Influence of Margin Geometry on Failure of Brittle Coatings on Compliant Substrates: Relevance to Failure of Dental Crowns

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Abstract. This paper explores the so-called “margin failures” observed in loaded curved bi-layer structures. Hemispherical bi-layer model test specimens consisting of glass shells with varying margin geometry filled with epoxy resin, simulating brittle crowns on tooth dentine, are loaded with compliant indenters along the (convex) axis of symmetry. Using this unique setup, the influence of margin geometry on margin failure is examined. Nearly all previous studies have utilised hard spherical indenters of various radii, and examined crack initiation and evolution at the contact point. However, the modes of fracture observed in this traditional contact problem, surface cone cracking or flexure-induced radial cracking initiate close to or inside the (small) contact area, and thus not explain the margin failures commonly observed by dentists. Crack growth at the margins distant from the contact zone cannot be generated under indentation using hard spherical indenters. The use of a compliant (soft) indenter distributes the indentation force over a large contact area, generating a compressive zone underneath the contact, and effectively inhibiting the modes of fracture typically observed using hard indenters (radial and cone cracking). Consequently, significant tensile stresses at the support margin become dominant, and the focus shifts to fracture initiating at the support margins. In this study, cylindrical indenters composed of PTFE Teflon, with a modulus several orders of magnitude lower than the indented materials, are used to examine margin fracture in brittle crown like structures. The specific focus is the effect of margin geometry – Chamfered; Round; Shoulder margins are examined, and their influences on crack initiation and damage evolution are reported.

Figure 1 Schematic drawing showing indentation with a cylindrical indenter at axial load \( P \) on a dome structure of inner radius \( r_s \) consisting of a brittle shell of thickness \( d \) supported by polymeric base extending depth \( h \) below the margin edges. Below are the three margin geometries adopted in this study, showing the surface treatments for the glass under-layer.
Introduction

Brittle coatings on compliant substrates are of great interest, due to their relevance to a wide range of engineering applications [1], as well as biomechanical implant structures [2]. The combination of a hard, brittle outer layer and a compliant, tough inner layer offers high wear resistance and damage tolerance, factors that are crucial to the lifetime of such structures. It has been well documented that under hard indenters, radial cracking at the coating under-surface, from flexure induced by concentrated loads at the top surface, has been identified as the most deleterious for system survival [3].

Whereas many studies have investigated damage modes in brittle/compliant bi-layers of the kind under consideration here, virtually all have concentrated on indentations with hard spheres [2-5]. These studies have enabled the identification of various damage modes and the dependencies of critical loads on geometrical variables such as coating thickness, indenter radius and sample radius [1-5, 7, 8], as well as on material properties such as interlayer elastic modulus. Most engineering contact problems experience a more complex loading. For example, occlusal loading in dental crowns is a special case in point. This is generally far from loading by a hard object (spherical indenter), involving contact with less stiff (soft) objects. Any complete analysis of structure failure requires the incorporation of these elements. Controlled experiments documenting such effects (shape irregularities, and soft indenters) need to be conducted. The types of curvature studied in this work are shown in Fig. 1.

Previous studies [4, 5, 8] examined the effect of specimen surface curvature on the evolution of subsurface radial cracks. It was demonstrated that surface curvature can play an important role in radial crack evolution under hard indenters. Accordingly, this study aims to measure the effect of margin geometry and softer indenters on the critical loads and growth of radial cracks in convex brittle layer specimens. It is shown that critical loads for initiation of radial cracks are sensitive to margin geometry, and that damage in brittle coating structures can vary significantly and extend to the margins away from the indentation area, especially for soft indenters having a large indentation area.

Experimental method

Glass/epoxy bi-layer structures were fabricated with specific attention to margin geometry, as indicated in Fig. 1. Borosilicate glass (D263, Menze-Glaser, Germany) was chosen as a brittle coating because of its good working range. This glass has a Young’s modulus of 72.9 GPa. Epoxy resin (Resin R2512, ATL Composites, Australia) with a Young’s modulus of 3.4 GPa was chosen as the support material, because of the ease with which it can be moulded to the shape of the glass coating, and its good bonding qualities. Furthermore, the low epoxy modulus promotes the growth of radial cracks, which are the central focus of this study.

