%). The divergent narrative of RAMM-593/2005 (as reported in section 8.4) has been partially echoed by the other two palstave axes. For instance, RAMM-A1951 also presents evidence of functional application (though perhaps a more considerable use-intensity), it has a fully processed microstructure; equally, RAMM-A1952 remains in an as-cast state, like RAMM-593/2005, but the use-history is unknown, and it has been deliberately broken. Considering that these palstave axes were found within a round barrow with an unusually large number of other axes, this assemblage could have had heightened significance, and these objects may have been specifically selected for their unique characteristics. Likewise, the two palstave axes found in Chagford, Devon, beneath an ancient field boundary, are both South-western types (though RAMM-345/1906 is a variant Crediton, and RAMM-355/1906 is not) and have high tin contents. The microstructure is only known for 354/1906, but both demonstrated evidence of a use-history. However, the cutting-edge of RAMM-354/1906 has been removed, while RAMM-355/1906 presents no such damages. Two of the four palstave axes (RCM-1910.21 and RCM-1910.22.2) that were found at Old County Hall, Truro, were included within this study. These two Crediton palstave axes present a contrasting biography from the off; RCM-1910.21 was fully manufactured, while RCM-1910.22.2 was left in an as-cast condition. However, they both exhibit a symmetrical cutting-edge which probably indicates a similar use-history.

Finally, there are a number of palstave axes found in association with each other than present entirely different narratives. The narratives of palstave axes MoS-81C (Group I) and MoS-81D (Group III), both uncovered at Old Cleeve, Somerset, are completely dissimilar. As mentioned in section 8.4, MoS-81D was an as-cast, unfinished, unused axe, on the other hand, MoS-81C was well manufactured and had obviously been used quite intensely (*Figure 174*). The placement of both worn and new within this multi-period hoard, perhaps, having special symbolic value. Likewise, two South-western palstave axes (RAMM-1897/7/6 and RAMM-A4124) that were part of an assemblage of eight, at least a few of which were found in an interesting upright arrangement under a boulder in Bovey Tracey, Devon, show conflicting use-histories. The cutting-edge of RAMM-1897/7/6 is suggestive of very limited or no use, while it is likely that RAMM-A4124 went through at least one cycle of use and sharpening. Lastly, a further duo of palstave axes, RAMM-1891/2/7 (Group I) and RAMM-1891/2/6 (Group II), were found in Chagford, Devon; like RAMM-345/1906 and RAMM-355/1906, these were also found an ancient field boundary. While the manufacture of these palstaves is similar, their use-histories are incomparable. RAMM-1891/2/6 appears to have been used intensely, with an extended period of use prior to deposition that ended with failure, whereas,

the symmetrical cutting-edge of RAMM-1891/2/7 does not indicate a great deal of use, and the axe has been sharpened before deposition. The detection of two very similar pairs of palstave axes in the same location could suggest that these deposits are contemporary with each other, and may even indicate that they were placed by the same group of individuals.



*Figure 174:* Photograph of the blade of palstave axes MoS-81C (left) and MoS-81D (right) (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

It is evident from the data presented above that, more often than not, palstave axes that had experienced very different lives often ended up in the same assemblage. It may be that this was a result of deliberate selection and that it was important that for the individuals of Bronze Age Britain to present objects with varying narratives within hoards. Building on the ideas of Bruck [69], [73], [74], [75], [78, p. 313], regarding the use of metalwork as a metaphor for the self, and the employment of deposition practices as a way to provide protection for members of the community, it is not hard to imagine that the selection of palstave axes could have been based on a desire to embody the narratives of particular individuals. Palstave axes, after all, probably would have been just about as commonplace as people in the Middle Bronze Age; and, as the tool that ushered in, and continued to further, agricultural settlement, they may have been considered to represent the metaphysical backbone of society. Whilst wildly speculative, it is a neat interpretation that the use-intensity of palstave axes within hoards could be a direct reflection of the life-histories of the people undertaking a ceremony or deposition practice, wherefore the most common age demographic (most likely young adults) is represented by axes that demonstrate evidence of minimal use. Of course, there is nothing to say that process of marrying together different palstave axes for deposition was symbolized in this way, or that any kind of belief dictated such systematic selection. Although, the patterns deduced throughout this section have exemplified that specific rules, which

remain largely unknown to us, could account for the variation in behaviour regarding the deposition of palstave axes.

# 9 Conclusions and Future Work

Palstave axes sit at the crux of the pervasive societal transformation that occurred within the Middle Bronze Age in Britain. Encapsulated within this transformation was the movement towards large-scale agricultural economies, alongside the growth of increasingly sophisticated social relationships and interactions. The technological innovation offered by the emergence of palstaves helped to facilitate this change; thus, the rich, dynamic relationships forged between people and axes embody the newly emergent (and highly complex) reconstitution of societal practice during the MBA. Hence, the stories that are engrained within the design, manufacturing, use, and discard of these objects not only personify the decisions, beliefs, and desires of those who they have journeyed with during life, but may also signify wider shifts within socio-cultural frameworks or ontological underpinnings. Despite this, the treatment of palstave axes throughout their period of consumption (use) was pinpointed as an area of relative neglect, restricting the potential for meaningful discussions about their contribution in defining sociality; thus, framing the direction of this project.

To compile full and nuanced accounts of the use of palstave axes, it was seen as imperative to be able to extract the maximum amount of information during analysis and be able to make proper sense of these observations. For that reason, the starting point of this project was directed towards understanding what actually happened to the material at the cutting-edge when the axe was used and how variations in the underlying structure may introduce subtle differences. To produce and record results accurately, it was seen necessary to deviate from the usual method for use-wear reconstruction experiments by adopting a highly controlled, sequential approach to conduct multi-faceted and novel experiments with replica equivalents. A significant amount of thought, research, and investigation has been given over to each decision relating to the methodological approach. A wide range of techniques have been introduced, which emphasises the commitment of the author to trialling new experimental methods that may translate over to the archaeological material. However, as with the development of any new approach, a process of continuous refinement was necessary, as new challenges were encountered and investigative revelations were made.

Despite the initial introduction of some sources of error when adapting hardness testing for the rough and angled surface of palstave axes, the investigation into the surface hardness of palstave axes demonstrated that the cutting-edge is made significantly harder by sharpening processes and work-hardening generated through use. Hence, the changing mechanical properties of the cutting-

edge in response to use-intensity was successfully documented. Looking at previous studies that have quantified hardness increase over percentage reduction through cold working [132], [247], it is possible to suggest a similar trend in surface hardness via impact testing. For instance, there appears to be a more rapid increase in hardness between 100 and ~200 HV, followed by a markedly slower rate as the material becomes more difficult to deform. For the first time in the history of metal use-wear analysis, high-power microscopy was used to establish the way that wear manifested on the surface of a metal object. While evidence of adhesion was apparent, abrasion (produced during both sharpening and use) was seen to have the greatest impact on the surface of the palstave axe. The form of surface wear at the cutting-edge in response to use-intensity was, therefore, successfully recorded. The increase in surface hardness and underlying fatigue can be visualized by the emergence of micro-cracking in some areas. The 14% tin-bronze was not examined by either technique - it would be interesting to see how the relationship between work-hardening and the form of wear would differ once the tin content is increased. It would also be useful to conduct some research on nano-indentation on the blade tip of a worked axe, as there is no current understanding about the depth of hardness increases introduced by sharpening and use.

Unfortunately, both surface hardness testing and SEM imaging were found to be unsuitable for application on ancient palstave axes. Furthermore, based upon the experience of conducting surface hardness testing on these artefacts, it seems unlikely that applying this technique to other archaeological material with considerable corrosion products on the exterior surfaces will have any value. Two further approaches were trialled that could be better transferred to the archaeological material. Firstly, the development of surface wear was successfully determined by low-power microscopy. A fascinating finding was that replica palstave axes with differing microstructural characteristics demonstrated differing rates of wear progression. Regrettably, the assessment of the density of use-striations and prevalence of sharpening grooves was purely qualitative. This means that identification of these features produces fairly vague assessments of the use sustained since the last sharpening, as the accuracy is too limited to be more specific. Secondly, visual inspection and photography showed that the frequency of major deformations on the cutting-edge is closely linked to the underlying microstructure of the palstave axe. Those with a partially recrystallized microstructure were considerably more resistant to deformation during extensive use at relatively low impact energies and when they were subjected to high energy testing. The deformation consistently manifested in the bending of the cutting-edge, and after sharpening, appeared as a depression. The removal of an area of bending generally left the blade slightly asymmetrical; over successive failures the blade could easily become quite lopsided. Schemes for

the development of surface wear and major deformations on the cutting-edge of palstave axes with varying alloy composition and processing were produced as reference material for the analysis of ancient palstave axes. However, it should be noted that the chosen opposition material was one of the harder varieties of timber that MBA palstave axes would have encountered. As a result, it is possible that softer wood species would have introduced a much slower and more subtle wear effect on the surface of the cutting-edge.

Ultimately, the results have demonstrated that the mechanical properties, surface wear and major deformations phenomena manifested at the cutting-edge of palstave axes when they are used can be successfully tracked by mechanical testing and sequential analysis. The experimental setup allowed many variables, which would have been impossible to manage during actualistic testing, to be monitored and controlled. The executed action was consistent throughout experimentation, with none of the minor adjustments in technique due to random variation or exhaustion on the part of the handler that would likely occur during actualistic testing. Finally, the opposition material and type of contact was controlled as closely as possible, though some disparity would have certainly been introduced by slight variation in the mechanical properties of in each oak block, and as the axe progressed from the 'initial cut' towards a 'deep incision'. Nonetheless, this largely follows the pattern that would be expected during a realistic tree-felling scenario. The closely controlled experimental setup and frequent measurement intervals have generally permitted the acquisition of highly congruent results across relevant samples, suggesting a repeatable and reliable methodology. The system, for instance, was so tightly controlled that relatively minor changes in hardness could be recorded accurately across the multiple specimens that underwent systematic hardness testing. Most striking is the data regarding the major deformation phenomena. Highly comparable results have been produced when testing with axes of a similar composition at 15J; for example, Axes 3 and 4 both experienced two failures, and Blades 1-3 did not fail at all. Equally, the expected relationship between the resistance to failure and the amount of cold-hammering at higher energy levels is very clearly demonstrated.

Some technical and methodological issues were encountered in the creation of bronze replica axes within the constraints of our modern understanding of their manufacture and in adapting and using a machine that was not designed for archaeological reconstruction testing. Firstly, considerable difficulty was experienced when trying to properly anneal the experimental specimens and it is apparent that the degree to which they were annealed and cold-hammered was not sufficient to generate full recrystallization of the microstructure. It is likely that bronze age palstaves were annealed and cold-hammered for longer or more severely than previously appreciated (by modern

metallurgists) to achieve maximum durability. Secondly, while using the drop-tower meant much reduced human labour, it was not actually very time efficient. Each cycle (from the instrument inverter moving the specimen to the right height, the drop, and the reset) took approximately one minute. It was vital for the user to be present at all times as it was common for the machine to experience an inverter malfunction every 5-10 tests. Therefore, the minimum total time spent using the drop-tower from the start to the cessation of testing was over 385 hours. This is a considerable amount of time for the number of specimens that were analysed, though the results of this time-exhaustive method do speak for themselves in terms of their repeatability. Lastly, looking back to the evaluation of the experimental design in section 5.2, it was posited that the motion of the drop would generate more failures in a focused area, at the centre of the blade. Out of the nine blade failures that occurred throughout experimentation, six were at the centre of the blade. Since the corner of the blade is ordinarily the first point of impact during an axe-swing, it is much more likely that this area would be more susceptible to failure. Re-sharpening of these areas would create a much exaggerated asymmetry of the blade, something which has probably been underrepresented in the experiments here-in. If further experimentation was to take place, a greater focus should be placed on accurately recording the development of asymmetry. This could be done by using a pendulum-style of impact tester, which better simulates the swing of an axe. This should better indicate the frequency of deformations on the corner that makes first contact with the opposition material.

While the assessment of asymmetry presents a slight caveat (it only reflects the minimum number of cycles of failure, use, and sharpening due to the possible levelling of the blade when deformations occur at opposite corners), it appeared to offer the best method for estimating the overall use-intensity of the ancient palstave axes analyse here-in. When united alongside the experimental insight regarding the tribological system of tin-bronze and how this influences other kinds of wear data, like evidence of deformations, sharpening striations, and use-striations, a relatively full picture could be produced about each axes history of production, use, and maintenance. Combining this data with other types of available biographical data, overall life trajectories were successfully constructed for each palstave axe in order to ascertain general trends. The discussion illuminated several distinctions within the dataset when it was separated by sample; for example, the palstave axes belonging to the south-west had a much higher tin content and may have been created by more skilful craftspeople. However, the comparable use-intensity data between the south-west and Coghlan samples reinforces that palstave axes with full processing and with minimal use were most frequently included within metalwork deposits. This

suggests that most palstave axes were created by a standardised approach that prepared the cutting-edge for use and that they had an active part to play in forest industries. Given the importance of timber for construction and wood-working during the MBA, palstave axes were, undoubtedly, very essential objects in facilitating economic and social endeavours. It appears, if functionalist interpretations of deposition are rejected, that the significance engrained by participation in this role seems to have been, at the very least, appreciated by Bronze Age individuals during selection for deposition, if not actually precluding palstave axes with use-histories for this treatment. Additional metalwork wear investigations focused around the use-intensity of palstave axes may help to reinforce this interpretation.

Another interesting trend is that very few of the palstave axes in either the south-west or Coghlan samples exhibited evidence of deliberate damage. Thus, palstave axes were treated differently to weapons and ornaments, which are frequently found with evidence of intentional destruction. Perhaps there were practical reasons for this contrast in treatment, or, maybe, their symbolic conceptualisation was related to new meanings gained through their importance in redefining the landscape or honoured past deposition traditions for axe-heads. Again, further investigations that assess the damage observed on palstave axes are required to further substantiate these ideas. Drawing upon the information presented in both the previous and present paragraphs, the 'common' life trajectory for palstave axes appears to be a complex story of both preparation for, and minimal application in, functional use, which coincides with a requirement for preservation of the blade and overall completeness. This convoluted biography disproves the idea that palstave axes were not used before deposition and suggests the purposeful selection of objects with specific use-histories (and morphology) for deposition.

On closer inspection of the data, the full diversity and complexity of the lives of palstave axes was revealed. It is quite clear that these objects held highly individualistic narratives, engrained with various, sometimes unknown, meanings by the manifold human agents that they were connected to. The composition of individual narratives was used to fully extract the story of each axe. From these, a number of fascinating observations about the more unusual and understated ways in which people and palstave axes interacted were exposed. For instance, a minority of palstave axes may have been cast purely for destruction and deposition. Evidence also points to the functional application of palstave axes with as-cast microstructures – the motive behind which, while possibly accidental, could be argued to have been deliberate in at least one case. Lastly, the deformations observed on the cutting-edge of a small number of palstave axes do not fit within the rubric presented by the experimental data and, thus, could represent marks that were produced when

the tool was used in an unusual way, or against a different opposition material. While all palstave axes may have been used in diverse ways, these artefacts, in particular, indicate that our preconceived notions about the roles that an 'axe' may assume could be rather limited. In addition, the relations that palstave axes helped to maintain within the society of Bronze Age Britain are much more extensive and disparate than previously thought.

Suggestions for future experimental and analytical work include:

- Completing tests with a pendulum-style impact tester or angling the block in the drop tower so that the experiments are better focused on the blade corner;

- Creating new replica axes with a larger range of compositions (maybe with slightly lower tin-bronze, for example, 5% and 8%) and ensuring that the microstructures have been fully recrystallized before testing;

- Attempting experiments with a range of different wood species;

- Accurately recording material loss during sharpening and tracking the development of asymmetry;

- Cutting open the blade post-experimentation to conduct nanoindentation to determine how the hardness changes from surface to the core.

- Undertaking experiments to examining the manifestation of corrosion and how this impacts the appearance of micro-wear marks;

- Conducting further analysis of collections of palstave axes, most likely from a particular region, choosing artefacts that have better contextual information if possible.

# Appendix A: Experimental data

## Hardness data

Presented here is the tabulated hardness data (HV) for Axes 1-4, and Blades 1 and 2. The values marked in red are measurements that were removed from any statistical summaries due to their seemingly anomalous nature.

| | | Blade | | | Pos 1 | | | Pos 2 | | | Pos 3 | | | Pos 4 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| *post-sharpen at 0* | 144.41 | 154.59 | 105.52 | 252.45 | 125.60 | 185.34 | 124.73 | 180.70 | 157.63 | 128.59 | 157.63 | 62.23 | 119.80 | 90.61 | 88.67 |
| | 114.65 | 138.88 | 100.10 | 171.93 | 108.52 | 140.60 | 167.33 | 171.34 | 170.53 | 196.60 | 114.14 | 88.89 | 102.22 | 122.02 | 90.43 |
| | 122.58 | 130.43 | 169.61 | 99.58 | 174.30 | 108.52 | 181.72 | 154.09 | 312.01 | 141.48 | 110.79 | 123.29 | 83.36 | 98.86 | 116.46 |

***Table 31:*** Raw hardness data for Axe 1.

|  | Blade | | | Pos 1 | | | Pos 2 | | | Pos 3 | | | Pos 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| post-sharpen | 119.12 | 134.23 | 126.34 | 322.30 | 94.60 | 122.72 | 175.26 | 124.30 | 184.29 | 79.42 | 120.63 | 101.10 | 98.55 | 80.12 | 87.08 |
|  | 306.35 | 137.20 | 190.98 | 162.91 | 181.46 | 146.88 | 180.07 | 122.72 | 284.93 | 62.96 | 131.91 | 83.00 | 89.63 | 88.32 | 103.46 |
|  | 96.55 | 131.99 | 140.69 | 150.28 | 132.47 | 146.88 | 99.79 | 129.20 | 184.03 | 88.11 | 95.08 | 101.15 | 69.81 | 74.20 | 94.65 |
| After 500 tests | 206.27 | 323.81 | 272.21 | 218.75 | 190.79 | 214.66 | 128.01 | 144.63 | 169.28 | 119.29 | 104.17 | 126.86 | 94.20 | 101.01 | 86.13 |
|  | 226.28 | 319.31 | 339.85 | 180.75 | 173.94 | 196.46 | 145.78 | 165.34 | 166.43 | 135.18 | 120.31 | 112.96 | 111.95 | 93.00 | 92.97 |
|  | 176.26 | 275.60 | 222.85 | 204.43 | 190.13 | 183.03 | 192.95 | 179.39 | 181.92 | 109.30 | 130.06 | 155.47 | 82.72 | 87.86 | 104.21 |

**Table 32:** Raw hardness data for Axe 2.

|  | Blade | | | Pos 1 | | | Pos 2 | | | Pos 3 | | | Pos 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| pre-sharpen 0 tests | 109.18 | 115.59 | 105.23 | 80.23 | 106.27 | 104.13 | 87.40 | 118.63 | 137.65 | 98.47 | 100.31 | 137.87 | 99.03 | 115.18 | 113.95 |
|  | 117.26 | 94.07 | 114.40 | 127.52 | 130.93 | 110.72 | 111.51 | 99.90 | 116.82 | 115.97 | 126.89 | 121.31 | 89.85 | 103.54 | 130.01 |

| Label | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 98.52 | 118.57 | 92.22 | 78.78 | 82.12 | 104.16 | 126.09 | 85.70 | 110.33 | 130.23 | 85.21 | 122.00 | 95.35 | 101.88 | 90.81 |
| *post-sharpen 0 tests* | 105.87 | 155.41 | 181.64 | 118.53 | 115.20 | 135.55 | 194.10 | 184.40 | 176.38 | 164.13 | 168.14 | 138.39 | 124.18 | 124.79 | 104.92 |
| | 138.82 | 145.92 | 192.53 | 146.75 | 119.55 | 154.61 | 170.39 | 160.62 | 177.46 | 143.60 | 162.96 | 133.38 | 103.01 | 90.03 | 109.98 |
| | 192.98 | 147.94 | 173.66 | 145.63 | 127.32 | 171.67 | 153.65 | 125.60 | 186.93 | 147.18 | 140.19 | 99.41 | 118.30 | 101.65 | 109.13 |
| *250 tests* | 163.89 | 135.11 | 180.15 | 168.35 | 124.85 | 150.70 | 177.68 | 133.19 | 172.12 | 133.28 | 137.90 | 146.51 | 123.65 | 120.61 | 130.72 |
| | 211.74 | 153.45 | 162.98 | 196.46 | 160.37 | 138.97 | 190.33 | 164.35 | 168.05 | 119.33 | 158.54 | 125.81 | 102.90 | 129.55 | 113.57 |
| | 123.39 | 148.21 | 173.70 | 133.35 | 124.43 | 133.78 | 191.20 | 155.13 | 184.56 | 142.83 | 145.32 | 107.34 | 97.76 | 133.25 | 133.96 |
| *500 tests* | 151.84 | 177.24 | 138.75 | 142.94 | 164.64 | 125.34 | 188.64 | 170.60 | 182.77 | 156.06 | 123.92 | 150.20 | 121.54 | 153.53 | 130.01 |
| | 189.62 | 167.69 | 163.00 | 171.04 | 162.05 | 164.37 | 180.35 | 142.23 | 148.90 | 128.12 | 123.99 | 136.99 | 127.10 | 137.33 | 141.51 |
| | 179.09 | 138.73 | 200.92 | 154.57 | 164.33 | 152.84 | 188.70 | 162.31 | 180.50 | 132.88 | 142.23 | 126.61 | 139.31 | 134.93 | 122.51 |
| *pre-sharpen 600 tests* | 156.65 | 214.73 | 196.46 | 146.83 | 154.83 | 149.64 | 186.98 | 167.33 | 150.78 | 130.63 | 146.24 | 148.30 | 135.69 | 143.76 | 129.20 |
| | 208.54 | 169.77 | 189.92 | 145.12 | 160.94 | 162.01 | 193.68 | 156.36 | 200.33 | 133.41 | 161.54 | 171.91 | 130.93 | 123.96 | 129.52 |
| | 178.03 | 180.50 | 198.68 | 162.18 | 177.80 | 163.22 | 169.63 | 226.03 | 185.16 | 129.44 | 166.86 | 130.21 | 140.21 | 122.24 | 110.57 |
| *post-sharpen 600 tests* | 195.23 | 179.37 | 190.24 | 172.49 | 163.61 | 250.04 | 174.61 | 153.10 | 168.35 | 125.81 | 129.78 | 140.62 | 147.12 | 116.55 | 126.09 |
| | 193.29 | 193.82 | 183.93 | 175.43 | 171.86 | 146.60 | 183.28 | 209.80 | 183.90 | 150.79 | 154.91 | 122.54 | 128.68 | 123.08 | 156.30 |
| | 186.53 | 182.46 | 211.10 | 179.67 | 184.24 | 165.30 | 204.49 | 181.95 | 180.17 | 125.68 | 148.24 | 133.97 | 149.40 | 119.34 | 119.63 |
| *750 tests* | 188.99 | 181.46 | 185.87 | 187.84 | 155.59 | 136.66 | 164.22 | 193.09 | 153.57 | 111.60 | 114.90 | 164.48 | 155.41 | 137.40 | 123.04 |
| | 192.34 | 174.04 | 219.93 | 193.15 | 155.67 | 190.79 | 162.70 | 190.22 | 223.12 | 147.14 | 106.36 | 161.86 | 147.55 | 114.33 | 127.76 |

| Label | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 192.98 | 189.92 | 174.25 | 142.20 | 118.09 | 147.70 | 182.18 | 168.14 | 192.73 | 135.80 | 156.44 | 163.32 | 103.20 | 121.26 | 132.83 |
| 1000 tests | 209.80 | 182.43 | 194.86 | 153.89 | 159.67 | 162.70 | 163.91 | 149.59 | 202.17 | 169.56 | 158.13 | 119.37 | 99.19 | 115.41 | 128.71 |
| | 163.87 | 142.28 | 184.16 | 172.94 | 126.74 | 173.75 | 191.89 | 156.99 | 205.04 | 110.67 | 128.69 | 111.71 | 137.41 | 114.18 | 122.00 |
| | 211.71 | 160.24 | 201.96 | 130.71 | 152.86 | 160.64 | 208.26 | 191.53 | 234.17 | 129.98 | 142.75 | 146.75 | 139.89 | 115.68 | 125.19 |
| pre-sharpen | <span style="color:red">300.57</span> | 179.67 | 186.56 | 146.18 | 166.61 | 161.26 | 139.93 | 173.73 | 173.09 | 161.04 | 132.53 | 144.21 | 118.69 | 132.96 | 136.33 |
| 1150 tests | 175.24 | 192.31 | 213.20 | 195.46 | 151.43 | 153.02 | 197.32 | 194.32 | 178.99 | 118.10 | 97.39 | 114.64 | 114.37 | 109.01 | 114.41 |
| | 236.99 | 186.58 | 209.08 | 181.54 | 190.87 | 132.50 | 189.70 | 190.96 | 174.35 | 136.88 | 138.34 | 140.43 | 157.65 | 118.58 | 135.95 |
| post- | 216.24 | 203.19 | 195.74 | 192.31 | 214.99 | 126.65 | 158.04 | 178.25 | 183.46 | 146.83 | 140.10 | 136.50 | 132.85 | 213.16 | 124.66 |
| sharpen | 238.33 | 225.40 | 214.24 | 134.33 | 178.00 | 152.13 | 174.59 | 173.18 | 241.50 | 131.25 | 121.72 | 178.52 | 125.85 | 118.01 | 137.01 |
| 1150 tests | 214.53 | 194.47 | 247.47 | 196.23 | 174.90 | 141.74 | 169.03 | 196.83 | 255.91 | 138.75 | 131.82 | 115.63 | 93.20 | 129.60 | 120.68 |
| 1250 tests | 195.37 | 209.01 | 174.21 | 171.58 | 148.92 | 170.25 | 209.39 | 178.99 | 195.37 | 132.28 | 131.95 | 111.45 | 96.98 | 121.54 | 145.65 |
| | 193.43 | 211.81 | 236.01 | 214.30 | 174.16 | 140.73 | 185.32 | 225.82 | 138.73 | 116.14 | 119.56 | 116.54 | 108.66 | <span style="color:red">328.47</span> | 122.57 |
| | 195.15 | 237.18 | 202.68 | 192.89 | 205.66 | 178.47 | 217.31 | 220.95 | 208.64 | 131.36 | 128.91 | 144.76 | 122.29 | 120.09 | 141.58 |
| 1500 tests | 209.99 | 243.59 | 184.32 | 215.38 | 179.95 | 195.63 | 171.58 | 191.56 | 158.67 | 139.77 | 156.93 | 143.17 | 115.15 | 121.15 | 127.05 |
| | 214.63 | 150.83 | 203.34 | 198.07 | 193.43 | 181.51 | 180.98 | 202.26 | 217.77 | 141.98 | 98.42 | 139.21 | 92.43 | 113.23 | 112.76 |
| | 167.74 | 289.60 | 198.42 | 137.63 | 160.70 | 147.23 | 205.32 | 205.72 | 201.69 | 140.40 | 119.65 | 148.81 | 118.75 | 143.62 | 145.03 |
| 1750 tests | 207.29 | 177.68 | 185.18 | 159.97 | 185.32 | 237.22 | 195.12 | 250.09 | 206.06 | 122.20 | 148.19 | 155.09 | 102.77 | 103.86 | 106.56 |
| | 210.79 | 252.95 | 291.45 | 158.58 | 221.47 | <span style="color:red">313.68</span> | 161.36 | 214.07 | 233.98 | 113.23 | 150.68 | 139.46 | 120.43 | 101.99 | 156.73 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 236.99 | 140.45 | 235.37 | 178.84 | 167.51 | 161.32 | 189.48 | 224.41 | 225.50 | 124.08 | 126.53 | 127.08 | 119.44 | 120.12 | 109.63 |
| 192.64 | 213.65 | 213.59 | 159.69 | 168.90 | 190.79 | 182.10 | 192.09 | 269.47 | 93.25 | 120.21 | 136.50 | 104.69 | 131.69 | 111.89 |
| 170.97 | 247.71 | 190.46 | 157.36 | 175.02 | 247.43 | 122.48 | 172.99 | 161.96 | 117.12 | 159.02 | 141.20 | 109.01 | 121.07 | 130.03 |
| 202.50 | 223.85 | 226.71 | 181.36 | 203.10 | 189.78 | 185.13 | 295.38 | 233.39 | 126.43 | 130.26 | 161.58 | 130.31 | 107.34 | 140.21 |
| 211.62 | 220.78 | 312.53 | 164.72 | 135.62 | 187.59 | 137.28 | 171.11 | 208.10 | 108.68 | 144.99 | 129.32 | 132.83 | 141.14 | 122.54 |
| 225.18 | 202.47 | 191.18 | 183.93 | 202.47 | 154.65 | 180.17 | 210.44 | 213.55 | 101.82 | 146.36 | 125.74 | 127.86 | 139.50 | 105.38 |
| 172.47 | 202.65 | 189.62 | 169.15 | 208.54 | 207.01 | 190.44 | 189.37 | 209.01 | 121.95 | 158.52 | 139.34 | 117.93 | 101.84 | 131.90 |
| 198.48 | 177.80 | 239.10 | 171.88 | 192.17 | 224.34 | 145.56 | 207.51 | 231.32 | 135.08 | 105.67 | 123.92 | 118.71 | 127.20 | 129.43 |
| 209.90 | 216.01 | 186.13 | 184.97 | 208.98 | 125.03 | 192.25 | 232.09 | 172.19 | 137.97 | 126.77 | 133.89 | 115.82 | 133.06 | 127.28 |
| 218.24 | 190.05 | 310.87 | 183.26 | 179.59 | 226.28 | 127.04 | 181.44 | 206.64 | 149.85 | 129.83 | 123.36 | 136.63 | 118.60 | 129.84 |

Labels: 2000 tests (rows 1–3), 2250 tests (rows 4–6), 2500 tests (rows 7–9).

**Table 33:** Raw hardness data for Axe 3.

| | Blade | | | Pos 1 | | | Pos 2 | | | Pos 3 | | | Pos 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| | 97.67 | 72.48 | 118.46 | 109.31 | 84.69 | 108.37 | 98.48 | 107.99 | 122.34 | 107.07 | 120.71 | 100.37 | 108.80 | 63.48 | 96.93 |
| | 145.48 | 122.51 | 115.02 | 115.13 | 100.65 | 68.04 | 115.29 | 126.24 | 119.26 | 87.18 | 102.51 | 88.60 | 131.80 | 128.47 | 114.65 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *pre-sharpen 0 tests* | 90.24 | 139.40 | 137.65 | 133.39 | 66.28 | 137.35 | 115.66 | 106.39 | 112.29 | 119.52 | 114.77 | 119.53 | 76.75 | 88.65 | 98.53 |
| | 135.80 | 126.22 | 131.24 | 79.22 | 87.86 | 139.76 | 133.64 | 111.45 | 106.28 | 126.49 | 69.48 | 106.72 | 97.48 | 102.04 | 91.92 |
| | 110.74 | 107.03 | 109.55 | 62.45 | 122.61 | 73.48 | 107.70 | 131.18 | 85.78 | 117.03 | 123.31 | 115.15 | 102.85 | 115.40 | 111.47 |
| *post-sharpen 0 tests* | 151.98 | 136.83 | 185.97 | 159.29 | 164.04 | 161.92 | 194.27 | 182.13 | 166.59 | 130.52 | 105.17 | 128.68 | 136.00 | 122.77 | 112.75 |
| | 148.72 | 165.63 | 161.36 | 169.70 | 186.64 | 163.63 | 164.35 | 124.22 | 157.67 | 134.15 | 141.91 | 198.28 | 143.35 | 106.63 | 98.53 |
| | 140.36 | 159.13 | 175.14 | 147.70 | 202.74 | 142.99 | 204.22 | 219.35 | 209.77 | 130.76 | 135.72 | 171.98 | 104.68 | 100.25 | 139.07 |
| | 133.20 | 166.10 | 203.16 | 141.48 | 174.45 | 173.70 | 194.69 | 179.79 | 194.16 | 113.85 | 123.99 | 162.11 | 101.20 | 179.17 | 91.74 |
| | 130.80 | 183.59 | 150.20 | 155.29 | 194.44 | 242.17 | 193.03 | 178.27 | 150.08 | 119.79 | 169.22 | 120.60 | 102.15 | 157.88 | 133.06 |
| *pre-sharpen 200 tests* | 141.20 | 133.99 | 190.71 | 115.51 | 200.98 | 190.00 | 230.16 | 169.01 | 179.79 | 112.80 | 124.60 | 161.36 | 94.66 | 101.19 | 139.14 |
| | 159.88 | 154.59 | 184.37 | 171.55 | 155.05 | 200.15 | 229.58 | 156.99 | 192.34 | 112.21 | 103.59 | 193.93 | 92.82 | 121.24 | 126.07 |
| | 173.97 | 162.33 | 154.59 | 172.40 | 152.21 | 175.53 | 175.67 | 204.13 | 157.36 | 111.72 | 115.91 | 147.87 | 142.92 | 112.00 | 134.14 |
| | 142.75 | 146.49 | 152.98 | 199.21 | 165.36 | 169.70 | 179.04 | 229.54 | 180.32 | 110.79 | 161.92 | 183.52 | 109.28 | 138.59 | 160.90 |
| | 158.96 | 154.51 | 162.96 | 190.08 | 160.45 | 145.23 | 176.04 | 176.67 | 151.30 | 145.39 | 144.23 | 137.88 | 120.11 | 132.17 | 129.12 |
| *post-sharpen 200 tests* | 108.84 | 158.69 | 183.90 | 168.44 | 183.88 | 183.88 | 185.68 | 145.67 | 204.68 | 129.18 | 127.26 | 156.48 | 104.76 | 185.95 | 126.00 |
| | 157.47 | 171.23 | 137.25 | 185.89 | 136.45 | 142.92 | 212.87 | 161.45 | 161.99 | 155.69 | 173.58 | 377.10 | 134.72 | 148.53 | 109.63 |
| | 177.78 | 127.13 | 224.90 | 225.64 | 135.29 | 154.57 | 155.85 | 179.24 | 237.26 | 111.16 | 95.08 | 106.68 | 104.28 | 172.28 | 113.70 |
| | 218.95 | 158.83 | 163.37 | 158.07 | 158.44 | 133.59 | 149.00 | 153.67 | 154.41 | 108.93 | 90.83 | 226.24 | 142.67 | 84.66 | 149.76 |
| | 167.26 | 143.73 | 201.75 | 224.66 | 189.48 | 132.06 | 189.18 | 193.01 | 59.62 | 110.73 | 140.43 | 145.15 | 116.53 | 104.94 | 133.76 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *pre-sharpen 500 tests* | 210.05 | 189.64 | 262.42 | 204.65 | 199.21 | 226.81 | 201.04 | 165.99 | 225.11 | 111.24 | 143.78 | 151.69 | 106.85 | 113.15 | 129.09 |
| | 164.33 | 212.29 | 159.36 | 178.00 | 192.56 | 159.94 | 126.36 | 153.77 | 244.10 | 122.50 | 99.08 | 135.65 | 121.07 | 136.78 | 113.98 |
| | 166.45 | 136.13 | 157.59 | 165.39 | 134.15 | 187.41 | 135.95 | 192.00 | 152.31 | 134.20 | 125.44 | 151.63 | 114.21 | 151.16 | 95.94 |
| | 140.71 | 144.00 | 146.14 | 172.47 | 153.33 | 161.99 | 224.41 | 151.36 | 156.34 | 110.92 | 135.16 | 123.45 | 116.54 | 129.87 | 107.32 |
| | 190.85 | 203.86 | 190.30 | 192.12 | 138.85 | 164.75 | 157.06 | 182.43 | 210.98 | 126.24 | 150.68 | 150.91 | 138.02 | 108.77 | 104.56 |
| *post-sharpen 500 tests* | 172.28 | 184.43 | 168.78 | 183.65 | 183.96 | 187.49 | 161.15 | 178.92 | 182.25 | 101.89 | 145.01 | 81.23 | 93.36 | 116.16 | 122.36 |
| | 173.75 | 184.56 | 203.98 | 139.02 | 146.09 | 194.83 | 205.20 | 150.45 | 133.55 | 198.65 | 118.00 | 123.82 | 98.02 | 139.71 | 101.83 |
| | 141.98 | 165.67 | 179.29 | 152.06 | 120.16 | 133.15 | 175.94 | 111.46 | 117.92 | 111.69 | 126.10 | 131.22 | 106.01 | 100.07 | 117.03 |
| | 183.23 | 191.87 | 187.14 | 160.30 | 140.69 | 160.64 | 187.76 | <span style="color:red">56.29</span> | 222.40 | 136.83 | 154.53 | 141.18 | 92.18 | 98.89 | 122.24 |
| | 185.05 | 165.41 | 191.53 | 165.90 | 167.99 | 109.03 | 179.72 | 172.16 | 186.85 | 126.95 | 114.13 | 140.12 | 113.71 | 140.59 | 125.53 |
| *1000 tests* | 169.10 | 208.70 | 189.67 | 116.51 | 190.30 | 205.41 | 209.96 | 136.00 | 175.82 | 118.24 | 114.16 | 173.01 | 130.13 | 155.53 | 100.66 |
| | 258.23 | 175.38 | 213.33 | 132.71 | 177.29 | 247.63 | 182.90 | 198.95 | 185.74 | 134.30 | 169.68 | 129.11 | 129.86 | 140.26 | 132.41 |
| | 178.74 | 151.39 | 173.32 | 213.75 | 172.33 | 168.08 | 159.59 | 267.18 | 127.94 | 108.44 | 114.54 | 129.83 | 130.15 | 138.27 | 93.44 |
| | 168.28 | 195.49 | 218.75 | 176.45 | 153.73 | 168.37 | 184.66 | 198.31 | 158.60 | 123.49 | 228.53 | 89.24 | 120.52 | 109.86 | 144.34 |
| | 141.72 | 173.18 | 142.18 | 157.20 | 215.68 | 182.77 | 204.68 | 178.72 | 184.35 | 120.57 | 153.87 | 90.24 | 102.28 | 119.41 | 122.33 |
| *1500 tests* | 235.41 | 174.06 | 229.76 | 136.91 | 204.46 | 154.63 | 190.82 | 260.05 | 189.54 | 137.72 | 110.23 | 121.20 | 104.95 | 135.82 | 137.28 |
| | 201.81 | 228.49 | 134.95 | 126.84 | 173.04 | 243.43 | 153.45 | 158.56 | 201.27 | 108.86 | 105.83 | 141.46 | 117.45 | 138.92 | 99.10 |
| | 161.00 | 190.35 | 212.52 | 181.69 | 150.35 | 132.37 | 205.93 | 164.26 | 195.46 | 129.92 | 106.37 | 182.54 | 102.08 | 130.79 | 120.43 |

|  | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 226.10 | 162.72 | 198.89 | 256.51 | 137.56 | 237.56 | 186.50 | 206.36 | 180.65 | 141.16 | 119.70 | 141.97 | 109.12 | 98.30 | 142.09 |
| | 174.85 | 200.03 | 225.04 | 224.90 | 154.77 | 170.16 | 204.95 | 161.86 | 150.29 | 136.20 | 163.06 | 141.04 | 119.40 | 143.19 | 116.36 |
| 2000 tests | 231.32 | 163.85 | 218.78 | 165.70 | 183.10 | 229.61 | 171.74 | 193.65 | 190.63 | 109.17 | 131.96 | 171.27 | 121.20 | 117.45 | 83.22 |
| | 240.88 | 182.41 | 217.61 | 149.38 | 145.70 | 155.05 | 174.16 | 195.17 | 150.41 | 149.02 | 124.02 | 184.61 | 154.33 | 121.99 | 97.75 |
| | 201.60 | 203.98 | 263.80 | 176.21 | 182.49 | 164.97 | 224.45 | 163.85 | 202.77 | 138.39 | 112.03 | 110.14 | 89.24 | 154.23 | 117.57 |
| | 159.84 | 202.68 | 215.88 | 155.85 | 171.04 | 181.72 | 225.85 | 208.20 | 168.49 | 85.31 | 90.67 | 136.26 | 134.72 | 111.61 | 121.43 |
| | 196.23 | 178.03 | 189.73 | 163.80 | 152.76 | 186.05 | 209.49 | 177.31 | 178.03 | 155.57 | 115.66 | 122.37 | 129.33 | 109.28 | 127.29 |
| 2500 tests | 205.35 | 202.89 | 183.31 | 202.32 | 196.57 | 189.26 | 182.20 | 197.03 | 190.33 | 116.51 | 145.21 | 126.62 | 91.94 | 130.40 | 115.37 |
| | 185.13 | 187.25 | 207.45 | 179.17 | 216.24 | 161.34 | 175.26 | 204.07 | 189.45 | 142.82 | 135.47 | 145.98 | 112.27 | 144.12 | 121.01 |
| | 190.05 | 205.66 | 192.25 | 172.90 | 206.39 | 175.63 | 233.80 | 96.32 | 174.95 | 135.52 | 112.08 | 131.79 | 114.74 | 107.58 | 137.75 |
| | 212.36 | 203.52 | 201.10 | 151.78 | 203.37 | 144.00 | 183.23 | 164.75 | 202.89 | 107.56 | 108.64 | 144.61 | 105.70 | 119.40 | 132.60 |
| | 214.89 | 204.89 | 214.69 | 179.19 | 182.05 | 162.05 | 222.71 | 186.90 | 195.37 | 153.39 | 127.59 | 138.56 | 125.31 | 114.35 | 116.37 |

*Table 34:* Raw hardness data for Axe 4.

|  | Blade | | | Baseline |
|---|---|---|---|---|
|  | 1 | 2 | 3 | 1 |
| pre-sharpen 0 tests | 63.44 | 93.01 | 100.38 | 88.89 |
|  | 88.93 | 78.05 | 76.88 | 101.84 |
|  | 87.52 | 91.23 | 86.65 | 74.77 |
|  | 102.85 | 101.50 | 91.32 | 108.25 |
|  | 100.88 | 104.35 | 87.27 | 91.92 |
| post-sharpen 0 tests | 157.57 | 181.77 | 181.79 | 140.34 |
|  | 154.59 | 221.95 | 132.09 | 156.71 |
|  | 172.71 | 164.31 | 163.89 | 140.41 |
|  | 161.13 | 167.10 | 151.10 | 152.02 |
|  | 164.92 | 157.63 | 158.67 | 131.74 |
| 250 tests | 162.61 | 184.27 | 171.67 | 140.31 |
|  | 174.49 | 217.81 | 152.11 | 136.10 |
|  | 176.09 | 198.77 | 183.13 | 113.86 |
|  | 180.42 | 185.53 | 163.24 | 150.29 |
|  | 153.12 | 201.72 | 167.19 | 158.46 |
| 500 tests | 183.75 | 185.53 | 184.03 | 149.21 |
|  | 234.47 | 197.49 | 154.93 | 147.83 |
|  | 172.14 | 244.42 | 217.31 | 143.60 |
|  | 184.37 | 185.24 | 167.78 | 158.04 |
|  | 169.70 | 200.18 | 177.83 | 136.08 |
| 750 tests | 180.90 | 275.27 | 183.75 | 128.48 |
|  | 202.80 | 222.15 | 197.41 | 135.98 |
|  | 207.85 | 189.07 | 204.37 | 126.89 |
|  | 186.18 | 183.39 | 173.11 | 159.94 |
|  | 203.73 | 195.51 | 199.27 | 143.24 |

| | | | | |
|---|---|---|---|---|
| **1000 tests** | 187.65 | 182.36 | 186.77 | 133.97 |
| | 250.83 | 177.48 | 223.37 | 137.20 |
| | 203.13 | 178.30 | 185.82 | 132.68 |
| | 196.14 | 187.27 | 168.53 | 134.57 |
| | 176.89 | 200.95 | 189.45 | 141.30 |
| **1250 tests** | 206.46 | 203.28 | 202.17 | 153.69 |
| | 212.29 | 224.52 | 182.95 | 158.15 |
| | 199.50 | 188.91 | 173.85 | 153.37 |
| | 206.80 | 188.45 | 226.28 | 136.06 |
| | 188.02 | 196.77 | 224.10 | 144.47 |
| **1500 tests** | 221.78 | 221.71 | 206.83 | 143.98 |
| | 230.45 | 174.49 | 171.34 | 136.35 |
| | 229.14 | 214.53 | 173.82 | 129.20 |
| | 205.38 | 212.94 | 210.69 | 159.94 |
| | 211.58 | 217.81 | 240.41 | 129.78 |
| **1750 tests** | 207.85 | 225.71 | 209.55 | 100.55 |
| | 191.48 | 188.64 | 210.85 | 132.07 |
| | 202.56 | 208.01 | 214.47 | 168.10 |
| | 206.33 | 182.43 | 211.04 | 158.27 |
| | 210.53 | 197.96 | 174.61 | 120.64 |
| **2000 tests** | 231.95 | 226.03 | 230.34 | 160.28 |
| | 245.30 | 219.83 | 183.49 | 166.54 |
| | 193.01 | 197.81 | 216.64 | 122.94 |
| | 185.68 | 230.52 | 211.84 | 167.89 |
| | 226.10 | 209.93 | 163.59 | 124.14 |

**Table 35:** Raw hardness data for Blade 1.

|  | Blade | | | Baseline |
|---|---|---|---|---|
|  | 1 | 2 | 3 | 1 |
| pre-sharpen 0 tests | 87.23 | 88.59 | 97.95 | 103.95 |
|  | 109.94 | 91.04 | 92.25 | 96.36 |
|  | 70.99 | 93.40 | 102.81 | 99.97 |
|  | 100.24 | 100.05 | 94.06 | 104.46 |
|  | 81.17 | 87.04 | 93.04 | 93.83 |
| hardened 0 tests | 125.65 | 146.29 | 110.96 | 92.90 |
|  | 96.29 | 102.50 | 131.43 | 104.24 |
|  | 93.31 | 155.65 | 138.32 | 103.31 |
|  | 81.30 | 117.77 | 153.29 | 110.14 |
|  | 108.96 | 133.01 | 140.03 | 121.43 |
| post-sharpen 0 tests | 152.21 | 153.87 | 170.95 | 146.38 |
|  | 157.28 | 165.05 | 173.80 | 171.27 |
|  | 188.45 | 153.10 | 184.56 | 235.82 |
|  | 191.12 | 163.69 | 179.49 | 125.85 |
|  | 162.63 | 150.62 | 175.24 | 154.21 |
| 250 tests | 178.05 | 137.95 | 180.25 | 175.12 |
|  | 154.89 | 154.63 | 193.45 | 156.34 |
|  | 167.37 | 170.58 | 182.59 | 173.20 |
|  | 149.84 | 207.95 | 185.60 | 130.93 |
|  | 161.86 | 170.18 | 173.66 | 142.69 |
| 500 tests | 163.87 | 190.87 | 177.68 | 161.54 |
|  | 148.90 | 184.06 | 251.87 | 138.63 |
|  | 174.37 | 200.47 | 204.59 | 175.00 |
|  | 153.91 | 188.16 | 192.14 | 167.19 |

|  | | | | |
|---|---|---|---|---|
|  | 178.50 | 169.19 | 167.69 | 197.64 |
| *750 tests* | 138.46 | 161.88 | 183.57 | 155.07 |
|  | 163.63 | 186.48 | 177.75 | 168.44 |
|  | 143.98 | 176.45 | 198.60 | 148.47 |
|  | 159.31 | 230.01 | 211.97 | 160.64 |
|  | 161.17 | 221.67 | 215.35 | 157.38 |
| *1000 tests* | 178.65 | 183.33 | 190.76 | 130.79 |
|  | 166.81 | 209.14 | 203.55 | 196.77 |
|  | 175.60 | 206.73 | 203.01 | 121.13 |
|  | 157.92 | 209.23 | 204.74 | 161.79 |
|  | 173.39 | 182.64 | 179.34 | 138.88 |
| *1250 tests* | 166.37 | 208.42 | 210.47 | 135.41 |
|  | 202.44 | 244.98 | 199.77 | 147.29 |
|  | 194.58 | 223.85 | 191.51 | 139.77 |
|  | 167.49 | 180.47 | 212.48 | 157.82 |
|  | 179.27 | 190.46 | 208.32 | 149.42 |
| *1500 tests* | 182.59 | 182.25 | 235.29 | 153.02 |
|  | 228.24 | 190.27 | 198.77 | 205.35 |
|  | 174.49 | 254.04 | 205.44 | 169.33 |
|  | 183.57 | 215.32 | 190.11 | 160.92 |
|  | 193.40 | 195.06 | 212.68 | 144.72 |
| *1750 tests* | 190.11 | 211.46 | 195.20 | 129.97 |
|  | 225.78 | 210.56 | 196.09 | 124.67 |
|  | 215.58 | 216.34 | 208.42 | 194.89 |
|  | 205.66 | <span style="color:red">305.46</span> | 176.70 | 166.37 |
|  | 197.38 | 211.97 | 205.20 | 176.36 |
|  | 168.14 | 204.80 | 212.71 | 161.79 |

| 2000 tests | 198.89 | 216.57 | 240.14 | 126.18 |
| | 175.94 | 182.77 | 257.67 | 149.59 |
| | 191.70 | 198.51 | 240.22 | 166.05 |
| | 174.42 | 195.03 | 198.77 | 169.79 |

*Table 36:* Raw hardness data for Blade 2.

Additional SEM images
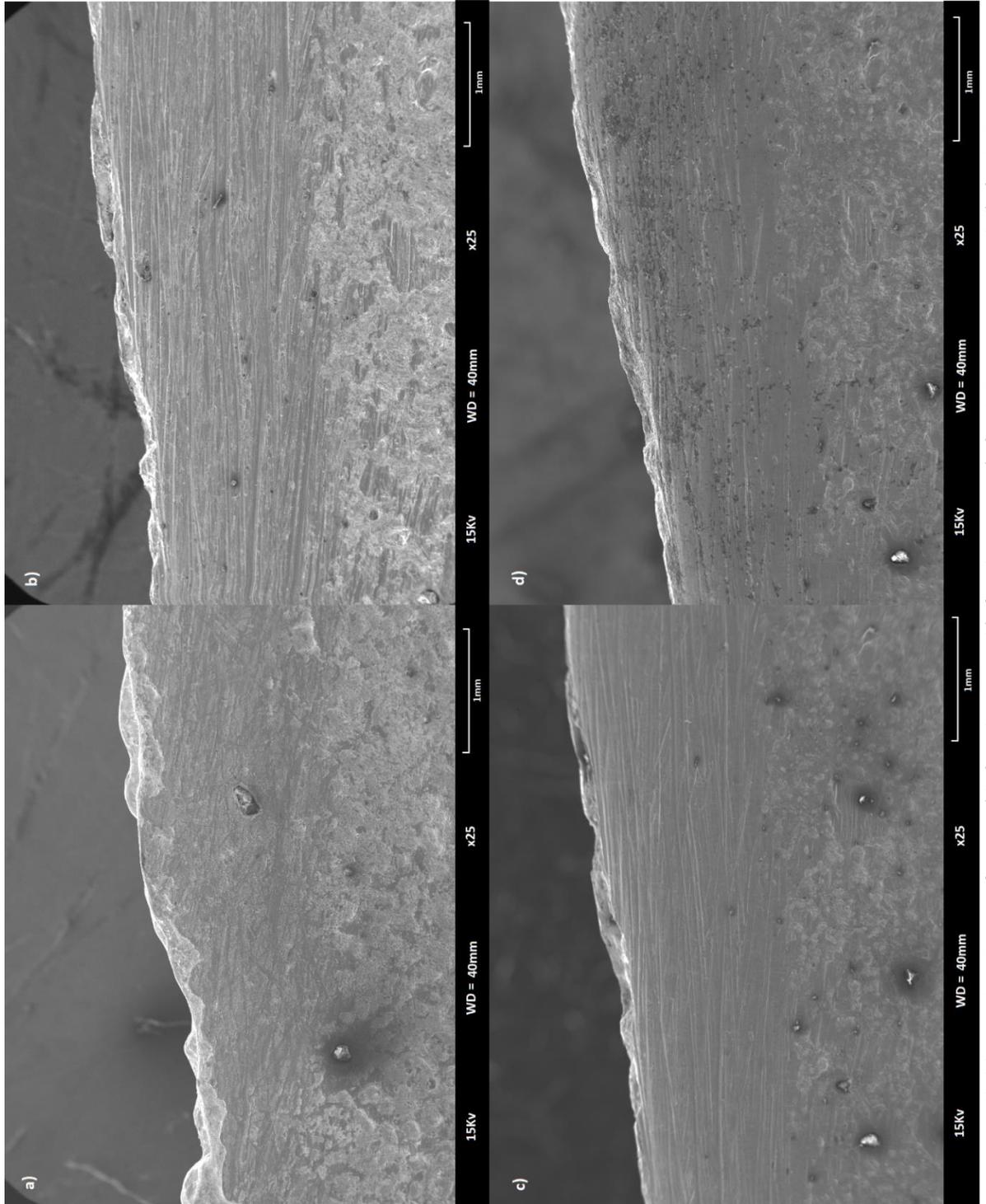


*Figure 175:* Bladelet 1 SL 1 at x25 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests.
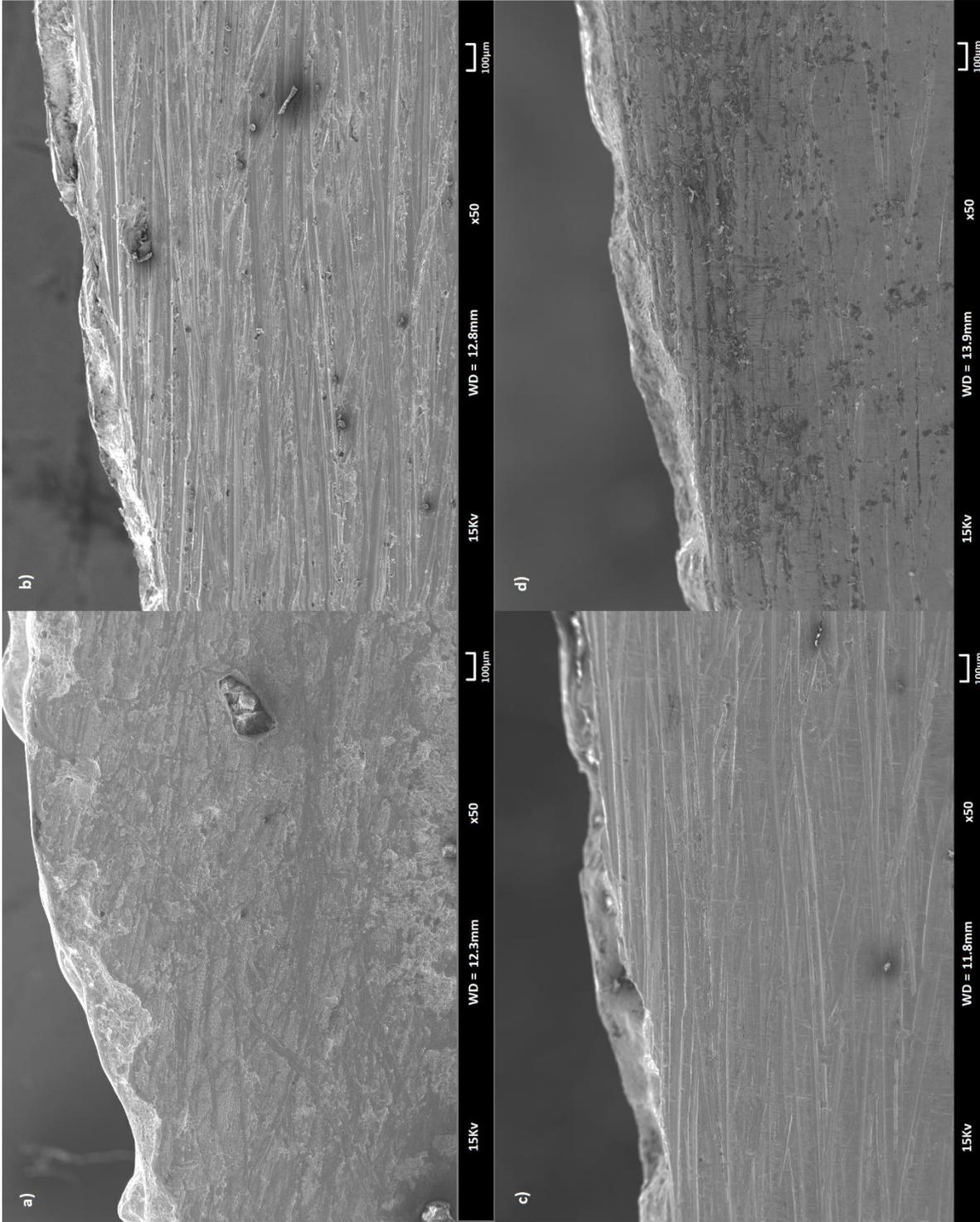
*Figure 176:* Bladelet 1 SL 1 at x50 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests.

