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Recent Developments in the Use of High Pressures for the Production of Nanostructured Materials

*Chuan Ting Wang, Zheng Li, Jing Tao Wang, and Terence G. Langdon**

This article is dedicated to Professor Reinhard Pippan on the occasion of his 70th birthday.

The use of pressure to achieve superior properties in metals, especially for use in a range of weaponry, has a long history dating back to the artisans of ancient China and many parts of Asia. Nevertheless, scientific principles were not introduced until the classic experiments conducted by Nobel Laureate Professor Percy Bridgman at Harvard University almost 100 years ago and these experiments led directly to the development of metal processing through the procedure now known as high-pressure torsion (HPT). This review provides a brief overview of the historical evolution of pressure as a convenient tool in metal-working and then summarizes the major features associated with the processing of metals by HPT and, more recently, the torsional straining of stacked disks in HPT to produce a range of hybrid materials. Finally, there is a brief report on the development of the relatively new processing procedure of tube high-pressure shearing (t-HPS) which may be used for the fabrication of metal matrix composites.

1. Introduction

The processing of metals through the application of high pressures has a long history dating back to ancient times but it is only within the last three or more decades that it has become recognized as a major scientific tool not only in achieving exceptional grain refinement but with the added capability of producing unusual and excellent properties in many structural materials. The possible significance of this approach was identified by Professor Reinhard Pippan of the Erich Schmid Institute of Materials Science in Leoben, Austria, with a very early report in 2002, one of the first publications in Europe outside of Russia, describing the experimental use of high-pressure torsion (HPT)[1] and this was followed by several additional papers in 2003[2–5] and numerous publications in later years. This present report provides a brief summary of the historical developments in this field and then describes very recent experimental data obtained by using a new and important processing procedure whereby pressure is applied through tube high-pressure shearing (t-HPS).

In order to place this report in perspective, it is first necessary to define the appropriate terminology. The processing of metals through the application of high pressures is defined by the general term of severe plastic deformation or severe plastic deformation (SPD) where the principles of SPD processing, and the various experimental techniques that may be used for SPD, were described in an early report.[6] Specifically, processing by SPD was defined formally as "any method of metal forming under an extensive hydrostatic pressure that may be used to impose a very high strain on a bulk solid without the introduction of any significant change in the overall dimensions of the sample and having the ability to produce exceptional grain refinement".[6] More recent reviews are now available documenting the later developments in SPD processing but the basic definition remains unchanged.[7–10]

Although this type of processing is now attracting much attention within the worldwide scientific community, the basic principles go back to ancient times and appear to have been initiated in China over two thousand years ago. Thus, it is necessary to first consider the significance of this type of processing in the pre-scientific age and then to examine the later development of scientific principles and well-formulated experimental techniques that are now associated with SPD processing.

2. Metal Processing in the Pre-Scientific Age

The period of human prehistory is often divided into the three consecutive time intervals of the Stone Age, the Bronze Age, and

C. T. Wang
School of Mechanical Engineering
Nanjing University of Science and Technology
Nanjing 210094, China

Z. Li, J. T. Wang
School of Materials Science and Engineering
Nanjing University of Science and Technology
Nanjing 210014, China

T. G. Langdon
Materials Research Group
Department of Mechanical Engineering
University of Southampton
Southampton SO17 1BJ, UK
E-mail: langdon@soton.ac.uk

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the Iron Age where this effectively delineates the gradual evolution from primitive man into a basic metal processing society. In a comprehensive review summarizing the historical development of the early types of SPD processing[11] it was suggested that the fabrication of high quality steel swords probably became important in ancient China in about 500 BC and this led to the fabrication of Bai-Lian steel where the sheet metal is, as defined by the Chinese term Bai-Lian, repeatedly folded and forged to make a stronger and more effective product. Often these products would have markings giving a number which appears to represent the number of consecutive foldings and forgings applied in their fabrication where 30, 50, or even up to 100 folds appear to be typical. In the primitive pre-scientific society prevailing at that time, these metal-working artisans would have appreciated the high quality of the finished products, and especially the high strengths that may be attained, but they would have no understanding of the significance of the folding-forging operation and the inherent need to introduce dislocations and thereby to achieve higher strength through grain refinement. Some later reports also describe the early developments in the SPD processing of swords and knives.[12,13]

In practice, the principles associated with the processing of Bai-Lian steels spread initially to Japan and then to India where the famous Wootz steel, exhibiting a high impact hardness, was developed in the period between about 300 BC and 300 AD. Wootz steel was characterized recently as “an advanced material of the ancient world” in recognition of the exceptional properties that were imparted into the material about two thousand years ago.[14] Later, Wootz steel and the processing technology spread through the Middle East where it was encountered in Damascus in ancient Syria by Europeans travellers and given the name Damascus steel.[15] This steel, which is an ultrahigh carbon steel, was produced up to approximately the middle of the 18th century in several countries including Persia where it was known as Poulad Janherder steel and Russia where it became famous as Bulat steel, However, ultimately the fabrication principles of this steel were essentially lost.[16] Despite this loss, it is important to note that, even in the absence of well-defined scientific principles, there were very significant developments in ancient times within the field now designated as SPD processing.

