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Orientation evolution in Hadfield steel single crystals under combined slip and twinning

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Abstract

The tensile deformation response and texture evolution of aluminum alloyed Hadfield steel single crystals oriented in the $\langle 1\,6\,9\rangle$ direction is investigated. In this material, the strain hardening response is governed by the high-density dislocation walls (HDDWs) that interact with glide dislocations. A microstructure-based visco-plastic self-consistent model was modified to account for mechanical twinning in addition to the prevailing contribution of the HDDWs. Simulations revealed the contribution of twinning to the overall work hardening at the later stages of deformation. Moreover, both the deformation response and the rotation of the loading axis associated with plastic flow are successfully predicted even at the high-strain levels attained (0.53). Predicting the texture evolution serves as a separate check for validating the model, motivating its utilization in single and polycrystals of other alloys that exhibit combined HDDWs and twinning.

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

1. Motivation and significance

In a recent study investigating the strain hardening response of aluminum alloyed Hadfield steel (HSwAl), we attributed the unusually high-strain hardening coefficients ($\approx G/23$[1]) observed in the single crystals of this alloy to the formation of high-density dislocation walls (HDDWs) (Canadinc et al., 2005). Aluminum was added to Hadfield steel at 2.58 wt%, which normally has a chemical composition of 13.93 wt% Mn, 1.30 wt% C and balance Fe. The resulting material (HSwAl) with a face-centered cubic (fcc) structure at room temperature displayed HDDWs that form and evolve as a result of plastic deformation. The interaction

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[1] G: the shear modulus.

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between the HDDWs and active slip systems was shown to lead to the blockage of the glide dislocations by HDDWs, and eventually to the high-strain hardening rates under tensile loading. In this alloy, the strain hardening behavior is governed by HDDWs in multi-slip orientations (⟨1 1 1⟩ and ⟨0 0 1⟩). However, twinning is also present as a secondary deformation mechanism in the single-slip orientation ⟨1 2 3⟩, although the volume fraction is much less than that of HDDWs (Canadinc et al., 2005). A microstructure-based model was proposed, that successfully predicts the tensile deformation response of HSwAl single crystals (Canadinc et al., 2005). The appeal of the model lies in the simplicity of the constitutive relationship that successfully captures the role of HDDWs and twinning (where prevalent) on the overall deformation response of the material.

Previously, the HDDWs had been observed by several researchers to be effective in materials of both face-centered cubic (fcc) and body-centered cubic (bcc) structures (Winther et al., 1997; Winther, 1998; Hansen and Juul Jensen, 1992; Juul Jensen and Hansen, 1990; Peeters et al., 2000, 2001; Raphanel et al., 1992; Liu and Hansen, 1995; Liu et al., 1998). These studies revealed the existence of HDDWs and their influence on the overall deformation response through detailed transmission electron microscopy (TEM) studies. The HDDWs have been shown to interact with dislocations that carry the plastic deformation on the active slip systems, resulting in an overall hardening: glide dislocations get trapped at the boundaries of the HDDWs, and thus the dislocation motion is blocked on an active slip system interacting with a HDDW. In our recent study on single crystals of HSwAl (Canadinc et al., 2005), we obtained results that very well agreed with these previous observations.

Contrary to many of the previous contributions that investigated the HDDWs in pure metals and alloys (Winther et al., 1997; Winther, 1998; Hansen and Juul Jensen, 1992; Juul Jensen and Hansen, 1990; Peeters et al., 2000, 2001; Winther, 1998; Raphanel et al., 1992; Liu and Hansen, 1995; Liu et al., 1998), we utilized single crystals (Canadinc et al., 2005) to study the HDDWs. This eliminated the complications resulting from grain boundary effects and interactions between neighboring grains. We established a model that supports our explanation of how the HDDWs contribute to the overall hardening by successfully predicting the material's response to applied loading for several crystallographic orientations: ⟨1 1 1⟩, ⟨0 0 1⟩, and ⟨1 2 3⟩. The key finding is that the volume fraction of HDDWs evolves with deformation leading to very high-strain hardening coefficients in this material.

Prior to our work on the strain hardening response of HSwAl (Canadinc et al., 2005), the unusual strain hardening response of Hadfield steel was linked to various causes, including the formation of twin boundaries that provided strong barriers to dislocation motion (Adler et al., 1986; Karaman et al., 2000a,b, 2001a,b,c). Interruption of the glide dislocation path by stacking faults (Shtremel and Kovalenko, 1987) has also been forwarded to explain the unusual strain hardening of the Hadfield steel. In addition, several researchers suggested that dynamic strain aging is the mechanism underlying the rapid strain hardening exhibited by Hadfield steel (Dastur and Leslie, 1981; Owen and Grujicic, 1999). Among these proposed mechanisms, twinning has been the most prevalent one to explain the unusual strain hardening of Hadfield steel. In order to investigate the role of slip on this unusual strain hardening in detail, we introduced aluminum to the microstructure of Hadfield steel (Canadinc et al., 2005). It has been shown that in low stacking fault energy alloys, intrinsic stacking faults serve as precursors to twinning, such that intrinsic stacking faults observed at the very early stages of deformation thicken into twin lamellae with further plastic deformation (Raghavan et al., 1969). Therefore, aluminum was added to the microstructure of Hadfield steel in order to increase the stacking fault energy and thereby suppress twinning, by preventing the formation of intrinsic stacking faults at small strains and their further growth into twin lamellae. Alloying Hadfield steel with aluminum suppressed twinning in multi-slip orientations or limited its occurrence to very low volume fractions (less than 5%) even at very high-plastic strains (more than 0.25) (Canadinc et al., 2005).

In the work presented herein, the focus is on validating the microstructure-based model by applying it to single crystals of other crystallographic orientations. Moreover, the texture evolution (rotation of the loading axis) is utilized as a separate tool for checking the validity of the model. Specifically, the experimentally measured textures were compared to the simulation results at various strains along the deformation. In addition, the role of twinning on the strain hardening response of a single-slip orientation single crystal was also investigated, in order to establish the contribution of twinning to the overall hardening in the presence of HDDWs.

The current work focuses on the texture evolution in the presence of HDDWs. The previous studies on HDDWs considered the texture evolution (Winther et al., 1997; Hansen and Juul Jensen, 1992; Juul Jensen