282
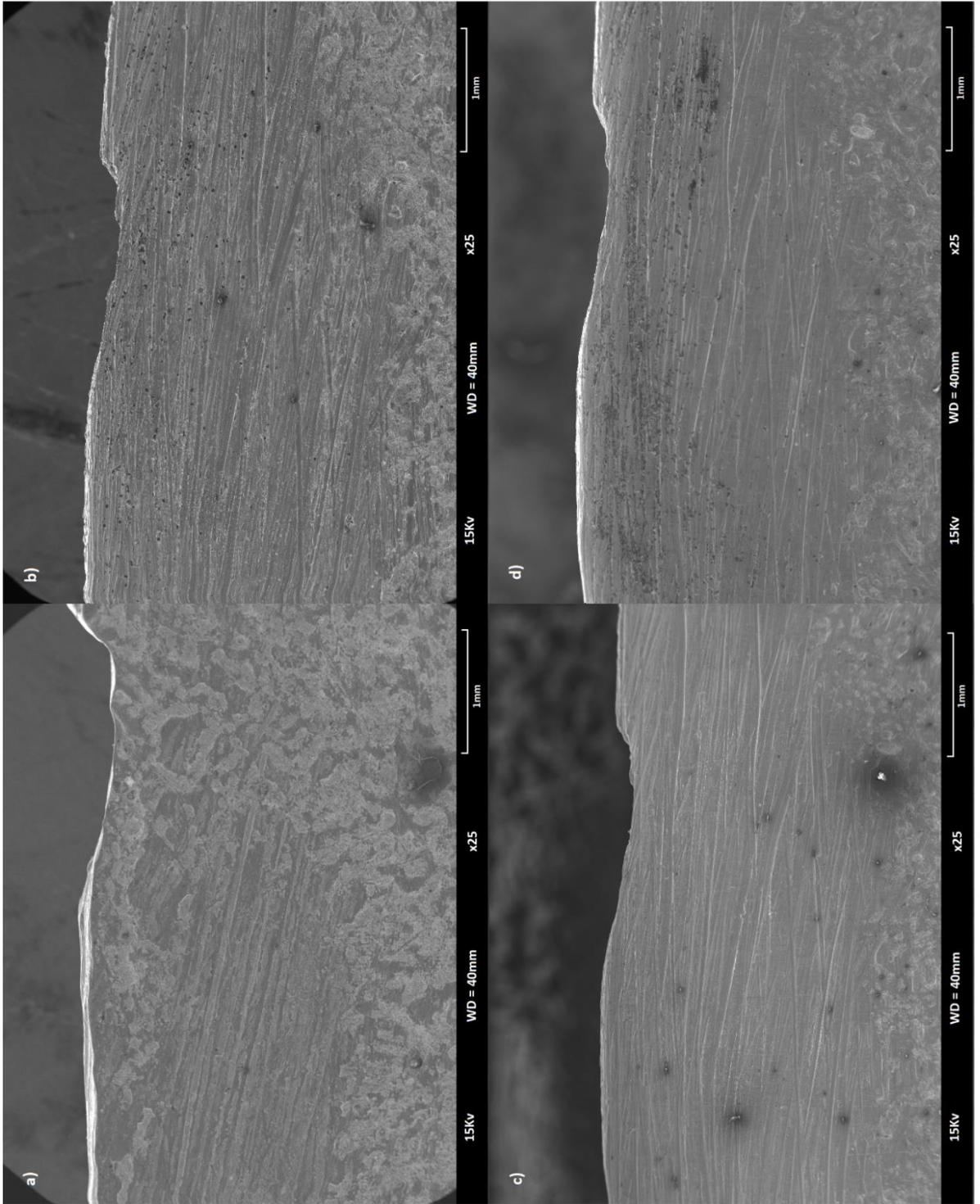
*Figure 177:* Bladelet 1 SL 2 at x25 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests.
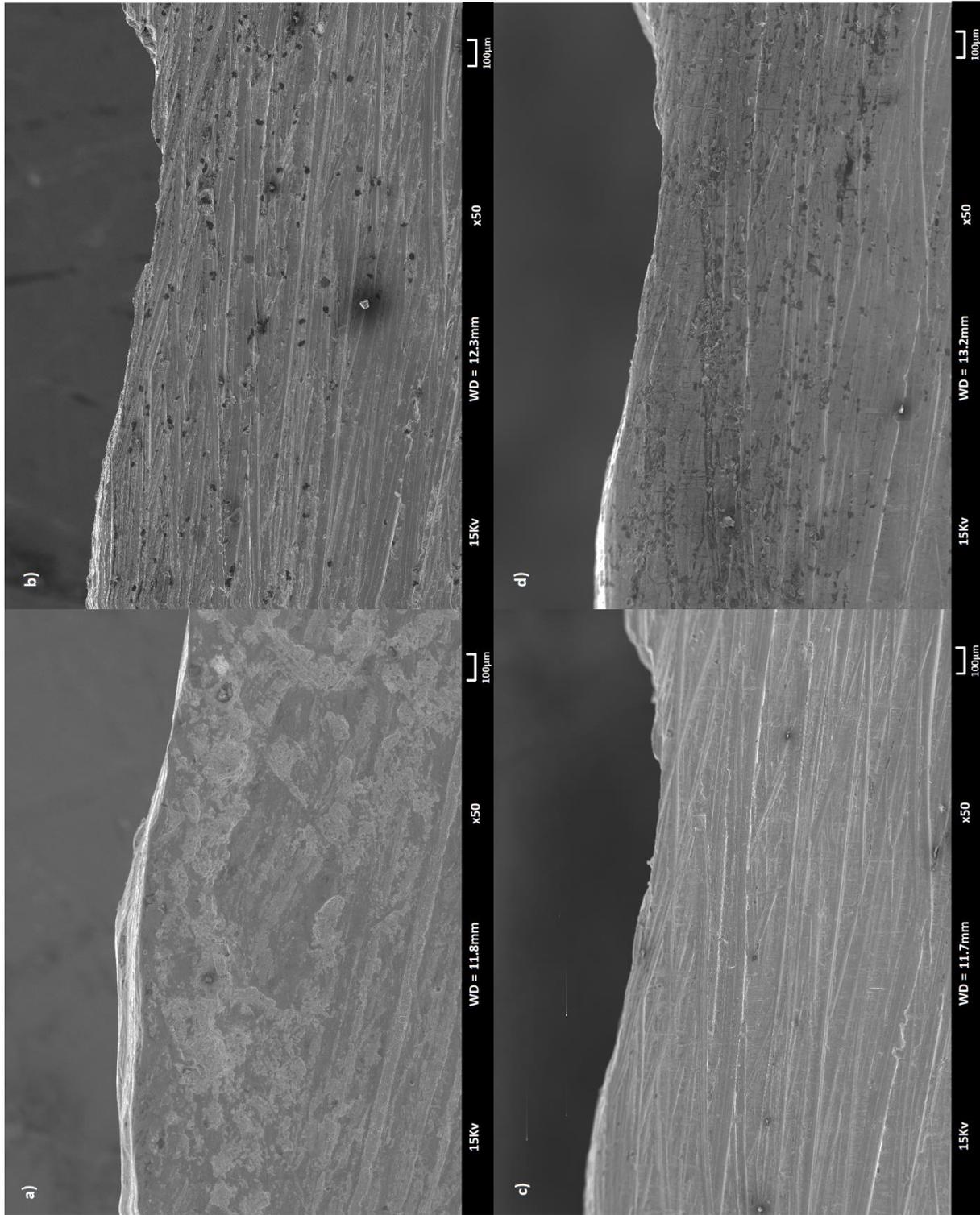
*Figure 178:* Bladelet 1 SL 2 at x50 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests.
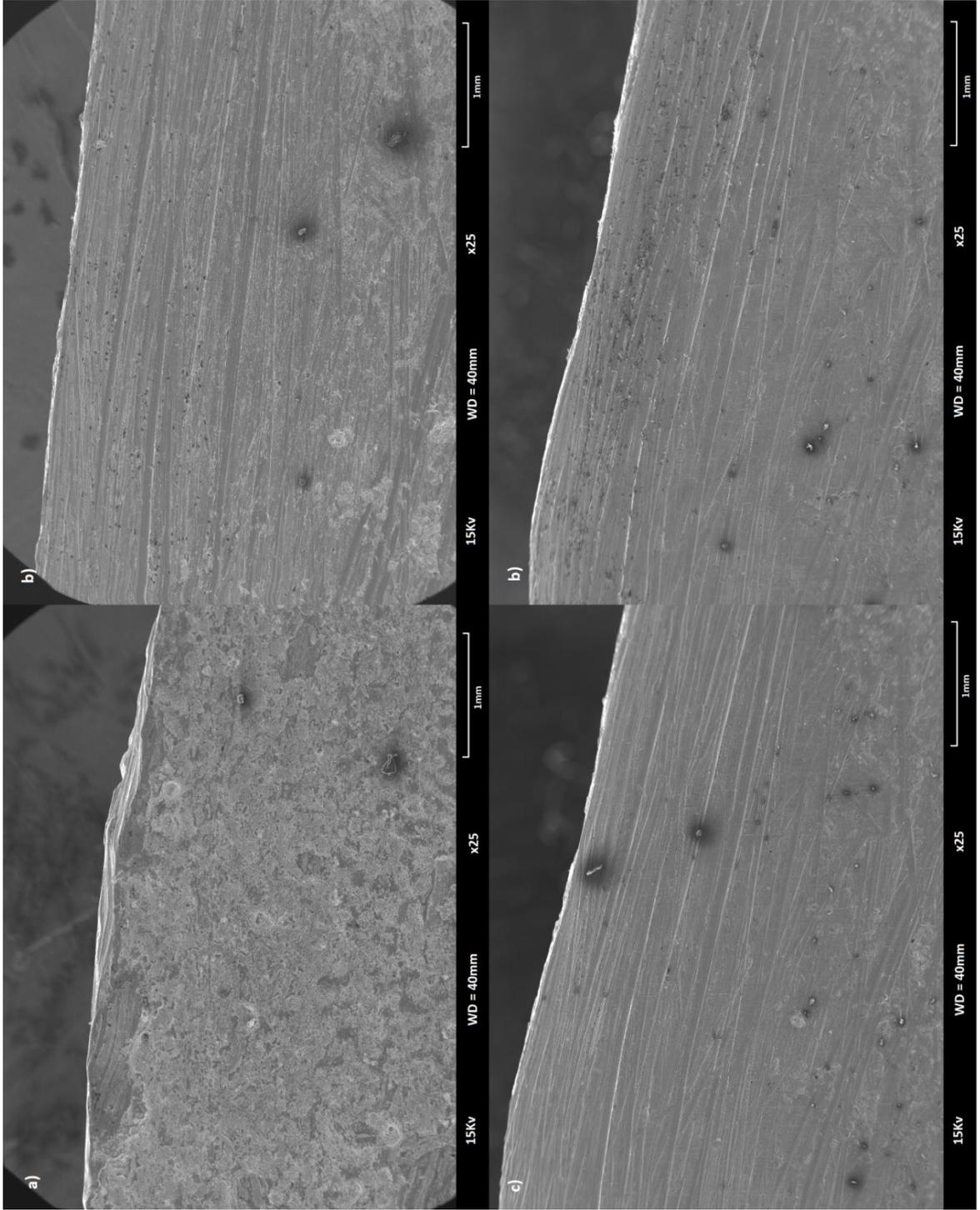
*Figure 179:* Bladelet 1 SL 3 at x25 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests.
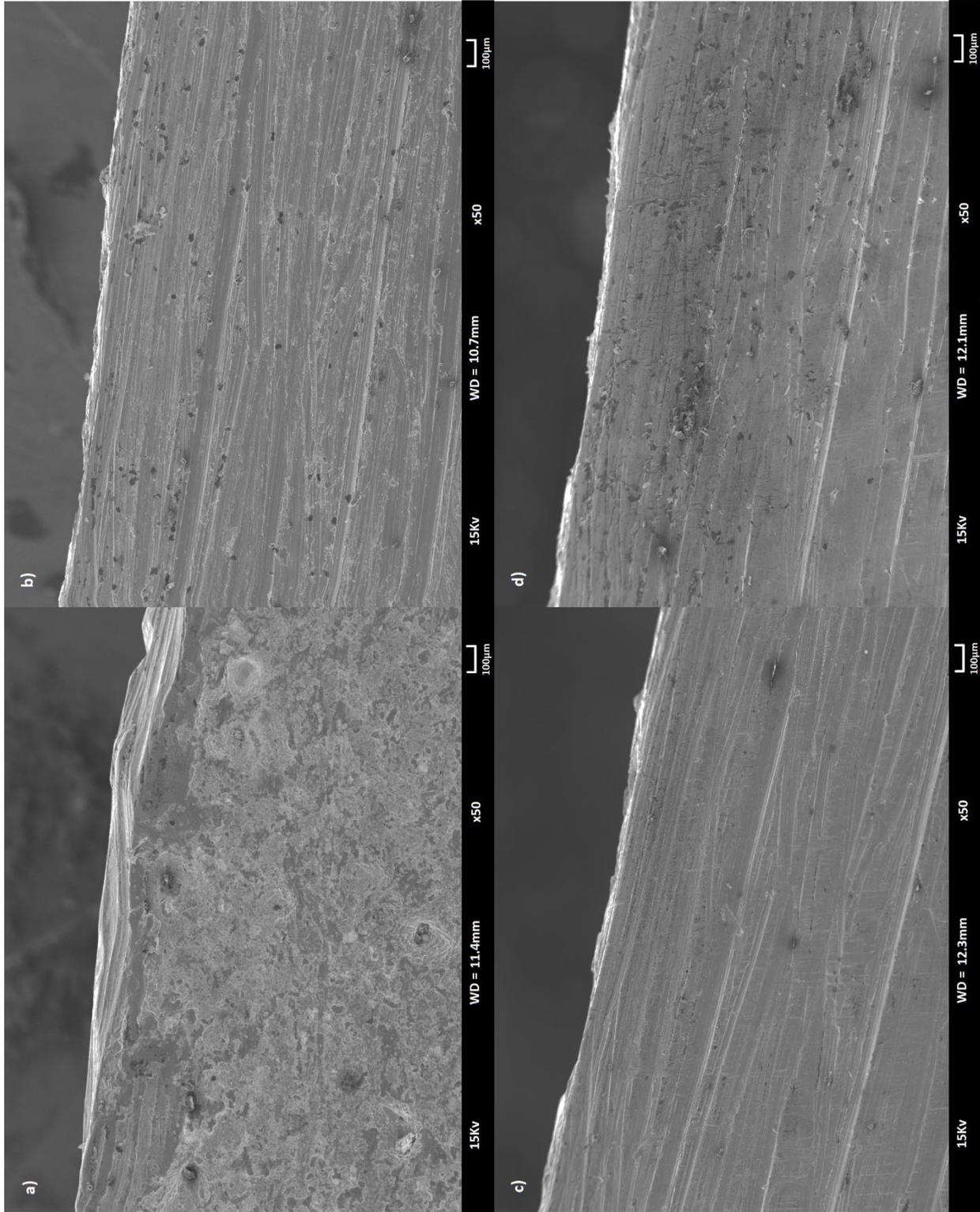
***Figure 180:*** Bladelet 1 SL 3 at x50 magnification: a) before sharpening; b) after sharpening; c) after 1250 impact tests; and, d) after 2000 impact tests.

**15Kv**  **WD = 12mm**  **x1000**  **10μm**
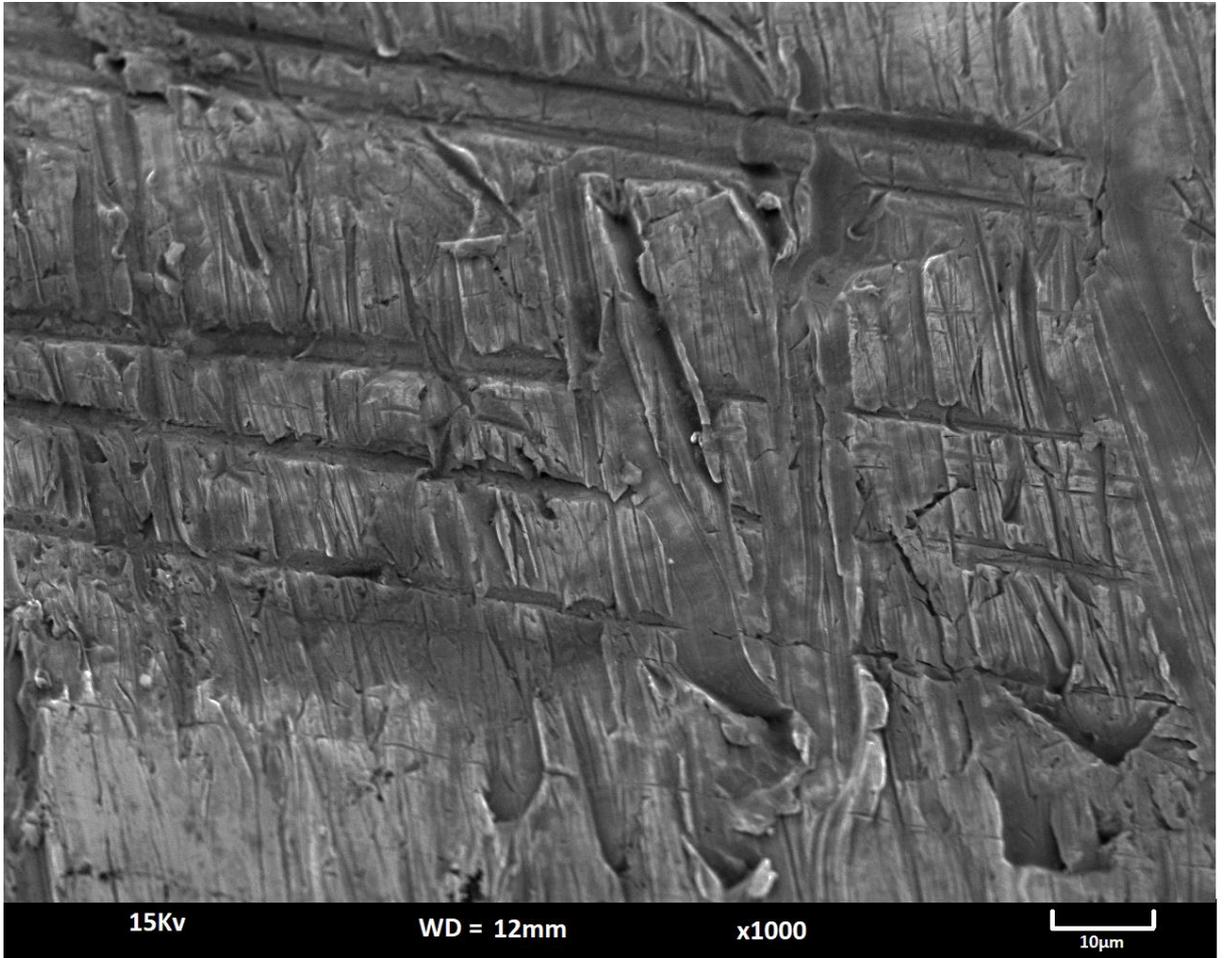
*Figure 181:* Blade 1, SL 3, x1000 magnification after 2000 impact tests.
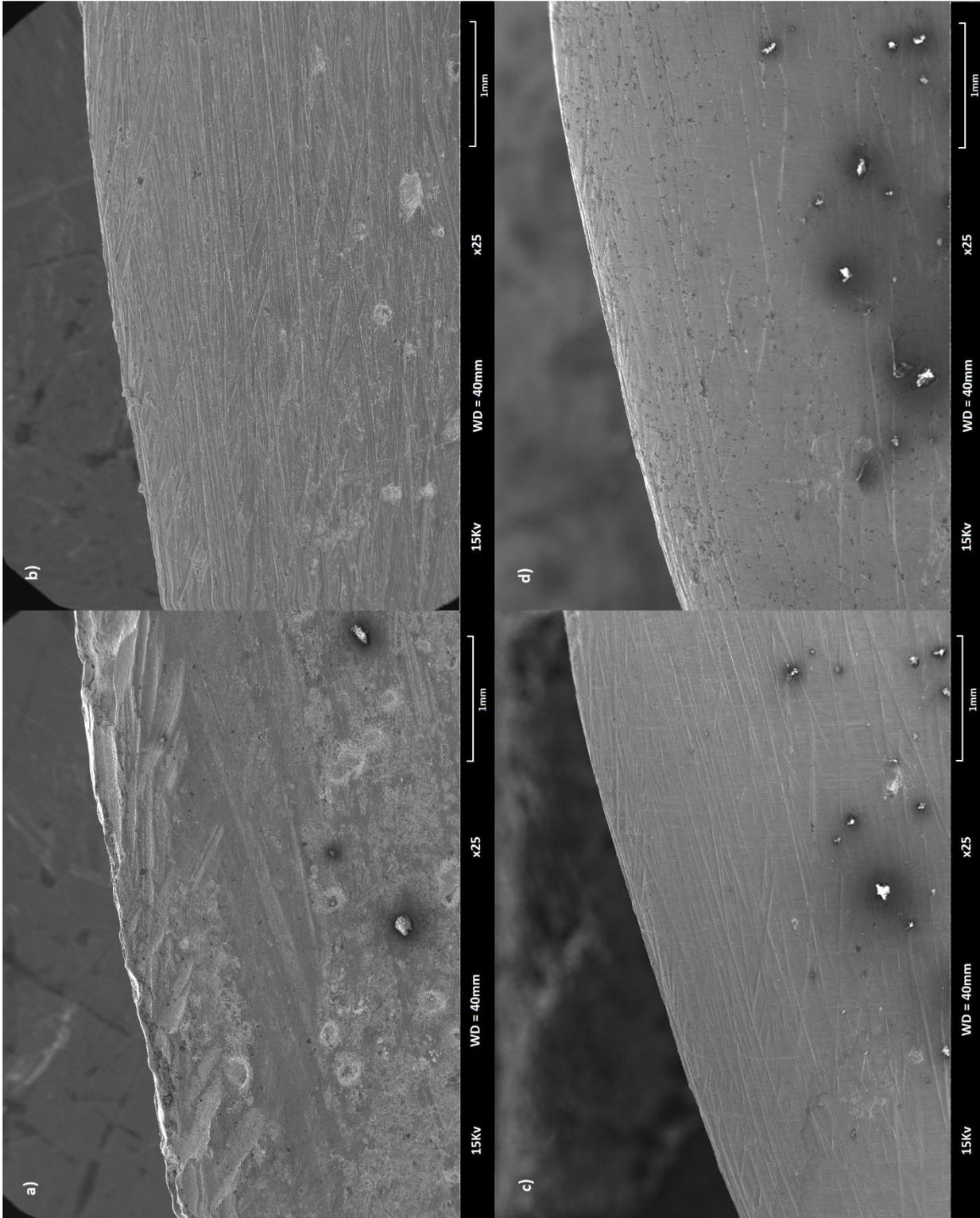
*Figure 182:* Bladelet 2 SL 1 at x25 magnification: a) before sharpening; b) after sharpening; c) after 1250 impact tests; and, d) after 2000 impact tests.
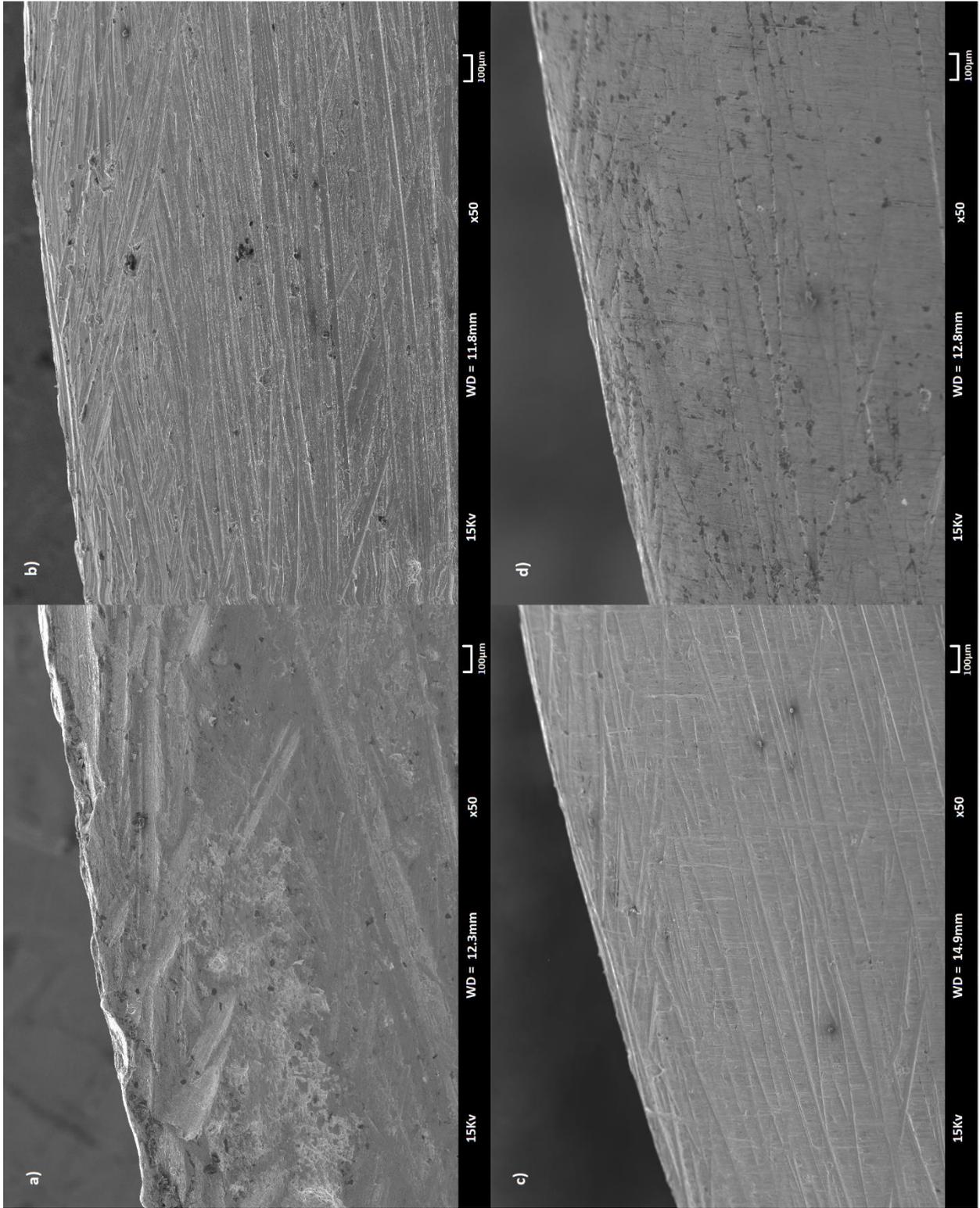
*Figure 183:* Bladelet 2 SL 1 at x50 magnification: a) before sharpening; b) after sharpening; c) after 1250 impact tests; and, d) after 2000 impact tests.

289
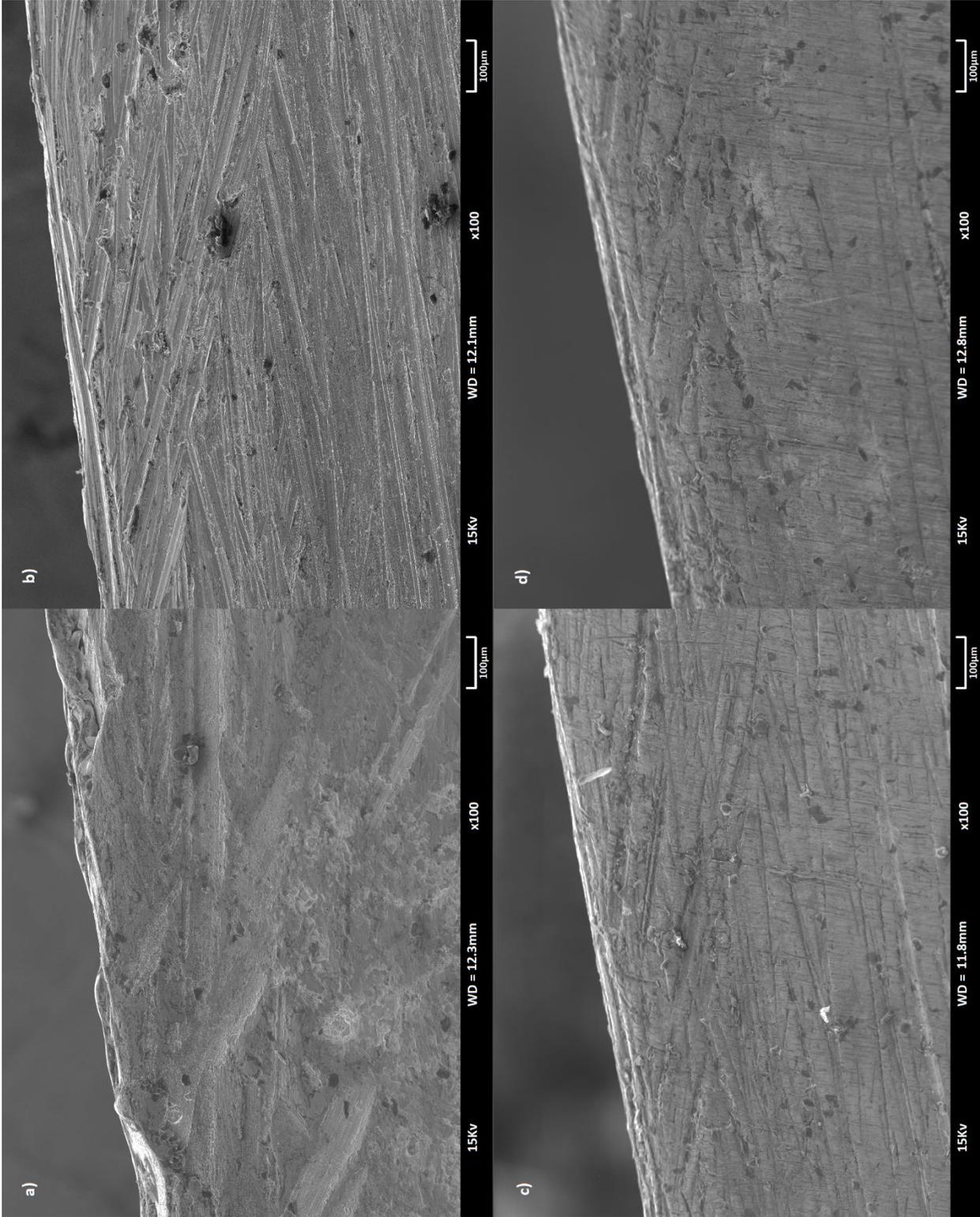
*Figure 184:* Bladelet 2 SL 1 at x100 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests.
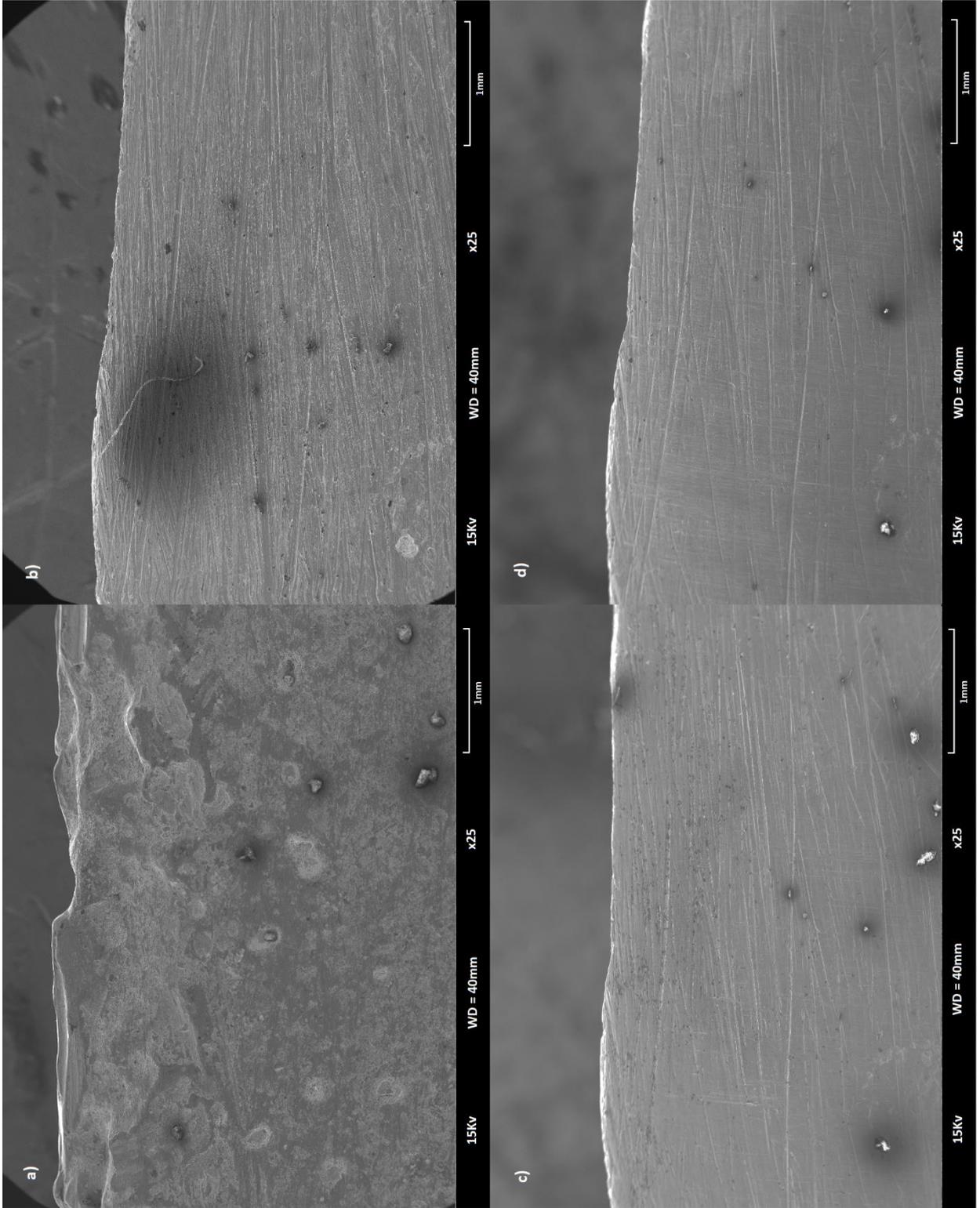
*Figure 185:* Bladelet 2 SL 2 at x25 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 1500 impact tests.
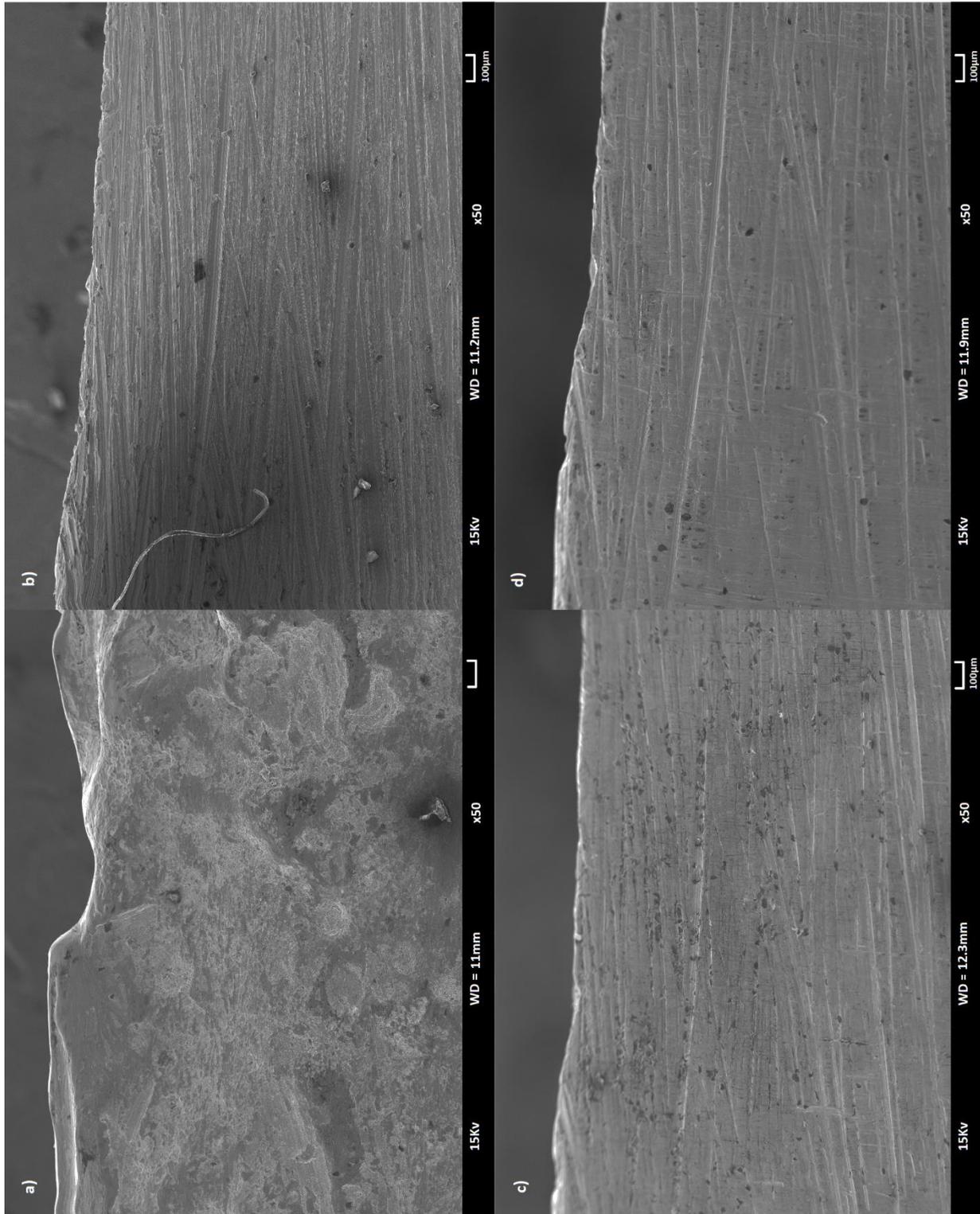
*Figure 186*: Bladelet 2 SL 2 at x50 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 1750 impact tests.
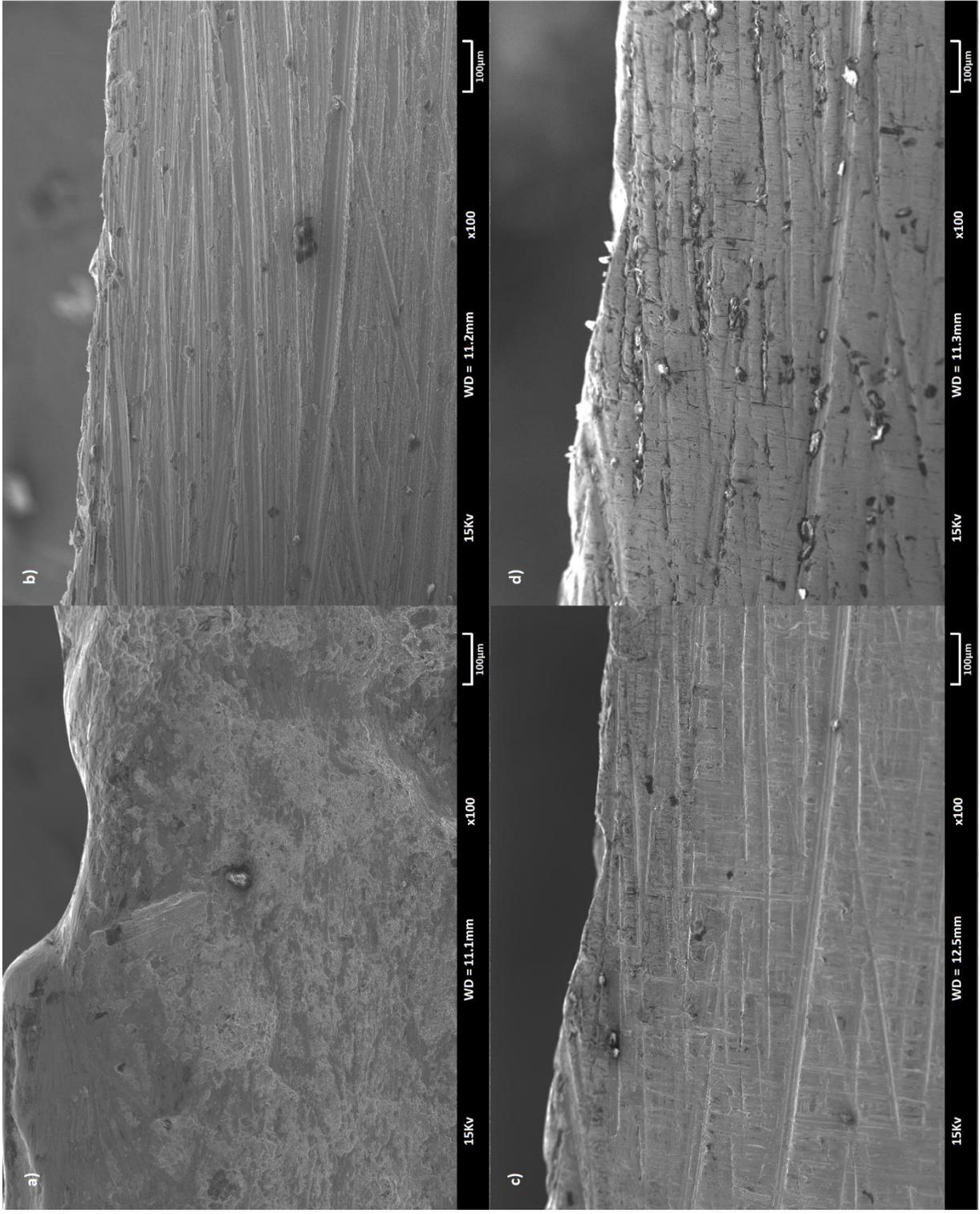
*Figure 187:* Bladelet 2 SL 2 at x100 magnification: a) before sharpening; b) after sharpening; c) after 1500 impact tests; and, d) after 2000 impact tests.
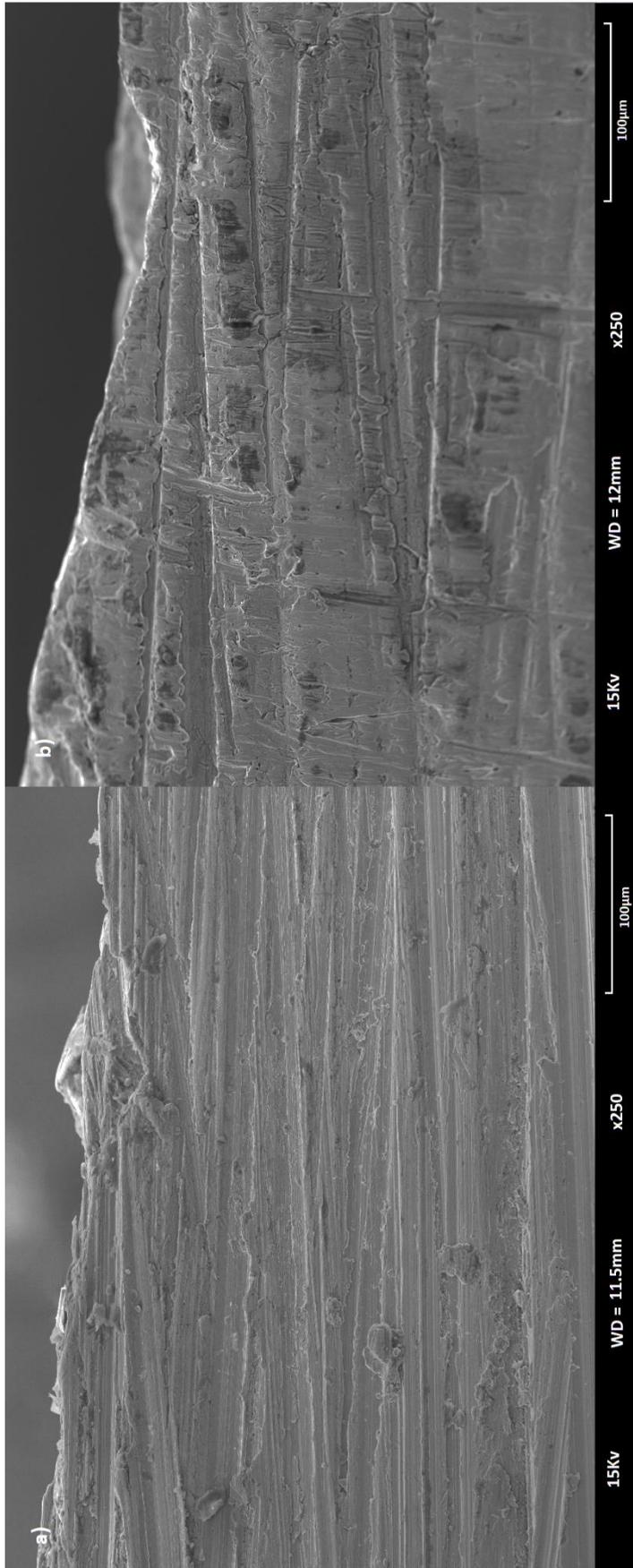
***Figure 188:*** Bladelet 2, SL 2, x250 magnification: a) after sharpening; and, b) after 1750 impact tests.
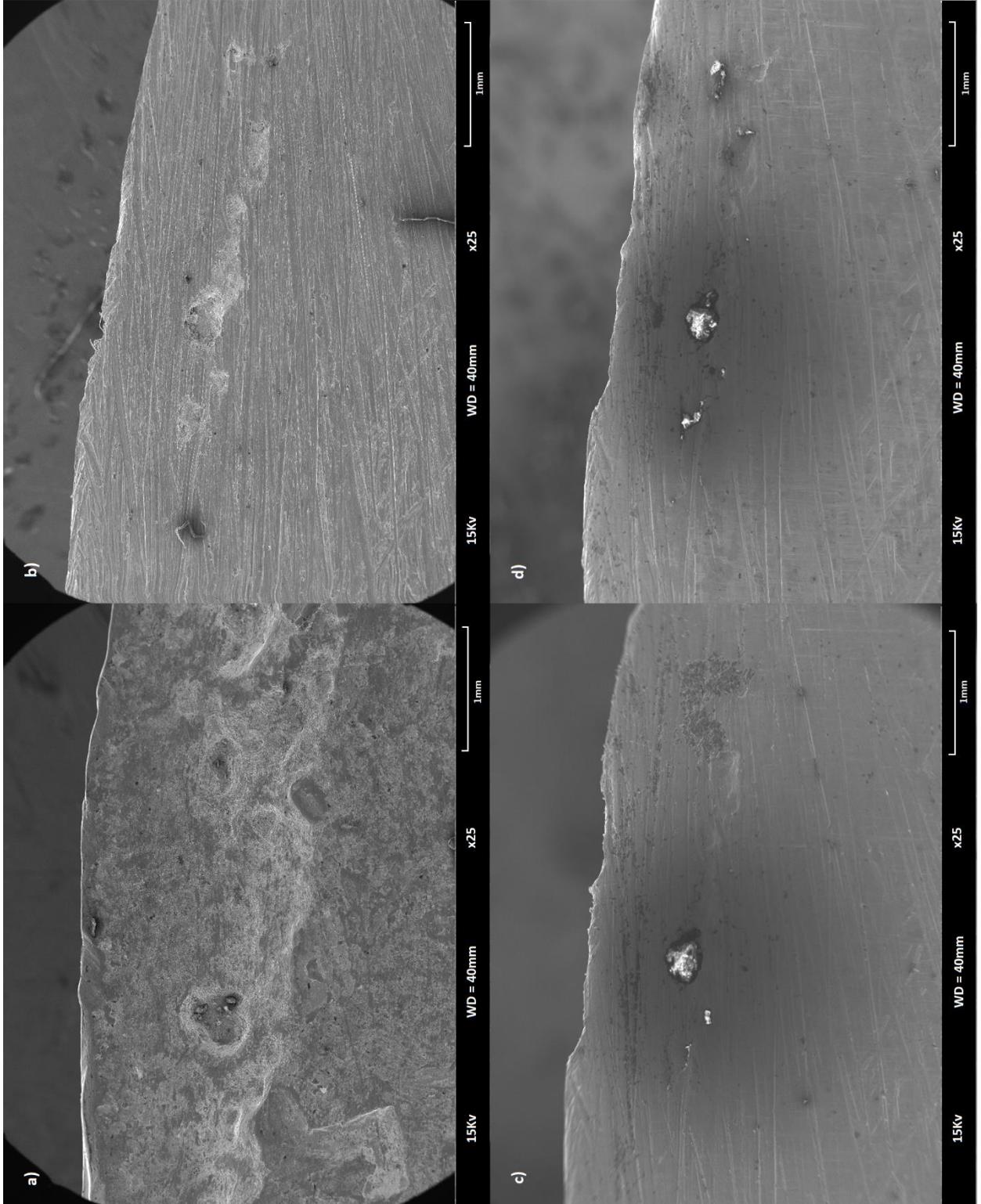
***Figure 189:*** Bladelet 2 SL 3 at x25 magnification: a) before sharpening; b) after sharpening; c) after 1000 impact tests; and, d) after 2000 impact tests.
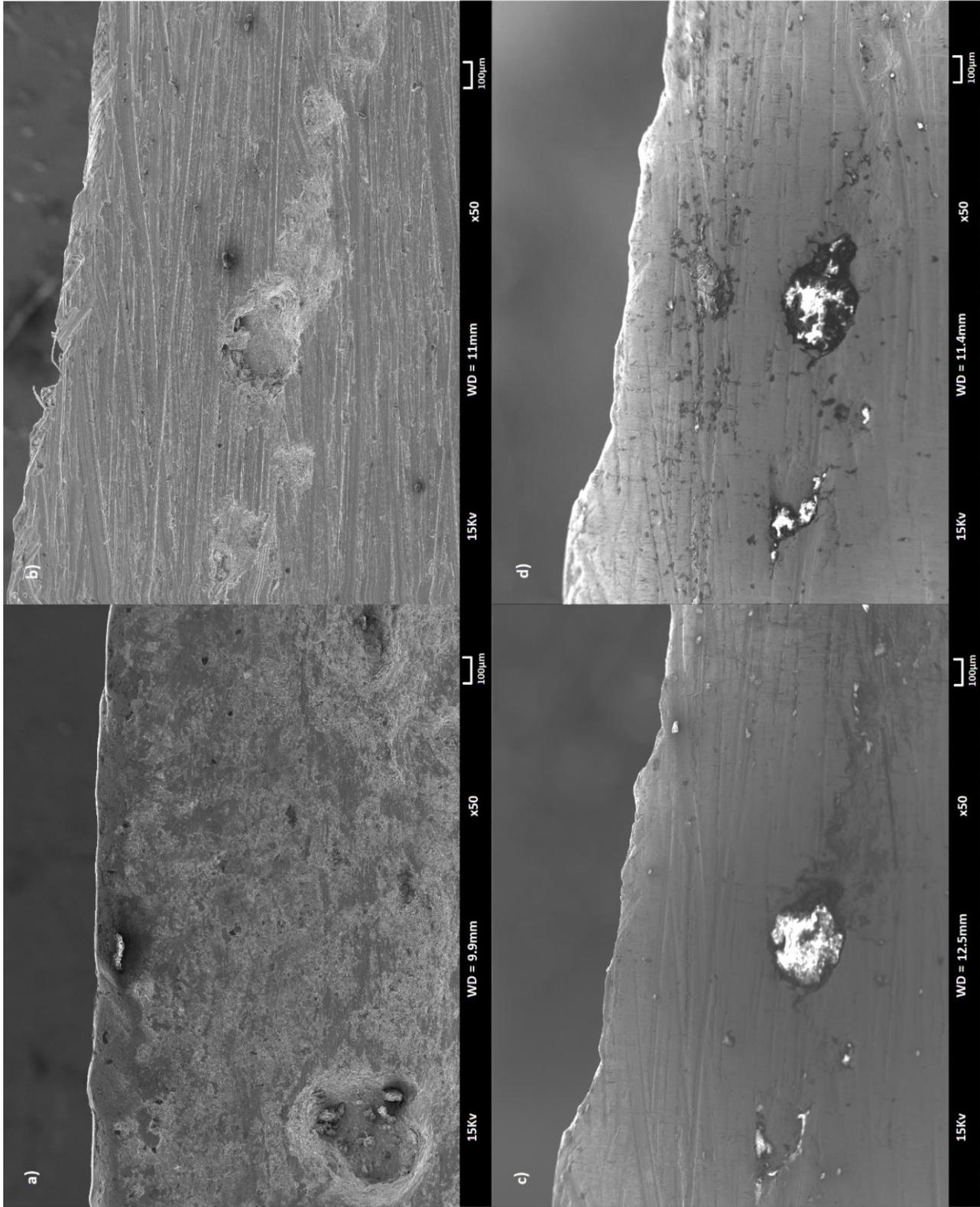
*Figure 190:* Bladelet 2 SL 3 at x50 magnification: a) before sharpening; b) after sharpening; c) after 1500 impact tests; and, d) after 2000 impact tests.

