3D surface roughness of a partial free form dental surface after enamel loss due to acidic erosion using optical and X-Ray CT metrology

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A partial human natural unprocessed dental sample was submerged in Citric Acid (0.3% pH.3.2), for 1 hour, without agitation, over a selected region (diameter 1.5 mm). The sample was measured using the TaiCaan XYRIS 2020 H instrument "before and after" the test and measured using X-Ray CT (XCT) in the "after" condition, for direct comparison with the optical measurement. The analysis of the sample was conducted using a 80 µm 3D gaussian filter to remove the surface form while maintaining the surface roughness. The 3 surfaces were compared and co-located to allow comparison of 3D surface roughness (Sa). A square region (0.6 x 0.6 mm) of the surface is segmented into 16 measurement regions (0.15 x 0.15 mm) and the roughness of each region compared. Results demonstrate that the "after" optical measurement shows a reduction of surface roughness proportional to the initial roughness of the surface. A comparison with the "after" XCT indicates a similar result to the optical data with a further reduction in roughness values when compared to the optical. We show that XCT generated surface data can be used to measure the surface changes on free form surfaces.

Key Words: Optical and X-CT Surface Metrology, dental surfaces.

Introduction

Human teeth are biological structures consisting of a hierarchical arrangement of enamel and dentine that forms the most durable organic structure of the human body, [1]. The mechanical properties of enamel are derived from its intimate union with underlying dentine resulting in a single biological unit capable of lasting the lifetime of a typical human adult, assuming a normal diet with good oral hygiene, without undergoing catastrophic failure. A biological disadvantage of teeth is their highly mineralised composition is susceptible to acids of external (dietary or other habits) and internal (bodily) origin. This process of bulk enamel loss due to acids of non-bacterial origin is termed erosive tooth wear, it is a multifactorial process where there is a combination of acid erosion, tooth to tooth contact (attrition), and/or tooth-to-foreign body contact (abrasion), [2].

X-ray computed tomography (XCT) is a non-destructive measurement technique used to visualise the surface morphology and internal features of. The technique can vary according to spatial resolutions, which can range from the nano (<0.4 µm,) to micro scale (5-50 µm). XCT has been used to evaluate large-scale volumetric loss of enamel following artificially induced erosive tooth wear investigating the processes of toothbrush abrasion, [3], tooth-to-tooth attrition [4], and dental erosion, [5]. XCT has been investigated in the application of surface metrology in the investigation of structured surfaces where the ability to measured hidden surfaces has been shown, [6,7]. The measurement technique is here utilised for the characterisation of microtextural changes (surface roughness) of unpolished natural human enamel following erosive tooth wear.

Metrology Systems

XCT system. The Xradia Versa 510, is used at 80kVp and 87.5µA. With 3201 projections at a 20 second exposure with 4x optical magnification. The voxel resolution is 1.106 µm. Source to object distance was 25mm, and detector to object distance was 51.5 mm. The raw data was post-processed with the commercial software VGStudio Max 2.1 used to generate surfaces. The data has 8-bit image resolution. The render settings used with-in VGStudio Max 2.1, are in 3 steps as follows; (1) to select a sample of the background and a sample of the volume of interest, (2) automatically detect the surface from a histogram, and (3) select meshed data as "very precise with no simplification". The data is further post-processed in BEX® and there converted from a 3D manifold surface to a 2.5D surface with a unique Z value for each grid position (X,Y); then re-sampled onto a fixed grid and segmented for measurement analysis, [6].

Optical System. The XYRIS 2020 H instrument used is a confocal scanning system (CFS) with a fixed grid spacing δ = 2 µm in X and Y (the measurement plane) and with a resolution of 0.025 µm in the vertical (Z) axis.

BEX Surface Analysis. All data is processed for surface measurement using BEX® (v1.2.5).

