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Effect of wear on stress distributions and potential fracture in teeth

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Abstract Finite element analysis is conducted on a tooth model with different degrees of wear. The model is taken as a hemispherical shell (enamel) on a compliant interior (dentin). Occlusal loading is simulated by contact with a flat or curved, hard or soft, indenter. Stress redistributions indicate that development of a wear facet may enhance some near-contact fracture modes (cone–ring cracks, radial–median cracks, edge-chipping), but have little effect on far-field modes (margin cracks). Contacts on worn surfaces with small, hard food objects are likely to be most deleterious, generating local stress concentrations and thereby accelerating the wear process. More typical contacts with larger-scale soft foods are unlikely to have such adverse effects. Implications concerning dietary habits of animals is an adjunct consideration in this work.

1 Introduction

The structure of human teeth has been well documented [1–3]. Enamel is the hardest and stiffest substance in the human body, and provides a protective coat about 1–2 mm thick for the otherwise vulnerable tooth interior. Dentin is more compliant with a modulus around a quarter that of enamel, and forms a cushioning support for the tooth. It is the relative stiffness and hardness of the enamel that gives rise to the protective function, by sustaining the bulk of the occlusal loading ('stress shielding'). It would appear desirable that this protective coating be preserved, certainly in humans. However, enamel is also highly brittle, with toughness little higher than that of glass [4], and is therefore very susceptible to fracture [5–7]. It is also prone to progressive wear during a lifetime of dental function, either from cumulative chewing on abrasive foods or excessive grinding ('bruxing'). Wear patterns on teeth surfaces can be useful in determining dietary preferences in extant or extinct animal species [8]. On occasion, wear can be so severe as to expose the underlying dentin, in some cases (especially in humans, carnivorous animals) diminishing the functional capacity, while in others (e.g., horses, cattle) actually providing some benefit by producing ridges for breaking down vegetation [9].

Over the past decade there has been considerable study of various modes of fracture in model tooth systems and dental prostheses [10–12]. The most recent of these employs hemispherical glass shells backfilled with dentin-like epoxy resins as representative of the tooth crown, with a hard or soft flat indenter representative of occlusal loading [13–15]. Some of the more basic modes are indicated in Fig. 1. Fractures can start either from the occlusal contact as radial–median cracks and run down to the crown margins (R), or begin from the margins and run up to the contact area (M). Both these fracture modes generally remain confined to the enamel in longitudinal ribbon-like configurations, except at ultra-high loads (typically $\gg$ 500 N) where they link up to spall the enamel off the dentin underlayer [16]. Additional, axisymmetrical cone or ring cracks (C) can also initiate at the top surface of the enamel [17]; when close to an edge, these cracks can cause chipping at the side walls [15], especially in contacts with small, hard particulates

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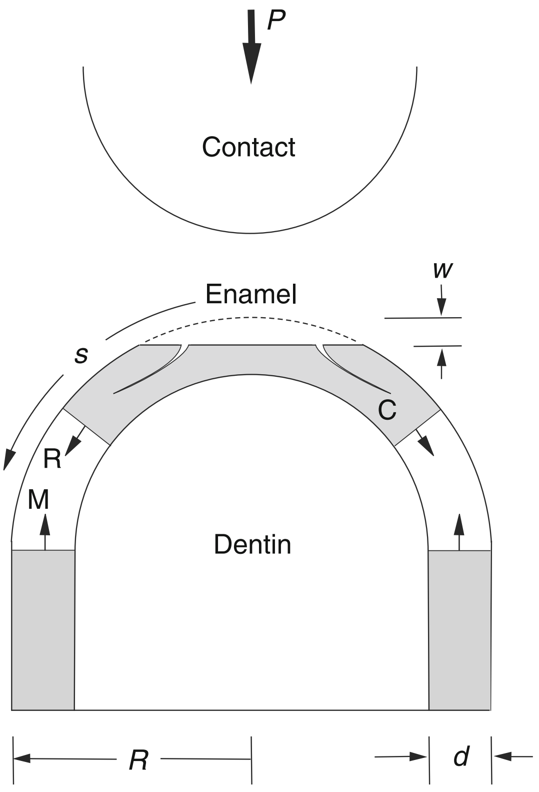

Fig. 1 Schematic of occlusal contact of a tooth cusp with wear facet. Enamel is regarded as a hemispherical shell encasing a soft dentin interior. Occlusal contact is made with a hard or soft indenter of specified radius

[18]. Longitudinal R and M cracks are driven by out-of-plane hoop stresses, ring or chipping cracks by in-plane principal stresses, in a combined contact–flexure field. Which of these crack types prevails is governed largely by the available food types—hard versus soft, small versus large [5, 7].

