The influence of complex surface geometry on contact damage in curved brittle coatings

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Abstract

The effects of complex geometry on contact damage in bi-layer systems composed of curved brittle coating layers on compliant polymeric substrate is investigated. Previous studies of this problem utilise relatively simple flat or singly curved (domed) model structures. It is not known the extent to which conclusions driven from such observations may extended to more complex (practical) geometry. Glass plates of 1000 \( \mu \text{m} \) thick are used as representative of the brittle coating layer, and epoxy filler under layer as representative of under layer support. A series of doubly curved specimens (having curvatures of 4 and 8 mm) are produced to allow investigation of the influence of complex curvature on the evolution of damage. The specimens are tested by indentation with spheres of 4 mm radius loaded along the convex axis of symmetry. For comparison, some specimens loaded parallel to the axis of symmetry but off-centre. The study explores the influence of supporting geometries on the conditions to initiate and propagate subsurface “radial” cracks, which are believed to be responsible for catastrophic failure of brittle-coating-based structures in certain applications, such as dental crowns. It is demonstrated that critical loads for initiation of radial cracks and the subsequent crack propagation are insensitive to complex geometry, so that simple monotonic indentation “axis and/or off-axis loading” with minimum geometrical complication “flat, simply curved” remains an appropriate route to study the evolution of radial cracks in practical brittle coating structures.

Keywords: Curved surfaces; Complex surface shapes; Supporting surface; Radial cracks; Brittle coating

1. Introduction

Layered structures composed of a brittle coating on a compliant substrate are of high interest in a variety of engineering applications such as tribological and electronic packaging [1,2], coated cutting tools and thermal barrier coatings [3–5] as well as biomechanical implant structures [6–12]. The lifetime and failure resistance of such structures are affected by a variety of parameters and limited by any one of a number of damage modes that may develop in the structure under contact loading. Fig. 1 (top) shows two major modes of coating failure: cone cracks (inner “Hertzian” and outer cone cracks) initiate at the top surface of the coating, and radial cracks initiate at the bottom surface of the coating. Careful selection of component properties and design of layer geometry to maximize the damage resistance of such systems is, therefore, essential. Radial cracking may initiate at the lower surface of the coating, where flexure induced by concentrated loads at the top surface is at its maximum. Radial cracks have been identified as the most dangerous in the context of system survival [1,13–15]. In particular, in thinner coatings, less than 1 mm, they can extend long distances subsurface, from the loading axis. In severe cases the cracks extend to the edge of the structure, see Fig. 1, resulting in premature failure.

The type of damage illustrated in Fig. 1 (bottom) has been implicated in catastrophic failure of dental crowns. A considerable amount of experimental and analytical investigation of contact damage modes in brittle/compliant bi-layer structures of the kind under consideration here has been carried out [3–12,16–22]. These studies have enabled determination of dependence of critical conditions for various damage modes on geometrical variables, such as, coating thickness and indenter sphere radius, as well as...
materials properties such as interlayer modulus mismatch, coating layer strength, hardness and toughness.

In previous studies [13–15], we examined the effect of changing specimen surface curvature on the evolution of subsurface radial cracks. We demonstrated that surface curvature could play an important role in the radial crack evolution, by strongly enhancing propagation to failure [13]. This work utilised simple curvature (single curved specimens) and central normal loading. Further studies have examined the effect of complex loading (having tangential and normal components) [14] and the effect of coating thickness [15].

In the current study, we examine the effect of further complications in geometry, by focusing on multiply curved specimens. We define the basic form of geometric complications and the state of loading in Fig. 2. The multiply curved structure is defined in terms of curvature by $r_s = (\infty, r_s, -r_s)$, indicating the combination of a flat section, a convex section and a concave section. It is shown that the critical loads for initiation of radial cracks in complex geometrical specimens and subsequent crack propagation are insensitive to such geometrical complexity. We conclude that normal monotonic indentation of specimens having minimum geometrical complication (flat, singly curved) would appear to be adequate for the study of the evolution of radial cracks in brittle coating structures.

2. Experimental procedure

Glass/epoxy layer structures were fabricated as a model bi-layer system with complex shapes, as indicated in Fig. 2. Borosilicate glass (D263, Menzel-Glaser, Postfach, Germany) was chosen as the brittle layer (coating), in the form of 1 mm thick plates $75 \, \text{mm} \times 25 \, \text{mm}$. This glass has a Young’s modulus 73 GPa. Epoxy resin (Resin R2512, ATL Composites, Southport, Australia) was chosen as the support material (substrate), Young’s modulus of 3.4 GPa.

