Abstract

In this report, we investigate and visualize the effect of shape irregularity on contact damage in a brittle coating on a stiff metal substrate. Hertzian contact damage in a dental porcelain layer of thickness between 0.25 and 0.75 mm, fused onto a Ni–Cr alloy substrate in both curved and planar geometries was studied with the aid of the finite element method and experimental investigation. Three failure modes were examined with varying porcelain layer thickness: cone cracking at the upper surface of the porcelain, median or interface cracking at the layer/substrate interface and plastic deformation below the contact area in the substrate. It is shown that curvature has very little effect on the initiation of surface cone cracks in this system, but substantial effect on the initiation of interface radial cracks. In particular, curvature reduces the critical load for the onset of interface cracks.

Keywords: Finite element method; Indentation; Crack; Shape irregularity; Bilayer; Transparent

1. Introduction

Layered structures composed of hard ceramic coatings on soft metal substrates are of interest in a variety of industrial and technological applications, including bioengineering and tribology. Systems combining the wear resistance of a porcelain coating layer and the ductility of a metal under layer have been developed for high damage tolerance applications, for example, crowns and bridges in restorative dentistry, coated cutting tools and thermal barrier coatings [1,2]. Contact damage tolerance of such systems is affected by a variety of parameters. Careful selection of component properties and layer geometry may therefore be used to maximize the damage resistance of such systems.

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0020-7403/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmecsci.2004.06.004
A considerable amount of experimental and analytical investigation of this type of system has been carried out using Hertzian indentation. With special reference to dental crowns, Zhao et al. [3–5] studied the contact damage modes of ceramic–metal bilayer composites, using Hertzian contact with a spherical indenter on a flat (planar) surface sample. The most recent work aimed at extending analysis to trilayers, pertinent to all-ceramic dental crowns, again focusing on the planar system [6]. Chul-Seung and Lawn [7] also studied the effect of tangential loading on radial cracking in brittle coatings, using a soda-lime glass as a brittle coating on polycarbonate plastic slabs for the substrate. For planar specimen geometry, they demonstrated that these effects are secondary, so that conventional normal indentation remains an appropriate test procedure for characterizing the mode of coating fracture. Currently, Ford et al. [8] are conducting a numerical study of contact damage in curved porcelain coatings on soft substrate bilayers, using finite element modeling. Furthermore, Ford et al. [9] are studying the contact damage in flat porcelain/Pd–alloy bilayers, as a theoretical extension to the experimental work done by Zhao et al. [3]. Regimes for different modes of damage have been determined, but it is not known how these might be affected by curvature of the layered structures. To the best of our knowledge, no previous studies of damage in non-planar (porcelain/metal bilayers) systems have been carried out.

In the present work, combined experimental/analytical investigations are carried out to compare the failure modes between planar and non-planar systems in order to identify the influence of shape irregularity. Tests are carried out using a case study of a dental porcelain (VITA OMEGA 900) with coating thicknesses \(d\) of 250, 500 and 750 \(\mu m\), fused onto a Ni–Cr alloy (Wiron 99) base, in two geometric configurations: planar surface and a convex spherical specimen with radius of curvature \(r_s\) = 4 mm. Both geometries were subject to indentation by a tungsten carbide sphere of radius \(r_i\) = 2 mm, in a load range up to 1000 N. The cuspal radius at the biting contact lies between 2 and 4 mm [1] and typical oral forces range up to 100 N [10]. Our choices of indenter radius \(r_i\), radius of curvature of the specimen \(r_s\) and the load range encompass these values. The principle modes of failure observed in these tests are shown in Fig. 1. Hertzian cone cracking (C) form at the upper surface of the porcelain layer, median (M) or interface cracks initiates at the lower surface of the porcelain layer and plastic yielding of the metal substrate.
Critical loads to initiate such cracks are evaluated as a function of the porcelain coating thickness and geometry. The relationship between the critical stresses and indentation loads to predict the critical condition under which different modes of failure occur, especially the underlying plastic deformation where it is difficult to obtain experimental data, were also evaluated.