Thus far, the bulk of the experimental investigations into the above fracture modes has concentrated on specimens with ideally rounded, unworn cuspal surfaces. The question arises as to how progressive wear might compromise the capacity of teeth to withstand continued functional loading over a lifetime without failure. The present study addresses this issue by conducting finite element analysis (FEA) calculations of model tooth structures with different degrees of wear at their cuspal surfaces. We argue that those fracture modes that operate in the vicinity of the occlusal contact—especially from contacts with small hard food objects—are likely to become more active, effectively accelerating the wear process. On the other hand, those modes that operate in the marginal areas are unlikely to be significantly affected, so that severely worn teeth may continue to function under certain conditions.

2 Methodology

Commercial FEA software, Abaqus version 6.7-1, was used in our stress calculations, using procedures described previously [13, 14, 19]. The tooth was modeled as a hard hemispherical enamel shell of thickness $d = 1.2$ mm and outer radius $R = 4$ mm as characteristic human molar dimensions [1], with soft dentin interior (Fig. 1). Loads P were applied axisymmetrically and friction-free at the tooth cusp by an ‘indenter’ (food object or opposing tooth). Computations were performed for cusps of relative wear depth w/d, in increments 0.25 from 0 (initial unworn surface) to 1.0 (enamel depth) and beyond (exposed dentin). Indenters were taken to be either flat, with intimate contact along the wear flat, or spherical, with radius 4 mm. Young’s modulus and Poisson’s ratio were chosen as follows [20, 21]: enamel, 90 GPa and 0.23; dentin, 18 GPa and 0.35; hard indenter, 90 GPa and 0.23 (tooth–tooth contact); soft indenter, 0.5 GPa and 0.22 (masticated food).

The FEA model was constructed with 1,000 elements [22]. The mesh grid size was refined, with concentration of elements in the vicinity of the contact, until the calculated stresses achieved convergence. Calculations were conducted for a contact load of 500 N. Principal in-plane stresses and out-of-plane hoop tensile stresses were evaluated at each stage of the wear process, for each indenter type.

3 Results and discussion

Calculated principal stress contours are shown in Fig. 2 for a hard flat indenter on a tooth with wear cusp at depth $w/d = 0.25$, for load 500 N. The contours in Fig. 2a represent maximum in-plane stresses and those in Fig. 2b out-of-plane hoop stresses. In this particular configuration the in-plane tensile stresses in Fig. 2a are concentrated in a region outside the edge of the wear flat, where ring or chipping cracks might be expected to generate [17]. The out-of-plane hoop tensile stresses in Fig. 2b are more uniformly distributed around the inner enamel wall, and are responsible for the propagation of radial–median cracks downward from the contact zone or margin cracks upward from the enamel base [7, 12].

Figure 3 plots principal stress distributions for the same hard flat indenter but for degrees of wear ranging from $w/d = 0$ to 1.25 in 0.25 increments, as a function of coordinate s/R around the shell circumference ($w/d = 1$ omitted to avoid clutter). Stresses σ are normalized relative to the cross-section area of the enamel base, as $2\pi\sigma Rd/P$. Edge locations of the flat are shown as short vertical gray lines. A maximum in the in-plane principle stress occurs within the

