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Thermal shock resistance of ceramics with temperature-dependent material properties at elevated temperature

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Abstract

This paper conducts thermal shock case studies for three typical thermal shock specimens that are important in thermal shock tests: a ceramic layer under a hot shock, a ceramic layer under a cold shock and a ceramic coating under a cold shock. All material properties are assumed to be functions of temperature. The temperature field without cracking is obtained by using the finite element/finite difference method. Time-varied thermal stress intensity factors are obtained by using the weight function method for various parameters of the problem. The thermal shock resistance curves are obtained and the critical size parameters, which control the applicability of the stress-based criterion and the fracture-mechanics-based criterion for the determination of the thermal shock resistance of ceramics, are explored. The studies demonstrate the significance of incorporating temperature-dependent material properties on the thermal shock resistance of ceramic materials for high-temperature applications. The dominant property change responsible for the improvement is the significant reduction in Young's modulus with increasing temperature. As a result, the thermal stress level is reduced considerably and the thermal shock resistance of the ceramic material is improved greatly.

Keywords: Thermal shock; Fracture mechanics; Temperature dependence of material properties

1. Introduction

Ceramic materials are used in many high-temperature applications due to their high melting point. However, they are particularly vulnerable to thermal shock failure because of their low toughness, low thermal conductivity, high Young's modulus and high thermal expansion coefficient. Thermal loads are often severe enough to induce a catastrophic fast fracture or a delayed fatigue failure. The degree of damage and strength degradation of the materials subjected to severe fluctuating thermal environments is a major limiting factor in relation to service requirements and lifetime performance. In order to be able to predict these thermally induced stresses, a detailed understanding of the thermal shock behavior of the material is essential.

Thermal shock failure of materials has been found extensively through theoretical and experimental studies [1–8]. Cracking and fracture of ceramic materials as a consequence of rapid temperature change has been found from the thermal shock experiments shown in Fig. 1 for ceramic disc specimens [9] and in Fig. 2 for glass ceramic slabs [10]. Under heating, a high surface temperature and a large temperature gradient across the material thickness may place the entire material sample in high compression – the surface is in a high compressive stress state. As a result of the high temperature and compression in the hot zone, viscoplastic deformations of the material occur, and cause the compressive stresses to relax. Consequently, during cooling, the stresses become tensile and therefore initiate or propagate surface cracks. Useful relations concerning the thermal shock behavior of homogeneous materials have been derived based on sample stress analysis [11] and fracture mechanics analysis [12], or both [13]. Crack propagation analysis for homogeneous materials has been conducted theoretically and experimentally [14–19].

In order to withstand the severe thermal loads, many structural components are made to be non-homogeneous.

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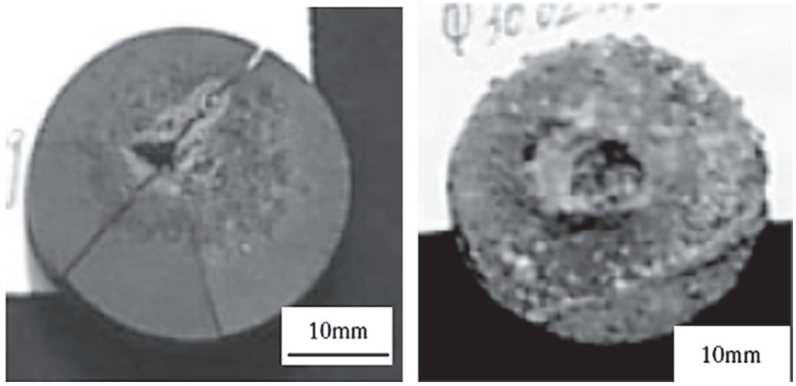

(a) A ceramic disc specimen (b) A ceramic-metal composite specimen

Fig. 1. Thermal shock fracture micrographs of ceramic and composites [9].

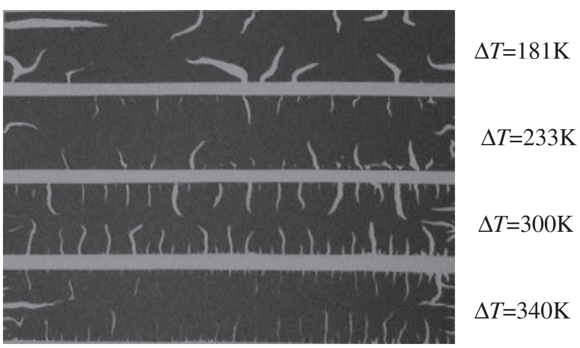

Fig. 2. Glass ceramic slabs shocked at the perimeter: hierarchical crack pattern on the thermally isolated side face [10].

Thermal barrier coating of ceramics used in jet engines, stainless steel cladding of nuclear pressure vessels and a great variety of diffusion-bonded materials used in microelectronics are just some examples. Non-homogeneity in structural components can also be functionally graded such that the material properties change continuously [20]. These non-homogeneous materials and structures may be subjected to severe residual stresses upon cooling from their processing temperatures. They may also undergo certain thermal cycling during the operation. In Ref. [21], an analytical model was developed to predict the surface crack growth and the resulting interface crack driving force as a function of the pre-crack morphology. Numerical studies of pre-existing surface cracks in interfacial thermal fractures of thermal barrier coatings were undertaken by Zhou and Kokini [22,23], and thermal fracture of interfaces in pre-cracked thermal barrier coatings was investigated by Kokini et al. [24]. Fracture response and thermal resistance of yttria-stabilized zirconia (YSZ)–NiCoCrAlY bond coat (BC) under thermomechanical loads were investigated by Rangaraj and Kokini [25]. The review paper of Evans et al. [26] reported the increasing amount of research into the reliability of thermal barrier coatings. Several thermal shock resistance predictions of non-homogeneous materials have also been made [27–29].

In a high-temperature environment, the thermomechanical properties of materials (e.g. Young's modulus, density ρ, specific heat c and thermal conductivity k) are very temperature-sensitive [30–32] and have strong influences on thermal shock behavior. Clearly, there is a real need for an analytical model capable of describing temperature-dependent material properties that may be encountered in such environments. However, because of the inherent mathematical difficulties, thermal shock analysis of structural materials with temperature-dependent material properties is very complicated. Systemic research on the thermal shock resistance behavior of materials with temperature-dependent material properties has not been undertaken at this time. Considering the fact that all materials have temperature-dependent properties, this paper establishes a methodology for the evaluation of thermal shock resistance of ceramic material materials at elevated temperature. The objective of the study is to obtain a series of solutions for examining the influence of such factors as material layer thickness, crack size and material properties on the thermal shock resistance of the ceramic materials. The paper conducts three thermal shock resistance case studies for ceramic materials: a hot thermal shock on a ceramic layer, a cold thermal shock on a ceramic layer and a cold thermal shock on a ceramic coating. In each case, the thermal shock resistance of the material layer is established based on the stress-based criterion and the fracture-mechanics-based criterion. Critical size parameters that control the thermal shock criterion are identified. The studies are useful for material scientists and engineers for the design of thermal-shock-resistant materials.

2. A ceramic layer under hot shock

Consider an infinitely long ceramic layer of thickness H. The layer is initially at a constant temperature. Without loss of generality, the initial constant temperature can be assumed as zero. The coordinate y is directed to the thickness direction of the layer. The surfaces $y = 0$ and $y = H$ of the layer are suddenly heated to a temperature T_0. Since the