To obtain curved surfaces, the glass plates were slumped over stainless steel balls of prescribed radius and subjected to heat treatment. In order to prevent the glass from sticking to the steel spheres, the heated spheres were sprayed with kiln wash (50% wt% Kaolin + 50 wt% alumina hydrate, mixed with 5 parts by volume of distilled water) at $\approx 230 ^\circ C$. The sprayed film was then lightly smoothed with a lint-free cloth. The glass plates were then subjected to the following heat treatment, in air: (1) heat to $\approx 750 ^\circ C$ and hold until the glass plates conform to the spherical die curvature, (2) rapidly cool to solidify the glass, (3) anneal to $\approx 560 ^\circ C$ and cool slowly to room temperature to avoid any residual stresses [13,23]. Glass surfaces with radius of curvature $r_s = (\infty, 8 \, \text{and} \, -8) \, \text{mm}$ and $r_s = (\infty, 4 \, \text{and} \, -4) \, \text{mm}$ were prepared in this way. The glass retained its original thickness of 1 mm during this treatment.

The prospective undersurface of each glass plate was given an abrasion treatment with 50 $\mu$m sand particles using a dental sandblasting machine (P-G4000, Harnish & Rieth, Winterbach, Germany), as in common dental
practice sandblasting is often used in the preparation of dental crowns [13,21,24]. This treatment conveniently reduces the strength level of the glass close to that of porcelain (a common dental material), as well as enhancing subsequent epoxy bonding [13,24]. Most importantly, it favours radial crack initiation at the glass under-surface, eliminating complications from premature cone cracking at the top surface [10,17]. Bonding of the glass plate to its compliant substrate was obtained by pouring the epoxy resin directly onto the abraded side of the glass plate.

Indentation tests were carried out in air using a tungsten carbide sphere of radius \( r_s = 4 \text{ mm} \) mounted in a screw-driven mechanical testing machine (Instron 4301. Instron Corporation Canton, MA). Care was taken to align the sphere and specimen so that the contact occurred either along the axis of symmetry for the axial loading tests, and parallel to the axis but contacting the surface at a point corresponding to \( \varnothing = 30^\circ \) (Fig. 2) for the off-axis cases. The specimens were clamped to prevent any sliding during testing. The load was applied to the convex surfaces at constant crosshead speed 0.1 mm min\(^{-1}\) (\( \sim 10 \text{ N s}^{-1} \)). Load up to 1500 N could be attained in this configuration. During loading, the specimens were viewed from the side and slightly from above using a video camera, such that the contact and side walls of the specimens were within the field of view at all times. A light source was placed behind the specimens to optimize crack visibility. A single-cycle indentation was performed on each specimen. Critical loads to initiate radial cracks at the glass under-surface were monitored in each specimen. Subsequent propagation of the radial cracks with further increase in the loading was then followed to the point of failure. Four to eight separate tests were run at each for each configuration. No delamination between the glass and the epoxy was observed in any of the tests until ultimate failure, attesting to the good bonding.

3. Results

3.1. Crack morphology

Fig. 3 shows representative photographs from video clips during indentation for specimens with complex geometry and different loading combinations (a) \( r_s = [\infty, 8, -8] \text{ mm} \) (axial loading, \( \varnothing = 0 \)) at \( P = 1300 \text{ N} \), (b) \( r_s = [\infty, 8, -8] \text{ mm} \) (off-axis loading, \( \varnothing = 30^\circ \)) at \( P = 900 \text{ N} \). In both systems, radial crack initiation and subsequent propagation followed the same pattern. Multiple radial cracks initiate as the load increased while individual cracks elongate and extend steadily to the convex hemispherical base. Further, increase in indentation load causes failure of the coating in the same manner observed for the single convex surface geometry [13,14]. Coating failure is defined as the point where material loss from the coating occurs (a segment of the coating pops off the surface, see Fig. 1 and 2(b). No extension of the radial cracks to the supporting geometries (flat and concave) where observed in this configuration.