3. Metal Processing in the Scientific Age with an Emphasis on the Effect of Pressure

The application of scientific principles to studies of natural phenomena began several centuries ago but initially there was relatively little emphasis on the effects of pressure on solids such as metals and geological materials. This changed with the advent of the classic experiments conducted by Professor Percy W. Bridgman at Harvard University which started shortly after the start of the 20th century but culminated especially in a series of classic experiments relating shearing stresses and high hydrostatic pressures as conducted and reported in the 1930s and 1940s.[17–19] A simple apparatus for simultaneously applying both a pressure and torsional straining to a thin disk was first proposed and illustrated schematically in 1935[17] and these principles essentially form the basis of the modern SPD processing procedure known as HPT.

In a later book published in 1952 Bridgman summarized much of the earlier experimental work and **Figure 1**, taken from this book, provides a valuable illustration of the very early use of HPT.[20] In this illustration, the two ends of a bar are held rigidly, the bar is subjected to longitudinal compression and the central section is rotated with respect to the ends. This rotation effectively imposes torsional straining on the two smaller machined segments having reduced radii. In describing the principles of this approach, Bridgman put forward the following observation:

“Although no feasible method has been found for conducting torsion experiments in a medium under hydrostatic pressure, something not dissimilar is possible by combining torsion with simple axial compression along the axis of twist.”

Bridgman used various modifications of these principles in order to process very large numbers of samples, both metallic and non-metallic, but with a primary interest in using high pressures for the production of phase transformations. A comprehensive review of this early work is now available.[21]

For comparison, **Figure 2** illustrates a modern HPT facility where the sample, in the form of a thin disk, is placed between two massive anvils, subjected to an applied pressure, *P*, and then either the top or bottom anvil is rotated to impose a torsional strain on the sample.[22] This is generally termed quasi-constrained HPT because the two anvils are not touching so that there is a small outflow of material around the periphery of the disk during processing.[23,24] This contrasts with unconstrained HPT where the sample is free to flow outwards over the total thickness of the disk and constrained HPT where no outward flow is possible because the disk fits within a cavity on the lower anvil.[25] Almost all modern HPT processing is now conducted under quasi-constrained conditions.

4. The Significance of Using Microstructural Analysis

Historically, Bridgman’s research made many new and important contributions to the understanding of physical principles

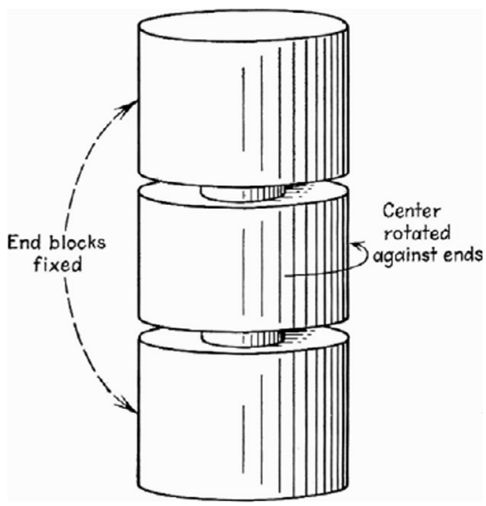

Figure 1. Schematic illustration of the apparatus used by Bridgman to achieve torsional straining combined with longitudinal compression.[20] Reproduced with permission.[33] Copyright 2008, Elsevier.

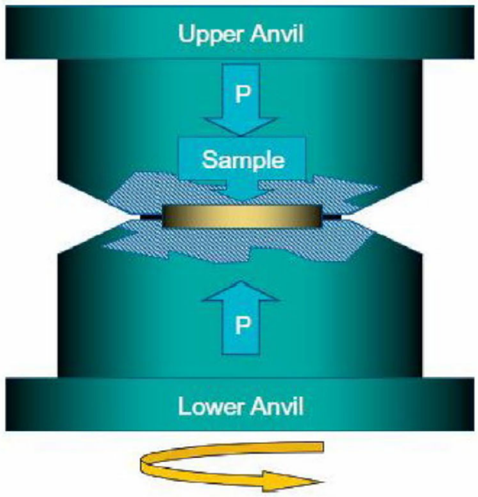

Figure 2. Illustration of the principles of HPT under quasi-constrained conditions.[22] Reproduced with permission.[22] Copyright 2008, Elsevier.

and in 1946 Bridgman received the Nobel Prize in Physics for his work in the field of high pressure physics. Furthermore, the results of Bridgman attracted much attention from high pressure physicists but, surprisingly, they received little or no interest within the materials science community. The reason was because Bridgman's research focused on the mechanics of deformation and it was conducted in the years before the availability of modern electronic instruments, such as transmission electron microscopes (TEM), so that it was not feasible to conduct critical microstructural examinations of the processed crystalline materials.

