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Mechanical properties of human enamel under compression: On the feature of calculations

Dmitry Zaytsev *

Ural Federal University, Ekaterinburg, Russia

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ABSTRACT

The paper is aimed at determination of the causes of shape effect in human tooth enamel under compression and correction of the relevant mechanical characteristics. For this purpose, six groups of samples with different ratios of the compression surface diagonal to the sample height, which consisted of 10 cuboid samples in each, were prepared from the backside of human enamel. The lateral deformation of a sample was calculated at the maximum compressive stress for correction of the mechanical characteristics. It is shown that the ratio between the lateral and axial deformations decreases with an increase in the ratio of the compression surface diagonal to the sample height. This is caused by the friction between the compression plates and the working surfaces of the enamel sample when the lateral deformation is suppressed. In addition, the slope of enamel sample by about 15° occurred during compression due to the inclination of rigid and low deformable enamel rods. The corrections of the elastic modulus and the compression strength taking into account the lateral deformation and the sample slope are carried out. The mechanical properties of enamel samples with the 2.1 aspect ratio are closer to the intrinsic properties of human enamel samples. The elastic modulus and the compression strength of human enamel under compression are 5.64 GPa and 363 MPa, respectively. The lateral deformation (~10%) may be considered as the critical parameter that indicates the strength of human enamel.

1. Introduction

Human enamel is the hardest tissue in the human body and mainly consists of inorganic components [1,2]. It is a natural shield which protects a tooth from both chemical–biological and mechanical effects. Failure of enamel may cause the tooth degradation. Recovering of its integrity could prevent it. Lifetime of the tooth after restoration is also determined by the compatibility of restorative material with tooth hard tissues. The mechanical compatibility is important because dangerous stresses can occur at the boundary between the restorative material and living tissue when the mechanical properties of the restorative material are distinct from dentin and enamel. Therefore, the mechanical properties of dental restorative materials should be close to the properties of human enamel. The knowledge of the strength properties of human enamel is needed for this. Since human teeth are used for grinding of food through compressive impacts of opposite teeth, the compression is the principal deformation scheme for testing the mechanical properties of human enamel.

There are not so many studies of the strength properties of human enamel with using macroscopic deformation schemes, such as compression, in the literature, despite high social importance of this problem [3–6]. This is caused by difficulties of manufacturing small-sized samples for compression testing, which are related to the small thickness of enamel in the tooth and the features of its abrading. Furthermore, it is very difficult to find a tooth in which the enamel would contain no cracks. One of the possible ways for solving this problem is using the animal tooth enamel, however it is necessary to prove its similarity with the human tooth enamel. Another way is application of the indentation technique to study the mechanical properties of human enamel. Indeed, many similar works can be found in the literature [7–10]. However, this technique is rather local, when properties of small volumes on the material surface are studied [11,12]. This is suitable for homogeneous materials, but not applicable for the composite materials, in which the structural component elements are commensurate with the indenter impact size [13,14]. Since the human tooth enamel is a natural composite material, which is composed of enamel rods of about 8 μm in diameter [1,2], the results of indentation test cannot provide reliable information on the bulk properties of human enamel.

Following Refs. [7–10], the compressive strength and the Young modulus of human enamel under compression vary in wide ranges from 100 to 400 MPa and from 10 to 80 GPa, respectively. Such scattering of results does not allow using them. It may be caused by the shape effect, when the mechanical properties of cuboid enamel samples strongly depend on the ratio of the compression surface diagonal d of a sample to its height h (the d/h ratio) under compression [15]. The origin of the shape effect may be caused by both intrinsic properties of the

* Department of Physics, Institute of Natural Sciences, Ural Federal University, 620083 Ekaterinburg, Lenin Avenue, 51, Russia
E-mail address: Dmitry.Zaytsev@urfu.ru.

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material and experimental factors, such as the friction force between the working surfaces of the sample and the compression plates that affects on the stress distribution in the bulk of the sample. Indeed, it has been shown that the shape effect of human dentin is caused by the friction between the compression plates and the working surfaces of samples [16]. Observation of the shape and the sizes of samples under compression should allow us to understand the reasons for the shape effect appearance. It is supposed that the shape effect in enamel samples occurs due to the friction as it takes place in testing the dentin samples. Measurement of the transverse size of a sample under load gives the opportunity to estimate the contribution of friction in its deformation behavior and determine the optimal d/h ratio of the sample for compression test, for which this contribution is minimal. In addition, the correction of the lateral deformation of the sample under compression will allow us to determine the mechanical properties of human enamel, which are closer to its intrinsic properties.

Thus, the aim of this work is to study in detail the deformation behavior of human enamel samples with different d/h ratios for determination of the causes of the shape effect and calculation of true mechanical properties of human enamel.