Methodology

The sample was measured by XYRIS 2020 H before the citric acid test, and then again after the test. A 1.5mm diameter hole was prepared in a clear PVC tape and used to cover the sample, exposing a region used for the wear study. The remainder of the tooth is then protected with the PCV tape. The object is then submerged in Citric Acid (0.3% pH 3.2), for 1 hour, without agitation of the sample. This is a novel test, as we are testing the wear on real dental sample with the outer enamel. The sample was measured using the TaiCaan XYRIS 2020 H instrument "before and after" the test and measured using X-Ray CT (XCT) in the "after" condition. Fig.1 (lower) shows a 2 mm square region of the surface measured after the test, using a 1.5 mm (white) circle to show the region of the erosive wear and contours to highlight the change of the surface. Three surfaces are investigated;

1. Original surface using XYRIS 2020 H, over 2x 2mm with fixed grid spacing δ = 2 µm.

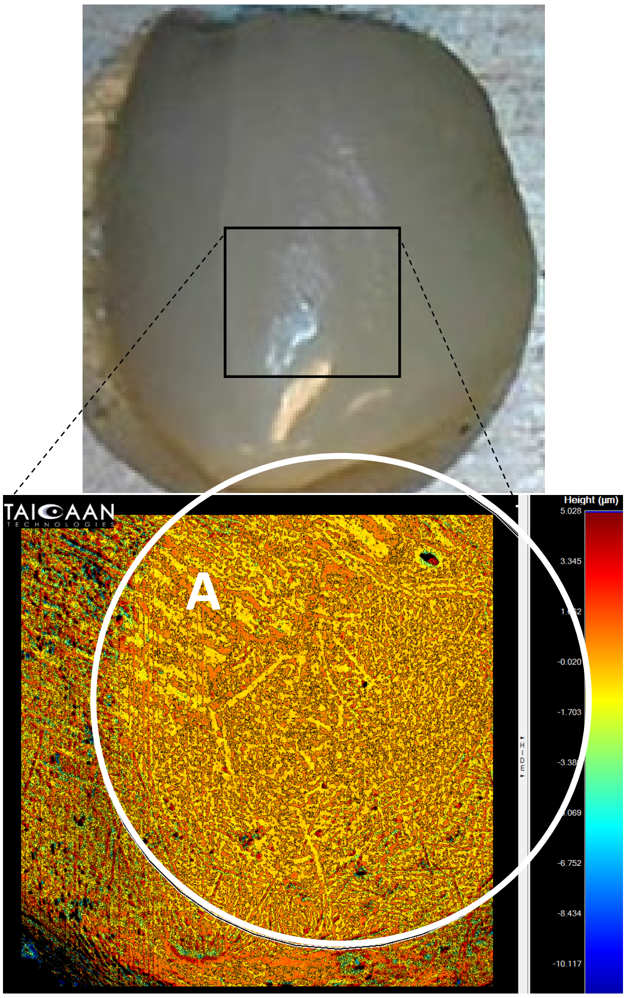

Fig. 1. Partial section of a human tooth (upper), XYRIS optical data (lower), 2 x 2 mm, after erosive test, 80 µm 3D gaussian filter, colour scale +5 to -11 µm, with superimposed 1.5 mm dia. circle around erosion region, 500 contours/mm.

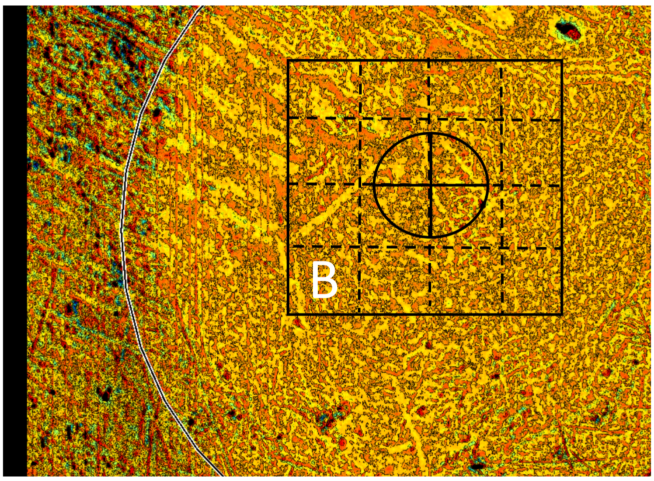

Fig. 2. Zoomed XRIS image of surface in Fig.1 with 1.5 mm dia. Circle and 0.6mm square region investigated, centred on scratch features as shown, with origin at centre of crosshair, ⊕.

