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Modeling spontaneous adiabatic shear band formation in electro-magnetically collapsing thick-walled cylinders

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ABSTRACT

The ability to simulate shear bands evolution in thick-walled-cylinder (TWC) experiments is required to understand their spontaneous formation and propagation. Recently we presented experiments on electro-magnetically collapsing metallic cylinders (Lovinger et al., 2015). Here we present numerical simulations that reproduce the experimental results for multiple shear bands in those TWC's. We present a detailed study of the initiation and propagation of the shear bands and their mutual interactions, which replicates many of the experimental observations. We investigate the influence of initial perturbations and pressure history on the initiation and final stages of the process using an energy-based failure model which incorporates a positive feedback mechanism. The numerical model is calibrated for four different materials to reconstruct the number of shear bands and their experimentally determined distribution. The results indicate that the number of shear bands is related to deformation micromechanisms operating in the material, such as twinning and martensitic transformations, which may hold back and eventually stall the shear bands evolution. The numerical simulations provide a reliable quantitative description of the shear bands distribution and spacing, thus paving the way for future predictive work of this failure mode.

1. Introduction

Modeling adiabatic shear banding (ASB) has been a standing issue for the past few decades. As shear localization is an important and often dominant failure mode at high strain rates, as well as a precursor to catastrophic failure, a reliable predictive capability is highly desirable. Such a modeling capability should faithfully represent the mechanics and the physics of the dynamic material behavior. ASB formation in a dynamically loaded metal is traditionally viewed as a structural and/or material instability. The strength of a material is considered to be controlled by two competing mechanisms: hardening, such as strain and strain-rate hardening, and softening such as thermal (Zener and Hollomon, 1943) and microstructure-related softening (Rittel et al., 2006, 2008; Osovski et al., 2012). The classical approach of Zener and Hollomon (1943), which was recently reported (Dodd et al., 2015) to have been presented earlier by Kravz-Tarnavskii (1928) and Davidenkov and Mirolubov (1935), relates the initiation of adiabatic shear localization to the dominance of the thermal softening over the hardening mechanisms. Namely, under high rate deformation, the thermal softening results in a loss of strength leading to a feedback mechanism between the plastic work and the consequent decrease in flow stress. In the last decade, an alternative process was proposed for ASB formation (Rittel et al., 2006, 2008; Osovski et al., 2012), identifying microstructural evolution (e.g. dynamic recrystallization) as the dominant softening mechanism. In these works, the dynamic stored energy of cold work was identified as the driving force for shear localization, which is, in fact, *preceded* and *triggered* by dynamic recrystallization (Rittel et al., 2006).

For each approach, a constitutive model that could capture the formation and evolution of adiabatic shear banding has to include a localization criterion and a positive feedback mechanism, due to the mutual relation between plastic work and material softening (either thermal or microstuctural). In addition, such a model should express the dependence on material thermo-mechanical and/or microstructural properties, in order to account for the susceptibility of materials to shear banding, and the different ASB characteristics in various materials as observed experimentally.

We recently presented an experimental study on the spontaneous evolution of adiabatic shear bands in collapsing Thick Walled Cylinders (TWC) (Lovinger et al., 2015, 2011). As detailed and explained in Lovinger et al. (2011), the examination of *spontaneous* adiabatic shear bands highlights the inherent susceptibility of a material to adiabatic shear banding, without any geometrical constraint related to stress concentrations. Following our

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experimental work, as well as other works on explosively driven TWCs (Xue et al., 2004, 2002; Meyers et al., 2003; Yang et al., 2008, 2009), we aim at modeling the formation and evolution of multiple adiabatic shear bands in TWCs, with the inherent complexity related to the mutual interactions between the shear bands during their growth. The number of shear bands and their spatial distribution, as well as the conditions prevailing at their onset of formation, as characterized in Lovinger et al. (2011), provide a large database to select a proper constitutive model together with a failure criterion, for different materials.

Numerical modeling of spontaneous shear band evolution, in TWC tests, is pursued in the literature through either 1D or 2D/3D modeling of shear bands. The 1D modeling follows different strength and failure models, in order to predict the spacing between shear bands (e.g. Grady, 1982; Wright and Okendon, 1996; Molinari, 1997; Daridon et al., 2004). 2D/3D numerical simulations are aimed at reproducing the formation and evolution of ASB's, and their interactions, as observed in experiments, (see e.g. Areias and Belytschko, 2007; Rabczuk and Samaneigo, 2008).

