journal

J. Am. Ceram. Soc., 91 [1] 198–202 (2008)
DOI: 10.1111/j.1551-2916.2007.02009.x

Fatigue Damage in Ceramic Coatings From Cyclic Contact Loading With a Tangential Component

Yu Zhang, Jae-Won Kim, and Joo-Hyung Kim

Department of Biomaterials and Biomimetics, New York University College of Dentistry, New York, New York 10010

Brian R. Lawn†

Materials Science and Engineering Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8520

The role of a tangential load component in cyclic contact-induced failure of a brittle coating layer is investigated. Tests are conducted on model bilayer systems consisting of glass plates bonded to polymeric substrates, using a spherical indenter in periodic off-axis loading, in a water environment. The principal damage is that of a partial cone crack which forms in the wake of the contact and propagates steeply through the coating layer with continued loading. The critical number of cycles required to propagate the cone cracks through the coating is substantially reduced in off-axis relative to axial loading, and diminishes rapidly with increasing peak load. It is confirmed that the superposition of sliding tractions at the contact can have a profoundly deleterious effect on coating lifetime.

I. Introduction

Laminate structures with brittle outer layers are often exposed to repeated contacts in nonnormal or sliding loading. This is true of engineering ceramic coatings and films subjected to sliding, scratching, and impact at the top surface. It is also true of biomechanical structures such as dental crowns and total hip replacements. Even though contacts may be "blunt," as indicated in Fig. 1, they can inflict lifetime-limiting damage to the structure. While there have been several studies of the nature of cyclic damage from blunt contacts in model brittle monoliths and coatings,[1–7] the question remains as to how the fatigue characteristics of a brittle outer layer may be enhanced by imposition of a superposed tangential component of surface loading.

Various fracture modes can occur in brittle layers from blunt contacts, depending on the specimen configuration.[8] In thicker brittle coatings, which will be our focus here, the fractures are principally classical cone cracks that form just outside the contact circle.[9,10] In contacts with superposed tangential loading—i.e., off-axis or sliding components—tensile stresses are substantially enhanced behind the trailing edge, reducing critical loads to initiate cone cracks from surface flaws and driving the cracks more steeply downward.[11–14] Because these cracks do not always complete themselves on the top surface, they are referred to as "partial" cones.[12] To a first approximation, the cones tilt relative to the specimen surface so as to remain near symmetrical about the vectorial axis of the net normal+tangential force, as indicated by the point-load representation in Fig. 2.[15] Fracture is further enhanced by intrusion of moisture from the environment into the cracks, leading to progressive slow crack growth under sustained load.[16] Cyclic loading in water can generate an additional, more deleterious kind of cone crack, the so-called "inner" cone, in which fluid entering surface flaws can mechanically drive fracture by "hydraulic pumping."[17] These cracks characteristically have radii about one half that of the maximum contact circle at their surface traces and, once initiated, propagate more steeply and more rapidly downward. Other fracture modes can also occur[4]: in sharp contacts and softer ceramics, "median" cracks, initiating from cumulative quasiplastic deformation; in thinner coatings, "radial" cracks, initiating from the bottom surface. However, these other modes will not be operative in the brittle-coating/blunt-contact conditions of interest in this work.

In this study, we examine the effect of cyclic nonnormal loading of a spherical indenter on the evolution of cone fractures in a brittle coating system consisting of a glass plate bonded to a polycarbonate base. The transparency of the glass makes this an ideal model system for investigating the fracture evolution during actual testing.[5] We are specifically interested in the conditions under which cone fractures may penetrate the coating and thus lead to transverse failure. We will show that superposition of a tangential component in the loading can substantially lower the coating lifetime.

II. Experimental Procedure

Glass/polycarbonate specimens were prepared as described previously.[18,19] Glass slides of thickness 1 mm (Daigger, Wheeling, IL) were prepared with polished edges for side viewing during testing. The top surfaces were abraded with 600 SiC grit to introduce a uniform density of new flaws for crack initiation, and the bottom surfaces were etched with 10% HF for 5 min to eliminate pre-existing flaws. Polycarbonate slabs 12.5 mm thick (AlN Plastics, Norfolk, VA) were used as support substrates. The glass slides were bonded to the polycarbonate bases with an epoxy resin (Harcos Chemicals, Bellesville, NJ) to form bilayers, with an interlayer adhesive thickness of less than 20 μm.

