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The role of dense dislocation walls on the deformation response of aluminum alloyed hadfield steel polycrystals

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Abstract

The deformation response and texture evolution of aluminum alloyed Hadfield steel polycrystals is explored in the presence of high-density dislocation walls. A recently developed visco-plastic self-consistent model accounting for the contribution of the dense dislocation walls to strain hardening was utilized in predicting the room temperature deformation response under tension and the accompanying texture evolution. The model successfully predicted the experimental results, demonstrating the utility of the model for polycrystals. Monitoring the texture evolution provided an independent check and validation of the model.

Keywords: Hadfield steel; Strain hardening; Crystal plasticity; Texture evolution; Microstructure; Dislocation walls; Polycrystal

1. Introduction

In a recent study, we have established a model that successfully predicts the tensile deformation response of aluminum alloyed Hadfield steel (HSwAl) single crystals [1]. The appeal of the model lies in the simplicity of the constitutive formulation utilized to predict the deformation response of the HSwAl single crystals in the presence of high-density dislocation walls (HDDWs). The key finding in single crystals is that the density of HDDWS evolves with deformation leading to a very high strain hardening rate in these materials. Depending on the crystallographic orientation the number of HDDWs varies with the effect highest in multiple slip orientations.

Prior to our work on Hadfield steel single crystals, the HDDWs had been observed in pure face-centered cubic (fcc) metals and body-centered cubic (bcc) alloys [2–10]. These works demonstrated the interaction of active slip systems with HDDWs resulting in an increased hardening. Our recent study [1] confirmed these previous observations and provided a simple model to capture the stress–strain response and evolution of HDDW volume fraction. An extension of the results to polycrystals has not been undertaken previously and will be considered in this work.

In the present work, the purpose is to extend the model [1], originally developed for single crystals of HSwAl, to the polycrystalline case utilizing the single crystal parameters and constants. To accomplish this, the deformation response of the polycrystalline samples of HSwAl and the texture evolution was measured experimentally. The deformation response and the texture change were predicted utilizing the recently developed model. The model uses a crystal plasticity framework with dislocation evolution and increased hardening associated with the presence of HDDWs. The model captured the room temperature tensile deformation response of the HSwAl polycrystals as well as the accompanying texture evolution. The results provide ground for extending the use of the model to other metallic alloys displaying HDDWs.

2. Experimental observations and mechanisms

In our previous work [1], we investigated the formation and evolution of HDDWs through a detailed transmission electron microscopy (TEM) study. Single crystals of several orientations were examined under TEM at various stages of deformation in order to shed light onto the role of HDDWs on the rapid strain hardening exhibited by HSwAl. The HDDWs are present at all stages of deformation, from small (Fig. 1(a)) to higher strain levels (Fig. 1(b)). The HDDWs reside predominantly on the $\{1\,1\,1\}$ planes in the fcc materials. As the deformation progresses, the

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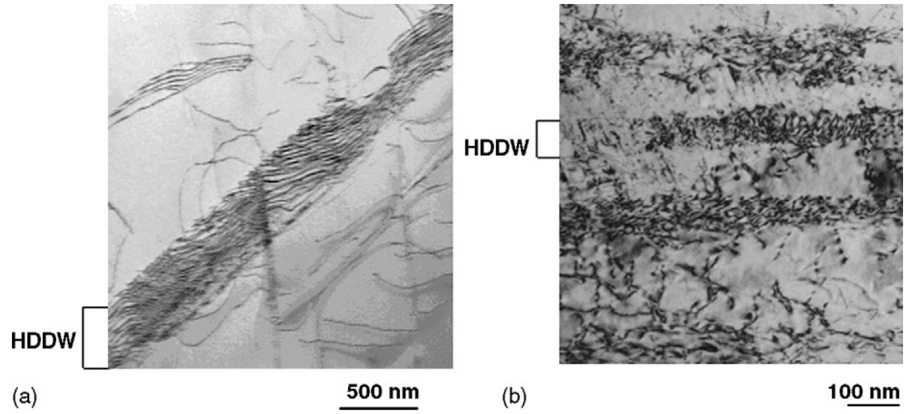

Fig. 1. TEM images showing the HDDWs and localized dislocation activities in single crystals under monotonic tensile loading. (a) HSwAl ⟨1 1 1⟩ orientation at 3% strain: early stages of HDDW formation. (b) HSwAl ⟨1 2 3⟩ orientation at 40% strain: the local density of dislocations trapped in the HDDWs becomes higher at larger strains.

