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Research paper

Sub-10-micrometer toughening and crack tip toughness of dental enamel

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ABSTRACT

In previous studies, enamel showed indications to occlude small cracks in-vivo and exhibited *R*-curve behaviors for bigger cracks ex-vivo. This study quantifies the crack tip's toughness (K_{I0}, K_{III0}), the crack's closure stress and the cohesive zone size at the crack tip of enamel and investigates the toughening mechanisms near the crack tip down to the length scale of a single enamel crystallite. The crack-opening-displacement (COD) profile of cracks induced by Vickers indents on mature bovine enamel was studied using atomic force microscopy (AFM). The mode I crack tip toughness K_{I0} of cracks along enamel rod boundaries and across enamel rods exhibit a similar range of values: $K_{I0,Ir} =$ 0.5–1.6 MPa m$^{0.5}$ (based on Irwin's 'near-field' solution) and $K_{I0,cz} =$ 0.8–1.5 MPa m$^{0.5}$ (based on the cohesive zone solution of the Dugdale–Muskhelishvili (DM) crack model). The mode III crack tip toughness $K_{III0,Ir}$ was computed as 0.02–0.15 MPa m$^{0.5}$. The crack-closure stress at the crack tip was computed as 163–770 MPa with a cohesive zone length and width 1.6–10.1 μm and 24–44 nm utilizing the cohesive zone solution. Toughening elements were observed under AFM and SEM: crack bridging due to protein ligament and hydroxyapatite fibres (micro- and nanometer scale) as well as microcracks were identified.

1. Introduction

Enamel is the outermost layer of teeth. Throughout our lifetime, enamel remains intact despite millions of mastication loadings in the form of compression, shear and torsion. These result in a distribution of cracks in enamel (Bodecker, 1953; Chai et al., 2009). Despite this, enamel could be considered as a damage-tolerant material against crack propagation due to the following reasons. Small cracks in enamel of 40 μm deep and 8 μm wide were observed to be occluded by mineral deposition, proposed as a key phenomenon to repair tiny enamel cracks in vivo (Hayashi, 1994). Studies of ex-vivo cracks over larger distances have shown that enamel exhibits *R*-curve behavior; the stress intensity increased from values between 0.5 and 1.5 MPa m$^{0.5}$ up to 2.5 MPa m$^{0.5}$ at 1.5 mm crack extension in human enamel (Bajaj and Arola, 2009a) and up to 4.4 MPa m$^{0.5}$ at 500 μm crack extension in bovine enamel (Bechtle et al., 2010a). The reported toughening mechanisms are crack bridging of tissue ligaments of ∼10 μm wide or bigger, microcracking, possible bridging by protein ligaments and crack deflection promoted by enamel rod decussations mainly existing in the inner enamel (Bajaj and Arola, 2009b; Bajaj et al., 2008).

The teeth of all mammals appear to be very similar on a histochemical basis (Oesterle et al., 1998). As a reference, the composition of human enamel varies about ∼90% of apatite crystallites, ∼8% of water and ∼2% of organic matrix by volume (Healy, 1998). In some studies, bovine enamel was

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