Nevertheless, research on HPT was conducted later by numerous scientists in Russia[26,27] and this led, in 1988, to the publication of a classic report documenting, through the use of HPT, the production of an average grain size of ≈0.3 μm as measured using TEM in an Al-4% Cu-0.5% Zr alloy.[28] This grain refinement to the submicrometer level was exceptional because a similar alloy of Al-6% Cu-0.4% Zr was developed in the UK and designated Supral 100 for use in superplastic forming operations. However, this British commercial alloy typically had grain sizes of ≈3–5 μm and this was about one order of magnitude larger than the Russian alloy processed by HPT. Furthermore, it was not possible in western laboratories to achieve grain refinement of this alloy to the submicrometer level using conventional thermo-mechanical processing.[29]

The demonstration of the exceptional grain refinement that may be achieved through HPT processing led to the gradual development of HPT facilities in many laboratories around the world and the consequent publication of numerous research reports. The first scientific papers published on the processing of metals by HPT outside of Russia appeared in 1996[30–32] and in 2008 a comprehensive review was published describing the results achieved in HPT processing to date.[33] Some of the more important results obtained from processing by HPT, both in the early research and more recently, are summarized in the following sections.

5. The Important Characteristics of HPT Processing

Several different SPD processing procedures are now available but the two techniques receiving most attention are HPT and equal-channel angular pressing (ECAP).[34] In ECAP the sample, in the form of a bar or rod, is pressed through a die constrained within a channel that is bent through a sharp angle, often equal to 90°, near the centre of the die. The procedures of HPT and ECAP are both capable of producing significant grain refinement but experiments show that the average grain sizes produced by HPT are smaller than in ECAP[35,36] and HPT also produces a higher fraction of boundaries having high angles of misorientation.[37]

There are three important differences between HPT and ECAP.

First, the sample sizes are generally small in all aspects of SPD processing but they are especially small in HPT where the sample is usually in the form of a thin disk. This is an important limitation in any attempts to make use of these materials for industrial productions. Recent reviews have examined the potential for using SPD processing, including HPT, in the fabrication of battery materials[38] and materials for advanced medical devices[39] but nevertheless it is readily recognized that a scaling up of the processing methods is needed for the successful commercialization of bulk samples in industry.[40] In practice, processing by HPT is not easily scaled to samples having large volumes[41–43] whereas it is relatively easy to scale to larger samples when processing by ECAP.[44,45]

Second, very large strains can be attained in HPT by simply continually rotating the sample through large numbers of turns. By contrast, processing by ECAP is labour-intensive because attaining a high strain requires removing the sample from the die after every pass and then reinserting for each subsequent pass.

Third, the strain introduced in ECAP is given by a simple relationship that, neglecting any minor effects along the outer edges of the sample due to contact with the die walls, applies equally throughout the cross-sectional area and over the total length of the sample.[46] In HPT processing the strain is more complex because it depends upon the radial position on the sample. Specifically, the equivalent von Mises strain, ε_{eq}, is given by a relationship of the form[47–49]

$$\varepsilon_{eq} = \frac{2\pi N r}{h\sqrt{3}} \qquad (1)$$

where N is the total number of turns in the torsional straining, r is the radial distance measured from the centre of the disk, and h is the initial height (or thickness) of the sample. Thus, it is readily apparent from Equation (1) that the strain varies across the disk such that there is a maximum strain at the outer edge but the strain reduces to zero at the centre of the disk. Attempts have been made recently to reduce this strain gradient by machining special anvils so that the depth of the depression containing the sample varies linearly with the radius.[50]

6. Examples of Fundamental Results in HPT Processing

Processing by HPT produces significant grain refinement and this was confirmed for a Cu-0.1% Zr alloy processed by quasi-constrained HPT at room temperature (RT) under an applied pressure of 6.0 GPa and with the alloy having an initial grain size of ≈20 μm.[51] Examples of the microstructures after HPT testing are shown in **Figure 3** where the left column is at the centre of each disk, the right column is at the edge and separate images are shown after 1) 1/4 turn; 2) 5 turns; and 3) 10 turns.[52] Inspection of Figure 3 shows that the original coarse grains are visible in the central region after 1/4 turn but there is evidence for grain refinement at the edge of the disk even after this very low strain. There is evidence for grain refinement throughout the samples after 5 and 10 turns, even in the central region where the strain is nominally zero, such that the grain sizes after 10 turns were measured as ≈270 and ≈230 nm at the centre and edge of the disk, respectively.

