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Competing Damage Modes in All-Ceramic Crowns: Fatigue and Lifetime

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Abstract A study is made of fracture from cyclic loading of WC spheres on the surfaces of brittle layers on compliant substrates, as representative of repetitive occlusal contact on dental crowns. Several damage modes—radial cracks at both top surface and cementation interface, and classical cone cracks as well as deep penetrating cone cracks from the top surface—have been identified and analyzed. The most dangerous fractures are radial cracks that initiate from either the top or bottom surfaces of the brittle layers and spread laterally to failure. In fatigue, these cracks are driven by chemical forces associated with the intrusion of water into the crack. Also dangerous are deep penetrating cone cracks which, unlike their classical cone crack counterparts, are mechanically driven by hydraulic pumping and can evolve rapidly with cyclic loading, threatening the lifetime of a dental crown veneer.

Introduction

Ceramic layer systems are used in many engineering and biomechanical applications. Where brittle layers are bonded to a compliant substrate, they sustain the bulk of stress, thereby protecting vulnerable underlayers. Classical examples are hard coatings on metal cutting tools and enamel on dentin in tooth structure. However, ceramic layers are subject to fracture and deformation, especially from concentrated loads and flexural stresses from contact loading. Again, a classical example is the biting force in tooth or crown function. There is a need to understand how different modes of fracture and deformation compete, especially in long-term cyclic loading.

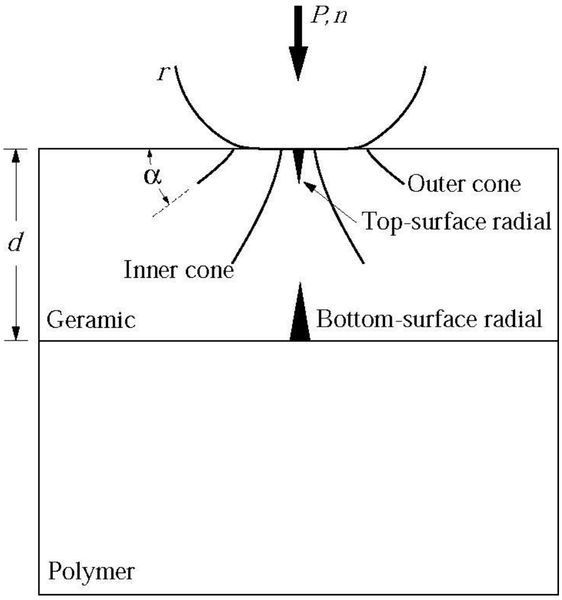

Figure 1. Schematic of crack geometry for cyclic contact with sphere of radius r at load P and number of cycles n on ceramic layer of thickness d on compliant substrate.

There can be several damage modes in such layer structures under contact loading. For a ceramic layer indented with a curved surface, e.g. sphere, damage usually occurs at the top surface, from near-contact stresses, or the bottom surface, from flexural stresses (Fig. 1). Generally, top surface modes dominate when the coating thickness d is large and sphere radius r is small. Conversely, lower surface modes dominate when d is small and r is large. The most dangerous damage mode is that of radial cracking, i.e. cracks that emanate outward from the contact axis with their planes normal to the plate surface. Such cracks can initiate from both top and bottom surfaces, and are highly susceptible to any tensile stresses parallel to the plate surface during subsequent function. Top-surface radials form due to quasiplastic damage accumulation, bottom-surface radials from microstructural flaws [1]. Another damage mode is top-surface cone cracking. In addition to conventional cone cracks that form outside the contact circle, inside cones are observed under cyclic loading in a wet environment [1,2]. These inner cones form much steeper angles to the surface and ultimately penetrate through the brittle coatings, and are associated with hydraulic pumping in water environments in cyclic loading.

In this study, we examine the competition between top-surface and bottom-surface damage modes in ceramic layer systems. We illustrate with data on model monoliths and bilayers consisting of ceramic plates on polycarbonate substrates, loaded at the top surface with a hard sphere. We obtain data for critical loads to produce cone cracks and radial cracks at the top and bottom ceramic surfaces, as a function of number of cycles. With these results, we draw conclusions concern the susceptibility of crown structures to sustained cyclic loading, consisting of a double ceramic (veneer/core) layer on dentin substrate. Our findings indicate that different modes dominate under different conditions of testing; and, moreover, that a mode which dominates in single-cycle loading may not continue to dominate in cyclic loading.

Experimental

Material Preparation. Monolith soda-lime glass bars of 6 mm thick were selected as a model veneer material to investigate the top-surface damage modes. The top surfaces of the glass bars were abraded with 600 grit SiC to introduce controlled flaws, to ensure top surface cracking and to reduce the glass strength near to that of the porcelain veneer. Glass has the distinct advantage of transparency, enabling *in situ* viewing of crack evolution through the entire loading process, and is representative of dental porcelain properties.

