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Continuous dynamic recrystallization during severe plastic deformation

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ABSTRACT

Severe plastic deformation (strains > 100%) has been shown to create significant grain refinement in polycrystalline materials, leading to a nanometric equiaxed crystalline structure for such metals as aluminum, copper and nickel alloys. This process, termed continuous dynamic recrystallization, is governed by evolution of the dislocation structure, which creates new grain boundaries from dislocation walls. In the proposed model, plasticity occurs which firstly involves dislocation multiplication, leading to strain hardening limited by dynamic recovery. After a critical dislocation density is reached new grain boundaries are formed by condensation of walls of dislocations, creating a new stable configuration that is favored due to a reduction of the system free energy. This evolution of the microstructure continues to develop, with a consequent progressive decrease in the average grain diameter. The proposed model provides a quantitative prediction of the evolution of the average grain size, as well as the dislocation density, during continued plastic strain. The model can be calibrated by use of results from any experiment that involves large plastic deformation of metals, subject to negligible annealing effects. In this paper, the model has been calibrated, and consequently validated, through experiments on *machining* of Al 6061-T6.

1. Introduction

Grain refinement is an important feature in many thermo-mechanical processes involved in manufacture engineering, producing material that is much stronger than that without grain refinement. This phenomenon can be achieved in several ways, the most common one being the activation of recrystallization (RX) by severe plastic deformation (SPD), with a consequent decrease in the average diameter of the grains. Severe plastic deformation typically involves plastic strains greater than 1 in manufacturing processes such as machining or metal cutting (Shankar et al., 2005) and equal channel angular pressing (ECAP) (Mishra et al., 2005; Valiev and Langdon, 2006), the former being the most effective since the maximum amount of shear equivalent plastic strain can be up to 15 (Shankar et al., 2005). This processes are able to create grain sizes in the range of nanometers, and such nanostructured materials are known to have much higher strength than those having grain size on the micron scale. Grain boundaries act as barriers to dislocation motion, with pile-ups forming whose extent is constrained by the grain size so that the driving force for them to penetrate

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the barrier is limited, *i.e.* the Hall–Petch effect (Hall, 1951; Petch, 1953). As a consequence the yield strength of the material is inversely proportional to the square root of grain size, leading to significant strengthening in nanostructured materials. The driving force for RX is the energy stored in the network of dislocations that is generated during plastic deformation. A fraction of the plastic work associated with such deformation is stored in this dislocation network. Once this energy becomes excessive the system finds it thermodynamically more favorable to reduce its free energy by condensing the dislocation structure into new grain boundaries associated with small, lower dislocation density crystallites.

A thermodynamically consistent model for RX during SPD, inspired by Le and Kochmann (2009), is proposed in this paper; it is described in Section 2, its calibration is reported in Section 3, computational results derived from the model are reported in Section 4 and compared with experiments on machining for the Aluminium Alloy Al 6061-T6 (Shankar et al., 2005), a discussion on the model and its comparison with other models is reported in Section 5 and its implementation in a finite element code is reported in Section 6.

2. Proposed model

The mechanical properties of a material are defined by its microstructure, and plastic deformation in metals affects these properties by modifying microstructural internal variables that control them (Rice, 1971). For example, a common model for yield strength in a metal superposes Taylor strengthening by dislocation–dislocation pinning (Taylor, 1934) and the Hall–Petch effect (Hall, 1951; Petch, 1953) due to dislocation pile-ups interacting with grain boundaries to give the yield strength in shear, τ_y, as Castro-Fernandez and Sellars (1989)

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

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 at that grain size. Plastic deformation causes the dislocation density to increase by dislocation multiplication at sources in the material and, as noted above, can also cause the grain size to change due to RX. The proposed model, based on a simple one developed by Le and Kochmann (2009) for continuous dynamic recrystallization (CDRX), describes the evolution of the dislocation density and the grain size on a thermodynamically consistent basis, as follows.

Consider the energy conservation during plastic deformation, but neglect the elastic strain energy of the macroscopic deformation as it is stored reversibly (see Le and Kochmann (2009) for more details). Thus only dissipative terms are included, giving

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

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 (*the latent heat rate*) (Taylor and Quinney, 1934). As is well known, the left hand side of Eq. (2) is the rate per unit volume at which the applied loads do provide plastic work to the material. Defining now a *latent heat capacity* as the fraction, κ, of plastic work being stored in the microstructure, then,

$$\dot{U}_m = \kappa \tau_y \dot{\gamma}_p. \tag{3}$$

At this point it is useful to describe the microstructural energy, U_m, as estimated by Berdichevsky (2006) as a function of the two microstructural parameters, such that

$$U_m(\rho, d) = -k\mu \left[Log\left(1 - \sqrt{\frac{\rho}{\rho_s}}\right) + \sqrt{\frac{\rho}{\rho_s}} \right] + \frac{\chi \Gamma_s}{2d}, \tag{4}$$

where k is a constant, χ is a grain shape factor (its value is 3 if we consider spherical grains), Γ_s is the surface energy of the grain boundary, and ρ_s is a theoretical saturation limit for the dislocation density; *i.e.* in the absence of RX ρ_s is the maximum dislocation storage capacity. By substitution of Eqs. (1) and (4) into Eq. (3) a differential equation in the rate of change of the two main variables ρ and d is obtained

$$\frac{k\mu}{2\rho_s(1-\sqrt{\rho/\rho_s})}\dot{\rho} - \frac{\chi\Gamma_s}{2d^2}\dot{d} = \kappa \left[\alpha b \mu \sqrt{\rho} + \lambda \left(\frac{1}{\sqrt{d}} - \frac{1}{\sqrt{d_0}} \right) \right] \dot{\gamma}_p. \tag{5}$$

As many theories and experiments indicate, RX commences only after a critical amount of plastic deformation is reached, associated with instability in the intragranular dislocation structure (Roberts and Ahlblom, 1978; Bailey and Hirsch, 1961; Luton and Sellars, 1969). This instability leads to the creation of low angle subgrain boundaries condensed from existing dislocations in the microstructure. At this point RX has started and all existing dislocations and many of the new ones produced will eventually be adsorbed into the subgrain boundaries, causing increasing misorientation across them until new, distinct, refined grains are created.

From now on, microstructural evolution is divided into two main stages: *prior to Recrystallization*, and during *Recrystallization* (equivalent to Stage I and Stage II respectively in the model proposed by Le and Kochmann (2009).

2.1. Prior to recrystallization

Before RX starts, grain size is approximately uniform and constant, equal to the initial value $d = d_0$ (Le and Kochmann, 2009). Experiments show that in this stage the biggest contribution to strain hardening is due to the continuous increase of dislocation density due to their multiplication at sources (Luton and Sellars, 1969; Kassner and Barrabes, 2005). In this situation the evolution of the dislocation density, ρ is associated with two competing processes; their multiplication in Frank-Read sources, and dynamic recovery due to dislocation–