Characterisation of contact damage in porcelain/metal and porcelain/polymer bilayers

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Abstract

Finite Element Analysis is used to examine contact damage induced by Hertzian indentation of porcelain coatings on various substrates. Critical loads for the onset of substrate plasticity are predicted for a system with plastically deforming substrate. Different forms of cracking in the porcelain coating are studied – “Hertzian” cone cracks close to the indenter, more distant “outer” cone cracks, and “radial” cracking at the coating/substrate interface. The effects of porcelain coating thickness and radius of curvature on the critical stresses for initiation of these cracks are examined.

Critical loads to initiate substrate plastic flow are found to increase with coating thickness for a brittle coating on a stiff substrate, as expected. It is determined that the dominant mode of coating cracking is largely dependent on substrate compliance. Hertzian cone cracking predominates in systems with stiff substrates, while radial cracking and outer cone cracking occurs first in systems with compliant substrates.

The effect of coating curvature is examined for the case of a brittle porcelain coating on a compliant glass polymer substrate. For a given coating thickness, the effects of curvature vary significantly – for thinner coatings, where outer cone cracks are dominant, highly convex surfaces are more resistant to cracking, whereas for thicker coatings, which are more prone to Hertzian cone cracking, concave surfaces produce a higher predicted critical load. Curvature is observed to have little effect on the critical load for the formation of radial cracks, which remains the dominant mode of failure in cases of thin coatings on compliant substrates.
1 Introduction

Structures composed of one or more wear resistant layers on a tough base material are commonly found in a variety of applications [1-3]. The application of particular interest in this study is found in the field of dentistry, where the wear resistance and aesthetic properties of a porcelain or ceramic coating, combined with metallic or polymeric substrates, make for an excellent method of tooth replacement, such as crowns [1, 4, 5].

There has recently been a large amount of experimental investigation of this type of system subjected to spherical contact loading (Hertzian indentation) [1, 5-12], chosen because of its similarity to the concentrated loadings which are generally applied to dental materials during service. A basic representation of Hertzian indentation is shown in figure 1 below.

Several types of failure may be observed. Plastic deformation can occur in the substrate for some materials. “Cone” cracks initiating at the coating surface exhibit an axisymmetric geometry when fully established. “Hertzian” cone cracks initiate close to the contact region, however under some circumstances it is also possible to observe cone cracks that initiate further away (“outer” cone cracks). Planar cracks may also occur in the coating, initiating at the coating/substrate interface. These so-called “radial” cracks lie along planes that intersect the load axis.

However, while experimental results provide characterisation of the behaviour of the system, modelling is required to understand the underlying failure mechanisms. In particular, finite element analysis (FEA) has been used to greatly increase our understanding of the failure modes and damage observed, and to provide predictions of behaviour in circumstances where it is difficult to obtain experimental data, such as limiting stress values for very small layer thicknesses.

Figure 1: Simplified representation of Hertzian indentation showing Hertzian and outer cone cracks, radial cracking and substrate deformation.
The overall intention is to better understand the different modes of failure present in this type of indentation. Through this, we hope to find a method to determine the optimum combination of materials and geometry to provide a tough, damage resistant multi-layer system, without the need for exhaustive experimental testing.

2 Methodology

Generally, we model systems as an elastoplastic substrate, elastic coating and elastic indenter. Stress fields are used to study the onset of failure. Crack growth is not modelled.

Porcelain was used for the coating in each study, because of its relevance to the dental systems studied, and its regular use in published experimental work. Material properties for the porcelain were taken to be Young’s modulus and Poisson’s ratio of 70GPa and 0.2 respectively [12, 13]. For the tungsten carbide indenter, used because of its high hardness and availability, the manufacturer’s figures of 550GPa and 0.34 respectively were used. Substrate materials and properties will be discussed in each section.

Using the ABAQUS finite element code, a 2.38mm indenter was modelled to match the experimental conditions, following the work performed by Zhao et al [12]. A typical mesh is shown in figure 2. The refinement along the vertical axis of symmetry of the block was necessary in order to calculate the substrate plastic deformation with sufficient accuracy, while the refinement on the layer surface was for accuracy in calculating contact radii and stress locations. The mesh in these regions was consequently reduced to an element size of 3.125 microns, while in areas away from the contact it increased to 100 microns to reduce computation time and output file size.

The model was initially tested for compliance with Hertz’s theory for elastic contact between a porcelain monolith and tungsten carbide indenter. The “Hertzian modulus”, or the ratio between the indentation stress (load/contact area) and indentation strain was calculated to be 27.8GPa, predicted accurately to within 0.8% by the model.

Figure 2: Typical mesh showing areas of refinement.
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The presence and magnitude of plastic deformation in the substrate was reported directly by the ABAQUS output code, allowing plastic deformation to be detected at its onset. However, critical load estimation for the various forms of coating cracks is more difficult.

