

# Role of prism decussation on fatigue crack growth and fracture of human enamel

Devendra Bajaj<sup>a</sup>, Dwayne Arola<sup>a,b,\*</sup>

<sup>a</sup> Department of Mechanical Engineering, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

<sup>b</sup> Department of Endodontics, Prosthodontics, and Operative Dentistry, Baltimore College of Dental Surgery, University of Maryland, Baltimore, MD 21201, USA

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## Abstract

The role of prism decussation on the crack growth resistance of human enamel is evaluated. Miniature inset compact tension (CT) specimens embodying a section of cuspal enamel were subjected to Mode I cyclic or monotonic loads. Cracks were grown in either the forward (from outer enamel inwards) or reverse (from inner enamel outwards) direction and the responses were compared quantitatively. Results showed that the outer enamel exhibits lower resistance to the inception and growth of cracks. Regardless of the growth direction, the near-threshold region of cyclic extension was typical of “short crack” behavior (i.e. deceleration of growth with an increase in crack length). Cyclic crack growth was more stable in the forward direction and occurred over twice the spatial distance achieved in the reverse direction. In response to the monotonic loads, a rising R-curve response was exhibited by growth in the forward direction only. The total energy absorbed in fracture for the forward direction was more than three times that in the reverse. The rise in crack growth resistance was largely attributed to a combination of mechanisms that included crack bridging, crack bifurcation and crack curving, which were induced by decussation in the inner enamel. An analysis of the responses distinguished that the microstructure of enamel appears optimized for resisting crack growth initiating from damage at the tooth’s surface.

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## 1. Introduction

Cyclic loading can cause the inception and growth of damage that reduces the “life” of engineering and biological materials [1]. The accumulation of cyclic damage often results in the generation of well-defined cracks that undergo subsequent growth and ultimately cause fracture under adequate driving forces and/or crack length [2–4]. Human teeth are susceptible to such fractures in the enamel crown [5], particularly in regions of the tooth that have

been restored [6]. While in tissues such as bone and cartilage the generation of microdamage and small cracks can be repaired by physiological processes [7], tissues of the tooth cannot undergo remodeling. They have been designed by nature to minimize the sensitivity to such defects and cracks [8,9]. In general, these materials achieve resistance to crack growth by the arrangement of their organic and inorganic constituents into densely packed hierarchical structures.

Human tooth enamel (Fig. 1a) is the most highly mineralized (96 wt.%) hard tissue of the body and is comprised of a comparatively low degree of organic matter (1 wt.%) and bound water (3 wt.%) [10]. It combines nanocrystals (~25 nm thick, ~100 nm wide and 500–1000 nm long) to form “keyhole”-shaped structures known as prisms (~4–8 μm in diameter). These prisms extend roughly perpendicular from the dentin–enamel junction (DEJ) towards the

\* Corresponding author. Address: Department of Mechanical Engineering, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA. Tel.: +1 410 455 3310; fax: +1 410 455 1052.  
E-mail address: [darola@umbc.edu](mailto:darola@umbc.edu) (D. Arola).