It is apparent from Equation (1) that the microstructure produced by HPT processing should be very inhomogeneous and this may be reflected in measurements of the local values of the Vickers hardness, *Hv*, at selected positions across the

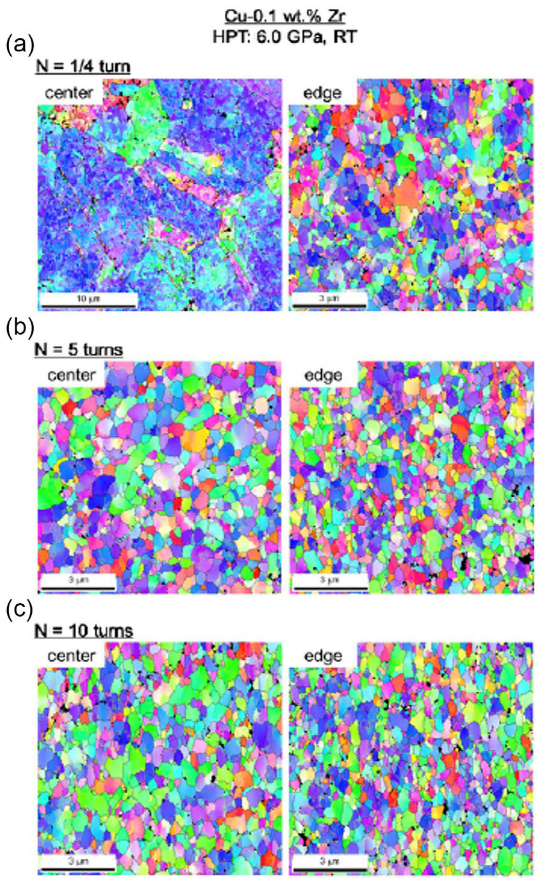

Figure 3. Electron backscatter diffraction images of Cu-0.1% Zr disks processed by HPT for a) 1/4 turn, b) 5 turns, and c) 10 turns in the central (left) and edge (right) positions.[52] Reproduced under Copyright Agreement with Scientific.Net.[52]

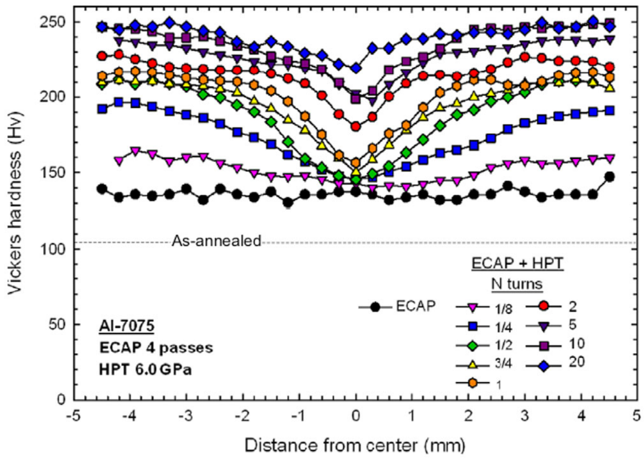

Figure 4. Values of the Vickers microhardness across diameters of disks of an Al-7075 alloy after ECAP for four passes and a combination of ECAP for four passes and various numbers of turns of HPT; the lower dashed line shows the as-annealed condition.[53] Reproduced with permission.[53] Copyright 2014, Elsevier.

diameters of HPT disks. An example is shown in **Figure 4** for an Al-7075 alloy where the lower horizontal line shows the hardness in the as-annealed condition and the experimental points are for samples processed through four passes of ECAP at 473 K (lower line) and then by ECAP followed by HPT at RT using a pressure of 6.0 GPa and various numbers of turns from 1/8 to 20 (upper lines).[53] It is apparent that lower hardness values are generally recorded in the central region of the disk but the hardness values tend to become more nearly equal across the diameter with increasing numbers of revolutions up to at least 20 turns.

If the torsional straining is continued through a sufficiently large number of revolutions then it is possible to achieve similar values of hardness across the HPT disk, even through the central region where the strain is nominally zero. An example is shown in **Figure 5** where separate disks of commercial purity Al (Al-1050) and the ZK60 Mg alloy were stacked in the HPT facility and then processed by up to 100 turns at RT under a pressure of 6.0 GPa.[54] After 100 turns it is evident that the hardness is remarkably high and homogeneous with a value of $Hv \approx 340$ across the disk.

An early proposal suggested that it may be possible to correlate the experimental points obtained from microhardness measurements by plotting the values of *Hv* against the equivalent strain.[55] An example of this approach is shown in **Figure 6** where the numerous datum points shown earlier in Figure 4 for the Al-7075 alloy, for both ECAP and ECAP + HPT, are replotted against equivalent strain to give all points clustered around a single line with the values of *Hv* increasing rapidly to a final saturation of $Hv \approx 250$.[53]

Although several reports were available showing that lower values of hardness were generally achieved in the vicinity of the centres of the disks in the early stages of HPT processing, experiments on pure Al of 99.99% purity brought the surprising result that the hardness in the centre of the disk in this material was initially higher than at the edge of the disk.[56]

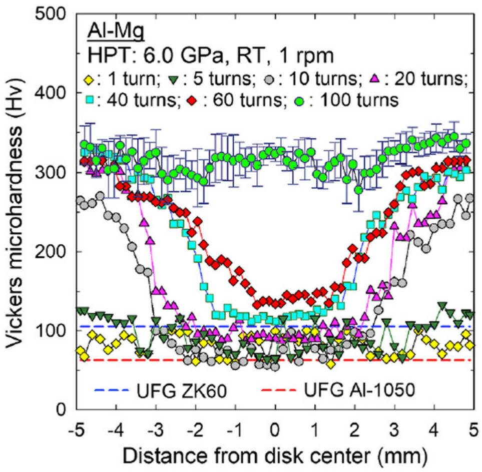

Figure 5. Hardness values where separate disks of commercial purity Al (Al-1050) and the ZK60 Mg alloy were stacked and then processed by up to 100 turns at RT under a pressure of 6.0 GPa: the results show that the hardness values are reasonably homogeneous across the diameter after 100 turns with an average value of $Hv \approx 340$.[54] Reproduced with permission.[54] Copyright 2020, Elsevier.

