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Profuse slip transmission across twin boundaries in magnesium

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ABSTRACT

In-situ SEM simple shear tests were performed on magnesium bicrystals of random misorientations at room temperature and 150 °C. $\{10\bar{1}2\}$ extension twins nucleated at the grain boundaries and grew with increasing strain. Rectilinear slip traces appeared in the grain interior of the bicrystal which corresponded to basal slip. By deflection at twin boundaries, these slip lines readily continued through the twins. Besides slip traces due to basal slip, additional slip lines were observed inside twins at 150 °C that evidenced the activation of non-basal slip. Supplemental tests were performed on single crystals, in which twinning/detwinning via migration of twin boundaries was observed. The obtained results are discussed with respect to direct and indirect slip transfer across $\{10\bar{1}2\}$ twin boundaries, the transmutation of $\langle a\rangle$ into $\langle c+a\rangle$ dislocations and the activation of first-order pyramidal slip as a result of slip-twin interaction.

1. Introduction

Deformation twinning in addition to dislocation slip makes plastic deformation of crystalline solids considerably more complicated. Being also a deformation mechanism, twinning in its mechanistic nature is yet very distinct from dislocation slip. While dislocation slip describes the glide of a line defect in the crystal lattice, the growth of a twin that is associated with a shear of the twinned volume can be understood as the migration of planar defects, i.e. the twin boundaries. To this end, concurrent activation of both deformation mechanisms inevitably leads to complex interactions between dislocations and twin boundaries, either when both the dislocation and the twin boundary are moving or when one is moving and the other is stationary (sessile). An analysis of the slip-twin interactions in crystalline structures is indispensable for a better understanding of the strain hardening process by twinning.

In a previous study [1] we reported on the formation of anomalous extension twins in a magnesium single crystal that was oriented for easy basal slip. Concurrent with a profuse appearance of such twins an increase of the work hardening rate was detected, suggesting that $\{10\bar{1}2\}$ twin boundaries pose significant obstacles to the propagation of dislocations. Complementary to our previous research on the crystallographic mechanisms of plasticity in Mg single crystals [1–6], the present study is concerned with achieving a basic understanding of slip-twin interaction on a macroscopic level by investigating the deformation produced by dislocations gliding through a twin. The unique approach utilized in this work is the use of bicrystalline specimens in order to nucleate deformation twins at the grain boundary while still presenting a simple enough model case to permit a forthright analysis. We combined a variety of state-of-the-art experimental methods and theoretical calculations to study slip transmission across $\{10\bar{1}2\}$ deformation twins. The investigation was focused on microstructural features, such as dislocations, twins and twin boundaries, and their interactions during in-situ deformation tests at ambient and elevated temperatures. The resulting knowledge helps to advance the current understanding of slip-twin interaction in polycrystalline aggregates from a macroscopic, statistical perspective that can be incorporated into mechanism-based constitutive laws to provide a predictive capability of the complex mechanical behavior of crystalline solids.

2. Background

Prior to presenting and discussing the results of the present study, it is useful to review earlier related work on dislocation slip transmission in deformation twins in hcp materials. The following narration reports major research thrusts in the literature over a period of 70 years and attempts to reveal major missing links for comprehending metal plasticity upon profuse twinning.

Two scenarios can be put forward in order to incorporate an

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exterior dislocation into a twin. Either the dislocation glides into the twin across the twin boundary or a stationary dislocation is encompassed by the growing twin; i.e. it is sheared by the moving twin boundary. However, from a geometrical point of view, the resulting dislocation in the twin is independent of the way in which it was incorporated [7,8].

One of the earliest studies in which a connection between slip in the matrix and in the twin was established in magnesium had been performed by Bakarian and Mathewson [9]. They carried out tension tests on single crystalline magnesium at elevated temperatures and observed the forcing of basal slip traces in $\{10\bar{1}2\}$ twins due to basal slip in the matrix. The authors acknowledged that such a match of the slip bands in both matrix and twin did not happen by chance and concluded that in all likelihood a stress interchange was responsible for their observation.

The nucleation and growth of twins in zinc crystals were studied by Price [10] utilizing transmission electron microscopy (TEM). It was reported that basal dislocations with a Burgers vector $[a]$ parallel to a $\{10\bar{1}2\}$ twinning plane entered the twin from the matrix. Such dislocations will be henceforth denoted by $[a_{0^\circ}]$. However, basal $[a]$ dislocations with a Burgers vector oblique to the twinning plane (denoted by $[a_{60^\circ}]$ and $[a_{120^\circ}]$ in this work) never crossed the twin boundary but were pushed ahead of it. Under the premise that basal dislocations with a Burgers vector oblique to the twin boundary plane could not be incorporated into the twin, Cooper and Washburn [11] hypothesized that the critical stress for twin boundary migration might be the stress necessary to push such $[a_{60^\circ,120^\circ}]$ dislocations in the matrix as they observed that the critical stress for twin boundary migration was sensitive to the density of $[a]$ dislocations.