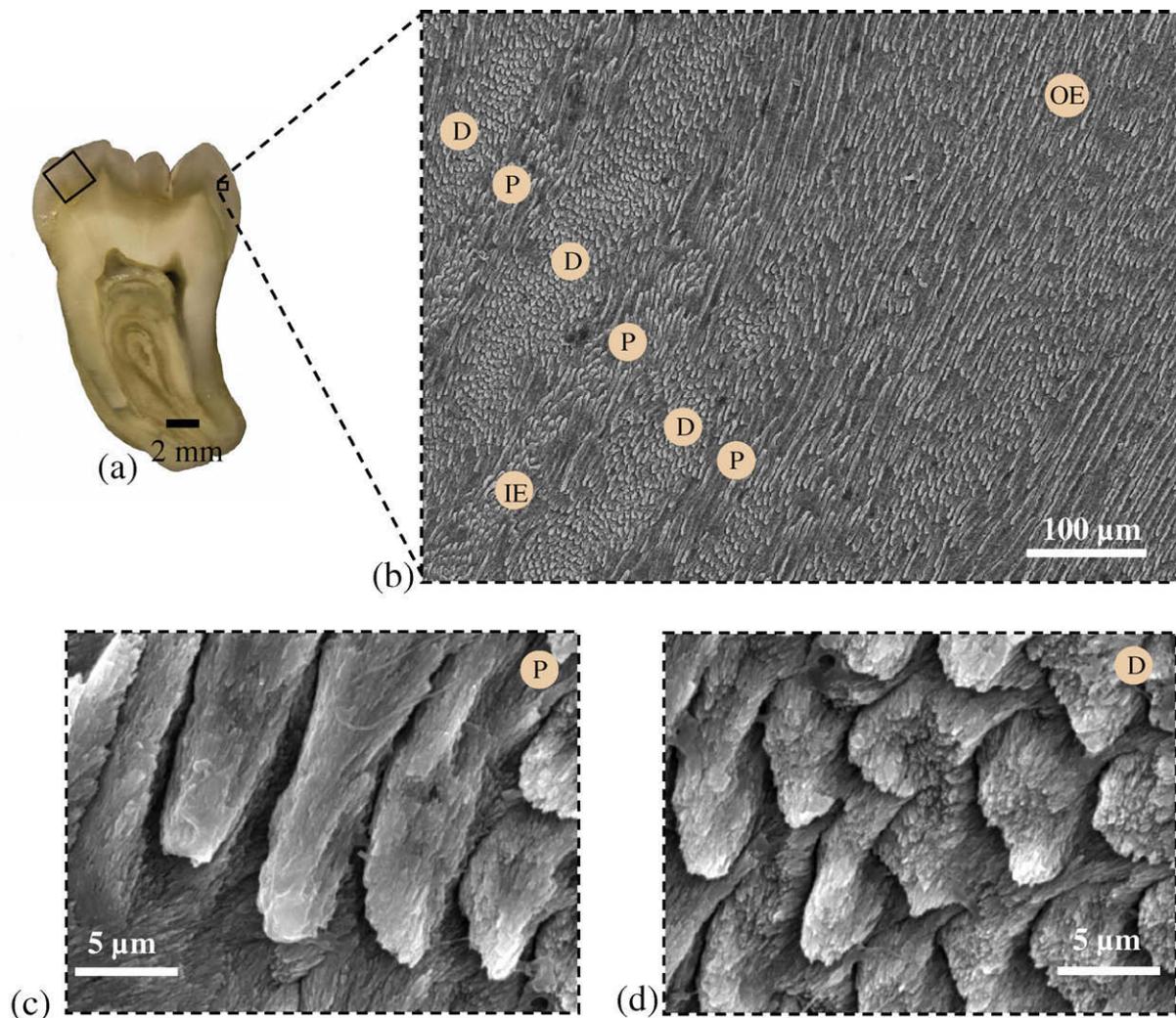


Fig. 1. Details pertaining to the microstructural arrangement of prisms in enamel. (a) A section of tooth and possible inset of enamel. (b) Distinction between the outer (OE) and the inner enamel (IE). Prisms are mostly oriented in a straight fashion in the outer enamel. Decussation, which is caused by crossing of prism bundles is mostly seen in the inner regions of the cuspal enamel and is comprised of bundles of prisms known as the parazone (P) and diazone (D) shown in (c) and (d), respectively.

surface of the tooth where they line up in a parallel fashion, essentially with their long axis perpendicular to the occlusal plane. The spaces between these tightly packed prisms are comprised of a non-collagenous organic matrix. It is the arrangement of these prisms that is responsible for the structural and the mechanical anisotropy in enamel, imparting greater toughness perpendicular to their longitudinal axis [11]. Natural cracks that develop in the enamel of human teeth are oriented along the long axis of the prisms [12], i.e. the direction with weakest resistance to extension [11]. This has raised questions concerning the microstructure of enamel and its role in achieving the necessary resistance to cracks extending from the tooth's surface inwards as well as those extending from the inner surface outwards.

There is presently little knowledge concerning the process of cyclic and monotonic crack growth in human enamel in comparison to that in bone (e.g. [13–17]) and dentin (e.g. [18–21]). While hydroxyapatite offers minimal

resistance to crack growth [22], the crossing of prism bundles in enamel imparts appreciable toughening [23,24]. Such features (Fig. 1b–d), known as decussation, are mostly seen in the inner regions of cuspal enamel [25]. Decussation has been identified in the enamel of many species [26,27] and the extent has been correlated with the magnitude of stresses that develop during mastication [28]. The high degree of decussation at or near the cusps results in greater surface area of prisms per unit volume [25], better crushing ability [29] and also might increase the resistance to fracture [24] by offering an “easy” (along the prisms) and a “difficult” (across the prisms) path for cracks to traverse. However, the contribution of this unique structure of enamel towards its crack growth resistance has not been explored in detail. Therefore, an evaluation of cyclic and monotonic crack growth in human enamel was conducted. Specifically, the role of decussation on crack growth resistance was examined by growing cracks in both forward and reverse directions.

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