Although the model will provide information about stresses within the structure, it cannot predict the critical load for fracture unless the stress data is combined with the knowledge of the fracture strength of the material. In order to provide an estimate of the fracture strength for Hertzian cone cracking, the experimentally determined critical indentation load for cone crack formation on a porcelain monolith was interpreted using the FEA model of this system. Taking the mean of the observed critical load range, the critical stress was determined by this to be 426MPa. However, it is important to differentiate between this “critical stress”, and a critical stress derived from a fracture mechanics analysis, using the fracture toughness of the material and an estimated flaw size. The critical stress quoted above is an estimate of the surface stress when cracks are first observed. Extremely high stress gradients are present in the material close to the layer surface just outside the contact area. 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 actual stress at this point would be much lower, and the calculated value of 426MPa can only be used as a calibrated critical surface stress estimation tool for this particular fracture process. In fact, using a value of $1\text{MPa(m)}^{1/2}$ for $K_{ic}$ [13] and an estimated initial flaw length of $a = 10$ microns, the predicted critical stress, as calculated from fracture mechanics, is 159MPa. This is the value used for radial and outer cone cracking.

3 Analysis of a brittle coating on a stiff substrate - porcelain on palladium alloy

In their experimental study of this type of system, Zhao et al [12] noted several different failure modes. The principle modes observed were Hertzian cone cracking of the porcelain layer, plastic yielding of the metal substrate, and the development of “radial” interface cracks. The modelling of this system, therefore, was to provide a theoretical extension to this work, concentrating on the damage caused by two major failure modes, namely substrate plastic deformation and the formation of cone cracks in the porcelain layer.

A tensile test performed on a palladium alloy specimen returned a modulus is 155GPa, and yield stress of 423MPa. The yield curve was digitised to provide input for modelling of strain hardening.

The depth of substrate plastic deformation as a function of applied load was plotted for various coating thicknesses. The horizontal intercept for each of the curves gives the critical load for yield for that layer thickness. A comparison between these theoretical yield critical loads and the experimentally observed yield critical loads is shown in figure 3. The divergence between the two curves at a layer thickness of 270 microns corresponds to the onset of coating fracture prior to substrate yield.
In a similar fashion, the maximum surface stress was plotted as a function of applied load for each coating thickness. The location of the maximum tensile stress remained at approximately 5% outside the contact radius, irrespective of load. The predicted critical loads using this value are also shown in figure 3, with experimental values shown for comparison. The good agreement between the predicted and measured critical loads confirms that once the simulation has been calibrated against a measurement made under one set of conditions, such as indentation of the monolith, it may then be used to provide useful predictions under a wider range of conditions.

4 Analysis of a brittle coating on a compliant substrate - porcelain on polymer

In a particular experimental study of damage in a porcelain coating on various metal substrates, Zhao et al [14] observed an interesting phenomenon in the critical load for cone cracking in porcelain on a gold substrate. The critical load increased with coating thickness up to approximately 300 microns, then decreased with further increases in coating thickness, a phenomenon not observed in systems with harder substrates (such as palladium alloy). The authors of [12] extended experimental studies to include porcelain on glass-filled polymer systems, as shown in figure 4. The peak critical load for these systems occurred at a higher coating thickness (700 microns), and it was also observed that the location of the initial cone crack shifted from well outside the contact area for thinner coatings, to immediately outside the contact area (approximately 110% of contact radius) for thicker coatings. This was also observed by Chai et al [11] in their study of systems with large modulus mismatches.

Hence, it was postulated that a separate mode of failure was occurring at the thinner coating thicknesses, in systems with compliant substrates. The effect
Figure 4: Predicted and observed critical load values for different crack modes.

occurs irrespective of whether substrate compliance results from a low elastic modulus or through plastic flow.

Consequently, the FEA model was used to study the stress fields produced by contact on a porcelain layer over a glass-filled polymer substrate (Young's modulus 17GPa and Poisson's ratio 0.3, consistent with values for dental prosthetic resin composites [15, 16], and human dentin [15]) and provide an explanation for the experimentally observed behaviour. This system has recently been used experimentally to amplify the bend effects leading to radial crack formation [11, 17, 18], and also serves as a model for studying the behaviour of outer cone cracking.

A sample tensile stress plot along the layer surface clearly showed a second maximum some distance away from the indentation for most coating thicknesses and indentation loads. Using the methods previously outlined, the critical load for each location was determined, leading to two separate critical load curves for cone cracking, also shown in figure 4. The second maximum, located well away from the contact area, is not observed in simulations porcelain coatings on stiffer substrates. Given that the modulus of the polymer is much lower than that of the porcelain, it is suggested that the presence of this second maxima is due largely to the increased deflection of the coating, leading to significant bending stresses. Such deflection is not evident in the porcelain/palladium system [12, 19], where the modulus of the substrate is higher than that of the porcelain coating, and the yield stress is relatively high. A corollary of this is that as bending occurs, the peak stress close to the contact is reduced.

