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An analysis of microstructural and thermal softening effects in dynamic necking

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ABSTRACT

The competition between material and thermal induced destabilizing effects in dynamic shear loading has been previously addressed in detail using a fully numerical approach in Osovski et al. (2013). This paper presents an analytical solution to the related problem of dynamic tensile instability in a material that undergoes both twinning and dynamic recrystallization. A special prescription of the initial and loading conditions precludes wave propagation in the specimen which retains nevertheless its inertia. This allows for a clear separation of material versus structural effects on the investigated localization. The outcome of this analysis confirms the dominant role of microstructural softening in the lower strain-rate regime (of the order of 10^3 s^{-1}), irrespective of the extent of prescribed thermal softening. By contrast, the high strain-rate regime is found to be dominated by inertia as a stabilizing factor, irrespective of the material's thermo-physical conditions, a result that goes along the predictions of Rodríguez-Martínez et al. (2013a) regarding dynamically expanding rings.

1. Introduction

Recrystallization is a process in which nucleation and growth of new strain-free grains, assumed to occur on grain boundaries, replace the deformed microstructure of a strained material. Together with slip, recovery, grain growth or phase transformation, it is one of the most important microstructural evolution processes. Recrystallization may occur after deformation, the post-deformation annealing process called *static* recrystallization, or during deformation. The latter is termed *dynamic* recrystallization (DRX), and it takes place in many alloys when they deform at high strains and high strain rates (Tanner and McDowell, 1999; Qu et al., 2005; Medyanik et al., 2007; Osovski and Rittel, 2012; Li et al., 2013). DRX initiates upon reaching a critical condition. The two most widely accepted criteria for the onset of DRX make use of a critical strain (Fan and Yang, 2011) or a critical dislocation density (Bailey and Hirsch, 1962; Ding and Guo, 2001). The last criterion is equivalent to a critical stored energy if the stored energy is assumed to be a function of dislocation density only (Brown and Bammann, 2012). Thus, Rittel et al. (2006, 2008) suggested to consider the dynamically stored energy of cold work, namely the part of the energy that is not dissipated into heat, as a criterion for the onset of dynamic recrystallization (DRX), which may appear long before final failure. Recently, Medyanik et al. (2007) proposed a criterion for the onset of DRX deformation mechanism, formulated in terms of temperature. This approach, however, still requires elevated temperatures as a trigger for DRX (0.4 to 0.5 of melting temperature), while this requirement stands in contradiction with some of the experimental observations reported by Rittel and Wang (2008).

When the critical value for the onset of DRX is reached, the elimination of dislocations reduces the stored energy,

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resulting in a decrease of flow stress, hardness and a simultaneous increase in the ductility (Ganapathysubramanian and Zabaras, 2004; Fan and Yang, 2011; Brown and Bammann, 2012). As a result, the material locally softens giving rise to inhomogeneous deformation patterns which can, in turn, be important precursors to plastic instabilities. Regarding dynamic shear loading conditions, Rittel et al. (2006, 2008) suggested that the onset of the so-called "adiabatic shear bands" is primarily related to microstructural transformations which were indeed observed long before any significant self-heating of the material develops. The formation of dynamically recrystallized grains, which may appear long before final failure, creates soft enclaves in the surrounding hardening material. Final failure occurs therefore as a result of the growth and coalescence of islands of dynamically recrystallized phase, as shown by Osovski et al. (2012a). Moreover, if DRX is present it may override thermal softening effects, thus emerging as the main cause of ASBs (Osovski et al., 2013) in materials that exhibit early DRX (e.g. Ti6Al4V alloy).

In parallel to adiabatic shear banding, which was considered by the above authors to analyze the respective influence of microstructural and thermal softening, dynamic necking represents a paradigmatic case of plastic instability occurring at high strain rates. Dynamic necking is known to be strongly affected by thermal effects since the deformation process approaches adiabaticity. In such conditions, the thermal softening of the material appears to be a critical factor for localization (Klepaczko, 1968; Fressengeas and Molinari, 1985). In materials with a strong thermal softening, the temperature increase may dictate the conditions for stability, on top of other softening effects. However, following the results by Rittel and coworkers for a shear stress state (Rittel et al., 2008; Osovski and Rittel, 2012; Osovski et al., 2012b,a, 2013), it is worth analyzing the respective influence of microstructural and thermal softening in dynamic necking inception.