2. Finite element modeling

A commercial finite element code (ABAQUS, version 6.3) is used to evaluate the stress distributions in the bilayer system. The axisymmetric bilayer curved model is represented by a quadrant circle of radius \( r_s = 4 \) mm, coating thickness \( d \) see Fig. 1. The bilayer flat model is represented by a rectangle having a height \( h + d \) and a width \( L \), with \( h \) and \( L \) large enough compared to the porcelain layer thickness \( d \) for the solution to be independent of the dimensions \( h \) and \( L \) and the substrate can be regarded as a half space [2]. The axisymmetric bilayer model (flat and/or curved) will be referred to as the “block”. The block was subjected to Hertzian indentation by a hemispherical indenter, represented by a quadrant circle of radius \( r_i = 2 \) mm pushed downward. The block was assumed to be sitting on a frictionless flat surface and the contact faces between the block and the indenter were frictionless. A typical mesh is shown in Fig. 2. The refinement on the layer surface and along the vertical axis of symmetry was necessary in order to calculate the contact radius and the substrate plastic deformation with sufficient accuracy. The element size in these regions reduced to 10 \( \mu m \). The nodes along the base were restricted to radial movement only, while the nodes along the vertical axis of symmetry were constrained to move axially. The porcelain coating and the indenter were taken to be elastic. Young’s modulus and Poison’s ratio parameters for input into ABAQUS were taken to be, for porcelain, 70 GPa, and 0.2 respectively, while for the tungsten carbide indenter the manufacturer’s figures of 614 GPa and 0.22 were used. The substrate metal was modeled as an elastoplastic material with Young’s modulus 255 GPa and Poison’s ratio 0.3 (manufacturer’s data). The hardness, \( H (HV_{10} 180) \), is used to provide estimates for the yield stress of the metal: \( Y = H/3 \) [11], a bilinear stress–strain curved is assumed, with no plastic strain-hardening present (strain-hardening coefficient = 0).

![Fig. 2. Typical finite element mesh, showing refinement along axis of symmetry and the top of the ceramic layer.](image-url)
Both finite element models (planar and non-planar) were tested for compliance with Hertz’s theory for elastic contact [12] between a porcelain monolith and tungsten carbide indenter, where the Hertzian modulus was calculated to be 27.7 GPa for the planar model. The model predicts the Hertzian modulus within 1%, with higher accuracy for the planar model, as shown in Fig. 3. The deviation between the model and the exact solution can be attributed to the element size on the contact area.

3. Experimental procedure

Porcelain/metal–alloy bilayers were prepared for indentation in two configurations: Substrate blocks $18 \times 12 \times 3 \text{ mm}^3$ and a half-sphere of 8 mm diameter. Wiron-99 alloy (Ni 65%, Cr 22.5%, Mo 9.5%, Nb 1.0%, Si 1%) was melted at 1310–1250°C and cast into substrate blocks using the lost wax method in an induction centrifugal casting furnace (GALLONI, ITALY). Following standard routines practiced by dental technicians, these blocks were then sandblasted (4 bar, 100 µm), oxidized at 900°C and sandblasted again at lower pressure and with finer sand grains (2 bar, 50 µm) to remove the oxide layer and provide a good bond with the porcelain layer. Porcelain (VITA OMEGA 900) was then applied to the substrate, in sequential layers of 200–300 µm, each layer sintered according to the manufacturer’s specified firing cycle. Materials used in this study are those commonly employed in the fabrication of dental crowns. The thermal expansion mismatch between the metal and porcelain was very low. For the metal, thermal expansion coefficient (TEC) (600°C) $13.9 \times 10^{-6} \text{ K}^{-1}$ and for the porcelain TEC (600°C) $14.0 \times 10^{-6} \text{ K}^{-1}$. Residual stresses in the coating can therefore be neglected [13,14].
3.1. Bonded-interface technique

The bonded-interface technique (BIT) was employed to reveal subsurface damage modes in the bilayers [15–17]. The sample preparation for bonded-interface specimens was as follows: Blocks were cut into halves parallel to their long axis and polished with loose diamond abrasives (mean diameter of 15, 9, 6 and 1 μm, respectively). Adhesive (Loctite 480, Loctite Corp., USA) was then applied to bond the two polished surfaces together. A small hand vice was used to exert pressure on the bonded faces to ensure a thin bond layer. Top surfaces were then polished again in the same manner as specified above, to ensure a smooth surface for indentation. The bond thickness was measured to be between 6 and 10 μm.