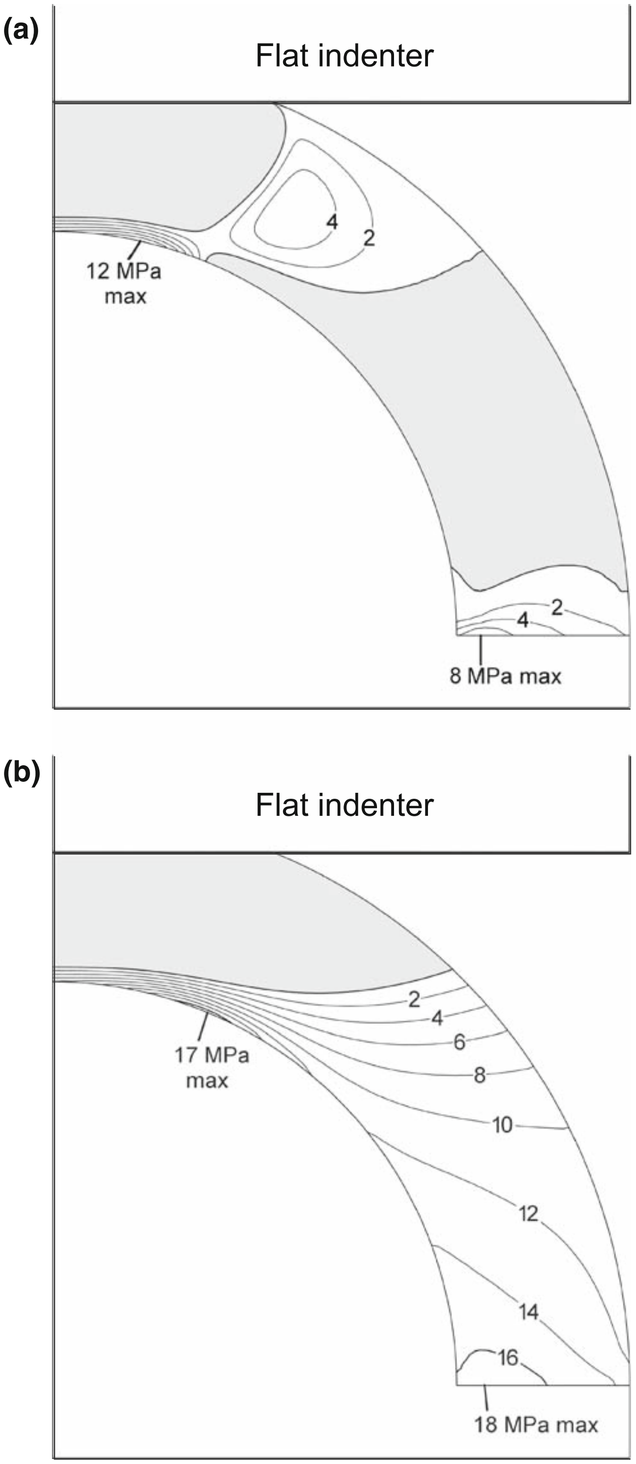

Fig. 2 Contours of stresses (MPa) in enamel with wear facet of depth one quarter the enamel thickness, loaded with flat hard indenter to 500 N: **a** in-plane principal stresses; **b** out-of-plane (hoop) stresses. Shaded areas indicate compressive stress

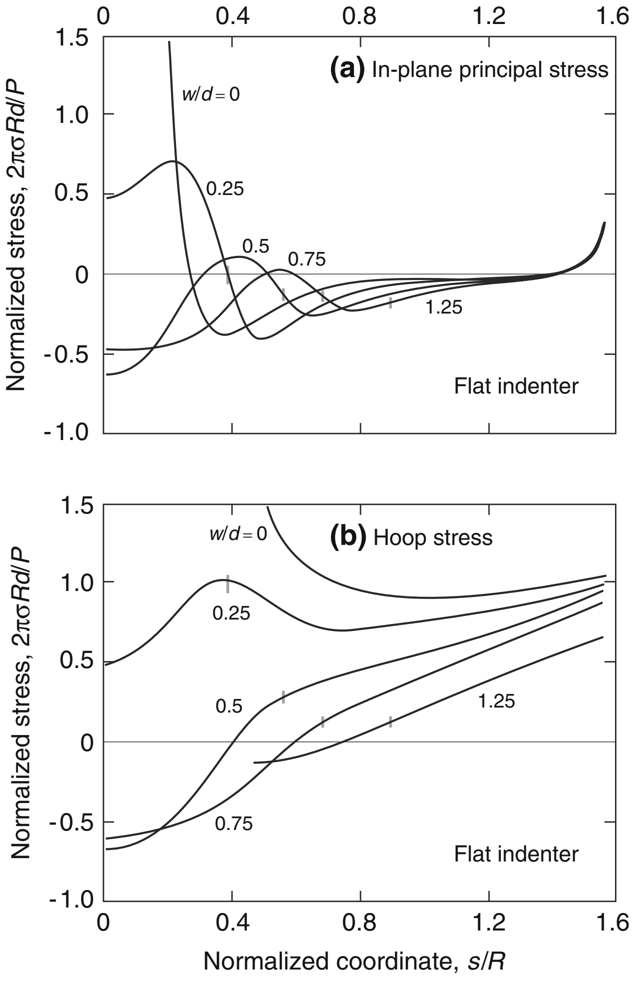

Fig. 3 Distribution of **a** in-plane maximum principal stresses along the enamel–dentin interface, **b** out-of-plane (hoop) stresses, in same system as Fig. 2, for cusp loaded with hard flat indenter. Short vertical gray lines indicate edges of wear flat