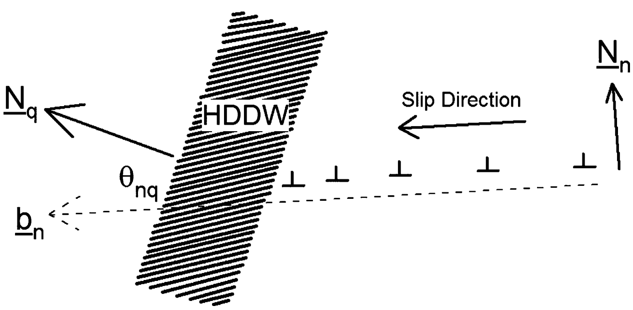

Fig. 2. A schematic showing the interaction between a HDDW that formed parallel to the plane of the active slip system (q) and another active slip system (n) within a single crystal (or grain).

volume fraction of HDDWs increases through the mutual trapping of glide dislocations due to the interaction of HDDWs with the active slip systems (Fig. 2). The dislocation density of the HDDWs is very high at the final stages of deformation, right before fracture.

The interaction of HDDWs with the active slip systems is illustrated in the schematic shown in Fig. 2 [1]. The interaction takes place simply because the HDDWs block the glide of dislocations on an active slip system. As plastic deformation progresses, a set of HDDWs that reside on the active slip system q (with the plane normal $\underset{\sim}{N}_q$) forms, and the HDDWs evolve with increasing strain. An HDDW may intersect the path of dislocations moving on the plane of another active slip system n (with the plane normal $\underset{\sim}{N}_n$) in the direction as specified by the burgers vector $\underset{\sim}{b}_n$. This results in the trapping of the dislocations on the slip system n in the HDDWs. The angle θ_{nq} between the vectors $\underset{\sim}{b}_n$ and $\underset{\sim}{N}_q$ constitutes a measure of this blockage of glide dislocations by HDDWs. When the HDDWs and the slip system n are coplanar the interference is minimized as manifested through the angle θ_{nq}.

3. Modeling

The present model utilizes a crystal plasticity description of the strain rate at the single crystal level, and the reference stress evolves with the dislocation density. In the current model, the HDDW-slip system interaction is incorporated into the overall rate of dislocation density ($\dot{\rho}$) in the following format:

$$\dot{\rho} = \sum_{n} \{k_1\sqrt{\rho} - k_2\rho\} \left|\dot{\gamma}^n\right| + \sum_{n}\sum_{q} \frac{K}{db} \cos \theta_{nq} \left|\dot{\gamma}^n\right| \qquad (1)$$

where k_1 and k_2 are constants, K is a geometric constant [1,11,12], α is the dislocation interaction parameter [13,14], and b represents the burgers vector. The first term $\sum_n \{k_1\sqrt{\rho} - k_2\rho\} |\dot{\gamma}^n|$ represents the a thermal (statistical) storage of moving dislocations ($k_1\sqrt{\rho}$) and dynamic recovery ($-k_2\rho$) in the domains outside the HDDWs [12], whereas the second term $\sum_n\sum_q \frac{K}{db} \cos \theta_{nq} |\dot{\gamma}^n|$ accounts for the contribution due to HDDWs formed parallel to the plane of the slip system q acting as effective obstacles to the moving of dislocations gliding on the active slip system n (Fig. 2). In other words, the second term represents an empirical geometric storage of dislocations due to HDDWs, which subdivide the grains and thereby decrease the mean free path of dislocations [12]. The angle θ_{nq} is the angle between the direction of slip in the active slip system n and the normal to the plane of the slip system q, and is incorporated as a measure of the interaction between HDDWs and glide dislocations in a geometric sense. The angle θ_{nq} is a variable, such that it can take different values depending on the active slip systems and the HDDWs they interact with. Moreover, the θ_{nq} continues to change as the deformation progresses due to the rotation of HDDWs in the matrix. The term d represents the average spacing between the dislocation sheets. The term $\dot{\gamma}^n$ stands for the rate of shear in the active slip system n.

By only accounting for the change in the overall rate of dislocation density (Eq. (1)), the model falls short of accounting for the rapid strain hardening of the HSwAl. The HDDWs are treated as impenetrable barriers to dislocation motion, acting as hard phases in the matrix, similar to precipitates. Accordingly, HDDWs are modeled as (elongated) ellipsoidal inclusions in the matrix. As plastic strain progresses, Orowan loops are stored around the HDDWs, giving rise to long-range internal stresses in the matrix [12]. This additional hardening (τ^B) due to HDDWs