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Thermal shock resistance enhancement of functionally graded materials by multiple cracking

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Abstract

Multiple cracking is a common phenomenon for a medium subjected to a sudden temperature change. In this paper, a multiple surface cracking analysis is carried out to investigate the thermal shock resistance behavior of functionally graded materials (FGMs). The FGM is taken to be a ceramic/metal composite with its gradation characterized by the local volume fractions of metal and ceramic phases. The finite element method is used to obtain the solution of the crack problem. The crack tip field intensity factors as well as the stress are computed as functions of the crack spacing, the normalized time, and the crack depth. Crack initiation behavior is discussed. It is found that the thermal shock resistance of the FGM is significantly enhanced by multiple cracking. That is, the thermal shock resistance is a monotonically increasing function of the crack density (crack density is the number of cracks per unit length; crack density increases with decreasing crack spacing). A single crack represents the lower bound solution for the thermal shock resistance of FGMs. It is also found that the gradation of the FGM has little influence on the crack tip thermal stress intensity factors but has a strong influence on the thermal shock resistance. Multiscale behavior of the thermal shock resistance of FGMs is discussed. Two critical size parameters, which control the applicability of the stress-based criterion and the fracture mechanics-based criterion to the determination of the thermal shock resistance of FGMs, are explored.

Keywords: Functionally graded materials; Multiple cracking; Thermal shock; Fracture mechanics; Thermal stresses

1. Introduction

To remedy the reliability and durability problems arising largely from high thermal and residual stresses and poor bonding strengths of the interfaces between dissimilar materials, functionally graded materials (FGMs) as a new class of advanced composites have been developed. In FGMs, spatial variations of thermophysical properties influence strongly the response to loading [1]. The presence of a functionally graded interface between two dissimilar materials can lead to a significant relaxation in stresses [2–6].

Since fracture is a key failure mode of FGMs, successful application of these materials depends on an understanding of their fracture mechanics. Assuming an exponential spatial variation of the elastic modulus, Erdogan and co-workers [7–10] have provided a number of analytical solutions for cracks in non-homogeneous elastic solids subjected to various loading conditions. The correspondence between near-tip field in inhomogeneous and non-homogeneous media has been demonstrated [11]. Delamination and cracking of FGMs at coating/substrate interfaces due to thermal loads have been the focus of investigations [3,12–14]. The influence of material gradation and thermal shock on crack propagation has been examined [15,16]. Also discussed have been the residual stresses, crack bridging, residual strength, fracture toughness, and R-curve

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behavior of FGMs [4,17,18]. In particular, Gu and Asaro [19] analyzed a semi-infinite crack in a strip of a FGM. Dag and Erdogan [20] studied the problem of a surface crack in a semi-infinite elastic graded medium under general loading conditions. Kim and Paulino [21] developed a finite element methodology for the fracture analysis of orthotropic FGMs where cracks were arbitrarily oriented with respect to the principal axes of material orthotropy. In [22], the thermal fracture behavior of metal/ceramic FGMs was evaluated by a burner heating method using a H_2/O_2 combustion flame. An experimental study was conducted to develop an understanding of the thermal fracture behavior of a compositionally graded thermal barrier coating (TBC) subjected to thermal shock loading [23]. An infinite FGM with a partially insulated crack subjected to a steady-state heat flux away from the crack region as well as mechanical crack surface stresses was investigated in [24]. The axisymmetric crack problem for thermal barrier coatings under a uniform temperature change was studied in [25].

Functionally graded ceramic/metal materials are expected to withstand sudden temperature changes or thermal shocks in service. However, under severe conditions thermal shocks can trigger crack propagation from initial flaws. Past experience suggests that cracks may be a roughly regular array of periodic cracks [26,27]. The cracks may form patterns of a characteristic hierarchical structure. This fact is evident from the quenching experiment results shown in Fig. 1 [28] for a homogeneous material, burner heating test results shown in Fig. 2 for a FGM [29], and thermomechanical fatigue test results for thermal barrier coating systems under cyclic thermomechanical loading [30]. The crack density increases with increasing temperature difference ΔT applied to the samples. The crack density is largest near the surface. This is because the cracks start from the surface and most of them are left behind at some stage of growth. Therefore, only few cracks reach into the deep interior of the sample. There seems to be a tendency to regularity, which is unexpected in view of the fact that cracking started from a random distribution of