Contact fatigue tests were conducted on the glass top surface with a spherical WC indenter of radius 1.58 mm. Two configurations were explored as shown in Fig. 2: (a) axial loading (control) and (b) off-axis loading at $\beta = 30°$ to the surface normal. The specimens were mounted into rigid support blocks, in the case of Fig. 2(b) into a block with a V notch, to minimize lateral movement during testing. The entire specimen fixtures were then immersed in a water bath for testing. Loads were delivered by a mechanical test machine, typically used by dental researchers to simulate chewing function (Elf 3300, Bose Corp., Eden Prairie, MN). Simple vertical strokes were made with maximum loads P_m up to 500 N and up to 10^6 cycles at frequency 1 Hz. The load–time waveform shown in Fig. 3 was used, with liftoff between successive cycles. This loading is

D. J. Green—contributing editor

Manuscript No. 23219. Received May 16, 2007; approved June 28, 2007.
This work was supported by a New York University Research Challenge Fund and a grant from the National Institute of Dental and Craniofacial Research (PO1 DE10976).
†Author to whom correspondence should be addressed. e-mail: brian.lawn@nist.gov

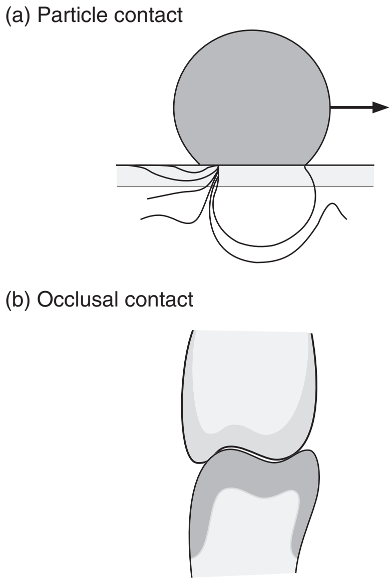

Fig. 1. Schematic of contact with tangential component of loading. (a) Sphere contact on flat brittle coating, with a sliding or impact tangential component. Tangential forces generate enhanced tensile stresses at trailing edges of the contacts. (b) Occlusal contact in tooth/crown structure, indicating off-axis contacts at cusps.

meant to simulate the kind of contact that may be experienced in normal chewing function.

The evolution of the cone cracks in the glass layer was followed *in situ* from the side using a video camera.[18] At points of interest the testing was stopped and the cracks were photographed from the top and side.

III. Results

(1) Cone Crack Morphology

Figure 4 shows top surface and side views of tests on glass/polycarbonate specimens in off-axis loading, for a maximum

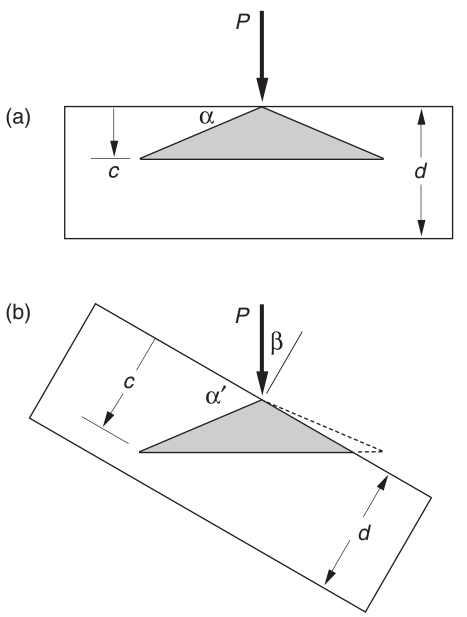

Fig. 2. Schematic showing cone crack geometry in a model bilayer consisting of a brittle layer on a compliant base (not shown): (a) axial loading and (b) off-axis loading at angle β. To first approximation, cone geometry remains "symmetrical" about the realigned load axis, with a portion of the cone intersecting the top surface at angle α′, resulting in "partial" cones. Failure occurs when the cone crack base at the deepest point of penetration *c* intersects the interface at thickness *d*.