# Additional digital microscope images
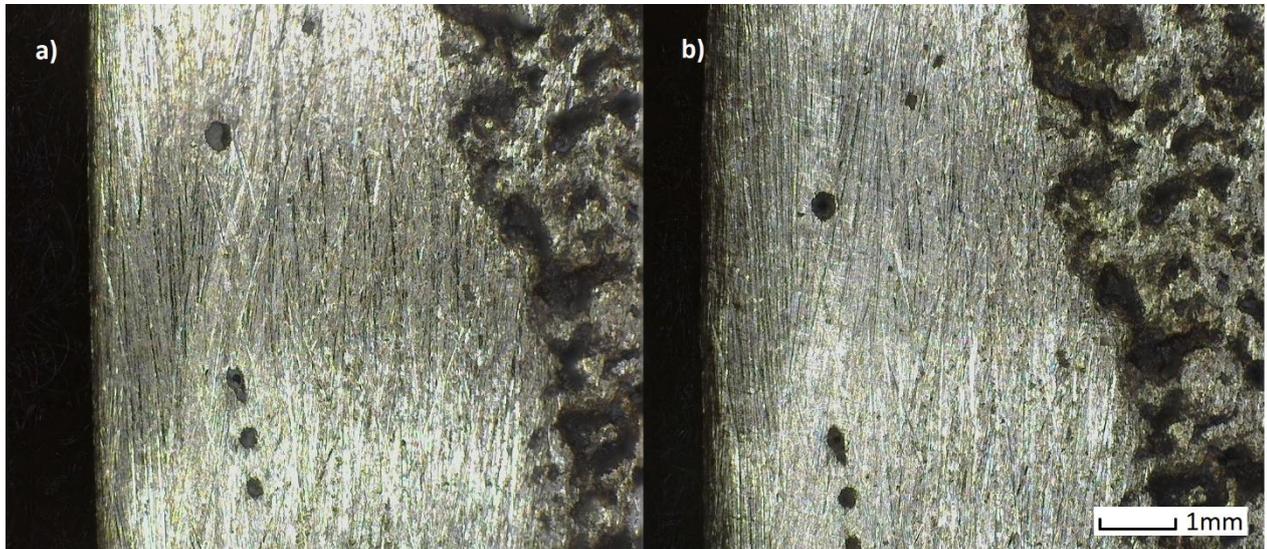


***Figure 191:*** Digital microscope images of Blade 4, SL 1, at x25 magnification, where: a) post-sharpening at 1050 impacts; b) 2000 impacts.
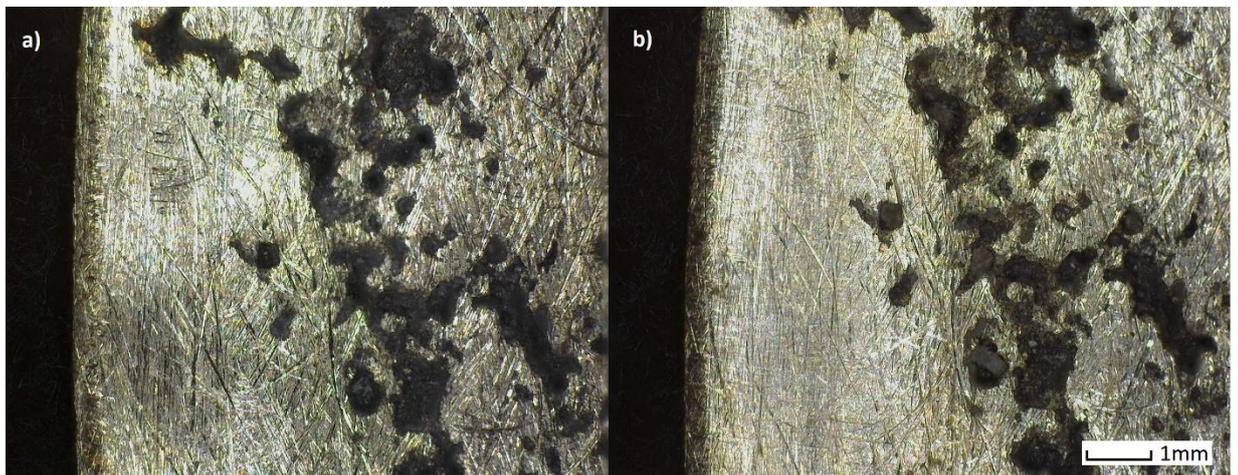


***Figure 192:*** Digital microscope images of Blade 4, SL 2, at x25 magnification, where: a) post-sharpening at 58 impacts; b) 1000 impacts.
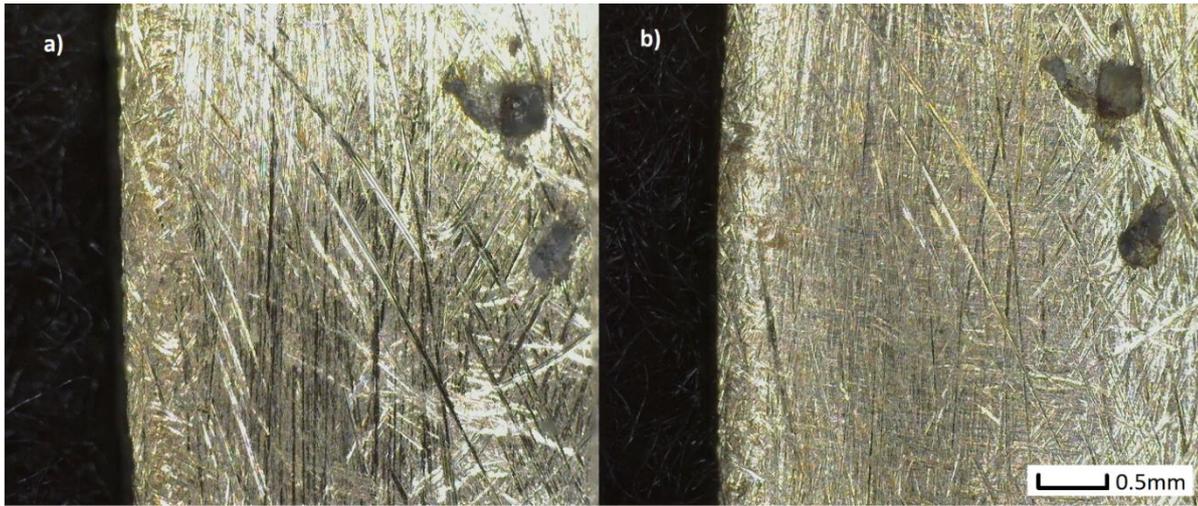
**Figure 193:** Digital microscope images of Blade 4, SL 2, at x50 magnification, where: a) post-sharpening at 58 impacts; b) 1000 impacts.
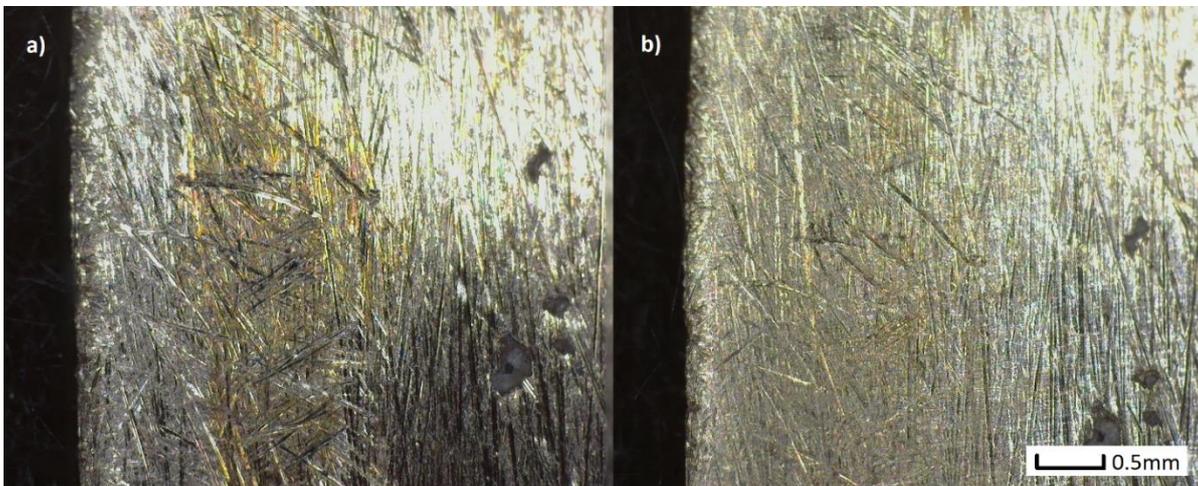


**Figure 194:** Digital microscope images of Blade 4, SL 3, at x50 magnification, where: a) post-sharpening at 58 impacts; b) 1000 impacts.
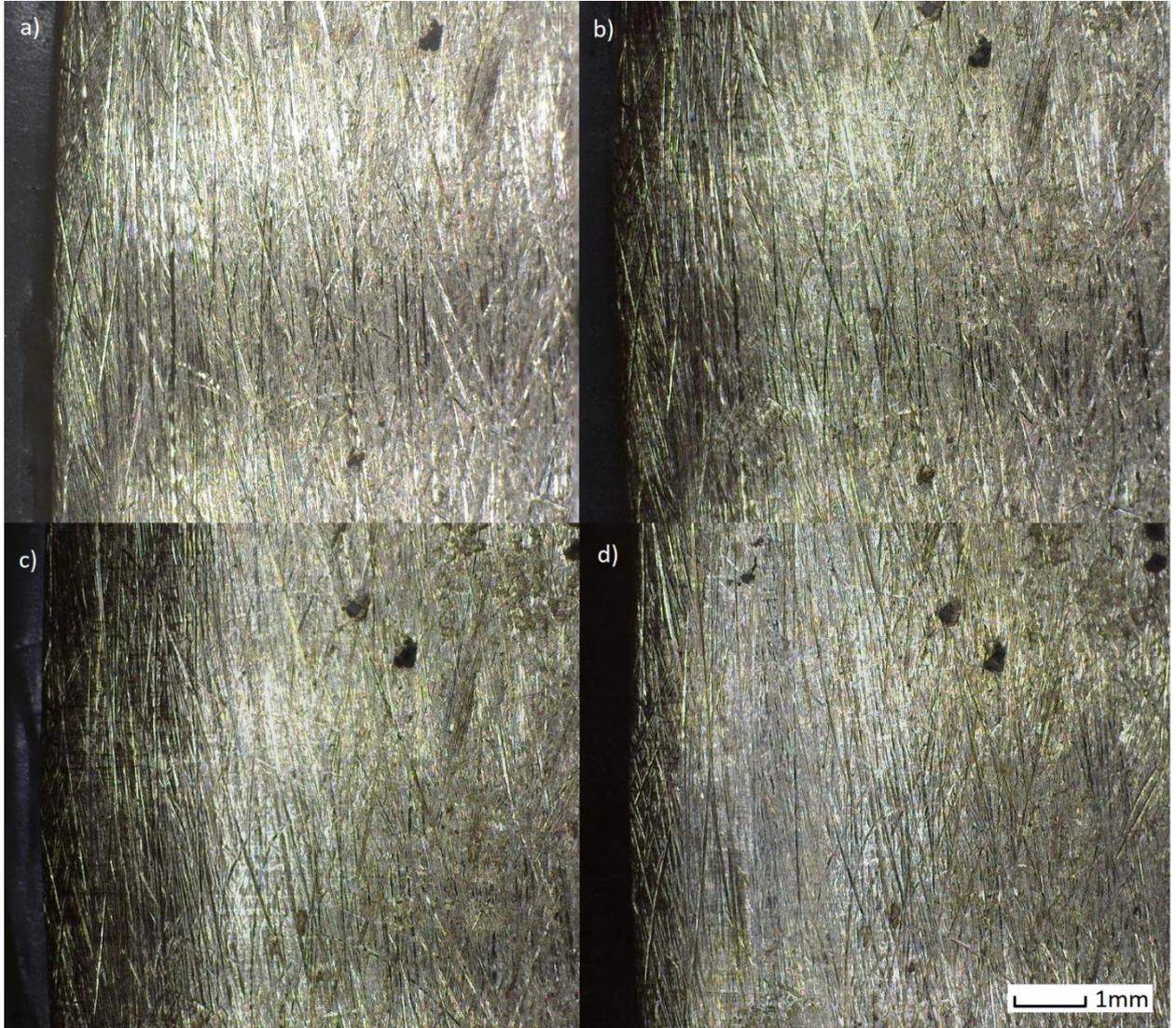
**Figure 195:** Digital microscope images of Bladelet 3, SL 2, at x25 magnification, where: a) post-sharpening; b) 1000 impacts; c) 2000 impacts; d) 3000 impacts.
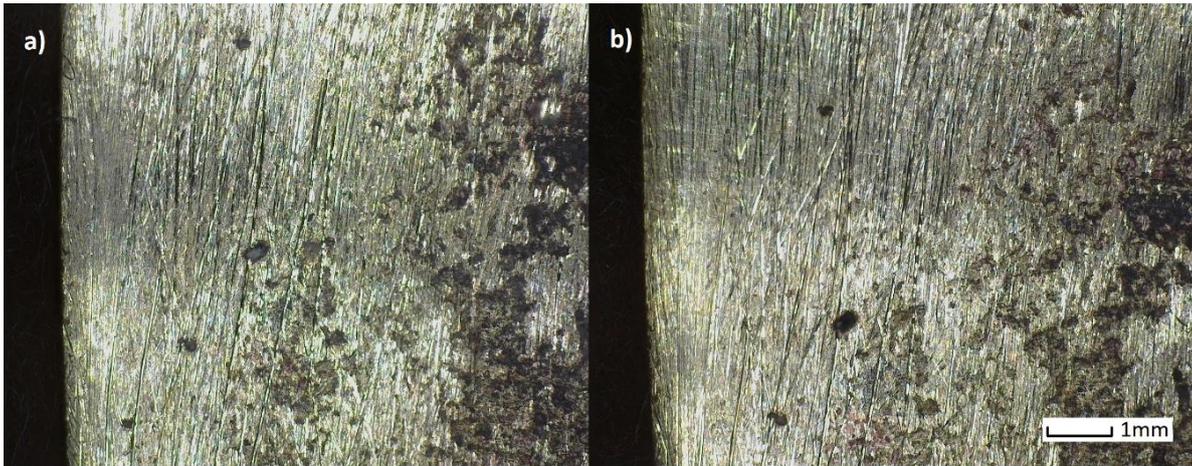
**Figure 196:** Digital microscope images of Blade 5, SL 1, at x25 magnification, where: a) post-sharpening at 50 impacts; b) 695 impacts.
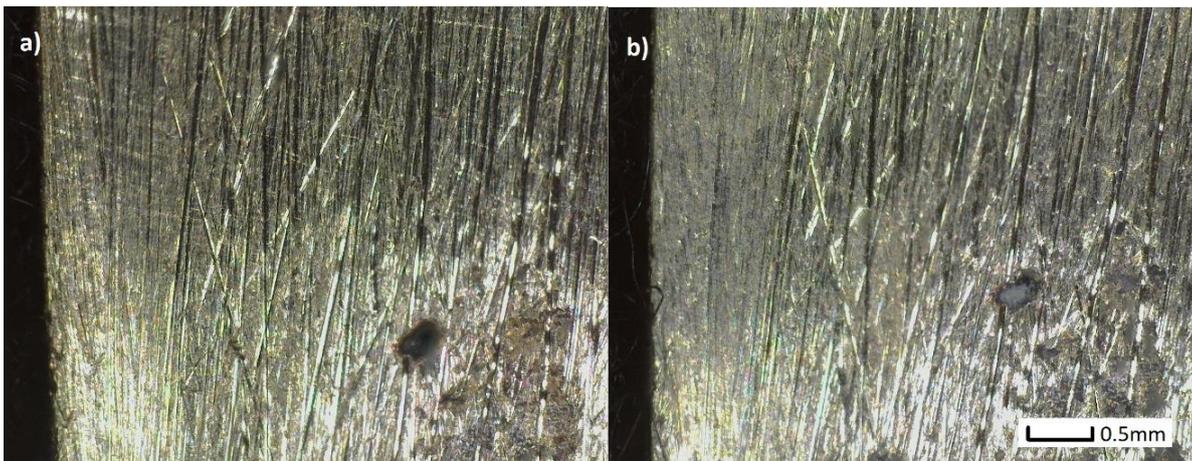


**Figure 197:** Digital microscope images of Blade 5, SL 1, at x50 magnification, where: a) post-sharpening at 50 impacts; b) 695 impacts.

**Figure 198:** Digital microscope images of Blade 5, SL 2, at x25 magnification, where: a) post-sharpening at 50 impacts; b) 695 impacts.
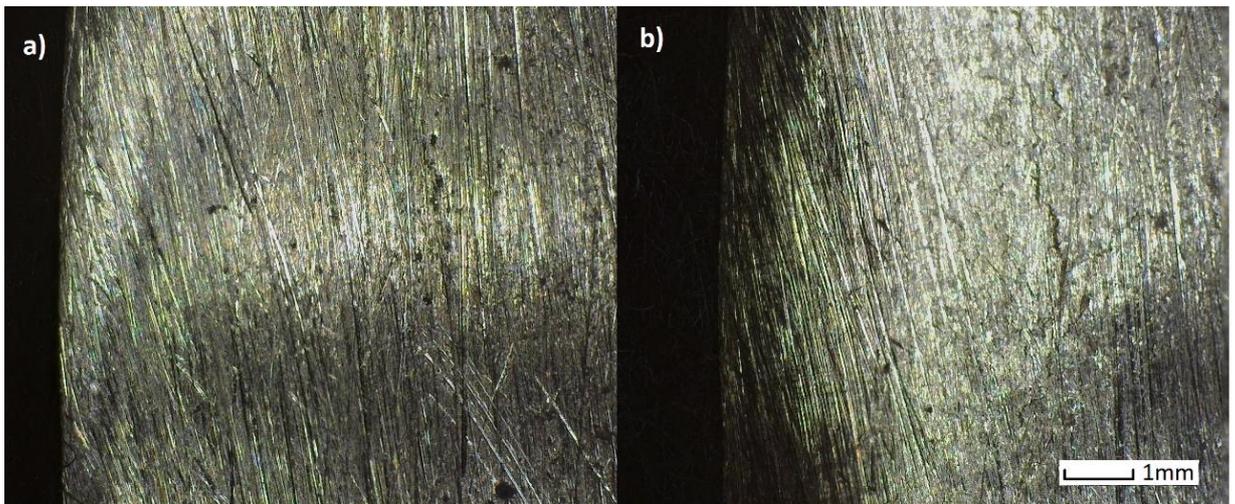


**Figure 199:** Digital microscope images of Bladelet 5, SL 3, at x25 magnification, where: a) post-sharpening at 50 impacts; b) 695 impacts.
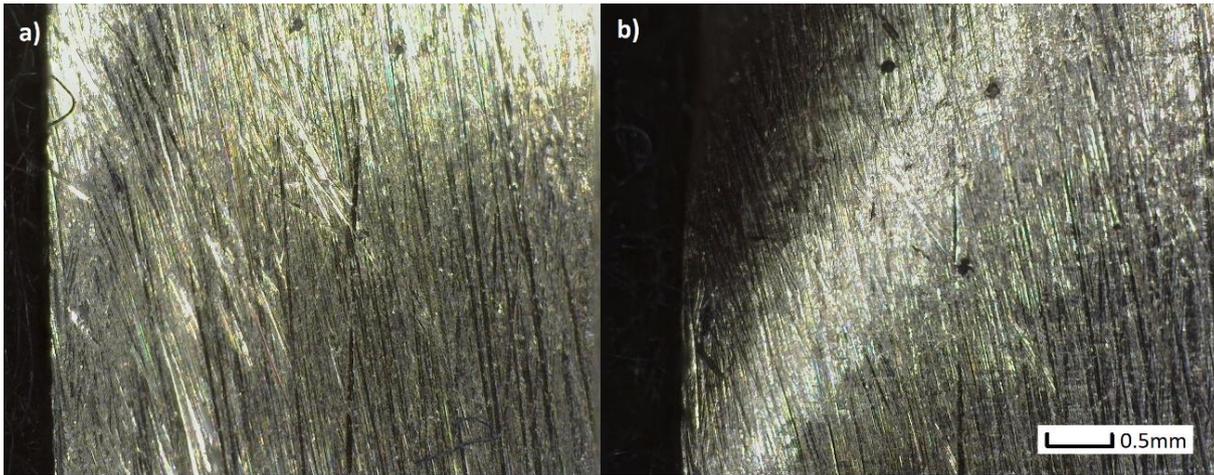
*Figure 200:* Digital microscope images of Blade 5, SL 3, at x50 magnification, where: a) post-sharpening at 50 impacts; b) 695 impacts.
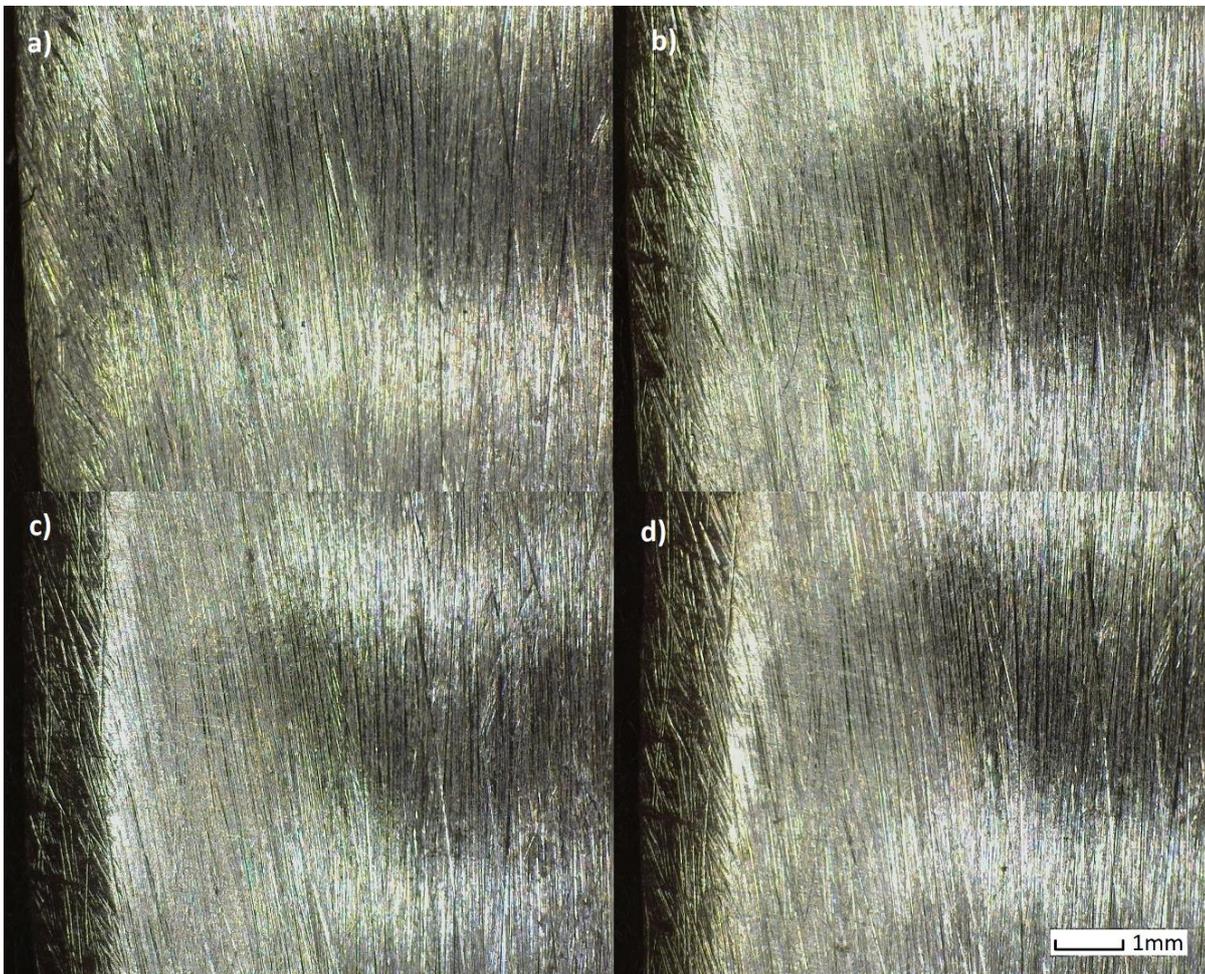


*Figure 201:* Digital microscope images of Blade 6, SL 1, at x25 magnification, where: a) post-sharpening at 1000 impacts; b) 2000 impacts; c) 3000 impacts; d) 3500 impacts.
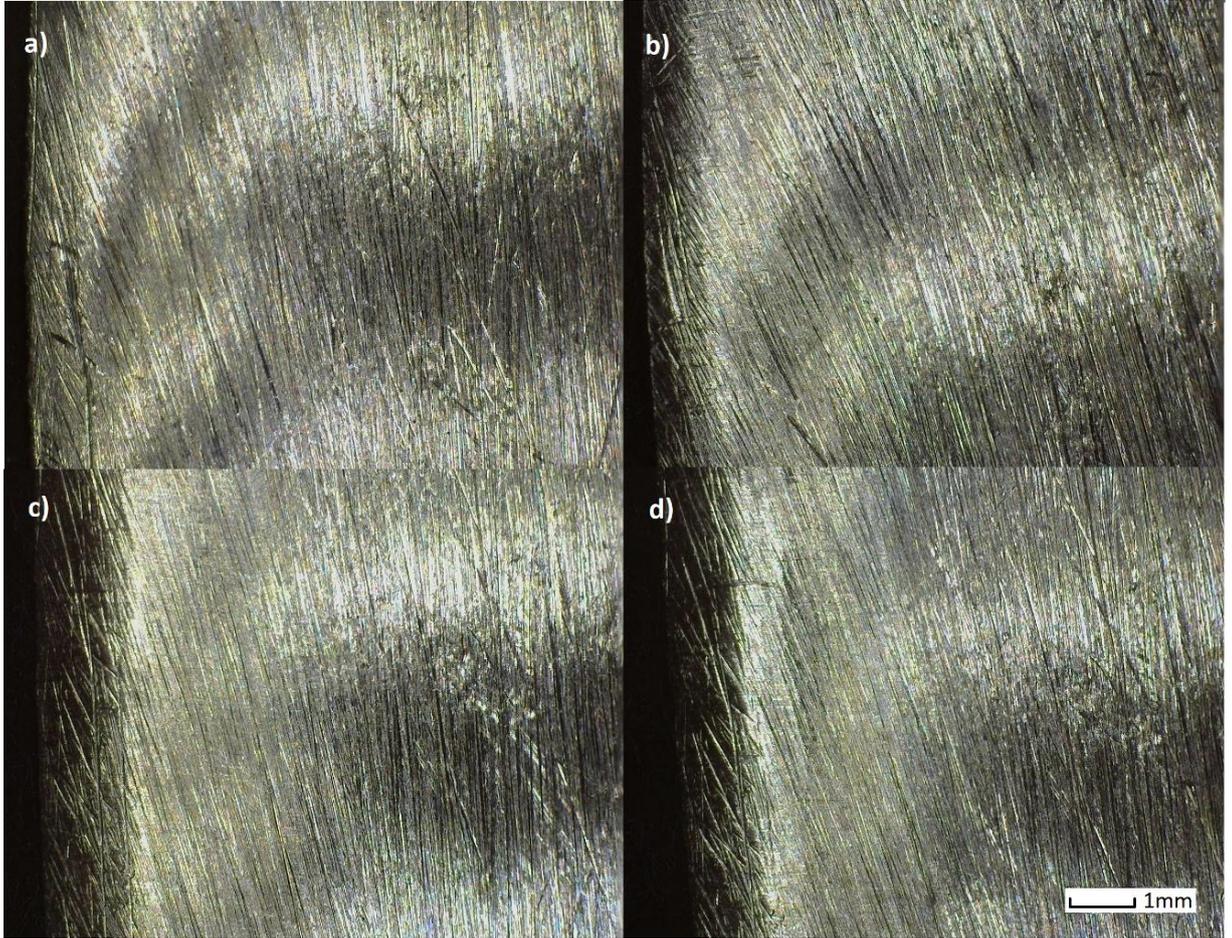
**Figure 202:** Digital microscope images of Blade 6, S2 1, at x25 magnification, where: a) post-sharpening at 1000 impacts; b) 2000 impacts; c) 3000 impacts; d) 3500 impacts.
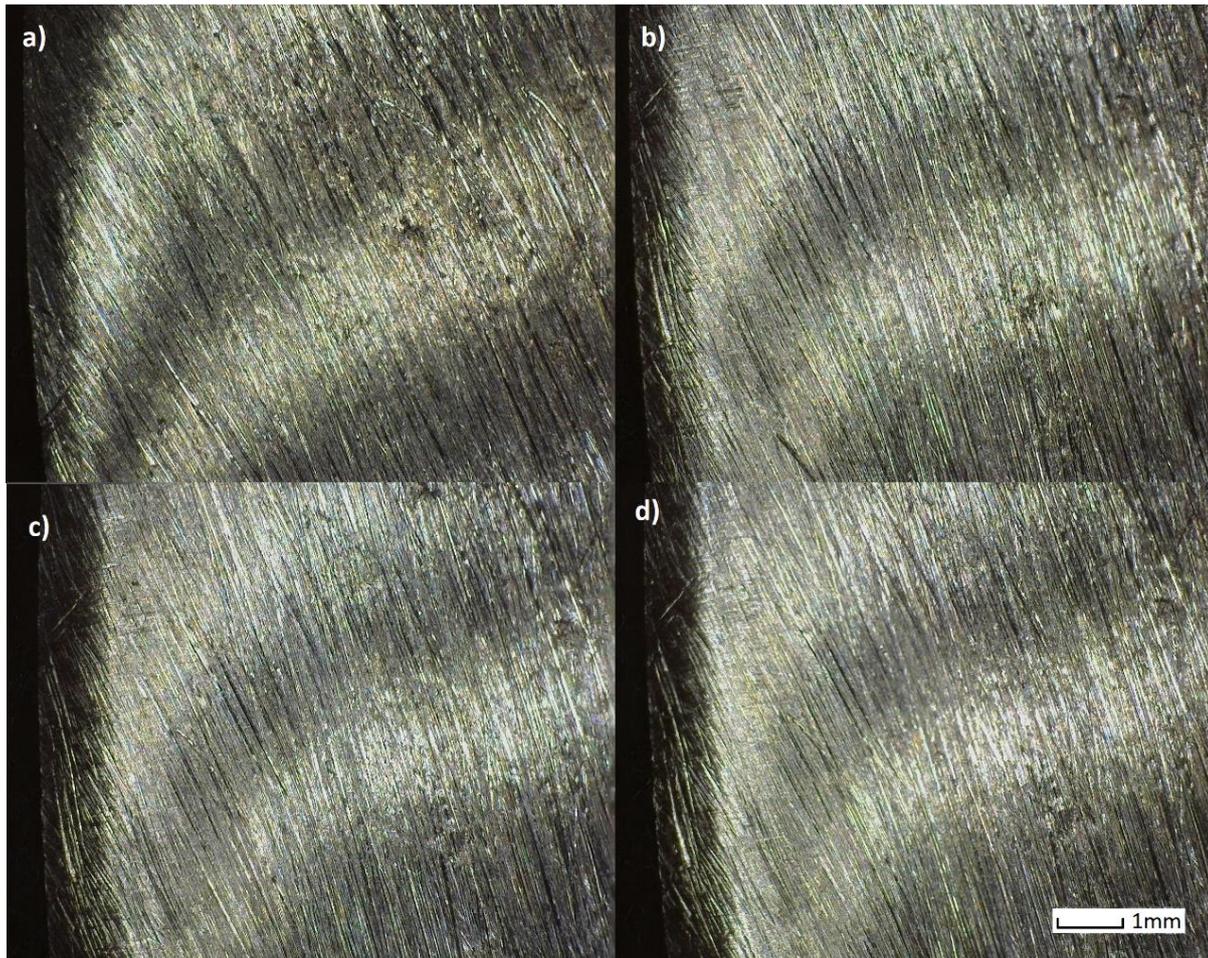
**Figure 203:** Digital microscope images of Blade 6, SL 3, at x25 magnification, where: a) post-sharpening at 1000 impacts; b) 2000 impacts; c) 3000 impacts; d) 3500 impacts.
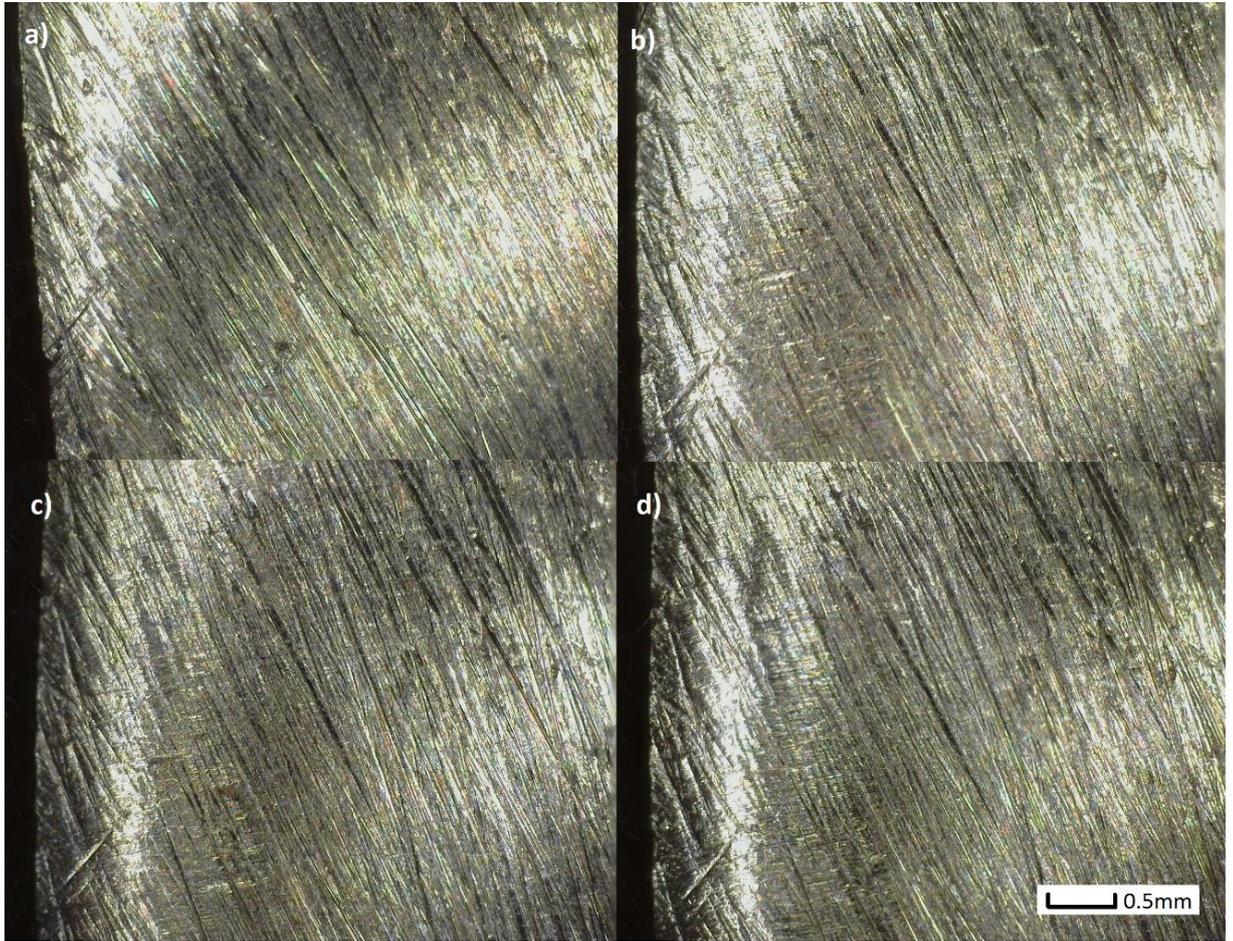
**Figure 204:** Digital microscope images of Blade 6, SL 3, at x50 magnification, where: a) post-sharpening at 1000 impacts; b) 2000 impacts; c) 3000 impacts; d) 3500 impacts.

Appendix B: Archaeological data

Axe narratives

Flanged axes

## 4A (Museum of Somerset) – Stoke St. Michael, Somerset
### Characteristic flow-chart

*Typological:*
*Flanged axe*

*Manufacturing:*
*High tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain lines*
*throughout sample*

*Use-wear:*
*Blunt*
*Moderate*
*asymmetry*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Single*


*Figure 205:* Photograph of palstave axe 4A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).


*Figure 206:* Metallograph of palstave axe 4A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).


*Figure 207:* Photograph of the cutting-edge of palstave axe 4A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, however, it is clear from the asymmetrical nature of the blade, that this specimen has definitely been subjected to several cycles of use, failure and sharpening – possibly, with a period of significant use just before deposition (the blade is blunt). There are no further damages to the axe. It was found in 1908 on the west side of Walltyning Plantation while digging a hole for a gate post.

**Publications:** [84, pp. 531, No. 747, Pl. 89],  [277, p. lxiv].

## OA93 (West Berkshire Museum) – Unknown, Ireland
### Characteristic flow-chart

*Typological:*
*Flanged axe*

*Manufacturing:*
*Low tin*
*Leaded*
*Severe porosity*
*Recrystallized*
*Twinned*
*Dendritic shading*
*Slip-banding*
*throughout sample*



*Figure 208:* Photograph of palstave axe OA93 (source: courtesy of West Berkshire Museum)**.**

*Use-wear:*
*Sharp*
*Symmetrical*
*No micrograph*



*Deposition:*
*Uncertain context*
*Unknown*
*Accidental*

*Figure 209:* Photograph of the blade of palstave axe OA93 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be of poor quality and has been hammered, annealed (heating was at low temperature, possibly in the region of 350° to 400°C), and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. It is not possible to ascertain whether this axe was used, as the blade is symmetrical and the cutting-edge is sharp. There are cracks in the flanges which probably formed in antiquity, maybe during use. Very little is known about the deposition circumstances of this axe.

**Publications:** [135, pp. 14, 15, Pl XIII, XIV], [278].

## OA322 (West Berkshire Museum) – Unknown, Ireland
### Characteristic flow-chart

*Typological:*
*Flanged axe*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Slip-banding*
*throughout sample*

*Use-wear:*
*Medium sharpness*
*Moderate asymmetry*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown*



*Figure 210:* Photograph of palstave axe OA322 (source: courtesy of West Berkshire Museum).



*Figure 211:* Photograph of the blade of palstave axe OA322 (source: courtesy of West Berkshire Museum).
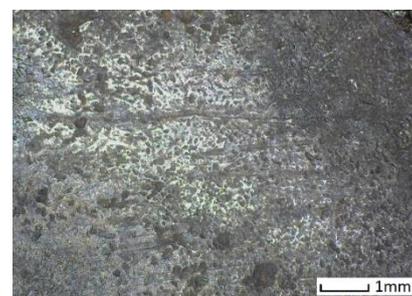


*Figure 212:* Micrograph of the hafting striations on the septum of palstave axe OA322 (source: courtesy of West Berkshire Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, but the moderate asymmetry of the cutting-edge and the hafting striations that are visible in the septum suggest that this axe has been subjected to several cycles of use, failure, and sharpening. There are no further observable damages. Very little is known about the deposition circumstances of this axe.

**Publications:** [135, pp. 15, Pl XV, XVI], [278].

# OA351 (West Berkshire Museum) – Unknown, Ireland
## Characteristic flow-chart

**Typological:**

*Flanged axe*

**Manufacturing:**

*Low tin, Leaded*

*No porosity*

*Recrystallized*

*Twinned*

*Dendritic shading*



*Figure 213:* Photograph of palstave axe OA351 (source: courtesy of West Berkshire Museum)**.**

**Use-wear:**

*Medium sharpness*

*Moderate asymmetry*

*Use-striations*

*Hafting striations*

**Deposition:**

*Post-depositional damage*

*Uncertain context*

*Unknown*
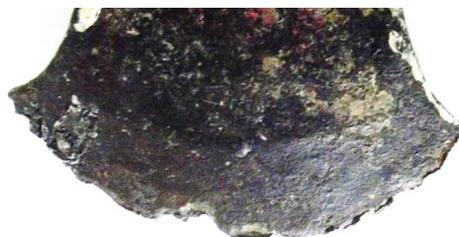


*Figure 214:* Photograph of the blade of palstave axe OA351 (source: courtesy of West Berkshire Museum)**.**
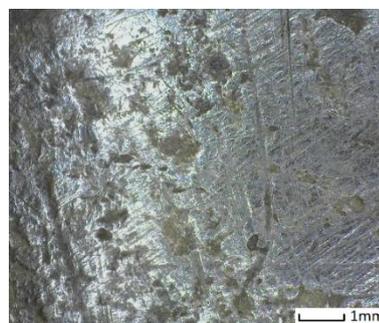


*Figure 215:* Micrograph of the use-striations on the blade of palstave axe OA351 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered, and annealed (heating was at low temperature, possibly in the region of 350° to 400°C). This suggests that there was intention for it to be used as a working axe, though the manufacturing that has been applied has not produced optimum mechanical specifications. On consideration of the metallurgy, moderate asymmetry and hafting striations, it is likely that this axe has gone through several extended cycles of use, each which eventually culminated in failure and resharpening. There are some notches on the cutting-edge, some of which look like they were formed in antiquity and others that are probably more likely the result of modern damage. The notching is interesting, as it suggests that this axe may have struck an opposition material that is much harder than timber. The idea that this axe was used in activities other than tree-felling is corroborated by the deep use-striations (prominent at x25 magnification) that have been recorded by microscopy. Consequently, it must be understood that the wear of this axe was probably accelerated. There are some areas of the blade that have been lost by corrosion. Very little is known about the deposition circumstances of this axe.

**Publications:** [135, pp. 17, Pl, XV, XVII], [278].

# 1961.497 (Ashmolean) – Wotton Glenville, Dorset
## Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*Low tin*
*No micrograph*

*Use-wear:*
*Sharp*
*Slight asymmetry*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Group*



*Figure 216:* Photograph of palstave axe 1961.497 (source: © Ashmolean Museum, University of Oxford).



*Figure 217:* Photograph of the blade of palstave axe 1961.497 (source: © Ashmolean Museum, University of Oxford).
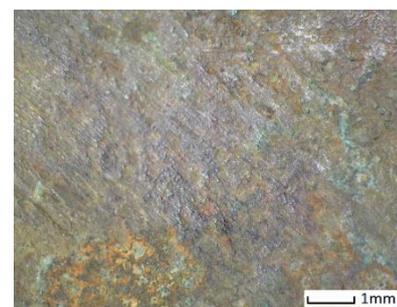


*Figure 218:* Micrograph of the hafting striations found on the septum of palstave axe 1961.497 (source: © Ashmolean Museum, University of Oxford).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe, however, no mounted sample was ever produced for this specimen. Therefore, very little can be ascertained regarding the manufacturing specifications. There is not enough data for an estimation of use-intensity after final sharpening, however, it seems likely that this axe sustained at least one cycle of use, failure, and sharpening due to the mild asymmetry of the cutting-edge and the prominent hafting striations within the septum. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 302, no. 486], [84, p. 472, nos. 396, Pl 51].

## E449 (Bristol City Museum and Art Gallery) – Solsbury Hill, Somerset
### Characteristic flow-chart

*Typological:*
*Gr.I palstave*

*Manufacturing:*
*Medium (low) tin*
*No metallograph*

*Use-wear:*
*Medium sharpness*
*Symmetrical*
*No micrograph*

*Deposition:*
*Accidental*
*Uncertain context*
*Single*



**Figure 219:** Photograph of palstave axe E449 (source: author's own, courtesy of Bristol Culture).



**Figure 220:** Photograph of the blade of palstave axe E449 (source: author's own, courtesy of Bristol Culture).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe, however, no mounted sample was ever produced for this specimen. Therefore, very little can be ascertained regarding the manufacturing specifications. Due to the symmetrical nature of the blade, and modern regrinding of the surface (which made microscopy impossible) it is not possible to determine whether this axe has been used. The flanges are very battered, and the patina is consistent on the areas of breakage, suggesting they happened in ancient times. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 332, No. 890], [84, p. 503, 589, Pl. 69]**,** [279, p. 57]

## E456 (Bristol City Museum and Art Gallery) – Unknown, Somerset
### Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*Medium (low) tin*
*No metallograph*

*Use-wear:*
*Blunt*
*Slight asymmetry*
*No micrograph*

*Deposition:*
*Post-depositional damage*
*Uncertain context*
*Unknown*



**Figure 221:** Photograph of palstave axe E456 (source: author's own, courtesy of Bristol Culture).



**Figure 222:** Photograph of the blade of palstave axe E456 (source: author's own, courtesy of Bristol Culture).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe, however, no mounted sample was ever produced for this specimen. Therefore, very little can be ascertained regarding the manufacturing specifications. There is not enough data for an estimation of use-intensity after final sharpening, however, the slight asymmetry of the cutting-edge indicates that this axe has experienced at least one cycle of use, failure, and resharpening. There is a patinated notch on the septum that is unlikely to be intentional. Very little is known about the deposition circumstances of this axe.

**Publications:** No known publications

# 1884.9.1 (Dorset County Museum) – Wareham, Dorset
## Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*High tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*



*Figure 223:* Photograph of palstave axe 1884.9.1 (source: courtesy of Dorset County Museum).

*Use-wear:*
*Sharp*
*Slight asymmetry*
*Sharpening striations*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown*
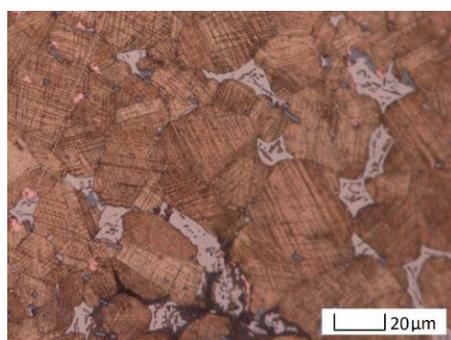


*Figure 224:* Metallograph of palstave axe 1884.9.1 (source: courtesy of Dorset County Museum).



*Figure 225:* Photograph of the blade of palstave axe 1884.9.1 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. It is likely, given the slight asymmetry of the cutting-edge and the hafting striations observed in the septum, that this axe went through at least one cycle of use, failure and sharpening. It is quite clear, from the micro-scale analysis, that this axe has been sharpened prior to deposition. This is particularly intriguing as it could suggest that it was intentionally prepared for its role in deposition practices. No damage was recorded and very little is known about the deposition circumstances of this axe.



*Figure 226:* Micrograph of the sharpening striations found on the blade of palstave axe 1884.9.1 (source: courtesy of Dorset County Museum).

**Publications:** [60, p. 303, 494], [84, p. 485, no. 465].

## 7B (Museum of Somerset) - Lyng, Somerset
### Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*Medium (high) tin*
*Microporosity*
*Slag inclusions*
*Recrystallized*
*Twinned*
*Strain banding is*
*present throughout*
*Deformed grains*

*Use-wear:*
*Medium sharpness*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain*
*Single*



*Figure 227:* Photograph of palstave axe 7B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
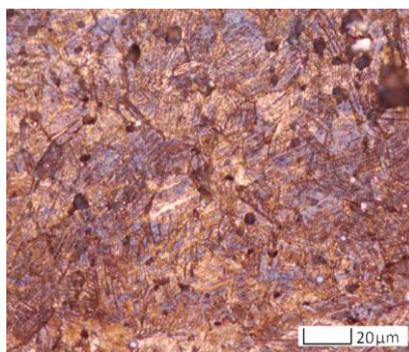


*Figure 228:* Metallograph of palstave axe 7B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 229:* Photograph of the blade of palstave axe 7B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be of poor quality, and has been annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used in tree-cutting, though the production specifications are not optimum. There is not enough data for an estimation of use-intensity after final sharpening (the axe was too corroded for micro-analysis), but the symmetrical condition of the blade suggests that the axe has been subjected to little use, if any at all. The cutting-edge has suffered some damages from corrosion. There is not much information available about the deposition circumstances.

**Publications:** [60, p. 331, Nos. 880, 882], [84, p. 518, No. 682, Pl. 78]**,** [280, pp. 85, 228, 245]**,** [281, p. 30]; [282, p. lxviii], [283, pp. 461].

## 8A (Museum of Somerset) – Wellington, Somerset
### Characteristic flow-chart

**Typological:**
*Gr. I palstave*

**Manufacturing:**
*High tin*
*No porosity*
*Recrystallized*
*Twinned*
*Stain-banding*
*throughout sample*

**Use-wear:**
*Sharp*
*Moderate asymmetry*
*No micrograph*

**Deposition:**
*Accidental*
*Uncertain context*
*Single*



**Figure 230:** Photograph of palstave axe 8A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
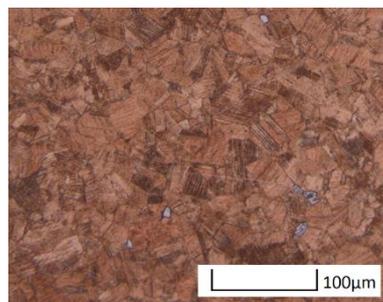


**Figure 231:** Metallograph of palstave axe 8A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
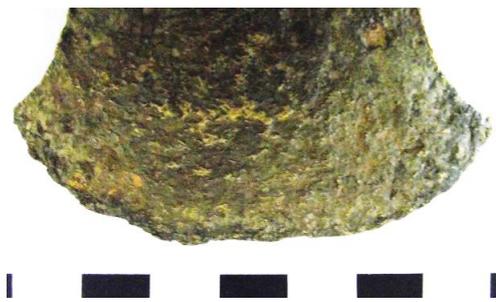


**Figure 232:** Photograph of the blade of palstave axe 8A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, however, the moderate asymmetry of the blade suggests that this axe has been subjected to many cycles of use, failure, and sharpening. The butt has been damaged, most likely when the sprue was removed. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 332, no. 886], [84, p. 537, no. 766], [284, p. 108], [285, p. 71].

## 81C (Museum of Somerset) – Old Ceeve, Somerset
### Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*Medium (high) tin*
*No porosity*
*Slag inclusions*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*
*Deformed crystals*

*Use-wear:*
*Sharp*
*Moderate asymmetry*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Group*



**Figure 233:** Photograph of palstave axe 81C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
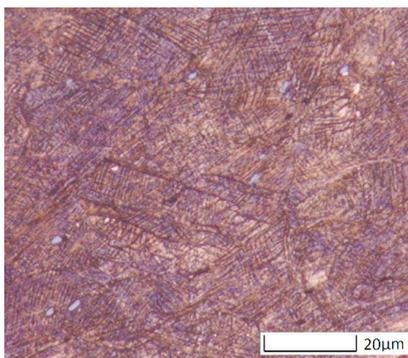


**Figure 234:** Metallograph of palstave axe 81C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 235:** Photograph of the blade of palstave axe 81C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, but on consideration of the moderate asymmetry of the cutting-edge, many cycles of use, failure, and resharpening are likely to have occurred. There are no observable additional damages. This axe was found with 81D; both were part of a multi-period hoard containing a flat axe and a socketed axe.

**Publications:** [60, p. 256, No. 113], [84, p. 521-522, No. 700b, Pl. 80, 81]**,** [283, pp. 454], [286]**,** [287, pp. 91, No. 22]**,** [288, pp. 327–329, No. 5]**,** [289, p. lxxv]**.**

## 7A (Museum of Somerset) – Unknown, Somerset
### Characteristic flow-chart

**Typological:**
*Gr. I palstave*

**Manufacturing:**
*Medium (low) tin*
*No porosity*
*Slag inclusions*
*Recrystallized*
*Twinned*
*Strain banding is*
*present throughout*
*Deformed crystals*

**Use-wear:**
*Medium sharpness*
*Symmetrical*
*Not finished*

**Deposition:**
*Deliberate damage*
*Uncertain context*
*Unknown*



**Figure 236:** Photograph of palstave axe 7A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
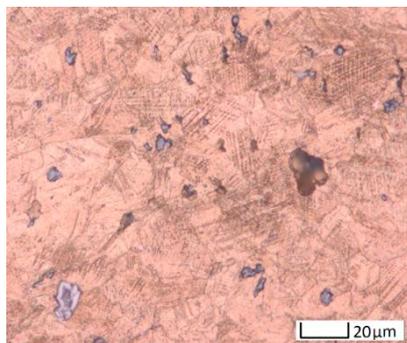


**Figure 237:** Metallograph of palstave axe 7A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 238:** Photograph of the blade of palstave axe 7A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used in tree-felling. Despite this, the axe seems not to have been finished, or sharpened, and there are certainly no signs of use. It appears as though the end of the butt has been removed in antiquity and there are some blow marks near the area of breakage, suggesting deliberate breakage. Nothing is known about the deposition circumstances.



**Figure 239:** Micrograph illustrating the unfinished state of the surface of palstave 7A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Publications:** [60, p. 322, no. 893], [84, p. 543, no. 805].

## 1884.119.108 (Pitt Rivers) – Holme, Cambridgeshire
### Characteristic flow-chart

*Typological:*

*Gr. I palstave*

*Manufacturing:*

*Low tin*

*No porosity*

*Recrystallized*

*Twinned*

*Strain-banding*

*throughout sample*



**Figure 240:** Photograph of palstave axe 1884.119.108 (source: Author's own, courtesy of Pitt Rivers Museum).

*Use-wear:*

*Sharp (regrinding)*

*Slight asymmetry*

*Hafting striations (as shown in micrograph)*

*Deposition:*

*Undamaged*

*Wetland*

*Group*



**Figure 241:** Photograph of the blade of palstave axe 1884.119.108 (source: Author's own, courtesy of Pitt Rivers Museum).



**Figure 242:** Micrograph of the hafting striations on the septum of palstave axe 1884.119.108 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening as the cutting-edge has received a major regrinding in modern times, however, the obvious asymmetry of the blade and the hafting striations recorded in the septum suggest that this axe has been through at least one cycle of use, failure and sharpening. This axe was found as part of a small hoard when the moor was being drained in 1848. The hoard contained three socketed axes, two gouges, a hammer, and a leaf-shaped spear-head.

**Publications:** [60, p. 299, no. 441], [66], [116, p. 122], [290].

## 1113/1912 (RAMM) – Shebbear, Devon
### Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*Medium (low) tin*
*Recrystallized*
*Twinned*
*Severe strain-banding*



**Figure 243:** Photograph of palstave axe 1113/1912 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

*Use-wear:*
*Sharp*
*Symmetrical*
*Unfinished*

*Deposition:*
*Undamaged*
*Uncertain context*
*Single*
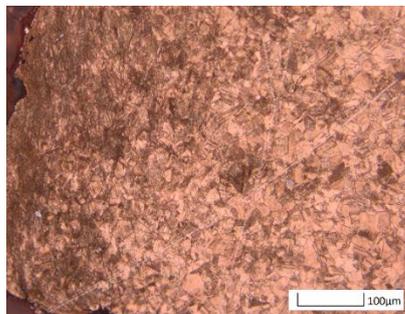


**Figure 244:** Metallograph of palstave axe 1113/1912 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 245:** Photograph of the blade of palstave axe 1113/1912 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be very sound, and has been hammered, annealed, and finished with a extensive final hammering. These manufacturing specifications indicate that this axe was well prepared for use. However, micro-analysis demonstrates there is a mottled surface very characteristic of an unfinished axe, hence it is likely that it has not been sharpened or used. The sharp blade must indicate that the axe began as a very close casting. The axe was found in clay, during drain-cutting, but little else is known about its provenance.



**Figure 246:** Micrograph of the unfinished surface of palstave axe 1113/1912 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Publications:** [60, p. 301, no. 462], [84, p. 453, no. 290, Pl 38].

