International Journal of Plasticity 65 (2015) 131–151

Contents lists available at ScienceDirect

International Journal of Plasticity

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

A unified model for metal failure capturing shear banding and fracture

Colin McAuliffe *, Haim Waisman

Department of Civil Engineering and Engineering Mechanics, Columbia University, 610 Seeley W. Mudd Building, 500 West 120th Street, Mail Code 4709, New York, NY 10027, United States

ARTICLE INFO

Article history:
Received 11 June 2014
Received in final revised form 25 August 2014
Available online 20 September 2014

Keywords:
A. Shear band
A. Failure
A. Fracture
B. Phase field

ABSTRACT

Dynamic fracture of metals may be brittle or ductile depending on factors such as material properties, loading rate and specimen geometry. At high strain rates, a thermo plastic instability known as shear banding may occur, which typically precedes fracture.

Experiments on notched plate impact show a ductile–brittle failure transition, where lower impact velocities lead to brittle behavior, while higher impact velocities lead to shear banding. For more complex problems such as armor penetration, both brittle fracture and shear banding have been observed in the same specimen, however, current failure models can either account for fracture or shear banding. For predictive numerical simulations of dynamic failure, it is thus crucial to account for both failure modes, since exclusion of either mode neglects important physics observed in experiments.

In this work a thermodynamically consistent model which accounts for both shear banding and dynamic fracture and can thus capture both failure bodes at intermediate strain rates, is presented. The model consists of an elastic–viscoplastic material with strain hardening, strain rate hardening, and thermal softening. Fracture is modeled with the phase field method, for which a novel modification is presented here to account for the creation of fracture surfaces by inelastic work. Numerical examples are presented to illustrate the basic behavior of the model, and to compare it to three special cases: a damage free case, an isothermal case, and an isothermal case where the contribution of inelastic work to fracture is excluded.

1. Introduction

Metals subjected to high strain rates may become unstable due to shear banding or fracture. Shear banding is a localization phenomenon where thermal softening leads to narrow zones of intense inelastic deformation (Wright, 2002). While a shear band typically precedes fracture, since the thermal softening leads to profound and rapid loss of load carrying capability, the shear band is considered a failure mode in its own right (Bai, 1982; Fressengeas and Molinari, 1987; Ling and Belytschko, 2009).

There are several examples of scenarios where high strain rate failure involves both shear bands and cracks. Shear banding as a precursor to void growth and fracture has been documented in several experimental works such as Backman and Finnegan (1973), Dormeval (1987), Irwin (1972), Odeshi et al. (4340), and Shockey. In addition, a ductile–brittle failure

* Corresponding author.
E-mail address: waisman@civil.columbia.edu (H. Waisman).

http://dx.doi.org/10.1016/j.ijplas.2014.08.016
0749-6419/

transition has been observed in the impact of notched plates by Kalthoff (2000), Kalthoff and Winkler (1987), and Zhou et al. (1996). It was found that failure by shear banding occurred above a critical impact velocity, while brittle fracture resulted from lower impact velocities. A final example is the impact of metal plate with a projectile, where shear bands have been identified propagating parallel to the impact direction, and cracks propagate perpendicular to the impact direction (Nickodemus et al., 2002), and shown schematically in Fig. 1. For predictive numerical simulations of dynamic failure, it is thus crucial to account for both failure modes, since exclusion of either mode neglects important physics observed in experiments.

Existing models for ductile fracture include two broad categories, the first of which being empirical or semi empirical criteria based on the experimentally observed effects of variables such as the stress state and the extent of inelastic strain or inelastic work (Bai and Wierzbicki, 2008; Brünig et al., 2008; Khan and Liu, 2012; Wierzbicki et al., 2005). The stress state variables used in these models are typically related to stress invariants. Examples are the hydrostatic stress, stress triaxiality, Lode angle parameter, and magnitude of the stress vector. This type of criteria has also been modified to incorporate rate and temperature effects (Johnson and Cook, 1985; Khan and Liu, 2012). In the second category are coupled damage models, which incorporate constitutive relations governing the progressive degradation of material strength through the growth of micro voids or micro cracks. Early examples are the well-known Gurson–Tvergaard–Needleman model for void nucleation, growth, and coalescence (Gurson, 1977; Tvergaard, 1990) and the continuum damage model of Lemaitre (1985). More recent models include Lassance et al. (2007), Lecarme et al. (2011), Shojaei et al. (2013), and Xue (2007). These models account for various sources of micro degradation, which is coupled to the macro response through one or more damage parameters which degrade the overall load carrying capacity of the material leading to failure. Generally speaking, the first category of models are simple to implement in a computational code and to calibrate to experimental data. On the other hand, models of the second type are considered to have a more solid micromechanical basis. Models of both types are discussed further and assessed in the works of Li et al. (2011) and Malcher et al. (2012).

