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Dynamic recrystallization and adiabatic shear localization

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ABSTRACT

It has recently been reported that, in alloys exhibiting early dynamic recrystallization (DRX), the onset of adiabatic shear bands (ASB) is primarily related to microstructural transformations, instead of the commonly assumed thermal softening mechanism as shown by Rittel et al. (2006, 2008) and Osovski et al. (2012b). Further, the dominant role of microstructural softening in the necking process of dynamically stretching rods showing DRX has been verified using linear stability analysis and finite element simulations by Rodríguez-Martínez et al. (2014). With the aim of extending this coupled methodology to shear conditions, this paper presents an analytical solution to the related problem of ASB 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, allowing for a clear separation of material versus structural effects on the localization process. A parametric study, performed on the constants of the constitutive model, permits the identification of their relative role in the onset of the dynamic instability. The main outcome of the analysis confirms the strong destabilizing effect played by the development of DRX, consistently with the former statement regarding ASB, and contributes to rationalize the observations of other authors.

1. Introduction

The analysis of dynamic shear instabilities, such as adiabatic shear bands (ASB), is of capital importance for the understanding of ductile failure of metals at high rates of deformation. The interested reader can find a wealth of experimental evidence in Bai and Dodd's book (Bai and Dodd, 2012), and a summary of the analytical results in Wright's book (Wright, 2002). The development of adiabatic shear bands is assumed to occur in three different stages: in the first step, the strain is homogeneous, and the strain hardening of the material overcomes any kind of heterogeneity present in the material; in the second step, after the maximum stress has been reached, a diffuse instability starts to develop due to the presence of softening effects. The strain begins to be rather heterogeneous. In the third stage, a strong instability is formed and deformation localizes in a narrow band (Marchand and Duffy, 1998). For decades, the classical explanation of Zener and Hollomon (1944) has been the prevailing assumption, which consists of the competition between strain hardening and thermal softening. Accordingly, adiabatic shear bands generation, as a typical mechanical instability, has been extensively studied by many authors. This instability can be triggered by both geometrical imperfections and the mechanical softening due to heat generation (thermal softening). However, the recent work by Osovski et al. (2012b) has challenged this assumption of a unique softening mechanism. These authors showed experimentally that, in addition to the potential effect of thermal softening, microstructural evolutions, such as dynamic recrystallization DRX, may indeed cause local softening and shear

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localization. Using a sort of "coarse-grained" finite element model, these authors assessed the relative influence that microstructural changes, and thermal softening may have on the shear band formation (Osovski et al., 2013). One of their main results was that, even in the absence of noticeable thermal softening, microstructural softening can be in itself a potent destabilizing mechanism.

Among the several analytical solutions for the dynamic shear localization problem, the seminal work of Molinari and Clifton (1987) is among the first to propose a structured approach to predict the onset and initial evolution of the instabilities. One should also mention here the work of Rodríguez-Martínez et al. (2014) who analyzed the onset of dynamic tensile necking using a perturbation analysis, for a material that can undergo both thermal and microstructural softening. It is therefore interesting to re-analyze dynamic shear localization, in the spirit of the above-mentioned authors, with the support of both analytical and numerical simulations, to broaden the problem and its solution to the general case of dynamic instabilities, thereby complementing the results for dynamic necking.

Therefore, the essence of this paper is an assessment of the onset of dynamic shear instabilities, using the approach of Molinari and Clifton (1987) and Molinari (1997), with an additional microstructural softening mechanism in accordance with the results of Rittel et al. (2008) and Osovski et al. (2012b). The idea is to generalize our approach proposed for the dynamic necking problem by adding the dynamic shear localization analysis. Consequently, we consider here a rectangular 2D plane-strain solid, treated analytically as a 1D solid, subjected to dynamic shear. The material can undergo both thermal and microstructural softening. From the modeling point of view, and following Molinari and Clifton (1987) and Molinari (1997), shear localization can be derived as the evolution of an initial perturbation. This problem is addressed within a 1D linear stability analysis, where the uncontrolled growth of the perturbation signals the onset of the shear instability. Next, the same problem is modelled numerically by considering a layer of finite thickness subjected to constant velocities at the boundaries, enforcing a shear loading configuration. Note that the problem is formulated in a way that cancels wave propagation effects (Rodríguez-Martínez et al., 2014; Zaera et al., 2014), such as to emphasize purely material aspects of the problem.

The main outcome of the analysis confirms the strong destabilizing effect played by the development of DRX in addition to thermal softening, in full accord with previous experimental evidence. In that respect, the present analysis complements and adds more generality to the problem of dynamic mechanical instabilities in strained solids.

The paper is organized as follows: the second section introduces briefly the 1D constitutive model for the material considered (Ti6Al4V). The third and fourth sections are devoted to present the linear stability methodology and the finite element modelling of the dynamic simple shear problem, respectively, taking into account strain-rate sensitivity and thermal effects, as well as microstructural transformations (twinning and DRX). The salient features of the stability analysis and the main results obtained from it are presented in Sections 5 and 6 respectively, while in Section 7 the results from the FEM analysis are summarized. Sections 8 includes a brief discussion of the results and highlights the main outcomes of this investigation.

2. 1D constitutive model for Ti6Al4V alloy

The material is assumed to obey Huber–Mises plasticity. The model considers three possible mechanisms responsible for the plastic flow: slip, twinning and dynamic recrystallization (DRX). Those three mechanisms are treated using a rule of mixture to describe the mechanical behaviour of the material. In the undeformed configuration the material is free of twins and DRX. Twinning is triggered by plastic deformation and complements dislocation activity, thereby increasing the 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 (Osovski et al., 2013). Dynamic recrystallization contributes to the material strain softening. Strain rate and temperature sensitivities of the flow stress are included in the material description. For the sake of brevity, only the main features of the model are presented in this paper while further details can be found in Osovski et al. (2013).

The thermo-viscoplastic flow law has the general form:

$$\tau_y = \Psi(\gamma^p, \dot{\gamma}^p, T) = h(\gamma^p)s(\dot{\gamma}^p)p(T) \tag{1}$$

where the functions $h(\gamma^p), s(\dot{\gamma}^p)$ and $p(T)$ define the plastic strain γ^p, plastic strain rate $\dot{\gamma}^p$ and temperature T dependencies of the material.

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

$$h(\gamma^p) = (1 - f_{DRX})\tau_y^0 + f_{DRX}\tau_y^{DRX} + (1 - f_{DRX} - f_{twins})\left(\tau_t\left(\frac{1}{\chi}\right) + \tau_d(\gamma^p)^n\right) \tag{2}$$

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 τ_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)). This is determined by the parameter $\tau_y^{DRX} = \tau_y|_{U=U_{DRX}}$ that has to be calculated in the integration procedure for each loading case. The third yield stress term is an isotropic strain hardening function where τ_t, τ_d and n are material constants and χ is given by $\chi = \frac{2\zeta(1-f_{twins})}{f_{twins}}$ with ζ being a material parameter.

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

$$f_{twins} = g(\gamma^p) = \begin{cases} \frac{1}{N}[\arctan(2\pi a\gamma^p - 2\pi d) - \arctan(-2\pi d)]; & U < U_{DRX} \\ f^*_{twins} = f_{twins}|_{U=U_{DRX}}; & U \geqslant U_{DRX} \end{cases} \tag{3}$$

where U is the stored energy of cold work (see Eq. (5)) and U_{DRX} is the threshold energy for the onset of the recrystallization process. Here, a, d and N are material