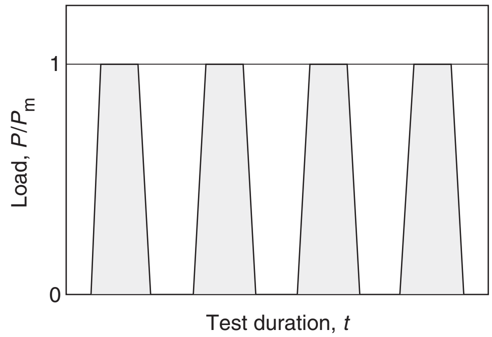

Fig. 3. Loading profile P/P_m versus time *t* for cyclic contact testing at a fixed frequency, showing loading with liftoff between contacts.

load $P_m = 120$ N at load angle $\beta = 30°$ (Fig. 2(b)) in water. Crack patterns are for a single-cycle test (left) and for a multicycle test at $n = 110$ cycles (right). In single-cycle loading, the surface view shows an elongated track with a series of small, closely spaced, incomplete ring crack traces at the trailing edge of the contact. The indenter appears to have slid from left to right in frictional contact over a distance of about 100 μm. The side view shows that, in this case, the ring cracks penetrate only a shallow depth into the glass layer, indicating partial cones in their incipient stage of formation. In other, similar single-cycle tests, a partial cone popped in on the first cycle on about half the occasions, suggesting that the selected load of 120 N was close to the critical value for initiation. In multicycle loading, the surface view shows a much higher density of ring crack traces over the sliding track, and a partial cone has formed at the trailing edge of the indenter. The side view reveals a steep penetration of the partial cone at an angle $\alpha' = 55° \pm 10°$ to the surface. Propagation has actually occurred down to the base of the glass layer. This latter configuration is deemed a "failure," in which the outer environment now has direct access to the coating/substrate interface. This angle compares with $\alpha = 23°$ for classical Hertzian cones in normal loading.[9,20,21] Note that the partial cone in this figure has not propagated around to the front of the contact, indicating that the crack is not yet fully formed.

Figure 5 shows the top surface and side views of another partial cone crack, under similar off-axis conditions as for Fig. 4 but now at load $P_m = 160$ N, after $n = 64$ cycles. The higher maximum load has produced a more fully formed partial cone, this time propagating around to the front of the contact.

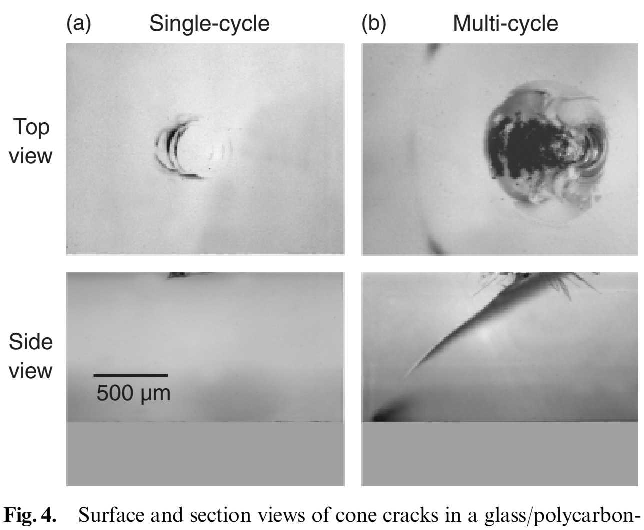

Fig. 4. Surface and section views of cone cracks in a glass/polycarbonate bilayer in off-axis loading at $\beta = 30°$: (a) $n = 1$ cycle, (b) $n = 110$ cycles. Indentation with a WC sphere of radius 1.58 mm at load $P_m = 120$ N, in water. Note the elongated track with multiple partial cones in single-cycle loading, indicating some left-to-right sliding at the contact point. Only the glass layer is shown in the side view.