2. Surface after erosive test with XYRIS 2020 H, over 2x 2mm with fixed grid spacing δ = 2 µm.
3. Surface after erosive test with XCT system, voxel resolution 1.106 µm

To determine surface change, we define a 0.6 mm square region within the 1.5 diameter circle shown (white line) in Fig.1, as shown in Fig.2, with the square region centred on a series of surface features visible in the 3 data sets (⊕). The surface is segmented into 16 sub-regions of 0.15 mm squares. For each region we determine the 3D surface roughness using the *Sa* amplitude parameter.

Results and Discussion

The three surfaces are shown in Fig's 1, 2, & 4. Fig.1 is the optical CFS measurement of the square region on the sample shown in the upper image in Fig.1. The surface form is removed using a 80 µm gaussian filter. It shows the upper left region labelled "A", has been subjected to prior surface damage, and exhibits a much higher surface roughness (~1.0 µm) than the region to the lower right (~ 0.4 µm), where the surface texture is shown to be more uniform with some surface scratching. Fig.2 is the same data as Fig.1 zoomed in to highlight the centre location of the segmented areas (⊕). Fig. 4 is the XCT surface after processing. It shows the rougher region above the region investigated located on the crosshair position.

The 0.15 mm square regions are identified with an error of +/- 1 grid spaces. The selection of the origin (⊕) shown in Fig.2, is +/- 3 grid spaces. A 10 times repeatability study of the bottom left corner "B" of the "before" surface shows a standard deviation in *Sa* of 0.5%, linked to the identification of the centre of each square region.

Optical Data (CFS). In Fig.3 the range of roughness (*Sa*) for the "before" surface, 16 regions is between 0.314 and 1.03 µm. This is evident from the data shown in Fig.2, where the top left surface is higher than the lower right surface. The data shows there to be a significant reduction in the surface roughness after the erosive test, with most data below the 1:1 relationship line. There are two data points with slightly higher values after the test, linked to some adhesive particles on the surface after the plastic film was removed. The higher the initial surface roughness the greater the reduction in roughness after the test, where the highest roughness of 1.03 µm is reduced by approximately 50%, to 0.53 µm, after.

XCT data. The trendlines for both optical and XCT show a high level of correlation between the data, with a reduced amplitude of *Sa* for the XCT data. The XCT and XYRIS data show near identical rate relationships with the new surface, the rougher the original surface the more the erosion.

The XCT surface, measured with a higher resolution (1.106 compared with 2.0 µm) in the measurement plane (X,Y), has a much lower resolution in the vertical axis (Z), where the resolution remains 1.106 µm, while the XYRIS 2020H is 0.025 µm. The optical system therefore has a 44x higher resolution capability for the amplitude data we are using for the roughness comparison. This is evident in Fig 4, where we compare the same region of the XCT surface as in Fig.2.

The lower vertical resolution of the XCT limits the accuracy of the *Sa*, as shown in Fig.4, where the magnitude of the roughness trend line is 44% lower than the CFS data. The *Sa* trend across the 16 sub-regions does however show a high correlation with the corresponding CFS data.

Discussion. The CFS system provides the reference measurement for the un-calibrated XCT. The CFS system is ideal for nominally flat surfaces but has a limitation which is a combination of the sensor gauge range and the slope of the