enamel inside the edge of the flat (Fig 3a). Another maximum occurs close to the outer surface of the enamel at the circle of contact (unworn surfaces, $w = 0$) or toward the edge of the flat (worn surfaces, $w/d > 0$) (Fig. 2a). These stress maxima indicate locations where cone or ring cracks traditionally occur. Note the decreasing magnitude of these maxima as the depth of the flat increases, due to spreading of the load, suggesting that increased wear may actually diminish the incidence of surface ring cracking (see also Fig. 5). It may be anticipated that this load-spreading effect would be reduced or eliminated in the case of any misalignment between the worn surface and flat indenter, but this is yet to be investigated.

By contrast, the maximum hoop stresses in Fig. 3b occur at the inner surface of the enamel, adjacent to the dentin junction. On unworn surfaces these stresses are highest immediately below the contact, in the region where radial–median cracks occur. On worn surfaces the stresses are compressive in this region, and become tensile around the side walls toward the base, favoring a transition from radial–median to margin cracks. Note, however, that the magnitudes of the actual margin stresses are relatively

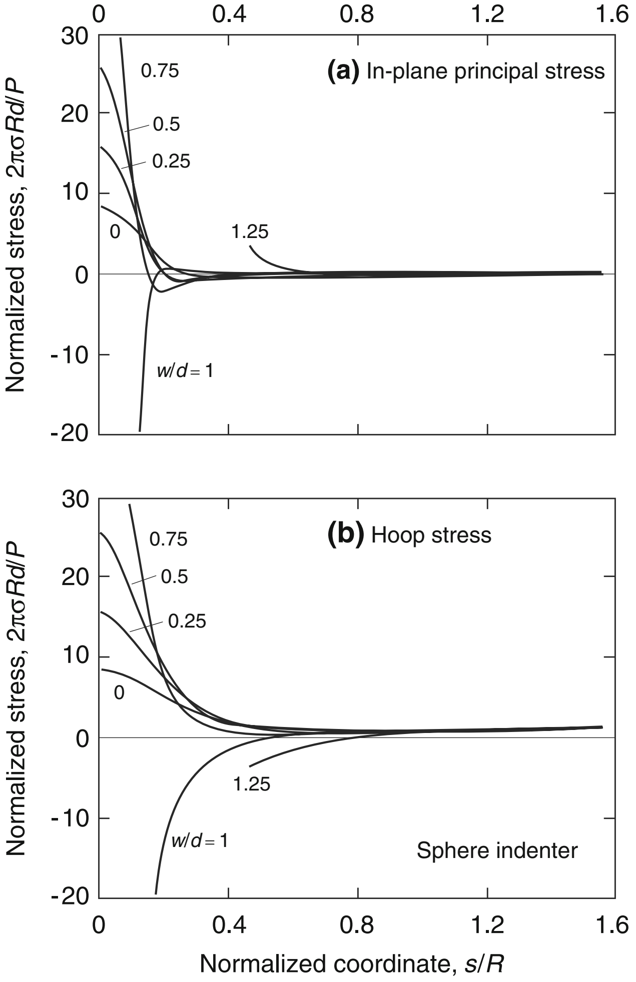

Fig. 4 Distribution of **a** in-plane maximum principal stresses along the enamel–dentin interface, **b** out-of-plane (hoop) stresses, in same system as Fig. 2, for cusp loaded with hard spherical indenter of radius 4 mm

unaffected by the wear process, diminishing as the wear increases.

The behavior of the system under the action of a flat soft indenter (not shown) is quite similar to the case of the flat, hard indenter. The soft contact engulfs the top of the specimen, regardless of the amount of wear, and generates an extended compressive zone there for both radial and hoop stresses [23]. The main difference between soft and hard flat indenters occurs when there is no wear—the soft indenter deforms to distribute its load, negating the tensile stress concentrations at the top surface evident in Fig. 3. Once the wear flat is introduced, the behavior of the two systems is not significantly different.

