CONTACT DAMAGE IN DENTAL MULTILAYERS: FROM EXPERIMENTS TO MECHANISM-BASED MODELS AND BIOINSPIRED DESIGN

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ABSTRACT

This paper presents the results of a combined experimental and computational study of contact damage in dental multilayers. Hertzian indentation experiments are used to explore the basic mechanisms of contact-induced deformation and pop-in. The insights developed in the experiments are then used to guide the development of mechanism-based mechanics models for the prediction of deformation and cracking in dental multilayers. Finally, bioinspired and mechanism-based models are proposed for the design of functionally graded multilayers that are more resistant to deformation and cracking.

1 INTRODUCTION

Occlusal activity in the oral cavity can lead to contact loads that are sufficient to induce serious damage in dental restorations [1]. The failure rate is high, for example, almost 20% of dental restorations with resin retained ceramics fail within the first five years of service in the oral cavity [2]. The major clinical failure mode is by sub-surface cracking from the interface between the crown and the dental cement [3]. The underlying mechanisms that lead to the formation of such cracks and the bioinspired design to avert this cracking are the subject of this paper.

Due to the complex structure and translucent nature of actual dental restorations, recent efforts have been made by Lawn and co-works [4] and Soboyejo *et al.* [5] to use flat multilayered structures (with equivalent elastic properties) in the study of contact-induced damage. This study presents a combined experimental and computational study of deformation and cracking/pop-in in model multilayers that are relevant to dental restorations. Hertzian indentation fatigue tests were performed on glass/epoxy/ceramic-filled polymer layers to simulate the potential effects of occlusal contacts under cyclic loading. Sub-surface/pop-in cracks were found at the interface between glass and epoxy. A combination of finite element and analytical models were then used to explain the observed damage mechanisms.

In order to increase the durability of dental restorations, we proposed to add a functionally graded material (FGM) layer between the ceramic and the cement by the inspiration of the modulus distribution across the dentin-enamel junction. The stresses of the graded and layered structures are computed by finite element simulation.

2 CONTACT FATIGUE AND MECHANICS MODELS

2.1 Contact fatigue test

Hertzian contact fatigue was used to simulate occlusal cyclic contacts. In an effort to view the cracks with an in-situ optical microscope and a Questar telescope (Questar Corporation, New Hope, PA), glass was used for the top layer of the tri-layer structure. The Young's modulus of glass is around 70GPa, which is similar to enamel and some ceramics for crowns. The fatigue experiments were performed in a servo-hydraulic testing machine. They were conducted at room temperature at a cyclic frequency of 5 Hz. The initial cyclic contact experiments involved cyclic loading between 20 and 120 N for a few million cycles (by rough estimation, 1 million cycles represents several years of occlusal loading). The peak loads were then increased in incremental stages, from 120 to 135, 140, 145 N. For each incremental loading step, the specimens were cyclically deformed for ~1 million cycles. The onset of cracking was observed with an in-situ Questar telescope and an optical microscope after crack initiation. Sharp changes in the local sample compliance (inferred from the load-displacement plots) were also used to identify the onset of crack growth/pop-in. The resulting composite deformation of the tri-layer system was measured with a capacitance displacement gauge. Typical plots of displacement versus time are obtained from the capacitance gauge presented in Fig. 1. These show the displacement-time behavior associated with the different cyclic loading ranges. A sharp change in compliance is observed after ~0.6 million cycles during loading between 20 and 140 N (Fig. 2). The change in compliance increases with increased cycling, and is associated with sub-surface crack growth from the interface between the epoxy and the top glass layer (Fig. 2).