The indentation was applied along the trace of the interface at the upper layer surface using an Instron Universal Testing Machine (Instron, model 8501, UK) with a 5 KN load cell, which is capable of controlling both the displacement and load. The indentation was carried out at a constant crosshead speed 0.1 mm min⁻¹ with a tungsten carbide (WC) indenter of radius (r_i) = 2.0 mm. The indented specimens were then immersed in acetone to separate the opposing halves. After cleaning, the specimens were viewed in an optical microscope (Zeiss Axioplan-2 Plus, Germany). Porcelain thickness were measured again from these sections.

3.2. Transparent porcelain without bonded-interface

Porcelain/metal–alloy bilayers were prepared as described in Section 3.1. Transparent porcelain (Window, VITA OMEGA 900) was used, which allows direct observation of the formation of interface cracks in the porcelain lower layer and calculation of the critical loads for these cracks. A porcelain layer of 250 ± 5 μm was utilized in both flat and spherical specimens. Thickness above 250 μm are not recommended for this porcelain, as this may result in very high porosity. The finished IJMS Editorial Office, UMIST porcelain thickness were determined by measuring the overall specimen dimension relative to the dimension of the substrate block.

The indentation was performed on the as-prepared bilayer surface. The specimens were viewed using an optical microscope (Zeiss Axioplan-2 Plus, Germany). Fig. 4 shows typical interface damage micrographs for a layer thickness d = 250 ± 5 μm, r_s = 4 mm, r_i = 2 mm. (a) Indentation load of
225 N, showing pop-in interface cracks at the lower porcelain layer surface. (b) Indentation load of 400 N showing the interface cracks penetrating through the layer thickness (pop-up at the upper layer surface) as well as cone cracks. The tests were repeated several times, each on a fresh specimen.

4. Results and discussion

4.1. Experimental results

Fig. 5 shows the BIT views of the top surface and side section of damage in bilayers, for a porcelain layer thickness of \(d = 250 \mu\text{m}\) and indentation loads of 200 and 600 N, on both planar and spherical specimens. The indentation load in all cases is well above the critical load. The cone crack patterns on the top surface show relatively little variation from flat to curved configurations at the same load (a and b), (c and d). At the low indentation load of 200 N, interface (radial) cracks can be seen in the curved specimen (b), while on the flat specimen (a) extended cone cracks can be seen but no radial cracks were observed. On the other hand, at the higher load of 600 N the crack patterns in both configurations (flat and curved) show relatively little variation. In this porcelain/metal bilayer system, it is hard to establish the sequence of formation of cracks using BIT. It is suggested that

![Figure 5](image_url)

Fig. 5. Half surface and side view micrographs showing damage in porcelain/metal bilayers, top row is a half view of cone cracks (upper layer surface), bottom row is the side view of the bonded interface. Coating thickness \((d) = 250 \mu\text{m}\). (a) 200 N (Flat), (b) 200 N (Curved), (c) 600 N (Flat), (d) 600 N (Curved) (C: Cone crack, M: Median or Interface crack).
interface cracks form first at lower porcelain layer thicknesses and cone cracks form first at higher porcelain layer thickness, as seen in Fig. 4 for transparent porcelain [3,4]. Delamination was not observed in any of the tests, suggesting a good bond between the porcelain layer and the substrate. Note that no experimental data were taken for the yield zone (substrate deformation), because it is very difficult to measure the depth of the plastic zone. Conversely, the finite element simulation easily provides data for the yield zone.

Fig. 6 shows the indentation stress–strain curves for porcelain and metal alloy monoliths, as well as for bilayers with porcelain layer thicknesses of \( d = 250 \) and \( 500 \) \( \mu \text{m} \). These curves are generated from experimental data. The contact radius (a) used to calculate the indentation stress (load/\( \pi a^2 \)) and the indentation strain (\( \alpha/r \)) where measured after unloading the specimen. Prior to indentation, the specimen surface is covered by a thin film of lubricant. The indentation radius is measured to the outer edge of the imprint left in the film by the indenter after unloading. The radius is measured by using the micrometer eyepiece (OMS-4, OLYMPOS, Japan) connected to an optical microscope. Note that for the flat geometry \( r = r_i \) and for the curved geometry the relative radius of curvature is used \( r = [1/r_i + 1/r_s]^{-1} \) [12]. The curve for monolithic porcelain shows a near-linear elastic behavior, with no elasto-plastic component [1]. On the other hand, the curve for the metal–alloy shows a strong non-linear characteristic, typical of ductile materials. The indentation stress–strain curves for the bilayer lie between the monolithic porcelain and metal/alloy curves, moving away from porcelain toward the metal with decreasing porcelain layer thickness. The bilayer curves fall increasingly below the porcelain curve at high loads, more rapidly in the thinner coating, as the load transfers to the substrate. The evolution of attendant radial cracks in the thinner coatings enhances this decline in sustainable contact stress in the high load region [3].