## 1891/2/7 (RAMM) – Chagford, Devon
### Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*High tin*
*Moderate porosity*
*Recrystallized*
*Twinned*
*Strain-banding near exterior*



**Figure 247:** Photograph of palstave axe 1891/2/7 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

*Use-wear:*
*Sharp*
*Symmetrical*
*Sharpening striations*

*Deposition:*
*Undamaged*
*Dryland*
*Group*
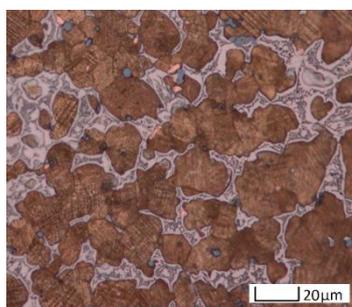


**Figure 248:** Metallograph of palstave axe 1891/2/7 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 249:** Photograph of the blade of palstave axe 1891/2/7 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used in tree-cutting. Since the cutting-edge is completely symmetrical (with the exception of some areas of corrosion) and very clear sharpening striations can be identified at the cutting-edge, it seems likely that this axe was prepared for use, but was deposited before it was used in tree-felling activities. There are no observable damages other than a few nicks on the blade that appear to be modern. The axe was found with 1891/2/6, buried under a hedge bank.



**Figure 250:** Micrograph of the sharpening striations found on palstave axe 1891/2/7 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Publications:** [24, p. 184, figs 1, 2, 7]**,** [60, p. 301, no. 465], [66, p. 82]**,** [84, p. 436, No. 204b, Pl. 131]**,** [291, p. 26]**.**

## A306 (RAMM) – Farway Hill, Honiton, Devon
### Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Annealing twins*
*Recrystallized*
*Strain-banding at edge of sample*

*Use-wear:*
*Blunt*
*Symmetrical*
*No hafting striations*

*Deposition:*
*Post-depositional damage*
*Single*
*Uncertain context*



*Figure 251:* Photograph of palstave axe A306 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
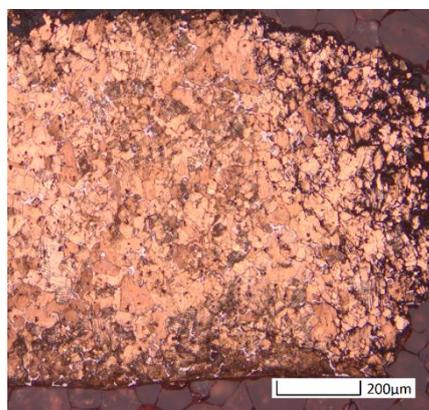


*Figure 252:* Metallograph of palstave axe A306 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
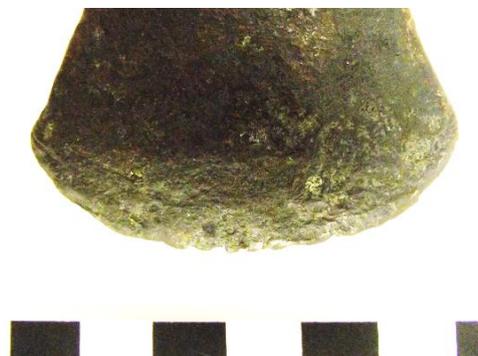


*Figure 253:* Photograph of the blade of palstave axe A306 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 254:* Micrograph of the septum of palstave axe A306, indicating no hafting striations (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. There is not enough data for an estimation of use-intensity after final sharpening, but the obtuse cutting-edge and lack of hafting striations suggest that this axe was not finished or used. The butt has a notch that exhibits several casting flaws and is not consistently patinated, indicating modern damage. While this axe is considered to be an isolated find, the landscape of Farway Hill is home to many Bronze Age tumuli and a multitude of finds have been recorded from the area.

**Publications:** [60, p. 301, No. 468], [84, p. 442, No. 235, Pl.30]**,** [283, pp. 270], [292, p. 365]**,** [293, p. 298]**,** [294, p. 343]**.**

## A320 (RAMM) - Drewsteignton, Devon
### Characteristic flow-chart

**Typological:**
*Gr. I palstave*

**Manufacturing:**
*Medium (low) tin*
*Severe porosity*
*Recrystallized*
*Strain-banding*
*throughout sample*

**Use-wear:**
*Very blunt*
*Slight asymmetry*
*No micrograph*

**Deposition:**
*Undamaged*
*Single*
*Uncertain context*



**Figure 255:** Photograph of palstave axe A320 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
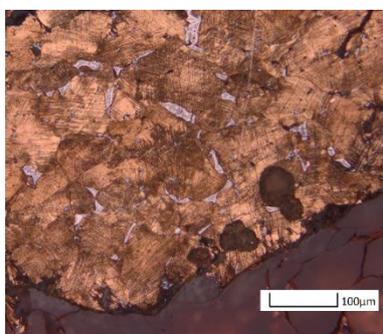


**Figure 256:** Metallograph of palstave axe A320 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 257:** Photograph of the blade of palstave axe A320 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be very unsound, and has been annealed, then finished with a final light hammering. There is not enough data for an estimation of use-intensity after final sharpening, but the blunt cutting-edge could suggest that it has not been sharpened or used. The slight asymmetry may have been introduced by the mould itself, as it is clear from the metallography that this is a fairly crude casting and the creator was probably not a skilful artisan. This axe is largely unprovenanced, so very little is known about the deposition circumstances.

**Publications:** [60, p. 301, No. 467], [66, p. 86]**,** [84, p. 440, 441, No. 226,  Pl. 29]**,**  [295, p. 96]**.**

# A6158 (RAMM) - Thorverton, Devon
## Characteristic flow-chart

*Typological:*
*Gr. I palstave*

*Manufacturing:*
*Medium (high) tin*
*No metallograph*
*Corroded sample*

*Use-wear:*
*Sharp*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown associations*



*Figure 258:* Photograph of palstave axe A6158 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 259:* Photograph of the blade of palstave axe A6158 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe, however, the mounted sample has since been lost. Therefore, very little can be ascertained regarding the manufacturing specifications. There is not enough data for an estimation of use-intensity after final sharpening, however, due to the sharpness and symmetry of the blade, it is possible that this axe was used very little, if at all. There are no damages, accept the modern regrinding of the cutting-edge, and it was discovered during the demolition of an old house.

**Publications:** [60, p. 301, No. 473], [84, p. 456, No.302, Pl. 40]**,** [283, pp. 306],

## OA324 (West Berkshire Museum) – Weybridge, Surrey
**Characteristic flow-chart**

*Typological:*

*Gr. I palstave*

*Manufacturing:*

*Low tin*

*Severe porosity*

*Slag*

*Recrystallized*

*Twinned*

*Strain-banding throughout sample*



*Figure 260:* Photograph of palstave axe OA324 (source: courtesy of West Berkshire Museum)**.**

*Use-wear:*

*Sharp*

*Moderate asymmetry*

*Sharpening striations (as shown in micrograph)*

*Hafting striations*





*Deposition:*

*Post-depositional damage*

*Uncertain context*

*Unknown*

*Figure 261:* Photograph of the blade of palstave axe OA324 (source: courtesy of West Berkshire Museum)**.**

*Figure 262:* Metallograph of the sharpening striations on the blade of palstave axe OA324 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, however the moderate asymmetry and hafting striations suggest that this axe was subjected to several cycles of use, failure, and resharpening. It is clear from the sharpness of the cutting-edge and the prominent sharpening striations that the axe was sharpened prior to deposition. It may have been used again, thereafter, but only to a limited extent. There is some distortion of the flanges, which is probably accidental damage that occurred after deposition. Very little is known about the deposition circumstances of this axe.

**Publications:** [135, pp. 13, Pl X, XI], [278].

## 1927.2567 (Ashmolean) – Penzance, Cornwall
**Characteristic flow-chart**

*Typological:*
*Gr. II palstave*

*Manufacturing:*
*Medium (high) tin*
*No metallograph*

*Use-wear:*
*Sharp (regrinding)*
*Moderate asymmetry*
*No micrograph*

*Deposition:*
*Undamaged*
*Single*
*Unknown*
*associations*



*Figure 263:* Photograph of palstave axe 1927.2567 (source: © Ashmolean Museum, University of Oxford).



*Figure 264:* Photograph of the blade of palstave axe 1927.2567 (source: © Ashmolean Museum, University of Oxford).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe, however, no mounted sample was ever produced for this specimen. Therefore, very little can be ascertained regarding the manufacturing specifications. On consideration of the moderate asymmetry, it seems very likely that this axe experienced many cycles of use, failure, and sharpening. A comprehensive assessment of use-intensity after final sharpening is not possible due to the considerable amount of cleaning that has occurred on the blade in modern times. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 300, no. 454]; [66, p. 81]; [84, p. 423, no. 121]; [296, p. 306]

## 1927.2594 (Ashmolean) – Bath Street, Bristol
### Characteristic flow-chart

*Typological:*

*Gr. II palstave*

*Manufacturing:*

*Medium (high) tin*

*No micrograph*

*Use-wear:*

*Medium sharpness*

*Moderate asymmetry*

*Use-striations*

*Deposition:*

*Undamaged*

*Single*

*Unknown*

*associations*



**Figure 265:** Photograph of palstave axe 1927.2594 (source: © Ashmolean Museum, University of Oxford).
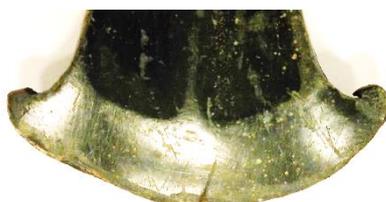


**Figure 266:** Photograph of the blade of palstave axe 1927.2594 (source: © Ashmolean Museum, University of Oxford).
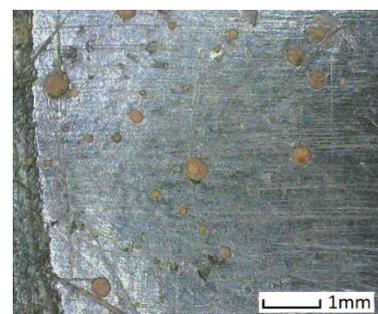


**Figure 267:** Micrograph of the use-striations on the cutting edge of palstave axe 1927.2594 (source: © Ashmolean Museum, University of Oxford).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe, however, no mounted sample was ever produced for this specimen. Therefore, very little can be ascertained regarding the manufacturing specifications. It is clear from the moderate asymmetry that this axe has been subjected to several cycles of use and sharpening. The microscopy analysis also revealed clear use-striations at the x25 magnification while no sharpening striations were visible, given this, and the medium sharpness, it is fair to assume that this axe experienced a period of high-intensity prior to deposition. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 330, no. 864]; [84, p. 504, no. 597]; [297, pp. 329, Pl 2].

## 1884.9.2 (Dorset County Museum) – Fontwell, Dorset
### Characteristic flow-chart

*Typological:*
*Gr. II palstave*

*Manufacturing:*
*High tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*present at sample*
*exterior*

*Use-wear:*
*Sharp*
*Symmetrical*
*Sharpening striations*
*Use-striations*
*Hafting-striations*

*Deposition:*
*Deliberate damage*
*Dryland*
*Single*



*Figure 268:* Photograph of palstave axe 1884.9.2 (source: courtesy of Dorset County Museum).
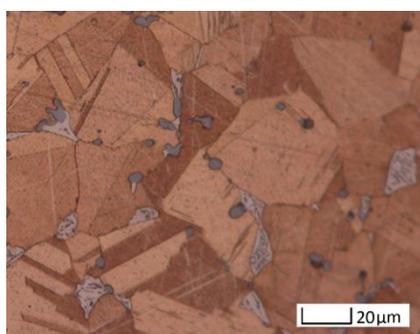


*Figure 269:* Metallograph of palstave axe 1884.9.2 (source: courtesy of Dorset County Museum).



*Figure 270:* Photograph of the blade of palstave axe 1884.9.2 (source: courtesy of Dorset County Museum).



*Figure 271:* Micrograph demonstrating both use and sharpening striations on the cutting-edge of palstave axe 1884.9.2 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. Since the cutting-edge is symmetrical it is unlikely that this axe experienced sustained use that culminated in blade failure. However, it seems probable that the axe was sharpened and then subjected to a period of use before deposition (possibly around 2000-3000 impacts as the sharpening striations are still evident). The blade has been damaged and the area of breakage has consistent patination, suggesting that this occurred in antiquity. It is unlikely that this kind of break would have occurred during use and there is no evidence of casting flaws, which may suggest intentional damage. This axe is said to have been ploughed up on the Downs by Fontwell Magna.

**Publications:** [60, p. 232, Pl. 8, No. 33], [84, p. 471, Pl.51, No.390a].

## 1884.119.113 (Pitt Rivers) – Thames, Wandsworth, London
### Characteristic flow-chart

*Typological:*

*Gr. II palstave*

*Manufacturing:*

*Low tin*

*Leaded*

*Micro-porosity*

*Dendritic*

*Use-wear:*

*Medium sharpness*

*Slight asymmetry*

*Not finished*

*Deposition:*

*Undamaged*

*Wetland*

*Unknown*



*Figure 272:* Photograph of palstave axe 1884.119.113 (source: Author's own, courtesy of Pitt Rivers Museum).



*Figure 273:* Photograph of palstave axe 1884.119.113 (source: Author's own, courtesy of Pitt Rivers Museum).
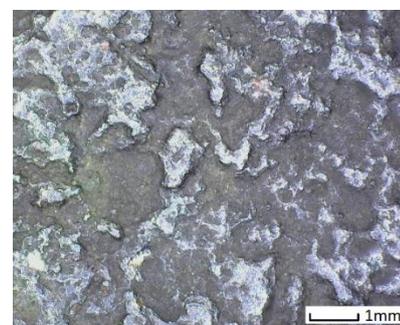


*Figure 274:* Micrograph demonstrating the unfinished condition of the surface of palstave axe 1884.119.113 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be fairly sound, and has not been subjected to any further processing after the initial casting. This suggests that there was little intention for the axe to be used as a working tool. While there does appear to be asymmetry on the blade, this seems much more related to the slight offsetting of the cast. It is quite unlikely, given the lack of manufacturing, evidence of flashing on the casting seams, and unfinished surface (as observed by microscopy), that this axe was ever sharpened, or used. Part of one of the flanges is not complete, but this is probably due to the very crude nature of the cast. Nothing is known about the deposition circumstances of this axe.

**Publications:** [60, p. 320, no. 728], [116, p. 132, no. 56].

## 593/2005 (RAMM) – Colyton, Devon
**Characteristic flow-chart**

*Typological:*
*Gr. II palstave*

*Manufacturing:*
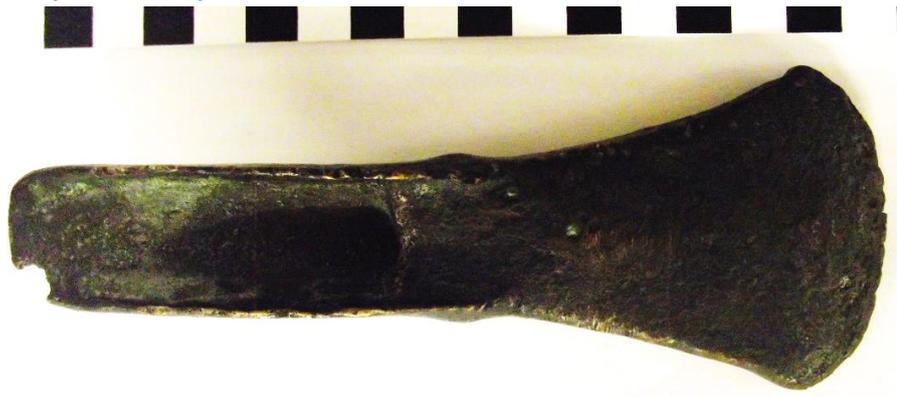*High tin*
*No porosity*
*Dendritic*



**Figure 275:** Photograph of palstave axe 593.2005 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

*Use-wear:*
*Symmetrical*
*Medium sharpness*
*Sharpening striations*
*Depression*

*Deposition:*
*Undamaged*
*Group*
*Dryland*
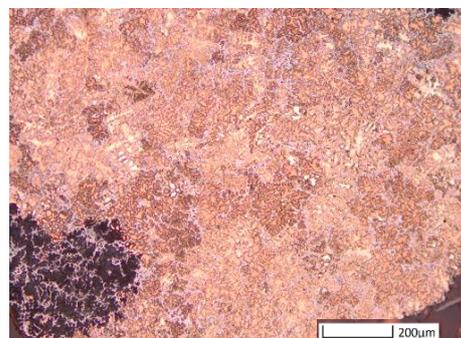


**Figure 276:** Metallograph of palstave axe 593.2005 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 277:** Photograph of the blade of palstave axe 593.2005 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
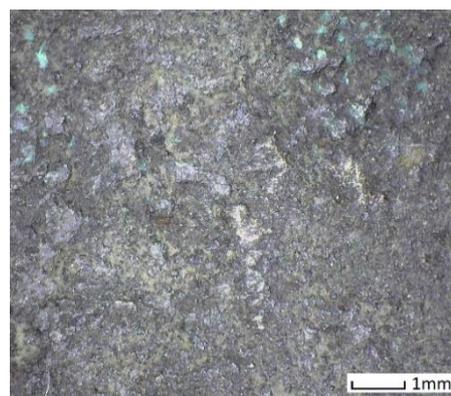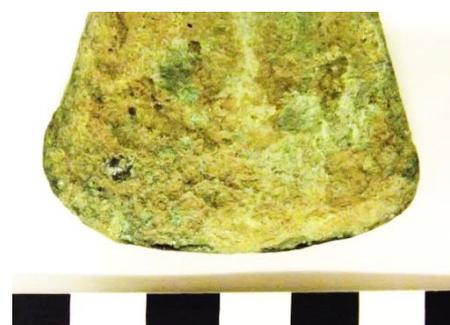
**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, but does not exhibit any evidence of further processing after it was initially cast. There is also flashing around the casting seams. Interestingly, while the axe has not been optimised for use during manufacturing, evidence of its employment as a tool can be observed. The blade appears to have a depression that could indicate fracture of the cutting-edge during use. As there is no blade asymmetry, it is fair to say that the axe was not subjected to many cycles of use and failure. The sharpening striations that are visible could reflect efforts to tidy remove the blade failure before deposition. There is some damage to the flanges, which look post-depositional. This axe was found with A1951 and A1952, which were all part of a large hoard found at Lovehayne farm of approximately one hundred palstaves. The deposit of metalwork was found when a round barrow was cut for stone.
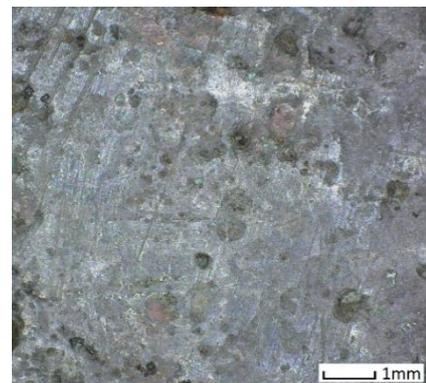


**Figure 278:** Micrograph of the sharpening striations present on the cutting-edge of palstave axe 593.2005 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Publications:** [60, p. 230, No.24, Pl.9], [66, pp. 81, 113]**,** [84, p. 438-9, No.217, Pl.27/28]**,** [292, pp. 362, 365, fig 19(4)]**,** [293, pp. 300, Pl.5, fig 3]**,** [294, p. 341, fig 1]**,** [298, pp. 647–648, Pl.9], [299, pp. 50, No. 208]**,** [300, pp. 140–144]**.**

## 1891/2/6 (RAMM) – Chagford, Devon
### Characteristic flow-chart

*Typological:*
*Gr. II palstave*

*Manufacturing:*
*Low tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding is present throughout*

*Use-wear:*
*Medium sharpness*
*Moderate asymmetry*
*Depression*
*Hafting striations*

*Deposition:*
*Post-depositional damage*
*Dryland*
*Group*



*Figure 279:* Photograph of palstave axe 1891/2/6 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
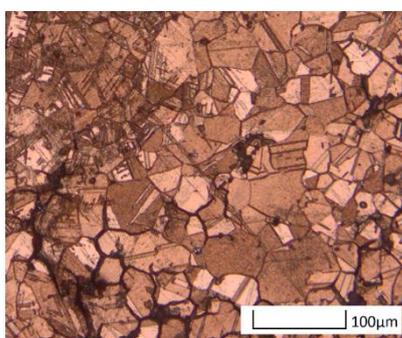


*Figure 280:* Metallograph of palstave axe 1891/2/6 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 281:* Photograph of the blade of palstave axe 1891/2/6 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
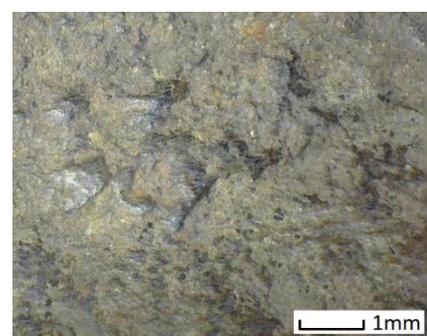


*Figure 282:* Micrograph of the hafting striations present on the septum of palstave axe 1891/2/6 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used in tree-cutting. In consideration of the moderate asymmetry of the cutting-edge and the obvious hafting striations, it is likely that this axe went through many cycles of use, failure, and sharpening. An area of depression is also apparent, which could suggest that the axe was decommissioned after the failure of the blade. The flanges have been damaged, but the change of patination suggests that this occurred in modern times. The axe was found buried under a hedge bank with 1891/2/7, an axe that does not demonstrate evidence of considerable use. It is interesting that these two axes, one which has a significant use-history and one that has no traces of use have been paired together.

**Publications:** [24, p. 184, figs 1, 2, 7]**,** [60, p. 301, No. 465], [66, p. 82]**,** [84, p. 436, No. 204b, Pl. 131]**,** [291, p. 26]**.**

# 1968.68.Y2 (West Berkshire Museum) – Yattendon, Berkshire
## Characteristic flow-chart

*Typological:*
*Gr. II palstave*

*Manufacturing:*
*Medium (low) tin*
*Mild porosity*
*Cracking*
*Partially recrystallized*
*Twinned*

*Use-wear:*
*Medium sharpness*
*Symmetrical*
*No micrograph*

*Deposition:*
*Deliberate damage*
*Dryland*
*Group*



*Figure 283:* Photograph of palstave axe 1968.68.Y2 (source: courtesy of West Berkshire Museum)**.**



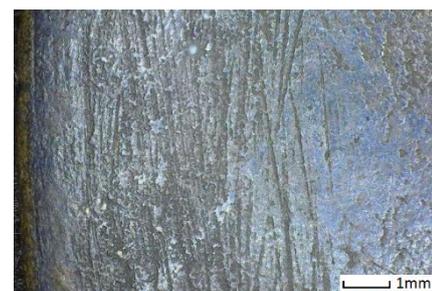*Figure 284:* Photograph of the blade of palstave axe 1968.68.Y2 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to of poor quality, and has been hammered, and partly annealed (the time of annealing was not long enough to induce full recrystallization). This suggests that there was intention for it to be used as a working axe, though the most optimum mechanical specifications have not been produced by manufacturing. Since the blade is symmetrical, and microscopy was not possible due to corrosion, it is not possible to determine whether the axe has been used. The axe has been broken across the body and there is some patination and corrosion, though this is not entirely consistent with the rest of the axe. The damage may have happened in antiquity but has since fragmented further as the specimen is highly corroded. This axe was found with 1968.68 Y3. In 1876, Alfred Waterhouse built a mansion, Yattendon Court, on top of the hill west of the village of Yattendon. In digging the foundations the workmen came upon a hoard of bronze objects all lying together... "the bronze object lay about 18 inches below the surface of the sod in a mass of gravel that had been turned red, purple and black by the action of fire". Examination of the objects made it quite clear that they had not been subjected to fire. The multi-period hoard consisted of 58 pieces of metalwork in total.

**Publications:** [137, pp. 6, 7, Pl I, IX], [301, p. 31].

## OA63 (West Berkshire Museum) – Weybridge, Surrey
### Characteristic flow-chart

*Typological:*
*Gr. II palstave*

*Manufacturing:*
*Low tin*
*No porosity*
*Recrystallized*
*Twinned*

*Use-wear:*
*Sharp*
*Symmetrical*
*No micrograph*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Unknown associations*



*Figure 285:* Photograph of palstave axe OA63 (source: courtesy of West Berkshire Museum)**.**



*Figure 286:* Photograph of the blade of palstave axe OA63 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered and annealed. This suggests that there was intention for it to be used as a working axe, though the most optimum mechanical specifications have not been produced by manufacturing. Since the blade is symmetrical, the cutting-edge is sharp, and microscopy was not possible due to modern cleaning, it is not possible to determine whether the axe has been used. The butt end has been broken unevenly, probably when the sprue was detached. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 340, no. 997], [135, pp. 12, 13, Pl XI]**,** [278]**.**

## OA264 (West Berkshire Museum) – Newbury, Berkshire
### Characteristic flow-chart



*Typological:*
*Gr. II palstave*

*Manufacturing:*
*Low tin*
*No porosity*
*Recrystallized*
*Twinned*

*Use-wear:*
*Sharp*
*Slight asymmetry*
*Hafting striations*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Single*

**Figure 287:** Photograph of palstave axe OA264 (source: courtesy of West Berkshire Museum)**.**
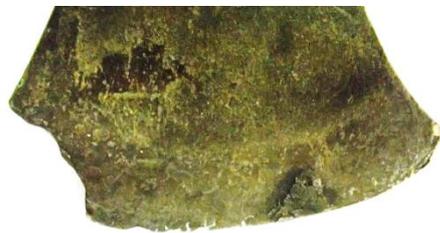


**Figure 288:** Photograph of the blade of palstave axe OA264 (source: courtesy of West Berkshire Museum)**.**
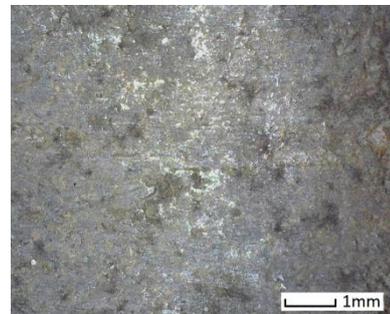


**Figure 289:** Micrograph of the hafting striations on the septum of palstave axe OA264 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered, and annealed. This suggests that there was intention for it to be used as a working axe, though it has not been manufactured to create the most optimum specifications. There is not enough data for an estimation of use-intensity after final sharpening, though the slight asymmetry of the blade and the clear hafting striations in the septum indicate that it most likely went through at least one cycle of use, failure, and resharpening. One blade tip has broken off, probably in antiquity. There are no blow marks so it is likely this was accidental. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 291, no. 312], [135, pp. 11, Pl VIII, IX]**,** [278]**,** [301, p. 24m no. B25], [302, p. 195].

## OA265 (West Berkshire Museum) – Speen, Berkshire
### Characteristic flow-chart



*Typological:*
*Gr. II palstave*

*Manufacturing:*
*Low tin*
*No porosity*
*Recrystallized*
*Twinned*
*Slip-banding near sample exterior*

**Figure 290:** Photograph of palstave axe OA265 (source: courtesy of West Berkshire Museum)**.**

*Use-wear:*
*Sharp*
*Symmetrical*
*Not finished*

*Deposition:*
*Undamaged*
*Wetland*
*Single*



**Figure 291:** Photograph of the blade of palstave axe OA265 (source: courtesy of West Berkshire Museum)**.**



**Figure 292:** Micrograph demonstrating the unfinished surface of palstave axe OA265 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. However, upon consideration of the use-wear analysis it seems highly unlikely that this axe was sharpened, or used. The cutting-edge is symmetrical and sharp, furthermore the low-power microscopy has demonstrated that the surface of the axe is in an unfinished state. There are some small notches on the blade, most likely formed post-recovery. The axe was found at a depth of 13 feet when cleaning out a pond at Donnington Grove, 1908.

**Publications:** [60, p. 291, no. 317], [135, pp. 11, Pl IX]**,** [278], [302, p. 195].

# 1884.9.3 (Dorset County Museum) – Fontwell, Dorset
## Characteristic flow-chart



*Figure 293:* Photograph of palstave axe 1884.9.3 (source: courtesy of Dorset County Museum).

**Typological:**

*Gr. III palstave*

**Manufacturing:**

*High tin*

*Micro-porosity*

*Recrystallized*

*Twinned*

*Strain-banding at sample exterior*

**Use-wear:**

*Sharp*

*Slight asymmetry*

*Depression*

*Hafting striations*

**Deposition:**

*Undamaged*

*Dryland*

*Single*
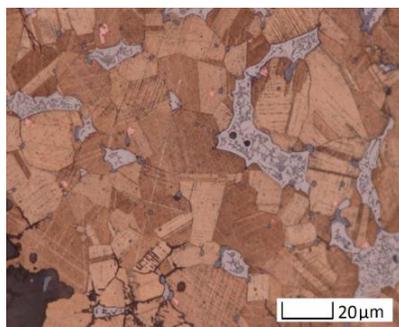


*Figure 294:* Metallograph of palstave axe 1884.9.3 (source: courtesy of Dorset County Museum).
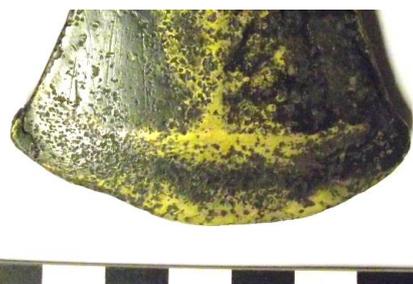


*Figure 295:* Photograph of the blade of palstave axe 1884.9.3 (source: courtesy of Dorset County Museum).



*Figure 296:* Micrograph of the hafting striations found on the septum of palstave axe 1884.9.3 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as working axe. There is not enough data for an estimation of use-intensity after final sharpening, but it seems likely, considering the slight asymmetry of the blade and the hafting-striations, that this axe was used. Given the depression on the cutting-edge, and the sharp condition of the blade, it is probable that the cutting-edge failed and was sharpened. It is not possible to ascertain whether the axe was used again after this. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 232, No. 33, Pl. 8], [84, p. 471, No.390a, Pl. 51]**.**

## 1954.40.1 (Dorset County Museum) – Thorncombe, Dorset
### Characteristic flow-chart



**Typological:**
*Gr. III palstave*

**Manufacturing:**
*Low tin*
*No porosity*
*Recrystallized*
*Strain-banding*
*throughout sample*

**Use-wear:**
*Sharp*
*Symmetrical*
*No micrograph*

**Deposition:**
*Undamaged*
*Uncertain context*
*Single*

*Figure 297:* Photograph of palstave axe 1954.40.1 (source: courtesy of Dorset County Museum).



100μm
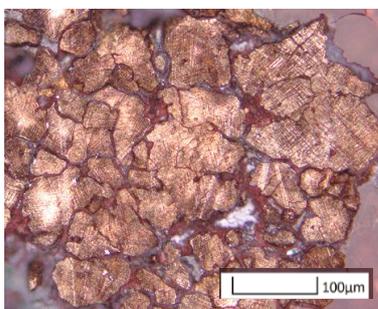
*Figure 298:* Metallograph of palstave axe 1954.40.1 (source: courtesy of Dorset County Museum).



*Figure 299:* Photograph of the blade of palstave axe 1954.40.1 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been annealed, and finished with a final extensive hammering. While this combination of manufacturing does not produce the most optimum microstructure for a working axe, it probably still suggests that there was intention for it to be used. It may be the case that a slightly less experienced artisan was responsible for the creation of this axe. It is difficult to ascertain much about the use-intensity of this axe, since it appears that the blade has been reground quite considerably in modern times. The palstave was recovered through ploughing from Hoskins field on Forde Grange Farm in 1954. It was found about 10 inches below the ground surface, close to a filled in drainage trench.

**Publications:** [60, p. 303, No.491], [84, p. 484-5, No.461, Pl.59]**,** [283, pp. 96, 97], [303, p. 97]**.**

## 12A (Museum of Somerset) - Rodney Stoke, Somerset
### Characteristic flow-chart



*Typological:*
*Gr. III palstave,*
*looped*

*Manufacturing:*
*High tin*
*Moderate porosity*
*Recrystallized*
*Twinned*
*Strain lines are*
*present throughout*

**Figure 300:** Photograph of palstave axe 12A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*Sharpening striations*
*Use-striations*
*Hafting striations*





**Figure 301:** Metallograph of palstave axe 12A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Figure 302:** Photograph of the blade of palstave axe 12A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

*Deposition:*
*Undamaged*
*Uncertain context*
*Single*



**Figure 303:** Micrograph demonstrating the use-striations at the cutting-edge of palstave axe 12A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used in tree-felling. A very comprehensive assessment of use-intensity was permitted on this axe. The cutting-edge exhibits slight asymmetry, the blade is of a medium level of sharpness, and the microscopic analysis has shown evidence of both use-striations and sharpening-striations (in some places). Given this, it is quite likely that this axe has gone through at least one failure and sharpening, and then significant use (to the point where sharpening would be advantageous again and most sharpening striations are diminished). The axe has received no further damages and, unfortunately, there is no relevant contextual information.

**Publications:** [60, p. 332, no. 889], [84, p. 524, no. 717, Pl 82]**,** [280, pp. 86, 250], [281, pp. 70–71].

338

## 14B (Museum of Somerset) – King's Sedgemoor, Somerset
### Characteristic flow-chart

*Typological:*

*Gr. III palstave, looped*

*Manufacturing:*

*High tin*

*Moderate porosity*

*Recrystallized*

*Twinned*

*Strain-banding*

*throughout sample*

*Deformed crystals*

*Use-wear:*

*Blunt*

*Symmetrical*

*Sharpening*

*striations*

*Deposition:*

*Undamaged*

*Wetland*

*Single*



*Figure 304:* Photograph of palstave axe 14B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
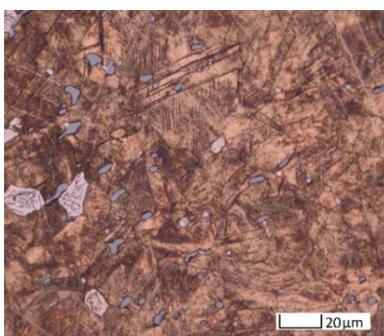


*Figure 305:* Metallograph of palstave axe 14B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 306:* Photograph of the blade of palstave axe 14B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
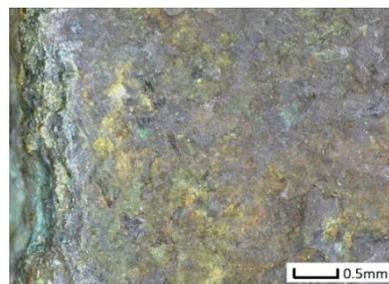


*Figure 307:* Micrograph of the sharpening striations present on the cutting-edge of palstave axe 14B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working tool. There is not enough data for an estimation of use-intensity after final sharpening, but the symmetrical condition of the blade suggests minimal use. There is also enduring sharpening-striations, which means that the axe is unlikely to have been subjected to very extensive use since the last sharpening interval. It appears that one blade tip has become detached post-deposition, and has been refitted. The butt was probably damaged when the sprue was removed. The axe was recovered on King's Sedgemoor while ditch-digging. It was supposedly recovered still hafted on its wooden handle, which was very fragile and was apparently straight. This handle did not survive.

**Publications:** [60, p. 331, No.881], [84, p. 526, No.730], [277, p. lxiv], [280, p. 243], [283, pp. 456], [304, p. 25].

## 75B (Museum of Somerset) – Milborne Port, Somerset
### Characteristic flow-chart

*Typological:*

*Gr. III palstave, looped*

*Manufacturing:*
*Medium (high) tin*
*Mild porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*
*Deformed crystals*

*Use-wear:*
*Blunt*
*Slight asymmetry*
*Use-striations*
*Hafting striations*
*Depression*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Single*



*Figure 308:* Photo graph of palstave axe 75B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 309:* Metallograph of palstave axe 75B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 310:* Photograph of the blade of palstave axe 75B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 311:* Micrograph of the use-striations present at the cutting-edge of palstave axe 75B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe. The metal appears to be fairly sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. The hafting-striations, slight asymmetry and significant depression allude to one or more cycles of use, failure, and sharpening, followed by a major failure of the blade (probably due to the mechanical weaknesses introduced by manufacturing). The impact of the final failure was not completely removed from the blade. The latest phase in the axe's history was a period of extremely high use-intensity, demonstrated by the bluntness of the cutting-edge, and the use-striations, which can be seen at x25 magnification without any evidence of sharpening striations. The butt has been damaged in antiquity, most likely when the sprue was removed. Unfortunately, there is no relevant contextual info for this axe.

**Publications:** [60, p. 331, No.883], [84, p. 518-9, No.685, Pl.79]**,** [283, pp. 462], [305, p. lxxxii], [306, p. lxxxii].

## 81D (Museum of Somerset) – Old Ceeve, Somerset
### Characteristic flow-chart

*Typological:*
*Gr. III palstave,*
*looped*

*Manufacturing:*
*Low tin*
*No porosity*
*Dendritic*

*Use-wear:*
*Blunt*
*Symmetrical*
*Not finished*

*Deposition:*
*Undamaged*
*Uncertain context*
*Group*



**Figure 312:** Photograph of palstave axe 81D (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
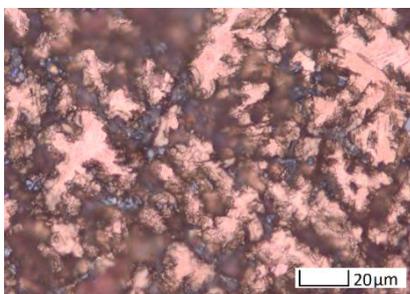


**Figure 313:** Metallograph of palstave axe 81D (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
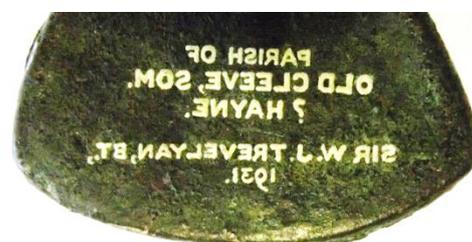


**Figure 314:** Photograph of palstave the blade of palstave axe 81D (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has not been subjected to any further processing after the initial casting. There is also visible casting seems on the cutting edge (which remains very obtuse). This suggests that there was no intention for it to be used as a working tool in its current state. The micrograph demonstrates that the axe has not been finished or sharpened and, unsurprisingly, there are no signs of use. Interestingly, this axe was found as part of a multi-period hoard containing a flat axe, two palstaves (the other of which is 81C) and a socketed axe.



**Figure 315:** Micrograph demonstrating the unfinished surface of palstave axe 81D (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Publications:** [60, p. 256, No. 113], [84, p. 521-522, No. 700b, Pl. 80, 81]**,** [283, pp. 454], [286]**,** [287, pp. 91, No. 22]**,** [288, pp. 327–329, No. 5]**,** [289, p. lxxv]**.**

## 84B (Museum of Somerset) – Sedgemoor, Somerset
### Characteristic flow-chart



*Typological:*

*Gr. III palstave,*
*looped*

*Manufacturing:*

*High tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*

*Use-wear:*

*Blunt*
*Severe asymmetry*
*Hafting striations*

*Deposition:*

*Undamaged*
*Uncertain context*
*Group*

**Figure 316:** Photograph of palstave axe 84B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
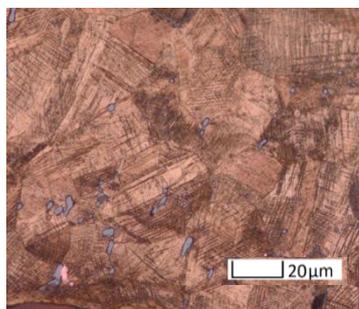


**Figure 317**: Metallograph of palstave axe 84B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
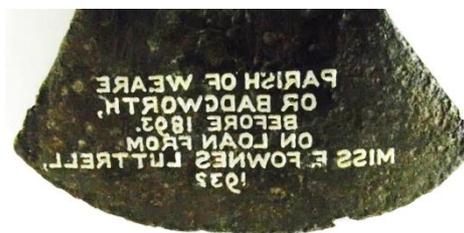


**Figure 319:** Photograph of the blade of palstave axe 84B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 318:** Micrograph of the hafting striations present on the septum of palstave axe 84B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, however, it is clear from the severe asymmetry of the blade that this axe has been through many cycles of use, failure, and sharpening, probably experiencing tens of thousands of impacts. This is further attested by the hafting striations that can be found within the butt. There are no further observable damages. The axe was found with two other palstaves and three torcs near Weare and Badgworth.

**Publications:** [24, p. 146]**;** [60, p. 259, no. 121]; [84, p. 536, no. 763, Pl, 92]**;** [307, p. lxxvi]**.**

## A331 (Museum of Somerset) – south Petherton, Somerset
### Characteristic flow-chart

*Typological:*
*Gr. III palstave,*
*looped*

*Manufacturing:*
*Low tin*
*Minor porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*
*Deformed crystals*

*Use-wear:*
*No micrograph*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Group*



**Figure 320:** Photograph of palstave axe A331 (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
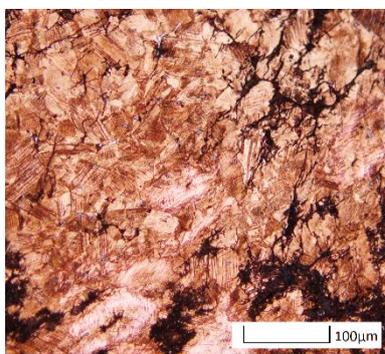


**Figure 321:** Metallograph of palstave axe A331 (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 322:** Photograph of the blade of palstave axe A331 (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe, however, the mounted sample has since been lost. The metal appears to be of relatively sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. One blade tip, and much of the cutting-edge, has been lost to post-depositional damage, so that an estimation of use-intensity after final sharpening, nor overall use-intensity, could not be made. In addition, the side-loop has been lost and flanges appear to have slight damage. Not much is known about the deposition circumstances of this axe, apart from that it was found with A332 and 13B.

**Publications:** [60, p. 333, no. 904], [84, p. 528, no.732a, Pl. 85]**,** [308, p. 143]**,** [309, p. 247]**,** [310]**.**

## A332 (Museum of Somerset) – South Petherton, Somerset
### Characteristic flow-chart



*Typological:*
*Gr. III palstave,*

*Manufacturing:*
*High tin*
*Moderate porosity*
*Recrystallized*
*Twinned*
*Strain-banding at sample exterior*
*Deformed crystals*

**Figure 323:** Photograph of palstave axe A332 (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

*Use-wear:*
*Blunt*
*Slight asymmetry*
*Use-striations*





*Deposition:*
*Accidental damage*
*Uncertain context*
*Group*

**Figure 324:** Metallograph of palstave axe A332 (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
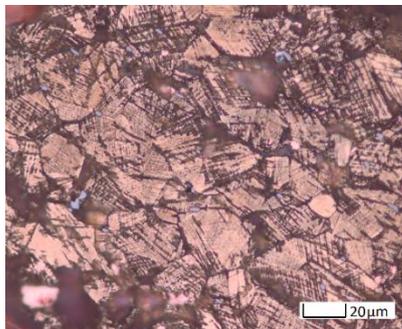
**Figure 325:** Photograph of the blade of palstave axe A332 (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

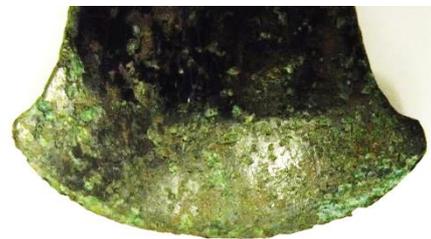

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The casting quality is poor, and the metal has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. The slight asymmetry of the blade suggests at least one cycle of use, failure, and sharpening. Striations generated via use are apparent at x25 magnification and seem to entirely obscure any prior evidence of sharpening. For this reason, and on consideration of the blunt condition of the cutting-edge, it is sensible to assume that this axe was

**Figure 326:** Micrograph of the use-striations present on the cutting-edge of palstave axe A332 (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

subjected to a period of very high use-intensity before deposition. The specimen is broken just above the stop ridge, which most likely occurred in antiquity but casting flaws indicate this was not intentional. The side-loop was broken in antiquity. Not much is known about the deposition circumstances of this axe, apart from that it was found with A331 and 13B.

**Publications:** [60, p. 333, no. 904], [84, p. 528, no.732b, Pl. 85]**,** [308, p. 143]**,** [309, p. 247]**,** [310]**.**

344

## 1884.119.12 (Pitt Rivers) – Unknown, Ireland
### Characteristic flow-chart

*Typological:*
*Gr. III palstave*

*Manufacturing:*
*Low tin*
*No porosity*
*Recrystallized*
*Twinned*

*Use-wear:*
*Sharp (regrinding)*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown associations*



**Figure 327:** Photograph of palstave axe 1884.119.12 (source: Author's own, courtesy of Pitt Rivers Museum).



**Figure 328:** Photograph of the blade of palstave axe 1884.119.12 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered and annealed. This suggests that while there may have been intention for it to be used as a working axe, the processing that it was subjected to is not optimum. There is not enough data for an estimation of use-intensity after final sharpening since much of the axe has undergone a major regrinding. The cutting-edge appear to be symmetrical, implying limited use, but it is impossible to say whether the axe was used or not for definite. Very little is known about the deposition circumstances of this axe.

**Publications:** [116, p. 124, No. 48]**.**

## 1884.119.105 (Pitt Rivers) – Worstead Common, Norfolk
### Characteristic flow-chart

*Typological:*
*Gr. III palstave*

*Manufacturing:*
*Low tin*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*

*Use-wear:*
*Slight asymmetry*
*Sharp*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown associations*



**Figure 329:** Photograph of palstave axe 1884.119.105 (source: Author's own, courtesy of Pitt Rivers Museum).



**Figure 330:** Photograph of the blade of palstave axe 1884.119.105 (source: Author's own, courtesy of Pitt Rivers Museum).



**Figure 331:** Micrograph of the hafting striations present on the septum of palstave axe 1884.119.105 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The casting quality is unknown, but it is clear that the axe has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, though the slight asymmetry and hafting-striations suggest that the axe has experienced at least one cycle of use, failure, and sharpening. Very little is known about the deposition circumstances of this axe.

**Publications**: [60, p. 325, no. 805], [116, p. 126, no. 50].

# 1884.119.135 (Pitt Rivers) – Unknown, Ireland
## Characteristic flow-chart

*Typological:*

*Gr .III palstave*

*Manufacturing:*

*Low tin*

*Recrystallized*

*Twinned*

*Strain lines present throughout sample*

*Use-wear:*

*Sharp*

*Slight asymmetry*

*Sharpening striations*

*Hafting-striations*

*Depression*

*Deposition:*

*Undamaged*

*Uncertain context*

*Unknown associations*



*Figure 332:* Photograph of palstave axe 1884.119.135 (source: Author's own, courtesy of Pitt Rivers Museum).



*Figure 333:* Photograph of the blade of palstave axe 1884.119.135 (source: Author's own, courtesy of Pitt Rivers Museum).



*Figure 334:* Micrograph of the sharpening striations on the cutting-edge of palstave axe 1884.119.135 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The quality of the material has not been specified, but the metallographic assessment indicates that the cutting-edge has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, however, it is very likely that this axe has gone through at least one cycle of use, failure and sharpening, since the cutting-edge is slightly asymmetrical and there are hafting striations in the septum. There is an area of slight depression, which was probably the location of bending that was partially removed by sharpening. This is corroborated by the sharpening striations that can be observed by microscopy – no use-striations overlay these, so it is likely that the axe has been used little, if at all, after this sharpening event. Very little is known about the deposition circumstances of this axe.

**Publications:** [116, p. 123, no. 47]**.**

# 1884.119.106 (Pitt Rivers) – Unknown, Suffolk
## Characteristic flow-chart

*Typological:*
*Gr. III palstave,*
*looped*

*Manufacturing:*
*Medium (low) tin*
*Minor porosity*
*Recrystallized*
*Twinned*
*Strain-banding at*
*exterior of sample*

*Use-wear:*
*Medium sharpness*
*Symmetrical*
*Sharpening striations*
*Use-striations*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Unknown associations*



*Figure 335:* Photograph of palstave axe 1884.119.106 (source: Author's own, courtesy of Pitt Rivers Museum).



*Figure 336:* Photograph of the blade of palstave axe 1884.119.106 (source: Author's own, courtesy of Pitt Rivers Museum).
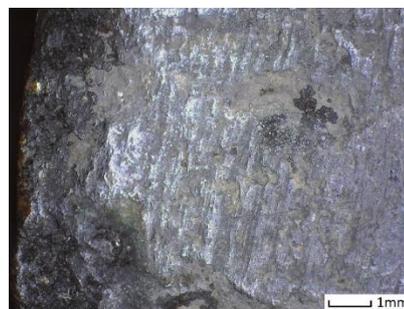


**Figure 337:** Micrograph of the sharpening striations and use-striations observed on the cutting-edge palstave axe 1884.119.106 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be fairly sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. This axe is an interesting specimen as upon first glance it would appear that it has been subjected to no use since it has a symmetrical cutting-edge and no hafting-striations. On examination of the cutting-edge by microscopy, clear sharpening striations can be observed. When analysis is conducted at x50 magnification, faint use-striations are shown to overlay these. This suggests that this axe has been used in the period prior to deposition, but probably not very intensely (0-500 impacts). Though, the cutting-edge is not sharp, which could indicate that the axe may have been used much more – or, perhaps, it was never sharpened greatly to begin with. The axe exhibits damage to the flanges (fragmentation, cracking and bending) which seems to be patinated in some areas and not in others, suggesting that the material loss may have occurred in antiquity and later, perhaps during recovery. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 337, no. 965], [116, p. 127, no. 51**].**

## 1892.67.86 (Pitt Rivers) – Unknown, Suffolk
**Characteristic flow-chart**

*Typological:*
*Gr. III palstave*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*

*Use-wear:*
*Sharp (regrinding)*
*Symmetrical*
*Notching*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown associations*



*Figure 338:* Photograph of palstave axe 1892.67.86 (source: Author's own, courtesy of Pitt Rivers Museum).



*Figure 339:* Photograph of the blade of palstave axe 1892.67.86 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, and since the blade is symmetrical it seems likely that the axe has not experienced very many cycles of use and sharpening. Much of the surface of the axe has been stripped in modern times, but the cutting-edge remains quite jagged. This notching could be use wear from hitting a very hard opposition material. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 337, no. 966], [116, p. 128, no. 52**].**

# 1892.67.121 (Pitt Rivers) – Cambridge Fens, Cambridgeshire
## Characteristic flow-chart

*Typological:*
*Gr. III palstave*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Recrystallized*
*Twinned*

*Use-wear:*
*Sharp (regrinding)*
*Moderate asymmetry*
*No micrograph*

*Deposition:*
*Post-depositional damage*
*Wetland*
*Unknown*



**Figure 340:** Photograph of palstave axe 1892.67.121 (source: Author's own, courtesy of Pitt Rivers Museum).
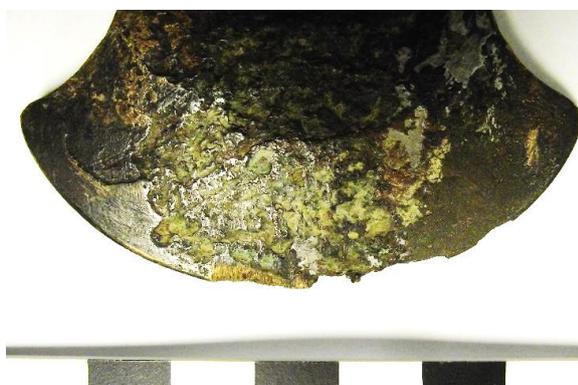


**Figure 341:** Photograph of the blade of palstave axe 1892.67.121 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered and annealed. This suggests that while there may have been intention for it to be used as a working axe, the processing that it was subjected to is not optimum. The moderate asymmetry of the blade most likely suggests that this axe has been subjected to several cycles of use and sharpening. It is difficult to tell anything about the period prior to deposition as the cutting-edge has been stripped by cleaning. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 295, no. 380], [116, p. 125 no. 49].

## 1904.31.2 (Pitt Rivers) – Tackley, Oxfordshire
**Characteristic flow-chart**



*Typological:*

*Gr. III palstave, looped*

*Manufacturing:*

*Medium (high) tin Recrystallized Twinned*

*Use-wear:*

*Blunt*

*Severe asymmetry*

*Use-striations*

*Hafting striations*

*Deposition:*

*Undamaged*

*Uncertain context*

*Unknown associations*

**Figure 342:** Photograph of palstave axe 1904.31.2 (source: Author's own, courtesy of Pitt Rivers Museum).
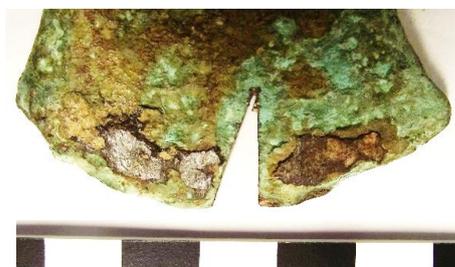


**Figure 343:** Photograph of the blade of palstave axe 1904.31.2 (source: Author's own, courtesy of Pitt Rivers Museum).



**Figure 344:** Micrograph of the use-striations observed on the cutting-edge of palstave axe 1904.31.2 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The casting quality is unknown, and the axe has has been hammered and annealed. This suggests that while there may have been intention for it to be used as a working axe, the processing that it was subjected to is not optimum. It is possible to say with confidence that this axe has been used; the blade is very asymmetrical, the cutting-edge is blunt, and there are hafting striations in the septum, suggesting that it has undergone many cycles of use, failure, and sharpening, with the period prior to deposition having been a period of high use-intensity. This is corroborated by the micro-level analysis, which has demonstrated that use-striations are visible even at the x25 magnification (with no sharpening striations detected). Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 328, no. 841], [116, p. 121, no. 45].

## 10/1980 (RAMM) - Dawlish, Devon
### Characteristic flow-chart

*Typological:*
*Gr. III palstave, looped*

*Manufacturing:*
*High tin*
*No porosity*
*Recrystallized*
*Strain-banding in some crystals*

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*Depression*
*No micrograph*

*Deposition:*
*Accidental damage*
*Single*
*Wetland*



**Figure 345:** Photograph of palstave axe 10/1980 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 346:** Metallograph of palstave axe 10/1980 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 347:** Photograph of the blade of palstave axe 10/1980 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening, though the slight asymmetry of the cutting-edge indicates that it was subjected to at least one cycle of use, failure, and sharpening. In addition, the axe has been deposited with a noticeable depression on the cutting-edge, which may have influenced the decision to deposit it within the ground. The butt has broken off in an accidental fashion in antiquity. The flanges have been broken in antiquity and suffered further fragmentation post-deposition. The axe was found in plough soil at Secmanton Farm - this may have been wetland in the Bronze Age.

