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Research Paper

Fracture mechanics analyses of ceramic/veneer interface under mixed-mode loading

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A B S T R A C T

Few studies have focused on the interface fracture performance of zirconia/veneer bilayered structure, which plays an important role in dental all-ceramic restorations. The purpose of this study was to evaluate the fracture mechanics performance of zirconia/veneer interface in a wide range of mode-mixities (at phase angles ranging from 0° to 90°), and to examine the effect of mechanical properties of the materials and the interface on the fracture initiation and crack path of an interfacial crack. A modified sandwich test configuration with an oblique interfacial crack was proposed and calibrated to choose the appropriate geometry dimensions by means of finite element analysis. The specimens with different interface inclination angles were tested to failure under three-point bending configuration. Interface fracture parameters were obtained with finite element analyses. Based on the interfacial fracture mechanics, three fracture criteria for crack kinking were used to predict crack initiation and propagation. In addition, the effects of residual stresses due to coefficient of thermal expansion mismatch between zirconia and veneer on the crack behavior were evaluated. The crack initiation and propagation were well predicted by the three fracture criteria. For specimens at phase angle of 0, the cracks propagated in the interface; whereas for all the other specimens the cracks kinked into the veneer. Compressive residual stresses in the veneer can improve the toughness of the interface structure. The results suggest that, in zirconia/veneer bilayered structure the veneer is weaker than the interface, which can be used to explain the clinical phenomenon that veneer chipping rate is larger than interface delamination rate. Consequently, a veneer material with larger fracture toughness is needed to decrease the failure rate of all-ceramic restorations. And the coefficient of thermal expansion mismatch of the substrates can be larger to produce larger compressive stresses in the veneer.

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1. Introduction

Bi-materials have been widely applied in aerospace, automotive, marine, microelectronic structures and other fields. In the prosthodontics field, zirconia-based bilayered restorations have been used extensively because the veneering porcelain sintered on zirconia presents a combination of both high strength and excellent esthetics (Liu et al., 2012). However, the weak interface between zirconia and veneer is one of the important factors leading to chipping and delamination (Roediger et al., 2010; Liu et al., 2012). Therefore, it has great significance to understand the fracture performance of zirconia/veneer interface, which has received little attention. The studies on the zirconia/veneer interface were mainly focused on the improvement of bond strength by means of different surface treatments (Fischer et al., 2008; Mosharraf et al., 2011; Kim et al., 2011). The measurement of bond strength was most prevalently performed with shear or tensile bond tests, which often showed cohesive fracture patterns within the veneer layer (Henriques et al., 2012). Recently, fracture mechanics approaches became more popular in the research of interfacial bonding performance of dental restorations (Soderholm, 2010; Jancar, 2011; Kotousov et al., 2011). A fracture mechanics methods proposed by Charalambides et al. (1989) was used to measure the interface toughness between zirconia and veneer (Göstemeyer et al., 2012; Wang et al., in press). Nevertheless, using this method can only yield a narrow range of mode-mixities (characterized by phase angle), which is defined as the ratio between the shear and opening modes at an interfacial crack tip. The actual occlusal loading scenarios are not just limited to near shear or opening conditions, which means an interfacial crack is always subjected to mixed mode conditions.

An interfacial crack subjected to mixed mode loading either kinks into substrates or propagates in the interface. The maximum energy release rate criterion (G_{max} criterion) (He et al., 1991; He and Hutchinson, 1988, 1989), the zero K_{II} criterion ($K_{II}=0$ criterion) (He and Hutchinson, 1989), and the maximum tangential stress criterion (MTS criterion) (Yuuki and Xu, 1992) can be used to predict the crack kinking behaviors including selection of crack path, the threshold of crack initiation, and the kinking angle. There are also some criteria for evaluating interface fracture (Charalambides et al., 1992; Hutchinson and Suo, 1992; Thurston and Zehnder, 1995), which present the relation between interface fracture toughness and mode-mixity. In general, the toughness of an interface, which can be characterized by stress intensity factors (SIF) or energy release rate (ERR), increases with the increase of phase angle. Consequently, in order to understand the fracture mechanism of bilayered all-ceramic restorations, it is necessary to investigate the zirconia/veneer interface in a wild range of mode-mixities by an effective method.

In the past, various experimental methods and test configurations have been used for determining the mixed-mode fracture performance of bi-material interfaces, such as four-point bending specimen (Charalambides et al., 1989), unsymmetric end-notched flexure specimen (Sundararaman and Davidson, 1998), double cantilever beam specimen (Cao and Evans, 1989), sandwich specimens (Suo and Hutchinson, 1989), Brazil-nut-sandwich specimen (Wang and Suo, 1990), and asymmetric four-point bending specimen (O'dowd et al., 1992a, 1992b). However, most of the mentioned test methods are not appropriate for the current zirconia/veneer combination. Four-point bending specimen and end-notched flexure specimen can only provide limited range of I/II mode-mixities; double cantilever beam specimen and sandwich specimens proposed by Suo and Hutchinson are not appropriate for brittle materials with low fracture toughness; Brazil-nut-sandwich specimen and asymmetric four-point bending specimen require complicated preparation process or complicated testing fixtures. The veneering porcelain is sintered on the zirconia under a high temperature to produce bilayered structure, and the veneer material which has relatively small fracture toughness turns to viscous-elastic state under high temperature. Therefore, a simple and valid test configuration that is suitable for the current material combination is needed. In this study, a modified beam test configuration was suggested for investigating the mixed mode fracture performance of the interface. The test configuration was proposed based on a sandwich interfacial fracture specimen (Suo and Hutchinson, 1989) and a SCB specimen (Ayatollahi et al., 2006) that were used for measuring mixed mode fracture toughness of homogeneous materials.

The purpose of this study was to evaluate the fracture mechanics performance of zirconia/veneer interface by investigating the propagation of an interfacial crack under a wide range of mode-mixities, and to examine the effect of fracture mechanical properties of the materials and the interface on the crack initiation and crack path. The structure of the paper was as follows. First, the specimen was described, and the relations between specimen geometries and phase angle were calibrated by means of several finite element analyses (FEA) to choose appropriate geometry dimensions. Secondly, the specimens were prepared based on the FEA results, and tested with three point bending method. Failure mode, fracture initiation load of all specimens and crack kinking angle of the kinking specimens were recorded. Finally, the experimental results were compared with theoretical results of the fracture criteria, and the clinical guiding significance of the study was presented.

2. Material and methods

2.1. Test specimen and numerical analyses

The oblique crack sandwich specimen can be easily made and tested in conventional testing machines. As shown in Fig. 1a, the specimen consists of two pieces of zirconia bonded with an interlayer of veneer. One interface of the two materials is normal to the horizontal plane, and another interface has an inclination angle ω relative to the horizontal direction. The oblique interface contains an interfacial edge pre-crack of a in length. The specimen has a height of w, a thickness of b, and a length of $2l_1+l_2$. The specimen is loaded by the vertical load P in standard three point bending mode with a span of l. s is the load offset distance from the location right above the open end of the crack. When the parameters