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Effect of Tangential Loading on Critical Conditions for Radial Cracking in Brittle Coatings

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Results of Hertzian contact tests investigating the effects of superposed tangential loads on the critical conditions for radial cracking at the undersurfaces of brittle coatings on compliant substrates are reported. It is demonstrated that these effects are secondary, so that conventional normal indentation remains an appropriate test procedure for characterizing this highly deleterious mode of coating fracture under a wide range of complex loading conditions.

I. Introduction

BRITTLE coatings are used to provide mechanical, thermal, and chemical protection for soft supporting substrates. Such coating structures may be subjected to complex concentrated loading, including tangential components. For example, coated cutting tools are subjected to sliding. Chewing motion of teeth or crowns in dental function has lateral and rotational components.[1] Thus, whereas conventional indentation tests are used in normal loading, in the interest of simplicity, there are issues concerning the effects of additional, superposed components. Changes in near-surface stress fields from tangential forces are well documented in Hertzian contacts on monolithic solids,[2,3] and can markedly diminish critical loads to initiate cone cracking and other damage modes in brittle surfaces.[4,5] This can lead to rapid acceleration of surface degradation and wear. On the other hand, the depth of the cracks is not so sensitive to tangential forces, so that properties like remaining strength are only slightly affected.[6] The implication is that the influence of superposed nonnormal loads remains concentrated in the near-contact regions, with only secondary effects on events in the far field.

This implication is pertinent to the failure of brittle coatings on compliant substrates. Contact loading causes the coatings to flex on their soft supports, generating dominant tensile stresses and then "radial" cracks at the lower coating surface.[7–10] These radial cracks initiate at lower loads in thinner coatings, and can extend in elongate fashion over long lateral distances. They are believed to be principal sources of failure in dental crowns.[11,12] The question arises: do tangential forces indeed have a minor influence on the critical loads to produce far-field radial cracks in coating structures, thereby enabling retention of normal contact testing as a means of characterizing fracture susceptibilities; or is it necessary to resort to testing machines with complex loading and to empirical (e.g., finite-element) stress analysis?

To answer this question, we investigate the conditions for initiation of radial cracks in a model brittle-coating/compliant-substrate system using Hertzian contacts with superposed tangential loading.

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II. Experimental Procedure

Soda–lime glass was chosen as a model brittle coating material for fabrication of test bilayers. The glasses were obtained in the form of plates 75 mm × 25 mm × 6 mm surface dimensions, and were ground and polished to prescribed thicknesses down to d = 0.4 mm. Top and bottom surfaces were preabraded with 600 SiC grit to introduce a high density of controlled starting flaws, so as to ensure reproducibility in ensuing contact tests.[8] Polycarbonate plastic slabs 12.5 mm thick (AIN Plastics, Norfolk, VA) were used for the substrates. The glass plates were then joined to the substrates with a thin layer (typically 10–20 μm) of epoxy adhesive, which was allowed to set for 24 h.

Hertzian tests were conducted on the finished bilayers with WC spheres of radius $r = 3.96$ mm by inclining the top surface at a prescribed angle $\alpha = 26.5°$ to the load axis of a loading machine (Model Instron 8502, Instron Corp., Canton, MA), Fig. 1(a). The load was applied at constant crosshead speed 0.2 mm·min^{-1}. This configuration resulted in superposed normal and tangential load components $P_n = P \cos \alpha$ and $P_t = P \sin \alpha$, equivalent to a static friction coefficient $\mu = P_t/P_n = 0.50$. The contacts were viewed *in situ* either from the side through the glass or directly from below the indenter through the polycarbonate with a video camera, and the critical values of applied load P for first crack initiation (radial or cone) were recorded.[8,13] Control tests were run in normal loading ($\alpha = 0$) to establish a reference base line.

Some sliding tests were conducted on horizontal surfaces, Fig. 1(b). Test samples were fixed onto the table of a stepper motor, and the table moved laterally at 120 μm·s^{-1} during contact. This configuration gave superposed normal and tangential load components P_n and $P_t = \mu P_n$. In these tests, the friction coefficient for sliding in air was $\mu \approx 0.2$. Again, the contacts were viewed *in situ* with a video camera. The normal load P_n was increased steadily at a rate of ~5 N·s^{-1} during contact until fracture was observed.