In order to produce curved glass/epoxy bi-layer structures, the glass plates were slumped over stainless steel balls of a prescribed diameter \( r_s = 6 \text{ mm} \) and subjected to heat treatment. Prior to addition of the supporting under-layer, the undersurfaces of the glass plates were abraded using a dental sandblasting machine \( (P-G4000, \text{Harnish & Rieth, Czech Republic}) \). The main undersurface was blasted with 50 \( \mu \text{m} \) sand particles, and the margins were trimmed using abrasive green stone, standard medium \( (\text{silicon carbide grits bonded with ceramic; equivalent to 1200 grit}), (\text{Halas Dental Limited, Australia}) \). This treatment favors preferential radial crack initiation at the glass undersurface, especially at the margins. It also introduces a more uniform surface flaw distribution, reducing the scatter and promoting test repeatability. After the glass shells were fabricated, as shown in Fig. 1, the shells were then fitted into a mould of the same lateral dimensions, with the hemispherical protrusion facing outward, and with the abraded surface always-facing inward. Epoxy resin was then poured into the mould in thin layers of \( \leq 5 \text{ mm} \) (with intermittent vibration to remove air bubbles); in order to prevent cracking of the glass due to thermal shrinkage, with each layer allowed curing for 24 hours before further material was added. Additional material was added to a substrate depth \( (h) \) of about 4 mm below the lowest point of the coatings. The bottom surface of
the specimen was ground to produce a flat surface normal to the indentation axis. Care was taken to align the indenter and specimen axes so that contact occurred axisymmetrically.

**Fracture testing.** Indentation tests were carried out in air at room temperature using a PTFE-Teflon (E-PLAS Pty. LTD, Australia) cylindrical indenters of 10 mm diameter and 10 mm height (Young’s modulus = 480 MPa), mounted in a screw-driven mechanical testing machine (Instron 4301, Instron Corp, Canton, MA). Adapters were manufactured to hold the indenters to the load cell. The tests were conducted under displacement control, at a crosshead speed of 0.1 mm/min (≈ 10 N/Sec).

A single cycle indentation was performed on each specimen to eliminate the effects associated with pre-existing cracks. During loading, the specimens were viewed from the side and from slightly above using a video camera, such that the contact and side walls of the specimen were within the field of view at all times. A light source was placed behind the specimens in order to optimise crack visibility. No delamination was observed between the glass and the epoxy layers in any of the tests before ultimate failure, attesting to good bonding.

**Results and discussion**

Figure 2 compares crack patterns for specimens having the same margin geometry (convex, chamfered edge) at common $r_s = 6$ mm, and coating thickness $d = 1$ mm on epoxy support base extending $h = 4$ mm, indented with a soft Teflon indenter: (a) load $P = 900$ N; (b) load $P = 1400$ N; (c) load $P = 1550$ N. For this geometry and in all systems (i.e. chamfered, rounded and shouldered edges), radial crack initiation and subsequent propagation followed the same pattern. A single radial crack initially popped in between the margin and the indentation area. As load increased, more radials popped while individual cracks linked at the border of the indentation area. Coating failure, defined as "the point where material loss from the coating occurs, or splitting between the coating and the supporting base occurs", can be seen in (Fig. 2(c)).

![Figure 2](image-url) Contact fractures in epoxy-filled glass domes of inner radius $r_s = 6$ mm, chamfered edges, indented with Teflon indenter at load $P$: (a) 900 N, (b) 1400 N, and (c) 1550 N. Showing failure from radial cracks. Note cracks locations and intensity as load increases (left to right).

Figure 3 compares crack patterns after unloading in specimens having the same convex geometry, $r_s = 6$ mm, but with different margin geometry (see Fig. 1): (a) chamfered margin, load $P = 1600$ N; (b) rounded margin, load $P = 1750$ N; (c) shouldered margin, load $P = 2000$ N. The radial cracks have a similar forms to those produced with a hard spherical indenter, as described in our preceding studies [4-6, 8]. With a more compliant indenter, crack growth was suppressed at the periphery of the indentation area, and in all cases no cracks were seen to initiate within the indentation area, or propagate to the top of the dome. Note the small increase in crack density as margin geometry changes (Fig. 3 (a) and (b), not so much between (b) and (c)).

Critical loads $P_R$ to initiate (I) subsurface radial cracks and to propagate radial cracks to failure (F) at the specimen edges were measured for various margin geometries. Fig. 4 shows the critical loads $P_R$ with standard deviation bounds for a minimum 3 tests in each case (error bars).
The results in Fig. 4 shows that both radial cracks critical loads $P_R$, for initiation (I) and failure (F) are influenced by margin geometry, although the margin geometry has less effect on failure loads (F), this observation is consistent with our previous study [6] where failure loads are seen to be less sensitive to other variables (i.e. indenter modulus).

The use of a soft indenter shifts the primary failure location in brittle crown-like structures to the margins, away from the contact point where cracking is observed under hard indenters. This is analogous to dental failures observed when chewing soft food, and brings the effect of margin geometry into focus – under a hard indenter, the margin is distant from the damage initiation, and consequently its geometry is largely irrelevant.

The present study shows that the margin geometry has a significant influence on the critical loads for radial crack initiation, with removal of coating material leading to cracks initiating at lower loads. This is an important result, since it implies that the lifetime of a dental crown could be significantly altered by the margin geometry. The effect on later stages of crack propagation to failure is less pronounced.

References
