Numerical simulations of dynamic crack growth along an interface

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Abstract. Dynamic crack growth is analyzed numerically for a plane strain bimaterial block with an initial central crack. The material on each side of the bond line is characterized by an isotropic hyperelastic constitutive relation. A cohesive surface constitutive relation is also specified that relates the tractions and displacement jumps across the bond line and that allows for the creation of new free surface. The resistance to crack initiation and the crack speed history are predicted without invoking any ad hoc failure criterion. Full finite strain transient analyses are carried out, with two types of loading considered; tensile loading on one side of the specimen and crack face loading. The crack speed history and the evolution of the crack tip stress state are investigated for parameters characterizing a PMMA/AI bimaterial. Additionally, the separate effects of elastic modulus mismatch and elastic wave speed mismatch on interface crack growth are explored for various PMMA-artificial material combinations. The mode mixity of the near tip fields is found to increase with increasing crack speed and in some cases large scale contact occurs in the vicinity of the crack tip. Crack speeds that exceed the smaller of the two Rayleigh wave speeds are also found.

1. Introduction

Fracture along or near an interface between phases plays a major role in limiting the toughness and ductility of multi-phase materials. This has motivated a substantial body of work on failure at interfaces. Nevertheless, a fracture mechanics framework for interfacial crack initiation and growth has been developed only relatively recently, see e.g., Rice [1], Shih [2], Hutchinson and Suo [3]. This late development is due, at least in part, to the fact that the identification of crack tip characterizing parameters for interfacial cracks is much less straightforward than for cracks in macroscopically homogeneous solids. For example, the elastic crack tip fields for a stationary interface crack in a body subject to pure mode I loading have both mode I and mode II components. Furthermore, because these fields are oscillatory, the mode mixity, the ratio of the mode I and mode II components, varies with distance from the crack tip. As a further complication, the near tip fields become compressive and give rise to contact across the bond line.

The extension of static fracture mechanics for homogeneous solids to interfacial fracture requires experiment to provide the toughness as a function of the mode mixity, with experimental studies showing that the apparent toughness increases as the ratio of mode II to mode I increases, as discussed, for example, in Hutchinson and Suo [3]. Since the mode mixity depends on distance from the crack tip, specification of the mixity also involves a characteristic length parameter. This is in contrast to the situation for homogeneous brittle solids where mode I crack initiation is characterized by a scalar parameter, e.g., a critical value of the stress intensity factor.
Interfacial fracture mechanics is even more complicated when crack growth and crack arrest under dynamic loading conditions are considered. For homogeneous brittle materials, the energy release rate as a function of crack speed (and possibly the amount of crack growth) is assumed to be a material property and known from experiment. Together with the singular elastic fields, which have an amplitude that depends on the loading, they give rise to a 'crack tip equation of motion,' Freund [4]. A similar approach for interfacial cracks would involve assuming that the energy release rate as a function of crack speed, of mode mixity and of the amount of crack growth is characteristic of a particular interface. Furthermore, the mode mixity varies with crack speed, Yang et al. [5], and the possible dependence on the crack speed of the characteristic length parameter used for specifying the mode mixity needs to be considered.

Theoretical studies of dynamic interfacial crack growth have been inhibited by the analytical complexity of the problem (even for crack growth along a bond line between two linear elastic materials) and by uncertainty concerning an appropriate fracture criterion. In spite of these difficulties basic problems of dynamic interfacial crack growth have been addressed by a number of authors, for example, Willis [6], Brock and Achenbach [7], Yang et al. [5], Liu et al. [8], Lo et al. [9]. In particular, Yang et al. [5] have obtained the singular fields for a crack growing dynamically along the bond line between two linear elastic materials. Their results, which pertain to crack speeds up to the Rayleigh wave speed of the more compliant of the two materials, give an oscillatory singularity, with the oscillation index becoming infinite at the smaller Rayleigh wave speed. Liu et al. [8] have presented crack tip singular fields for crack speeds greater than the smaller Rayleigh wave speed that are quite different from the sub-Rayleigh wave speed fields; for example, the order of the stress singularity depends on crack speed and is less than 1/2.

Recently, Rosakis and co-workers [8, 10, 11] have carried out a series of experimental studies of dynamic interfacial crack growth that give the crack speed history and the crack tip stress and strain fields under well-characterized conditions. The experimental results show crack speeds exceeding the smaller Rayleigh wave speed, increased mode mixity with increasing crack speed and the development of a contact region along the bond line. Several attempts have been made to develop interfacial fracture criteria that are consistent with the experimental results, [12, 13]. Lo et al. [9] have carried out finite element crack growth computations to simulate the experiments of Tippur and Rosakis [10]. They used a node release method in conjunction with a mode mixity and crack speed dependent critical energy release rate criterion. An iterative technique was used to obtain a criterion that gave a crack speed history consistent with the measurements. The extent to which such a criterion is characteristic of the interface and is independent of the specimen configuration and imposed loading history remains to be determined.

In this investigation, computations of dynamic interfacial crack growth are carried out where the crack speed history and the effect of inertia on the apparent toughness are direct outcomes of the analysis. The basis for the theoretical framework is the cohesive surface decohesion formulation in Needleman [14]. Crack initiation and crack growth are calculated directly in terms of the properties of the materials and of the parameters characterizing the cohesive surface separation law, which include a strength and the work of separation per unit area. Hence, a characteristic length enters the formulation. This framework has been used to address a variety of issues involving separation of surfaces in solids; in particular, quasi-static crack growth in homogeneous solids and along interfaces, Needleman [15, 16], Tvergaard and