III. Results

Either cone or radial cracks initiated first in the glass coating layer, depending on the layer thickness d: In thicker specimens

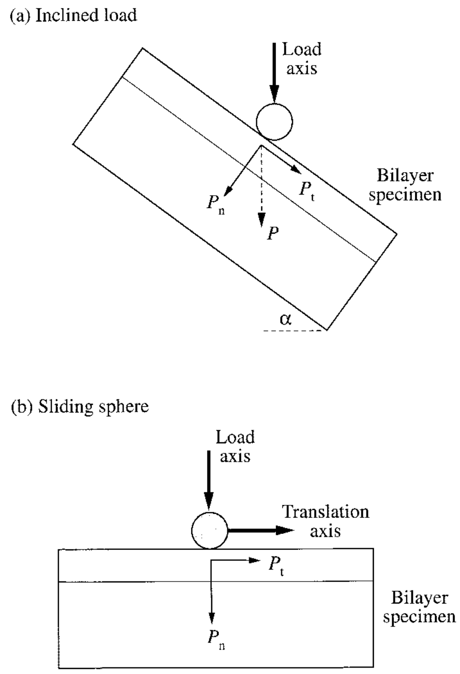

Fig. 1. Experimental arrangement for indentation of bilayer surface with superposed tangential force component, showing (a) inclined and (b) sliding configuration.

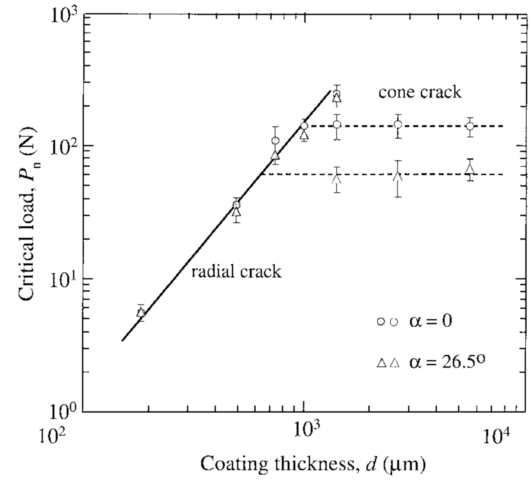

Fig. 3. Relation between critical normal load P_n for cone and radial fracture and coating thickness d for Hertzian contacts on glass/polycarbonate bilayers. Filled symbols indicate radial cracks, open symbols cone cracks. Circles indicate normal loading, triangles inclined loading. Lines are theoretical fits.

($d > 1$ mm, approximately), conventional cone cracks formed first; in thinner specimens ($d < 1$ mm), radial cracks formed first. Photographs of radial cracks in normal and inclined specimens are shown for normal loading (Fig. 2(a)) and inclined loading (Fig. 2(b)), viewed from below the contact. In these figures, the contact area is visible as the central dark circular shape with bright reflection spot. The radial cracks are not always exactly perpendicular to the glass surfaces and hence appear as broad shadows rather than linear traces. Initiation always occurred subsurface from some point within the contact shadow, close to the normal load axis. The shape and size of the popped-in radial cracks were indistinguishable in normal and inclined loading, within the natural variations in the crack patterns. In particular, the radial crack pattern did not appear to align preferentially along the tangential force direction (arrow in Fig. 2(b)). With increased load beyond the threshold, the radial cracks expanded radially outward and multiplied in the same manner as described in previous normal-load studies.[8,13]

Figure 3 plots critical values of load P_n for first fracture as a function of glass layer thickness. The data represent normal loading (circles) and inclined loading (triangles), radial cracks (filled symbols) and cone cracks (unfilled symbols). Error bars are standard deviations, for a minimum five indentations at each condition. Radial cracks occur first at small d, cone cracks first at large d. Whereas the critical loads for radial cracking are sensitive to d, those for cone cracking are not. On the other hand, radial cracking is insensitive to load inclination (within the error bounds), while cone cracking is not. The solid line is a $P_n(d)$ prediction using the relation

