Journal of the Mechanics and Physics of Solids 000 (2018) 1–14

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

Dynamic mode II crack growth along an interface between an elastic solid and a plastic solid

A. Needleman

Department of Materials Science & Engineering, Texas A&M University, College Station, TX 77843, USA

ARTICLE INFO

Article history:
Received 25 October 2017
Revised 21 January 2018
Accepted 21 January 2018
Available online xxx

Keywords:
Fracture
Dynamic fracture
Plasticity
Finite elements

ABSTRACT

Dynamic crack growth is analyzed numerically for a planar bimaterial block with an initial edge crack subject to mode II impact loading along the side of the block. The crack is constrained to grow along a weak interface directly ahead of the initial crack tip. A cohesive constitutive relation, that relates tractions and displacement jumps, is specified across the weak interface. The normal traction along the interface is taken to be a linear function of the normal displacement across the interface while the shear traction is taken to be a nonlinear function with the shear traction approaching zero for large displacement jumps, thus allowing mode II crack propagation. The material on the impact side of the interface is taken to be a linear elastic (actually hypoelastic) solid while the material on the other side of the interface is taken to be an isotropically hardening elastic-viscoplastic solid. Both plastically incompressible and plastically compressible solids are considered. Results are presented for the effects of plastic deformation on the evolution of near crack tip fields, on the crack speed history, and on the tractions that develop at the interface. The effects of various parameter variations are also explored. It is found that plasticity can result in tensile normal tractions developing on the interface in the crack tip vicinity and that the transition to an intersonic crack speed via a daughter crack mechanism can take place in the presence of small amounts of plastic straining.

1. Introduction

The prediction of crack speeds is a basic question in the theory of dynamic fracture mechanics. In classical elastic dynamic fracture mechanics, the maximum attainable crack speed for a crack with an initial speed less than the Rayleigh wave speed is the Rayleigh wave speed, see e.g. Freund (1998). However, Andrews (1976) carried out numerical calculations that showed that with a cohesive-type formulation, the speed of a model II crack could exceed the Rayleigh wave speed. In the calculations of Andrews (1976), the crack travels at the Rayleigh wave speed and a micro-crack eventually nucleates ahead of the initial crack. This micro-crack begins propagating at a speed above the shear wave speed and grows both back toward the initial crack and ahead (i.e., the direction in which the main crack is propagating). When the micro-crack links up with the main crack, it appears that the main crack has "jumped" to a speed exceeding the shear wave speed.

Motivated by the calculations of Andrews (1976), Burridge et al. (1979) analyzed the stability a mode II crack in an elastic solid with a slip weakening cohesive relation. Burridge et al. (1979) found that cracks traveling at steady speeds less than the Rayleigh wave speed, as well as cracks traveling at speeds above $\sqrt{2}$ times the shear wave speed and below the dilational

E-mail address: needle@tamu.edu

https://doi.org/10.1016/j.jmps.2018.01.011

Please cite this article as: A. Needleman, Dynamic mode II crack growth along an interface between an elastic solid and a plastic solid, Journal of the Mechanics and Physics of Solids (2018), https://doi.org/10.1016/j.jmps.2018.01.011

wave speed were stable in the sense that the driving force would need to increase for the crack speed to increase. Cracks traveling at speeds between the shear wave speed and $\sqrt{2}$ times the shear wave speed were unstable in that a decreasing driving force would be associated with an increase in crack speed. Also, crack propagation speeds between the Rayleigh wave speed and the shear wave speed are forbidden, (Burridge et al., 1979).

The first experimental evidence of this Andrews mechanism for attaining super shear wave speed crack growth in homogeneous elastic solids subject to remote loading was given by Rosakis et al. (1999). Rosakis et al. (1999) introduced a weak interface directly ahead of a notch tip by bonding two pieces of Homalite together and subjecting the specimen to mode II type loading. Thus, a well-defined fracture plane was introduced into a homogeneous solid forcing straight ahead crack growth. A crack speed exceeding the shear wave speed was seen. In experiments on pre-stressed specimens of Homolite with various crack orientations, Xia et al. (2004) found crack speeds that could range from sub-Rayleigh wave speeds to crack speeds somewhat below the longitudinal wave speed with, in some cases, a micro-crack nucleation mediated transition from a near Rayleigh crack wave speed to a supershear crack speed.