Two clinical relevant dental ceramics were selected as model materials for studying bottom-surface radial cracking: a dense fine-grain alumina (CoorsTek, Golden, CO), and an yttria-stabilized zirconia (Y-TZP, Norton, East Granby, CT). The ceramic plates, ~1 mm thick, were polished to 1 μm finish and epoxy bonded to 12.5 mm thick polycarbonate substrates. These ceramics are representative of dental cores used to support porcelain veneers. Although opaque, their undersurfaces can be viewed *in situ* during testing.

Fatigue Experiments. Contact fatigue tests were carried out by loading the specimen top surfaces with a WC sphere of radius r = 1.58 mm to prescribed maximum loads $P_{\max}$, in water. The numbers of cycles n required to initiate each crack type were recorded [3]. Cone cracks in monolith glass were observed using a video camera system from the side. Top-surface radial cracks in monolith glass were determined by interrupting the test after a prescribed number of cycles and examining the specimen in transmitted light. Bottom-surface radials in bilayers were observed *in situ* using a video camera system from below.

Results

Top Surface Damage. Fig. 2 shows side views of cone crack evolution in a soda-lime glass monolith specimen as a function of number of cycles n. This figure shows the initial formation of a classical outer cone crack (Fig. 2a), followed by appearance and ultimate dominance of a deeper inner cone crack (Figs. 2b to 2d). The inner cones form only in cyclic loading in water. In bilayer specimens, the inner cones accelerate in their later stages, and may penetrate layers of thickness d = 1 mm or greater.

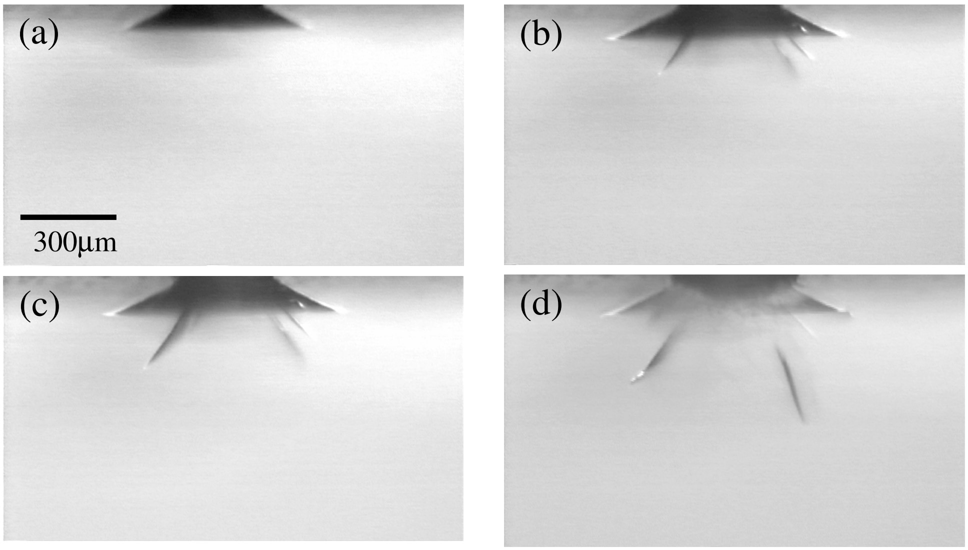

Fig. 2 Video side views of cone crack evolution in glass, indentation with WC sphere of r = 1.58 mm, cyclic loading between P_{max} = 120 N and P_{min} = 2 N at 1 Hz in water: (a) n = 6 cycles, (b) n = 7000 cycles, (c) n = 25000 cycles, (d) n = 160000 cycles.

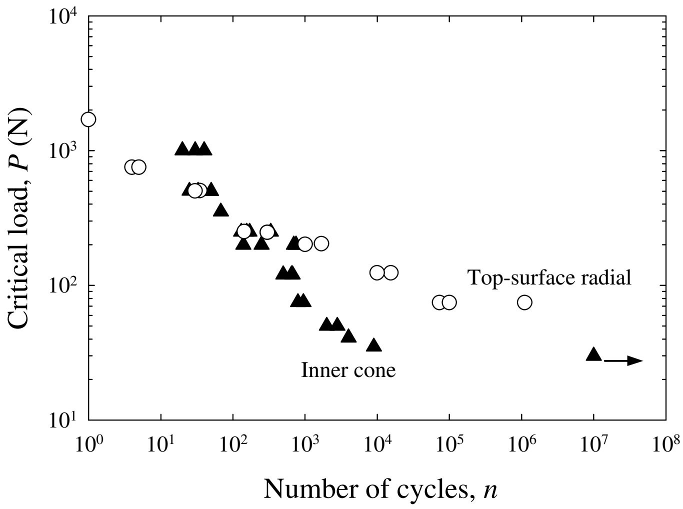

Figure 3. Maximum load versus number of cycles for onset of the inner cone cracks and top-surface radial cracks in monolith glass, in water (r = 1.58 mm). Arrow indicates runouts.