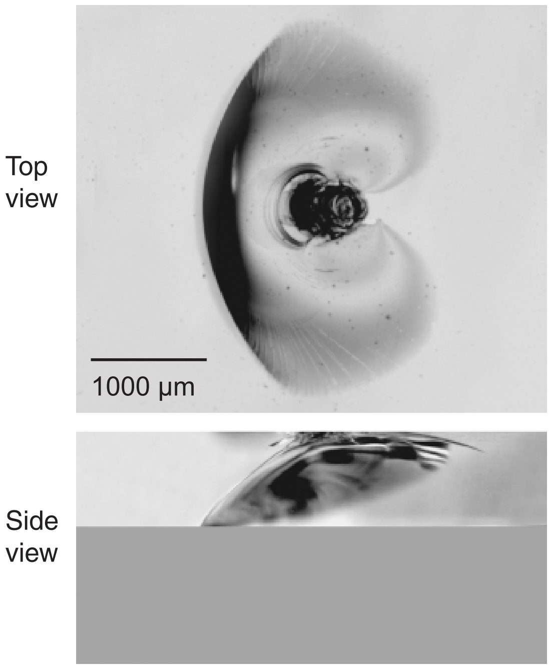

Fig. 5. Surface and side views of a cone crack in multi-cycle loading for $P_m = 160$ N, in off-axis loading at $\beta = 30°$. Tests in water.

(2) Fracture Evolution

In situ video monitoring enables us to follow the entire evolution of cone crack development, from initiation (pop-in from ring crack to partial cone) to full penetration through the glass plate (failure). Figure 6 shows an example, in which crack depth c below the top surface (Fig. 2) is plotted as a function of the number of cycles n for tests with a WC sphere of radius 1.58 mm at a maximum load $P_m = 120$ N in water. Data are shown for (a) axial and (b) off-axis loading at $\beta = 30°$. Again, failure is deemed to occur when crack depth c reaches the interface at plate thickness $d = 1$ mm, i.e., at the upper axis of the plots.

It is immediately apparent that crack growth is substantially slower in axial relative to off-axis loading. In axial loading (Fig. 6(a)), shallow ring cracks form from surface flaws and pop in within a few cycles, and subsequently grow into full outer cones at a steady rate. It has been demonstrated that this steady-state growth is entirely consistent with time-integrated slow crack growth.[19] After some hundreds of cycles, these cracks are overtaken by steeper, inner cone cracks, which ultimately become the source of failure.[17,19] The driving force for these inner cones is augmented by a hydraulic pumping mechanism. These cracks require an ''incubation'' time to become effective, but then quickly evolve and dominate. In the absence of the inner cones, the plate would not fail at the operating load over the cycle range covered here.

The corresponding response in off-axis loading (Fig. 6(b)) is quite different. In this case the cone crack, partially formed as in Fig. 4, pops in after one or two cycles, but to a considerably greater depth. Growth thereafter is more rapid than in axial loading, without any clearly defined steady-state growth before failure. In this case, the crack appears to be a classical partial cone, and failure occurs before any secondary, inner cone has a chance to appear. It is clear that the tangential loading component has a strong influence on the crack geometry, and thence on the lifetime characteristics of the coating.

The data in Fig. 6 relate to just one maximum load, $P_m = 120$ N. To determine how the failure mechanics depends on load, a plot of number of cycles n_F to failure is given in Fig. 7 as a function of P_m, again for axial loading and off-axis loading at $\beta = 30°$. The lifetimes diminish steadily with increasing peak load, indicating a significant fatigue effect. Comparing the two data sets shows a substantial decline in lifetime in off-axis relative to axial loading, by over two orders of magnitude, consistent with the data shifts in Fig. 6. In the case of axial loading, outer cracks dominate at high P_m and low n_F (gray symbols), and inner cone cracks at low P_m and high n_F (unfilled symbols). In the case of off-axis load-