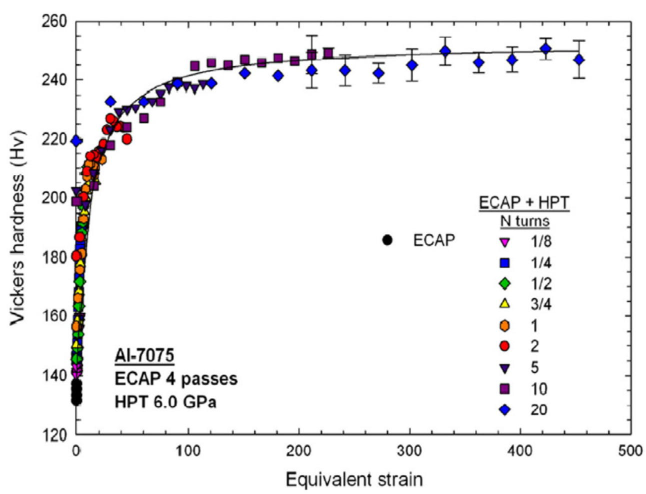

Figure 6. Values of the Vickers microhardness for an Al-7075 alloy plotted against the equivalent strain after processing by ECAP for four passes or a combination of ECAP for four passes and various numbers of HPT turns: the hardness datum points were shown earlier in Figure 4.[53] Reproduced with permission.[53] Copyright 2014, Elsevier.

Later experiments were conducted on the same material to investigate the hardness homogeneity through the thickness of the disks and it was established that the microhardness values were independent of the plane of sectioning within the disk. **Figure 7** shows examples of the hardness values recorded across sections of the disk where the upper and lower sections refer to positions measured at ≈200 μm from the initial upper and lower surfaces of the disk, respectively, and the centre refers to a section cut through the middle of the disk.[57] These colour-coded diagrams display the higher hardness values recorded in the central regions of the disks after 1/2 turn and they demonstrate there is no significant difference between the three separate planes of sectioning. The higher hardness values recorded in the centres of the disks of some materials in the early stages of HPT processing are due to the ease of recovery at the disk edges.[56] Thus, in high purity Al the stacking fault energy is high and recovery occurs rapidly around the edge of the disk so that this hardness is then lower than around the central position. There are several other reports of initial higher hardness values in the centres of the disks as, for example, in a Zn-22% Al eutectoid alloy[58] and a detailed discussion on the nature of hardness evolution in HPT processing is now available.[59]

7. The Use of HPT Processing in the Fabrication of Metal Matrix Hybrids

Several earlier reports described using HPT processing for the cold consolidation at RT of, for example, Cu machining chips[60] or Ti powder[61] but recently this approach was expanded to investigate the potential for using HPT to fabricate metal matrix hybrids.[62] A significant advantage of this approach is that no heating is needed during the processing operation and, in addition, there is the possibility of using different amounts of materials to make hybrids having different structures.[63] There are also results showing that the grain sizes in hybrid materials are smaller than in pure metals.[64–66]

The principle associated with the production of hybrid materials through HPT processing is illustrated in **Figure 8** where a single disk of the ZK60 Mg alloy was placed between two disks of the Al-1050 alloy and these three disks were stacked together within the HPT processing facility as shown in Figure 8a.[67] The configuration is illustrated schematically in Figure 8b and this stacking of three disks is representative of numerous experimental procedures that have been used in the production of hybrid materials.[67] There are also some reports where the same principle was followed but the disks were extremely thin so that it was possible to stack a larger number for the HPT processing. For example, in experiments on pure Cu and pure Ta the disks of both materials were cut to have thicknesses of 25 mm and then 19 Cu disks and 18 Ta disks were stacked so that Cu was the outer disk at the top and bottom and the stacking was then subjected to conventional HPT processing.[68]

Figure 9 shows an example of the results obtained by processing the stack of disks shown in Figure 8 by subjecting to quasi-constrained HPT at RT under an applied pressure of 6.0 GPa using a rotational speed of 1 rpm,[69] The processing was conducted through various numbers of rotations up to a total of 100 turns where the latter corresponds to a maximum shear strain at the edge of the disk of ≈4000. The upper image in Figure 9 shows the microstructures on the cross-sectional planes after processing through 1 and 100 turns, the TEM images in the second row show the grain configurations after processing through 100 turns at the disk edge (left) and at the disk centre (right) and the lowest image shows the colour-coded hardness distribution across the total cross-section after 100 turns. In these experiments a supersaturation of Mg with an average of ≈15 at% was introduced into the Al matrix and a detailed analysis of several samples showed that a bonding of the separate Al–Mg phases was achieved in the early stages of the HPT processing with a pressure of 6.0 GPa but a very high shear strain, typically