Fig. 3 compares the number of cycles n required to initiate the top-surface inner cone and radial cracks in monolith glass under otherwise identical cyclic loading conditions, in water. Data points are individual measurements. Filled symbols indicate inner cones, unfilled symbols top-surface radials. The critical loads required to initiate inner cones at any given load diminish steadily with increasing number of cycles. The same is true of radial cracks, but the decline is substantially less pronounced. Hence whereas for the given contact conditions here radial cracking may dominate inner cones at low n, the reverse becomes true at high n.

Bottom Surface Damage. Fig. 4 shows a bottom view of bottom-surface radial in an alumina/polycarbonate bilayer system. The star shape cracks are typical for all ceramic coatings on compliant substrates.

Fig. 5 plots maximum load versus number of cycles to onset of radial fracture from the ceramic bottom surface, for polished Y-TZP and alumina bilayers. This plot, from an earlier study [3], is reproduced here to establish a base for determining the critical loads associated with undersurface radial cracking. Data points are individual test results, arrows indicate runouts after 10^7 cycles. The falloff is relatively slow, consistent with a slow crack process [4], amounting to a loss in strength of about a factor of 2 to 4 over a year or more.

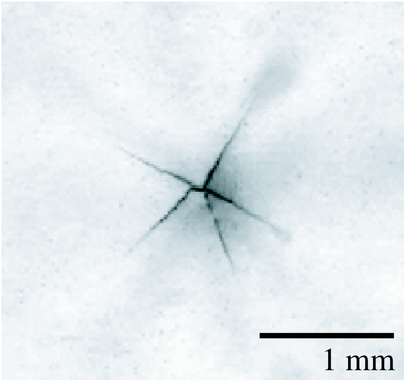

Figure 4. Bottom-surface radial cracking from an alumina plate (d = 1 mm) on polycarbonate bilayer under cyclic loading with WC sphere of r = 3.18 mm.

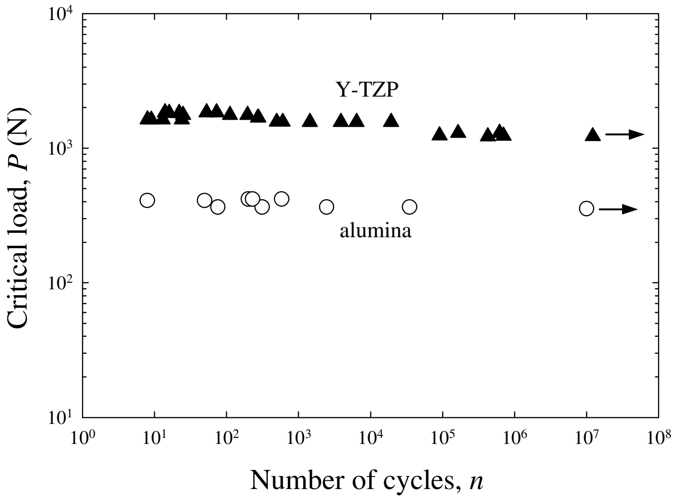

Figure 5. Maximum contact load versus number of cycles for the initiation of bottom-surface radial cracks for Y-TZP and alumina cores in bilayer systems, ceramic thickness d = 1 mm. Arrows indicate runouts after 10^7 cycles.

Predictive Basis for More Complex Dental Crown Systems

Data of the kind shown in Figs. 3 and 5 form the basis for ultimate predictions of responses for more complex dental crown system. In such systems, we expect a competition between top-surface cone (or radial) cracks and bottom surface radial cracks. Top-surface cones or radials are relatively unaffected by replacing the lower portion of a ceramic layer with second, core ceramic, although they are reasonably sensitive to the presence of a compliant (dentin) underlayer. Therefore the P–n plot from Fig. 3 can be readily used to predict the top-surface damages in a glass/ceramic/dentin trilayer system indented under identical contact conditions. Of course, in a real dental system the contact will be more complex, dependent on cuspal radius r as well as material properties (especially elastic modulus of opposing tooth enamel). These dependencies are currently being determined, using classical Hertzian contact analysis and fracture mechanics relations.

Relations for initiating bottom-surface radials have been more widely studied [5]. Basically, the critical load P_R depends on ceramic layer thickness d and ceramic/dentin modulus ratio E_*/E_s. The quantity E_* is an "effective modulus", a combination of moduli of the veneer and core ceramic layers [6]. For multi-cycle loading, degradation is due principally to slow crack growth from intrinsic flaws, and has the simple form $P_R = P_0/n^{1/N}$ where N is a crack velocity exponent [3,4]. The data in Fig. 3 satisfy this dependence to good approximation.

A more detailed analytical understanding of these fracture modes is ongoing.

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