Fig. 4 compares crack patterns in the geometry combinations mentioned above, but in this case indentation was carried out on a highly convex surface, radius of curvature \( r_s = 4 \text{ mm} \) (a) \( r_s = [\infty, 4, -4] \text{ mm} \) (axial loading, \( \varnothing = 0 \)) \( P = 930 \text{ N} \), (b) \( r_s = [\infty, 4, -4] \text{ mm} \) (off-axis loading, \( \varnothing = 30^\circ \)) \( P = 620 \text{ N} \). In this system, (highly convex surface) steady propagation of the radial cracks from the near contact zone is followed by a sudden jump to the base of the hemispherical convex surface. In some specimens the initiation load was so high that the radial cracks popped-in immediately to the convex hemispherical base and extended in to the adjacent flat surface (Figs. 4(a) and (b)). Further increase in load resulted in specimen failure (material dislodgement) without any further propagation of the cracks into the adjacent concave surface. In our previous study [13], radial cracking was also found to be inhibited in axial contact on concave surfaces.

3.2. Radial cracks evolution

Critical loads \( P_R \) to initiate subsurface radial cracks were measured as a function of specimen curvature \( r_s^{-1} \). Data are plotted in Fig. 5 for both axial loading, \( \varnothing = 0 \) (circles) and off-axis loading, \( \varnothing = 30^\circ \) (triangles). Filled symbols from previous studies on singly curved specimens are also shown
Error bars are standard deviations, for a minimum of four indentations at each condition. As before [13], the data for axial and off-axis loading overlap within the scatter bands, indicating that the small reduction in normal loading \( (P_n = 0.87P) \) is inconsequential to the crack initiation, as is superposition of the tangential component \( (P_t = 0.5P) \). Furthermore, the data show that while the critical loads, \( P_R \), are insensitive to the curvature of the specimen immediately beneath the indenter, they are insensitive to the geometrical complexity of the surrounding support structure.

Fig. 6 shows typical circumferential plots of radial crack length \( (s) \) (crack length measured around the curved surface) as a function of indentation load, for axial loading \( (\varphi = 0) \) on convex specimens \( r_s = 8 \) and \( 4 \) mm as well as on flat specimens from the previous study [13] for comparison. The popped in radial cracks first extend steadily with increasing load, but then propagate relatively abruptly to the base of the hemispherical cap (convex surface), with increasing abruptness at smaller \( r_s = 4 \) mm. Further, increase in load does not extend the cracks into the adjacent surfaces (flat and concave) but instead causes linkage of neighbouring radial arms and, ultimately, material dislodgment. Note that for the highly convex surface \( (r_s = 4 \) mm) the radial cracks extended slightly into the flat surface, as represented by the dashed line in Fig. 6. Apart from this observation, there is no significant difference between these data and the data observed on singly curved specimens [13].

The loads to achieve crack propagation to the base (edge of the convex dome) are summarized in Fig. 7 for all such tests, filled symbols (circles) for axial loading \( (\varphi = 0) \) from the previous study [13] and un-filled circles for off-axis loading [14]. Where as the effect of surface curvature on the failure condition is strongly evident, the complexity of the surrounding support structure once again has little effect on the failure loads. The complex geometry considered here slightly reduces the failure loads for axial loading.

4. Discussion

In this report, we investigated the initiation and propagation of radial cracks in curved (convex) brittle coating layers on compliant substrates due to axisymmetric and off-axis contacts on the top of convex surface adjacent
to flat and concave surfaces. The observations from the previous studies [13–15] and the current study highlight the importance of local surface curvature on the fracture behaviour. Generally, higher contact loads are required to initiate radial cracks in curved surfaces (Fig. 5), while the load to complete failure is reduced (Fig. 6). On the other hand, complexity in the surrounding support structure has relatively little effect on the failure load.

The methodology used in this study provides useful guidelines, but the data do not provide general quantitative predictions of failure in all brittle-coating structures. A detailed three-dimensional stress analysis is needed to understand the enhancement of stress distribution around the indenter and the extension of stress contours to adjacent surfaces at higher loads. We have considered only single-cycle loading. Fatigue due to repeated loading must exacerbate the failure process.

The results in this study show the insensitivity of the critical loads for radial crack initiation in complex geometrical specimens. Normal indentation loading with minimum geometrical complication (single shape) would appear to be a adequate route to study the evolution of radial cracks in brittle coating structures, in single-cycle loading considered in this study.

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References