**Publications:** [84, p. 548, No.847]**,** [283, p. 299]**.**

## 45.1955.1 (RAMM) - Chagford, Devon
### Characteristic flow-chart

*Typological:*
*Gr. III palstave*

*Manufacturing:*
*Medium (high) tin*
*No porosity*
*Twinned*
*Stain-banding*
*throughout sample*

*Use-wear:*
*Medium sharpness*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Single*
*Uncertain*
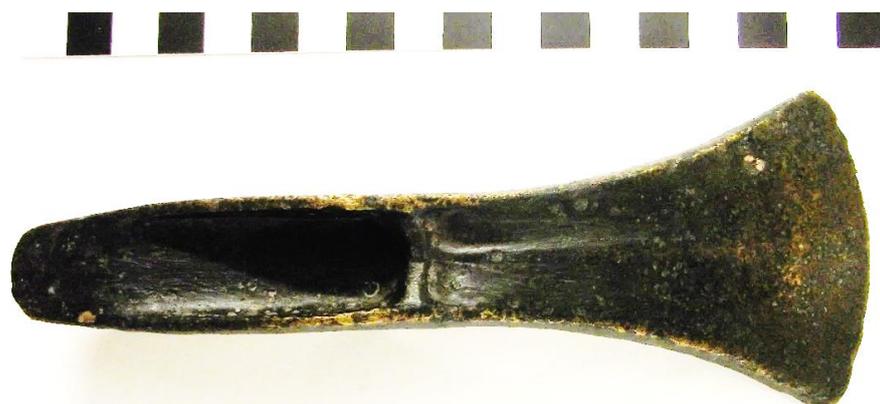


*Figure 348:* Photograph of palstave axe 45.1955.1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
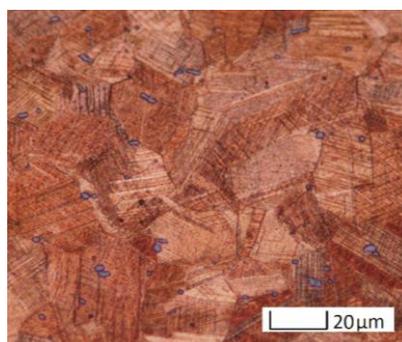


*Figure 349:* Metallograph of palstave axe 45.1955.1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 350:* Photograph of the blade of palstave axe 45.1955.1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. Due to modern cleaning it was not possible to recover enough data for an estimation of use-intensity after final sharpening. The palstave was found at the old granite quarry of Quarterdon, but no further contextual information is known.

**Publications:** [84, p. 436, No. 203b, Pl 26]**,** [311, p. 459]**,** [312, pp. 215, Pl. 26b]**.**

# 50/1971 (RAMM) - Tiverton, Devon
## Characteristic flow-chart

**Typological:**

*Gr. III palstave,*
*looped*

**Manufacturing:**

*High tin*
*Microporosity*
*Recrystallized*

**Use-wear:**

*No micrograph*

**Deposition:**

*Deliberate damage*
*Uncertain context*
*Single*



*Figure 351:* Photograph of palstave axe 50/1971 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
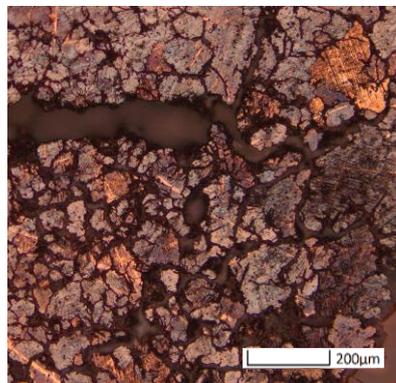


*Figure 352:* Metallograph of palstave axe 50/1971 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
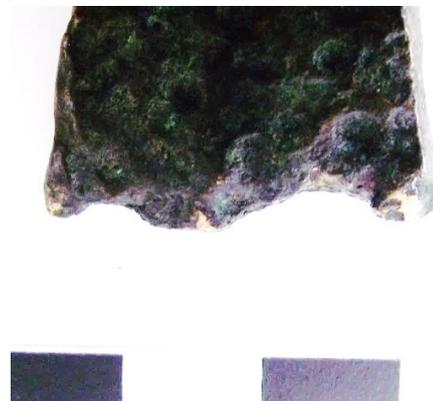


*Figure 353:* Photograph of the blade of palstave axe 45.1955.1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been annealed. This suggests that there may not have been intention for this axe to be a working tool. There is not enough data for an estimation of use-intensity after final sharpening, or to posit whether this axe has been used at all, but it is unlikely given the lack of manufacturing. The blade has been entirely removed in antiquity, mostly likely in an intentional manner (an impact mark is noticeable). The flanges and side-loop have also been damaged in antiquity, with further degradation post-deposition. Very little is known about the circumstances of deposition.

**Publications:** [84, p. 450, No.279, Pl. 34]**,** [283, p. 284]**,** [313, p. 283, fig. 2].

## 60/1954 (RAMM) - Hemyock, Devon
### Characteristic flow-chart

*Typological:*
*Gr. III palstave,*
*looped*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Recrystallized*
*Twinned*

*Use-wear:*
*Sharp*
*Severe asymmetry*
*Sharpening*
*striations*
*Hafting striations*

*Deposition:*
*Accidental damage*
*Uncertain*
*Group*



*Figure 354:* Photograph of palstave axe 60/1954 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
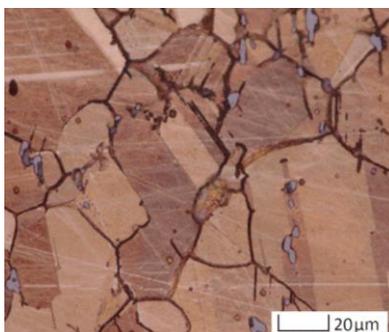


*Figure 355:* Metallograph of palstave axe 60/1954 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 356:* Photograph of the blade of palstave axe 60/1954 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
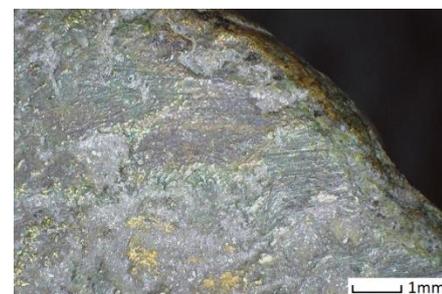


*Figure 357:* Micrograph of the sharpening striations present on the cutting-edge of palstave axe 60/1954 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The casting quality is good, and the axe has been hammered and annealed. This suggests that while there may have been intention for it to be used as a working axe, the processing that it was subjected to is not optimum. It is clear that this axe has gone through many cycle of use, failure, and sharpening (probably into the tens of thousands of impacts). Interestingly, however, the axe has been sharpened directly before deposition (there are no use-striations overlaying sharpening marks). The side-loop was broken in antiquity and the flanges have also been damaged in antiquity, with further degradation post-deposition. The axe was part of a hoard of palstaves, found pre-1892, though this is the only one that now survives.

**Publications:** [60, p. 229, No.22], [84, p. 443, No.242, Pl.31]**,** [283, p. 256]**,** [314, pp. 320, Pl. 14b]**.**

## 70/1974 (RAMM) - Unknown
### Characteristic flow-chart

*Typological:*
*Gr. III palstave*

*Manufacturing:*
*High tin*
*Minor porosity*
*Slag inclusions*
*Recrystallized*
*Twinned*
*Strain-banding in*
*some crystals*

*Use-wear:*
*Medium sharpness*
*Moderate asymmetry*
*Bending*
*Depression*
*No micrograph*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Unknown*



**Figure 358:** Photograph of palstave axe 70/1974 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
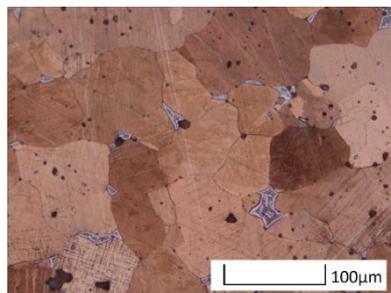


**Figure 359:** Metallograph of palstave axe 70/1974 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 360:** Photograph of the cutting-edge of palstave axe 60/1954 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after final sharpening. However, the moderate asymmetry, a large depression, and bending of one blade tip, indicate that the axe experienced several cycles of use, failure, and sharpening, then the blade failed quite catastrophically and it the axe was retired. The other blade tip had broken away, this may have occurred in antiquity. Unfortunately, there is little known about the deposition circumstances.

**Publications:** [84, p. 441, No.228, Pl.29], [283, p. 268], [315, pp. 325–6, fig. 1].

## 130/1979 (RAMM) - Upottery, Devon
### Characteristic flow-chart

**Typological:**

Gr. III palstave

**Manufacturing:**

High tin
Moderate porosity
Recrystallized
Twinned
Strain-banding
throughout sample.

**Use-wear:**

Medium sharpness
*No micrograph*

**Deposition:**

Undamaged
Uncertain context
Single



*Figure 361:* Photograph of palstave axe 130/1979 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
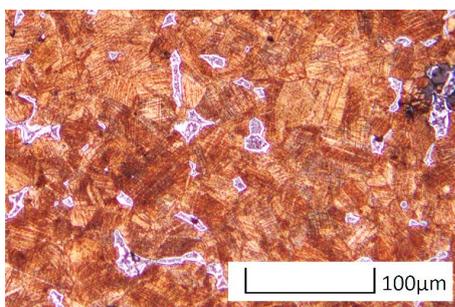


*Figure 362:* Metallograph of palstave axe 130/1979 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 363:* Photograph of the blade of palstave axe 130/1979 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe, though it was not produced to a particularly high standard. There is not enough data for an estimation of use-intensity, but this axe was probably not used due to casting defect at blade. The deposition circumstances remain unknown.

**Publications:** [84, p. 458 No.310, Pl.41], [283, p. 267].

# A289 (RAMM) - Rockbeare, Devon
## Characteristic flow-chart



**Figure 364:** Photograph of palstave axe A289 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

*Typological:*
*Gr. III palstave*

*Manufacturing:*
Low *tin*
*Recrystallized*
*Twinned*
*Stain-banding in some crystals*

*Use-wear:*
*Blunt*
*Symmetrical*
*Not finished (shown in the micrograph)*

*Deposition:*
*Undamaged*
*Uncertain*
*Group*
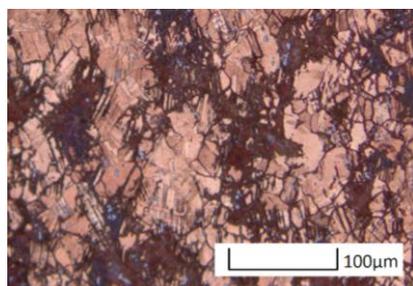


**Figure 365:** Metallograph of palstave axe A289 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 366:** Photograph of the blade of palstave axe A289 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
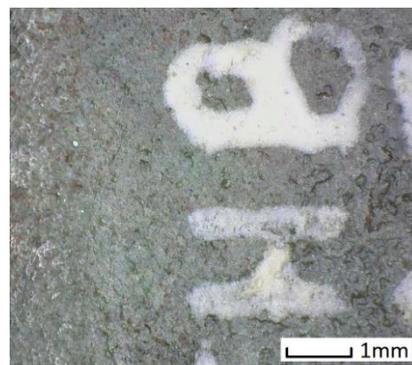


**Figure 367:** Micrograph of the unfinished surface of palstave axe A289 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The corroded nature of the sample meant that the casting quality could not be ascertained. The axe has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. However, the blunt, symmetrical blade, alongside the lack of finishing exhibited in the micrograph indicates that this axe was probably not used. Not very much is known about the deposition circumstances, though this is one of two palstave axes that were found in the same field.

**Publications:** [60, p. 230, No.26], [84, p. 435, No.200], [283, p. 300]**,** [292, p. 365], [293, p. 298], [294, p. 345].

## A6462 (RAMM) – Cullompton, Devon
### Characteristic flow-chart

**Typological:**

*Gr. III palstave*

**Manufacturing:**

*High tin*

*Minor porosity*

*Recrystallized*

*Twinned*

*Strain-banding*

*throughout sample*

*Deformed crystals*

**Use-wear:**

*Blunt*

*Symmetrical*

*No micrograph*

**Deposition:**

*Post-depositional*

*damage*

*Unknown*

*associations*

*Single*



**Figure 368:** Photograph of palstave axe A6462 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
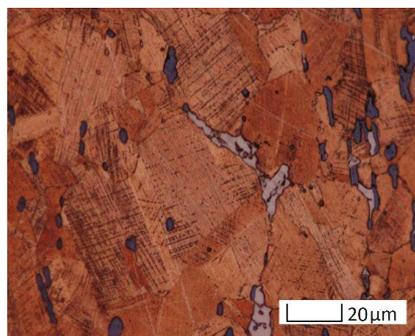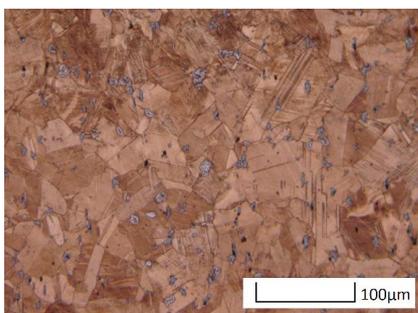


**Figure 369:** Metallograph of palstave axe A6462 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 370:** Photograph of the blade of palstave axe A6462 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The axe appears to be of an okay quality, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity in the final use-cycle, though the blunt condition of the blade could indicate that it was not sharpened or used. The end of the butt has been damaged, but this was most likely post-depositional as the patination is not consistent. The side-loop is also cracked, which was probably the result of corrosion. Not very much is known about the deposition circumstances.

**Publications:** [60, p. 301, No.471], [84, p. 548, no.230, Pl. 29], [283, p. 266].

## OA331 (West Berkshire Museum) – Unknown, Ireland
### Characteristic flow-chart



*Typological:*

*Gr.III palstave*

*Manufacturing:*

*Low tin*

*Minor porosity*

*Cracking*

*Partial recrystallization*

*Twinned*

*Use-wear:*

*Blunt*

*Slight asymmetry*

*No micrograph*

*Deposition:*

*Undamaged*

*Uncertain context*

*Unknown*

*Figure 371:* Photograph of palstave axe OA331 (source: courtesy of West Berkshire Museum)**.**
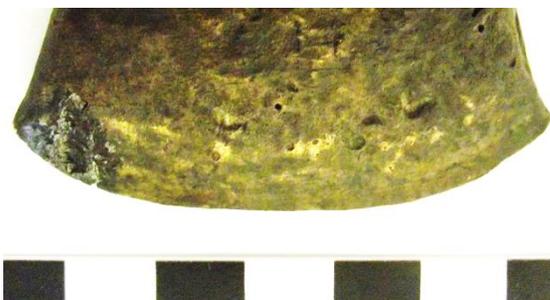


*Figure 372:* Photograph of the blade of palstave axe OA331 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be fairly sound, and has been hammered and lightly annealed. This suggests that there was probably intention for it to be used as a working axe, however, it has not received the optimum manufacturing specifications. There is not enough data for an estimation of use-intensity after final sharpening, but the slight asymmetry suggests that the axe has probably been subjected to at least one cycle of use and sharpening, possibly more. Since it is hafted it was not possible to make an assessment of the septum for hafting striations, which could have indicated the intensity of use further. Very little is known about the deposition circumstances of this axe.

**Publications:** [135, pp. 16, 17, Pl. XV, XVII]**,** [278]**.**

## 14A (Museum of Somerset) - Ham Hill, Somerset
### Characteristic flow-chart



**Figure 373:** Photograph of palstave axe 14A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

*Typological:*
*Gr.IV palstave,*
*looped*

*Manufacturing:*
*High tin*
*No porosity*
*Recrystallized*
*Twinned Crystals*
*Strain-banding is*
*present throughout*
*Deformed crystals*

*Use-wear:*
*Blunt*
*Severe asymmetry*
*Notching*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Group*
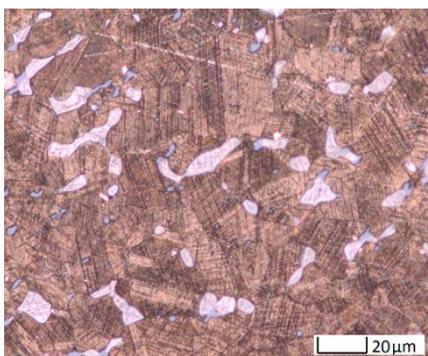


**Figure 374:** Metallograph of palstave axe 14A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 375:** Photograph of the blade of palstave axe 14A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used in tree-felling. There is not enough data for an estimation of use-intensity, but the severe asymmetry of the cutting-edge indicates the axe has been used intensely. Interestingly, there is quite significant notching of the cutting-edge, which strongly suggests that the axe has hit a harder opposition material than wood. This axe is also very unique as it is said to have been found with a human skeleton. The location of discovery, Ham Hill, is the site of an Iron Age hillfort, where much metalwork has been recovered.

**Publications:** [60, p. 331, No.879], [84, p. 532, Nos.749, Pl .89], [107], [280, pp. 241–242], [283, p. 446], [308, pp. 143–4, fig. 3], [316, p. 49, fig. 19.2], [317, p. 30], [318, pp. 39–42, Pl. 6], [319], [320], [321].

## 1961.498 (Ashmolean) – Unknown, England
### Characteristic flow-chart

*Typological:*
*South-western*
*palstave, looped*

*Manufacturing:*
*High tin*
No micrograph

*Use-wear:*
*Medium*
*Symmetrical*
No micrograph

*Deposition:*
*Accidental damage*
*Uncertain context*
*Single*



**Figure 376:** Photograph of palstave axe 1961.498 (source: © Ashmolean Museum, University of Oxford).
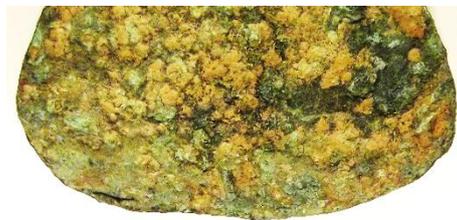


**Figure 377:** Photograph of the blade of palstave axe 1961.498 (source: © Ashmolean Museum, University of Oxford).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe, however, no mounted sample was ever produced for this specimen. Therefore, very little can be ascertained regarding the manufacturing specifications. Since the blade is symmetrical and microscopy could not be undertaken due to corrosion, it is not possible to determine if this axe was used or not. It appears that the very end portion of the butt has been broken off – the patina looks consistent with the rest of the axe so it is likely that this was contemporary, though no blow marks to suggest the breakage was intentional. Very little is known about the deposition circumstances of this axe.

**Publications:** [84, p. 472, no. 397].

## 1884.9.5 (Dorset County Museum) – Wareham, Dorset
### Characteristic flow-chart



*Figure 378:* Photograph of palstave axe 1884.9.5 (source: courtesy of Dorset County Museum).

*Typological:*
*South-western*
*palstave*

*Manufacturing:*
*Medium (low) tin*
*Moderate porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*
*Deformed crystals*

*Use-wear:*
*Medium sharpness*
*Moderate asymmetry*
*No micrograph*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Unknown*
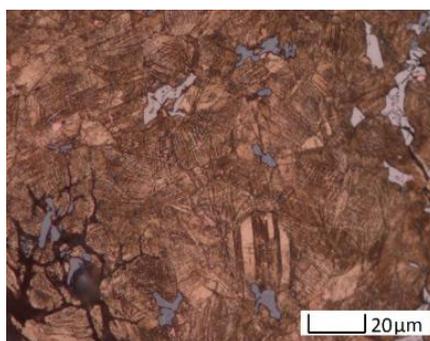


*Figure 379:* Metallograph of palstave axe 1884.9.5 (source: courtesy of Dorset County Museum).
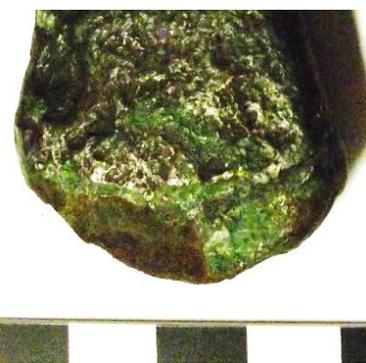


*Figure 380:* Photograph of the blade of palstave axe 1884.9.5 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the moderate asymmetry of the blade could indicate that this axe has been used – though, it is quite obvious that the blade has suffered from a serious corrosion attack. The axe is also broken across the stop-ridge, an area which is consistently patinated and corroded, suggesting that this damage happened in antiquity. Knight [13, p. 170] has suggested that breaks across the stop-ridge, like this, may have occurred during use of the object, rather than due to desire to deliberately damage the object.

**Publications:** [60, p. 303, Pl 32, 493], [84, p. 485, no. 466].

# 1902.1.4 (Dorset County Museum) – Dewlish, Dorset
## Characteristic flow-chart



**Typological:**
*South-western palstave, looped*

**Manufacturing:**
*Medium (high) tin
No porosity
Recrystallized
Twinned
Strain-banding near sample exterior*

**Figure 381:** Photograph of palstave axe 1902.1.4 (source: courtesy of Dorset County Museum).

**Figure 383:** Photograph of the blade of palstave axe 1902.1.4 (source: courtesy of Dorset County Museum).

**Use-wear:**
*Medium sharpness
Moderate asymmetry
Bending*
*No micrograph*
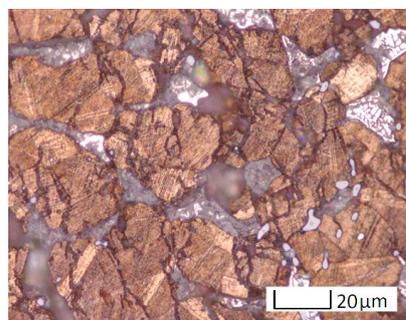


**Figure 382:** Metallograph of palstave axe 1902.1.4 (source: courtesy of Dorset County Museum).
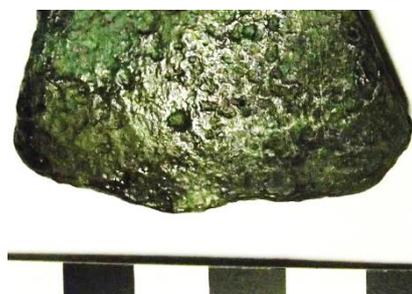


**Deposition:**
*Undamaged
Uncertain context
Group*

**Narrative:** Composition analysis has shown that this is a medium high tin palstave axe. The metal appears to be sound and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the moderate asymmetry exhibited by the cutting-edge strongly suggest that this axe has been subjected to several cycles of use, failure, and sharpening. Interestingly, there is clear bending of the cutting-edge, which, alongside the medium sharpness of the blade, suggests that this axe has experienced a period of high use-intensity prior to deposition. This phase ended when the blade failed, and no sharpening has taken place to correct it. This palstave axe is one of five – the others of which, (1902.1.1, 1902.1.2, 1902.1.3, and 1902.1.5), are included in this study – found in a field near Turnpike Road, Dewlish Hill.

**Publications:** [60, p. 231, No. 31, Pl. 7], [84, p. 468. No. 369].

## 1955.48 (Dorset County Museum) – Abbotsbury, Dorset
**Characteristic flow-chart**

*Typological:*
*South-western*
*palstave, looped*

*Manufacturing:*
Medium *(high)* tin
*No porosity*
*Cracks*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*Depression*
*No micrograph*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Single*



**Figure 384:** Photograph of palstave axe 1955.48 (source: courtesy of Dorset County Museum).
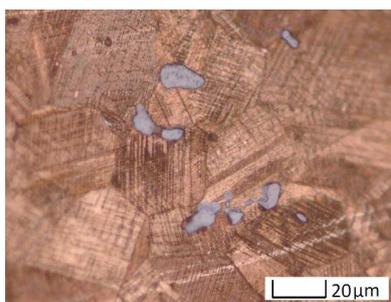


**Figure 385:** Metallograph of palstave axe 1955.48 (source: courtesy of Dorset County Museum).



**Figure 386:** Photograph of the blade of palstave axe 1955.48 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe. The metal has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. While the metal is generally sound, the final hammering may have introduced some brittleness into the microstructure, as there are some substantial areas of cracking. There is not enough data for an estimation of use-intensity after the final sharpening event, but the slight asymmetry indicates that this axe has definitely been used. Moreover, the depression at the cutting-edge suggests that the blade has failed, and that this area of deformation was not completely removed from the cutting-edge by sharpening prior to deposition. The side-loop is broken, this probably happened in antiquity, but it not likely to have been intentional.

**Publications:** [60, p. 302, No.476], [84, p. 461, No.327, Pl.44]**,** [303, p. 97]**.**

## 9B (Museum of Somerset) – Ham Hill, Somerset
### Characteristic flow-chart

**Typological:**
*South-western palstave, looped*

**Manufacturing:**
*Medium (high) tin*
*No porosity*
*Dendritic*

**Use-wear:**
*Sharp*
*Slight asymmetry*
*Sharpening striations*

**Deposition:**
*Undamaged*
*Uncertain context*
*Single*



*Figure 387:* Photograph of palstave axe 9B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
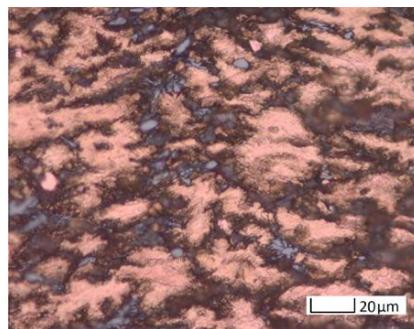


*Figure 388:* Metallograph of palstave axe 9B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
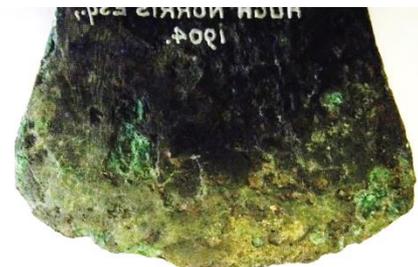


*Figure 389:* Photograph of the blade of palstave axe 9B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 390:* Micrograph presenting the sharpening striations on the cutting-edge of palstave axe 9B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and does not appear to have been subjected to any further processing after the initial cast. This suggests that there was, perhaps, little intention for it to be used as a working tool. However, the blade demonstrates some asymmetry, which indicates that the axe has, in fact, been used. Due to the susceptibility of the microstructure to plastic deformation, it is likely that this axe failed fairly rapidly and was then resharpened to remove the contortion at the cutting-edge. Since the blade is sharp and sharpening striations are still visible, the axe was probably used only a minimal amount, if at all, after the last sharpening interval, before it was deposited. The axe was discovered at Ham Hill, the site of an Iron Age hillfort, where much metalwork has been recovered.

**Publications:** [60, p. 332, No.895], [84, p. 533, No.751], [283, pp. 452, 453], [308, p. 163], [322, p. Lxxv-Lxxxii].

## 10B (Museum of Somerset) – Glastonbury, Somerset
### Characteristic flow-chart



*Typological:*
*South-western*
*palstave, looped*

*Manufacturing:*
*Medium (low) tin*
*Mild porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*
*Deformed crystals*

*Use-wear:*
*Medium sharpness*
*Moderate asymmetry*
*Sharpening striations*
*Hafting striations*
*Depression*

*Deposition:*
*Accidental damage*
*Wetland*
*Single*

**Figure 391:** Photograph of palstave axe 10B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
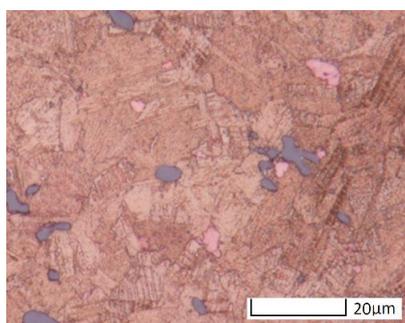


**Figure 392:** Metallograph of palstave axe 10B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
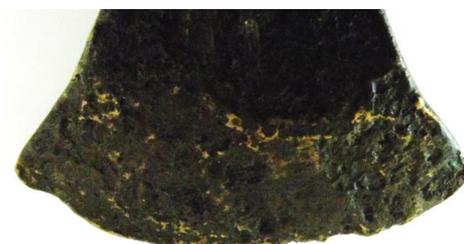


**Figure 393:** Photograph of the blade of palstave axe 10B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
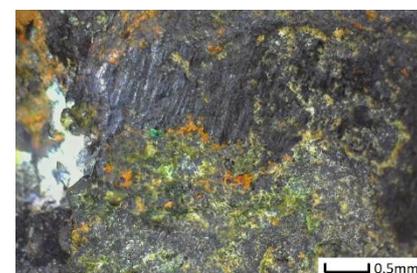


**Figure 394:** Micrograph of the sharpening striations at the cutting-edge of palstave axe 10B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. This specimen is an interesting one – it has more than definitely experienced several cycles of use and failure (as suggested by the moderate asymmetry and hafting striations). The axe has failed (a depression still remains on the cutting-edge) and has clearly been sharpened before deposition, probably to try to correct the failure (which has not been completely successful). The butt has been damaged, probably when the sprue was removed. This specimen was found within the peat of the Tubaries - many bronze implements have been recovered from this area though their association to one another is unknown.

**Publications:** [60, p. 333, no. 901, 1359, 1416, 1578, 1579, 1887, 1985], [84, p. 333, no. 901, 1359, 1416, 1578, 1579, 1887, 1985], [280, p. 98], [283, p. 514], [317, p. 83]; [323].

## 41B (Museum of Somerset) – Taunton, Somerset
### Characteristic flow-chart

*Typological:*
*South-western*
*palstave, looped*

*Manufacturing:*
*High tin*
*No metallograph*



*Figure 395:* Photograph of palstave axe 41B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

*Use-wear:*
*Medium sharpness*
*Symmetrical*
*Use-striations*
*Hafting-striations*
*Notching*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Group*



*Figure 396:* Photograph of the blade of palstave axe 41B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
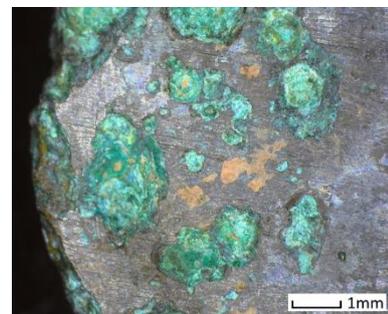


*Figure 397:* Micrograph of the use-striations observed on the cutting-edge of palstave axe 41B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe, however, the mounted sample has since been lost. Therefore, very little can be ascertained regarding the manufacturing specifications. There is much that can be said about the use-history of this axe. Firstly, it has a symmetrical blade, which means it is unlikely to have gone through many cycles of use, failure, and sharpening. However, the cutting-edge has several areas of notching, which suggests that this axe has been used to hit an opposition material harder than wood. The micro-scale analysis also demonstrates very clear use-striations, without any sign of sharpening striations. Ordinarily, this would suggest a period of very high use-intensity prior to deposition, but since it is not possible to know the type of material that this axe came in contact with, the severity of wear cannot be assumed to be a good reflection of this. There is some further damage to the axe, i.e., two breaks across the septum. On one break there is no patination, and so it must have happened post-recovery, but the other is patinated, indicating that is occurred in antiquity. The axe was discovered as part of a hoard of approximately 40 objects, consisting mostly of pins, rings and palstaves, which was found by workmen in 1877, three feet below the surface in red clay. The surface around and beneath the hoard was stained a dark colour, which has been attributed to the slight decomposition of the surface of the objects.
**Publications:** [24, p. GB.43], [60, p. 258-259, No.120], [66, pp. 116, 178, 218, 367–368, 466, Figs. 214, 418], [84, p. 534, No.752bb, Pl.138]**,** [283, p. 500]**,** [324, pp. 94–95, 178, Table 7.3], [325, p. 94].

## 81B (Museum of Somerset) – Lyng, Somerset
### Characteristic flow-chart



*Typological:*
*South-western*
*palstave*

*Manufacturing:*
*Medium (high) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*
*Deformed crystals*

*Use-wear:*
*Sharp*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Group*

**Figure 398:** Photograph of palstave axe 81B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
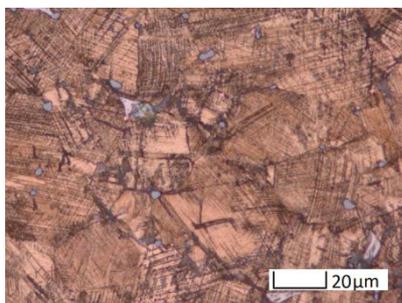


**Figure 399:** Metallograph of palstave axe 81B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 400:** Photograph of the blade of palstave axe 81B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, however, it is likely that this axe has not sustained extended use, as the blade is entirely symmetrical and the cutting-edge is sharp. Though, these characteristics could be related to the significant regrinding that the blade has been subjected to in modern times. This axe is one of two that were found in Lyng, on or near the Isle of Athelney.

**Publications:** [60, p. 331, Nos. 880, 882], [84, p. 518, No.682, Pl.78], [280, pp. 85, 228, 245], [281, p. 30], [282, p. Lxviii], [283, p. 460].

# 11/1974 (RAMM) - Bridford, Devon
## Characteristic flow-chart

*Typological:*
*South-western*
*palstave, looped*

*Manufacturing:*
*High tin*
*Minor porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*

*Use-wear:*
*Blunt*
*Symmetrical*
No micrograph

*Deposition:*
*Undamaged*
*Dryland*
*Single*



*Figure 401:* Photograph of palstave axe 11/1974 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
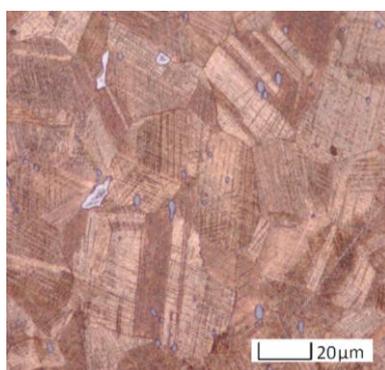


*Figure 402:* Metallograph of palstave axe 11/1974 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
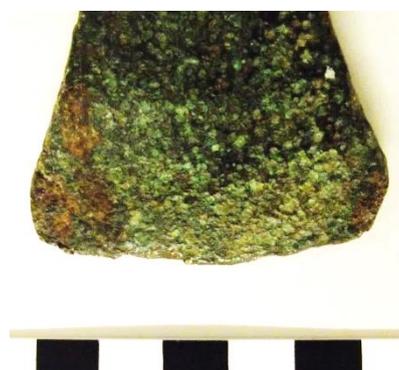


*Figure 403:* Photograph of the blade of palstave axe 11/1974 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be of a standard quality, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, though the blunt blade most likely indicates that this was not sharpened or used. The noticeable depressions along the cutting-edge are not patinated, and so were most likely introduced post-recovery. The axe deposited in a complete condition and discovered (during building operations in 1972) close to the origin of several natural springs.

**Publications:** [84, p. 435, no. 198, Pl 25]**,** [326, p. 167, fig 1, 3], [327, p. 142].

## 102/1970 (RAMM) - Caton, Devon
### Characteristic flow-chart

**Typological:**
*South-western palstave, looped*

**Manufacturing:**
*High tin*
*Minor porosity*
*Recrystallized*
*Twinned*
*Strain-banding in some crystals*

**Use-wear:**
*Medium sharpness*
*Slight asymmetry*
*Bending*

**Deposition:**
*Post-depositional damage*
*Dryland*
*Single*



***Figure 404:*** Photograph of palstave axe 102/1970 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
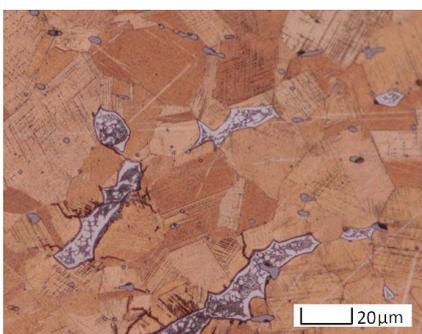


***Figure 405:*** Metallograph of palstave axe 102/1970 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



***Figure 406:*** Photograph of the blade of palstave axe 102/1970 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be of an okay quality, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, though the slight asymmetry and potential area of bending indicates that the axe has failed and not been re-sharpened before deposition. The side-loop of this axe is broken, this was probably weakened by use and then further degraded by corrosion after deposition. Damage to the flanges, however, is definitely modern as it is not patinated. The axe was found on the road from Caton to Stormsdown during a South Devon Water Board excavation.

**Publications:** [84, p. 432, no. 184, Pl 23]**,** [327, p. 142]; [328].

## 355/1906 (RAMM) – Week, Devon
### Characteristic flow-chart

*Typological:*
*South-western palstave, looped*

*Manufacturing:*
*Medium (high) tin*
*No metallograph*
*Corroded sample*

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*Hafting striations*

*Deposition:*
*Accidental damage*
*Dryland*
*Group*



*Figure 408:* Photograph of palstave axe 355/1906 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 409:* Photograph of the blade of palstave axe 355/1906 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
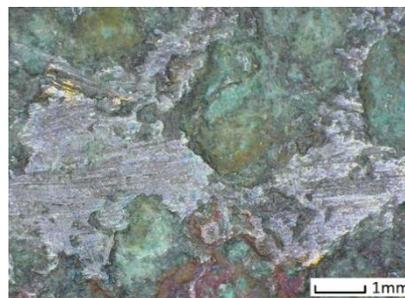


*Figure 407:* Micrograph of the hafting striations on the septum of palstave axe 355/1906 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe, however, the mounted sample was too corroded to examine. Therefore, very little can be ascertained regarding the manufacturing specifications. There is not enough data for an estimation of use-intensity after the final sharpening event, though the slight asymmetry and hafting striations suggests that the overall use-intensity is a minimal one. There is damage to the butt, probably from removal of the sprue. This axe was found with 354/1906/1, beneath a very old hedge or barrier – Knight [244, pp. 307, 308] comments that the find spot is near several natural springs and overlooks the River Bovey.

**Publication:** [24, p. 184, figs. 7, 1, 2], [60, p. 231, Pl. 9, No.28], [84, p. 450, No.278, Pl.34], [283, pp. 307, 308].

## 1897/7/6 (RAMM) – Bovey Tracey, Devon
**Characteristic flow-chart**

*Typological:*
*South-western palstave, looped*

*Manufacturing:*
*Medium (high) tin*
*Minor porosity*
*Recrystallized*
*Twinned*
*Strain-banding throughout sample*

*Use-wear:*
*Blunt*
*Symmetrical*
*No micrograph*

*Deposition:*
*Post-depositional damage*
*Uncertain context*
*Group*



**Figure 410:** Photograph of palstave axe 1897/7/6 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
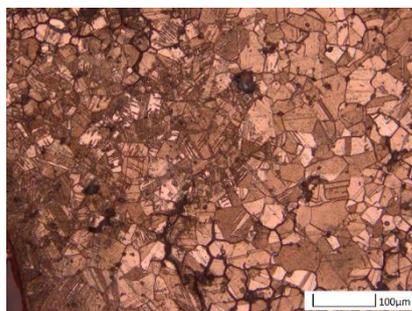


**Figure 411:** Metallograph of palstave axe 1897/7/6 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 412:** Photograph of the blade of palstave axe 1897/7/6 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. These manufacturing specifications indicate that this axe was well prepared for use. There is not enough data for an estimation of use-intensity, though the blunt, symmetrical condition of the cutting-edge may suggest that it was not sharpened or used. There is some damage to the flanges, but this looks like it is post-depositional. There are cracks across the butt that jettison off a large casting flaw. It was found with A4124 – and both were both part of a hoard of eight palstaves. Accounts of the deposition circumstances differ slightly. Way [294, p. 346] records that four palstaves were found beneath a boulder and another four were found under another, all placed upright within the ground; alternatively, Croker [329, p. 186] and Tucker [330, p. 119] state that only four were found under a boulder, and the others were scattered nearby.

**Publications:** [60, p. 230, No.25, Pl.9], [84, p. 433, No.188, Pl.24]**,** [294, p. 346], [312, pp. 214–215, Pl. 26a], [329, p. 186], [330, p. 119], [331, p. 51].

## A1951 (RAMM) - Colyton, Devon
### Characteristic flow-chart



*Typological:*

*South-western palstave, looped*

*Manufacturing:*

*High tin*

*Minor porosity*

*Recrystallized*

*Twinned*

*Strain-banding near edge of sample*

*Figure 413:* Photograph of palstave axe A1951 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

*Use-wear:*

*Blunt*

*Moderate asymmetry*

*Use-striations*

*Hafting striations*



*Figure 414:* Metallograph of palstave axe A1951 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 415:* Photograph of the blade of palstave axe A1951 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

*Deposition:*

*Post-depositional damage*

*Dryland*

*Group*



*Figure 416:* Micrograph of the use-striations on the cutting-edge of palstave axe A1951 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. It is clear, from the moderate asymmetry, that this axe has gone through many cycles of use and sharpening. The bluntness of the cutting-edge and the evidence of use-striations (without any remnant sharpening striations) indicate that this axe was deposited after a period of very intense use (probably many thousands of cycles). There is damage to the butt that looks contemporary, but is not necessarily intentional, and the flanges have been damaged post-deposition. This axe was found with 593/2005, and A1952, which were all part of a large hoard found at Lovehayne farm of approximately one hundred palstaves [294, p. 341]. They were found when a round barrow was cut for stone. **Publications:** [60, p. 230, No.24, Pl.9], [66, pp. 81, 113]**,** [84, p. 438-9, No.217, Pl.27/28]**,** [283, p. 278]**,** [292, pp. 364, 365, fig 19(4)]**,** [293, pp. 300, Pl.5, fig 3]**,** [294, p. 341f, fig 1]**,** [298, pp. 647–648, Pl.9]**,** [299, pp. 50, No. 208]**,** [300, pp. 140–144]**.**

## A1952 (RAMM) - Colyton, Devon
### Characteristic flow-chart

*Typological:*
*South-western*
*palstave*

*Manufacturing:*
*High tin*
*No porosity*
*Dendritic*

*Use-wear:*
*No micrograph*

*Deposition:*
*Deliberate damage*
*Dryland*
*Group*



*Figure 417:* Photograph of palstave axe A1952 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
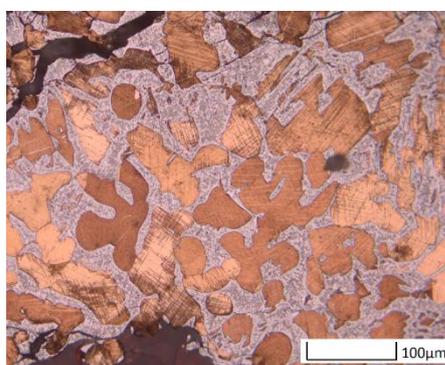


*Figure 418:* Metallograph of palstave axe A1952 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 419:* Photograph of the blade of palstave axe A1952 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has received no further processing after the initial cast. This suggests that there probably was no intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity. The axe is broken across the body, and a significant proportion of the cutting-edge is missing. Although it is probable that this axe was prone to fracture during use (high tin and large grain size), the locations of fracture are indicative of intentional damage. Further degradation from corrosion may have occurred at weakened areas post-deposition. The axe was found with 593/2005 and A1951, which were all part of a large hoard found at Lovehayne farm of approximately one hundred palstaves. They were found when a round barrow was cut for stone.

**Publications:** [33, p. 230, No.24, Pl.9], [66, pp. 81, 113], [55, p. 438-9, No.217, Pl.27/28], [283, p. 279], [292, pp. 364, 365, fig 19(4)], [293, pp. 300, Pl.5, fig 3], [294, p. 341f, fig 1], [298, pp. 647–648, Pl.9], [299, pp. 50, No. 208], [300, pp. 140–144].

## A4214 (RAMM) - Bovey Tracey, Devon
### Characteristic flow-chart

*Typological:*
*South-western*
*palstave, looped*

*Manufacturing:*
*Medium (low) tin*
*No metallograph*

*Use-wear:*
*Blunt*
*Slight asymmetry*
*No micrograph*

*Deposition:*
*Accidental/post-*
*depositional*
*damage*
*Dryland*
*Group*



*Figure 420:* Photograph of palstave axe A4214 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 421:* Photograph of the blade of palstave axe A4214 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium-low tin palstave axe, however, the mounted sample has since been lost. Therefore, very little can be ascertained regarding the manufacturing specifications. There is not enough data for an estimation of use-intensity, though the slight asymmetry indicates that his axe has been subjected to at least one cycle of use, failure, and sharpening. The butt has broken off in an accidental fashion in antiquity, while the side-loop has been broken post recovery [244, p. 294]**.** This axe was found with 1897/7/6 and is part of a hoard of eight palstaves. Accounts of the deposition circumstances differ slightly. Way [294, p. 346] records that four palstaves were found beneath a boulder and another four were found under another, all placed upright within the ground; alternatively, Croker [329, p. 186] and Tucker [330, p. 119] state that only four were found under a boulder, and the others were scattered nearby.

**Publications:** [60, p. 230, No.25, Pl.9], [84, p. 433, No.188, Pl.24]**,** [283, p. 294]**,** [294, p. 346], [312, pp. 214–215, Pl. 26a], [331, p. 51], [330, p. 119], [329, p. 186].

## 1974.10.1 (Royal Cornwall Museum) – St. Mellion, Cornwall
### Characteristic flow-chart

*Typological:*
*South-western*
*palstave*

*Manufacturing:*
*Low tin*
*Microporosity*
*Dendritic*

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Single*



**Figure 422:** Photograph of palstave axe 1974.10.1 (source: Author's own, courtesy of Royal Cornwall Museum).



**Figure 423:** Metallograph of palstave axe 1974.10.1 (source: Author's own, courtesy of Royal Cornwall Museum).



**Figure 424:** Photograph of the blade of palstave axe 1974.10.1 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be fairly sound, and has received no further processing after the initial cast. This suggests that there probably was no intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the slight asymmetry of the cutting-edge indicates that this axe has experienced at least one cycle of use, failure and sharpening. There are no further damages exhibited on this palstave. This artefact was ploughed up on Herrod Down in 1921, though further circumstances are not known.

**Publications:** [84, p. 424, No.128, Pl.16]**,** [283, p. 335]**,** [313, p. 82].

# 1927.2571 (Ashmolean) – Crediton, Devon
## Characteristic flow-chart

*Typological:*
*South-western*
*palstave, Variant*
*Crediton*

*Manufacturing:*
*Medium (low) tin*
*No micrograph*

*Use-wear:*
*Blunt*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Group*



**Figure 425:** Photograph of palstave axe 1927.2571 (source: © Ashmolean Museum, University of Oxford).
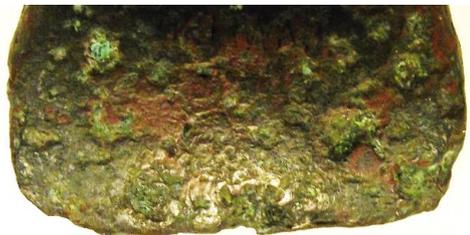


**Figure 426:** Photograph of the blade of palstave axe 1927.2571 (source: © Ashmolean Museum, University of Oxford).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe, however, no mounted sample was ever produced for this specimen. Therefore, very little can be ascertained regarding the manufacturing specifications. Due to the symmetrical nature of the blade, and corrosion of the blade (which made microscopy impossible) it is not possible to determine whether this axe has been used. This specimen is one of two palstaves that were found with two rapiers, and recorded as hoard by Sir John Evans.

**Publications:** [24, p. 184, fig. 7], [60, p. 229, No.21], [84, p. 439, No.219a, Pl.28], [134, pp. 200, No. 3], [283, p. 6]  [332, pp. 243–244, Pl. 6], [333, p. GB.4], [334, pp. 95, Nos. 59, 60], [335, pp. 320, No.5].

## 1884.9.22 (Dorset County Museum) – Colliton, Dorset
### Characteristic flow-chart

*Typological:*
*South-western*
*palstave, variant*
*Crediton*

*Manufacturing:*
*High tin*
*Moderate porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Group*



**Figure 427:** Photograph of palstave axe 1884.9.22 (source: courtesy of Dorset County Museum).
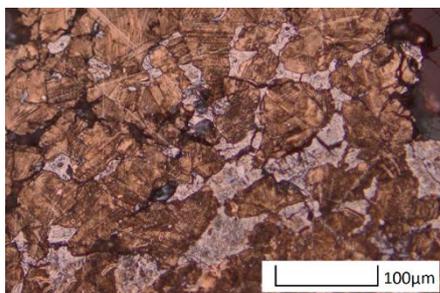


**Figure 428:** Metallograph of palstave axe 1884.9.22 (source: courtesy of Dorset County Museum).



**Figure 429:** Photograph of the blade of palstave axe 1884.9.22 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, however, the slight asymmetry of the cutting-edge indicates that this axe has experienced at least one cycle of use, failure, and sharpening. This axe was found in Eglesham Meadow, with another palstave and two arm rings.

**Publications:** [60, p. 231, No.32, Pl. 11 and 54], [84, p. 469, No. 372], [303, p. 90].

## 80C (Museum of Somerset) - Sedgemoor, Somerset
### Characteristic flow-chart

*Typological:*
*South-western palstave, variant Crediton*

*Manufacturing:*
*Medium (high) tin*
*No porosity*
*Slag inclusions*
*Recrystallized*
*Strain banding is present throughout*
*Deformed crystals*

*Use-wear:*
*Sharp*
*Slight symmetry*
*Depression*

*Deposition:*
*Undamaged*
*Wetland*
*Single*



*Figure 430:* Photograph of palstave axe 80C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
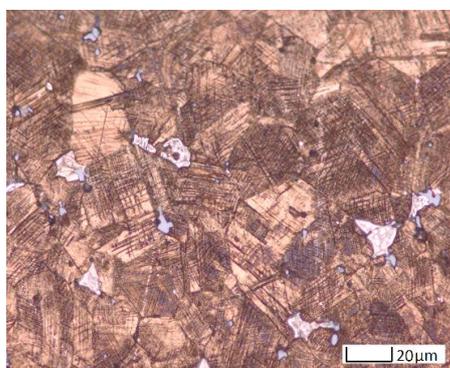


*Figure 431*: Metallograph of palstave axe 80C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 432:* Photograph of the blade of palstave axe 80C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be of a poor quality, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used in tree-felling. There is not enough data for an estimation of use-intensity after the final sharpening event, but the slight asymmetry of the cutting-edge and area of depression indicate that is was mostly definitely used and has failed (probably due to the crude nature of the casting) and then, perhaps, has been resharpened to permit further use. No further damages can be observed. The axe was discovered at Midgeley Farm during peat digging.

**Publications:** [60, p. 231, 330, no. 868], [84, p. 536, no. 765]**,** [336, pp. xcvi–cvi, xcvi]**.**

## 1884.119.114 (Pitt Rivers) – Weyhill, Andover
### Characteristic flow-chart



**Figure 433:** Photograph of palstave axe 1884.119.114.

*Typological:*
*South-western palstave, variant Crediton*

*Manufacturing:*
*Medium (high) tin Recrystallized Twinned Strain-banding throughout sample*

*Use-wear:*
*Blunt*
*Symmetrical*
*Depression*
*Sharpening striations*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown associations*



**Figure 434:** Photograph of the blade of palstave axe 1884.119.114.



**Figure 435:** Micrograph of the sharpening striations on the cutting-edge of palstave axe 1884.119.114.

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The casting quality is not known, but the axe appears to have been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but it appears that this axe has been subjected to a period of use, the blade has failed, and there has, thereafter, been attempts to sharpen the cutting-edge to remove the deformation. This is corroborated by the micro-scale analysis that demonstrates sharpening striations, with no evidence of use-striations. It is not possible to know if other cycles of use and sharpening preceded this. Very little is known about the deposition circumstances of this axe.

**Publications:** [60, p. 308, Pl. 31, 564], [116, pp. 133, No.57].

## 354/1906/1 (RAMM) - Week, Devon
**Characteristic flow-chart**



*Figure 436:* Photograph of palstave axe 354/1906/1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

*Typological:*
*South-western palstave, variant Crediton*

*Manufacturing:*
*High tin*
*Minor porosity*
*Recrystallized*
*Twinned*
*Strain-banding in some crystals*

*Use-wear:*
*Hafting striations*

*Deposition:*
*Deliberate damage*
*Dryland*
*Group*



*Figure 437:* Metallograph of palstave axe 354/1906/1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
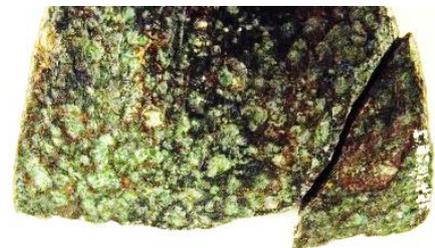


*Figure 438:* Photograph of the blade of palstave axe 354/1906/1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



*Figure 439:* Micrograph of the hafting striations on the septum of 354/1906/1 (source: author's own, courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The casting quality is okay, and the axe appears to have been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, though the hafting striations recorded on the butt tentatively suggest that it has been used. The broken area at the cutting-edge is consistently patinated, which indicates that it was broken in antiquity; although there are no visible impact marks, it is unlikely that the whole cutting-edge would break off accidentally. The break across the blade tip is more likely to have occurred post-deposition as exposed areas of unpatinated bronze are visible. This axe was found with 355/1906, beneath a very old hedge or barrier – the find spot is near several natural springs and overlooks the River Bovey [244, p. 307]**.**

**Publications:** [24, p. 184, figs. 7, 1, 2]**,** [60, p. 231, Pl. 9, No.28], [84, p. 450, No.278, Pl.34]**,** [283, p. 307]**.**

## 1880.16 (Royal Cornwall Museum) – Lelant, Cornwall
### Characteristic flow-chart

*Typological:*
*South-western*
*palstave, variant*
*Crediton*

*Manufacturing:*
*Medium (high) tin*
*Moderate porosity*
*Dendritic*

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Single*



*Figure 440:* Photograph of palstave axe 1880.16 (source: Author's own, courtesy of Royal Cornwall Museum).
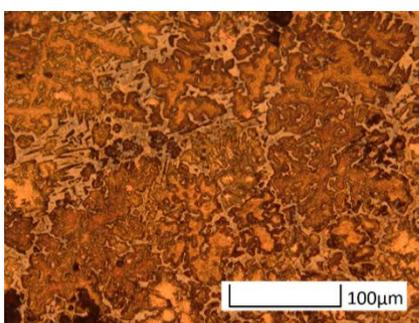


*Figure 441:* Metallograph of palstave axe 1880.16 (source: Author's own, courtesy of Royal Cornwall Museum).



*Figure 443:* Photograph of the blade of palstave axe 1880.16 (source: Author's own, courtesy of Royal Cornwall Museum).



*Figure 442:* Micrograph of the hafting striations on the septum of 1880.16 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and has received no further processing after the initial cast. This suggests that there probably was no intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the combination of prominent hafting striations within the septum and the slight asymmetry of the cutting-edge indicate that this axe has been been through at least one cycle of use, failure and sharpening. There are no damages exhibited on this palstave axe and very little is known about the deposition circumstances in which it was found.

**Publications:** [84, p. 414, No.83, Pl.10]**,** [283, p. 376]**.**

# 1909.15.3 (Royal Cornwall Museum) – Veryan, Cornwall
## Characteristic flow-chart

**Typological:**

*South-western palstave, variant Crediton*

**Manufacturing:**

*Medium (low) tin*
*Minor porosity*
*Dendritic*

**Use-wear:**

*Blunt*
*Symmetrical*
*Sharpening striations*

**Deposition:**

*Undamaged*
*Dryland*
*Single*



*Figure 444:* Photograph of palstave 1909.15.3 (source: Author's own, courtesy of Royal Cornwall Museum).
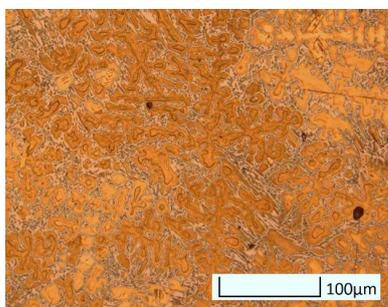


*Figure 445:* Metallograph of palstave 1909.15.3 (source: Author's own, courtesy of Royal Cornwall Museum).



*Figure 446:* Photograph of the blade of palstave 1909.15.3 (source: Author's own, courtesy of Royal Cornwall Museum).