4.2. Finite element analysis

Fig. 7 shows the tensile stress maxima (\( \sigma_{11} \)) normal to cone cracks (C) at the coating upper surface as a function of applied load for given porcelain layer thicknesses. The location of the
Fig. 7. Maximum layer surface tensile stress vs applied load for given layer thickness, curved and flat modes (F: Flat, C: Curved).

Fig. 8. Sample stress field, curved mode, showing high stress gradients at the layer surface just outside the contact area, associated with Hertzian cone cracks, and at the lower layer surface near the indentation axis, associated with interface cracking.

maximum tensile stress field ($\sigma_{11}$), which governs cone cracks, remains just outside the contact area close to the layer surface, irrespective of the load [18], as shown in Fig. 8. The abbreviation F refers to flat and C to curved specimens. These data can be used to predict the critical load at which the Hertzian cone crack first appears [9]. The experimental mean critical load for cone crack formation on a porcelain monolith was interpreted with the FEA model, the resulting critical stress calculated to be 356 MPa, as shown in Fig. 9. It is important to differentiate between this critical stress, and a critical stress derived from the fracture mechanics analysis, using the fracture toughness of the material and an estimated flaw size. The 356 MPa critical stress quoted above is an estimate of the surface stress when Hertzian cone cracks are first observed. However, very high stress gradients are present in the material close to the coating surface just outside the contact area, as shown in Fig. 8. The presence of initial flaws in the experimental material means that the actual crack tip will be below the surface at the end of the flaw. Consequently, the critical (failure) stress at this point, as
predicted from fracture mechanics, would be much lower, and the calculated value of 356 MPa can only be used as a calibrated critical surface stress estimation tool for this particular fracture process [9,19]. The predicted critical load curves generated using the critical stress of 356 MPa for cone cracks over the full thickness range and the experimental data are shown in Fig. 10. Note that the critical loads for cone crack formation decrease with decreasing layer thickness, at first slowly and then more rapidly in the thin layer region for both geometries. The effect of curvature on critical loads for cone crack formation at the surface of the coating is apparently small in this system. Note that in the present porcelain/metal system where the substrate has a much higher modulus than the porcelain layer, the stiff substrate limits the coating deflection, resulting in a higher maximum Hertzian tensile stress outside the contact area (less than 10% outside the contact radius). As a result, the cone cracks form at relatively low loads.

The curves show relatively good agreement between the FEA model and the experimental data for both the planar and non-planar geometry. More deviation between the experimental data and analytical predictions is seen at lower thickness $d = 250 \, \mu m$. This can be attributed to the material data,
where manufacturer specifications are taken for use in the FEA. Furthermore, during manufacture of the specimens the metal is heated several times to temperatures close to 1000°C. This can alter the metal properties. The data obtained experimentally represents an average of at least five individual indentations.

Fig. 11 shows the maximum tensile stress at the interface between the porcelain layer and the metal/alloy. The deviations between the planar and spherical specimen plots become less significant with increasing coating thickness and almost vanish at higher coating thicknesses above 750 μm. It is noticeable that at lower coating thicknesses (below 250 μm) and lower indentation loads (200–400 N), the spherical geometry is significantly more likely to initiate interface cracking. This is in accord with the experimental observations, as shown in Figs. 4 and 5. For example, interface cracks are not apparent in the planar specimen Fig. 4(a), while they are well advanced in the spherical specimen at the same load Fig. 4(b).

