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Bimaterial interface fracture: A discrete dislocation model

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Abstract

The influence of mode mixity on crack growth and failure at a metal/ceramic bimaterial interface is examined within the discrete dislocation (DD) plasticity framework. Plasticity occurs via the motion of dislocations embedded in a linearly elastic medium with physically based rules governing dislocation nucleation, motion and annihilation. The numerical procedure uses a new superposition technique, developed specifically to allow the efficient solution of DD problems containing elastic inhomogeneities. The existence of an interface crack in the unloaded configuration is assumed and the remote loading is given by the elastic bimaterial crack solution, in accordance with the small scale yielding assumption. A mode-independent cohesive zone law characterizes the interface ahead of the initial crack tip, with a small amount of viscous damping added to the interface constitutive description to avoid convergence problems. The model predicts crack growth with a resistance curve and an increasing fracture toughness with mode mixity, qualitatively similar to recent continuum plasticity calculations but much smaller in magnitude. The quantitative differences arise from the large opening stresses induced by dislocations which drives separation in cases where continuum plasticity can not. Crack tip blunting and shielding, the existence of preferential slip planes, localized regions of large deformation and competition between ductile and brittle fracture all emerge naturally from the boundary value problem solution and provide insight into the observed toughness trends.

Keywords: Crack tip plasticity; Dislocations; Fracture mechanics; Bimaterials

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1. Introduction

The increasing demand for microscale structures has motivated the development of modeling techniques that capture the relevant features of material deformation at this scale. A significant body of experimental evidence (Fleck et al., 1994; Ma and Clarke, 1995; Stolken and Evans, 1998) shows that plasticity in metal specimens with characteristic lengths on the micron scale exhibit a size effect: smaller is stronger. Classical continuum plasticity does not include a length scale, thus any size effects are precluded. Clearly, for metal deformation at small scales, the underlying microstructural effects are important and can not be averaged in a continuum sense. Handling the micron scale in a fully atomistic environment is near the limit of present computations. Thus the micron scale effectively lies between two modeling regimes. Recently, a number of new methods have been developed that are well suited to the analysis of microscale metal structures. One such class of methods involves the non-local plasticity theories (e.g., Fleck and Hutchinson, 1997; Acharya and Bassani, 2000; Gurtin, 2002) that are continuum based but include higher order stresses and strains, introducing a length scale. These theories have been shown to reproduce experimentally observed size effects (Fleck and Hutchinson, 1997). The discrete dislocation (DD) method of Van der Giessen and Needleman (1995) is also appropriate for analyzing microscale deformation in metals. In this method, dislocations are embedded in an isotropic, linearly elastic continuum, and plastic flow occurs by the motion of dislocations and is entirely an outcome of the boundary value problem solution. During loading geometrically necessary dislocations are created as necessary, and size-dependent plastic response emerges.

The DD method has recently been applied to a wide range of mechanical problems, including characterization of plastic flow in composites of varying microstructure (Cleveringa et al., 1997), crack growth in plastic materials (Cleveringa et al., 2000), fatigue crack growth (Deshpande et al., 2002) and size effects in model Al/Si alloys (Benzerga et al., 2001) and thin films (Nicola et al., 2003). The DD method has also proven useful in acting as a numerical experiment for the validation of various nonlocal theories (e.g. Shu et al., 2001; Bittencourt et al., 2003). The standard DD formulation of Van der Giessen and Needleman (1995) is computationally intensive, especially when applied to problems that contain elastic inhomogeneities. For this reason most of the existing DD literature has focused on homogeneous bodies, often with some degree of symmetry to further simplify the computation. In O'Day and Curtin (2004) a new superposition technique was developed to efficiently solve inhomogeneous DD problems. A preliminary analysis of interface crack growth in a metal/ceramic (i.e. elastic-plastic/elastic) bimaterial was performed, and increasing toughness with increasing substrate modulus was observed under mode I-type loading.

The bimaterial interface crack problem is well understood within a continuum plasticity framework. Tvergaard and Hutchinson (1993) have analyzed the case of a power law elastic-plastic material on a rigid substrate; Tvergaard (2001) extended the analysis to include finite substrate moduli. When crack growth is included via a cohesive zone model in a continuum plasticity framework, the cohesive strength is of