*Figure 447:* Micrograph of the sharpening striations on the cutting-edge of palstave 1909.15.3 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be of a standard quality, and has received no further processing after the initial cast. This suggests that there probably was no intention for it to be used as a working axe. Since the blade is symmetrical, and microscopy was not possible due to corrosion, it is not possible to determine whether the axe has been used. There may be some evidence for sharpening at the cutting-edge. This axe displays no damages and was found in 1834 on the site of an old hedge.

**Publications:** [60, p. 300, No. 459], [84, p. 428, No. 147b], [296, p. 310].

## 1909.74 (Royal Cornwall Museum) – North Crofty, Cornwall
### Characteristic flow-chart



*Figure 448:* Photograph of palstave axe 1909.74 (source: Author's own, courtesy of Royal Cornwall Museum).

*Typological:*
*South-western palstave, variant Crediton*

*Manufacturing:*
*High tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding in some crystals*

*Use-wear:*
*Sharp*
*Slight asymmetry*
*Depression*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Single*
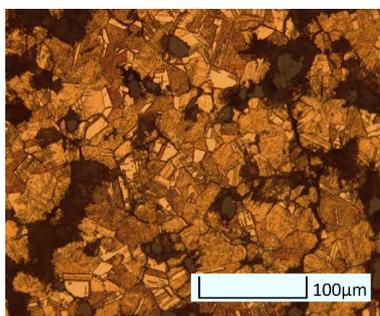


*Figure 449:* Metallograph of palstave axe 1909.74 (source: Author's own, courtesy of Royal Cornwall Museum).



*Figure 450:* Photograph of the blade of palstave axe 1909.74 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was probably intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the slight asymmetry of the cutting-edge and area of depression indicate that is almost definitely experienced one cycle of use and then has failed and then, perhaps, has been resharpened to permit further use. There are no further damages exhibited on the axe. This artefact was dug up in a field by a miner, and a rapier was also found in the same field at another time.

**Publications:** [60, p. 226, No.16], [84, p. 411, No. 68b, Pl. 7]**,** [296, p. 299]**.**

## 1910.21 (Royal Cornwall Museum) – Truro, Cornwall
### Characteristic flow-chart

*Typological:*
*South-western palstave, variant Crediton*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding throughout sample*
*Deformed crystals*

*Use-wear:*
*Blunt*
*Symmetrical*
*No micrograph*

*Deposition:*
*Post-depositional damage*
*Dryland Group*



*Figure 451:* Photograph of palstave axe 1910.21 (source: Author's own, courtesy of Royal Cornwall Museum).
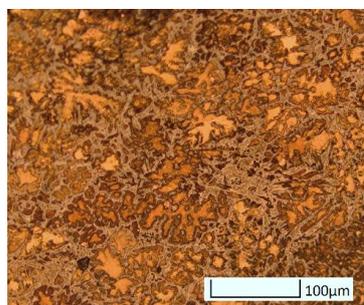


*Figure 452:* Metallograph of palstave axe 1910.21 (source: Author's own, courtesy of Royal Cornwall Museum).



*Figure 453:* Photograph of the blade of palstave axe 1910.21 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was probably intention for it to be used as a working axe. Since the blade is symmetrical (and microscopy was not possible due to corrosion), it is not possible to determine whether the axe has been used. The flanges have fractured away – this is most likely due to the severe corrosive attack that has taken place over the majority of the object. This axe was one of four palstaves (alongside 1910.22.2) found during the digging of foundations for offices at Old County Hall, Truro.

**Publications:** [60, p. 228, No. 19], [84, p. 427, No. 144, Pl 18, 135], [256, p. 80, 81, 309, fig. 22b].

## 1910.22.2 (Royal Cornwall Museum) – Truro, Cornwall
## Characteristic flow-chart

*Typological:*
*South-western*
*palstave, variant*
*Crediton*

*Manufacturing:*
*Medium (high) tin*
*No porosity*
*Dendritic*

*Use-wear:*
*Medium sharpness*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Group*



**Figure 454:** Photograph of palstave axe 1910.22.2 (source: Author's own, courtesy of Royal Cornwall Museum).
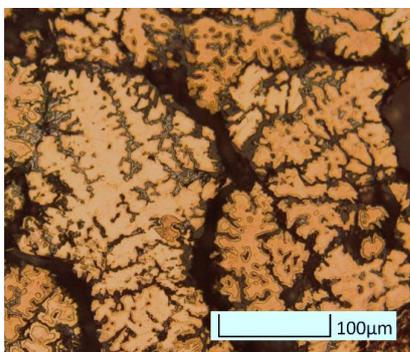


**Figure 455:** Metallograph of palstave axe 1910.22. (source: Author's own, courtesy of Royal Cornwall Museum).



**Figure 456:** Photograph of the blade of palstave axe 1910.22.2 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and has received no further processing after the initial cast. This suggests that there probably was no intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity, however, since the blade is symmetrical (and microscopy was not possible due to corrosion and regrinding), it is not possible to determine whether the axe has been used. Though, it seems unlikely due to the microstructure. This axe was one of four palstaves (alongside 1910.21) found during the digging of foundations for offices at Old County Hall, Truro.

**Publications:** [33, p. 228, No. 19], [55, p. 427, No. 144, Pl 18, 135]**,** [295, p. 80, 81, 309, fig. 22b]**.**

## 1919.9.5 (Royal Cornwall Museum) – Lanherne, Cornwall
### Characteristic flow-chart

*Typological:*
*South-western palstave, variant Crediton*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Dendritic*

*Use-wear:*
*Sharp*
*Slight asymmetry*
*Not finished*

*Deposition:*
*Deliberate damage*
*Dryland*
*Group*



**Figure 457:** Photograph of palstave axe 1919.9.5 2 (source: Author's own, courtesy of Royal Cornwall Museum).
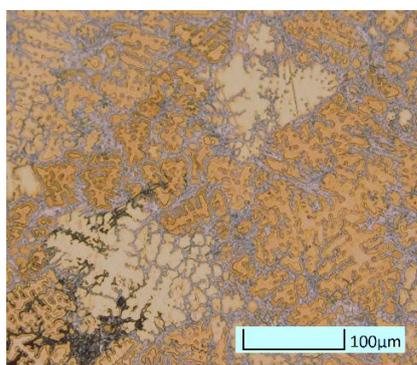


**Figure 458:** Metallograph of palstave axe 1919.9.5 2 (source: Author's own, courtesy of Royal Cornwall Museum).



**Figure 459:** Photograph of the blade of palstave axe 1919.9.5 2 (source: Author's own, courtesy of Royal Cornwall Museum).



**Figure 460:** Micrograph of the unfinished surface of palstave axe 1919.9.5 2 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has received no further processing after the initial cast. This suggests that there probably was no intention for it to be used as a working axe. It is likely that this axe was not finished, sharpened, or used. Though the cutting-edge is slightly asymmetrical, this looks more like a casting defect than a result of re-sharpening. Furthermore, the mottled appearance of the surface of the blade under the microscope suggest that this axe was not prepared for use. It appears that this axe was deliberately damaged; the blade is broken below the stopridge (there are visible blow marks here), and the blade and the hafting plate have been refitted. The end portion of the butt is missing, and since the patination is consistent, it is likely that this has also been deliberately removed. This axe was part of a large find said to contain palstaves, a rapier, part of a saw, a bar of bronze, and several socketed axes (said to be of Breton type). The hoard was found in 1813 in just above tin stream.

**Publications:** [60, p. 300, No. 451], [66, pp. 116, 184], [84, p. 417, No 93c]**,** [283, p. 3]**,** [296, pp. 89, 92, 164–5, 181, 303, 309], [337, pp. 337–8], [338, p. 354].

# 1893.2.1 (Dorset County Museum) – Rew, Dorset
## Characteristic flow-chart



**Figure 461:** Photograph of palstave axe 1893.2.1 (source: courtesy of Dorset County Museum).

*Typological:*
*Transitional palstave, looped*

*Manufacturing:*
*Medium (high) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding throughout sample*

*Use-wear:*
*Sharp*
*Slight asymmetry*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown associations*
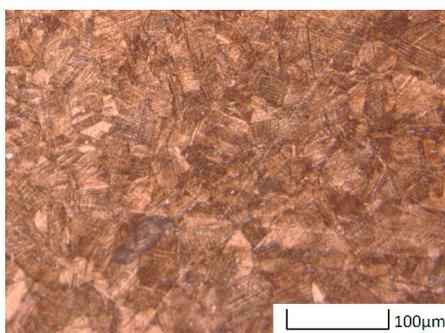


**Figure 462:** Metallograph of palstave axe 1893.2.1 (source: courtesy of Dorset County Museum).



**Figure 463:** Photograph of the blade of palstave axe 1893.2.1 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the slight asymmetry suggests that the axe has gone through at least one cycle of use, failure, and sharpening. Although, it is difficult to say this for certain, as the axe appears to have been significantly sharpening during modern regrinding.  Very little is known about the deposition circumstances of this axe.

**Publications:** [84, p. 493, Pl 63, no. 512].

## 1902.1.1 (Dorset County Museum) – Unknown
### Characteristic flow-chart

*Typological:*
*Transitional palstave*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Dendritic*

*Use-wear:*
*Blunt*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Group*



*Figure 464:* Photograph of palstave axe 1902.1.1 (source: courtesy of Dorset County Museum).
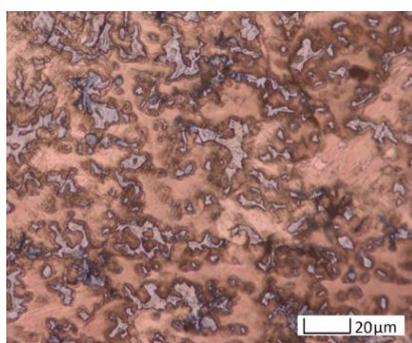


*Figure 465:* Metallograph of palstave axe 1902.1.1 (source: courtesy of Dorset County Museum).



*Figure 466:* Photograph of the blade of palstave axe 1902.1.1 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has not received any further processing after the initial cast. This suggests that the axe had not been subjected to full manufacturing yet, and that, perhaps, there was little intention for the axe to be used as working axe. The cutting-edge is blunt and symmetrical, thus, further corroborating the idea that this axe was not finished, sharpened, or used. One of five (the others of which, 1902.1.2, 1902.1.3, 1902.1.4 and 1902.1.5, are included in this study), found in a field near Turnpike Road, Dewlish Hill.

**Publications**: [60, p. 231. Pl. 7, No. 31], [84, p. 468. No. 369].

## 1902.1.2 (Dorset County Museum) – Unknown
### Characteristic flow-chart

*Typological:*

*Transitional palstave*

*Manufacturing:*

*High tin*

*Severe porosity*

*Dendritic*

*Use-wear:*

*Medium sharpness*

*Symmetrical*

*No micrograph*

*Deposition:*

*Undamaged*

*Dryland*

*Group*



**Figure 467:** Photograph of palstave axe 1902.1.2 (source: courtesy of Dorset County Museum).
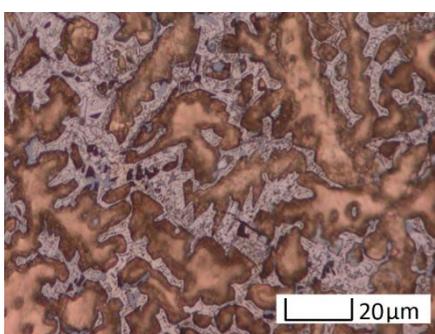


**Figure 468***: Metallograph of palstave axe 1902.1.2 (source: courtesy of Dorset County Museum).



**Figure 469:** Photograph of the blade of palstave axe 1902.1.2 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a high tin palstave axe. The metal appears to be of poor quality, and has not received any further processing. This suggests that the axe had not been subjected to full manufacturing yet, and that, perhaps, there was little intention for the axe to be used as working axe. The cutting-edge is of medium sharpness and symmetrical, thus, further corroborating the idea that this axe was not finished, sharpened, or used. One of five (the others of which, 1902.1.1, 1902.1.3, 1902.1.4 and 1902.1.5, are included in this study), found in a field near Turnpike Road, Dewlish Hill.

**Publications:** [60, p. 231. Pl. 7, No. 31], [84, p. 468. No. 369]**.**

## 1902.1.3 (Dorset County Museum) – Unknown
### Characteristic flow-chart

*Typological:*
*Transitional palstave, looped*

*Manufacturing:*
*Medium (high) tin Dendritic*

*Use-wear:*
*Sharp*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Group*



**Figure 470:** Photograph of palstave axe 1902.1.3 (source: courtesy of Dorset County Museum).
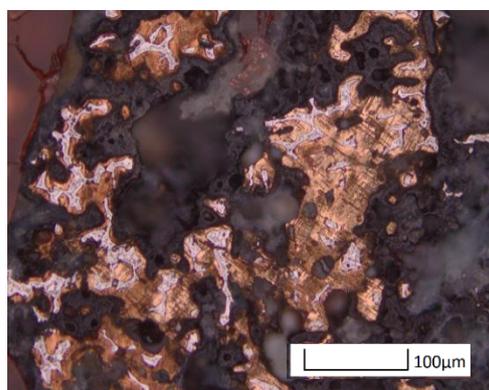


**Figure 471:** Metallograph of palstave axe 1902.1.3 (source: courtesy of Dorset County Museum).



**Figure 472:** Photograph of the blade of palstave axe 1902.1.3 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metallographic sample is very corroded, and so it is difficult to infer much about the metallurgical specifications, though it appears that the metal has not experienced any further processing after the initial cast. This suggests that the axe had not been subjected to full manufacturing yet, and that, perhaps, there was little intention for the axe to be used as working axe. Though the cutting-edge is sharp and, indeed, symmetrical, the lack of processing, and the flashing that still remains around the casting seams, suggests that this axe has probably not been completely finished and likely not, used. Very little is known about the deposition circumstances of this axe. One of five (the others of which, 1902.1.1, 1902.1.2, 1902.1.4 and 1902.1.5, are included in this study), found in a field near Turnpike Road, Dewlish Hill.

**Publications:** [60, p. 231. Pl. 7, No. 31], [84, p. 468. No. 369].

## 1902.1.5 (Dorset County Museum) – Unknown
### Characteristic flow-chart



**Typological:**

*Transitional palstave, looped*

**Manufacturing:**

*Medium (low) tin*

*Dendritic*

**Figure 473:** Photograph of palstave axe 1902.1.5 (source: courtesy of Dorset County Museum).

**Use-wear:**

*Blunt*

*Symmetrical*

*No micrograph*

**Deposition:**

*Undamaged*

*Dryland*

*Group*
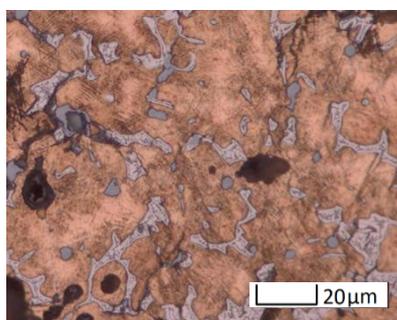


**Figure 474:** Metallograph of palstave axe 1902.1.5 (source: courtesy of Dorset County Museum).
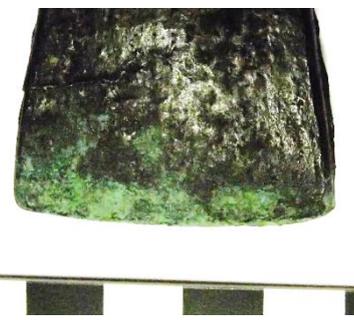


**Figure 475:** Photograph of the blade of palstave axe 1902.1.5 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metallographic sample is very corroded, and so it is difficult to infer much about the metallurgical specifications, though it appears that the metal has not experienced any further processing after the initial cast. This suggests that the axe had not been subjected to full manufacturing yet, and that, perhaps, there was little intention for the axe to be used as working axe. The cutting-edge is blunt and symmetrical, and there is flashing around the casting seams, further corroborating the idea that this axe was not finished, sharpened, or used. Very little is known about the deposition circumstances of this axe. One of five (the others of which, 1902.1.1, 1902.1.2, 1902.1.3 and 1902.1.4, are included in this study), found in a field near Turnpike Road, Dewlish Hill.

**Publications:** [60, p. 231. Pl. 7, No. 31], [84, p. 468. No. 369].

## 1948.14.2 (Dorset County Museum) – Winterborne Abbas/Eggardon, Dorset
### Characteristic flow-chart

*Typological:*
*Transitional palstave, looped*

*Manufacturing:*
*Medium (high) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Slip-banding throughout sample*

*Use-wear:*
*Medium sharpness*
*Slight asymmetry*
*No micrograph*

*Deposition:*
*Accidental damage*
*Dryland*
*Single*



*Figure 476:* Photograph of palstave axe 1948.14.2 (source: courtesy of Dorset County Museum).



20 μm
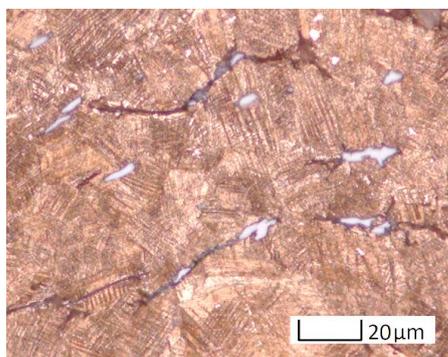
*Figure 477:* Metallograph of palstave axe 1948.14.2 (source: courtesy of Dorset County Museum).



*Figure 478:* Photograph of the blade of palstave axe 1948.14.2 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, however, due to the slight asymmetry of the blade, it is possible to say with some certainty that this axe experienced at least one cycle of use, failure, and sharpening. There is some damage to the butt – this was probably introduced in antiquity when the sprue was removed. There is also a notch on the septum that is unlikely to be intentional and is probably more related to the removal of the sprue. This axe was found near the Roman road between Winterbourne Abbas and Eggardon, though little else is known about the deposition circumstances.

**Publications:** [60, p. 303, no. 500], [84, p. 491, No. 504, Pl. 62], [283, p. 139].

## 1963.15.1 (Dorset County Museum) – Grimstone, Dorset
**Characteristic flow-chart**

*Typological:*
*Transitional*
*palstave, looped*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*
*Deformed crystals*

*Use-wear:*
*Sharp*
*Slight asymmetry*
*Depression*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Group*



**Figure 479:** Photograph of palstave axe 1963.15.1 (source: courtesy of Dorset County Museum).
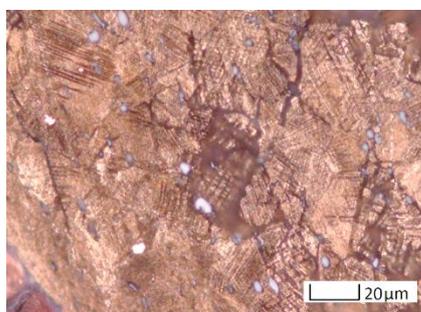


**Figure 480:** Metallograph of palstave axe 1963.15.1 (source: courtesy of Dorset County Museum).



**Figure 481:** Photograph of the blade of palstave axe 1963.15.1 (source: courtesy of Dorset County Museum).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the slight asymmetry of the cutting-edge indicates that this axe has gone through at least one cycle of use, failure, and sharpening. An area of depression also exists along the cutting-edge, which suggests that it may have failed prior to deposition. This palstave was found as part of a hoard of bronze axe-heads and rings was found digging a stanchion-pit for the railways at Grimstone in 1961, an area which has previously yielded evidence of prehistoric settlement.

**Publications:** [60, p. 232, 54, No. 34, Pl. 11], [84, p. 482, No. 445a, Pl. 56]**,** [303, p. 105].

## 10A (Museum of Somerset) - Glastonbury, Somerset
### Characteristic flow-chart

**Typological:**

*Transitional palstave, looped*

**Manufacturing:**

*Low tin*

*No porosity*

*Slag inclusions*

*Recrystallized*

*Twinned*

*Strain banding is present throughout*

**Use-wear:**

*Symmetrical*

*No micrograph*

**Deposition:**

*Accidental damage*

*Wetland*

*Single*



*Figure 482:* Photograph of palstave axe 10A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 483:* Metallograph of palstave axe 10A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 484:* Photograph of the blade of palstave axe 10A (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be of poor quality and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used in tree-felling. There is not enough data for an estimation of use-intensity after the final sharpening event, but the asymmetry of the cutting-edge may suggest that this palstave axe experienced at least one cycle of use, failure, and resharpening. The side-loop has been broken but this is unlikely to have been intentional. The axe was found within the peat of the Tubaries - many bronze implements have been recovered though their association with one another is not known.

**Publications:** [60, p. 333, no. 900], [84, p. 514-6, no. 655]**,** [280, p. 98], [283, p. 515]**,** [323].

# 75.AA.4 (Museum of Somerset) - Radstock, Somerset
## Characteristic flow-chart

*Typological:*
*Transitional*
*palstave, looped*

*Manufacturing:*
*Low tin*
*Moderate porosity*
*Recrystallized*
*Twinned*
*Strain banding is*
*present throughout*
*Deformed grains*

*Use-wear:*
*Medium sharpness*
*Moderate asymmetry*
*No micrograph*

*Deposition:*
*Undamaged*
*Dryland*
*Group*



**Figure 485:** Photograph of palstave axe 75.AA.4 (source: courtesy of Somerset County Council and south West Heritage Trust, 2020).
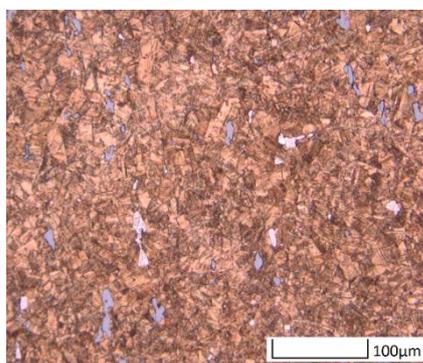


**Figure 486:** Metallograph of palstave axe 75.AA.4 (source: courtesy of Somerset County Council and south West Heritage Trust, 2020).
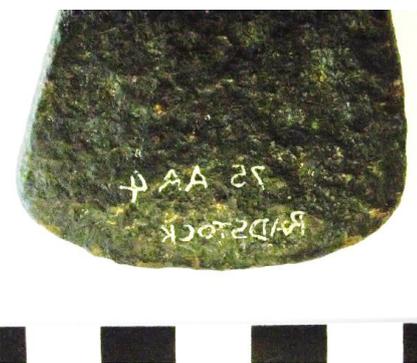


**Figure 487:** Photograph of the blade of palstave axe 75.AA.4 (source: courtesy of Somerset County Council and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be of poor quality, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used in tree-felling. There is not enough data for an estimation of use-intensity after the final sharpening event, but the moderate asymmetry of the cutting-edge suggests that the axe has experienced several cycles of use, failure, and resharpening. This axe is part of a significant Bronze Age find that was discovered in 1873 during the construction of the railway station in Midsomer Norton. It was found with a leaf-shaped and double-edged sword which has been attributed to the Wilberton phase (c.1000-850 BC). The find spot is within the river valley below the Radstock and Camerton round barrows.

**Publications:** [60, p. 332, no. 888], [84, pp. 521, No. 696, Pl. 80], [339, pp. 67–68], [340, p. 132], [341, p. 6].

## 17B (Museum of Somerset) – Sherford, Somerset
### Characteristic flow-chart

*Typological:*
*Transitional palstave, looped*

*Manufacturing:*
*Medium (high) tin*
*No micrograph*

*Use-wear:*
*Sharp*
*Symmetrical*
*Use-striations*
*Hafting striations*

*Deposition:*
*Accidental damage*
*Dryland*
*Group*



*Figure 488:* Photograph of palstave axe 17B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 489:* Photograph of the blade of palstave axe 17B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



*Figure 490:* Micrograph of the use-striations observed on the cutting-edge of palstave axe 17B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium-high tin palstave axe, however, the mounted sample has since been lost. Therefore, very little can be ascertained regarding the manufacturing specifications. The cutting-edge is sharp and appears to be very symmetrical, suggesting minimal use, if any at all. However, on further micro-level inspection it is clear that there are very distinct use-striations, while sharpening striations are not observable. While experiencing a period of high use-intensity before deposition, this axe has most likely not gone through many cycles of use and sharpening (since the blade is symmetrical). The butt has been damaged, probably when the sprue was removed. This palstave was found with five other palstaves and one spearhead by workmen digging a drain in 1879 below the surface of a lane. While this was a 'dryland' find, the location of discovery is near several streams and overlooks the River Tone to the north [283, pp. 288, 289].

**Publications:** [24, pp. 145, 179], [60, p. 258, No.117], [66, pp. 90, 330, 464], [84, pp. 534, No.753e], [283, pp. 288, 289], [342, p. GB.45].

## 1892.67.120 (Pitt Rivers) – Mettingham, Suffolk
**Characteristic flow-chart**

*Typological:*

*Transitional palstave, looped*

*Manufacturing:*

*Low tin*

*Mild porosity*

*Recrystallized*

*Twinned*

*Strain-banding at the sample exterior*

*Use-wear:*

*Blunt*

*Symmetrical*

*Hafting striations*

*Deposition:*

*Accidental damage*

*Uncertain context*

*Group*



**Figure 491:** Photograph of palstave axe 1892.67.120 (source: Author's own, courtesy of Pitt Rivers Museum).



**Figure 492:** Photograph of the blade of palstave axe 1892.67.120 (source: Author's own, courtesy of Pitt Rivers Museum).



**Figure 493:** Micrograph of the hafting striations on the septum of palstave axe 1892.67.120 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be fairly sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, but the combination of prominent hafting striations within the septum and the blunt cutting-edge suggest that this axe has been used, possibly experiencing a period of high use-intensity prior to deposition. Since the blade is symmetrical, it is not likely that this axe has gone through many cycles of use and sharpening. Only stumps remain of the side-loop, but there are no further observable damages. This is one of two palstave axes found in 1847, near the castle at Mettingham.

**Publications:** [60, p. 336, No. 941], [116, pp. 131, No.54]**,** [288, p. 361]**,** [343, p. 414]**.**

## A4148 (RAMM) - Washfield, Devon
### Characteristic flow-chart

*Typological:*
*Transitional palstave, looped*

*Manufacturing:*
*Medium (high) tin*
*Microporosity*
*Recrystallized*
*Twinned*
*Strain-banding in few crystals*

*Use-wear:*
No micrograph

*Deposition:*
*Accidental/post-depositional*
*Dryland*
*Group*



**Figure 495:** Photograph of palstave axe A4148 (source: courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).
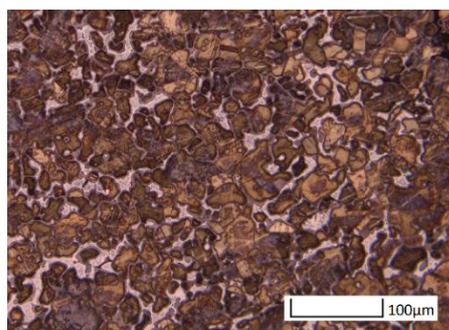


**Figure 496:** Metallograph of palstave axe A4148 (source: courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).



**Figure 494:** Photograph of the blade of palstave axe A4148 (source: courtesy of Royal Albert Memorial Museum & Art Gallery, Exeter City Council).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be mostly sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used in tree-felling. There is not enough data for an estimation of use-intensity after the final sharpening event, or to even posit whether this axe had been used at all. The cutting-edge and corner of the blade are broken, which Knight [244, pp. 255] considers to be post-depositional damage. Most of the side loop is also missing, this probably broke away in antiquity. This palstave axe was found with many associated items (now lost) at Beauchamp Farm. Knight [244, pp. 255] points out that this find spot overlooks the Exe river valley to the east and is close to many natural springs.

**Publication:** [83, pp. 229, No. 20, Pl. 31], [84, pp. 458, No. 313, Pl. 41], [107, p. 209], [283, pp. 255].

## 1962.12 (West Berkshire Museum) – Unknown, England
### Characteristic flow-chart

*Typological:*
*Transitional*
*palstave, looped*

*Manufacturing:*
*Low tin*
*Minor porosity*
*Recrystallized*
*Twinned*
*Strain-banding*
*throughout sample*

*Use-wear:*
*Blunt*
*Slight asymmetry*
*Sharpening striations*
*Use-striations*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown*
*associations*



**Figure 498:** Photograph of palstave axe 1962.12 (source: courtesy of West Berkshire Museum)**.**



**Figure 499:** Photograph of the blade of palstave axe 1962.12 (source: courtesy of West Berkshire Museum)**.**



**Figure 497:** Micrograph of the use-striations at the cutting-edge of palstave axe 1962.12 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be fairly sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. The slight asymmetry of the cutting-edge  and hafting striations within the septum indicate that this axe has gone through at least one cycle of use, failure, and sharpening. On consideration of the use-striations (which obscure sharpening striations in most places and are apparent even at x25 magnification) and bluntness of the cutting-edge, this axe has clearly experienced a period of high use-intensity prior to deposition. Very little is known about the deposition circumstances of this axe.

**Publications:** [116, pp. 13, 14, Pl. XI, XII], [278].

## 1968.68.Y3 (West Berkshire Museum) – Yattendon, Berkshire
### Characteristic flow-chart

*Typological:*
*Transitional palstave*

*Manufacturing:*
*Low tin*
*Severe porosity*
*Dendritic*

*Use-wear:*
No micrograph

*Deposition:*
*Deliberate damage*
*Dryland*
*Group*



*Figure 500:* Photograph of palstave axe 1968.63.Y3 (source: courtesy of West Berkshire Museum).



*Figure 501:* Photograph of the blade of palstave axe 1968.63.Y3 (source: courtesy of West Berkshire Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be of poor quality, and has not received any further processing. This suggests that there was little intention for it to be used as a working axe. Since the blade is no longer present and the axe is broken across the stopridge, it was not possible to conduct any use-wear analysis. The blade has most likely been broken clean off in antiquity and there are many blow marks to indicate this. The break across the stopridge probably occurred in antiquity, though it is difficult to tell if this was deliberate. The axe was found with 1968.68 Y2. In 1876, Alfred Waterhouse built a mansion, Yattendon Court, on top of the hill west of the village of Yattendon. In digging the foundations the workmen came upon a hoard of bronze objects all lying together... "the bronze object lay about 18 inches below the surface of the sod in a mass of gravel that had been turned red, purple and black by the action of fire" [301, p. 31]. Examination of the objects made it quite clear that they had not been subjected to fire. The multi-period hoard consisted of 58 pieces of metalwork in total.

**Publications:** [137, pp. 7, 8, Pl. I, IX], [301, p. 31].

## OA325 (West Berkshire Museum) – Co. Antrim, Ireland
**Characteristic flow-char**

*Typological:*
*Transitional palstave, looped*

*Manufacturing:*
*Medium (low) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding at sample exterior*

*Use-wear:*
*Sharp*
*Symmetrical*
*No micrograph*

*Deposition:*
*Undamaged*
*Uncertain context*
*Unknown associations*



*Figure 502:* Photograph of palstave axe OA325 (source: courtesy of West Berkshire Museum)**.**



*Figure 503:* Photograph of the blade of palstave axe OA325 (source: courtesy of West Berkshire Museum)**.**

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity as the blade is completely symmetrical and the cutting-edge has been reground in modern times. Very little is known about the deposition circumstances of this axe.

**Publications:** [116, pp. 16, PL. XIII, XVI], [278].

## 12C (Museum of Somerset) – Curland, Somerset
### Characteristic flow-chart

*Typological:*

*Double looped palstave*

*Manufacturing:*

*Medium (low) tin*

*No porosity*

*Recrystallized*

*Twinned*

*Strain-banding throughout sample*

*Deformed crystals*

*Use-wear:*

*Blunt*

*Symmetrical*

*Not finished*

*Deposition:*

*Undamaged*

*Uncertain context*

*Single*



**Figure 504:** Photograph of palstave axe 12C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
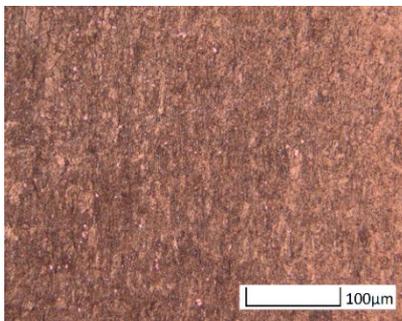


**Figure 505:** Metallograph of palstave axe 12C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 506:** Photograph of the blade of palstave axe 12C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
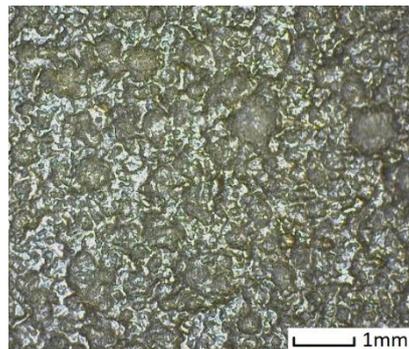


**Figure 507:** Micrograph of the unfinished surface of palstave axe 12C (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a medium (low) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was intention for it to be used as a working axe. However, the micro-scale analysis suggests that the axe has not been finished or sharpened, and has not been used. No damages have been recorded. The axe was found in 1934 when a post hole was dug in the yard of a smallholding at Mount Pleasant, Curland.

**Publications:** [60, pp. 331, No. 875, Pl. 33], [84, pp. 512, No. 645, Pl. 73], [344, p. 61, fig. 1].

## 13B (Museum of Somerset) – South Petherton, Somerset
### Characteristic flow-chart



**Figure 508:** Photograph of palstave axe 13B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
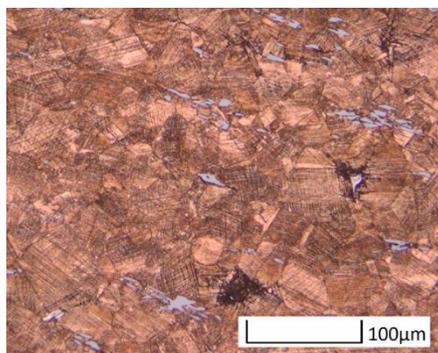
*Typological:*
*Double looped palstave*

*Manufacturing:*
*Low tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding throughout sample*
*Deformed crystals*

*Use-wear:*
*Very blunt*
*Slight asymmetry*
*Hafting striations*

*Deposition:*
*Undamaged*
*Uncertain context*
*Single*



**Figure 509**: Metallograph of the blade of palstave axe 13B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 511:** Photograph of the blade of palstave axe 13B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
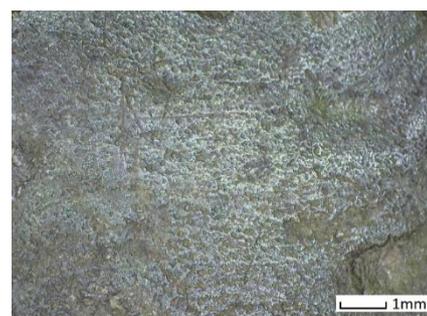


**Figure 510:** Micrograph of the hafting striations observed on the septum of palstave axe 13B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final light hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final resharpening event, however, the slightly asymmetry of the blade and the hafting striations show that this axe has certainly been used and has probably failed, and required resharpening at least once. Though, the blunt nature of the cutting-edge may suggest that there has been a period of very high use-intensity prior to deposition. Not much is known about the deposition circumstances of this axe, apart from that it was found with A331 and A332.

**Publications:** [60, pp. 332, No. 894], [84, pp. 528, No. 732c, Pl. 85], [308, p. 143], [309, p. 247], [310].

## 1919.9.6 (Royal Cornwall Museum) – Helston, Cornwall
### Characteristic flow-chart

*Typological:*
*Double-looped palstave*

*Manufacturing:*
*Low tin*
*Severe porosity*
*Recrystallized*
*Twinned*
*Strain-banding in some grains*

*Use-wear:*
*Blunt*
*Symmetrical*
*No micrograph*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Group*



*Figure 512:* Photograph of palstave axe 1919.9.6 2 (source: Author's own, courtesy of Royal Cornwall Museum).
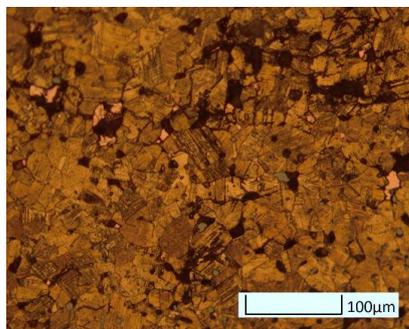


*Figure 513:* Metallograph of palstave axe 1919.9.6 2 (source: Author's own, courtesy of Royal Cornwall Museum).



*Figure 514:* Photograph of the blade of palstave axe 1919.9.6 2 (source: Author's own, courtesy of Royal Cornwall Museum).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe. The metal appears to be a poor quality, and has been hammered, annealed, and finished with a final extensive hammering. This suggests that there was probably intention for it to be used as a working axe. Since the blade is symmetrical, and microscopy was not possible due to corrosion, it is not possible to determine whether the axe has been used. The blade is broken above the stopridge (there are no visible blow marks here), the blade and the hafting plate have been refitted. The flanges are largely missing, though this typology has little flange anyway. Both side-loops are also broken. This axe was found with an assemblage of arm rings and axes at "Penrose", probably in the Helston area, though the exact find spot and circumstances are unknown.

**Publications:** [60, pp. 228, No. 18],  [66, p. 385, fig. 479], [84, pp. 409–10, No. 64, Pl. 7], [283, p. 333], [344, p. 66].

# 63B (Museum of Somerset) - Stogursey, Somerset
## Characteristic flow-chart

*Typological:*
*Narrow-bladed*
*palstave, looped*

*Manufacturing:*
*Low tin*
*No metallograph*

*Use-wear:*
*Medium*
*Symmetrical*
*Sharpening*
*striations*

*Deposition:*
*Accidental damage*
*Uncertain context*
*Single*



**Figure 515:** Photograph of palstave axe 63B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).
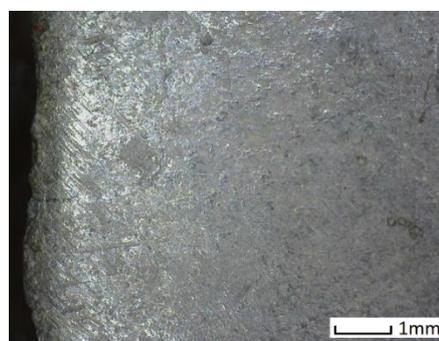


**Figure 516:** Photograph of the blade of palstave axe 63B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).



**Figure 517:** Micrograph of the sharpening striations on the cutting-edge of palstave axe 13B (source: author's own, courtesy of Somerset Archaeological and Natural History Society and south West Heritage Trust, 2020).

**Narrative:** Composition analysis has shown that this is a low tin palstave axe, however, the mounted sample has since been lost. Therefore, very little can be ascertained regarding the manufacturing specifications. Since the axe has a symmetrical cutting-edge and has evidence of sharpening-striations, it seems likely that it was either unused or prepared for deposition. It is curious that despite clear evidence of sharpening, the blade is not actually sharp. One flange wing is broken, most likely due to casting flaws [244, pp. 531, 532]. Very little is known about the deposition circumstances of this axe.

**Publications:** [283, pp. 531, 532], older references unknown due to a mistake in [84].

407

# 1884.119.136 (Pitt Rivers) – Unknown, Ireland
## Characteristic flow-chart



*Figure 518:* Photograph of palstave axe 1884.119.136 (source: Author's own, courtesy of Pitt Rivers Museum).

**Typological:**

*Narrow-bladed palstave*

**Manufacturing:**

*Medium (high) tin*
*No porosity*
*Recrystallized*
*Twinned*
*Strain-banding throughout sample*

**Use-wear:**

*Blunt*
*Hafting striations*

**Deposition:**

*Deliberate damage*
*Uncertain context*
*Unknown associations*



*Figure 519:* Photograph of the blade of palstave axe 1884.119.136 (source: Author's own, courtesy of Pitt Rivers Museum).
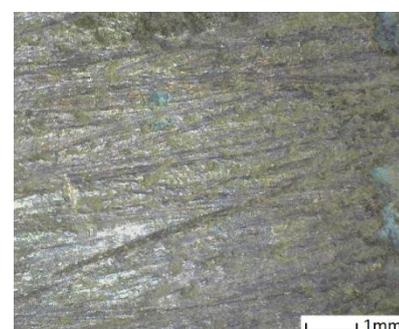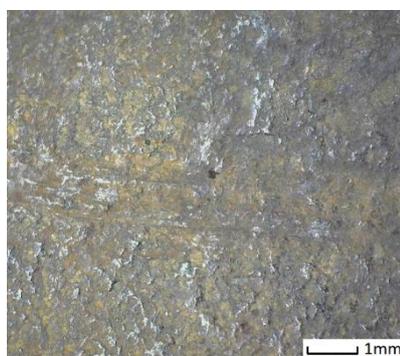


*Figure 520:* Micrograph of the hafting striations situated on the septum of palstave axe 1884.119.136 (source: Author's own, courtesy of Pitt Rivers Museum).

**Narrative:** Composition analysis has shown that this is a medium (high) tin palstave axe. The metal appears to be sound, and has been hammered, annealed, and finished with a final moderate hammering. This suggests that there was intention for it to be used as a working axe. There is not enough data for an estimation of use-intensity after the final sharpening event, however, on account of the hafting-striations, it is possible to tentatively assume this has axe been used. There is significant flattening of the cutting-edge, but the areas of deformation are not consistently patinated, possibly suggesting they were formed in modern times. A corner of the blade is missing, as well as parts of the flanges, and the end of the butt. Consistent patination exists on all areas of damage, this indicates that these areas of metal were deliberately removed in antiquity.

**Publications:** [116, pp. 135, No. 58].

Tabulated data

| Museum | Reg. no. | Primary published reference | Period cal BC | Typology | Location |
|--------|----------|------------------------------|---------------|----------|----------|
| Ash | 1927.2594 | Pearce 1983 | 1500-1250 | Gr.II palstave | Bath Street, Bristol, Somerset |
| | 1927.2567 | Pearce 1983 | 1500-1250 | Gr.II palstave | Penzance, Cornwall |
| | 1927.2571 | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | Crediton, Devon |
| | 1961.498 | Pearce 1983 | 1400-1100 | south-western palstave, looped | Wotton Glenville, Dorset |
| | 1961.497 | Pearce 1983 | 1500-1250 | Gr.I palstave | Wotton Glenville, Dorset |
| BCMaAG | E449 | Pearce 1983 | 1500-1250 | Gr.I palstave | Solsbury Hill, Bath, Somerset |
| | E456 | Unknown | 1500-1250 | Gr.I palstave | n/a Somerset |
| DCM | 1948.14.2 | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Winterborne Abbas/Eggardon, Dorset |
| | 1963.15.1 | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Grimstone, Dorset |
| | 1954.40.1 | Pearce 1983 | 1400-1100 | Gr.III palstave | Thorncombe, Dorset |
| | 1902.1.1 | Pearce 1983 | 1250-1000 | Transitional palstave | Dewlish, Dorset |
| | 1902.1.5 | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Dewlish, Dorset |
| | 1902.1.2 | Pearce 1983 | 1250-1000 | Transitional palstave | Dewlish, Dorset |

| | | | | | |
|---|---|---|---|---|---|
| | 1902.1.4 | Pearce 1983 | 1400-1100 | south-western palstave, looped | Dewlish, Dorset |
| | 1902.1.3 | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Dewlish, Dorset |
| | 1955.48 | Pearce 1983 | 1400-1100 | south-western palstave, looped | Abbotsbury, Dorset |
| | 1884.9.2 | Pearce 1983 | 1500-1250 | Gr.II palstave | Fontwell, Dorset |
| | 1884.9.3 | Pearce 1983 | 1400-1100 | Gr.III palstave | Fontwell, Dorset |
| | 1884.9.5 | Pearce 1983 | 1400-1100 | south-western palstave | Wareham, Dorset |
| | 1884.9.1 | Pearce 1983 | 1500-1250 | Gr.I palstave | Wareham, Dorset |
| | 1893.2.1 | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Rew, Dorset |
| | 1884.9.22 | Pearce 1983 | 1250-1000 | south-western palstave, variant Crediton | Dorchester, Dorset |
| **MoS** | 12A | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | Rodney Stoke, Somerset |
| | 14A | Pearce 1983 | 1400-1100 | Gr.IV palstave, looped | Ham Hill, Somerset |
| | 63B | Unknown | 1250-1000 | Narrow-bladed palstave, looped | Stogursey, Somerset |
| | 7A | Pearce 1983 | 1500-1250 | Gr.I palstave | n/a, Somerset |
| | 80C | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | Sedgemoor, Somerset |
| | 10A | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Glastonbury, Somerset |
| | 7B | Pearce 1983 | 1500-1250 | Gr.I palstave | Lyng, Somerset |

| | | | | |
|---|---|---|---|---|
| 75.AA.4 | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Radstock, Somerset |
| 14B | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | King's Sedgemoor, Somerset |
| 75B | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | Milborne Port, south Somerset |
| 81C | Pearce 1983 | 1500-1250 | Gr.I palstave | Old Ceeve, Somerset |
| 9B | Pearce 1983 | 1400-1100 | south-western palstave, looped | Ham Hill, Somerset |
| 4A | Pearce 1983 | 1500-1100 | Flanged axe | Stoke St. Michael, Somerset |
| A332 | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | south Petherton, Somerset |
| A331 | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | south Petherton, Somerset |
| 81D | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | Old Ceeve, Somerset |
| 17B | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Sherford, Somerset |
| 12C | Pearce 1983 | 1250-1100 | Double looped palstave | Curland, Somerset |
| 84B | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | Sedgemoor, Somerset |
| 13B | Pearce 1983 | 1250-1100 | Double looped palstave. | south Petherton, Somerset |
| 81B | Pearce 1983 | 1400-1100 | south-western palstave | Lyng, Somerset |
| 10B | Pearce 1983 | 1400-1100 | south-western palstave, looped | Glastonbury, Somerset |
| 8A | Pearce 1983 | 1500-1250 | Gr.I palstave | Wellington, Somerset |

| | | | | | |
|---|---|---|---|---|---|
| | 41B | *Pearce 1983* | *1400-1100* | *south-western palstave, looped* | *Taunton, Somerset* |
| ***RAMM*** | 11/1974 | *Pearce 1983* | *1400-1100* | *south-western palstave, looped* | *Bridford, Devon* |
| | 45/1955/1 | *Pearce 1983* | *1400-1100* | *Gr. III palstave* | *Chagford, Devon* |
| | 354/1906/1 | *Pearce 1983* | *1400-1100* | *south-western palstave, variant Crediton* | *Week, Devon* |
| | 355/1906 | *Pearce 1983* | *1400-1100* | *south-western palstave, looped* | *Week, Devon* |
| | A306 | *Pearce 1983* | *1500-1250* | *Gr.I palstave* | *Honiton, Devon* |
| | A320 | *Pearce 1983* | *1500-1100* | *Gr.I palstave* | *Drewsteignton, Devon* |
| | 1113/1912 | *Pearce 1983* | *1500-1250* | *Gr.I palstave* | *Shebbear, Devon* |
| | A6462 | *Pearce 1983* | *1400-1100* | *Gr.III palstave, looped* | *Cullompton, Devon* |
| | 1897/7/6 | *Pearce 1983* | *1400-1100* | *south-western palstave, looped* | *Bovey Tracey, Devon* |
| | 593/2005 | *Pearce 1983* | *1400-1100* | *south-western palstave* | *Colyton, Devon* |
| | A1951 | *Pearce 1983* | *1400-1100* | *south-western palstave, looped* | *Colyton, Devon* |
| | A1952 | *Pearce 1983* | *1400-1100* | *south-western palstave* | *Colyton, Devon* |
| | 102/1970 | *Pearce 1983* | *1400-1100* | *south-western palstave, looped* | *Caton, Devon* |
| | 130/1979 | *Pearce 1983* | *1400-1100* | *Gr.III palstave* | *Upottery, Devon* |
| | 70/1974 | *Pearce 1983* | *1400-1100* | *Gr.III palstave* | *Unknown* |

| | A289 | Pearce 1983 | 1400-1100 | Gr.III palstave | Rockbeare, Devon |
|---|---|---|---|---|---|
| | A4148 | Pearce 1983 | 1250-1000 | Transitional palstave, looped | Washfield, Devon |
| | A4214 | Pearce 1983 | 1400-1100 | south-western palstave, looped | Bovey Tracey, Devon |
| | A6158 | Pearce 1983 | 1500-1250 | Gr.I palstave | Thorverton, Devon |
| | 1891/2/7 | Pearce 1983 | 1500-1250 | Gr.I palstave | Chagford, Devon |
| | 1891/2/6 | Pearce 1983 | 1500-1250 | Gr.II palstave | Chagford, Devon |
| | 10/1980 | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | Dawlish, Devon |
| | 50/1971 | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | Tiverton, Devon |
| | 60/1954 | Pearce 1983 | 1400-1100 | Gr.III palstave, looped | Hemyock, Devon |
| *RMoC* | 1910.22 2 | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | Truro, Cornwall |
| | 1910.21 | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | Truro, Cornwall |
| | 9.1919.5 | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | Lanherne, Cornwall |
| | 1909.15.3 | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | Veryan, Cornwall |
| | 1880.16 | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | Lelant, Cornwall |
| | 1974.10.1 | Pearce 1983 | 1400-1100 | south-western palstave | St. Mellion, Cornwall |
| | 9.1919.6 | Pearce 1983 | 1250-1000 | Double looped palstave | Helston, Cornwall |

| | 1909.74 | Pearce 1983 | 1400-1100 | south-western palstave, variant Crediton | North Crofty, Cornwall |
|---|---|---|---|---|---|

*Table 37:* Table containing the chronological, typological, and contextual data for the south-west palstaves.

| Museum | Reg. no. | Primary published reference | Period cal BC | Typology | Location |
|---|---|---|---|---|---|
| PR | 1884.119.105 | Allen et al. 1970 | 1400-1100 | Gr.III palstave | Worstead Common, Norfolk |
| | 1884.119.106 | Allen et al. 1970 | 1400-1100 | Gr.III palstave, looped | Suffolk |
| | 1884.119.108 | Rowlands 1976 | 1500-1250 | Gr. I palstave | Holme, Cambridgeshire |
| | 1884.119.113 | Rowlands 1976 | 1500-1250 | Gr. II palstave | Thames, Wandsworth, London |
| | 1884.119.114 | Rowlands 1976 | 1400-1100 | south-western palstave, variant Crediton | Weyhill, Andover |
| | 1884.119.12 | Rowlands 1976 | 1400-1100 | Irish palstave | Ireland |
| | 1884.119.135 | Allen et al. 1970 | 1400-1100 | Gr.III palstave | Ireland |
| | 1884.119.136 | Rowlands 1976 | 1250-1000 | Narrow-bladed palstave | Ireland |
| | 1892.67.120 | Rowlands 1976 | 1250-1000 | Transitional palstave, looped | Mettingham, Suffolk |
| | 1892.67.121 | Rowlands 1976 | 1400-1100 | Gr.III palstave | Cambridge Fens |
| | 1892.67.86 | Rowlands 1976 | 1400-1100 | Gr.III palstave | Suffolk |

| | 1904.31.2 | Rowlands 1976 | 1400-1100 | Gr.III palstave, looped | Tackley, Oxfordshire |
|---|---|---|---|---|---|
| **RBM** | 1962.12 | Coghlan 1970 | 1250-1000 | Transitional palstave, looped | England |
| | OA331 | Coghlan 1970 | 1400-1100 | Gr.III palstave | Ireland |
| | OA325 | Coghlan 1970 | 1250-1000 | Transitional palstave, looped | Co. Antrim, Ireland |
| | OA324 | Coghlan 1970 | 1500-1250 | Gr. I palstave | Weybridge, Surrey |
| | OA322 | Coghlan 1970 | 1500-1100 | Flanged axe | Ireland |
| | OA264 | Rowlands 1976 | 1500-1250 | Gr. II palstave | Newbury, Berkshire |
| | OA351 | Coghlan 1970 | 1500-1100 | Flanged axe | Ireland |
| | OA93 | Coghlan 1970 | 1500-1100 | Flanged axe | Ireland |
| | OA265 | Rowlands 1976 | 1500-1250 | Gr. II palstave | Speen, Berkshire |
| | OA63 | Rowlands 1976 | 1500-1250 | Gr. II palstave | Weybridge, Surrey |
| | 1968.68.Y2 | Coghlan 1970b | 1500-1250 | Gr. II palstave | Yattendon, Berkshire |
| | 1968.63.Y3 | Coghlan 1970b | 1250-1000 | Transitional palstave | Yattendon, Berkshire |

*Table 38:* Table containing the chronological, typological, and contextual data for the Coghlan palstaves.