2. Material and methods

2.1. Sample preparation

Twenty caries-free human molars and premolars were used in this work. They did not contain visible damages and were extracted from the mature (25–40 years old) male and female subjects according to the medical diagnosis and the Ethic Protocol (№. 3 of March 16, 2012) of the Urals State Medical University at Yekaterinburg, Russia. The enamel samples for mechanical testing were cut off from the backside of the tooth crown by means of a diamond saw with water irrigation according to the technique described previously and the scheme in Fig. 1 [15]. The disk diameter was 35 mm whereas its thickness was 0.15 mm. The enamel rods had a similar orientation with respect to the compression surface for all prepared samples and the angle of their inclination was roughly 45° at such a scheme of cutting [15]. The back surfaces of the samples were abraded using abrasive papers and polishing pastes with different grain sizes for removing the damaged layer arising during cutting. The minimal size of paste grains was 5 μm. Six groups of samples with different d/h ratios, each consisted of 10 cuboid samples, were prepared (see Table 1 and Fig. 2). The study of the shape effect assumes that the samples have different sizes at the same volume. However, it is impossible to produce the samples from the human enamel that would meet these requirements because the thin layer of enamel in the tooth and its complex shape limit both the height and width of a sample. Besides, there is a minimal thickness of the samples since they are destroyed under fabrication when their thickness becomes less than 0.5 mm. Therefore, the sample volume increases with the d/h ratio (Table 1). It is supposed that this difference in the sample volumes is not significant insomuch as the size effect is usually manifested when the sample sizes are different more than by one order of magnitude [17]. The diameter of enamel rods is about 8 μm [1]. Enamel rods grow from the dentin–enamel junction to the outer surface of enamel in a tooth (1.5–3 mm). Hence, the enamel rod passes through the whole sample. The diameter of an enamel rod is much smaller than the sample sizes (1.5–3 mm). The number of rods in the samples varies from ~35,000 to ~140,000. Therefore, the amount of enamel rods does not affect upon mechanical properties of the samples on this scale.

Table 1
Geometrical parameter of enamel samples.

d/h ratio	Sizes		Volume (mm^3)
	a (mm)	h (mm)	
2.1	1.50	1.00	2.250
3.0	1.80	0.85	2.754
4.0	2.00	0.70	2.800
4.8	2.20	0.65	3.146
5.9	2.50	0.60	3.750
6.8	2.90	0.60	5.046

Note: a is the grain of the compression surface, h is the height of sample and d is the diagonal of compression surface.

2.2. Microscopic characterization of samples

A scanning electron microscope (SEM) JEOL-JEM 6390LV (Japan) with an accelerated voltage of 20 kV and Canon photo microsystem (Cannon D60 with Canon EF-S 60 mm f/2.8 Macro USM and Canon Macrolite MT-24 EX) were used for attestation of back surfaces of the samples.

2.3. Mechanical testing

The testing machine Shimadzu AGX-50 kN (Japan) was used for uniaxial compression at room conditions. The rate of loading was 0.1 mm/min in all tests. Processing of the results including statistical analysis (standard deviation) was carried out by Trapezium-X standard software for Shimadzu. The axial deformation of the sample was measured by the testing machine, whereas the lateral deformation of the sample was indicated at the maximal stress by means of the Canon photo microsystem, where the width of sample was compared *in situ* with the etalon (Cu wire L = 3.36 mm). This technique was used in the previous work [16]. The irreversible deformation of the enamel sample was extracted from measuring its height prior to and after testing by using a micrometer whereas the elastic deformation is the difference between the axial deformation and the irreversible deformation. Compression strength was considered as the maximal stress on the deformation curve, whereas the elastic modulus was calculated from the slope of the linear part of the deformation curve as a proportion between the stress and the strain. The corrected compression strength was calculated as the maximal force at testing divided by the area of the compression surface of the sample, which was obtained

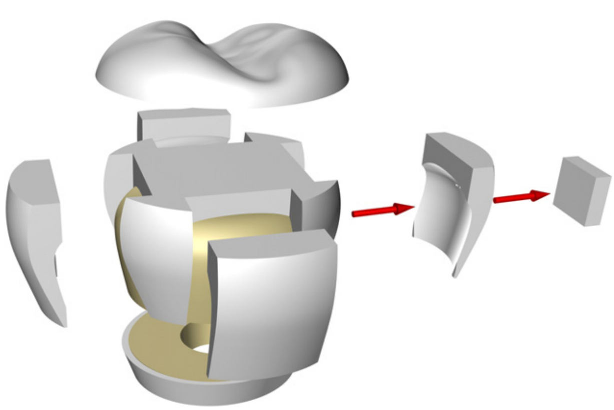

Fig. 1. The scheme of sample preparation for mechanical testing [15].

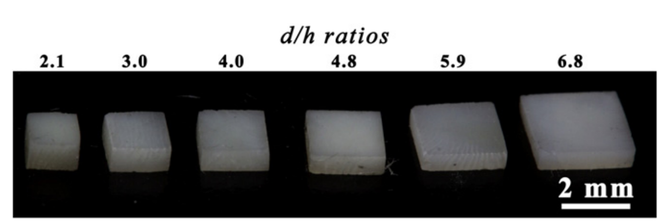

Fig. 2. The enamel samples with different d/h ratios.