When examining the combined curves it becomes immediately apparent that the results from FEA qualitatively predict the observed peak in the critical load for the formation of cone cracks. To the left of the peak, at lower coating thicknesses, the outer crack is favoured (ie lower critical load), while the crack close to the contact area is favoured for thicker coatings. However, the peak occurs at a higher stress and at a smaller coating thickness than indicated experimentally, an anomaly possibly explained by the prior presence of radial cracks which are not modelled. As seen in figure 4, it is likely that interface
cracks will occur before the critical cone crack load is reached. The presence of radial interface cracks was noted in the experimental work [12, 14, 20], but no critical load information was able to be recorded.

These results indicate that in order to reduce cone cracking in systems composed of a stiffer coating over a soft substrate, an optimal coating thickness can be found. Simply making the stiff coating as thick as possible will not improve the resistance of such systems to cone cracking.

5 The effect of curvature

A key motivation for studying layered structures is the relevance to dental applications. Natural teeth and dental prostheses (crowns) both consist of layered structures [1, 4, 5]. To this point, Hertzian studies have dealt exclusively with spherical contact on flat surfaces, yet teeth and crowns exhibit some curvature or shape irregularity [21, 22]. In occlusal contact (contact between the crushing surfaces of upper and lower teeth), “a convex surface ... may come into contact with a convex or a concave segment of another tooth; always, however, curved segments contact curved segments” [21]. Typical radii of the curved contacting surfaces are 2 – 4mm [1, 21]. This can significantly alter the stresses within the coating, so the FEA model was further developed to gain an insight into the effect of curvature on the nature and onset of contact damage.

Several different meshes were developed for each coating thickness, corresponding to several different radii of curvature R (see figure 5 for sample mesh). The coatings ranged from significantly convex (R = 4mm) to slightly concave (R = 10mm). Combined with the 2.38mm radius of the indenter, a wide range of contact conditions relevant to occlusal contact in human teeth are thus modelled. Figure 6 shows critical load predictions generated for the range of surface curvatures and coating thicknesses modelled.

The stresses in the vicinity of the interface driving radial cracking are not significantly affected by the curvature of the sample. However, this form of

![Sample mesh showing curved (400 micron) coating (R = 6mm).](image)
cracking is clearly important in coatings of thickness less than 600 microns, as the critical load for initiation of radial cracks is significantly less than that for the cone cracks. Indeed, such cracks are considered to be the primary source of failure in dental crowns [23]. The resulting effect of these cracks on the later initiation of cone cracks is unknown at this time, however it is unlikely that the presence of such cracks will qualitatively change the behaviour [14].

Outer cone crack critical loads increase as the samples become more convex. Stresses causing these cracks result from the stiffer coating deflecting in a beam-like fashion, causing a tensile stress maximum to occur on the surface approximately 1mm away from the contact axis. As the sample becomes more convex, load bearing compressive stresses in the coating increase, reducing the tension on the coating surface and hence the relevant tensile maximum. Resistance to flexure induced outer cone cracks is therefore enhanced by making the surface more convex.

It is also clear that the predicted critical load for the onset of this type of crack is very sensitive to the radius of curvature of the coating. In the case of a 400 micron coating, the predicted critical load for outer cone cracks ranged from 366N for the concave sample with radius of curvature 10mm, up to 919N for the convex sample with radius of curvature 4mm – a factor of 251%. Since nearly all dental prostheses are curved, this observation has important implications.

Stress maxima causing Hertzian cone cracking, located less than 10% outside the contact radius, increase as the samples become more convex. This is contrary to the effect described above, and is due to the localised nature of stresses inducing Hertzian cone cracking. As the coating becomes more convex, the apparent stiffness of the coating increases, intensifying localised effects and
raising the maximum stress. In the case of thicker coatings, where Hertzian cone cracks are favoured, resistance to cracking is therefore enhanced by making the surface flatter, or concave.

Again, comparison of critical loads for different radii of curvature at the same coating thickness highlights the significant effect of the curved surface. For a coating thickness of 460 microns, the critical load ranged from 170N (convex, radius 4mm) to 478N (concave, 10mm) – a factor of 281%.

So, surface curvature significantly affects the predicted critical loads for surface damage of the porcelain coating on a compliant substrate. For thinner coatings where outer cone cracking is the predominant mode of surface damage, a more convex surface is beneficial. For thicker coatings, flatter or more concave surfaces exhibit a higher critical load. Conversely, for systems requiring convex surfaces, relatively thin coatings are predicted to withstand higher indentation loads before the onset of cone cracking, whereas for concave or flat systems, thicker coatings are recommended.

6 Conclusions

Finite element analysis has been used to model indentation of porcelain coatings on various substrates. Predicted critical loads agree well with experimentally observed values, and the model provides a powerful tool in interpreting the behaviour of these systems. It is also a valuable tool for predicting the initiation of cracking modes which are difficult to observe experimentally.

References