| Museum | Reg. no. | Corrosion | Modern cleaning | Macro use-wear analysis completed | Micro use-wear analysis completed |
|---|---|---|---|---|---|
| Ash | 1927.2594 | Some pitting corrosion, greeny-brown patina | Yes | Yes | Yes |
| | 1927.2567 | Good condition, bronzey sheen | Yes | Yes | No |
| | 1927.2571 | Corrosion pitting, red-brown patina | No | Yes | No |
| | 1961.498 | Badly corroded, orange-green patina | No | Yes | No |
| | 1961.497 | Some pitting corrosion, brown patina | Yes | Yes | Yes |
| BCMaAG | E449 | Corrosion pitting, bronzey sheen | Yes | Yes | No |
| | E456 | Badly corroded, greeny-brown patina | No | Yes | No |
| DCM | 1948.14.2 | Good condition, bronzey sheen | Yes | Yes | Yes |
| | 1963.15.1 | Corrosion pitting, light greeny-brown patina | Yes | Yes | Yes |
| | 1954.40.1 | Corrosion pitting, light green patina | Yes | Yes | Yes |
| | 1902.1.1 | Some corrosion pitting, dark brown patina | Yes | Yes | No |
| | 1902.1.5 | Some corrosion pitting, dark brown patina | No | Yes | No |
| | 1902.1.2 | Some corrosion pitting, dark brown patina | Yes | Yes | Yes |
| | 1902.1.4 | Badly corroded, grey-green patina | Yes | Yes | Yes |
| | 1902.1.3 | Some corrosion pitting, dark brown patina | Yes | Yes | No |

| | | | | | |
|---|---|---|---|---|---|
| | 1955.48 | Badly corroded, greeny-brown patina | No | Yes | Yes |
| | 1884.9.2 | Good condition, dark brown patina | Yes | Yes | Yes |
| | 1884.9.3 | Some corrosion pitting, dark brown patina | Yes | Yes | Yes |
| | 1884.9.5 | Badly corroded, dark greeny-brown patina | No | No | Yes |
| | 1884.9.1 | Some corrosion pitting, grey-green patina | No | Yes | Yes |
| | 1893.2.1 | Some corrosion pitting, bronzey sheen | Yes | Yes | No |
| | 1884.9.22 | Corrosion pitting, grey-green patina | No | Yes | No |
| MoS | 12A | Some corrosion pitting, dark brown patina | No | Yes | Yes |
| | 14A | Some corrosion pitting, dark brown patina | Yes | Yes | No |
| | 63B | Some corrosion pitting, green patina | No | Yes | Yes |
| | 7A | Good condition, brown patina | No | Yes | Yes |
| | 80C | Some corrosion pitting, grey-green patina | Yes | Yes | No |
| | 10A | Some pitting corrosion, greeny-brown patina | Yes | Yes | No |
| | 7B | Badly corroded, greeny-brown patina | No | Yes | No |
| | 75.AA.4 | Some corrosion pitting, dark brown patina | Yes | Yes | No |
| | 14B | Good condition, light greeny-brown patina | No | Yes | Yes |

| | 75B | Good condition, light greeny-brown patina | Yes | Yes | Yes |
|---|---|---|---|---|---|
| | 81C | Good condition, light greeny-brown patina | Yes | Yes | No |
| | 9B | Corrosion pitting, greeny-brown patina | No | Yes | Yes |
| | 4A | Some corrosion pitting, light green patina | No | Yes | No |
| | A332 | Badly corroded, light green patina | No | Yes | Yes |
| | A331 | Corrosion pitting, light green patina | No | No | No |
| | 81D | Good condition, light grey-green patina | No | Yes | Yes |
| | 17B | Good condition, grey-green patina | No | Yes | Yes |
| | 12C | Good condition, dark brown patina | No | Yes | Yes |
| | 84B | Some corrosion pitting, grey brown patina | Yes | Yes | Yes |
| | 13B | Badly corroded, green patina | No | Yes | Yes |
| | 81B | Good condition, dark brown patina | Yes | Yes | No |
| | 10B | Some corrosion pitting, dark brown patina | No | Yes | Yes |
| | 8A | Corrosion pitting, light brown patina | Yes | Yes | No |
| | 41B | Corrosion pitting, dark brown patina | Yes | Yes | Yes |
| **RAMM** | 11/1974 | Corrosion pitting, green patina | No | Yes | No |

| | | | | | |
|---|---|---|---|---|---|
| | 45/1955/1 | Some pitting corrosion at blade, brown patina | Yes | Yes | No |
| | 354/1906/1 | Corrosion pitting, green patina | Yes | No | Yes |
| | 355/1906 | Corrosion pitting, green patina | Yes | Yes | Yes |
| | A306 | Corosion pitting, brown patina | No | Yes | No |
| | A320 | Badly corroded, green patina | No | Yes | No |
| | 1113/1912 | Good condition, brown patina | No | Yes | Yes |
| | A6462 | Corrosion pitting, green-brown patina | No | Yes | No |
| | 1897/7/6 | Corrosion pitting, light green patina | No | Yes | No |
| | 593/2005 | Corrosion pitting only on butt, dark brown patina | No | Yes | Yes |
| | A1951 | Corrosion pitting, dark greeny-brown patina | No | Yes | Yes |
| | A1952 | Badly corroded, green patina | No | No | No |
| | 102/1970 | Badly corroded, green patina | No | Yes | No |
| | 130/1979 | Corrosion pitting,  green patina | Yes | No | No |
| | 70/1974 | Corrosion pitting, dark brown patina | Yes | Yes | No |
| | A289 | Corrosion pitting, green patina | No | Yes | Yes |
| | A4148 | Badly corroded, dark greeny-brown patina | No | No | No |

| | | | | | |
|---|---|---|---|---|---|
| | A4214 | *Corrosion ptting, dark green patina* | *No* | *Yes* | *No* |
| | A6158 | *Corrosion pitting, dark brown patina* | *Yes* | *Yes* | *No* |
| | 1891/2/7 | *Badly corroded, dark brown patina* | *No* | *Yes* | *Yes* |
| | 1891/2/6 | *Corrosion pitting, dark greeny-brown patina* | *No* | *Yes* | *Yes* |
| | 10/1980 | *Corrosion pitting, light green patina* | *No* | *Yes* | *No* |
| | 50/1971 | *Corrosion pitting, dark greeny-brown patina* | *No* | *No* | *No* |
| | 60/1954 | *Badly corroded, dark greeny-brown patina* | *No* | *Yes* | *Yes* |
| **RMoC** | 1910.22 2 | *Corrosion pitting, bronzey sheen* | *Yes* | *Yes* | *No* |
| | 1910.21 | *Corrosion pitting, bronzey sheen* | *Yes* | *Yes* | *No* |
| | 9.1919.5 | *Good condition, browny-purple patina* | *No* | *Yes* | *Yes* |
| | 1909.15.3 | *Good condition, dark greeny-brown patina* | *No* | *Yes* | *Yes* |
| | 1880.16 | *Corrosion pitting, grey-green patina* | *Yes* | *Yes* | *No* |
| | 1974.10.1 | *Badly corroded, grey-green patina* | *No* | *Yes* | *No* |
| | 9.1919.6 | *Badly corroded, greeny-brown patina* | *No* | *Yes* | *No* |
| | 1909.74 | *Corrosion pitting, bronzey sheen* | *Yes* | *Yes* | *No* |

***Table 39:*** Table containing the data regarding the condition of the south-west sample and their suitability for different types of analysis

| Museum | Reg. no. | Corrosion | Modern cleaning | Macro use-wear analysis completed | Micro use-wear analysis completed |
|--------|----------|-----------|-----------------|-----------------------------------|-----------------------------------|
| PR | 1884.119.105 | Corrosion pitting, dark brown patina | Yes | Yes | Yes |
| | 1884.119.106 | Good condition, dark brown patina | yes | Yes | No |
| | 1884.119.108 | Corrosion pitting, bronzey sheen | Yes | Yes | Yes |
| | 1884.119.113 | Badly corroded, dark greeny-brown patina | No | Yes | Yes |
| | 1884.119.114 | Some corrosion pitting, greeny-brown patina | No | Yes | No |
| | 1884.119.12 | Good condition, bronzey sheen | Yes | Yes | No |
| | 1884.119.135 | Some pitting corrosion, dark brown patina | Yes | Yes | Yes |
| | 1884.119.136 | Some pitting corrosion, dark brown patina | No | Yes | Yes |
| | 1892.67.120 | Badly corroded, light greeny-brown | No | Yes | No |
| | 1892.67.121 | Corrosion pitting, brown patina | Yes | No | No |
| | 1892.67.86 | Corrosion pitting, bronzey sheen | Yes | Yes | No |
| | 1904.31.2 | Badly corroded, greeny-brown patina | No | Yes | No |
| RBM | 1962.12 | Some pitting corrosion, greny-brown patina | No | Yes | No |

| | | | | | |
|---|---|---|---|---|---|
| | OA331 | Good condition, bronzey sheen | Yes | Yes | No |
| | OA325 | Good condition, bronzey sheen | Yes | Yes | No |
| | OA324 | Good condition, bronzey sheen | No | Yes | No |
| | OA322 | Some pitting corrosion, brown patina | Yes | Yes | No |
| | OA264 | Good condition, greeny-brown patina | No | Yes | No |
| | OA351 | Some corrosion pitting, brown patina | Yes | No | Yes |
| | OA93 | Good condition, bronzey sheen | Yes | Yes | Yes |
| | OA265 | Some pitting corrosion, dark brown patina | No | Yes | No |
| | OA63 | Good condition, light greeny-brown patina | No | Yes | Yes |
| | 1968.68.Y2 | Badly corroded, green patina | Yes | Yes | No |
| | 1968.63.Y3 | Some pitting corrosion, bronzey sheen | No | Yes | No |

*Table 40:* Table containing the data regarding the condition of the Coghlan sample and their suitability for different types of analysis.

| Museum | Museum no. | %Cu | %Sn | %As | %Pb | Unetched | Etched |
|--------|-----------|-----|-----|-----|------|----------|--------|
| Ash | 1927.2594 | 84.59 | 14.06 | 0.39 | 0.13 | Drilled sample | Drilled sample |
| | 1927.2567 | 84.49 | 14.09 | 0.62 | 0.38 | Drilled sample | Drilled sample |
| | 1927.257 | 87.18 | 12.24 | tr | tr | Drilled sample | Drilled sample |
| | 1961.498 | 84.33 | 14.79 | 0.35 | - | Drilled sample | Drilled sample |
| | 1961.497 | 89.34 | 10.50 | 0.13 | tr | Drilled sample | Drilled sample |
| BCMaAG | E449 | 88.27 | 11.73 | - | 2.20 | Drilled sample | Drilled sample |
| | E456 | 88.03 | 11.97 | - | - | Drilled sample | Drilled sample |
| DCM | 1948.14.2 | 85.24 | 13.40 | 0.33 | 0.10 | No porosity. Crack. Copper oxide is in the form of long stringers. | Recrystallized, twinning crystals. Many strain lines and grains are quite misshapen. |
| | 1963.15.1 | 86.26 | 12.29 | 0.42 | 0.14 | No porosity. Copper oxide is globular in form. | Recrystallized, twinned crystals. Most grains contain strain lines. Grains are misshapen. |
| | 1954.40.1 | 88.79 | 9.70 | 0.81 | 0.22 | No porosity. A few areas of globular copper oxide. | Recrystallized. All grains contain strain lines. |

| | | | | | | |
|---|---|---|---|---|---|---|
| *1902.1.1* | *86.79* | *11.87* | *0.28* | *0.07* | *No porosity. Globular copper oxide present in considerable amounts. Some cracks internally.* | *Dendritic - fairly fine dendrites.* |
| *1902.1.5* | *87.58* | *11.39* | *0.25* | *0.13* | *Big globular oxide inclusions.* | *Dendritic - coarse structure. Many pinky inclusions.* |
| *1902.1.2* | *82.70* | *15.67* | *0.36* | *0.37* | *A few big pores. Globular copper oxide network.* | *Dendritic - dendrites have been deformed.* |
| *1902.1.4* | *84.33* | *14.00* | *0.64* | *0.09* | *No porosity. Globular copper oxide.* | *Recrystallized twinned grains. Strain-banding is present in some grains.* |
| *1902.1.3* | *78.59* | *12.50* | *0.48* | *8.10* | *n/a too corroded* | *Possibly dendritic* |
| *1955.48* | *85.11* | *13.37* | *0.51* | *0.26* | *No porosity. Big crack down middle of sample. Globular copper oxide.* | *Recrystallized twinned grains. Dense strain lines.* |
| *1884.9.2* | *84.21* | *14.75* | *0.40* | *-* | | *Recrystallized twinned crystals. Strain lines are present in some grains.* |

| | 1884.9.3 | 81.07 | 17.82 | 0.39 | - | Network of micro-porosity. Very small stringers of copper oxide. | Recrystallized twinned grains. Not many strain lines in grains on one side, much more dense strain lines in grains on other side. |
|---|---|---|---|---|---|---|---|
| | 1884.9.5 | 86.19 | 12.68 | 0.30 | 0.12 | Pores that have been hammered down into cracks. Stringers of copper oxide that have been hammered. | Recrystallized twinned grains. Many strain lines are present, grain is misshapen. |
| | 1884.9.1 | 84.14 | 14.53 | 0.31 | 0.13 | No porosity. Copper oxide slightly elongated. | Recrystallized twinned grains. Lots of strain lines in grains. |
| | 1893.2.1 | 86.48 | 12.91 | 0.27 | 0.08 | No porosity. Copper oxide inclusions have been elongated into stringers. | Recrystallized twinned grains. Lots of strain lines. |
| | 1884.9.22 | 81.52 | 16.94 | 0.58 | 0.15 | A fair bit of porosity. Globular copper oxide is present. | Recrystallized twinned grains. Strain lines are present. |
| MoS | 12A | 83.79 | 14.87 | 0.45 | 0.33 | Possibly a long stringer of copper sulphide running down centre. | Recrystallized, twinned microstructure. Many strain lines are prevalent. |

| | | | | | | |
|---|---|---|---|---|---|---|
| 14A | 83.78 | 14.91 | 0.45 | 0.19 | No porosity. Copper oxide stringers. | Recrystallized twinned microstructure. Crystals exhibit many strain lines and are very deformed. |
| 63B | 78.01 | 10.65 | 0.26 | 10.80 | Sample lost | Sample lost |
| 7A | 87.91 | 11.83 | 0.09 | 0.03 | No porosity. Areas where slag inclusions have been deformed by hammering. Copper oxide stringers. | Recrystallized microstructure. Crystals exhibit many strain lines and are very deformed. |
| 80C | 85.46 | 13.19 | 0.62 | 0.23 | No porosity. A big glassy slag inclusion. Globular copper oxide inclusions. | Recrystallized microstructure. Many strain lines and many grains are very deformed. |
| 10A | 89.57 | 10.06 | 0.25 | 0.03 | Two big pieces of slag. Copper oxide inclusions are stringer-like. | Recrystallized twinned microstructure. Many crystals exhibit strain lines. |
| 7B | 83.14 | 12.66 | 0.64 | 3.10 | Network of micro pores. Big slag inclusions. Globular copper oxide inclusions. | Recrystallized, twinned microstructure. All grains have strain lines, some are very deformed. |

| | | | | | | |
|---|---|---|---|---|---|---|
| 75.AA.4 | 79.35 | 8.23 | 0.24 | 11.50 | A few moderately sized pores and microporosity. Copper oxide stringers. | Recrystallized twinned microstructure. All crystals exhibit strain lines and some near exterior are completely deformed. |
| 14B | 84.43 | 14.34 | 0.43 | 0.21 | One big pore. Copper oxide stringers. | Recrystallized twinned microstructure. Very deformed crystals. |
| 75B | 81.79 | 14.00 | 0.32 | 0.51 | Slight porosity. Copper oxide globules present. | Recrystallized microstructure. Crystals are very deformed. |
| 81C | 85.06 | 13.27 | 0.71 | 0.61 | No porosity. Big slag inclusion that has been elongated. Copper oxide stringers. | Recrystallized microstructure. Most crystals have lost shape and all have strain lines. |
| 9B | 85.11 | 13.38 | 0.31 | 0.37 | No porosity. Globular copper oxide is present. | Could be dendritic or possibly just have a lot of eutectoid - difficult to tell. |
| 4A | 84.87 | 14.44 | 0.34 | tr | No porosity. Few copper oxide inclusions, but they are of a large size. | Recrystallized, twinned microstructure. Lots of strain lines. |

| | | | | | | |
|---|---|---|---|---|---|---|
| A332 | 84.37 | 14.65 | 0.38 | 0.06 | Moderate porosity. Globular copper oxide is present. | Recrystallized, twinned microstructure. Some strain-banding near exterior of sample and crystals deformed near the edge. |
| A331 | 88.71 | 10.30 | 0.38 | tr | Minor porosity. Globular copper oxide is present. | Recrystallized, twinned microstructure. Strain-banding in all crystals and many are deformed. |
| 81D | 88.89 | 9.61 | 0.18 | 0.40 | No porosity. | Looks to be in a dendritic form but hard to tell. |
| 17B | 84.42 | 12.81 | 0.41 | 0.16 | Sample lost | Sample lost |
| 12C | 87.81 | 11.56 | 0.15 | 0.09 | No porosity. Copper oxide stringers. | Recrystallized twinned microstructure. Crystals are deformed towards one side of the sample. |
| 84B | 83.78 | 14.84 | 0.35 | 0.16 | No porosity. Copper oxide stringers. | Recrystallized twinned microstructure. |
| 13B | 91.15 | 8.41 | 0.32 | - | Copper oxide inclusions are present. | Recrystallized twinned microstructure. Crystals are completely deformed. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 81B | 84.66 | 14.11 | 0.32 | 0.25 | No porosity. Copper oxide is visible in a globular form. | Recrystallized twinned microstructure. Grains have many strain lines and are deformed in places. |
| | 10B | 87.84 | 11.79 | 0.08 | 0.07 | Some small pores. Copper oxide inclusions are stringer-like. | Recrystallized twinned microstructure. Most grains contain strain lines - many are deformed. |
| | 8A | 85.17 | 14.67 | 0.07 | 0.03 | No porosity. Very tiny copper oxide inclusions. | Recrystallized, twinned microstructure. Strain lines throughout most of sample. |
| | 41B | 84.07 | 14.43 | 0.63 | 0.15 | Sample lost | Sample lost |
| RAMM | 11/1974 | 84.68 | 14.61 | 0.20 | 0.05 | Minor porosity. Stringers of copper oxide are present. | Recrystallized, twinned microstructure. Strain-banding throughout sample. |
| | 45/1955/1 | 86.52 | 13.09 | 0.28 | - | No porosity. Small copper oxide stringers are present. | Recrystallized, twinned grains microstructure. Strain-banding throughout sample. |
| | 354/1906/1 | 85.01 | 14.56 | 0.30 | 0.04 | Minor porosity. Globular copper oxide is present. | Recrystallized, twinned microstructure. Strain-banding |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | *in some crystals.* |
| *355/1906* | *85.72* | *13.25* | *0.20* | *0.11* | *Not much sample left - it is completely corroded.* | *n/a too corroded* |
| *A306* | *86.02* | *12.35* | *0.90* | *0.29* | *No porosity. Small globules of copper oxide.* | *Recrystallized twinned microstructure. Strain-banding near the exterior of the sample* |
| *A320* | *84.52* | *11.34* | *1.06* | *2.60* | *Areas of severe porosity. Small globular copper oxide inclusions.* | *Recrystallized microstructure. Many crystals are strain-banded.* |
| *1113/1912* | *87.90* | *11.73* | *0.23* | *0.08* | *Some microporosity present. Elongated copper oxide inclusions.* | *Recrystallized twinned microstructure. Strain-banding, complete deformation on one side.* |
| *A6462* | *84.65* | *14.37* | *0.58* | *0.03* | *Some minor porosity. Globular copper oxide is present.* | *Recrystallized, twinned grains microstructure. Strain-banding throughout sample and many deformed grains at cutting-edge.* |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1897/7/6 | 84.82 | 13.85 | 0.32 | 0.11 | Very little porosity. Globular copper oxide inclusions. | Recrystallized twinned microstructure. Much strain-banding. |
| 593/2005 | 79.03 | 19.70 | 0.22 | 0.15 | No porosity. Globular copper oxide is present. | Dendritic microstructure. |
| A1951 | 84.54 | 14.39 | 0.23 | 0.33 | Minor porosity. | Recrystallized twinned microstructure. Some strain-banding near edge of sample. |
| A1952 | 83.44 | **15.53** | 0.26 | 0.11 | No porosity. Small globules of copper oxide. | Dendritic microstructure. |
| 102/1970 | 84.00 | 15.04 | 0.39 | 0.19 | Some minor porosity. Small stringers of copper oxide are present. | Recrystallized, twinned microstructure. Strain-banding in some crystals. |
| 130/1979 | 84.72 | 15.12 | 0.09 | - | Some moderate porosity. No copper oxide present. | Recrystallized, twinned microstructure. Strain-banding throughout sample. |
| 70/1974 | 83.65 | 15.35 | 0.39 | 0.17 | Some porosity and slag stringers. Very few spots of globular oxide are present. | Recrystallized, not twinned microstructure. A few crystals with strain-banding. |

| | | | | | | |
|---|---|---|---|---|---|---|
| A289 | 88.47 | 10.80 | 0.20 | 0.03 | Porosity levels unknown. Globular copper oxide is present. | Recrystallized, twinned microstructure. Some strain-banding in crystals. |
| A4148 | 85.10 | 13.61 | 0.39 | 0.15 | Some microporosity. Globular copper oxide inclusions. | Recrystallized, twinned microstructure. Strain-banding only in a few crystals. |
| A4214 | 86.49 | 12.27 | 0.42 | 0.05 | Sample lost | Sample lost |
| A6158 | 85.27 | 13.13 | 0.92 | 0.14 | Porosity unknown. Globular copper oxide is present. | Recrystallized - corrosion prohibited full assessment. |
| 1891/2/7 | 82.89 | 15.76 | 0.51 | 0.32 | Areas of moderate porosity. Globular copper oxide inclusions. | Recrystallized twinned microstructure. Strain-banding near the exterior. |
| 1891/2/6 | 88.12 | 7.96 | 0.42 | 3.30 | No porosity present. Globular copper oxide inclusions. | Recrystallized microstructure. Slip-banding is present in most of crystals. |
| 10/1980 | 83.29 | 14.50 | 0.31 | 0.07 | No porosity. Small stringers of copper oxide are present. | Recrystallized, twinned microstructure. Strain banding in some crystals. |
| 50/1971 | 84.96 | 14.52 | 0.19 | 0.14 | Network of small pores. | Recrystallized - corrosion |

| | | | | | | | prohibited full assessment. |
|---|---|---|---|---|---|---|---|
| | 60/1954 | 86.06 | 12.50 | 0.73 | 0.25 | No porosity. Globular copper oxide is present. | Recrystallized, twinned microstructure. No strain banding is visible. |
| *RCM* | 1910.22 2 | 84.12 | 13.94 | 0.17 | 1.00 | No pores. Some intermetallic inclusions. | Dendritic |
| | 1910.21 | 87.02 | 12.31 | 0.10 | 0.20 | No porosity. Intermetallic inclusions. | Recrystallized, twinned grains. Most grains contain a lot of strain lines. In one area near the edge of the sample, grains have been significantly deformed. |
| | 9.1919.5 | 88.08 | 11.52 | 0.20 | - | No porosity. Intermetallic inclusions. | Dendritic |
| | 1909.15.3 | 87.19 | 11.60 | 0.56 | 0.16 | Minor porosity. Some intermetallic inclusions. | Dendritic |
| | 1880.16 | 85.29 | 13.21 | 0.44 | tr | Moderate porosity. | Deformed dendrites. |
| | 1974.10.1 | 88.67 | 10.46 | 0.45 | 0.08 | Network of microporosity exists. Small globules of copper oxide. | Dendritic |

| ID | Cu | Sn | As | Pb | | |
|---|---|---|---|---|---|---|
| 9.1919.6 | 93.06 | 6.44 | 0.28 | - | Severe porosity. Globules of copper oxide are present. | Recrystallized, twinned grains. Some grains contain some strain lines. |
| 1909.74 | 84.45 | 14.30 | 0.59 | 0.09 | No porosity. No intermetallic inclusions. | Recrystallized, twinned grains. A few strain lines are exhibited within the grains. |

*Table 41:* Table presenting the composition of Copper, Tin, Arsenic, and Lead, as well as the metallographic analysis, for each palstave axe within the south-west sample.

The full composition and metallographic data for the Coghlan axes can be found within [116], [135], [137]. While the 'fair use' clause has been evoked for the incorporation of this data within the main body of work and the axe narratives, exact or full reproduction of the data cannot be presented here due to copyright law.

| Museum | ID | Casting seams | No n/a | No Yes | No n/a | Casting defects | Trapped gases |
|---|---|---|---|---|---|---|---|
| Ashmolean | 1927.2594 | Yes | n/a | n/a | n/a | No | No |
| | 1927.2567 | Yes | n/a | n/a | n/a | No | Yes, on the butt |
| | 1927.257 | Yes | n/a | No | n/a | No | Yes, in the flange |
| | 1961.498 | Yes | n/a | n/a | n/a | No | Yes, in the septum |
| | 1961.497 | Yes | n/a | n/a | n/a | No | No |
| Bristol | E449 | No | n/a | No | n/a | No | No |

|  |  | Yes | n/a | n/a | n/a | No | No |
|---|---|---|---|---|---|---|---|
|  | E456 | Yes | n/a | n/a | n/a | No | No |
| Dorchester | 1948.14.2 | Yes | n/a | n/a | n/a | No | No |
|  | 1963.15.1 | Yes | n/a | n/a | n/a | No | Yes, in the septum |
|  | 1954.40.1 | n/a | n/a | Yes | n/a | No | No |
|  | 1902.1.1 | Yes | n/a | No | n/a | No | No |
|  | 1902.1.5 | Yes | n/a | n/a | n/a | No | Yes, on the blade |
|  | 1902.1.2 | Yes | n/a | n/a | n/a | No | Yes, on the butt |
|  | 1902.1.4 | Yes | n/a | n/a | n/a | No | No |
|  | 1902.1.3 | Yes | No | Yes | Yes | No | No |
|  | 1955.48 | Yes | n/a | No | n/a | No | No |
|  | 1884.9.2 | Yes | n/a | n/a | n/a | No | Yes, in the septum |
|  | 1884.9.3 | Yes | No | n/a | Yes | No | Yes, in the septum |
|  | 1884.9.5 | Yes | n/a | n/a | n/a | No | No |
|  | 1884.9.1 | Yes | n/a | No | n/a | No | No |
|  | 1893.2.1 | Yes | No | n/a | Yes | No | No |
|  | 1884.9.22 | Yes | n/a | No | n/a | No | Yes, on the butt |
| Museum of Somerset | 12A | Yes | No | No | Yes | No | No |
|  | 14A | Yes | Yes | No | No | No | No |
|  | 63B | Yes | Yes | No | No | No | Yes, in the septum |
|  | 7A | Yes | n/a | n/a | n/a | No | No |
|  | 80C | Yes | n/a | n/a | n/a | No | Yes, all over the |

|  |  |  |  |  |  |  | septum and butt |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | 10A | Yes | n/a | n/a | n/a | No | No |
|  | 7B | No | No | n/a | Yes | Yes, one hole in the flange | No |
|  | 75.AA.4 | Yes | No | Yes | No | No | Yes, in the septum |
|  | 14B | Yes | n/a | No | n/a | No | No |
|  | 75B | Yes | No | No | Yes | No | No |
|  | 81C | Yes | n/a | No | n/a | No | No |
|  | 9B | Yes | No | n/a | No | No | No |
|  | 4A | No | n/a | n/a | n/a | No | No |
|  | A332 | No | Yes | No | No | No | No |
|  | A331 | No | No | n/a | Yes | No | No |
|  | 81D | Yes | Yes | No | No | No | No |
|  | 17B | Yes | n/a | n/a | n/a | No | No |
|  | 12C | Yes | n/a | No | n/a | No | Yes, in the septum |
|  | 84B | Yes | n/a | Yes | n/a | No | Yes, in the septum |
|  | 13B | Yes | No | n/a | Yes | No | No |
|  | 81B | Yes | n/a | n/a | n/a | No | No |
|  | 10B | Yes | No | Yes | No | No | Yes, in the stopridge |
|  | 8A | No | n/a | n/a | n/a | No | Yes, on the flange |
|  | 41B | No | n/a | n/a | n/a | No | No |
| RAMM | 11/1974 | Yes | n/a | n/a | n/a | No | No |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 45/1955/1 | *Yes* | *n/a* | *n/a* | *n/a* | *No* | *Yes* |
| | 354/1906/1 | *No* | *n/a* | No | *n/a* | *No* | *Yes, in the septum* |
| | 355/1906 | *Yes* | *n/a* | *n/a* | *n/a* | *No* | *No* |
| | A306 | *No* | Yes | Yes | No | *Yes, large defect on butt* | *Yes* |
| | A320 | *No* | *n/a* | *n/a* | *n/a* | *No* | *No* |
| | 1113/1912 | *Yes* | *n/a* | *n/a* | *n/a* | *No* | *Yes, on the butt* |
| | A6462 | *Yes* | No | No | Yes | *No* | *No* |
| | 1897/7/6 | *Yes* | No | No | No | *No* | *Yes, on the butt* |
| | 593/2005 | *Yes* | *n/a* | *n/a* | *n/a* | *Yes, defect in flange* | *No* |
| | A1951 | *Yes* | *n/a* | *n/a* | *n/a* | *No* | *No* |
| | A1952 | *No* | *n/a* | No | *n/a* | *No* | *No* |
| | 102/1970 | *No* | *n/a* | No | *n/a* | *No* | *Yes, on the butt* |
| | 130/1979 | *Yes* | Yes | No | No | *Yes, large casting defect at the cutting-edge* | *Yes* |
| | 70/1974 | *Yes* | *n/a* | No | *n/a* | *No* | *No* |
| | A289 | *No* | *n/a* | No | *n/a* | *No* | *Yes, in the septum* |
| | A4148 | *Yes* | *n/a* | No | *n/a* | *Ni* | *No* |
| | A4214 | *Yes* | No | *n/a* | Yes | *No* | *No* |

| | A6158 | No | n/a | n/a | n/a | No | Yes, in the septum |
|---|---|---|---|---|---|---|---|
| | 1891/2/7 | No | n/a | n/a | n/a | No | No |
| | 1891/2/6 | No | n/a | n/a | n/a | No | Yes, in the septum |
| | 10/1980 | No | No | No | Yes | No | Yes, in the septum |
| | 50/1971 | No | n/a | n/a | n/a | No | No |
| | 60/1954 | Yes | n/a | n/a | n/a | No | Yes, in the septum and stopridge |
| RCM | 1910.22 2 | Yes | Yes | No | No | No | Yes, many |
| | 1910.21 | Yes | No | No | Yes | n/a | Yes |
| | 1919.9.5 | Yes | n/a | n/a | n/a | No | No |
| | 1909.15.3 | Yes | n/a | n/a | n/a | No | No |
| | 1880.16 | Yes | n/a | n/a | n/a | No | Yes |
| | 1974.10.1 | No | n/a | n/a | n/a | Yes, big hole under stopridge and on the side of one flange | Yes |
| | 1919.9.6 | Yes | No | No | No | No | Yes |
| | 1909.74 | Yes | n/a | Yes | n/a | No | Yes |

**Table 42:** Table presenting the evidence of manufacturing observed on the south-west palstave axes.

| Museum | ID | Casting seams | Incomplete polishing | Hammering | Sharpening striations | Casting defects | Trapped gases |
|---|---|---|---|---|---|---|---|
| Pitt Rivers | 1884.119.105 | Yes | n/a | n/a | n/a | No | Yes, in the body |
| | 1884.119.106 | Yes | No | No | Yes | No | Yes, in the butt |
| | 1884.119.108 | Yes | n/a | No | n/a | No | No |
| | 1884.119.113 | Yes | Yes | No | No | No | No |
| | 1884.119.114 | No | No | No | Yes | No | No |
| | 1884.119.12 | Yes | n/a | n/a | n/a | No | No |
| | 1884.119.135 | Yes | No | No | Yes | No | No |
| | 1884.119.136 | Yes | n/a | n/a | n/a | No | No |
| | 1892.67.120 | Yes | n/a | n/a | n/a | No | Yes, small holes all over |
| | 1892.67.121 | Yes | n/a | No | n/a | No | No |
| | 1892.67.86 | Yes | n/a | n/a | n/a | No | Yes, in the butt |
| | 1904.31.2 | No | No | n/a | No | No | No |
| Newbury | 1962.12 | Yes | No | No | Yes | No | Yes, in the butt |

| | OA331 | Yes | n/a | No | n/a | No | Yes, a few holes |
|---|---|---|---|---|---|---|---|
| | OA325 | Yes | n/a | No | n/a | No | Yes, in the butt |
| | OA324 | Yes | No | Yes | Yes | No | No |
| | OA322 | No | n/a | No | n/a | No | No |
| | OA264 | Yes | n/a | No | n/a | No | No |
| | OA331 | No | No | No | No | No | No |
| | OA93 | No | n/a | Yes | n/a | No | No |
| | OA265 | Yes | Yes | No | No | No | No |
| | OA63 | Yes | n/a | No | n/a | Yes, in the septum | No |
| | 1968.68.Y2 | No | n/a | n/a | n/a | No | No |
| | 1968.63.Y3 | Yes | n/a | No | n/a | No | No |

*Table 43:* Table presenting the evidence of manufacturing observed on the Coghlan palstave axes.

| Museum | Museum no. | Use-striations | Hafting striations | Contortions to the cutting-edge | Blade sharpness | Asymmetry |
|---|---|---|---|---|---|---|
| Ashmolean | 1927.259 | Yes | n/a | No | Medium | Yes, moderate |
| | 1927.257 | n/a | n/a | No | Sharp (regrinding) | Yes, moderate |
| | 1927.257 | n/a | n/a | No | Blunt | No |

| | | | | | | |
|---|---|---|---|---|---|---|
| | *1961.498* | n/a | n/a | No | Medium | No |
| | *1961.497* | n/a | Yes | No | Sharp | Yes, mild |
| *Bristol* | *E449* | n/a | n/a | No | Medium | No |
| | *E456* | n/a | n/a | No | Blunt | Yes, slight |
| *Dorchester* | *1948.14.2* | n/a | No | No | Medium | Yes, slight |
| | *1963.15.1* | n/a | n/a | Yes | Sharp (regrinding) | Yes, slight |
| | *1954.40.1* | n/a | No | No | Sharp (regrinding) | No |
| | *1902.1.1* | n/a | No | No | Blunt | No |
| | *1902.1.5* | n/a | No | No | Blunt | No |
| | *1902.1.2* | n/a | No | No | Medium | No |
| | *1902.1.4* | n/a | n/a | Yes | Medium | Yes, moderate |
| | *1902.1.3* | n/a | No | No | Sharp | No |
| | *1955.48* | n/a | n/a | Yes | Medium | Yes, slight |
| | *1884.9.2* | Yes | Yes | No | Sharp | n/a |
| | *1884.9.3* | n/a | Yes | Yes | Sharp | Yes, slight |
| | *1884.9.5* | n/a | n/a | No | Medium | Yes, moderate |
| | *1884.9.1* | No | Yes | No | Sharp | Yes, slight |
| | *1893.2.1* | n/a | n/a | No | Sharp (regrinding) | Yes, slight |
| | *1884.9.22* | n/a | n/a | No | Medium | Yes, slight |
| *Somerset* | *12A* | No | Yes | No | Medium | Slight |
| | *14A* | n/a | n/a | No | Blunt | Significant |
| | *63B* | No | n/a | No | Medium | No |
| | *7A* | No | No | No | Medium | No |
| | *80C* | No | n/a | Depression | Sharp | Slight |
| | *10A* | n/a | No | No | n/a | No |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 7B | n/a | n/a | No | Medium | No |
| | 75.AA.4 | n/a | n/a | No | Medium | Moderate |
| | 14B | No | No | No | Blunt | No |
| | 75B | Yes | Yes | Depression | Blunt | Slight |
| | 81C | n/a | n/a | No | Sharp | Moderate |
| | 9B | No | n/a | No | Sharp | Slight |
| | 4A | n/a | n/a | No | Blunt | Slight |
| | A332 | yes | n/a | No | Blunt | No |
| | A331 | n/a | n/a | n/a | n/a | n/a |
| | 81D | No | No | No | Very blunt | No |
| | 17B | Yes | Yes | No | Sharp | No |
| | 12C | No | No | n/a | Blunt | No |
| | 84B | n/a | Yes | No | Blunt | Significant |
| | 13B | n/a | Yes | No | Very blunt | Slight |
| | 81B | n/a | No | No | Sharp | No |
| | 10B | No | Yes | Depression | Medium | Moderate |
| | 8A | n/a | n/a | No | Sharp | Moderate |
| | 41B | Yes | Yes | Yes | Medium | No |
| RAMM | 11/1974 | n/a | n/a | No | Blunt | No |
| | 45/1955/1 | n/a | n/a | No | Medium | No |
| | 354/1906/1 | n/a | Yes | No | n/a | n/a |
| | 355/1906 | n/a | Yes | No | Medium | Slight |
| | A306 | n/a | No | No | Blunt | No |
| | A320 | n/a | n/a | No | Very blunt | No |
| | 1113/1912 | No | No | No | Sharp | No |
| | A6462 | n/a | n/a | No | Blunt | No |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 1897/7/6 | n/a | n/a | No | Blunt | No |
| | 593/2005 | No | n/a | Depression | Medium | Slight |
| | A1951 | Yes | Yes | No | Blunt | Moderate |
| | A1952 | n/a | n/a | n/a | n/a | n/a |
| | 102/1970 | n/a | n/a | Bending | Medium | Slight |
| | 130/1979 | n/a | n/a | No | Medium | n/a |
| | 70/1974 | n/a | n/a | Depression and bending | n/a | No |
| | A289 | No | n/a | No | Blunt | No |
| | A4148 | n/a | n/a | n/a | n/a | n/a |
| | A4214 | n/a | n/a | No | Blunt | Slight |
| | A6158 | n/a | No | No | Sharp | No |
| | 1891/2/7 | No | n/a | No | Sharp | No |
| | 1891/2/6 | n/a | Yes | Depression | Medium | Moderate |
| | 10/1980 | n/a | n/a | Depression | Medium | Slight |
| | 50/1971 | n/a | n/a | n/a | n/a | n/a |
| | 60/1954 | No | Yes | No | Sharp | Severe |
| RCM | 1910.22 2 | n/a | n/a | no | Medium | no |
| | 1910.21 | n/a | n/a | No | Blunt | No |
| | 9.1919.5 | No | No | No | Sharp | Slight but this is definitely related to casting |
| | 1909.15.3 | No | No | No | Blunt | No |
| | 1880.16 | n/a | Yes | No | Medium | Yes, slight |
| | 1974.10.1 | n/a | n/a | No | Medium | Yes, slight |
| | 9.1919.6 | n/a | No | no | Blunt | No |

| | 1909.74 | n/a | n/a | Yes | Sharp | Yes, slight |
|---|---|---|---|---|---|---|

**Table 44:** Table presenting the evidence for use observed on the south-west palstave axes.

| Museum | Museum no. | Use-striations | Hafting striations | Contortions to the cutting-edge | Blade sharpness | Asymmetry |
|---|---|---|---|---|---|---|
| Pitt Rivers | 1884.119.105 | n/a | Yes | No | Sharp | Yes, slight |
| | 1884.119.106 | yes | No | No | Medium | No |
| | 1884.119.108 | n/a | Yes | No | Sharp (regrinding) | Yes, slight |
| | 1884.119.113 | No | No | No | Medium | Yes (shoddy casting) |
| | 1884.119.114 | No | Yes | Depression | Blunt | No |
| | 1884.119.12 | n/a | n/a | No | Sharp (regrinding) | No |
| | 1884.119.135 | No | Yes | Depression | Sharp | Yes, slight |
| | 1884.119.136 | n/a | Yes | n/a | Blunt | n/a |
| | 1892.67.120 | n/a | Yes | No | Blunt | No |
| | 1892.67.121 | n/a | n/a | No | Sharp (regrinding) | Yes, moderate |
| | 1892.67.86 | n/a | n/a | No | Sharp (regrinding) | No |
| | 1904.31.2 | Yes | Yes | No | Blunt | Yes, severe |
| Newbury | 1962.12 | Yes | Yes | No | Blunt | Yes, slight |
| | OA331 | n/a | n/a | No | Blunt | Yes, slight |
| | OA325 | n/a | n/a | No | Sharp | No |
| | OA324 | No | Yes | No | Sharp | Yes, moderate |

|  | OA322 | n/a | Yes | No | Medium | Yes, slight |
|---|---|---|---|---|---|---|
|  | OA264 | n/a | Yes | No | Sharp | Yes, slight |
|  | OA351 | Yes | Yes | No | Medium | Yes, moderate |
|  | OA93 | n/a | No | No | Sharp | No |
|  | OA265 | No | No | No | Sharp | No |
|  | OA63 | n/a | n/a | No | Sharp | No |
|  | 1968.68.Y2 | n/a | n/a | No | Medium | No |
|  | 1968.63.Y3 | n/a | n/a | n/a | n/a | n/a |

*Table 45:* Table presenting the evidence for use observed on the Coghlan palstave axes.

| *Museum* | *Museum no.* | *Damage* | *Terrain* | *Associations* |
|---|---|---|---|---|
| *Ashmolean* | *1927.259* | No | uncertain | Single |
|  | *1927.257* | No | uncertain | Single |
|  | *1927.257* | No | uncertain | Group |
|  | *1961.498* | Accidental | uncertain | Single |
|  | *1961.497* | No | uncertain | Group |
| *Bristol* | *E449* | Accidental | uncertain | Single |
|  | *E456* | Post-depositional | uncertain | Unknown |
| *Dorset* | *1948.14.2* | Accidental | dryland | Single |
|  | *1963.15.1* | None | dryland | Group |
|  | *1954.40.1* | None | uncertain | Single |
|  | *1902.1.1* | None | dryland | Group |
|  | *1902.1.5* | None | dryland | Group |
|  | *1902.1.2* | None | dryland | Group |

| | | | | |
|---|---|---|---|---|
| | *1902.1.4* | None | uncertain | Group |
| | *1902.1.3* | None | dryland | Group |
| | *1955.48* | Accidental | uncertain | Single |
| | *1884.9.2* | Deliberate | dryland | Single |
| | *1884.9.3* | None | dryland | Single |
| | *1884.9.5* | Accidental | uncertain | Unknown |
| | *1884.9.1* | None | uncertain | Unknown |
| | *1893.2.1* | None | uncertain | Unknown |
| | *1884.9.22* | None | dryland | Group |
| *Somerset* | *12A* | None | uncertain | Single |
| | *14A* | None | dryland | Group |
| | *63B* | Accidental | uncertain | Single |
| | *7A* | Deliberate | uncertain | n/a |
| | *80C* | None | wetland | Single |
| | *10A* | Accidental | wetland | Single |
| | *7B* | None | uncertain | Single |
| | *75.AA.4* | None | dryland | Group |
| | *14B* | Post-depositional | wetland | Single |
| | *75B* | Accidental | uncertain | Single |
| | *81C* | None | uncertain | Group |
| | *9B* | None | uncertain | Single |
| | *4A* | None | dryland | Single |
| | *A332* | Accidental | uncertain | Group |
| | *A331* | Accidental | uncertain | Group |
| | *81D* | None | uncertain | Group |
| | *17B* | Accidental | dryland | Group |

| | | | | |
|---|---|---|---|---|
| | *12C* | None | uncertain | Single |
| | *84B* | None | uncertain | Group |
| | *13B* | None | uncertain | Single |
| | *81B* | None | uncertain | Group |
| | *10B* | Accidental | wetland | Single |
| | *8A* | Accidental | uncertain | Single |
| | *41B* | Accidental | uncertain | Group |
| *RAMM* | *11/1974* | None | dryland | Single |
| | *45/1955/1* | None | uncertain | Single |
| | *354/1906/1* | Deliberate | dryland | Group |
| | *355/1906* | Accidental | dryland | Group |
| | *A306* | Post-depositional | uncertain | Single |
| | *A320* | None | uncertain | Single |
| | *1113/1912* | None | uncertain | Single |
| | *A6462* | Post-depositional | uncertain | unknown |
| | *1897/7/6* | Post-depositional | uncertain | Group |
| | *593/2005* | Post-depositional | dryland | Group |
| | *A1951* | Accidental/Post-depositional | dryland | Group |
| | *A1952* | Deliberate | dryland | Group |
| | *102/1970* | Post-depositional | dryland | Single |
| | *130/1979* | None | uncertain | Unknown |
| | *70/1974* | Accidental | uncertain | Unknown |
| | *A289* | None | uncertain | Group |

| | A4148 | Post-depositonal | dryland | Group |
|---|---|---|---|---|
| | A4214 | Accidental/Post-depositional | dryland | Group |
| | A6158 | None | uncertain | Unknown |
| | 1891/2/7 | None | dryland | Group |
| | 1891/2/6 | Post-depositional | dryland | Group |
| | 10/1980 | Accidental | Wetland | Single |
| | 50/1971 | Deliberate | uncertain | Single |
| | 60/1954 | Accidental | uncertain | Group |
| Cornwall | 1910.22 2 | None | dryland | Group |
| | 1910.21 | Post-depositonal | dryland | Group |
| | 9.1919.5 | Deliberate | dryland | Group |
| | 1909.15.3 | None | dryland | Single |
| | 1880.16 | None | uncertain | Single |
| | 1974.10.1 | None | dryland | Single |
| | 9.1919.6 | Accidental | uncertain | Group |
| | 1909.74 | None | dryland | Single |

*Table 46:* Table presenting the data relating to damage and context for the south-west palstave axes.

| Museum | Museum no. | Damage | Terrain | Associations |
|---|---|---|---|---|
| Pitt Rivers | 1884.119.105 | None | uncertain | Unknown |

| | | | | |
|---|---|---|---|---|
| | 1884.119.106 | Accidental/Post-depositional | uncertain | Unknown |
| | 1884.119.108 | None | wetland | Group |
| | 1884.119.113 | None | wetland | Unknown |
| | 1884.119.114 | None | uncertain | Unknown |
| | 1884.119.12 | None | uncertain | Unknown |
| | 1884.119.135 | None | uncertain | Unknown |
| | 1884.119.136 | Deliberate | uncertain | Unknown |
| | 1892.67.120 | Accidental | uncertain | Group |
| | 1892.67.121 | Post-depositional | wetland | Unknown |
| | 1892.67.86 | None | uncertain | Unknown |
| | 1904.31.2 | None | uncertain | Unknown |
| Berkshire | 1962.12 | None | uncertain | Unknown |
| | OA331 | None | uncertain | Unknown |
| | OA325 | None | uncertain | Unknown |
| | OA324 | Accidental | uncertain | Unknown |
| | OA322 | None | uncertain | Unknown |
| | OA264 | Accidental | uncertain | Single |
| | OA351 | Post-depositional | uncertain | Unknown |
| | OA93 | Accidental | uncertain | Unknown |
| | OA265 | None | wetland | Single |
| | OA63 | Accidental | uncertain | Unknown |
| | 1968.68.Y2 | Deliberate | dryland | Group |
| | 1968.63.Y3 | Deliberate | dryland | Group |

*Table 47:* Table presenting the data relating to damage and context for the Coghlan palstave axes.

# References

[1]    Y. Marshall, "The social lives of lived and inscribed objects: a Lapita perspective," *J. Polyn. Soc.*, vol. 117, no. 1, pp. 59–101, 2008.

[2]    A. Dolfini, "The function of Chalcolithic metalwork in Italy: an assessment based on use-wear analysis," *J. Archaeol. Sci.*, vol. 38, no. 5, pp. 1037–1049, 2011.

[3]    M. Mate, *Tribology on the small scale: a bottom up approach to friction, lubrication, and wear*. Oxford: Oxford, 2007.

[4]    C. Gutiérrez Sáez and I. . Lerma, "Traceology on Metal. Use-Wear Marks on Copper-Based Tools and Weapons," in *Use-Wear and Residue Analysis in Archaeology*, J. J. Marreiros, N. Mazzucco, J. F. Gibaja, and N. N. Bicho, Eds. Springer, 2015, pp. 171–189.

[5]    B. Roberts and B. S. Ottaway, "The Use and Significance of Socketed Axes During the Late Bronze Age," *Eur. J. Archaeol.*, vol. 6, no. 2, pp. 119–140, 2003.

[6]    S. Moyler, "Life on the cutting edge: Interpreting patterns of wear on Scottish Early Bronze Age axe," University of Southampton, 2007.

[7]    S. D. Bridgford, "Mightier then the pen? An edgewise look at Irish Bronze Age sword," in *Material harm: archaeological studies of war and violence*, J. Carman, Ed. Glasgow: Cruithne Press, 1997, pp. 95–115.

[8]    S. Bridgford, "Weapons, warfare and society in Britain 1250–750 BC Vol.2," University of Sheffield, 2000.

[9]    R. O'Flaherty, "The Early Bronze Age Halberd in Ireland: Function and Context," University College Dublin, 2002.

[10]   R. O'Flaherty, "A weapon of choice–experiments with a replica Irish Early Bronze Age halberd," *Antiquity*, vol. 81, no. May 2006, pp. 423–434, 2007.

[11]   D. Brandherm, "Use-wear on Bronze Age halberds: the case of Iberia," in *Bronze Age warfare: manufacture and use of weaponry.*, M. Uckelmann and M. Mödlinger, Eds. Oxford: Archaeopress, 2011, pp. 23–38.

[12]   A. Dolfini and R. J. Crellin, "Metalwork wear analysis: The loss of innocence," *J. Archaeol. Sci.*, vol. 66, pp. 78–87, 2016.

[13]   M. G. Knight, "The Intentional Destruction and Deposition of Bronze Age Metalwork in South West England, Volume 1," University of Exeter, 2018.

[14]   M. Barber, *Bronze and the Bronze Age: Metalwork and Society in Britain C.2500-800 BC*. Stroud: Tempus, 2003.

[15]   C. J. Stevens and D. Q. Fuller, "Did neolithic farming fail? The case for a Bronze Age agricultural revolution in the British Isles," *Antiquity*, vol. 86, no. 333, pp. 707–722, 2012.

[16]   C. B. Burgess and D. Coombs, *Bronze Age Hoards: some finds old and new*. Oxford: British Archaeological Reports 67, 1979.

[17]   A. Bevan, S. Colledge, D. Fuller, R. Fyfe, S. Shennan, and C. Stevens, "Holocene fluctuations

in human population demonstrate repeated links to food production and climate," *Proc. Natl. Acad. Sci.*, vol. 114, no. 49, pp. E10524–E10531, 2017.

[18] J. Schibler and S. Jacomet, "Short climatic fluctuations and their impact on human economies and societies: the potential of the Neolithic lake shore settlements in the Alpine Foreland 173–82.," *Environ. Archaeol.*, vol. 15, no. 2, pp. 173–82, 2010.

[19] D. Yates, "Bronze Age agricultural intensification in the Thames Valley and Estuary," in *Bronze Age Landscapes: Tradition and Transformation*, J. Bruck, Ed. Oxford: Oxbow, 2002, pp. 65–82.

[20] D. R. Fontijn, "Sacrificial landscapes : Cultural biographies of persons, objects and 'natural' places in the Bronze Age of the southern Netherlands, c. 2300-600 BC," *Analecta Praehist. Leiden. ; 33 ; 34*, no. December, pp. 239–246, 2002.

[21] S. Arnoldussen and D. Fontijn, "Towards familiar landscapes? On the nature and origin of Middle Bronze Age landscapes in the Netherlands.," *Proc. Prehist. Soc.*, vol. 72, pp. 289–317, 2006.

[22] J. Woodbridge, R. M. Fyfe, N. Roberts, S. Downey, K. Edinborough, and S. Shennan, "The impact of the Neolithic agricultural transition in Britain: a comparison of pollen-based land-cover and archaeological 14C date-inferred population change," *J. Archaeol. Sci.*, vol. 51, pp. 216–224, Nov. 2014.

[23] A. F. Harding, *European Societies in the Bronze Age*. Cambridge: Cambridge University Press, 2000.

[24] M. A. Smith, "Some Somerset hoards and their place in the Bronze Age of Southern Britain," *Proc. Prehist. Soc. (New Ser.*, vol. 25, no. 5, pp. 144–187, 1959.

[25] T. Darvill, *Prehistoric Britain*, 1st ed. New Haven: Yale University Press, 1987.

[26] R. R. Bishop, "Did Late Neolithic farming fail or flourish? A Scottish perspective on the evidence for Late Neolithic arable cultivation in the British Isles," *World Archaeol.*, vol. 47, no. 5, pp. 834–855, 2015.

[27] J. McKinley, "Human remains and diet," in *Hambledon Hill, Dorset, England. Excavation and survey of a Neolithic monument complex and its surrounding landscape*, no. 1, R. Mercer and F. Healy, Eds. English Heritage, 2008, pp. 477–534.

[28] R. Bradley, *The Prehistory of Britain and Ireland*. Cambridge: Cambridge University Press, 2007.

[29] J. M. Coles and A. F. Harding, *The Bronze Age in Europe: An Introduction to the Prehistory of Europe c. 2000-700BC*. London: Methuen & Co Ltd.

[30] D. T. Yates, "Bronze Age field systems in the Thames Valley," *Oxford J. Archaeol.*, vol. 18, no. 2, pp. 157–170, 1999.

[31] J. Moore, "Bronze Age activity: the site in its landscape," in *Reading Business Park: A Bronze Age landscape*, J. Moore and D. Jennings, Eds. Oxford: Oxford University Committee for Archaeology, 1992, pp. 118–123.

[32] F. Pryor, *The Flag Fen Basin: Archaeology and Environment of a Fenland Landscape*. Swindon: English Heritage Press, 2001.

[33]    E. Davies, J. Grove, J. Heathcote, C. Johns, and J. Nowakowski, *A30 Project: Archive Report on the archaeological excavations at Penhale Round, Fraddon, Cornwall 1993*. Truro: Cambridge Archaeological Unit, 1994.

[34]    B. Caswell, "A Place called Home: Understanding Bronze Age (c.2400-800 cal BC) Settlement in Britain," Durham, 2020.

[35]    B. Coles and J. M. Coles, *Sweet Track to Glastonbury: the Somerset Levels in Prehistory*. London: Thames & Hudson.

[36]    I. Tyers, "Tree-ring analysis of archaeological timbers from the Testwood III site, Netley Marsh, Hampshire," 2004.

[37]    R. Brunning, "Structural Wood in Prehistoric England and Wales," University of Exeter, 2007.

[38]    J. Wallis and M. Waugham, "Archaeology and the landscape in the Lower Blackwater valley," *East Anglian Archaeol.*, vol. 82, 1988.

[39]    D. Tomalin, R. . Loader, and R. G. . Scaife, *Coastal archaeology in a dynamic environment: A Solent case study*. Oxford: Archaeopress, 2012.

[40]    T. Allen, "Eton College Rowing Course at Dorney Lake," *Curr. Archaeol.*, vol. 181, pp. 20–25, 2002.

[41]    R. Van de Noort, "Seafaring and Riverine Navigation in the Bronze Age of Europe," in *The Oxford Handbook of the European Bronze Age*, A. Harding and H. Fokkens, Eds. Oxford: Oxford University Press, 2013, pp. 382–397.

[42]    E. Wright, R. Hedges, A. Bayliss, and R. Van de Noort, "New AMS dates for the Ferriby Boats: a contribution to the origin of seafaring," *75*, vol. Antiquity, pp. 726–734, 2001.

[43]    P. Clark, *The Dover Bronze Age Boat*. English Heritage., 2004.

[44]    O. T. . Roberts, "The Brigg 'raft' reassessed as a round bilge Bronze Age boat," *Int. J. Naut. Archaeol.*, vol. 21, no. 3, pp. 245–258, 1992.

[45]    D. Gibson, M. Knight, K. Murrell, and D. Weeks, "Waterworld: Must Farm's Bronze Age Boats," *Curr. Archaeol.*, vol. 263, pp. 12–19, 2012.

[46]    Q. Wang, S. Strekopytov, B. W. Roberts, and N. Wilkin, "Tin ingots from a probable Bronze Age shipwreck off the coast of Salcombe, Devon: Composition and microstructure," *J. Archaeol. Sci.*, vol. 67, pp. 80–92, 2016.

[47]    Q. Wang, S. Strekopytov, and B. W. Roberts, "Copper ingots from a probable Bronze Age shipwreck off the coast of Salcombe, Devon: Composition and microstructure," *J. Archaeol. Sci.*, vol. 97, no. June, pp. 102–117, 2018.

[48]    R. Sheperd, *Prehistoric Mining and Allied Industries*. London: Academic Press, 1980.

[49]    P. Ashbee, "The Wilsford Shaft," *Antiquity*, vol. 37, no. 146, pp. 116–120, 1963.

[50]    P. Daniel, *Archaeological Excavations at Pode Hole Quarry: Bronze Age Occupation on the Cambridgeshire Fen-edge. BAR British Series 484.* Oxford: Archaeopress, 2009.

[51]    A. Garner, J. Prag, and R. Housley, "The Alderley Edge Shovel," *Curr. Archaeol.*, vol. 137, pp.

172–175, 1994.

[52] C. Earwood, *Domestic wooden artefacts in Britain and Ireland from Neolithic to Viking times*. Exeter: University of Exeter Press, 1993.

[53] S. Denison, "Bronze age ard, cereal grains, fields," *Br. Archaeol.*, vol. 26, p. 3, 1997.

[54] H. S. Green, "Late Bronze Age wooden hafts from Llyn Fawr and Penwyllt, and a review of the evidence for the selection of wood for tool and weapon handles in Neolithic and Bronze Age Britain," *Bull. Board Celt. Stud.*, vol. 28, no. 1, pp. 137–141, 1978.

[55] J. . Coles, "Ancient wood, woodworking and wooden houses," *euroREA J. (Re)construction Exp. Archaeol.*, vol. 3, pp. 50–57, 2006.

[56] D. Goodburn, "Assembly and construction techniques," in *The Dover Bronze Age Boat*, P. Clark, Ed. Swindon: English Heritage, 2004, pp. 124–162.