$$P_n = \frac{B\sigma_F d^2}{\log(CE_c/E_s)} \quad (1)$$

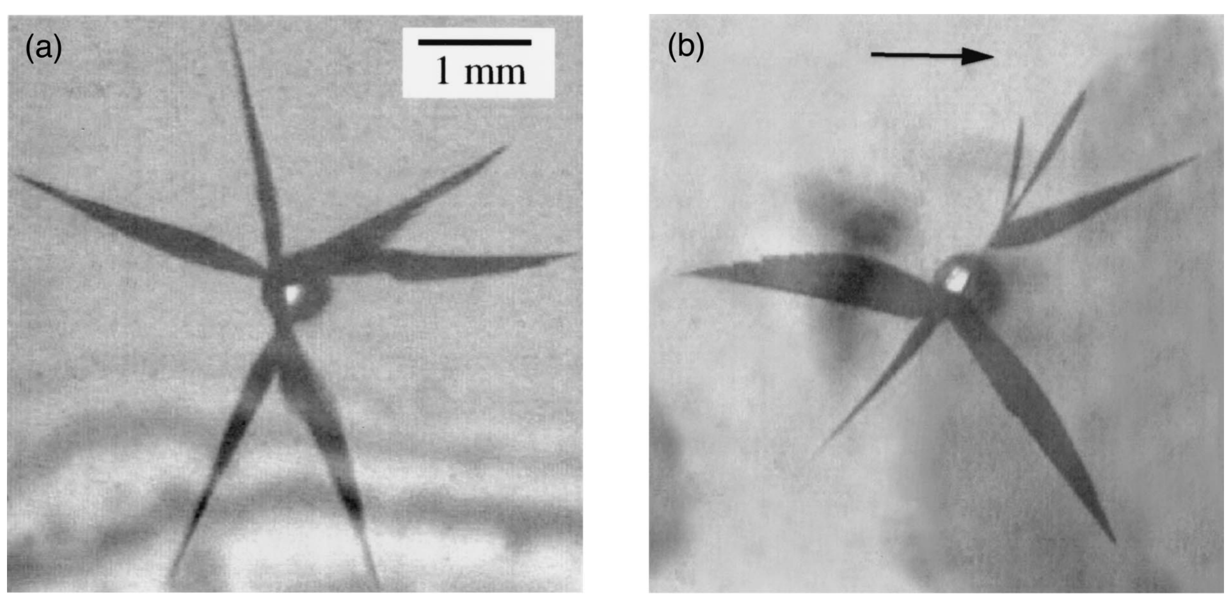

Fig. 2. Fracture at bottom surface of glass coating on polycarbonate substrate, loaded with WC spherical indenter, radius $r = 3.18$ mm: (a) normal loading, $\alpha = 0°$, $P_n = 163$ N; (b) inclined loading, $\alpha = 26.5°$, $P_n = 148$ N. Contact area is evident as central dark circular shadow, with bright reflection spot. Arrow in (b) indicates direction of tangential force.

for radial cracking in normal loading, where σ_F is the strength of the coating, E_c/E_s the coating/substrate Young's modulus ratio, and $B = 2.04$ and $C = 0.94$ coefficients evaluated elsewhere from best fits to data for well-behaved ceramics.[8–10,14] The dashed horizontal lines are empirical thickness-independent best fits to the cone crack data.

Similar observations were made in the sliding tests, i.e., a radial crack geometry and critical load relatively independent of sliding direction at first initiation. However, once the radial cracks were initiated, they translated with the moving sphere, forming extended lateral fractures. Interestingly, these cracks remained wholly subsurface throughout the entire translation, until ultimately at very high loads they penetrated to the upper surface of the coating (failure).

IV. Discussion

Taken together, the observations in Section III point to a minimal effect of tangential forces on the contact conditions to produce subsurface radial cracking in brittle coatings on compliant substrates. Regardless of surface inclination, i.e., inclined or normal (Fig. 1(a)), contact loading produces similar, orientation-independent radial crack geometries, at similar locations directly below the contact area, at similar critical normal loads. This result contrasts with the well-documented strong tangential-force dependence of surface cone crack initiation, evident in Fig. 3 (Section I). Sliding (Fig. 1(b)) also produces similar radial crack patterns at initiation, but in that configuration the radial cracks translate with the indenter, increasing the prospect of propagation to failure as the contact approaches the edges of the specimen.

Physically, the case for the insensitivity of radial fracture to tangential loading may be argued simply on grounds of symmetry, without recourse to a detailed three-dimensional stress analysis. In normal loading, the radial distribution of tensile stresses responsible for radial cracking at the lower coating surface has a well-defined maximum at the contact axis.[15] The superposition of surface tangential forces can be expected to enhance the tensile stresses behind the indenter and the compressive stresses ahead, but to have a null effect along the contact axis.[2,3] Because the radial cracks invariably initiate directly under the contact (Fig. 2), and the orientation in the crack pattern remains randomly disposed relative to the normal load axis, it can be concluded that the magnitude and location of the maximum tensile stress remains unchanged as tangential loads are imposed, at least over the range of friction coefficients ($0 \leq \mu \leq 0.5$) covered in our experiments.

The insensitivity of the critical load data for radial cracking to lateral components in contact loading has certain implications concerning the integrity of brittle coating layers. Normal Hertzian loading, with minimum geometrical complication, would appear to be a perfectly adequate route to characterizing the resistance to initiation of subsurface radial cracking, certainly in static loading. Moving contacts (sliding) may enhance subsequent propagation once the radial cracks are formed, further increasing the potential for premature failure. Repeat (contact fatigue) loading might be expected to diminish the critical loads for radial cracking, e.g., by slow crack growth in the coating or by viscoelastic relaxation of the polymeric-based support. Such prospects serve only to reinforce the need to design against radial crack initiation in the first place, e.g., by ensuring that the strength σ_F and thickness d of the coating material in Eq. (1) do not fall below minimum levels in relation to nominal operating contact loads.[9]

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