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Loading configuration effects on the strength reliability of alumina–zirconia multilayered ceramics

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Abstract

The loading configuration effects on the strength reliability of alumina/zirconia multilayered systems, designed with internal compressive stresses, have been investigated. The existence of a threshold strength behaviour, as previously assessed under longitudinal flexure, has been evaluated by indentation-strength tests under transverse flexure. Additionally, the influence of flaw interactions on the strength reliability under both loading configurations has also been studied. Experimental findings show a higher strength level under transverse flexure, as far as the failure-controlling flaw is located between two compressive layers. It is found however that multiple artificial and natural flaws may interact affecting the strength of the specimen under transverse loading. As a consequence, although higher strength values result from this configuration, a more reliable design is rather attained when the loading axis is applied normal to the layer plane, a loading mode where similar effects are negligible.

Keywords: A. Layered structures; B. Strength; C. Damage tolerance; C. Transverse cracking; Loading configuration

1. Introduction

Ceramic materials exhibit a relatively wide strength distribution owed to the quite variable characteristics of the flaws induced during their processing and/or machining, i.e. nature, geometry and size, together with their relative orientation with respect to the applied loads. This broad range of strength values and their inherent brittleness have limited the use of ceramics in structural applications. However, as a direct consequence of remarkable progress in terms of microstructural design and advanced processing [1–3], toughness and reliability of structural ceramics have been increasingly enhanced by recourse to crack shielding resulting from microstructure-related mechanisms [4–11]. Particular attention has been paid to fibre and layered reinforced ceramics, where the better mechanical performance is associated with not only the second phase or layer addition, but also the arrangement of the fibres or the layer assemblage with respect to the loading axis, as well as the sliding resistance of the fibre–matrix interface or the interlayer fracture energy, respectively [7,12,13]. According to these studies, when the crack front is oriented parallel to the aligned fibres, the crack propagates catastrophically through the composite at the initial cracking stress, i.e. there is not any crack shielding from the fibres arranged normal to the loading direction. On the other hand, when the fibres are oriented perpendicular to the crack front, cracks originated at the outer ceramic layer get arrested at the ceramic–fibre interfaces, providing a higher resistance to crack propagation.

As an extension of this laminar ceramic/fibre-reinforced concept, multilayered architectural designs have also been attempted in many ways aiming to improve both the resistance to crack propagation and the mechanical reliability of ceramic components [11,14–17]. This approach has

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demonstrated to be less cost effective than the one based on fibre structures and more accurate in terms of tailoring mechanical requirements. Within this context, a commonly used multilayered structural design is that associated with the presence of compressive residual stresses developed in the laminate during cooling from sintering [11,18,19], as related to differences in elastic or thermal properties (Young's modulus, thermal expansion coefficient, etc.) between the layers, as well as to phase transformations and/or chemical reactions within them [8,15,20]. In particular, ceramic composites with a layered structure such as alumina/zirconia have been reported to exhibit relatively large apparent fracture toughness, energy absorption capability and, consequently, non-catastrophic failure behaviour [8,14,15,21,22].

In addition to the architectural design, loading conditions (Fig. 1) may strongly affect the mechanical response of a layered structure [14]. Although it is well-documented that multilayered ceramics exhibit an enhanced fracture behaviour, independent of the specific loading configuration under consideration, i.e. with loading axis either parallel (transverse flexure) [11] or perpendicular (longitudinal flexure) [17,23,24] to the layer plane, studies where the mechanical strength of such multilayered systems are directly compared as a function of loading orientation are quite scarce. In this regard, a recent work from Moon et al. [25] on alumina–zirconia multilayered composites has shown that relative layer orientation with respect to the crack-tip front exerts a pronounced influence on the crack growth resistance behaviour of the material, thus pointing out the need for further investigation from this perspective if these materials are to be properly implemented in structural applications.