In this work, the role of both microstructural and thermal softening on the localization of plastic deformation in dynamically stretching rods is examined. Two different modeling methodologies are used: linear stability technique derived within a quasi-1D theoretical framework and finite element simulations of slender bars subjected to uniaxial tension. The constitutive equation accounts for hardening due to twinning and softening –dynamic recrystallization– microstructural effects, as well as for thermal softening of the material. A parametric study, performed on the constants of the constitutive model, driving these effects, allows for the identification of their relative role in the onset of dynamic necking.

2. Constitutive model

The constitutive model uses Huber–Mises plasticity as in the previous work of Osovski et al. (2013). The model considers three possible mechanisms responsible for the plastic flow: slip, twinning and dynamic recrystallization. Those three mechanisms are treated using a rule of mixture to describe the mechanical, microstructural and thermal evolution of the material. In the undeformed configuration the material is only formed by the slip phase. Twinning is triggered by plastic deformation and complements dislocation activity increasing the material flow stress and strain hardening. Twinning is assumed to stop once DRX starts, whose onset is determined by a threshold value of the stored energy of cold work. Dynamic recrystallization contributes to the material strain softening. It should be noted that the material is considered strain rate independent in order to facilitate interpretation of the respective influence that microstructural and thermal softening effects have on flow localization.

In this paper, flow localization in a rapidly stretched bar is analyzed using linear stability -derived within a 1D framework– and finite element simulations –developed within a 3D framework-. Therefore one-dimensional and three-dimensional approaches will be presented, understanding that both coincide in their essential features and that, for a uniaxial state of stress, the 3D model provides the same results as its 1D counterpart.

2.1. 1D model

The material constitutive equations of the problem were presented in Osovski et al. (2013) and will only be repeated here for the sake of clarity. The effective yield stress is calculated by the following expression:

$$\sigma_y = \Psi(\bar{\varepsilon}^p, T) = h(\bar{\varepsilon}^p)p(T) \tag{1}$$

where the functions $h(\bar{\varepsilon}^p)$ and $p(T)$ gather the strain $\bar{\varepsilon}^p$ and temperature T dependencies of the material, which are defined as follows:

- The function $h(\bar{\varepsilon}^p)$ is composed by three terms and reads as follows:

$$h(\bar{\varepsilon}^p) = (1 - f_{DRX})\sigma_y^0 + f_{DRX}\sigma_y^{DRX} + (1 - f_{DRX} - f_{twins})\left(K_t\left(\frac{1}{\chi}\right) + K_d(\bar{\varepsilon}^p)^n\right) \tag{2}$$

where f_{DRX} and f_{twins} are the volume fractions of DRX and twins respectively. The first yield stress term in the previous expression represents the initial yield stress of the material –which is controlled by the slip phase– and it is defined by σ_y^0. The second yield stress term is to be understood as the flow stress at which DRX first appears (upon reaching the energetic threshold given by U_{DRX}, see Eqs. (3) and (4)) which is determined by the parameter $\sigma_y^{DRX} = \sigma_y|_{U=U_{DRX}}$ (to be calculated in the integration procedure for each loading case). The third yield stress term is an isotropic strain hardening function which consists of two parts: (a) the contribution of evolving density of twins, acting as barriers for dislocation motion, enters the equation as a Hall–Petch like term, where K_t is a strain hardening parameter and χ is the average distance between twins given by $\chi = \frac{2t(1-f_{twins})}{f_{twins}}$ with t being the average twin width; and (b) the strain hardening resulting from dislocation activity during deformation with K_d being the strain hardening parameter and n the strain hardening exponent.

The evolution law for the twins volume fraction is as follows: