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Mechanical behavior of low carbon steel subjected to strain path changes: Experiments and modeling

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ABSTRACT

The mechanical response of a low carbon steel under complex strain path changes is analyzed here in terms of dislocation storage and annihilation. The mechanical tests performed are cyclic shear and tensile loading followed by shear at different angles with respect to the tensile axis. The material behavior is captured by a dislocation-based hardening model, which is embedded in the Visco-Plastic Self-Consistent (VPSC) polycrystal framework taking into account the accumulation and annihilation of dislocations, as well as back-stress effects. A new and more sophisticated formulation of dislocation reversibility is proposed. The simulated flow stress responses are in good agreement with the experimental data. The effects of the dislocation-related mechanisms on the hardening response during strain path changes are discussed.

1. Introduction

The strain path changes that take place during industrial forming processes of metallic systems have been studied by several authors during the last decade [1–7]. Investigations show that the strain path change can affect the evolution of dislocation-related microstructure and thus leads to evident changes in the yield stress and flow stress evolution [7–12]. When the shear on a slip system is reversed, the internal back-stress induced during the previous loading usually facilitates the activation of glide on the reverse direction, leading to the Bauschinger effect [13–19]. As consequence, the flow stress is significantly lower than for the monotonic stress-strain curve during several percents of strain after reloading. Moreover, after the strain path is changed, the dislocation structure generated during previous loading is gradually dissolved and replaced by the structure being created in the new strain path [1].

The modeling of the hardening behavior of polycrystals subjected to monotonic strain or complex strain path changes has been recently addressed by several authors [7,10,20–24]. Among the different models proposed, the continuum approach by Rauch et al. [9], called RGVB model from now on, explicitly accounts for the dislocation accumulation/annihilation under strain reversal.

Kitayama et al. reformulated the RGBV model for a crystallographic framework [25]. This improved RGBV model tracks the dislocation density evolution on each slip system in each grain for two populations, namely, forward and reversible dislocations. During monotonic loading the evolution of dislocation density for both populations is described using the Kocks-Mecking approach. If the shear on the slip system is reversed, only the reversible dislocations are allowed to glide on the opposite direction and have the potential to recombine. A reversibility parameter P was introduced to measure the fraction of reversible dislocations generated as a function of strain. $(1-P)$ measures the fraction of non-reversible dislocations. This parameter is assumed to be equal for all slip systems in one grain and calculated as a function of accumulated

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debris density. It is set to be 1 at the beginning of deformation and decreases gradually to 0 with increasing accumulated strain. This model was embedded in the visco-plastic self-consistent (VPSC) framework, which allows the grain orientation and crystallography to be accounted for explicitly. The information about strain path changes does not need to be enforced empirically but is implicitly built in the model by keeping track of shear reversals in each slip system during the simulations. Kitayama et al. [25] applied this model to predict the response of a rolled low carbon (LC) steel sheet subjected to uniaxial tension followed by simple shear reloading along different directions, and forward-reverse simple shear tests. Note that the formulation does not account for the Bauschinger effect and that the proposed evolution of the reversibility parameter P is such that at about 50% accumulated strain P is about 0.5 and at 80% accumulated strain the generation rate of reversible dislocations becomes negligible.

More recently, Wen et al. [26] successfully extended the crystallographic RGBV model to HCP materials by including a formulation for the back-stress acting on the slip systems, and by accounting for twinning contribution to deformation. The effect of the back-stress is introduced as a correction term to the CRSS of each system depending on the density of reversible dislocations stored in such system.

In the present work, the simulations for tension-shear tests on LC steel done by Kitayama et al. [25] are repeated using the new formulation of the Bauschinger effect to evaluate the flow stress response during the initial 1–2% strain after reloading. In addition, the crystallographic RGBV model is employed for simulating cyclic loading of this LC steel up to very large strain amplitudes. A new formulation of the reversibility parameter P is proposed since the previous version reduces P monotonically with the accumulated strain and (incorrectly) predicts increasingly larger hysteresis loops in the case of cyclic loading. In the new formulation, the parameter P is calculated individually for each slip system s instead of being equal for all systems in one grain. It is also assumed to vary according to the current states of dislocation configurations.

2. Crystallographic RGBV model

The crystallographic RGBV model allows tracking down the dislocation density evolution in each slip system inside each grain throughout the plastic deformation process. The dislocations accumulated during pre-strain may be annihilated progressively during strain path changes. This dislocation evolution model was proposed by Kitayama et al. [25] who implemented it in the VPSC polycrystal framework [27,28]. The model tracks down the direction of shear in each slip system of each grain and identifies shear strain reversals induced by changes of the strain path or by grain reorientation associated with large strain plastic deformation.