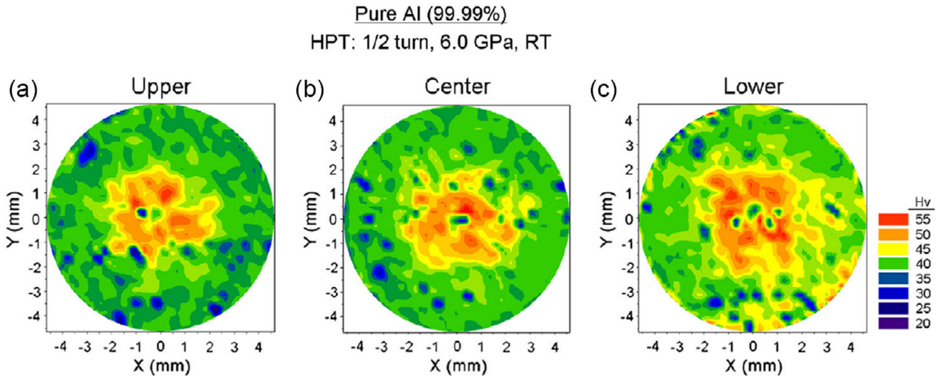

Figure 7. Hardness values recorded across sections of a disk of high purity Al where the upper and lower sections are at ~200 μm from the initial upper and lower surfaces, respectively, and the centre refers to a section cut through the middle of the disk: these plots reveal the higher hardness values recorded in the central region of the disk for a material where there is rapid recovery around the edge of the disk.[57] Reproduced with permission.[57] Copyright 2011, Elsevier.

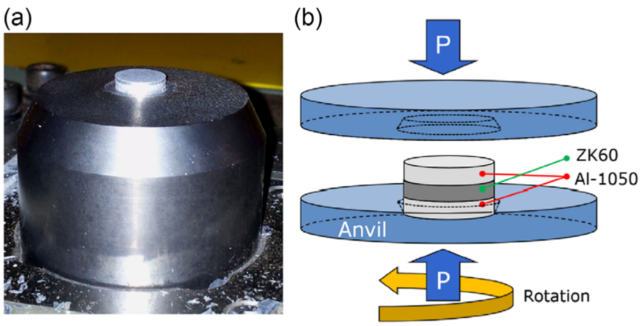

Figure 8. The fabrication of a hybrid material by stacking a single disk of the ZK60 Mg alloy between two disks of the Al-1050 alloy a) within the HPT facility: b) a schematic illustration of the stacking.[67] Reproduced with permission.[67] Copyright 2015, Elsevier.

of at least ≈2500, was required to attain the Al alloy in a fully supersaturated condition.[70] It was readily apparent from these results that processing through 100 turns, which gave a shear strain at the disk edge of ≈4000, was sufficient to accelerate the diffusion of the separate elements during the microstructural refinement and thereby to produce a fully supersaturated alloy. Furthermore, it is apparent from the colour-coded microhardness map in Figure 9 that the sample after 100 turns has a fully homogeneous nanostructure with an exceptionally high final hardness of ≈340 *Hv* which is due both to the grain refinement and to the effect of solid solution strengthening. These and other results demonstrate, therefore, the potential for using this type of HPT processing to produce a wide range of different structural materials.

Finally, many of the more recent results, including for the fabrication of metal matrix hybrids, are described in a recent review outlining the principles of SPD processing and ultrafine-grained materials.[71]

8. Recent Results Using Tube High-Pressure Shearing

There is a significant limitation associated with conventional HPT processing because of both the introduction of a radial strain gradient and the use of disks that are usually exceptionally thin. These problems may be overcome using alternative procedures such as high-pressure tube twisting (HPTT)[72,73] or t-HPS.[74] The historical developments of t-HPS were described in an earlier report and **Figure 10** illustrates the various schemes that have been developed to conduct this type of processing.[75] Briefly, t-HPS requires a direct compression from the die parts to the tube sample so that there is the effective development of a hydrostatic pressure that leads to a state of static friction between the tube wall and the central mandrel and thereby makes it possible to achieve a relative rotation between the inner and outer wall surfaces of the tube.[76]

Numerous results are now available from processing by t-HPS including examples of the production of exceptional superplastic properties with maximum elongations of ≈1870% in a Pb-40% Sn alloy[77] and ≈1820%[78] and 2320%[79] in a Bi-43% Sn alloy. An example of using t-HPS for the development of superplastic flow is shown in **Figure 11** where an as-cast Pb-62% Sn alloy exhibited a flow stress of ≈19 MPa and an elongation to failure of only 164% when pulled in tension at a temperature of 298 K under a strain rate of $1.0 \times 10^{-4}\ s^{-1}$. This result is not superplastic because superplasticity is defined as a tensile elongation of at least 400%.[80] However, when the cast alloy was additionally processed by t-HPS for 53 turns and tested in tension under the same conditions the flow stress was reduced to ≈6 MPa and the elongation to failure increased to 1380% which confirms the occurrence of true superplastic flow. This decrease in flow stress and increase in tensile ductility is consistent with the expectations for materials subjected to grain refinement through SPD processing.[81]

