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Computational simulations of thermal shock cracking by the virtual crack closure technique in a functionally graded plate

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ABSTRACT

Thermal cracking in a ceramic/metal functionally graded plate under thermal shock loading, when the plate is cooled from high-temperature to ambient low one, is numerically analyzed with the commercial finite element software ABAQUS™. Continuous position-dependent functions were created for the mechanical and thermal coefficients of FGM and, then, implemented as user-defined material properties via respective subroutines of the ABAQUS code. In order to find a temperature field and associated thermal stresses in the FGM plate, a linear quasi-static thermoelastic problem for a plane strain state is solved. The distributions of temperature and thermal induced stresses accounting for residual stresses inside the plate are calculated under conditions of both the steady state and transient thermal processes. The solution of the transient heat conduction problem is used for crack propagation simulation using the virtual crack closure technique. The crack lengths developed on the ceramic surface during the thermal shock for different graduation profiles are computed. It is shown that the crack lengths are influenced by the material gradient profile of the functionally graded plate. Hence, the conclusions on the crack resistance of FGM plates are drawn.

1. Introduction

It is well-known that traditional layered composite materials and metals possessing high strength and toughness at room and moderately elevated temperatures becomes incapable for employing under the ultra high temperatures. On the other hand ceramic materials demonstrate superior properties in heat resistance. However, the use of ceramics in engineering applications is usually limited due to their low toughness. Combining gradually ceramic and metal materials into one material system, so-called a functionally graded material (FGM), allows one to get advantages of the both materials as an alternative to structures with a bimaterial interface. The ceramic constituents of FGMs withstand high temperatures due to their excellent thermal resistance, while the metal constituents provide better mechanical performance reducing the possibility of catastrophic brittle fracture. FGMs originally developed as thermal barrier coatings for aerospace structures and fusion reactors [1] have nowadays received a wide spread as structural components in transportation, energy, electronics and biomedical engineering for the general use in high temperature environments [2]. Hence, studies of thermal-induced stresses in FGMs are extremely necessary. Moreover, the existence of microcracks and other defects in FGMs due to features of fabrication processes can essentially affect their material behavior. Therefore, the fracture analysis of FGMs under thermal loading conditions are important to ensure their durability in engineering applications.

A number of issues must be addressed in order to effectively model thermal cracking in functionally graded materials. These include profiles of material gradients and their magnitudes, specimen geometry, residual stress distributions, crack-wake and process zone effects for advancing crack, etc. In this respect, various analytical and computational approaches have been employed to investigate crack-tip stress distribution and crack propagation in FGMs [3]. The correspondence between crack-tip fields in homogeneous and non-homogeneous continua, which permits application of standard analysis techniques in FGMs has been demonstrated in [4,5]. This fact in conjunction with the simplest approximations of graded material properties allowed researchers to get analytically tractable solutions of many practical tasks reducing them to one-dimensional models. For instance, a closed-form solution of thermal stress intensity factor (TSIF) for a strip of metal/ceramic FGM

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with exponentially varying thermo-mechanical properties with an edge crack subjected to steady state thermal load was obtained in [6], while the transient thermal problem for such type of graded materials was presented in [7,8] for a cracked semi-infinite plate and a plate with an edge crack, respectively. Authors in [9] have used an analytical approach based on the layered model to study edge cracked strips of ceramic/ceramic and ceramic/metal FGMs with constant elastic moduli and thermal properties graded according to the power law under transient thermal loading conditions. Both the distributions of temperature and thermal-induced stresses in vicinity of the crack have been found.

Different sophisticated techniques for solving more complicated thermo mechanical fracture problems in FGMs have also been found in the literature. In [10] the thermal shock problem in a ceramic/metal FGM strip with thermal and thermoelastic constants, varying as polynomial functions in the width direction was considered and the influence of residual stresses in the FGM strip on the TSIF and the length of cracks developing due to the thermal shock were evaluated by comparing experimental data and theoretical results. Authors in [11] proposed a meshless method based on the local boundary integral equation and the moving least square approximation for computing the dynamic stress intensity factors in continuously non-homogeneous FGM solids under a transient dynamic load. A crack problem in functionally graded semi-infinite plane with embedded periodic surface cracks subjected to model I mechanical loads or thermal loading has been solved by using Fourier integrals and Fourier series in [12]. An approach based on integral equations has been used to study fracture processes in the vicinity of interface cracks in functionally graded/homogeneous bimaterials subjected to tensile loading and a heat flux in [13,14]. This technique was also applied to investigate the interaction of two edge cracks inclined arbitrary to the interface of a functionally graded layer and homogeneous substrate under cyclic heating–cooling thermal loading in [15]. A high potential for solving fracture mechanics tasks of structural elements of FGMs has the direct approach that follows the original idea of Cosserat, this technique was successfully applied for analyzing mechanical behavior of uncracked functionally graded beams and plates in [16,17].

