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Research Paper

# On crack growth in molar teeth from contact on the inclined occlusal surface

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ABSTRACT

Extracted human molar teeth are indented by hard balls laid at the central fossa, sectioned, and their interior examined for damage. Contact on the fissured enamel coat generally occurs on three distinct spots. The main forms of damage are radial cracks growing from the DEJ to the occlusal surface and median radial and cylindrical cracks growing from a contact spot to the DEJ. For large balls failure by edge chipping near a cusp apex may occur. The median cracks tend to run unstably to the DEJ upon reaching the middle part of the enamel coat. The corresponding load, $P_{FM}$, and the load needed to initiate radial cracks at the DEJ, $P_{FR}$, are taken to signal crown failure. The mean values of $P_{FM}$ and $P_{FR}$ are on the order of 1000 N.

A conical bilayer model defined by thickness $d$, inclination angle $\theta$, failure stress $\sigma_F$ and toughness $K_C$ of the enamel coat is developed to assess crown failure. The analytical predictions for $P_{FR}$ and $P_{FM}$ agree well with the tests. The results indicate that enamel thickness is so designed as to ensure that $P_{FR}$ and $P_{FM}$ just exceed the maximum bite force under normal conditions while the choice of $\theta$ seems to reflect a compromise between needs to resist crown failure and break hard food particles. Both $P_{FR}$ and $P_{FM}$ are greatly reduced with reducing $d$, which points to the danger posed by tooth wear. The analytical expressions for $P_{FR}$ and $P_{FM}$ may also apply to other multi-cusp mammalian or prosthetic molar crowns. Cone cracking, suppressed in the anisotropic tooth enamel, may be an important failure mode in prosthetic crowns.



## 1. Introduction

The fracture behavior of natural and prosthetic teeth has drawn a vast body of research due to its criticality for survival. Natural dental crowns are made of a hard enamel layer resting on a soft dentin. During its lifetime the occlusal surface experiences repeating concentrated forces which may damage the enamel and eventually cause crack penetration into the dentin and a complete crown failure. This is especially true for molar teeth, the most posterior teeth which contain four or five cusps surrounding a lower central part (central fossa) (Lucas, 2004), which do the bulk of food grinding (Talim and Gohil, 1974; Burke, 1992; Lubisich et al., 2010). Occlusal forces may operate on different parts of the

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crown and in a variety of forms, including tooth to tooth contact and contact with hard food items or foreign objects. Of interest in this study are localized forces delivered to the inclined occlusal surface near the central fossa. Although such loading is considered a leading cause for failure in dental crowns (e.g., Kelly, 1999; Dejak et al., 2003), little quantitative information is available on the distribution of internal damage and failure conditions of the enamel coat. It is this aspect which is of main concern here.

The structure of enamel is well documented; a thorough overview of the subject is given by Ang. et al. (2011). Enamel consists of aligned prisms or rods made of hydroxyapatite nanocrystals glued by thin protein layers. The rods, about 5 μm in diameter are connected by ≈ 1 μm thick interrod material which differs from rod enamel in the direction of crystalline patterns. The crystals of rods and interrods meet at sharp angles, resulting in a protein rich space called the rod sheath. The rods are grouped into Hunter–Schreger bands which orientations can undulate and cross each other much like a basket weave. A recent study examining the internal damage in a flattened enamel cusp due to indentation by a hard ball (Chai, 2014) reveals two primary forms of damage, both of which emanate from the contact region: penny-like radial cracks and cylindrical cracks. The latter are confined to the weak interrod regions. It was shown in the above study in indentation testing of thin, flat enamel layers glued onto a soft support that cracks may initiate from the lower surface of the enamel layer. Such cracks tend to propagate quickly toward the occlusal surface.