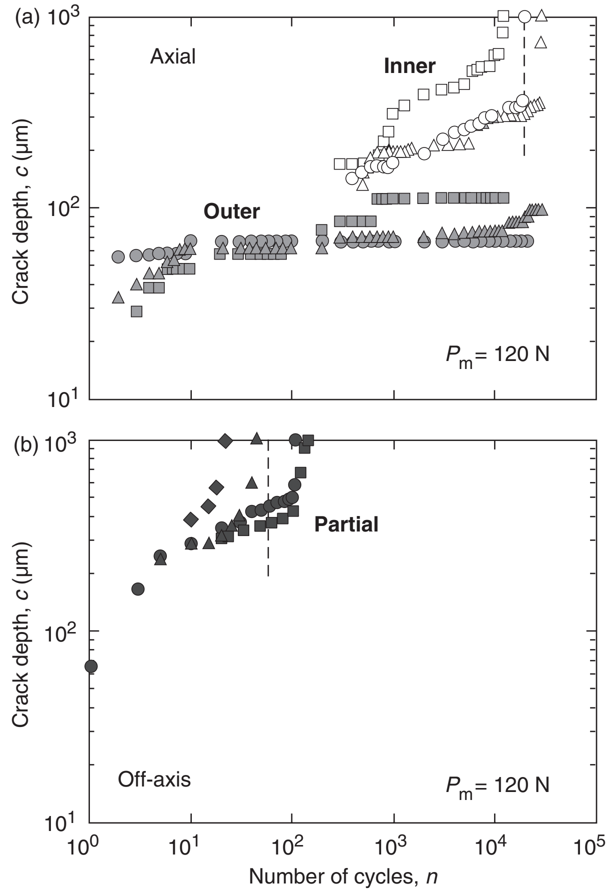

Fig. 6. Plot of crack depth c as a function of number of cycles n in a glass/polycarbonate bilayer, for (a) an axial load and (b) an off-axis load at $\beta = 30°$. Indentation with a WC sphere of radius 1.58 mm, maximum load $P_m = 120$ N, in water. Failure occurs when crack depth c reaches the interface at glass thickness $d = 1$ mm at critical number of cycles n_F (vertical dashed lines). Note the substantially enhanced crack growth in off-axis loading.

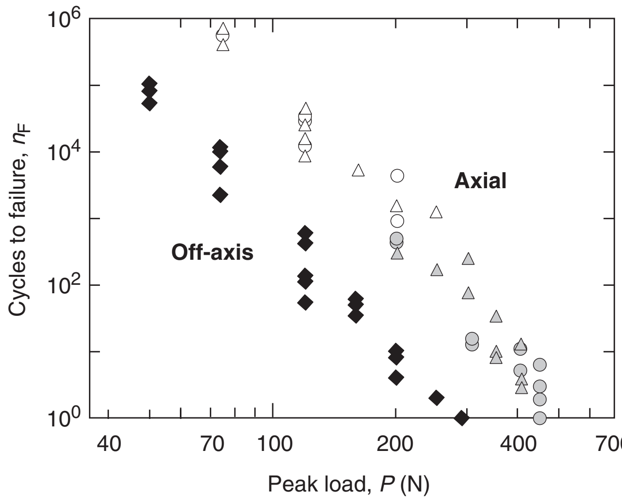

Fig. 7. Plot of number of cycles n_F to a failure as function of maximum load P_m in glass/polycarbonate bilayers, for axial loading and off-axis loading at $\beta = 30°$. Indentation with a WC sphere of radius 1.58 mm, in water. Note the diminished lifetimes in off-axis loading.

ing, failure is exclusively from partial outer cones over the data range.