Despite these efforts, a clear description of fracture and crack growth in graded materials has remained a challenging task yet and requires powerful and precise numerical methods. The Finite Element Method (FEM) is undoubtedly a favorite technique for analyzing mechanical and thermal problems including those involving FGMs. The main issue encountered in application of the FEM to FGMs is concerned with modelling a material with continuously varying properties. The simplest way involves the use of homogeneous elements each with different properties, however, it leads to a stepwise change in properties in the direction of the material gradient. Such models have already been used by a number of researchers and reasonable results have been obtained, e.g. [18] among many others. A more advanced way of including property variation into a FE model is to utilize elements that themselves contain a gradient in properties. Authors in [19] proposed a two-dimensional (2-D) graded finite element with material properties evaluated directly at the Gauss points. An alternative element was developed in [20], a fully isoparametric element formulation that interpolates material properties at each Gauss point from the nodal values, using the same shape functions as the deformations was proposed. One can notice that comparisons of graded and homogenous elements under various loading conditions with analytical solutions in the literature showed that graded elements give far greater accuracy for modelling FGMs [21].

Moreover, in the case of FGMs, appropriate modifications accounting for material inhomogeneity must be made as compared with the analysis of homogeneous materials for predictions of stresses near the crack-tip and tracking the path of a crack growing in the material, where mode mixity arises not only from geometrical and loading configurations but also from the material nonhomogeneity. It has been proven in [22] that when the traditional version of the J-integral is implemented into the FEM via the domain integration method, it is path dependent in the case of FGMs, and it can provide accurate results only if it is evaluated very close to the crack tip using small elements. A modified path independent $\tilde{J}$-integral, computed for the nonhomogeneous materials was also proposed in [23] later. However, this quantity is cumbersome to compute. Previous works on crack growth simulation in FGMs includes a number of prediction models. For example, a local remeshing technique to predict the crack path in the quasi-static four-point bending fracture test has been used in [24]. The intrinsic cohesive element formulation in the context of finite element method can be found, e.g. in [25,26]. Recently, the novel extended finite element method (XFEM) has been applied to model arbitrary crack growth in FGMs under thermo-mechanical loading in [27,28] among others.

In this paper, a finite element-based model is described, for a graded ceramic/metal plate containing an edge crack initially perpendicular to the material gradient under thermal shock loading conditions. Investigating this configuration provides insight into the failure behavior of graded materials in thermal resistance applications. Experiments have shown that for ceramic/metal FGMs, cracks generally nucleate near the ceramic surface exposed to the environment temperature and then grow towards the metal side. To understand clearly this phenomenon by means of numerical modelling, the paper proposes a finite element approach within the ABAQUS code [29], where the two-dimensional graded finite element with spatially varying thermal and mechanical properties is developed using appropriate user-defined subroutines. The propagation of crack induced by thermal shock in conjunction with residual stresses is simulated using the virtual crack closure technique (VCCT). The VCCT originally developed for homogeneous materials in [30] by using the Irwin's assumption has proven its efficiency for composite materials, e.g. [31,32]. This technique is also very suitable for FGMs, since it is based on the local characteristic of the crack tip parameters. The crack lengths depending on the material profiles are discussed here in detail. This is of particular interest since works reported previously in the literature on this subject are limited.

2. Material properties

In order to model temperature and strain/stress distributions in FGMs, one needs an appropriate estimate for thermomechanical properties of the graded composites. A large number of papers on effective material properties of graded materials have been published, and they can be classified largely into theoretical homogenization techniques and experimental methods. The theoretical predictions are usually based on the framework of continuum theory of nonhomogeneous media and often exploit other simple rules of mixtures or variational methods or micromechanical models [2].

In this paper, a plate of width $w = 10$ mm and length $2l = 40$ mm made of a metal/ceramic functionally graded material composed of particles of the titanium alloy Ti–6Al–4V and the zirconium dioxide ZrO_2 ceramic is considered, Fig. 1. The mechanical and thermophysical properties of the constituents of the graded material at a reference temperature of 1000 K, taken from the paper [18], are presented in Table 1.

The effective mechanical and thermophysical properties of the Ti–6Al–4V/ZrO_2 FGM are calculated from its constituent materials and their volume fractions. It is assumed that the volume fraction