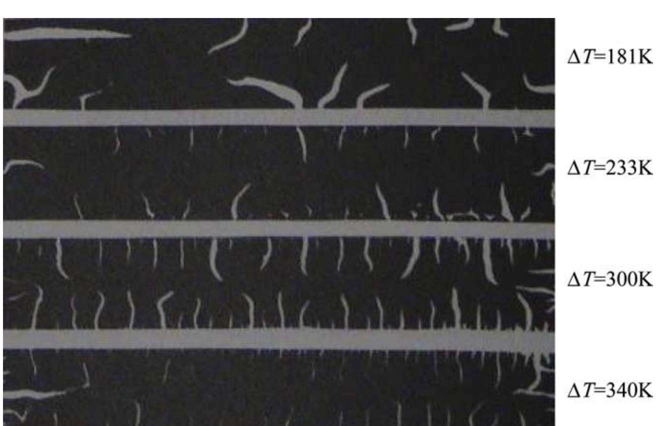

Fig. 1. Glass/ceramic slabs shocked at the perimeter, showing hierarchical crack pattern on a thermally isolated side face [28].

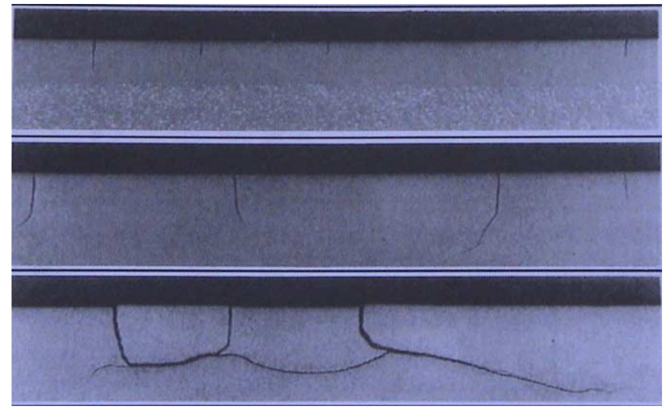

Fig. 2. Cross-section of PZT/stainless steel FGM after a burner heating test [29]. (Three different FGM compositional profile variations are shown. A number of cracks are observed at the central part where the combustion flame impinged. These cracks are found to be vertical cracks initiated from the surface. They occasionally tend to deflect toward the direction parallel to the surface.)

initial flaws. Useful relations concerning thermal shock behavior of homogeneous materials have been derived by Hasselman [31] based on sample stress analysis. Work on multiple crack propagation for homogeneous materials was done by Pompe et al. [32] and Bahr et al. [28,33]. The qualitative discussion of time-dependent strain energy release rate curves in homogeneous materials was later substantiated by calculations for a thermally shocked strip [34], by Pompe et al. [35], and by a bifurcation theory for the determination of the crack propagation [36].

As for the multiple thermal cracking of FGMs, problems have been solved for surface cracks [37] and internal cracks [38]. Recently, Wang et al. [39] performed a thermal shock resistance evaluation for FGMs based on a fracture mechanics analysis. However, the results were only for a single dominant crack. As shown from experimental results (Figs. 1 and 2), there is really a need to establish a numerical model for multiple cracking for thermal shock resistance prediction of FGMs. This paper reports an investigation of a FGM plate subjected to a transient temperature loading on its surfaces. Results are obtained for various parameters of the problem. Thermal stress and stress intensity release by multiple cracking are studied. To simplify the analysis, only the crack initiation behavior is discussed, and the crack growth behavior and the thermal shock damage are not described. The thermal shock resistance problem is based on the crack initiation prediction. This is a main limitation of the crack resistance problem. In order to reflect more practical cases, crack propagation behavior and damage evaluation should be included. However, this has not been done in the present paper since the problem is too complicated as the material considered is non-homogeneous. Although there is a limitation, it is estimated that the proposed model can provide a simple, initial prediction for the thermal shock resistance of FGMs since the crack initiation behavior is essential for the strength behavior of materials.