In this paper a combined thermal softening shear banding and phase field fracture model is presented, which falls into the coupled damage model category. The shear band model consists of an elastic–viscoplastic, strain hardening, strain rate hardening, and thermally softening material. Thermal diffusion is accounted for, which weakly defines a length scale and regularizes the problem. This type of model and diffusive regularization have been studied in Batra (1987), Batra and Jin (1994), Batra and Kim (1991), Batra and Ravinsankar (2000), Batra and Zhang (2004), McAuliffe and Waisman (2012, 2014), and Wright and Walter (1987). Fracture is accounted for with the phase field method, which is a regularized Griffith type (Griffith, 1921) fracture model based on energy minimization (Bourdin et al., 2008; Francfort and Marigo, 1998; Miehe et al., 2010,). The crack is approximated as a continuous entity, whose width is defined by a small process zone parameter, see Fig. 1. It is thus possible to approximate the fracture energy with a volume integral, which does not require a procedure for tracking the crack surface. It has been shown in Bourdin et al. (2000) and Francfort and Marigo (1998) that in the limit as the process zone parameter tends to zero, the phase field approximation to the fracture energy converges to that of the discontinuous crack. Phase field models have been extended to account for dynamic brittle fracture in Borden et al. (2012) and Bourdin et al. (2011).

Growth of cracks in the phase field models cited above is driven by the elastic free energy. The elastic energy can then be split into portions which contribute to fracture and portions which do not. For example Borden et al. (2012) and Miehe et al. (2010,) decompose the strain energy using the principal strains, where only the tensile principal strains contribute to fracture. Inelasticity has been introduced to the phase field model by Borden (2012) who combined the phase field model for dynamic fracture with the finite deformation plasticity models in Simo and Hughes (1998). In addition, modeling of thermo mechanical damage in tungsten subject to conditions found in a fusion reactor was conducted by Crosby and Ghoniem (2012), who combined the phase field model with small deformation plasticity. For an inelastic material, the growth of the elastic free energy will be limited by yielding; in fact the elastic free energy can decrease once thermal softening begins. For metals, where the inelastic response is independent of volumetric deformations, it is conceivable that the elastic free

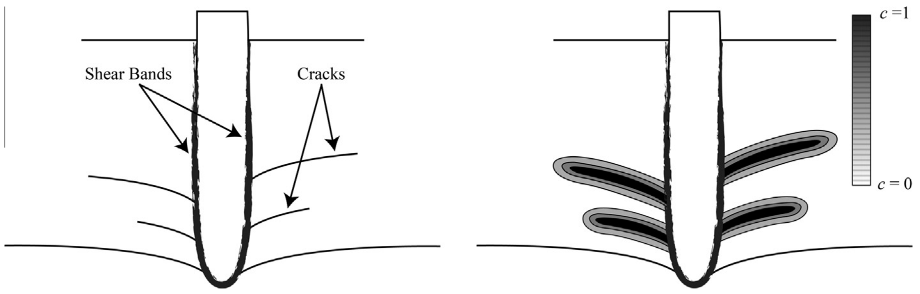

Fig. 1. On the left, a schematic illustration of a projectile penetrating a metal plate, such as those shown in Nickodemus et al. (2002). Shear failure occurs parallel to the impact direction while crack radiate out perpendicular to the impact direction. On the right, an illustration of the phase field approximation to a crack is shown. Phase field models treat cracks as continuous entities where the extent of the damage to the material is characterized by the phase field parameter c. The parameter is 1 in the fully fractured phase and 0 in the undamaged phase. The width of the diffusive crack is determined by the parameter l_0.