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Thermal loading in multi-layered and/or functionally graded materials: Residual stress field, delamination, fatigue and related size effects

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Abstract

The stress field and fracture propagation due to thermal loading in multi-layered and/or functionally graded composite materials are extensively analysed. Regarding fracture, we have focused the attention on delamination between the layers due to brittle or fatigue thermally induced crack propagations. The statically indeterminate stress analysis is solved coupling equilibrium, compatibility and constitutive equations. Fracture analysis is based on the classical Griffith's criterion rewritten for composite structures under thermal loading. As an example, a two-layer prismatic structure is considered, each layer being composed by a different functionally graded material. The solution is particularized for the case of a linear grading. The size and shape effects are discussed and an optimization procedure is proposed. A numerical application of the findings to hard metal and diamond based cutters concludes the paper.

Keywords: Thermal loading; Functionally graded materials; Residual stresses; Delamination; Size-effects

1. Introduction

The spatial variation of the physical properties of the materials is an attractive alternative to composite solids, opening new possibilities for optimizing both materials and structural components to achieve high performance and efficiency. Such materials are collectively referred to as functionally graded materials or FGMs. Gradual variation of material properties in FGMs, unlike abrupt changes encountered in discretely layered systems, is known to improve failure performance while preserving the intended thermal, tribological, and/or structural benefits of combining dissimilar materials. Consequently, the concept of using

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FGMs, for improving material performance, has recently received considerable attention from the research community (Paulino, 2002). On the other hand, it also poses at the same time challenging mechanics problems including the understanding of stress distribution and fracture behavior. These open problems will be considered in the present paper.

Pioneer papers on fracture mechanics of FGMs were written by Atkinson and List (1978), Delale and Erdogan (1983) and Eischen (1987). They show that the asymptotic crack tip stress field presents the same square root singularity as that encountered in homogeneous materials. More recently, Erdogan (1995) propose the multiplication of the conventional stress at a given point in crack tip vicinity by the ratio of the Young's modulus evaluated at that point to the Young's modulus at the crack tip. This hypothesis satisfies the equations of compatibility exactly, although—being limited in its own region of dominance—it obviously does not satisfy the equilibrium conditions.

Extensive research on various aspects of fracture of isotropic FGMs has been recently conducted, not only under mechanical loads, as previously discussed, but also under thermal loads (Jin and Noda, 1993; Erdogan and Wu, 1996; Jin and Batra, 1996; Wang et al., 2000; Jin and Paulino, 2001; Wang and Noda, 2001), Mixed-Mode I, II (Eischen, 1987; Ozturk and Erdogan, 1997, 1999) and Mode III (Babaei and Lukasiewicz, 1998). Experimental investigations on fracture of FGMs are limited by the high costs of the facilities required for processing FGMs. Relatively fewer experimental and numerical investigations of the fracture behavior of FGMs have been conducted. Among the few experimental investigations on FGMs, Parameswaran and Shukla (1998) have shown that increasing toughness in the direction of crack growth reduces crack jump distance in discretely layered FGMs. The extension of the crack analysis to the more general case of a re-entrant corner (Carpinteri and Pugno, 2005) in FGMs has been recently proposed (Carpinteri et al., in press).

In this paper we focus the attention on the stress field and fracture propagation due to thermal loading in multi-layered and/or functionally graded composite materials. The related size and shape effects are also discussed. The statically indeterminate stress analysis is solved coupling equilibrium, compatibility and constitutive equations, and extending the approach already established for torsional loading on bi-component prismatic or cylindrical (Pugno, 1999, 2001; Pugno and Surace, 2000, 2001; Pugno and Carpinteri, 2002) beams in static or dynamic regime. Regarding fracture, the attention is posed on delamination between the layers due to brittle or fatigue thermally induced crack propagations. Fracture analysis is based on the classical Griffith's criterion rewritten for composite structures under thermal load. The same approach was successfully applied by Pugno and Carpinteri (2002) to study the crack propagation under mechanical loading in prismatic and cylindrical homogeneous adhesive joints. This analysis can be considered the natural extension to thermal loading and functionally graded materials of the research on axially loaded tubular structures (Pugno and Carpinteri, 2003). An example of application to hard metal and diamond based cutters (Lammer, 1988; Huang et al., 1997) concludes the paper.

2. Thermal stresses in FGMs

The problem of residual stresses (induced by hot bonding of two different layers) is equivalent, neglecting the algebraic sign, to the problem of thermal stresses induced by a temperature increase in an already bonded two-layer structural component. This principle can be summarized as $\Delta T +$ bonding $\equiv$ bonding $- \Delta T$. As a consequence, we could study the problem of residual stresses induced in a composite structure (Fig. 1) bonded at an increased temperature ΔT, as the problem of thermal stresses induced by a decreased temperature (minus) ΔT.

Let us consider the two-layered structural component reported in Fig. 1. The axial equilibrium along the longitudinal axis (x) provides the tangential stresses at the interface of the two layers (Fig. 1) (Pugno and Surace, 2001):