In this work extracted human molar teeth are indented by hard balls freely laid at the central fossa, a straightforward loading approach commonly used for studying complete fracture in natural (Dietschi et al., 1990; Chai et al., 2011; Spears and Compton, 1996) and prosthetic (Dietschi et al., 1990; Bonfante et al., 2009; Sun et al., 2014) teeth. Of interest in this study is the evolution of damage in the enamel layer excluding onset of dentin fracture. Section 2 discusses the material and testing methods used while Section 3 presents the experimental results along with analytical relationships for predicting crown failure. Section 4 details the role played by key morphological and material features on the fracture resistance of a crown. This section also examines the applicability of the results to mammalian and prosthetic molar teeth. The main findings are summarized in Section 5 along with major conclusions.

## 2. Experimental

Twenty five mandibular second molar human teeth are used. The teeth, supplied by the School of Dental Medicine at Tel-Aviv University, have been extracted from adults aged 20–40. The teeth were carefully examined under a stereo microscope to exclude those having cracks, discoloration, carries or geometric abnormality. The selected teeth, kept in distilled water at all times prior to testing, are encased in an epoxy base for support before they are indented with tungsten carbide (W/C) balls freely laid at the central fossa. The balls are pressed by a rigid platen at a rate of 0.1 mm/min using a standard loading frame operated in a stroke-control mode. The specimens are unloaded at predetermined load value $P$ ranging from 300 N to 1600 N. Four different ball radii are used: $r=0.78$, 1.57, 1.98 and 3.14 mm. After unloading the teeth are sectioned longitudinally or transversely on different planes to reveal the internal damage. This is followed by polishing the sections using a series of diamond pastes ending with 1 μm size particles. The polished sections are observed with optical microscopy for damage. The fracture morphology is studied as a function of ball radius and applied load. Key morphological features such as enamel's thickness and inclination angle are documented for each specimen.

The experimental work is complemented by a fracture mechanics analysis in conjunction with the Finite Element (FEM) technique for predicting loads needed to initiate and propagate radial cracks across the enamel coat as a function of geometric and material system variables. The FEA analysis is conducted using a commercial code (Ansys, inc). While further details are differed to Section 3, following the availability of test results, two relevant analytical relationships are presented at this stage. The first concerns the load $P_{FR}$ needed to initiate radial cracks at the subsurface of a hard layer glued onto a soft substrate (Chai et al., 1999; chai, 2014)

$$P_{FR} = B^{-1}\sigma_F d^2 \tag{1}$$

$$B \equiv (1-2\nu_e)/4\pi + 0.72\log k,\ k \equiv E_e(1-\nu_d^2)/E_d(1-\nu_e^2),$$

where $d$ is the layer thickness, $E$ and $\nu$ are elastic constants with subscripts "e" and "d" denoting layer and substrate, respectively. Eq. (1) was applied to a 0.45 mm thick enamel layer produced from the enamel coat, resulting in enamel failure stress $\sigma_F=118.7$ (24.6) MPa (Chai, 2014). The second relationship, associated with spherical indentation of flat, polished enamel surfaces, relates the depth of radial crack, $c_d$, to load $P$ by (Chai, 2014)

$$P = \alpha K_C c_d^{3/2}, \tag{2}$$

where $\alpha K_C = 15.9$ (4.0) MPa m$^{1/2}$ and $K_C$, the fracture toughness of enamel, equals to 0.94 MPa m$^{1/2}$. Note that $c_d$ is the average from all radial cracks observed in a given tooth section.

Enamel and dentin are complex anisotropic materials. For the present purposes enamel, dentin and ball are assumed isotropic and linearly elastic with Young's modulus and Poisson's ratio given as $(E_e, E_d, E_i)=(90, 18, 600)$ GPa, $(\nu_e, \nu_d, \nu_i)=(0.32, 0.31, 0.22)$, in that order.

## 3. Results

### 3.1. *Fracture morphology*

Fig. 1 shows the indented surface for two specimens. The morphology represent the general behavior observed. In the case of the 1.57 mm ball radius (a) the load from the ball is transmitted to the fissured enamel surface over three distinct spots located well within the central fossa. Fig. 2 is an optical image of a transverse section cut slightly below the contact spots. As shown, a set of radial cracks (R) emanate from each spot. At a lower magnification (not shown) some of these cracks are seen to reach the dentin/enamel junction (DEJ). As the applied load is increased such radial cracks may lead to tooth