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Dynamic investigation of a functionally graded layered structure with a crack crossing the interface

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Abstract

The dynamic response of a functionally graded layered structure with a crack crossing the interface is analyzed. The in-plane impact loading condition is considered. By using the Laplace and Fourier integral transforms, singular integral equation method and residue theory, the present problem is reduced to a singular integral equation in the Laplace transform domain. The influences of Young's modulus ratio, thickness ratio, and crack length and location on the dynamic stress intensity factors (DSIFs) are investigated. Particularly, the DSIFs corresponding to different crack locations are shown in the case when the crack center moves from one layer to another layer through the interface. The peak and static values and overshoot characteristics of the DSIFs are analyzed. It is found that these values typically exhibit kinking behavior when the crack tips arrive at the interface. This study is different from previous other investigations in the following respects: (1) the dynamic response of a crack crossing the interface of a functionally graded structure is studied analytically, which has hardly been done in the past and (2) the present model can be reduced to some important problems, such as a functionally graded coating-substrate structure with a crack in the graded coating or homogeneous substrate or one intersecting the interface.

Keywords: Dynamic response; Functionally graded layered structures; Crack; Dynamic stress intensity factors (DSIFs)

1. Introduction

In a traditional layered structure, the mismatch of material properties between different layers results in high residual and thermal stresses and consequently leads to cracking and debonding. From this viewpoint, functionally graded materials (FGMs), which exhibit gradual variations in properties, have been developed. In recent years, functionally graded layered structures such as functionally graded coating-substrate systems have been widely studied for their important applications in preventing heat penetration, wear, and corrosion

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in some engineering fields. Functionally graded structures can be used to realize enhanced reliability and durability over conventional discrete layered or coating systems (Miyamoto et al., 1999). Since fracture is a key failure mode of FGMs, many challenging problems related to the fracture behavior of functionally graded structures have arisen. In this regard, the successful application of these materials depends on the understanding of their fracture mechanics (Han and Wang, 2006).

In the past few decades, many static fracture problems in FGMs have been investigated as stated below. Some early theoretical studies on the fracture behaviors of FGMs were conducted by Delale and Erdogan (1983), Erdogan et al. (1991a,b), Noda and Jin (1993), Jin and Noda (1994), Chen and Erdogan (1996), Choi (1996), and Erdogan and Wu (1997). Through these investigations, it has been revealed that the singularities in the crack-tip field in nonhomogeneous materials are the same as those in homogeneous ones provided that the properties of the former are continuous and piecewise differentiable. In recent years, many crack problems in all types of functionally graded structures have been studied. Ueda (2001) studied a layered plate with a crack perpendicular to the functionally graded interface. Choi (2001) studied a functionally graded interfacial structure containing a crack at an arbitrary angle to the graded interfacial zone. Dag and Erdogan (2002a,b) analyzed the behavior of surface cracks in FGMs under mixed-mode loading. Considering the orthotropic properties, Guo et al. (2004c) studied the surface crack problem for a functionally graded orthotropic strip with an internal crack as well as an edge crack. With regard to the interface crack problems in functionally graded layered structures, Guo et al. (2004a) and Chen (2005) investigated isotropic and orthotropic coating-substrate systems subjected to mechanical and thermal loading, respectively. To solve the crack problems analytically, the material properties in most of the above references are assumed to be exponential functions. On the other hand, some important numerical simulations regarding the static fracture behaviors of FGMs have been conducted, including the elastic two-dimensional crack problem (Kim and Paulino, 2002) and the surface crack problems in three-dimensional FGMs (Walters et al., 2004 and Yildirim et al., 2005).

It should be mentioned that the external loading is usually dynamic in nature under actual conditions. In particular, the dynamic impact may result in much more serious results than those from static loading. Therefore, it is very important to investigate the dynamic fracture response of functionally graded structures under transient impact loading. The torsional impact problems have been investigated by Li and his coworkers (2001 and 2002). In their papers, Li et al. (2001) considered the problem of a cylindrical crack located in the FGM interlayer between two coaxial elastic dissimilar homogeneous cylinders under the torsional impact loading. The dynamic stress intensity factor (DSIF) is found to increase rapidly to the peak value and then decrease and tend to the static value with almost no oscillations. The transient fracture problem of a nonhomogeneous orthotropic strip with a crack perpendicular to the surface was investigated by Chen and his coworkers (2005). On the other hand, Guo et al. (2004b, 2005) studied the transient fracture behavior of a functionally graded coating-substrate system and a layered structure with a functionally graded interfacial layer containing a crack vertical to the boundary under in-plane impact loading, respectively. In their papers, it was found that the DSIF for the internal crack usually increases rapidly to a peak value and then tend to the static value with minimal oscillations. Considering the antiplane shear impact condition, Choi (2004, 2006) analyzed the elastodynamic crack problem for a layered structure with a functionally graded interfacial zone. In their investigations, a crack that was vertical or inclined to the interface was located in the homogeneous medium related to the graded interfacial zone. Recently, Wang and Mai (2006) considered a periodic array of cracks in an infinite functionally graded material under transient mechanical loading. By means of the Schmidt method, Zhou et al. (2004) and Ma et al. (2005) investigated the elastic wave problems in FGMs. It is almost impossible to analytically solve the dynamic crack problem for FGMs with arbitrary properties: in order to do so the moduli and mass density in most of the above references are assumed to be exponential functions. For FGMs with general properties, some approximate methods and numerical methods are used. Wang et al. (2000) conducted an approximate analysis of the dynamic crack problem of FGMs by dividing the material into a number of strips with homogeneous properties. Huang and Wang (2004) developed a multilayered model to conduct the fracture analysis of a functionally graded interfacial zone under harmonic antiplane loading. Dag (2006) and Song and Paulino (2006) analyzed the DSIFs for nonhomogeneous materials by using the finite element method (FEM). Finally, some experimental studies of the dynamic fracture of FGMs were conducted by Parameswaran and Shukla (1998), Rousseau and Tippur (2001a,b), Kawasaki and Watanabe (2002) and Yao et al. (2007).