IV. Discussion

The present study has demonstrated that addition of a tangential loading component to cyclic contact of a spherical indenter on a brittle coating surface can substantially diminish the coating lifetime. Specifically, we have compared the lifetimes of glass plates bonded to polymeric bases for cyclic loads applied normally ($\beta = 0$) and at an angle ($\beta = 30°$) to the top surface. In the case of angular loading, some sliding is apparent at the contact site, equivalent to a coefficient of friction $f = \tan \beta = \tan 30° = 0.58$.[15] It is well documented that superposition of such a tangential component enhances the tensile stress field at the trailing edge of the contact and suppresses it at the forward edge.[11–13] However, while this stress redistribution can account for the ease of initiating trailing cone cracks in the first place, it is only a small part of the explanation. In fact, once fully formed, cone cracks become somewhat insensitive to the near-contact conditions, such that to a first approximation, the actual sizes of the cones in Figs. 2(a) and (b) measured from surface to base along the load axis remain basically the same.[15] It is as if the far field of the contact is simply rotated to remain coaxial with the vectorial load axis, i.e., $\alpha' = \alpha + \beta$, without otherwise much affecting the cone mechanics.[15] This means a steeper descent of the cone rim toward the coating lower surface, effectively magnifying the crack coordinate c in Fig. 2. In addition, the coating is subject to flexure on the compliant polymeric substrate, so that once the cone penetrates close to halfway through the plate it experiences a superposed flexure field, further accelerating the cone downward.[18,22] This accounts for the rapid upward bending of the data sets toward criticality in Fig. 6. It is apparent from angular considerations alone that cone cracks will penetrate the glass layer more rapidly in off-axis loading.

In multicycle loading, there is the issue of alternative crack systems, briefly alluded to in "Introduction." We have mentioned inner cone cracks, which form within a periodic contact zone. Inner cones become active in cyclic axial loading with spheres, and are indeed the dominant failure mode in Fig. 6(a) as well as in the high-load region of the axial-load data in Fig. 7. In such cases, water enters surface flaws within the contracting and expanding contact circle and is mechanically driven into the crack by a pumping mechanism.[17] The operation of a similar mechanism is feasible in sliding, and could account, in part at least, for the deviations toward shorter lifetimes of the low-load data in Fig. 7. It is possible that more severe contacts could further enhance the role of hydraulic pumping in other loading configurations, e.g., repeat sliding (machining) or rolling over large distances (pitting fissures in bearings).[23,24]

Another fracture mode that can play a critical role in brittle coating systems is that of radial cracking. These initiate from flaws at the coating bottom surface, driven primarily from flexure of the coating on a more compliant substrate.[7,8,18,25–27] Radial cracking of this kind dominates in thinner coating layers, because of enhanced flexure.[25] Interestingly, the critical conditions in this case are relatively insensitive to any superposed tangential load component, because imposition of shear tractions at the surface does little to alter the hoop tensile stress state responsible for initiating radial cracks at the lower surface.[28]

Finally, some comments on the clinical relevance of the present study to dental function are in order. Our off-axis test contains some elements of similarity to occlusal (biting) contact in teeth and crowns, notwithstanding cuspal curvature (Fig. 2(b)).[7] Typically, cuspal contacts occur at angles close to the 30° used in our current test, with characteristic cuspal radii 1–2 mm, i.e., in the range of the sphere indentation experiments described in this work.[29] The small amount of sliding evident at the contact site in Fig. 4 also simulates lateral motion of opposing dentition during chewing.[30] In addition, the "liftoff" time profile in Fig. 3 may be considered to be representative of the broader elements of chewing. As to the use of abraded glass in our tests, mechanical properties such as modulus and strength are similar to those of dental porcelain.[7] Our polycarbonate substrates are more compliant than tooth dentin, and this may be expected to affect the quantitative but not the qualitative aspects of the cone crack data in Figs. 6 and 7. Testing in water may be expected to accelerate the evolution of partial cone cracks somewhat relative to air, owing to reduced slow crack growth, and could also influence the angle of cone penetration by altering the coefficient of friction.[15] The major difference between our model configuration and actual dental crown structures is the presence of an additional, core support layer (e.g., hard and stiff metals or ceramics) in the latter.[31] Cone fracture is expected to be a persistent mode of failure in such cases, especially in crowns with ultra-strong zirconia cores where porcelain chipping is the major source of clinical failure.[32]

Acknowledgments

Certain equipment, instruments, or materials are identified in this paper in order to specify experimental details. Such identification does not imply recommendation by the National Institute of Standards and Technology.

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