Processing by t-HPS provides a simple method for fabricating bimetallic composites and in this respect the end product has similarities to the composites that may be synthesized using the SPD procedure of accumulative roll bonding (ARB).[82] In ARB a sheet is rolled to reduce the thickness to about one-half of the thickness in the pre-rolled condition, the rolled sheet is then cut into two halves that are stacked together with the contact surfaces degreased and wire-brushed and finally the stacked sample is rolled again to one-half of the thickness. By repetitively

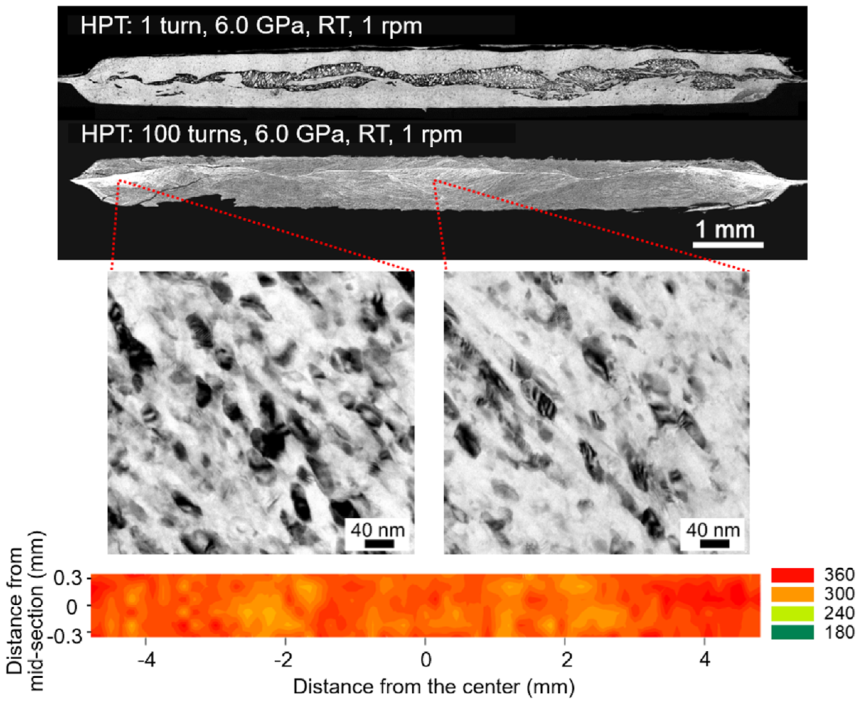

Figure 9. Examples of the results obtained by HPT processing the stack of disks shown in Figure 8: the upper image shows the microstructures on the cross-sectional planes after processing through 1 and 100 turns, the central TEM images show the grains after 100 turns near the disk edge (left) and at the disk centre (right) and the lowest image shows a homogeneous hardness distribution across the cross-section after 100 turns.[69] Reproduced under Copyright Agreement with Springer Nature.[69]

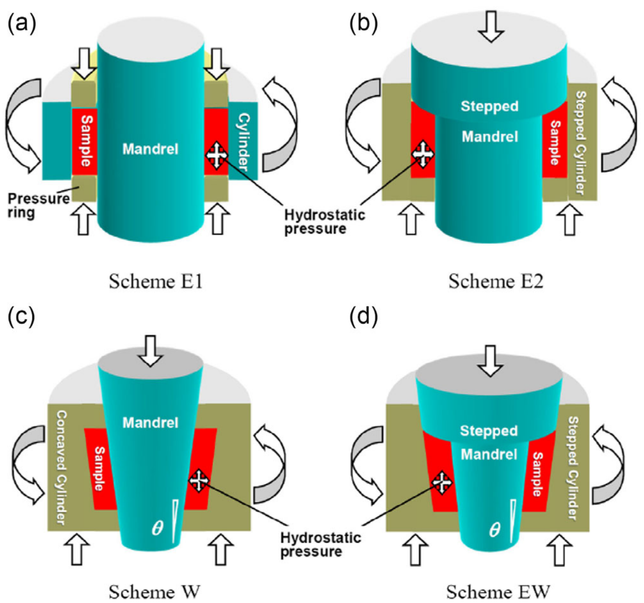

Figure 10. The various schemes developed for conducting processing by t-HPS. a) Scheme E1, b) Scheme E2, c) Scheme W, d) Scheme EW.[75] Reproduced with permission.[75] Copyright 2023, Japan Institute of Metals and Materials.