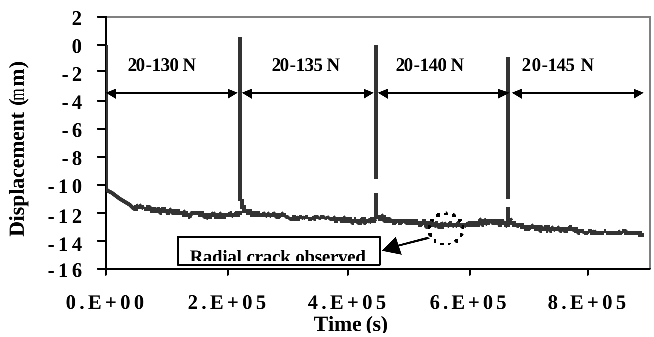

Fig. 1 Maximum displacement-time curves obtained under cyclic loading

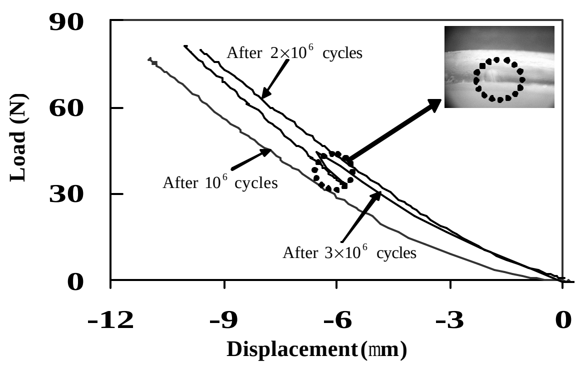

Fig. 2 Changes in compliance and sub-surface cracking modes

To investigate effects of sub-surface roughness on Hertzian contact fatigue behavior of tri-layer structures, cracks were introduced to glass subsurface using grinding sand papers with different grids that are corresponding to known SiC_4 particle size ranges. Sand paper of 120 and 600 grids were used to generate cracks by moving glass slides on sand papers. A constant pressure was used to control crack size for each glass slide. Hertzian contact fatigue tests were then carried out on these tri-layer structures with controlled subsurface crack sizes in a servo-hydraulic testing machine. Maximum load levels ranging from 40N to 100N were used. All tests were conducted under constant load ratio of 0.1. Tri-layer structures with different sub-surface crack sizes failed very quickly at similar maximum load level of 95N. However, those with smaller surface cracks can survive longer fatigue life under the same load levels. For example, at a maximum load of 60N, the numbers of cycle to failure are 5000 and 1000 for smaller and larger crack structures, respectively. This indicated that crack size in the sub-surface of top layer is one of the most important factors to affect the performance of dental tri-layer structures.

2.2 Fatigue mechanisms

In an effort to better understand the mechanisms, a combined finite element and analytical modeling framework was used. Two possible mechanisms of stress build-up were considered:

2.2.1 Plastic deformation due to ratcheting

The plastic ratcheting can lead to more rapid stress build-up in the ceramic layer. Figure 3 is the finite element simulation of principal stress increment with load cycles between –20N and –120N. The cement is assumed to be elastic and perfectly plastic materials, with yield strength of 5 MPa. We can see that if there are no defects on the bottom surface of the top layer ceramic, the principal stress does not increase with increased load cycles at this load range and yield strength. However, when a defect is introduced, the principal stress increases rapidly with increased load cycles. The stress increment is due to plastic strain accumulation of the epoxy or cement layer. This phenomenon, called ratcheting, has recently been discovered in microelectronic structures [6]. In the current study, ratcheting was shown to be significant when flaws were present at the bottom of the top ceramic layer. In such cases, ratcheting can occur, resulting in stress build-up at much faster rates than those observed in the absence of flaws (Fig. 3). The tensile stress build-up in the top ceramic layer may, ultimately, be sufficient to cause cracking. Hence, the above finite element results suggest that ratcheting may be an important factor in the fatigue of damage of dental multilayers. If this is the case, one way of engineering fatigue resistance would be to select combinations of materials and multilayered geometries that can lead to "shakedown" [6] under occlusal loading. In "shakedown" condition, the stress increment will stop after a certain number of load cycles. If the final maximum stress does not high enough to cause cracking, this structure is safe. This is clearly a challenge for future work.

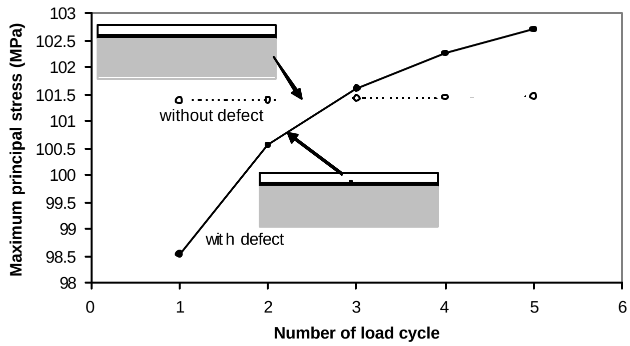

Fig. 3 Stress increment after cyclic loading. The stress plotted is the maximum tensile stress near the ceramic/cement interface. For the simplicity of simulation, the defect is assumed with square shape and located at the bottom center of the top ceramics layer.

2.2.2 Sub-critical crack growth

The third possible mechanism of fatigue damage is by sub-critical crack growth. This may occur by stress corrosion cracking of the ceramic layer or by a mechanics-driven crack growth mechanism. The possibility of stress corrosion cracking in glass and zirconia has been demonstrated by a number of researchers [7, 8]. Such mechanisms are likely to occur during occlusal activity in the saline environment in the oral cavity.

However, the possibility of a mechanics-driven sub-critical crack growth mechanism is also interesting, which is referred to as the hydraulic fracture mechanism. Under contact stress, the viscous cement material may flow into defects at the bottom surface of the ceramic top layer. Such defects are induced by crown fabrication processes [1]. The intrusive cement may "glue" the crack walls, making it harder to propagate [1]. On the other hand, the cement exerts pressure on the crack faces. Combined with the tensile stress caused by Hertzian contact, the pressure can cause crack growth when the crack driving force reaches the sub-critical crack growth thresholds. The crack growth rate depends on the cement flow rate. Based on this idea, the crack-tip mechanics-driven crack growth rate due to the hydraulic fracture mechanism can be estimated. By substituting parameters summarized of dental restorations, the crack growth rate is estimated on the order of 300 nm/s. Assuming that this is an average crack growth rate, this could lead to crown failure in ~10 years of occlusal activity. It is important to note that the model we described here is a plane strain model, which is different from the shape of the radial subsurface cracks in dental restorations. But the qualitative picture described by our model should be generic.