Furthermore, although a single crack within a thick tensile layer can be arrested by thin compressive layers, there is a possibility that other cracks and/or flaws may coexist close to each other, either in the same or in adjacent layers, varying in certain cases the critical failure scenario for the material. Within this context, the effective stress intensity factor for interacting cracks has been the topic of research of several studies following both analytical [26–28] and experimental [29] approaches. In general, it has been found that two closely spaced cracks can interact to increase the stresses at the corresponding crack tips, thus affecting the fracture response of the component in the zone where the cracks are located.

In a previous work, the authors have shown that a single crack, located at the outer tensile layer of an alumina–zirconia laminated system can be arrested by the first internal thin compressive layer when extending under longitudinal flexure [24]. As a result of such crack – layer architecture interaction, these laminates exhibit an almost constant failure stress regardless of the size of the pre-existing cracks (artificially introduced by recourse to indentation techniques), i.e. a threshold stress below which the probability of failure is nearly zero. As it is shown in Fig. 4 from Ref. [24], this is completely different from the failure behaviour experienced by monolithic alumina-based brittle ceramics, where the flexural strength continuously decreases with increasing indentation load, i.e. flaw size. Because this interesting finding (i.e. the existence of a threshold stress) has been discerned only under longitudinal flexure (Fig. 1a), an immediate query is raised whether such a mechanical response would also apply under conditions where the load axis is set parallel to the layers, i.e. in transverse flexure (Fig. 1b).

The purpose of this work is to investigate the loading configuration effects on the strength reliability of an optimally designed alumina/zirconia multilayered system [22]. In doing so, the existence of a threshold strength behaviour under conditions of transverse flexure is assessed. Additionally, the influence of flaw interactions on the strength reliability under both loading configurations is also addressed.

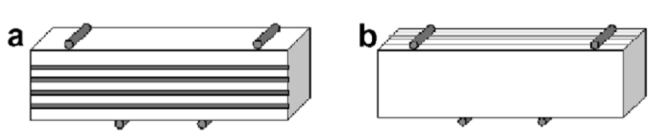

Fig. 1. Scheme of a testing configuration where the loading axis is applied (a) perpendicular (longitudinal flexure) and (b) parallel (transverse flexure) to the layer plane.

2. Experimental procedure

2.1. Material of study

Starting powders were submicron-sized alumina (HPA 0.5, Condea, USA) with a mean particle size (d_{50}) of 0.3 μm, tetragonal zirconia polycrystals (Y-TZP) with 3 mol% of Y_2O_3 (TZ-3YS, Tosoh, Japan) with $d_{50} =$ 0.4 μm, and pure zirconia (TZ-0, Tosoh, Japan) with $d_{50} = 0.3$ μm. Slurries were prepared to a solid loading of 36.5 vol% by mixing starting powders with DI water, containing a 0.8 wt% of a commercial acrylic based polyelectrolyte (Duramax D-3021, Rohm&Haas, USA) used for stabilisation. Sequential slip casting [30,31] was used to fabricate laminates composed of five thick layers, referred to as ATZ, alternated with four thin layers, named as AMZ. The thickness of the layers was controlled from the measurement of the wall thickness after different casting times for both ATZ and AMZ suspensions. A slurry composed of Al_2O_3/5 vol% Y_2O_3-stabilised ZrO_2 (t-ZrO_2), was used to form the thick ATZ layers. The t-ZrO_2 was employed to control the grain size of the Al_2O_3 during densification. In order to form the thin AMZ layers a slurry containing Al_2O_3/30 vol% ZrO_2 (m-ZrO_2), was utilised. Details of the colloidal processing procedure may be found elsewhere [32]. The laminate plates were sintered at 1550 °C for 2 h in air. Several bar-shaped specimens (3.8 mm × 3.2 mm × 25 mm) were cut from the plates and the top and lateral surfaces of each sample polished to a 3 μm finish with a diamond abrasive. A homogeneous layer thickness, i.e.