The relation between dislocations and the critical resolved shear stress (CRSS) τ_d^s, given by a form of the Taylor law extended to describe the latent hardening associated with dislocation-dislocation interactions within various materials as discussed by Refs. [29–36], is used in this work instead of the simpler approach by Kitayama et al. [25] for BCC steel:

$$\tau_d^s = \tau_0^s + \mu b^s \sqrt{\alpha^{ss}\rho^s + \sum_{s \neq s'} \alpha^{ss'}\rho^{s'}} \quad (1)$$

here, ρ^s is the dislocation density on system s, τ_0^s the initial CRSS, μ the shear modulus, b^s the magnitude of the Burgers vector and $\alpha^{ss'}$ the latent hardening matrix.

In the model of Kitayama et al., the dislocation density on each slip system is comprised of forest and reversible dislocations [25]. The latter can recombine when shear on a slip system is reversed, which is in fact a mechanism of dislocation annihilation. Reversible dislocations are also responsible for a back-stress contribution $\Delta\tau_B^s$ to the CRSS on the slip system s, such that:

$$\tau^s = \tau_d^s + \Delta\tau_B^s \quad (2)$$

as discussed in Section 2.2. In order to introduce the reversible dislocations in the model, each slip system s is split into s^+ and s^-, which correspond to the activation of slip in the arbitrarily defined positive and negative direction of the Burgers vector. Note that when the system shears in one direction $(d\gamma s + (or\ -) > 0)$, the opposite system is inactive $(d\gamma s - (or\ +) = 0)$. The dislocation density on system s is decomposed as:

$$\rho^s = \rho^s_{for} + \rho^{s+}_{rev} + \rho^{s-}_{rev} \quad (3)$$

where ρ^s denotes the total dislocation density on slip system s, ρ^s_{for} is the forest or non-reversible dislocation density, ρ^{s+}_{rev} and ρ^{s-}_{rev} represent the reversible dislocation density on s^+ and s^-, respectively. The total dislocation density in one grain is given by:

$$\rho = \sum_s \rho^s = \sum_s \left(\rho^s_{for} + \rho^{s+}_{rev} + \rho^{s-}_{rev}\right) \quad (4)$$

The crystallographic RGBV model relies on the Kocks-Mecking concept [37] of a storage term and a recovery term for the evolution of each component, with the added assumption that a fraction P^s of the stored dislocations can be reversed. When the slip system contributes 'positive' shear $(d\gamma^{s+} > 0;\ d\gamma^{s-} = 0)$, the increment of ρ^s_{for} and ρ^s_{rev} are given by:

$$\begin{aligned} d\rho^s_{for} &= (1 - P^s)\frac{d\gamma^{s+}}{b\Lambda} - f\rho^s_{for}d\Gamma \\ d\rho^{s+}_{rev} &= P^s\frac{d\gamma^{s+}}{b\Lambda} - f\rho^{s+}_{rev}d\Gamma \\ d\rho^{s-}_{rev} &= -\frac{1}{b\Lambda}\left(\frac{\rho^{s-}_{rev}}{\rho^s_0}\right)^m d\gamma^{s+} \end{aligned} \quad (5)$$

here Λ is a dislocation mean free path defined by:

$$\frac{1}{\Lambda} = \frac{\sqrt{\rho}}{K} + \frac{1}{D} \quad (6)$$

where ρ is the total dislocation density in one grain given by Eq. (4). K is the number of forest dislocations that a moving segment is able to cross before being immobilized by the obstacles and D is the average grain size. In Eq. (5) $d\Gamma$ is used in the thermal recovery term instead of $d\gamma^{s+}$ because the concurrent slip on any of the slip systems can facilitate thermally activated recombination on a particular slip system [9]. In the case of monotonic loading, the sum of the first two terms in Eq. (5) over all systems gives the classic Kocks-Mecking evolution law for the total dislocation density [25,37]. The reversibility fraction P^s is a function of accumulated dislocation density and, different from Kitayama et al. [25] and Wen et al. [26], it is assumed here to depend on the specific activity of each system. In the initial deformation stages all dislocations generated are assumed to be reversible ($P^s = 1$) and, as dislocations accumulate, the reversibility decreases towards $P^s = 0$. The evolution of the reversibility fraction with dislocation density is discussed in Section 2.3.

The last term in Eq. (5) describes the recombination of reversible dislocations ρ^{s-}_{rev} created on system s during the previous deformation history, in a manner inspired by the 'areal glide' with 'percolation/debris-accumulation' model of Kocks [13]. ρ^s_0 is the