3 BIOINSPIRED FUNCTIONALLY GRADED DESIGN

From the above analyses, we can see that the tensile stress concentration at the interface in the ceramic layer causes the subsurface cracking. In order to reduce the tensile stress concentration, we need to learn some lessons from the nature tooth. Natural tooth consists of two distinct materials: enamel with ~65 GPa Young's modulus and dentin with ~20GPa Young's modulus. They are bonded by dentin-enamel-junction (DEJ). The Young's modulus across the DEJ gradually decrease from that of enamel to dention [10, 11]. This will dramatically reduce the stress in the enamel, as will be shown later.

Inspired by the DEJ structure, we propose a new dental crown restoration structure. A functionally graded layer is fabricated at the bottom of the ceramic. In this layer, the Young's modulus gradually decreases from that of the dental ceramic to a lower value. Then the structure is bonded with the dentin-like polymer by dental cement. The purpose of this function graded layer is to reduce the stress concentration. If the Young's modulus of the FGM layer is high, the stress will be concentrated in the FGM layer at the interface between the FGM layer and the cement; if the Young's modulus of the FGM layer is low, the stress will be concentrated at the interface between the dental ceramic and the FGM layer. The optimal design should ensure the stress uniformly distributed in the FGM layer and continuous at the interface of ceramic and the FGM layer. Based on this design criteria, the Young's modulus in the FGM layer should decrease from that of the ceramic at the interface of ceramic and FGM layer to a lower value at the interface of the FGM layer and the cement layer. The optimal lower value can be obtained by finite element simulation. Figures 4 show the maximum principal stress distribution in the dental multilayers with FGM design and without FGM design. We can that the stress in FGM design is quite uniform and much lower that that in non-FGM design.

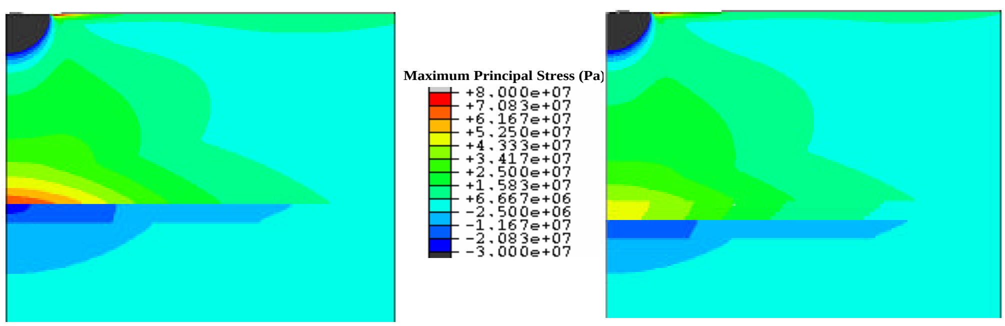

Fig. 4 Maximum principal stress distributions in dental multi-layered structures: (a) existing dental crown restoration; (b) FGM design

We then extend our simulations to a range of dental ceramics (Fig. 5). In all of the cases, the graded architectures reduced the maximum principal stresses by ~30%. Such reductions in stress are likely to improve the durability of dental multi-layers with graded interlayers between the dentin and crown layers.

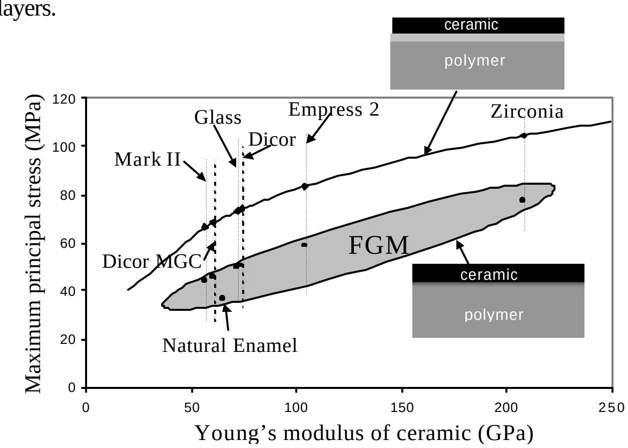

Figure 5 Maximum principal stress in the ceramic and FGM layer.

4 CONCLUDING REMARKS

This paper studies the contact loading induced damages in dental multilayers. Cyclic loading induced cracking has been observed in dental multilayers. The observation of cracking under cyclic Hertzian contact loading is attributed to the stress build-up in the top ceramic layer due to ratcheting phenomena or sub-critical crack growth mechanisms. Ratcheting is exacerbated by the presence of defects (cracks/notches). Similarly, sub-critical crack growth is associated with the existence of pre-existing notches or cracks. It may occur by stress corrosion cracking, or by a mechanics-driven hydraulic fracture mechanism. To reduce the stress in the dental crown restoration structures, we proposed to use a bioinspired functionally graded material layer. Finite element simulations show that this method can significantly reduce the stress.

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