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Twin nucleation and migration in FeCr single crystals

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ABSTRACT

Tension and compression experiments were conducted on body-centered cubic Fe -47.8 at pct. Cr single crystals. The critical resolved shear stress (CRSS) magnitudes for slip nucleation, twin nucleation and twin migration were established. We show that the nucleation of slip occurs at a CRSS of about 88 MPa, while twinning nucleates at a CRSS of about 191 MPa with an associated load drop. Following twin nucleation, twin migration proceeds at a CRSS that is lower than the initiation stress (≈114–153 MPa). The experimental results of the nucleation stresses indicate that the Schmid law holds to a first approximation for the slip and twin nucleation cases, but to a lesser extent for twin migration particularly when considerable slip strains preceded twinning. The CRSSs were determined experimentally using digital image correlation (DIC) in conjunction with electron back scattering diffraction (EBSD). The DIC measurements enabled pinpointing the precise stress on the stress–strain curves where twins or slip were activated. The crystal orientations were obtained using EBSD and used to determine the activated twin and slip systems through trace analysis.

1. Introduction

Understanding the deformation response of iron based body-centered cubic (bcc) alloys has significant merit, as these alloys form the basis of materials that are widely utilized in structures. Depending on the alloy composition and in particular grain orientations, twinning can occur in conjunction with slip resulting in complex mechanical behavior. In bcc materials a twin typically nucleates with an abrupt load drop, in some cases even in the 'elastic' region of the stress–strain curve [1,2]. Following twin nucleation at a critical resolved shear stress (CRSS) level τ^T, twin migration proceeds at a stress level τ^M that is lower. Twin migration is also the result of twin–twin and twin–slip dislocation reactions occurring at twin boundaries. Experimental evidence of twin migration, supported by local strain measurements, can provide further insight for developments of bcc plasticity models, in particular on the hardening effect related to twin growth induced by twin/slip interactions. From the experimental point of view, measuring τ^T and τ^M requires local strain measurements and knowledge of the activated twin systems. In this study, we utilize local strain measurements from high resolution digital image correlation (DIC) to establish the twin nucleation and migration stresses. Accurate measurements of the CRSSs τ^T and τ^M allow us to provide valuable information for an initial evaluation of the Schmid law for bcc twinning, in particular for the migration stress. The Schmid law has been utilized for slip [3,4] and twinning [5] in face-centered cubic (fcc) crystals. For bcc slip, deviation from the Schmid law is well known [6–8]. Since the present study also allows measurements of the critical stress

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for slip τ^s, we provide a critical check on the Schmid law for slip as well.

The majority of the previous investigations on FeCr have been undertaken on polycrystals [9–14]. In this study we utilize single crystals to activate specific twin and slip systems. This approach has been successfully employed in our previous work on fcc metals [15]. Based on the results of our experiments, we broadly classify four general types of single crystal deformation behaviors (Fig. 1).

For Case I, twinning represents the main deformation mechanism and it initiates within the elastic region of the stress–strain curve. Twin–twin interactions govern hardening behavior for this case. In Case II the hardening behavior is governed by twin–slip interactions and twin nucleation is preceded by pronounced slip activity. Case III represents orientations with a limited number of activated slip systems (1 or 2 slip systems). Finally, Case IV represents the occurrence of multiple-slip systems (>2 slip systems) with clear evidence of hardening. Examples of each one of the four cases will be given in the Results section along with the critical stress magnitudes and the activated twin/slip systems.

The Fe–Cr alloy is chosen as it shows twinning at room temperature. In earlier works on a Fe–47.8Cr alloy, Marcinkowski conducted indentation experiments and observed the presence of twinning and slip predominantly on <111>{112} systems [14]. Since it is not easy to identify the slip and twin systems coinciding with {112} planes by simple optical observations, we utilized DIC and Electron Back Scattering Diffraction (EBSD), as the combination of these tools facilitates this distinction. Indexing the twin systems with EBSD and measuring local strain fields allow us to monitor the nucleation and evolution of both slip and twinning during deformation. Particular emphasis is placed on the analysis of the deformation mechanism at the early stages of plasticity (either corresponding to first yielding or twin migration subsequent to the load drop). DIC was utilized at higher resolutions compared to conventional studies and provides microscale resolution measurements and allows pinpointing strain localizations due to slip and twin activation.