The calculated depths of the substrate plastic deformation zone as a function of applied load are shown in Fig. 12, for coating thicknesses, \( d = 250, 500 \) and 750 μm. Note that the curves shown only represent depth, not the total volume of the plastic zone. The curves confirm that thicker coatings afford greater protection against substrate plastic deformation. The load required to produce yield increases with increasing layer thickness. The rate of increase of the plastic zone depth decreases as the zone widens at higher loads [9]. This applies to both planar and non-planar geometries as expected. The deviations between the two curves generally decrease with increasing layer thickness. A soft substrate allows the coating to bend under the immediate contact, transforming the nature of the stress field away from ideal Hertzian toward that of plate flexure, allowing build-up of tensile stress at the lower coating surface [3,15]. Once the substrate yields, the damage mode becomes more complicated. Zhao et al. [3–5] suggested that in ceramic/metal bilayer systems, the substrate yielding may appear as initial damage in the bilayer structure. Furthermore, laminar cracks (see Fig. 5(c)) in the coating are observed only after yield in the substrate. Such contact induced laminar cracks are the result of the elastic spring back in the ceramic coating relative to the irreversibly deformed substrate. Initial laminar cracks occur within the lower half of the coating thickness, immediately above the interface. The critical loads for onset of yield (plastic deformation) are shown in Fig. 13. The curves for substrate yield are drawn with low contrast.
To make use of the data to predict the onset of the interface fracture mode, we use the fracture toughness of the material ($K_{IC}$)

$$K_{IC} = 1.12\sigma(\pi a)^{1/2}.$$ 

Substituting a value of 1 MPa ($m^{1/2}$) for $K_{IC}$ [20,21] and estimating initial the flaw length, $a$, to be 10 μm based on the typical pore size in the porcelain, the predicted critical stress is 159 MPa [9]. The predicted critical stress can then be used to calculate critical loads for cracks originating directly under the indenter. Critical loads based on this method are shown in Fig. 13, with the substrate yield critical loads and the predicted cone crack critical loads included for comparison.

A critical loads comparison between FEA model predictions and experimental data is shown in Fig. 14 for both cone and interface cracking, the porcelain layer thickness in both configurations (planar/non-planar) are $d = 250$ μm, note that a minus 10% error bars added to the experimental
Fig. 14. Comparison between FEA prediction and experimental data, curved mode, layer thickness 250 μm.

Fig. 15. Comparison of predicted critical loads for different failure modes, showing the effect of indenter size and layer thickness \((d)\) \([R \text{ (curvature ratio)} = r_i/r_s]\) (F: Flat, C: Curved).

values for interface cracks since the cracks are first seen at certain load. The actual critical load will be less than this value. For example, the cracks are first seen at 250 N but not seen at 225 N.

The dependence of predicted critical loads for different failure modes, on porcelain layer thickness \((d)\) and the indenter size \((r_i)\) are shown in Fig. 15. Comparison of critical loads for different curvature ratio \(R\), defined as indenter radius \((r_i)\)/specimen radius \((r_s)\), at the same porcelain layer thickness, highlight the significant effect of the specimen geometry and the effect of radius of curvature. For each indenter size the critical load for cone cracking increases with increasing layer thickness, where as increasing the indenter radius increases the critical load at a given layer thickness. The critical loads for interface cracking at a given layer thickness and for substrate yielding, are relatively insensitive to the indenter radius.

5. Conclusions

This study shows a comparison between the planar and non-planar specimen geometries, for the same material combination. Little difference was observed in the critical loads to produce cone
cracking at the surface of the coating at a given thickness and a given indenter radius. This has been confirmed both experimentally and by finite element analysis.

On the other hand, at lower thicknesses below 250 µm, the non-planar specimen appears to be significantly more susceptible to interface cracking. Critical loads required to produce yield in the substrate, which are hard to obtain experimentally, has been studied using FEA modeling. The results indicate that substrate yield is also sensitive to specimen geometry.

Finally, while we see little difference in the critical loads for cone cracks initiation between the planar and the non-planar systems at a given indenter radius, the ratio of indenter radius to specimen radius is important. This is clearly an important parameter to consider in future experimental studies.

Acknowledgements

The authors gratefully acknowledge Mr. Chris Ford (University of Western Australia) and Dr. Brian Lawn (NIST, Maryland) for many useful discussions. We also thank the staff at the Oral Health Centre (University of Western Australia) for their technical assistance and allowing the use of Dental Laboratory. This work is supported by grant from the Australian Research Council.

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