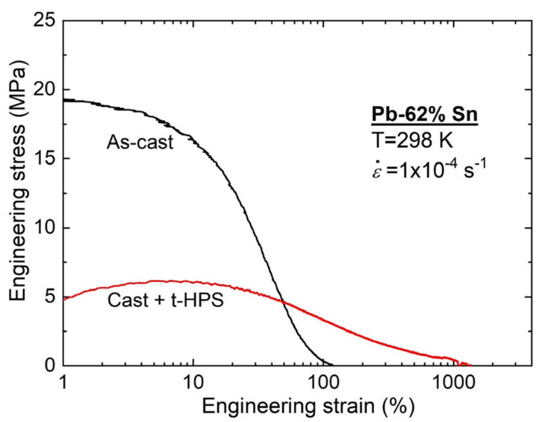

Figure 11. Stress–strain curves for a Pb-62% Sn alloy in the as-cast condition where the alloy is not superplastic and then cast and additionally processed by t-HPS for 53 turns to give true superplastic flow.

following this process, it is possible to accumulate a very large strain within the sheet and this provides a method for producing a metal matrix composite. Nevertheless, ARB is similar to ECAP because it is again a labour-intensive process which requires significant effort to achieve very high strains. By contrast, relatively similar metal matrix composites may be produced using t-HPS and, as documented elsewhere.[75] These composites are achieved in a single processing operation by continuing the shearing through multiple passes. This suggests, therefore, that t-HPS will become a valuable tool in the future production of composite metals.

9. Summary and Conclusions

1) The application of pressure in metal-working operations has a long history dating back to the production of Bai-Lian steel by repetitively folding and forging in ancient China and continuing through the production of Wootz steel in India which evolved as Poulad Janherder steel in Persia, Bulat steel in Russia and Damascus steel in the Middle East; 2) Comprehensive experiments evaluating the effect of pressure in metal-working were conducted by Nobel Laureate Professor Percy Bridgman at Harvard University about 80–90 years ago. The research by Bridgman led to the development of processing by HPT which has now become an established procedure for fabricating strong materials having exceptionally small grain sizes; 3) Processing by HPT provides the capability of achieving submicrometer or even nanometer grain sizes in crystalline materials. Generally, the HPT samples are in the form of thin disks and the strain imposed varies with the radial position such that there is a maximum strain at the edge of the disk and the strain in the central region is zero. This suggests that the microstructure will be inhomogeneous across the disk in HPT and this should be reflected in measurements of the Vickers microhardness. In practice, however, the hardness is initially generally low in the central region but gradually, with increasing numbers of turns, the hardness values become reasonably equal over the disk diameter. In some materials where recovery is rapid at the edge of the disk, higher values of hardness may be recorded initially in the central region; 4) Hybrid materials may be fabricated easily using HPT processing by stacking disks having different compositions within the HPT facility. An example is discussed for the Al–Mg system where a supersaturation of Mg was introduced in the Al matrix and after 100 turns, equivalent to a shear strain of ≈4000 at the disk edge, a fully supersaturated alloy was produced. For these conditions, there was a fully homogeneous structure with a high final hardness of ≈340 Hv; and 5) t-HPS is a relatively new processing technique where a tube sample is subjected to a relative rotation between the inner and outer wall surfaces. This process is capable of producing excellent ultrafine-grained microstructures that exhibit exceptional superplastic properties. Processing by t-HPS provides the capability of synthesizing bimetallic composites that have similarities to those produced using the alternative procedure of ARB. However, by contrast to ARB which is labour-intensive, the synthesis may be achieved in a single step using t-HPS and this demonstrates the high value of this processing method.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

equal-channel angular pressing, high-pressure torsion, severe plastic deformation, tube high-pressure shearing, ultrafine-grained materials

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Chuan Ting Wang is now a professor at School of Mechanical Engineering, Nanjing University of Science & Technology. He received his Ph.D. degree from University of Southampton in 2013 and then carried out post-doctoral research at University of Southern California between 2013 and 2014. His main research interests are flow behavior of materials under high pressure and dynamic behavior of materials under impact.

Zheng Li completed his Ph.D. at Nanjing University of Science and Technology (NJUST), P.R. China in 2018, where he worked on severe plastic deformation (SPD) of metals. He is now a Research Scientist in Jing Tao Wang's group at School of Materials Science and Engineering in NJUST and focuses on restructuring materials by deformation (REMADE), plasticity theory of crystals and other solid-state phenomena.

Jing Tao Wang graduated in powder metallurgy from the Northeast Polytechnique Institute at Shenyang, China, in 1982 and received his Ph.D. in materials processing from the same Institute in 1990. He is now Professor of Materials Processing at the Nanjing University of Science and Technology, and the director of National Centre for International Research on Nano & Micro Materials and Technology, China. His research deals primarily with the Restructuring of Materials by Deformation, especially equal-channel angular pressing and tube high-pressure shearing (t-HPS).

Terence G. Langdon graduated in physics from the University of Bristol in 1961 and received his Ph.D from Imperial College, University of London, in 1965. He is now Professor of Materials Science at the University of Southampton, UK, and Professor of Engineering Emeritus at the University of Southern California, USA. His research deals primarily with the mechanical properties of materials, especially creep, superplasticity and the processing of ultrafine-grained materials using severe plastic deformation.