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The respective influence of microstructural and thermal softening on adiabatic shear localization

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ABSTRACT

It has recently been shown that dynamic shear failure of crystalline solids can be initiated by local microstructural changes (dynamic recrystallization, DRX), instead of the commonly assumed thermal softening mechanism. We systematically investigate the respective contribution of thermal and microstructural softening to the initiation of dynamic shear localization, by means of a fully coupled numerical model incorporating the two softening mechanisms in an adjustable manner. Our results indicate that, for those materials that exhibit early DRX, (e.g. Ti6Al4V), the role of thermal softening is negligible, whereas for materials with late (e.g. pure Ti) or no DRX, thermal softening effects become dominant. The strength of the thermomechanical coupling term (thermal softening) is found to determine the local temperatures, with the strongest effect being achieved in the absence of coupling, together with the formation of thermal "hot spots". Thermal softening is found to regulate the evolution of the local temperature, in the sense that the softened material both stores and dissipates smaller increments of strain energy. The results of this study allow for a general classification of the material proneness to dynamic shear localization as a function of its thermo-physical characteristics.

1. Introduction

Since the early seminal contribution of Zener and Hollomon (1944), it has been commonly accepted that the main reason for adiabatic shear localization is the competition between strain hardening and thermal softening, as a result of thermomechanical coupling. Thermal softening is assumed to gradually reduce the strain-hardening capacity of a material to a point where it reaches a plateau, followed by a negative slope which is interpreted as the sign of instability. Based on this premise, a large body of analytical and numerical work has been dedicated to the subject. While an exhaustive list of references is beyond the scope of this paper, one should mention the book of Bai and Dodd (1992) which lists a wealth of experimental observations, and that of Wright (2002), which discusses extensively modeling aspects of the phenomenon. One should also mention the early work of Molinari and Clifton (1987) who modeled shear localization based on a geometrical perturbation approach. Note here that one could also study the effect of a thermal perturbation, and show that its growth may lead to instability. Such a perturbation would arise, for example, from "hot spots", namely local sharp gradients in temperature, that develop in the strained material as a result of a local thermomechanical heterogeneity. As of today, irrespective of the constitutive model that is adopted, a prevailing criterion for the onset of adiabatic shear localization is the attainment of a critical strain value. This parameter can also be viewed as a failure criterion for engineering design. It is important to note that such an approach marks the onset of the catastrophic failure, thereby lumping initiation and growth of the adiabatic shear band in one and single parameter.

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Recently, Medyanik et al. (2007) proposed a criterion for the onset of adiabatic shear bands (ASB) which was related to the appearance of DRX, by assuming a minimum temperature for its onset. Thereafter, the build-up of DRX is assumed to cause the material to behave like a viscous fluid, resulting in stress collapse. The approach used in this work, however, still requires elevated temperatures as a trigger for DRX and subsequent ASB, while this requirement stands in contradiction with some of the experimental observations reported by Rittel and Wang (2008).

Alternatively, Rittel et al. (2006, 2008) suggested to consider the dynamically stored energy of cold work (SECW) as a criterion for the *onset* of shear localization. This energy, once it reached a certain threshold, was suggested to lead to the formation of dynamically recrystallized grains (DRX), which may appear long before final failure, and whose effect was create 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. (2012). In other words, these authors suggested that the onset of dynamic shear localization is primarily related to microstructural transformations which were indeed observed long before any significant self-heating of the material develops (Rittel et al., 2008). In this context, Schoenfeld and Kad (2002) modeled the dynamic mechanical response of Ti6Al4V using crystal plasticity concepts and a cell method. In their work, both slip and twinning were represented, contributing to different local flow stresses, depending on the cell orientation. In addition, the contribution of anisotropy to adiabatic shear band formation was explicitly addressed. One should also mention the work of Clayton (2009) who considered energy storage concepts and microstructural heterogeneity in aluminum alloys to model their dynamic performance. In this work, a coarse grained model of crystal plasticity was used, leading to the conclusion that the microstructure should be tailored to obtain optimal impact toughness of these materials. Stored energy considerations were applied as a criterion for the onset of dynamic shear localization was examined numerically by Dolinsky et al. (2010) and was shown to be successful for a variety of problems involving dynamic loading.

In a recent work, Osovski et al. (2012) compared their microstructural observations of annealed Ti6Al4V and commercially pure Ti which were impacted dynamically to pre-determined levels of strain. These authors observed that while Ti6Al4V exhibits early DRX at about half its failure strain (Rittel et al., 2008), pure Ti only shows DRX at the late stages of its deformation, close to 0.9 its failure strain. Moreover, while Ti6Al4V deforms essentially by *slip* (dislocation mediated plasticity), pure Ti exhibits massive *twinning* which precedes markedly the formation of DRX and immediate subsequent failure. These findings were rationalized in terms of strain energy storage, noting that twinning, which does not store significant amounts of energy (Padilla et al., 2007; Bever et al., 1973), acts therefore as a delaying factor for dynamic recrystallization. Osovski et al. (2012) modeled the interaction between slip-DRX-twinning using a finite element model for which each element represents a typical grain of the material. This model allowed for the characterization of the evolution of the DRX'ed phase whose continuity is interpreted as final failure. Moreover, since each of the three deformation micromechanisms stores energy in a different manner, local temperatures could be calculated at the grain level, revealing that the overall temperature rise remained quite modest throughout the deformation process while no localized hot elements (hot spots) were observed, in agreement with previous experimental work. Yet, this work did not consider the degradation of the mechanical properties with the increase of temperature, even modest, nor did it consider latent heat release associated with recrystallization.

Consequently, the dynamic shear localization process can be triggered by two softening mechanisms, one microstructural and the second thermal. However, very little is known on the respective contribution and importance of each mechanism to the overall failure process. Therefore, the following fundamental questions remain to be elucidated:

1. What is the precise contribution of thermal softening, if at all, with respect to the above-mentioned microstructural softening. In other words, is thermal softening alone, sufficient to trigger dynamic shear localization, and if not, when does it become significant?
2. What is the contribution of the enthalpy release which is associated with the recrystallization process? How does it affect the thermal balance, both globally and locally?
3. What is the contribution of hot spots, if any, to the onset of adiabatic shear failure?

This paper attempts to answer these questions through numerical modeling, based on suitable modifications of the model developed by Osovski et al. (2012), which did not address these aspects. Throughout this work, typical materials will be considered, whose thermomechanical and physical properties (detailed in the sequel) are selected such as to cover the cases of materials that exhibit DRX only (e.g. Ti6Al4V), mixed DRX and twinning (e.g. pure Ti), or no DRX (e.g. pure Ta).

The present paper is organized as follows: We first present in detail the numerical model, choice of internal variables and their physical meaning. Next we report the main results of the systematic simulations, to be discussed in the following section. This section is followed by a summary and conclusions, thus answering the questions posed above.

2. Micromechanical model

2.1. Physical assumptions underlying the micromechanical model

Following the experimental observations of Osovski et al. (2012), our model considers three possible deformation mechanisms responsible for the plastic flow: twinning (twin boundary formation), slip (dislocation motion), and a third mechanism referred to as DRX-mediated plasticity. Those three mechanisms are treated using a rule of mix-