Examining 1D modeling of shear bands, Grady (1982), Wright and Okendon (1996) and Molinari (1997) performed a perturbation analysis for the shear instability, using constitutive equations which incorporate strain and/or strain rate hardening and thermal softening. This approach ties the mathematics of perturbations with the physical material instability phenomena, suggesting that shear bands evolve at a spacing which is determined by minimum energy considerations, matching a dominant wave number, issued from the perturbation calculation. Grady (1982) accounted for a viscous constitutive equation and linear thermal softening. Later works by Wright and Okendon (1996) and by Molinari (1997) addressed this issue with a similar approach, by extending the material's constitutive law to include rate dependency (Wright and Okendon, 1996), and strain hardening (Molinari, 1997). The outcome of these works consists of analytical expressions for the spacing between shear bands. The ability of these models to predict shear band spacing was examined experimentally in several works with dynamically collapsed thick walled cylinders. Xue et al. (2004) found a good agreement for 304L stainless steel. On the other hand, significant discrepancies between the experimental results and the models' predictions were found for CP-Titanium and Ti–6Al–4V (Xue et al., 2002). Recently, Lovinger et al. (2015) found significant discrepancies between predictions from these models and their results from electro-magnetically (EM) driven TWC tests for seven different materials. It was suggested that the limited ability of these analytical 1D models, to predict the measured spacing, seems to coincide with earlier work in the literature (e.g. Rittel et al., 2006, 2008; Osovski et al., 2012), indicating that thermal softening is not the dominant factor responsible for the onset of localization.

Daridon et al. (2004) examined shear band spacing for more complex constitutive models. Using a 1D perturbation model with periodic boundary conditions, they studied the spacing between shear bands in Titanium and HY100 steel. Three material models were examined: Johnson and Cook (1983) (JC) model, a power law model and the MTS (Mechanical Threshold) model (Follansbee and Kocks, 1988). The results were compared with the experimental TWC spacing results for Titanium (Xue et al., 2002), showing that while the JC model predicted much larger spacings (by an order of magnitude), the MTS model predicted the experimental results quite well. The work of Daridon et al. (2004) follows an approach which addresses the initiation of shear bands through the *flow stress* ("strength") model, unlike other works, as shown in what follows, which search to define a *failure* or *damage* model.

Medyanik et al. (2007) defined a new criterion for shear band formation, based on experimental observations of dynamic recrystallization (DRX) in the shear bands. The onset of localization is associated with a critical temperature for recrystallization which is of the order of 0.4–0.5 T_m (melting temperature) of the material. The authors presented simulations using two constitutive models: one for the bulk material and one to describe the material inside the shear band. The shear band criterion signals the shift from one model to the other and it is based on a critical DRX temperature with strain rate dependency. The JC constitutive model was used in the simulations for the bulk material, and a viscous fluid model for the material inside the shear band. The simulations agree well with the band width, their velocity and the measured temperature rise in the bands (Medyanik et al., 2007). Though good agreement was achieved, the model is restricted to a predefined perturbation as determined by a notch and the forced localization. Additional questions arise regarding the physical meaning of two distinct criteria, before and after ASB formation, and the fact that it was shown that DRX is not linked to a specific temperature rise (Rittel et al., 2008).

Considering now 2D and 3D numerical simulations which take into account also the spatial behavior of the multiple shear bands during their evolution, Areias and Belytschko (2007) suggested a two-scale model to simulate ASB's using the extended Finite Element (FE) method (XFEM). The shear bands are accounted for by using a local partition of unity. When material instability is detected, the FE temperature and displacement fields are enriched with a fine scale function which is able to model the high gradients within the shear band. They implemented this model to reproduce a large variety of shear band experiments and satisfactory agreements were achieved for many of them. For the TWC experiment, the model demonstrates the formation of multiple ASB's, yet it only shows qualitative resemblance to experimental results.

Rabczuk and Samaneigo (2008) modeled 3D shear band evolution in TWC experiments. They treat the shear bands as discontinuities, neglecting their width. The localization criterion is defined by the material instability, shifting at this point to a non-continuous space, while the discontinuity is modeled and controlled by a cohesive law. The 3D TWC simulations show the formation of multiple adiabatic shear bands only in a qualitative manner. These 2D and 3D numerical works (Firstenberg et al., 2006; Lovinger and Partom, 2009) account for the discontinuity of the shear bands' space, but they lack a physical model for shear band evolution and do not describe well the physics of the multiple shear bands' formation.

Firstenberg et al. (2006) used a different failure approach to account for shear band formation. The model defines a strain-based damage parameter, $0 \le D \le 1$, which evolves through the following relations:

$$D = \frac{\varepsilon_p^{eff} - \varepsilon_i}{\varepsilon_f - \varepsilon_i} \qquad \varepsilon_i < \varepsilon_p^{eff} < \varepsilon_f \tag{1}$$

where ε_p^{eff} is the effective plastic strain, ε_i is the initial plastic strain, at which localization begins, ε_f is the final plastic strain, at which the stress decreases to zero. The damage parameter (D) is used to account for the decrease in the flow stress (Y) through:

$$Y = Y_0 \cdot (1 - D) = Y_0 \frac{\varepsilon_f - \varepsilon_p^{eff}}{\varepsilon_f - \varepsilon_i} \tag{2}$$

The flow stress decrease provides the positive feedback needed to cause shear localization. In Firstenberg et al. (2006), the model was used to simulate perforation tests, showing good agreement with the experimental results and reproducing failure characteristics. The damage mechanism effectively corresponds to the thermal/microstructure softening. Lovinger and Partom (2009) used this model in 2D numerical simulations to simulate multiple adiabatic shear bands and obtained a fair comparison with explosively driven TWC test results. This model was further examined

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