In summary, based on the four cases illustrated in Fig. 1, we address the following main issues: (i) the advancement of DIC methods using *ex situ* and stitching techniques to obtain local strain measurements which, in conjunction with EBSD, can be used to identify and determine the activated twin and slip systems; (ii) depending on the crystal orientation, the precise determination of the critical stress for twin (τ^T) and slip nucleation (τ^S), by pinpointing local strain disturbances using DIC. Therefore, we discuss the implications of these experimentally determined stresses with respect to the Schmid law; (iii) making a distinction between twin nucleation τ^T and twin migration τ^M critical stresses; (iv) the interactions of twins,

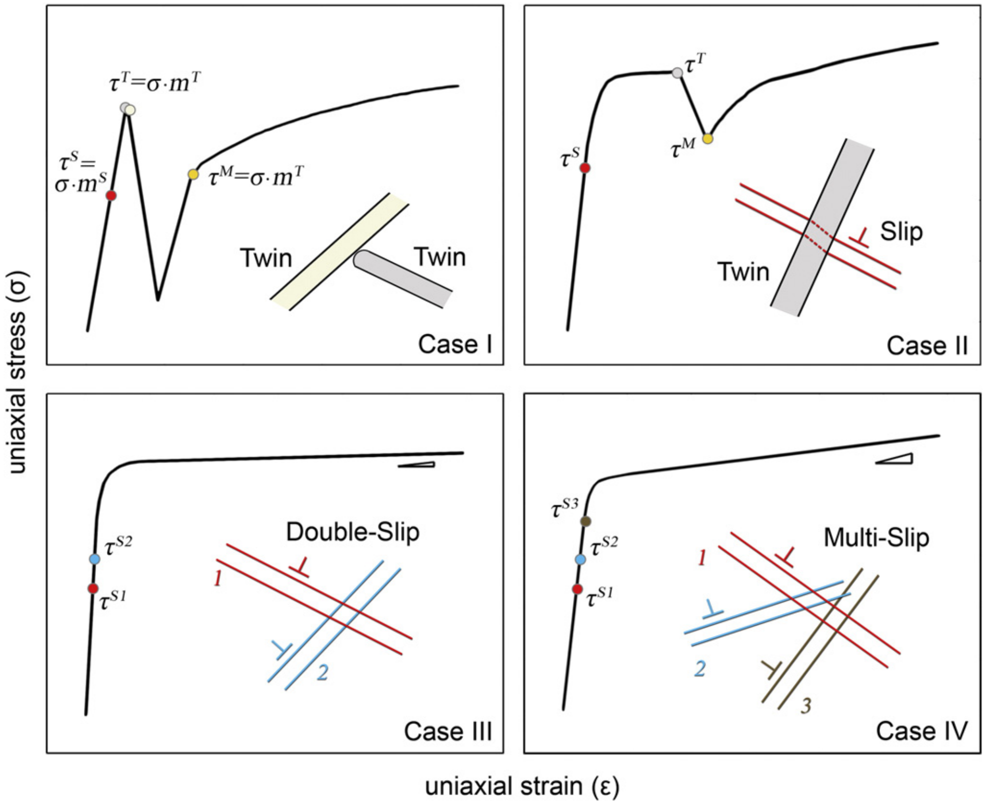

Fig. 1 – Schematic of the possible crystal deformation behaviors. The CRSSs for slip nucleation (τ^S), twin nucleation (τ^T) and twin migration (τ^M) are determined by multiplying the axial stress in the loading direction with the Schmid factors for the active slip (m^S) and/or twin (m^T) systems. Case I represents crystal hardening governed by twin–twin interactions. In Case II large slip activity precedes twin nucleation and twin–slip interactions dominate the hardening. Case III represents crystal orientations characterized by a limited number of activated slip systems. In Case IV multiple slip systems develop leading to crystal hardening.