Subsequently, the Andrews mechanism was seen in the atomistic calculations of Abraham and Gao (2000) and in the finite element calculations of Needleman (1999) where a plane strain model of the specimen configuration of Rosakis et al. (1999) was analyzed. A variety of calculations of crack growth along a weak interface between elastic solids (e.g. Barras et al., 2014; Chen and Gao, 2010; Hao et al., 2004; Needleman and Rosakis, 1999; Williams and Hadavinia, 2006), have since been carried out. These analyses have shown the dependence of crack speed on interface strength, elastic properties and loading mode. In particular, under certain conditions, the crack propagation speeds can exceed the shear wave speed of at least one of the materials adjacent to the interface.

The question arises as to the effect of plasticity on the course of rupture along a weak interface. There has been some interest in this topic related to geophysical issues (e.g. Ben-Zion and Shi, 2006; Erickson et al., 2017; Hok et al., 2010; Shi et al., 2010), where the rupture along the interface is characterized by frictional slip. However, the effect of plasticity along a weak interface under dynamic shear loading where propagation occurs by decohesion has been essentially unexplored, in particular in circumstances where, in the absence of plasticity, the crack would achieve an intersonic speed.

Here, plane strain calculations are carried out modeling the configuration in the experiments of Rosakis et al. (1999). The problem formulation and numerical method are essentially the same as in Needleman (1999). The configuration modeled is a rectangular block with a weak interface subject to impact loading on one side of the interface. The elastic properties are taken to be uniform. However, the material on one side of the interface, the side not subject to impact, is taken to be an isotropically hardening elastic-viscoplastic solid. Both plastically compressible and plastically incompressible solids are considered. In Khan et al. (2017) it was found that plastic compressibility can have a significant effect on mode I quasi-static crack tip fields. The interface is characterized by a cohesive relation that is linear for separation normal to the interface but nonlinear in shear. The nonlinearity is such that the shear traction at first increases, then reaches a maximum and subsequently decreases to zero monotonically with increasing shear separation.

Since the material on the impact side is taken to be elastic, the stress carried by the loading wave and the speed of the loading wave are independent of the specified plastic material properties. Attention is confined to the crack growth history prior to any wave reflections reaching the current crack tip. The main focus is on the effect of various plastic material properties and of interface shear strength on the evolution of crack growth and on the interface tractions that develop. Particular attention is given to the effect of plasticity in circumstances that, for a homogeneous elastic solid, would lead to intersonic crack speeds. Parameter variations are also explored, particularly in the context of non-dimensional groups characterizing the governing equations.

2. Problem formulation

2.1. Governing equations

The governing equations, the boundary conditions and the specimen geometry are the same as in Needleman (1999). For completeness, a brief summary of the formulation is given here.

Using a Lagrangian description and finite strain kinematics, the principle of virtual work is written as

$$\int_V \mathbf{s} : \delta \mathbf{F} dV - \int_{S_{int}} \mathbf{T} \cdot \delta \mathbf{\Delta} dS = \int_{S_{ext}} \mathbf{T} \cdot \delta \mathbf{u} dS - \int_V \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \cdot \delta \mathbf{u} dV \tag{1}$$

In Eq. (1) the nominal stress tensor is denoted by $\mathbf{s}$, $\mathbf{u}$ is the displacement vector, $\mathbf{F}$ is the deformation gradient, $\mathbf{\Delta}$ is the displacement jump across a cohesive surface, $\mathbf{A}$: $\mathbf{B}$ denotes $A^{ij}B_{ji}$, V, S_{ext} and S_{int} are the volume, external surface area and internal cohesive surface area, respectively, of the body in the reference configuration. The density of the material in the reference configuration is ρ and the traction vector $\mathbf{T}$ and the reference configuration normal $\mathbf{n}$ are related by $\mathbf{T} = \mathbf{n} \cdot \mathbf{s}$. Also, $\mathbf{s} = \mathbf{F}^{-1} \cdot \boldsymbol{\tau}$, where $\boldsymbol{\tau}$ is the Kirchhoff stress, $\boldsymbol{\tau} = \det(\mathbf{F})\boldsymbol{\sigma}$, with $\boldsymbol{\sigma}$ being the Cauchy stress.

Plane strain conditions are assumed and a convected coordinate formulation is used with a Cartesian coordinate frame as reference. The $y^1 - y^2$ plane is the plane of deformation and with the origin of the coordinate system at the initial crack tip as shown in Fig. 1. Computations are carried out for edge cracked rectangular specimens of dimension $w \times L$ with an initial crack of length a_i along $y^2 = 0$. At $t = 0$, the body is stress free and at rest.

Please cite this article as: A. Needleman, Dynamic mode II crack growth along an interface between an elastic solid and a plastic solid, Journal of the Mechanics and Physics of Solids (2018), https://doi.org/10.1016/j.jmps.2018.01.011