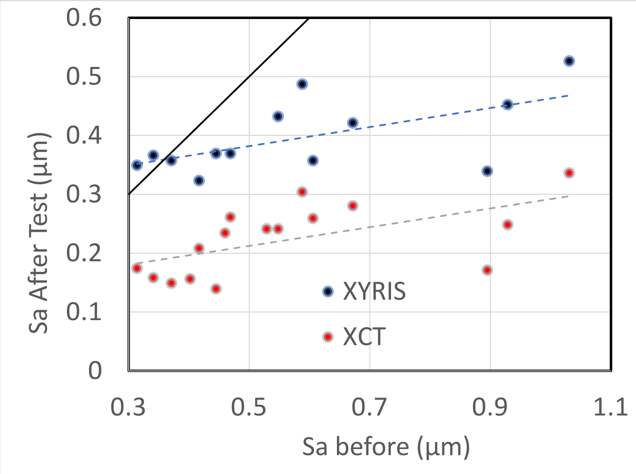

Fig. 3. Surface roughness Sa before the test and after, for two measurement systems (XYRIS and XCT). Solid line is the 1:1 relationship.

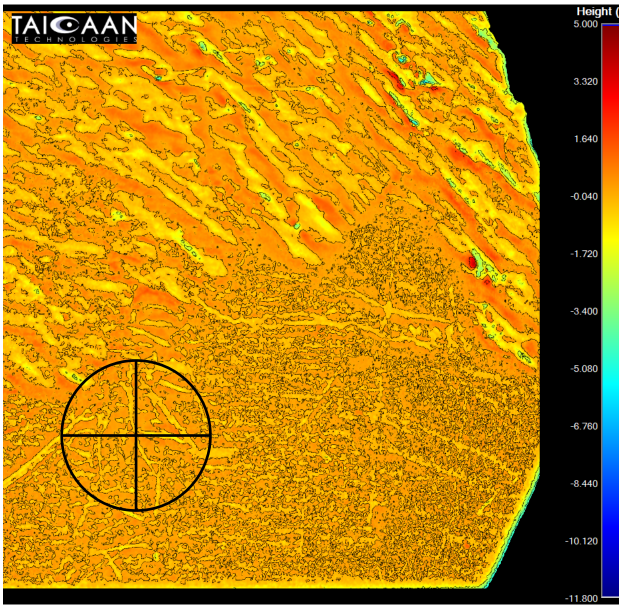

Fig. 4. XCT surface as Fig. 2, using the same vertical colour scaling as Fig.1, with the same location feature ⊕ as Fig. 2

surface. The limitation will depend on the sensor used. Fig.5 shows a whole tooth with the two dotted lines representing the range within the measurement can be undertaken. Fig.6 is an example measurement of a human molar tooth with sensor gauge rage limited to 3 mm. XCT systems have the potential to measure the whole object but is potentially limited by the voxel size of a larger surface area.

The XCT methodology developed here is beneficial in the study of a full dental surface. In addition, new methods of full, rather than a planar surface roughness analysis can then utilised to determine the changes in surface roughness over the whole object.

Conclusions

The optical "top-down" CFS measurements of 16 segmented areas of a dental sample show a reduction in surface roughness (*Sa*) after acidic erosion, proportional to the initial roughness.

The result is confirmed with a 3D XCT measurement of the same "after" sample. The XCT result shows a similar trend as the

Fig. 5. Whole tooth with the top surface measurement region limitation of the optical (CFS) method, with dotted lines representing the sensor gauge range.

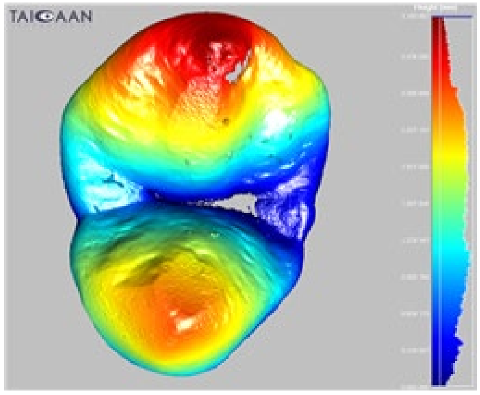

Fig. 6. An example whole tooth measurement with the CFS system, 8x8 mm (δ = 20 µm)

optical surface measurement, with a lower level of roughness. The XCT data is limited in roughness measurement axis, by the voxel resolution. The XCT has the capability to measure a whole tooth surface and should be calibrated by an optical surface measurement of a partial surface, as shown here.

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