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Latent heat saturation in microstructural evolution by severe plastic deformation

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ABSTRACT

During plastic deformation, most of the dissipated work is released as heat, but a fraction of it, usually small, is stored in the microstructure, is called *latent heat* and is associated with the network of dislocations that develops. The rate of energy storage in the microstructure divided by the rate of plastic dissipation is defined as the *latent heat capacity*. Latent heat remains stored in the microstructure of cold worked specimens after quenching. This energy is associated with modified mechanical properties, *e.g.* hardness, and is released upon annealing. Saturation of this stored energy has been observed in experiments after a specific amount of plastic deformation is reached. A thermodynamically consistent model for continuous dynamic recrystallization is proposed in this paper with the aim of explaining the phenomenon of latent heat saturation and relating it to grain refinement. The proposed model has three essential features: (i) the latent heat increases in the specimen during plastic deformation as plastic work is continuously dissipated; (ii) the rate of latent heat storage per unit work, *i.e.* the latent heat capacity, is related to the internal architecture of the microstructure and decreases to zero as a consequence of microstructural evolution; (iii) the relationship between the latent heat and the microstructure is described through the use of two parameters: (a) the dislocation density and (b) the average grain diameter. A comparison of the proposed model with experiments is reported and a validation for the prediction of microstructural evolution, as well as the evolution of the latent heat and latent heat capacity, is provided.

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1. Introduction

The mechanical properties of a material depend on its physical state, and in particular, for solid materials, on the configuration of the microstructure. Many authors have developed constitutive models that are sensitive to the heterogeneity of the material, as well as its microstructure, for small deformations (Mindlin, 1964; Bacca et al., 2013) and for large deformations (Aifantis, 1984). Less attention has been dedicated to the development of constitutive models that are sensitive to the evolution of the microstructure, as well as the mechanical properties linked to it. The proposed work attempts to contribute to this field on a thermodynamically consistent basis.

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Microstructural evolution occurs via mechanical processes that involve cold working of the material. The resulting change in microstructure is associated with the amount of plastic deformation experienced by the material and becomes significant after severe plastic deformation (SPD) associated with processes such as low-speed machining (Shankar et al., 2005; Bacca et al., 2015). Experiments performed by Taylor and Quinney (1934) on torsion of metal rods have shown how this evolution is measured by *latent heat*, *i.e.* the energy that remains stored in the specimen after the specimen is quenched. This energy is considered to be stored in the microstructure, is responsible for the evolution of the microstructure as it is associated with the network of dislocations that develops, and increases continuously with plastic work (Bever et al., 1973). The Taylor and Quinney (1934) experiments on torsion, as well as experiments on machining (Saldana et al., 2012) demonstrate saturation of the latent heat for a finite amount of plastic strain, with continuous reduction to zero of the rate of storage of latent heat per unit work (called the *latent heat capacity*).

Some constitutive models based on latent heat storage have previously been developed with the aim of predicting microstructure evolution in metals (Bernacki et al., 2009; Le and Kochmann, 2009; Quan et al., 2011; Brown and Bammann, 2012; Bacca et al., 2015), with a focus on the phenomenon of dynamic recrystallization. This phenomenon has also been studied with different approaches such as phase field models (Militzer, 2011; Moelans et al., 2013; Sreekala and Haataja, 2007; Suwa et al., 2008), which considers the nucleation and subsequent growth of new grains within the “old” microstructure, and with the use of finite element techniques as well as other methodologies such as cellular automata (Hallberg, 2011). However, the *latent heat saturation* (LHS) phenomenon is neglected in those models and a physical interpretation has not been reported in the literature.

In the present paper, a thermodynamically consistent model for continuous dynamic recrystallization (CDRX) created by SPD is provided. In this model, an evolution of the micro and nanomechanisms that accommodate macroscopic plastic deformation is considered, and a physical interpretation for the phenomenon of LHS is provided.

As will be explained in this paper, grain refinement is created by CDRX and gives a reduction of the average grain diameter, allowing the microstructure ultimately to develop a grain boundary sliding (GBS) mechanism for plastic deformation. When this mechanism of plastic deformation becomes predominant over other mechanisms associated with dislocation motion, microstructure evolution is complete and no further energy can be stored in the system as latent heat, giving LHS.

An explanation of the proposed model and all its features is provided in Section 2; results on the prediction of the evolution of the microstructure as well as the latent heat and latent heat capacity are given in Section 3; discussion of the model and its conditions of applicability are reported in Section 4; finally some conclusions are drawn in Section 5.

2. The constitutive model

2.1. Basic principles

In the present work, an improved version of the simple model for CDRX developed by Bacca et al. (2015) is developed. The basic principles of the original model are explained in this section, with more detail given in Bacca et al. (2015), while the proposed new features are explained in the subsequent sections.

In the model the yield strength is given by superposition of two main contributions: (i) Dislocation strengthening, which mechanism involves pinning of dislocations by others, as described by Taylor (1934); (ii) Grain boundary strengthening, as described by Hall (1951) and Petch (1953). The total yield strength in shear, in agreement with Castro-Fernáandez and Sellars (1989) and Le and Kochmann (2009), has the form

$$\tau_y = \alpha b \mu \sqrt{\rho} + \lambda \left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{d_0}} \right), \tag{1}$$

where α is a phenomenological constant for Taylor hardening (usually taken as unity), b is the Burgers vector, μ is the shear modulus, ρ is the dislocation density, λ is the Hall-Petch coefficient, d is the current average grain size, and d_0 is a reference grain size that is sufficiently large so that the Hall-Petch effect is negligible. With condition $d = d_0$, eq. (1) only accounts for changes to hardness caused by changes to ρ.

During plastic deformation, energy conservation can be written neglecting reversibly stored macroscopic elastic strain energy, *i.e.* identifying only dissipative terms, in order to obtain the rate equation (with superposed dots indicating differentiation with respect to time or rates)

$$\tau_y \dot{\gamma}_p = \dot{Q} + \dot{U}_m, \tag{2}$$

where $\dot{\gamma}_p$ is the rate of change of the shear equivalent plastic strain, $\dot{Q}$ is the rate per unit volume at which mechanical work is dissipated as heat, and $\dot{U}_m$ is the rate per unit volume at which plastic work is stored in the microstructure as latent heat (the *latent heat rate*) (Taylor and Quinney, 1934). The right-hand side of eq. (2) corresponds to the amount of plastic work per unit volume supplied to the system at the unit time and can be associated with the rate of change of a hardening energy potential W_p, for which $\tau_y = \partial W_p / \partial \gamma_p$, thus $\dot{W}_p = \tau_y \, \dot{\gamma}_p$ (Chang and Kochmann, 2015). The left-hand side of eq. (2) is the rate per unit volume at which the applied loads do plastic work on the material. If we define a latent heat capacity, κ, as the rate at which plastic work is stored in the microstructure as latent heat, divided by the rate of total plastic work, we have

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