[57] R. Lee, "Influences of Wood-Crafting on Technological Development in Middle to Late Bronze Age Southern England," University of Southampton, 2014.

[58] R. Sands, "Prehistoric Woodworking: the analysis and interpretation ofBronze and Iron Age toolmarks. Wood in Archaeology Vol.1.," UCL Institute of Archaeology, 1997.

[59] P. Budd and T. Taylor, "The faerie smith meets the bronze industry: magic versus science in the interpretation of prehistoric metal-making," *World Archaeol*, vol. 27, pp. 133–43, 1995.

[60] M. J. Rowlands, *The production and distribution of metalwork in the Middle Bronze Age in southern Britain. Vol I.* Oxford: British Archaeological Reports, 1976.

[61] B. S. Ottaway, "Innovation, production and specialization in early prehistoric copper metallurgy," *Eur. J. Archaeol.*, vol. 4, no. 1, pp. 87–112, 2001.

[62] R. Bradley, *The Passage of Arms: an archaeological analysis of prehistoric hoards and votive deposits*. Cambridge: Cambridge University Press, 1990.

[63] R. Bradley, "The interpretation of later Bronze Age metalwork from British rivers," *Int. J. Naut. Archaeol. Underw. Explor.*, vol. 8, no. 1, pp. 3–6, 1979.

[64] R. Bradley, "Hoards and the deposition of metalwork," in *Oxford Handbook of the European Bronze Age*, H. Fokkens and A. Harding, Eds. Oxford: Oxford University Press, 2013, pp. 121–139.

[65] J. Joy, "Hoards as collections : re-examining the Snettisham Iron Age hoards from the perspective of collecting practice Hoards as collections : re-examining the Snettisham Iron Age hoards," *World Archaeol.*, vol. 48, no. 2, pp. 239–253, 2017.

[66] J. Evans, *The Ancient Bronze Implements, Weapons, and Ornaments, of Great Britain and Ireland*. London: Longmans, Green & Co, 1881.

[67] R. Wiseman, "Random accumulation and breaking: The formation of Bronze Age scrap hoards in England and Wales," *J. Archaeol. Sci.*, vol. 90, pp. 39–49, 2018.

[68] S. Needham, M. Bates, C. J. Frieman, and D. Parham, *Claimed by the Sea: Salcombe, Langdon Bay, and other marine finds of the Bronze Age*. 2013.

[69] J. Brück, "Fragmentation, personhood and the social construction of technology in Middle

and Late Bronze Age Britain," *Cambridge Archaeol. J.*, vol. 16, no. 3, pp. 297–315, 2006.

[70] S. Shennan, "Commodities, transactions, and growth in the central-European Early Bronze Age," *J. Eur. Archaeol.*, vol. 1, no. 2, pp. 59–72, 1993.

[71] D. Britton, "A Study of the Composition of Wessex Culture Bronzes," *Archaeometry*, vol. 4, no. 1, pp. 39–52, 1961.

[72] M. Mauss, *The Gift: The form and reason for exchange in archaic societies*. London, 2002.

[73] J. Brück, "Death, Exchange and Reproduction in the British Bronze Age," *Eur. J. Archaeol.*, vol. 9, no. 1, pp. 73–101, 2006.

[74] J. Brück, "Settlement, landscape and social identity: the Early-Middle Bronze Age transition in Wessex, Sussex and the Thames Valley," *Oxford J. Archaeol.*, vol. 19, no. 3, pp. 273–300, 2000.

[75] J. Brück, "Body metaphors and technologies of transformation in the English Middle and Late Bronze Age," in *Bronze Age landscapes, tradition and transformation.*, J. Brück, Ed. Oxford: Oxbow, 2001, pp. 146–60.

[76] R. Bradley, *A Geography of Offerings: Deposits of Valuables in the Landscapes of Ancient Europe*. Oxford: Oxbow Books, 2017.

[77] O. Dietrich, "Learning from ' Scrap ' about Late Bronze Age Hoarding Practices : A Biographical Approach to Individual Acts of Dedication in Large Metal Hoards of the Carpathian Basin Learning from ' Scrap ' about Late Bronze Age Hoarding Practices : A Biographical App," vol. 9571, no. July 2017, 2014.

[78] J. Brück, "Ritual and Rationality: some problems of interpretation in European Archaeology," *Eur. J. Archaeol.*, vol. 2, pp. 313–344, 1999.

[79] D. R. Fontijn, *Sacrificial Landscapes. Cultural Biographies of Persons, Objects and 'Natural' Places in the Bronze Age of the Southern Netherlands*. Leiden: University of Leiden Press, 2002.

[80] J. Bruck, "A place for the dead: the role of human remains in the Late Bronze Age," *Proc. Prehist. Soc.*, vol. 61, no. May, pp. 245–277, 1995.

[81] A. Woodward *et al.*, "Ritual in Some Early Bronze Age Gravegoods," *Archaeol. J.*, vol. 162, no. November, pp. 31–64, 2005.

[82] S. Piggott, "The Early Bronze Age in Wessex," *Prehist. Soc.*, vol. 3, pp. 52–106, 1938.

[83] M. J. Rowlands, *The production and distribution of metalwork in the Middle Bronze Age in southern Britain. Vol II.* Oxford: British Archaeological Reports, 1976.

[84] S. M. Pearce, "The Bronze Age metalwork of south western Britain," *Oxford Br. Archaeol. Reports*, vol. Brit Archa, no. Ser 120, 1983.

[85] S. Needham, C. B. Ramsey, D. Coombs, C. Cartwright, and P. Pettit, "An independent chronology for British Bronze Age metalwork : The results of the Oxford Radiocarbon Accelerator Programme," *Archaeol. J.*, vol. 154, no. December, pp. 55–107, 1998.

[86] K. L. Hollenback and M. B. Schiffer, "Technology and Material Life," *Oxford Handb. Mater. Cult. Stud.*, no. March, pp. 3–4, 2012.

[87]    C. Conneller, *An Archaeology of Materials: Substantial Transformations in Early Prehistoric Europe*. London: Routledge, 2012.

[88]    D. Pye, *The Nature and Art of Workmanship*. Cambridge: Cambridge University Press, 1968.

[89]    A. Jones, "Archaeometry and materiality: materials based analysis in theory and practice," *Archaeometry*, vol. 3, no. October 2003, pp. 327–338, 2004.

[90]    J. Joy, "Reinvigorating object biography: reproducing the drama of object lives," *World Archaeol.*, vol. 41, no. 4, pp. 540–556, 2009.

[91]    J. Bradfield, "Use-Trace Analysis of Bone Tools : a Brief Overview of Four Methodological Approaches," *South African Archaeol. Bull.*, vol. 70, no. 201, pp. 3–14, 2015.

[92]    A. Leroi-Gourhan, *Le Geste et la Parole 1: Technique et language*. Paris: Albin Michel, 1964.

[93]    R. Cresswell, "Avant-propos," *Tech. Cult.*, vol. 1, pp. 5–6, 1976.

[94]    M. B. Schiffer, "Archaeological context and systemic context," *Am. Antiq.*, vol. 37, no. 2, pp. 156–165, 1972.

[95]    M. B. Schiffer, *Behavioral Archeology*. New York: Academic Press, 1976.

[96]    M. B. Schiffer, *Formation Processes of the Archaeological Record*. Albuquerque: University of New Mexico Press, 1987.

[97]    F. Sigaut, "Technology," in *Companion Encyclopedia of Anthropology*, T. Ingold, Ed. London: Routledge, 1994, pp. 420–459.

[98]    C. Humphries and A. C. T. Smith, "Talking objects : Towards a post- social research framework for exploring object narratives," 2014.

[99]    I. Kopytoff, "The cultural biography of things: commoditization as process," in *The Social Life of Things: Commodities in Cultural Perspective*, A. Appadurai, Ed. Cambridge: Cambridge University Press, 1986, pp. 64–91.

[100]   C. Gosden and Y. Marshall, "The cultural biography of objects," *World Archaeol.*, vol. 31, no. 2, pp. 169–178, 1999.

[101]   A. Blanco-gonz, "Tracking the social lives of things : biographical insights into Bronze Age pottery in Spain," pp. 441–455, 2017.

[102]   K. Knorr Cetina, "Sociology with Objects. Social Relations in Postsocial Knowledge Societies," *Theory, Cult. Soc.*, vol. 14, no. 4, pp. 1–30, 1997.

[103]   J. Law and A. Mol, "Notes on Materiality and Sociality 43(2): 274–94," *Sociol. Rev.*, vol. 43, no. 2, pp. 274–294, 1995.

[104]   W. Schinkel, "'Inertia Creeps', or a Phenomenological Perspective on Objects in Sociology," *J. Organ. Chang. Manag.*, vol. 17, no. 4, pp. 396–407, 2004.

[105]   P. Northover, "The analysis ofWelsh Bronze Age metalwork," in *Guide catalogue of the Bronze Age collection*, H. Savory, Ed. Cardiff: National Museum of Wales, 1980, pp. 229–243.

[106]   J. P. Northover and B. E. P. Staniaszek, "The properties of leaded bronze alloys," in

*Proceedings of the 22nd Symposium on Archaeometry: Held at the University of Bradford, U.K., 30th March-3rd April 1982*, 1982, pp. 262–272.

[107]   B. Rohl and S. P. Needham, *The circulation of metal in the British Bronze Age: the application of lead isotope analysis*. London: British Museum, 1998.

[108]   Z. EL Morr, F. Cattin, D. Bourgarit, Y. Lefrais, and P. Degryse, "Copper quality and provenance in Middle Bronze Age I Byblos and Tell Arqa (Lebanon)," *J. Archaeol. Sci.*, vol. 40, no. 12, pp. 4291–4305, Dec. 2013.

[109]   M. . Levine, "Determining the Provenance of native copper artifacts from Northeastern North America: evidence from instrumental neutron activation analysis," *J. Archaeol. Sci.*, vol. 34, no. 4, pp. 572–587., 2007.

[110]   E. Pernicka, "Provenance Determination of Archaeological Metal Objects," in *Archaeometallurgy in Global Perspective*, 2014, pp. 239–268.

[111]   Y. Klein, S., Brey, G. P., Durali-Müller, S., & Lahaye, "Characterisation of the raw metalsources used for the production of copper and copper-based objects with copper isotopes," *Archaeol. Anthropol. Sci.*, vol. 2, pp. 45–56, 2010.

[112]   M. Brauns, R. Schwab, G. Gassmann, G. Wieland, and E. Pernicka, "Provenance of Iron Age iron in southern Germany: a new approach," *J. Archaeol. Sci.*, vol. 40, no. 2, pp. 841–849, Feb. 2013.

[113]   Haustein, M., Gillis, C. & Pernicka, E., "Tin Isotopy-a New Method for Solving Old Questions," *Archaeometry*, vol. 52, no. 5, pp. 816–832, 2010.

[114]   P. K. Schmidt and C. B. Burgess, *The axes of Scotland and northern England*. Munich: C.H. Beck'sche Verlagsbuchhandlung., 1981.

[115]   J. J. Butler, "Bronze Age Connections across the North Sea," *Palaeohistoria*, vol. 9, 1963.

[116]   I. M. Allen, M. A. Britton, and H. H. Coghlan, *Metallurgical Reports on British and Irish Bronze Age Implements and Weapons in the Pitt Rivers Museum*. Oxford: Oxford University Press, 1970.

[117]   M. G. Knight, "The Intentional Destruction and Deposition of Bronze Age Metalwork in South West England Volume 3 Table of Contents," vol. 3, 2018.

[118]   S. Collins, "Experimental investigations into edge performance and its implications for stone artefact reduction modelling," *J. Archaeol. Sci.*, vol. 35, pp. 2164–2170, 2008.

[119]   F. Monna *et al.*, "Morphometry of Middle Bronze Age palstaves. Part II - spatial distribution of shapes in two typological groups, implications for production and exportation," *J. Archaeol. Sci.*, vol. 40, no. 1, pp. 507–516, 2013.

[120]   B. W. Roberts *et al.*, "Collapsing Commodities or Lavish Offerings? Understanding Massive Metalwork Deposition at Langton Matravers, Dorset During the Bronze Age-Iron Age Transition," *Oxford J. Archaeol.*, vol. 34, no. 4, pp. 365–395, 2015.

[121]   R. A. Williams and C. Le Carlier de Veslud, " Boom and bust in Bronze Age Britain: major copper production from the Great Orme mine and European trade, c . 1600–1400 BC ," *Antiquity*, vol. 93, no. 371, pp. 1178–1196, 2019.

[122]   B. Forel *et al.*, "Morphometry of Middle Bronze Age palstaves by Discrete Cosine

Transform," *J. Archaeol. Sci.*, vol. 36, no. 3, pp. 721–729, 2009.

[123]   G. Bould, "WILT-0323E2: A Bronze Age Palstave," 2016. [Online]. Available: https://finds.org.uk/database/artefacts/record/id/802968. [Accessed: 12-May-2017].

[124]   A. Byard, "BERK-0AAC5D: A Bronze Age socketed axehead," 2016. [Online]. Available: https://finds.org.uk/database/artefacts/record/id/750373. [Accessed: 12-May-2017].

[125]   S. P. Needham, *The Petters Late Bronze Age Metalwork*. London: British Museum, 1990.

[126]   C. R. Musson, W. J. Britnell, J. P. Northover, and C. J. Salter, "Excavations and metal-working at Llwyn Bryn-Dinas Hillfort, Llangedwyn, Clwyd," *Proc. Prehist. Soc.*, vol. 58, pp. 265–283, 1992.

[127]   R. H. Bewley, I. H. Longworth, S. Browne, J. P. Huntley, and G. Varndell, "Excavation of a Bronze Age cemetary at Ewanrigg, Maryport, Cumbria," *Proc. Prehist. Soc.*, vol. 58, no. July 1949, pp. 325–354, 1992.

[128]   D. Bond, *Excavation at the North Ring, Mucking, Essex*. Chelmsford: East Anglian Archaeology Report 43, 1988.

[129]   L. Webley and S. Adams, "Material Genealogies: Bronze Moulds and their Castings in Later Bronze Age Britain," *Proc. Prehist. Soc.*, pp. 1–18, 2016.

[130]   J. Heeb and B. S. Ottaway, "Experimental Archaeometallurgy," in *Archaeometallurgy in Global Perspective*, B. W. Roberts and C. P. Thornton, Eds. New Work: Springer, 2014, pp. 161–192.

[131]   B. Ottaway and S. Seibel, "Dust in the wind: experimental casting of bronze in sand moulds," in *Paléométallurgie des cuivres. Actes du col- loque de Bourg-en-Bresse et Beaune*, M.-C. Frère-Sautot, Ed. Montagnac: Monique Mergoil, 1998, pp. 59–63.

[132]   Q. Wang and B. S. Ottaway, *Casting experiments and microstructure of archaeologically relevant bronzes*. Oxford: Archaeopress, 2005.

[133]   M. Eccleston and B. S. Ottaway, "Experimental casting of copper and bronzes in Sand Moulds," in *Proceedings of the 31st International Symposium on Archaeometry*, E. Jerem and K. Biró, Eds. Oxford: BAR Archaeolingua Central European Series, 2002, pp. 185–189.

[134]   M. A. Brown and A. E. Blin-Stoyle, "A Sample Analysis of British Middle and Late Bronze Age Material, using Optical Spectrometry," *Proc. Prehist. Soc.*, vol. 25, no. 6, pp. 188–208, 1959.

[135]   H. H. Coghlan, *British and Irish Bronze Age implements in the Borough of Newbury Museum*. Newbury: Borough of Newbury Museum, 1970.

[136]   H. H. Coghlan and M. Cook, "Studies of British and Irish Celts : First Series . Reports of the Ancient Mining and Metallurgy Committee of the Royal Anthropological Institute," *Man*, vol. 53, no. July, pp. 97–101, 1953.

[137]   H. H. Coghlan, *A Report Upon the Hoard of Bronze Age Tools and Weapons from Yattendon, Near Newbury, Berkshire*. Newbury: Borough of Newbury Museum, 1970.

[138]   T. L. Kienlin, E. Bischoff, and H. Opielka, "Copper and bronze during the Eneolithic and Early Bronze Age: A metallographic examination of axes from the Northalphine region," *Archaeometry*, vol. 48, no. 3, pp. 453–468, 2006.

[139] T. L. Kienlin, "Aspects of the Development of Casting and Forging Techniques from the Copper Age to the Early Bronze Age of Eastern Central Europe and the Carpathian Basin," in *Anatolian Metal V*, Ü. Yalçın and C. Wirth, Eds. Gerda Henkel Stiftung, 2011, pp. 127–136.

[140] G. Kuijpers, "Bronze Age Metalworking in the Netherlands (c.2000-800BC)," Sidestone Press, 2008.

[141] T. L. Kienlin, "Copper and Bronze: Bronze Age Metalworking in Context," in *The Oxford Handbook of the European Bronze Age.*, H. Fokkens and A. Harding, Eds. Oxford: Oxford University Press, 2013, pp. 414–436.

[142] J. J. Butler and H. Steegstra, "Bronze Age metal and amber in the Netherlands (II:2) Catalogue of the Palstaves," *Palaeohistoria*, vol. 39/40, pp. 163–275.

[143] J. M. Coles, S. V. E. Heal, and B. J. Orme, "The Use and Character of Wood in Prehistoric Britain and Ireland.," *Proc. Prehist. Soc.*, vol. 44, pp. 1–45, 1978.

[144] K. Brophy and G. Noble, "From Beakers to Daggers: Bronze Age burial practice at Forteviot," *PAST Newsl. Prehist. Soc.*, vol. 67, pp. 1–3, 2011.

[145] V. Rots, "Hafting and raw materials from animals. Guide to the identification of hafting traces on stone tools," *Anthropozoologica*, vol. 43, no. 1, pp. 43–66, 2008.

[146] K. Spindler, *The Man in the Ice*. London: Weidenfield & Nicolson, 1994.

[147] T. Kienlin and B. S. Ottaway, "Flanged axes of the North-Alpine region: an assessment of the possibilities of use-wear analysis on metal artefacts," *L'Atelier du bronzier en Eur. du XXe au VIIIe siècle avant notre ère Du Miner. au métal du métal à l'objet*, pp. 271–86, 1998.

[148] M. Taylor, "Flag Fen: the wood," *Antiquity*, vol. 66, pp. 476–498, 1992.

[149] L. Barfield, "The Iceman Reviewed," *Antiquity*, vol. 68, no. 258, pp. 10–17, 1994.

[150] F. Sauter, U. Jordis, A. Graf, W. Werther, and K. Varmuza, "Studies in organic archaeometry I: identification of the prehistoric adhesive used by the 'Tyrolean Iceman' to fix his weapons," *Arkivoc*, vol. 2000, no. v, pp. 735–747, 2000.

[151] A. F. Harding, "Bronze agricultural implements in Bronze Age Europe," in *Problems in economic and social archaeology*, D. De G Sieveking, I. H. Longworth, and K. E. Wilson, Eds. Colorado: Westview Press, 1975.

[152] P. Rivers, *Excavations in Cranborne Chase near Rushmore, on the borders of Dorset and Wilts, 1893-1896. Vol.IV: [South Lodge Camp, Rushmore Park; Handley Hill entrenchment; Stone and Bronze Age barrows and camp, Handley, Dorset; Martin Down camp..]*. 1898.

[153] P. Ashbee, *The Bronze Age Round Barrow in Britain*. London: Phoenix House., 1960.

[154] R. J. Crellin, "Examining the British and Irish Early Bronze Age flat axes of the Greenwell Collection at the British Museum," *J. Archaeol. Sci. Reports*, no. August, pp. 1–31, 2017.

[155] H. Godwin, "A Middle Bronze Age Palstave from Buried Forest at Woodwalton Fen, Hunts. Data for the Study of Post-Glacial History. VIII," *New Phytol.*, vol. 41, no. 3, pp. 165–170, 1942.

[156] M. Brennand *et al.*, "The survey and excavation of a bronze age timber circle at Holme-

next-the-sea, Norfolk, 1998-9," *Proc. Prehist. Soc.*, vol. 69, pp. 1–84, 2003.

[157] L. Webley, M. Knight, K. Roberts, E. Simmons, C. Swaysland, and M. Taylor, "Middle Bronze Age Finds at Langtoft Common, Lincolnshire," *Cambridge Archaeol. Unit, Univ. Cambridge*, no. 656, 2004.

[158] J. Johannsen, "Serial Production and Metal Exchange in Early Bronze Age Scandinavia: Smørumovre Revisited," *Bar Int. Ser.*, vol. 2, pp. 73–83, 2015.

[159] J. R. Mathieu and D. a. Meyer, "Comparing Axe Heads of Stone, Bronze, and Steel: Studies in Experimental Archaeology," *J. F. Archaeol.*, vol. 24, no. 3, pp. 333–351, 1997.

[160] C. Cessford, *Assemblage Biography and the Life Course : An Archaeologically Materialized Temporality of Richard and Sarah Hopkins*. 2014.

[161] M. Giles, *A Forged Glamour: Landscape, Identity and Material Culture in the Iron Age*. Oxford: Windgather Press, 2012.

[162] J. Wall, "The Role of Daggers in the Early Bronze Age," *Oxford J. Archaeol.*, vol. 6, no. 1, pp. 115–118, 1987.

[163] H. J. Greenfield, "The Origins of Metallurgy in the Central Balkans based on the Analysis of Cut Marks on Animal Bones," *Environ. Archaeol.*, vol. 5, no. 1, pp. 93–106, 2000.

[164] T. L. Kienlin, "Von den Schmieden der Beile: Zu Verbreiotung und Angleichung metallurgischen Wissens im Verlatu der Fruhbronzezeit," *Praehist. Zeitschrift*, vol. 82, no. 1, pp. 1–22, 2007.

[165] A. Greener and E. Ben-yosef, "The ground stone assemblage of a metal workers community : An unexplored dimension of Iron Age copper production at Timna," *J. Lithic Stud.*, vol. 3, no. 3, pp. 1–30, 2016.

[166] P. J. Bray and a. M. Pollard, "A new interpretative approach to the chemistry of copper-alloy objects: source, recycling and technology," *Antiquity*, vol. 86, no. 333, pp. 853–867, Jan. 2015.

[167] P. J. Bray and a. M. Pollard, "A new interpretative approach to the chemistry of copper-alloy objects: source, recycling and technology," *Antiquity*, vol. 86, no. 333, pp. 853–867, 2012.

[168] D. Yates and R. Bradley, "The Siting of Metalwork Hoards in the Bronze Age of South-East England," *J. Antiq.*, vol. 90, pp. 41–72, 2010.

[169] R. Taylor, *Hoards of the Bronze Age in southern Britain: analysis and interpretation (British Series 228)*. Oxford: British Archaeological Reports, 1993.

[170] S. A. Semenov, *Prehistoric Technology*. Barnes and Noble, 1964.

[171] W. J. Stemp, A. S. Watson, and A. A. Evans, "Surface analysis of stone and bone tools," *Surf. Topogr. Metrol. Prop.*, vol. 4, no. 1, p. 013001, 2015.

[172] N. ANDERSON, P.C., KOROBKOVA, G.F., LONGO, L., PLISSON, H. y SKAKUN, "Varions viewpoints on the work of S . A . Semenov," *roots use-wear Anal. Sel. Pap. S.A. Semenov.*, vol. 2, p. pp.11-19., 2005.

[173] R. Tringham, G. Cooper, G. Odell, B. Voytek, and A. Whitman, "Experimentation in the

Formation of Edge Damage: A New Approach to Lithic Analysis," *J. F. Archaeol.*, vol. 1, no. 1–2, pp. 171–196, Jan. 1974.

[174] L. H. Keeley, *Experimental determination of stone tools uses: A microwear analysis*. Chicago: University of Chicago Press., 1980.

[175] J. Kamminga, "Over the edge. Functional analysis of Australian stone tools," *Occas. Pap. Anthropol. Anthropol. Museum, Universiry Queensl.*, vol. 12, 1982.

[176] P. C. Vaughan, "Lithic microwear experimentation and the functional analysis of a Lower Magdalenian stone tool assemblage," Pennsylvania University., 1981.

[177] S. Olsen, "A study of bone artifacts from Grasshopper Pueblo," *Kiva*, vol. 44, pp. 341–73, 1979.

[178] S. Olsen, "Bone artifacts from Kinishba Ruin: their manufacture and use," *Kiva*, vol. 46, pp. 39–67, 1980.

[179] S. Olsen, "Analytical Approaches to the Manufacture and Use of Bone Artifacts in Prehistory," in *(London: Institute of Archaeology, University of London)*, 1984.

[180] C. Gutierrez and I. Llopis, "La funcionalidad sobre material metálico. Bases y aplicaciones de estudio," in *Actas del VII Congreso Ibérico de Arqueometría*, S. Rovira, M. García Heras, M. Gener, and I. Montero Ruiz, Eds. Madrid: CSIC, 2008, pp. 432–447.

[181] J. Penman, "The old copper culture: an analysis of old copper artifacts," *Wisconsin Archaeol.*, vol. 58, pp. 3–23, 1977.

[182] K. L. Ehrhardt, "Copper Working Technologies , Contexts of Use , and Social Complexity in the Eastern Woodlands of Native North America," pp. 213–235, 2009.

[183] P. Schauer, "Eine urnenfelderzeitliche Kampfweise. Archäologisches Korrespondenzblatt," vol. 9, no. 1, pp. 69–80, 1979.

[184] K. Kristiansen, "The consumption of wealth in Bronze Age Denmark," in *New directions in Scandinavian archaeology*, K. Kristiansen and C. Paludan-Müller, Eds. Copenhagen: The National Museum of Denmark, 1978, pp. 158–190.

[185] K. Kristiansen, "Krieger und Häuptlinge in der Bronzezeit Dänemarks: Ein Beitrag zur Geschichte des Bronzezeitlichen Schwertes," *Jahrb. des Römisch-Germanischen Zentralmuseums*, vol. 31, pp. 187–208, 1984.

[186] R. B. Gordon, "Laboratory Evidence of the Use of Metal Tools at. Machu Picchu (Peru) and Environs," *J. Archaeol. Sci.*, vol. 12, no. 4, pp. 311–327, 1985.

[187] B. Quilliec, "Use, wear and damage: treatment of bronze swords before deposition," *Bar Int. Ser.*, pp. 67–78, 2008.

[188] C. Soriano Llopis, I. Gutierrez Sáez, "Use wear Analysis on Metal: The Influence of Raw Material and Metallurgical Production Processes," in *2nd International Conference, Archaeometallurgy in Europe*, 2007, pp. 115–124.

[189] P. J. Reynolds, "The Nature of Experiment in Archaeology," in *Archaeology of the Bronze and Iron Age. Proceedings of the International Archaeological Conference Szazhalombatta, 3-7 October 1996*, 1999.

[190]  J. M. Coles, *Archaeology by Experiment*. London: Hutchinson, 1973.

[191]  D. B. Bamforth, "Conducting Experimental Research as a Basis for Microwear Analysis," in *Designing Experimental Research in Archaeology: Examining Technology through Production and Use*, J. F. Ferguson, Ed. Boulder: University Press of Colorado, 2010, pp. 93–110.

[192]  R. Hermann, A. Dolfini, R. J. Crellin, Q. Wang, and M. Uckelmann, "Bronze Age Swordsmanship: New Insights from Experiments and Wear Analysis," *J. Archaeol. Method Theory*, vol. 27, no. 4, pp. 1040–1083, 2020.

[193]  B. Molloy, "Use-wear analysis and use-patterns of Bronze Age swords," *Bronze Age Warf. Manuf. Use Weapon.*, pp. 67-84., 2011.

[194]  B. Molloy, "Martial arts and materiality: A combat archaeology perspective on Aegean swords of the fifteenth and fourteenth centuries BC," *World Archaeol.*, vol. 40, no. 1, pp. 116–134, 2008.

[195]  A. L. Van Gijn, "Science and interpretation in microwear studies," *J. Archaeol. Sci.*, vol. 48, pp. 166–169, 2014.

[196]  R. O'Flaherty, M. D. Gilchrist, and T. Cowie, "Ceremonial or deadly serious? New insight into the function of Irish early Bronze Age halberds," in *Bronze Age warfare: manufacture and use of weaponry.*, M. Uckelmann and M. Mödlinger, Eds. Oxford: Archaeopress, 2011, pp. 39–52.

[197]  J. J. Butler and J. v. d. Waals, "Bell Beakers and early metal- working in the Netherlands," *Palaeohistoria*, vol. 12, pp. 44–139, 1966.

[198]  H. H. Coghlan, *Notes on the prehistoric metallurgy of copper and bronze in the old world*, 2nd ed. Oxford: Oxford University Press, 1975.

[199]  T. Penniman and A. I., "A metallurgical study of four Irish Early Bronze Age ribbed halberds in the Pitt Rivers Museum, Oxford," *MAN*, vol. 60, pp. 85–89, 1960.

[200]  E. Figueiredo, R. J. C. Silva, M. F. Araújo, and J. C. Senna-Martinez, "Identification of ancient gilding technology and Late Bronze Age metallurgy by EDXRF, Micro-EDXRF, SEM-EDS and metallographic techniques," *Microchim. Acta*, vol. 168, no. 3, pp. 283–291, 2010.

[201]  D. Dungworth, "An experimental study of early bronze smithing techniques," in *Accidental and Experimental Archaeometallurgy*, D. Dungworth and R. C. P. Doonan, Eds. London: Historical Metallurgy Society, 2013, pp. 149–152.

[202]  O. Oudbashi and P. Davami, "Metallography and microstructure interpretation of some archaeological tin bronze vessels from Iran," *Mater. Charact.*, vol. 97, pp. 74–82, Nov. 2014.

[203]  D. Mu, P. H. Nan, J. Y. Wang, G. D. Song, and W. G. Luo, "Metallurgical and Chemical Characterization of Bronze Remains Found at the Houhe Site in Shanxi Province, China," *Jom*, vol. 67, no. 7, pp. 1659–1666, May 2015.

[204]  M. Modlinger, "Ritual object or powerful weapon? the usage of central Europe Bronze Age swords," in *Warfare in Bronze Age Europe: Manufacture and Use of Weaponry.*, M. Uckelmann and M. Modlinger, Eds. Oxford: Archaeopress, 2011, pp. 153–166.

[205]   K. Anderson, "Slashing and thrusting with Late Bronze Age spears: analysis and experiment," *Antiquity*, vol. 85, no. May 2010, pp. 599–612, 2011.

[206]   H. McKerrell and R. F. Tylecote, "The working of copper-arsenic alloys in the Early Bronze Age and the effect on the determination of provenance," *Proc. Prehist. Soc.*, vol. 38, pp. 209–218, 1972.

[207]   C. Horn, "Weapons, fighters and combat: spears and swords in Early Bronze Age Scandinavia," *Danish J. Archaeol.*, vol. 2, no. 1, pp. 20–44, 2013.

[208]   J. York, "The Life Cycle of Bronze Age Metalwork From the Thames," *Oxford J. Archaeol.*, vol. 21, no. 1, pp. 77–92, 2002.

[209]   C. Soriano Llopis, I. Gutierrez Sáez, "Use-wear analysis on metal: the influence of raw material and metallurgical production processes," *Archaeometall. Eur.*, pp. 115–124, 2007.

[210]   Micropasts, "Bronze Age Palstaves," 2015. [Online]. Available: https://sketchfab.com/micropasts/collections/bronze-age-palstaves. [Accessed: 21-Feb-2018].

[211]   J. A. Barceló and J. Pijoan-López, "Using Neural Networks to distinguish kinematics in use-wear analysis," *Bar Int. Ser.*, vol. 1227, pp. 427–431, 2004.

[212]   J. A. Barceló, "Automatic Archaeology: Bridging the Gap between Virtual Reality, Artificial Intelligence, and Archaeology," in *Theorizing Digital Cultural Heritage*, F. Cameron and S. Kenderdine, Eds. Cambridge, US: The MIT Press, 2007, pp. 437–456.

[213]   A. A. Evans and R. E. Donahue, "The elemental chemistry of lithic microwear: an experiment," *J. Archaeol. Sci.*, vol. 32, no. 12, pp. 1733–1740, 2005.

[214]   P. C. Anderson, J.-M. Georges, R. Vargiolu, and H. Zahouani, "Insights from a tribological analysis of the tribulum," *J. Archaeol. Sci.*, vol. 33, no. 11, pp. 1559–1568, 2006.

[215]   A. A. Evans and R. E. Donahue, "Laser scanning confocal microscopy: a potential technique for the study of lithic microwear," *J. Archaeol. Sci.*, vol. 35, no. 8, pp. 2223–2230, 2008.

[216]   A. Ollé and J. Vergès, "SEM functional analysis and the mechanism of microwear formation," *Prehist. Technol. 40 Years Later Funct. Stud. Russ. Leg.*, pp. 39–49, 2008.

[217]   N. E. Stevens, D. R. Harro, and A. Hicklin, "Practical quantitative lithic use-wear analysis using multiple classifiers," *J. Archaeol. Sci.*, vol. 37, no. 10, pp. 2671–2678, 2010.

[218]   L. Astruc, R. Vargiolu, M. Ben Tkaya, N. Balkan-Atlı, M. Özbaşaran, and H. Zahouani, "Multi-scale tribological analysis of the technique of manufacture of an obsidian bracelet from Aşıklı Höyük (Aceramic Neolithic, Central Anatolia)," *J. Archaeol. Sci.*, vol. 38, no. 12, pp. 3415–3424, 2011.

[219]   A. A. Evans and D. MacDonald, "Using metrology in early prehistoric stone tool research: Further work and a brief instrument comparison," *Scanning*, vol. 33, no. 5, pp. 294–303, 2011.

[220]   C. Giusca, A. Evans, D. Macdonald, and R. Leach, "The Effect of Use Duration on Surface Roughness Measurements of Stone Tools," vol. NPL Report, pp. 1–15, 2012.

[221]   W. J. Stemp and S. Chung, "Discrimination of surface wear on obsidian tools using LSCM and RelA: Pilot study results (area-scale analysis of obsidian tool surfaces)," *Scanning*, vol.

33, no. 5, pp. 279–293, 2011.

[222]  W. J. Stemp, M. D. Andruskiewicz, M. A. Gleason, and Y. H. Rashid, "Experiments in ancient Maya bloodletting: quantification of surface wear on obsidian blades," *Archaeol. Anthropol. Sci.*, vol. 7, no. 4, pp. 423–439, 2015.

[223]  J. J. Ibáñez, P. C. Anderson, J. González-Urquijo, and J. Gibaja, "Cereal cultivation and domestication as shown by microtexture analysis of sickle gloss through confocal microscopy," *J. Archaeol. Sci.*, vol. 73, pp. 62–81, 2016.

[224]  F. d'Errico and L. Backwell, "Assessing the function of early hominin bone tools," *J. Archaeol. Sci.*, vol. 36, no. 8, pp. 1764–1773, 2009.

[225]  J. Bradfield, "Investigating the potential of micro-focus computed tomography in the study of ancient bone tool function: results from actualistic experiments," *J. Archaeol. Sci.*, vol. 40, no. 6, pp. 2606–2613, 2013.

[226]  L. Tumung, B. Bazgir, and A. Ollé, "Applying SEM to the study of use-wear on unmodified shell tools: an experimental approach," *J. Archaeol. Sci.*, vol. 59, pp. 179–196, 2015.

[227]  A. Ollé and J. M. Vergès, "The use of sequential experiments and SEM in documenting stone tool microwear," *J. Archaeol. Sci.*, vol. 48, pp. 60–72, 2014.

[228]  T. F. J. Quinn, *The Application of Modern Physical Techniques to Tribology*. New York: Van Nostrand Reinhold Company, 1972.

[229]  A. Majumdar and B. Bhushan, "Role of fractal geometry in roughness characterization and contact mechanics of rough surfaces," *ASME J. Tribol.*, vol. 112, pp. 205–216, 1990.

[230]  I. M. Hutchings, "Materials in Tribology -Opportunities and Challenges⌷," in *Total tribology : engineering lubrication and wear lifecycle*, I. Sherrington, W. B. Rowe, and R. J. K. Wood, Eds. London: Professional Engineering Publishing, 2002, pp. 27–38.

[231]  G. W. Stachowiak and A. W. Batchelor, *Engineering Tribology*. Oxford: Butterworth-Heinemann, 2013.

[232]  B. Bhushan, *Principles and Applications of Tribology*. New Jersey: John Wiley & Sons, 2013.

[233]  J. Takadoum, *Materials and Surface Engineering in Tribology*. New Jersey: John Wiley & Sons, 2013.

[234]  W. Borchardt-Ott, *Crystallography An Introduction*, 3rd ed. 2012.

[235]  J. R. Davis, *Copper and Copper Alloys*. Ohio: ASM International, 2001.

[236]  C. Hammond, *The Basics of Crystallography and Diffraction*. Oxford: Oxford University Press, 2009.

[237]  J. Henderson, *The science and archaeology of materials. An investigation of inorganic material*. London: Routledge, 2000.

[238]  S. P. Needham, M. N. Leese, D. R. Hook, and M. J. Hughes, "Developments in the Early Bronze Age metallurgy of southern Britain," *World Archaeol.*, vol. 20, no. 3, pp. 383–402, 1989.

[239]  R. F. Cochrane, "Micrograph no 485," *Dissemination of IT for the Promotion of Materials*

*Science*, 2002. [Online]. Available: https://www.doitpoms.ac.uk/miclib/full_record.php?id=485. [Accessed: 05-May-2017].

[240]   R. J. D. Tilley, *Principles and Applications of Chemical Defects*. Florida: CRC Press, 1998.

[241]   W. Borchardt-Ott, *Crystallography*. Berlin: Springer-Verlag Berlin Heidelberg, 2012.

[242]   D. Dungworth and D. Dungworth, "Further Experiments in Annealing Low Tin Bronze Further Experiments in Annealing Low Tin Bronze," 2002.

[243]   Brush Wellman Inc, "Grain Size and Material Strength," *Technical Tidbits*, no. 15, 2010.

[244]   U. of Cambridge, "Introduction to mechanical testing - Results 2," 2018. [Online]. Available: https://www.doitpoms.ac.uk/tlplib/mechanical-testing/results2.php. [Accessed: 21-Feb-2018].

[245]   J. R. Maréchal, "Etude sur les propriétés mécaniques des cuivre à l'arsenic, suivie de quelques considérations générales sure l'ancienneté comparée des métaux," *Métaux Corros. Ind.*, vol. 33, pp. 377–383, 1958.

[246]   P. Budd and B. S. Ottaway, "The properties of arsenical copper alloys: implications for the development of Eneolithic metallurgy," in *Archaeological sciences*, P. Budd, B. Chapman, C. Jackson, R. Janaway, and B. S. Ottaway, Eds. Oxford: Oxbow, 1991, pp. 132–42.

[247]   H. Lechtman, "Arsenic Bronze: Dirty Copper or Chosen Alloy? A View from the Americas," *J. F. Archaeol.*, vol. 23, no. 4, pp. 477–514, 1996.

[248]   K. Holmberg and A. Matthews, *Coatings Tribology Properties, Techniques and Applications in Surface Engineering*. Amsterdam: Elsevier Ltd, 1994.

[249]   B. Bhushan, *Introduction to Tribology*. New Jersey: John Wiley & Sons, 2013.

[250]   B. Bhushan, *Modern Tribology Handbook*. New Jersey: John Wiley & Sons, 2000.

[251]   R. H. Farmer, "Corrosion of Metals in Association with Wood," *Wood*, vol. 27, pp. 326–328, 443–446, 1962.

[252]   L. Robbiola, J.-M. Blengino, and C. Fiaud, "Morphology and mechanisms of formation of natural patinas on archaeological Cu–Sn alloys," *Corros. Sci.*, vol. 40, no. 12, pp. 2083–2111, Dec. 1998.

[253]   C. Soffritti, E. Fabbri, M. Merlin, G. L. Garagnani, and C. Monticelli, "On the degradation factors of an archaeological bronze bowl belonging to a private collection," *Appl. Surf. Sci.*, vol. 313, pp. 762–770, 2014.

[254]   D. Imbardelli, M. C. Gallucci, and G. Chidichimo, "SEM and electrochemical characterization of bronze artifacts from the Francavilla archaeological site," *Archaeol. Anthropol. Sci.*, 2016.

[255]   B. E. Mcclendon and B. E. Mcclendon, "The Sickle's Edge : an Experimental Use-wear Approach to Investigating Sickle Deposition in Bronze Age Europe," The University of Wisconsin-Milwaukee, 2015.

[256]   L. G. Troalen, D. Cox, T. Skinner, A. Ramsey, and D. Bate, "Three-dimensional computed tomography X-Radiographic investigation of a 17th-century watch from the wreck of the Swan, off Duart Point, Mull, Scotland," *Int. J. Naut. Archaeol.*, vol. 39, no. 1, pp. 165–171,

2010.

[257] H.-Y. Nguyen *et al.*, "Seeing through Corrosion: Using Micro-focus X-ray Computed Tomography and Neutron Computed Tomography to Digitally 'Clean' Ancient Bronze Coins," *MRS Proc.*, vol. 1319, 2011.

[258] J. Miles, G. Earl, D. Hinton, I. Sinclair, and M. Mavrogordato, "The use of computed tomography within the study of archaeological coins," *Archaeol. Digit. Era. Pap. from 40th Annu. Conf. Comput. Appl. Quant. Methods Archaeol.*, vol. 6, pp. 35–41, 2012.

[259] M. H. G. Kuijpers, "Early Bronze Age metalworking craftsmanship. An inquiry into metalworking skill and craft based on axes in the North-Alpine region," University of Cambridge, 2014.

[260] H. J. B. Birks, J. Deacon, and S. Peglar, "Pollen Maps for the British Isles 5000 Years Ago," *Proc. R. Soc.*, vol. 189, pp. 87–105, 1975.

[261] S. C. Beckett, "Pollen Influx in Peat Deposits: Values From Raised Bogs in the Somerset Levels, south western England," *New Phytologist*, vol. 83, no. 3. pp. 839–847, 1979.

[262] P. Drewett, "New Evidence for the Structure and Function of Middle Bronze Age Round Houses in Sussex," *Archaeol. J.*, vol. 136, no. 1, pp. 3–11, Jan. 1979.

[263] L. Main *et al.*, "Excavation of a Timber Round-House and Broch at the Fairy Knowe, Buchlyvie, Stirlingshire, 1975-8," *Proc. Soc. Antiq. Scotl.*, vol. 128, pp. 293–417, 1998.

[264] D. W. Green, "Mechanical Properties of Wood," in *Wood handbook: Wood as an Engineering Material*, D. W. Green, J. E. Winandy, and D. E. Kretschmann, Eds. Madison: United States Department of Agriculture Forest Service, 1999, pp. 4.1-4.45.

[265] W. Simpson and A. TenWolde, "Physical properties and moisture relations of wood," in *Wood handbook: Wood as an Engineering Material*, D. Green, J. Winandy, and D. Kretshmann, Eds. Madison: United States Department of Agriculture Forest Service, 1999, pp. 3.1-3.24.

[266] H. Seltman, "Experimental Design and Analysis," *Online B.*, p. 428, 2015.

[267] B. Bril, R. Rein, T. Nonaka, F. Wenban-Smith, and G. Dietrich, "The role of expertise in tool use: Skill differences in functional action adaptations to task constraints.," *J. Exp. Psychol. Hum. Percept. Perform.*, vol. 36, no. 4, pp. 825–839, 2010.

[268] V. Schmitt, "Social and Physical Cognition in Old World Monkeys submitted by," *Dr. Thesis*, 2012.

[269] L. V Luncz *et al.*, "Resource depletion through primate stone technology," *Elife*, vol. 6, pp. 1–16, 2017.

[270] A. A. Zaidi, B. C. Mattern, P. Claes, B. McEcoy, C. Hughes, and M. D. Shriver, *Investigating the case of human nose shape and climate adaptation*, vol. 13, no. 3. 2017.

[271] RStudio, "RStudio: Integrated Development for R. RStudio, Inc." RStudio, Boston, 2015.

[272] D. Bates, M. Maechler, B. Bolker, and S. Walker, "Fitting Linear Mixed-Effects Models Using lme4," *J. Stat. Softw.*, vol. 67, no. 1, pp. 1–48, 2015.

[273] E. El-danaf, M. Soliman, and A. Al-mutlaq, "Correlation of Grain Size , Stacking Fault Energy

, and Texture in Cu-Al Alloys Deformed under Simulated Rolling Conditions," *Adv. Mater. Sci. Eng.*, vol. 2015, no. 3, pp. 1–12, 2015.

[274]  M. Radivojević *et al.*, "The Provenance, Use, and Circulation of Metals in the European Bronze Age: The State of Debate," *J. Archaeol. Res.*, vol. 27, pp. 131–185, 2019.

[275]  D. Scott, "Metallography and microstructure of ancient and historic metals," *Endeavour*, vol. 16, no. 3, p. 152, 1992.

[276]  P. Harbison, "The Axes of the Early Bronze Age in Ireland. Prähistorische Bronzefunde IX:1. Munich.," *Prähistorische Bronzefunde. Munich.*, vol. IX:1, 1969.

[277]  "Additions to the museum," *PSANHS*, vol. 69, pp. lxiii–lxxii, 1923.

[278]  H. H. Coghlan, "An Examination of two Bronze Age Flat Axes from Ireland," *Archaeol. Austriaca*, vol. 41, pp. 48–65, 1967.

[279]  L. V. Grinsell, *Guide Catalogue to the South Western British Prehistoric Collections*. Bristol: Bristol City Museum, 1968.

[280]  D. Dobson, *The Archaeology of Somerset*. 1931.

[281]  PSANHS, "The Museum," *PSANHS*, vol. 14, pp. 29–32, 1867.

[282]  PSANHS, "Additions to the museum," *PSANHS*, vol. 75, pp. lxvi–lxxiv, 1929.

[283]  M. G. Knight, "The Intentional Destruction and Deposition of Bronze Age Metalwork in South West England, volume 2," University of Exeter, 2018.

[284]  H. S. G. Gray, "Additions to the museum from January 1st to December 31st 1912," *Somerset Archaeol. Nat. Hist.*, vol. 58, pp. 104–123, 1912.

[285]  L. A. Humphreys, *Materials for the history of Wellington, co. Somerset*. 1889.

[286]  H. S. . Gray, "Bronze implements found in the parish of Old Cleeve, Somerset," *PSANHS*, vol. 77, pp. 136–137, 1931.

[287]  M. G. Knight, "The Mnemonics of 'Out-of-Time' Bronze Objects: An Assessment of Earlier Bronze Objects in Later Bronze Age Contexts," University of Exeter, 2014.

[288]  Needham S P, "The EBA Axeheads of Central & Southern England," Cardiff, 1983.

[289]  PSANHS, "Additions to the museum," *PSANHS*, vol. 78, pp. lxxv–lxxxiii, 1932.

[290]  C. F. Pendleton, "Aspects of bronze age metalwork in northern East Anglia," University of Nottingham., 1992.

[291]  S. M. Pearce, "The Middle and Late Bronze Age metalwork of the South West, and its relationship to settlement," *PDAS*, vol. 34, pp. 17–40, 1976.

[292]  R. Burnard, "Early Man," in *The Victoria History of the Counties of England: Devon Volume 1*, W. Page, Ed. Archibald Constable and Company Ltd, 1906, pp. 341–372.

[293]  R. Kirwan, "Notes on the prehistoric archaeology of East Devon Part III," *TDA*, vol. 4, no. I, pp. 295–304, 1870.

[294]  A. Way, "Antiquities of Bronze found in Devonshire," *Archaeol. J.*, vol. 26, no. 1, pp. 339–

351, 1869.

[295] R. R. Kirwan, "Notes on the Pre-historic Archaeology of East Devon. Part IV," *Trans. Devonsh. Assoc.*, vol. 2, pp. 641–653, 1871.

[296] H. O. Hencken, *The Archaeology of Cornwall and Scilly*. London: Methuen & Co. Ltd., 1932.

[297] J. E. Pritchard, "Bristol Archaeological Notes for 1903," *Trans. Bristol Gloucestersh. Archaeol. Soc.*, vol. 27, pp. 327–339, 1904.

[298] R. Kirwan, "Memoir of the examination of three barrows at Broad Down, Farway, near Honiton," *TDA*, vol. 2, no. 2, pp. 619–649, 1868.

[299] D. Boughton, "The Early Iron Age socketed axes in Britain: A study of their typology, distribution, associations and contexts," University of Lancashire., 2015.

[300] R. N. (ed) Worth, "Second report of the barrow committee," *TDA*, vol. 12, pp. 119–151, 1880.

[301] V. Roskill, "Bronze Implements of Newbury Region," *Trans. Newbury Dist. F. Club*, vol. 8, pp. 10–41, 1937.

[302] P. H. Ditchfield and W. Page, *The Victoria history of Berkshire*. London: A. Constable and company, 1906.

[303] R. A. H. Farrar, "Archaeological fieldwork in Dorset in 1953 and 1954," *PDNHAS*, vol. 76, pp. 74–99, 1954.

[304] PSANHS, "The Museum," *PSANHS*, vol. 1, no. i, pp. 22–26, 1849.

[305] H. S. G. Gray, "Additions to the museum from July 2nd 1924 to July 21st (annual meeting) 1925," *Somerset Archaeol. Nat. Hist.*, vol. 71, pp. lxxxi–lxxxvii, 1925.

[306] PSANHS, "Additions to the museum," *PSANHS*, vol. 71, pp. lxxxi–lxxxvii, 1925.

[307] H. S. G. Gray, "Additions to the Museum," *Somerset Archaeol. Nat. Hist.*, vol. 78, pp. lxxv–lxxxiii, 1932.

[308] H. S. G. Gray, "Proceedings of the Somerset Archaeological and Natural History Society," *Somerset Archaeol. Nat. Hist.*, vol. 51, 1905.

[309] H. Norris, "Antiquities and works of art exhibited," *Arch J*, vol. 10, pp. 246–248, 1853.

[310] S. M. Pearce, "A palstave hoard from South Petherton, Somerset," *PSANHS*, vol. 118, pp. 54–55, 1974.

[311] J. W. Brailsford, "Bronze Age stone monuments of Dartmoor," *Antiquity*, vol. 12, 1938.

[312] A. Fox, "Twenty-third report on the archaeology and early history of Devon," *TDA*, vol. 88, pp. 212–221, 1956.

[313] S. M. Pearce, "Stone and bronze implements found in Devon," *PDAS*, vol. 26–30, pp. 236–238, 1972.

[314] A. Fox, "Twenty-second report on the archaeology and early history of Devon," *TDA*, vol. 87, pp. 319–326, 1955.

[315] S. M. Pearce, "Prehistoric implements from Devon," *PDAS*, vol. 33, pp. 125–127, 1975.

[316] G. Appleby, "Metalwork," in *Excavations at Ham Hill, Somerset (2011)*, A. Slater and M. Brittain, Eds. Cambridge: Cambridge Archaeological Unit Report No. 1101, 2012, pp. 48–56.

[317] H. S. G. Gray, "The 'Walter Collection' in Taunton Castle Museum," *PSANHS*, vol. 48, no. ii, pp. 24–78, 1902.

[318] R. C. Hoare, "Account of antiquities found at Hamden Hill, fragments of British chariots," *Archaeologia*, vol. 21, pp. 39–48, 1827.

[319] A. J. Lawson, "Copper alloy objects', in McKinley, J.I. 'Excavations at Ham Hill, Montacute," *PSANHS*, vol. 142, pp. 109–112, 1998.

[320] J. I. McKinley, "Excavations at Ham Hill, Montacute," *PSANHS*, vol. 142, pp. 77–137, 1998.

[321] R. J. C. Smith, "Montacute, Ham Hill Stone Quarry ST 48201605', in Webster, C.J. and Croft, R.A. (ed) 'Somerset Archaeology, 1994'',''" *PSANHS*, vol. 138, p. 171, 1995.

[322] PSANHS, "Additions to the museum," *PSANHS*, vol. 73, pp. lxxv–lxxxii, 1927.

[323] W. Stradling, "The turbaries between Glaston and the sea," *PSANHS*, vol. 1, no. ii, pp. 48–62.

[324] E. G. Fregni, "The Compleat Metalsmith : Craft and Technology in the British Bronze Age," no. June, 2014.

[325] J. H. Pring, "On Some Evidences of the Occupation of the Ancient Site of Taunton by the Britons," *Arch J.*, vol. 37, pp. 94–8, 1880.

[326] S. M. Pearce, "The finds of Bronze Age material from Kent's Cavern, Torquay', Torquay," *Nat. Hist. Soc. Trans. Proc.*, vol. 16, pp. 176-194., 1974.

[327] S. Pearce, "The distribution and production of Bronze Age metalwork," *Devon Archaeol. Soc. Proc.*, vol. 37, pp. 136–145, 1979.

[328] A. Passmore, "Linhay Hill Quarry, Ashburton, Devon: Historic Environment Assessment.," 2015.

[329] J. G. Croker, "Proceedings at the meetings of the Archaeological Institute," *Arch J.*, vol. 9, pp. 185–186, 1852.

[330] C. Tucker, "Notices of antiquities of bronze found in Devonshire," *Arch J.*, vol. 24, no. 1, pp. 110–122, 1867.

[331] D. and C. N. and Queries, "Devon and Cornwall Notes and Queries," *Devon and Cornwall Notes and Queries*, vol. 133.

[332] A. Fox, "Nineteenth report on the archaeology and early history of Devon," *TDA*, vol. 84, pp. 242–248, 1952.

[333] C. F. C. Hawkes and M. A. (eds) Smith, *Inventaria Archaeologica 2nd Set: GB.* London, 1955.

[334] B. A. V. Trump, "The origin and development of British Middle Bronze Age rapiers," *PPS*, vol. 28, pp. 80–102, 1962.

[335]  B. O'Connor, *Cross-Channel Relations in the Later Bronze Age*. Oxford: British Archaeological Reports International Series 91., 1980.

[336]  H. S. G. Gray, "Additions to the museum from June 22 1932 to July 11 (annual meeting) 1933.," *Somerset Archaeol. Nat. Hist.*, vol. 79, 1933.

[337]  F. V. Jago, "Letter to Samuel Lysons on discovery of celts and swords on Long Moor, Lanhearn House, Mawgan," *Archaeologia*, vol. 17, pp. 337–8, 1814.

[338]  J. B. Cornish, "Early Man," in *The Victoria History of the Counties of England: Cornwall Volume 1*, W. Page, Ed. London: Archibald Constable and Company Ltd, 1906, pp. 353–374.

[339]  A. Gunstone, "A Middle Bronze Age palstave from Radstock," *Proc. Somerset Archaeol. Nat. Hist. Soc.*, vol. 119, pp. 67–68, 1975.

[340]  A. J. H. Gunstone, "A bronze palstave from Radstock, Somerset: addendum.," *Somerset Archaeol Natur Hist*, vol. 121, p. 132, 1977.

[341]  E. La Trobe-Bateman, "Avon extensive urban survey. Archaeological Assessment Report. Norton-Radstock," no. December, 1999.

[342]  M. A. (ed) Smith, *Inventaria Archaeologica 7th Set: GB*. London: Garraway Ltd., 1959.

[343]  "Proceedings of the Suffolk Institute of Archaeology," *Suffolk Inst. Archaeol.*, vol. 3, no. 3, p. 414, 1863.

[344]  H. S. G. Gray, "Double-looped palstave found at Curland near Taunton," *Ant. J.*, vol. 17, pp. 63–69, 1937.