Figure 4 is an analogous plot for the case of a hard spherical indenter of radius 4 mm centered on the tooth axis. The stresses are now much more concentrated around the contact (note higher stress scale relative to Fig. 3). Concentrations of in-plane principal stresses (Fig. 4a) and hoop stresses (Fig. 4b) are located on the inner enamel surface under the contact. These stresses increase as w/d increases, associated with enhanced flexure of the thinning coat. This kind of contact is likely to promote subsurface ring and radial cracking as wear proceeds, augmenting the material removal process. Ultimately, at $w/d > 1$, the contact presses only on the dentin, alleviating the stress intensity in the enamel. As before, the margin hoop stresses (Fig. 4b) are little affected by cuspal wear (cf. Fig. 3b).

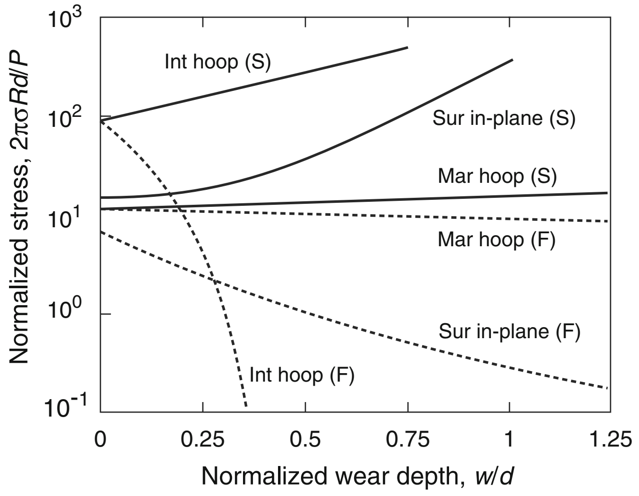

Fig. 5 Maximum in-plane principal stresses on the surface (Sur) and out-of-plane hoop stresses on the enamel/dentin interface (Int) beneath the indenter and at the margin (Mar), as function of relative wear depth, for hard flat indenter (F) and hard spherical indenter (S)

Finally, Fig. 5 shows the variation in pertinent surface (Sur), interface (Int) and margin (Mar) stresses within the enamel for flat (F) and spherical (S) contacts. In this plot the margin hoop stresses are relatively unaffected by indenter geometry and hardness, and change only slightly with progressive wear. In the case of a flat indenter, the onset of wear causes the load to distribute over a larger contact area, resulting in a reduction in stresses both on the surface and at the interface, with the margin hoop stress at least an order of magnitude larger than the near-field stresses. Of greater interest are the strong increases in near-field surface and hoop stresses with increasing wear in the case of a spherical indenter, indicating strong enhancement of radial cracking, ring cracking, and chipping as wear progresses.

4 Discussion

Wear produces facets that can redistribute occlusal stresses on tooth cusps. Our FEA evaluations of a model tooth structure suggests that wear can, in some circumstances, accelerate vulnerability of enamel to degradation (and hence to further wear) by premature formation of cuspal ring cracks and subsurface radial–median cracks. In addition, wear leads to flats with sharp peripheries and diminished side-wall inclination, rendering the enamel increasingly susceptible to edge chipping [18, 24, 25]. This is most likely in contacts with hard, small food objects, such as grits, nuts, and seeds [5], where the stresses in the enamel are highly concentrated. On the other hand, wear can spread the occlusal load, especially in flat and soft contacts, thereby diminishing the magnitudes of local flexural stresses and inhibiting radial–median cracking. This latter suggests that wear can actually have some benefit in normal chewing function on soft foods. Hoop stresses remote from the wear flat are less sensitive to occlusal conditions, so susceptibility to failure from margin cracks is barely enhanced by wear and the capacity to sustain ultra high loads without catastrophic failure of the remaining tooth structure is hardly diminished.

Our hemispherical model of a tooth cusp is clearly simplistic. Human teeth, especially molars, have a more complex and convoluted cuspal configuration than the representation in Fig. 1. Tooth enamel is also anisotropic in its mechanical properties, with higher modulus in longitudinal compared to transverse orientations in relation to the mineralized rod structure [2, 26]. We have used just an averaged modulus in our calculations. Cracks, once formed, tend to propagate along the weak interfaces between rather than across rods, so crack directions are governed by microstructural as well as stress considerations. Microstructural elements such as ‘tufts’—hypocalcified, protein-filled fissures that emanate into the enamel from the enamel–dentin junction [1, 27, 28]—are likely to have a strong influence on where radial and margin cracks initiate, by providing favored starting points for fractures [12, 21]. Notwithstanding all these issues, the general findings here may be expected to have a certain generality in the way they handle stress distributions and predict fracture paths in the near- and far-contact regions.

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