With respect to twinning in zirconium, Westlake [12] proposed that the interaction of two different oblique basal $[a_{60^\circ}]$ and $[a_{120^\circ}]$ dislocations (the sum of which is a $[10\bar{1}0]$ dislocation) with a $(10\bar{1}2)$ twin boundary may result in the formation of a $[c]$ dislocation in the twin, in addition to a twinning dislocation [13]. Such a twinning dislocation can glide along the interface under a suitable mechanical stress and is responsible for the migration of the twin boundary.

The incorporation of slip dislocations at $\{10\bar{1}2\}$ twin boundaries in zinc was studied by Yoo and Wei [14] from a purely geometrical point of view based on a formalism provided by Sleeswyk and Verbraak [7] for the incorporation of dislocations in mechanical twins in the bcc lattice. Yoo and Wei considered that the Burgers vector of a dislocation that is incorporated into a twin must undergo the homogeneous twinning shear. The authors established that (i) a basal pure screw dislocation (with a Burgers vector parallel to the twinning plane) can cross slip from the basal plane in the matrix onto the basal plane in the twin. However, (ii) basal dislocations with a Burgers vector oblique to the twin boundary plane (mixed dislocations) would be transformed into $\langle c+a\rangle$ type dislocations residing on a prismatic plane upon incorporation into the twin. In the following, these two cases will be referred to as direct (Burgers vector $[a_{0^\circ}]$ parallel to the twin boundary) and indirect slip transmission, where the Burgers vector $[a_{60^\circ}]$ or $[a_{120^\circ}]$ is oblique to the twin boundary. Both the direct and indirect transmission across a $\{10\bar{1}2\}$ twin boundary can be expressed in a generalized form by Eqs. (1) and (2), respectively. Subscripts m and t denote the reference frame of the matrix and twin.

$$[a_{0^\circ}]_m \rightarrow [a_{0^\circ}]_t \tag{1}$$

$$[a_{60^\circ,120^\circ}]_m \rightarrow \frac{1}{2}\langle c+a\rangle_t \pm \boldsymbol{b}_t \tag{2}$$

In the latter case, a unit twinning dislocation $\boldsymbol{b}_t$ is left behind at the twin boundary. As shown by Wang and Agnew [15] the reaction proposed by Westlake [12] is in fact a variant of these basic reactions. It is noteworthy that the $[a]$ component of the $\langle c+a\rangle$ dislocation in reaction (2) must be parallel to $[a_{0^\circ}]_t$.

Yoo and Wei [14] also witnessed basal slip traces across the twin boundaries as well as twin growth and concluded from their study that indirect slip transfer had taken place, since the twin interface would have been stationary otherwise. They also identified slip traces in a twin that protruded past the twin boundary into the matrix. This particular observation was explained in terms of cross slip that did not necessarily occur at the twin interface. In other words, dislocations could proceed on the prismatic plane past the twin boundary and cross slip onto the basal plane some distance away from the twin boundary itself.

A comprehensive TEM analysis on the interaction between basal slip and $\{10\bar{1}2\}$ twins in zinc was performed by Tomsett and Bevis [16,17]. In a first study [16] both the direct and indirect slip transfer were found to operate, depending on the relative orientation of the slip dislocation and twin boundary. The authors also determined $\left\{1\bar{1}00\right\}\langle11\bar{2}3\rangle$ slip to operate inside the twin as a consequence of indirect slip transfer, where two either $[a_{60^\circ}]$ or $[a_{120^\circ}]$ dislocations were necessary to form a single $\langle11\bar{2}3\rangle$ dislocation in the twin, while leaving behind a zonal twinning dislocation [18,19] with a Burgers vector $2\boldsymbol{b}_t$ in the boundary. Moreover, in a second study [17] it was shown that stacking faults in the basal plane (I_2) in the twin can arise as well by transformation of a basal $[a]$ dislocation in the matrix into a sessile $[c]$ and two glissile Shockley partial dislocations in the twin, all of which can be thought of as decomposition products of a $\langle11\bar{2}3\rangle$ dislocation. In a non-dissociated form reaction (2) then becomes:

$$2\times[a_{60^\circ,120^\circ}]_m \rightarrow \langle c+a\rangle_t \pm 2\boldsymbol{b}_t \rightarrow [a_{0^\circ}]_t + [c]_t \pm 2\boldsymbol{b}_t \tag{3}$$

Yoo [20] extended the geometrical analysis and derived 26 possible reactions of perfect dislocations with four different twin types in hcp metals while also taking into account the elastic interaction. With respect to magnesium, it was reported that the interaction between basal mixed dislocations, i.e. $[a_{60^\circ}]$ and $[a_{120^\circ}]$, and $\{10\bar{1}2\}$ twin boundaries ought to be repulsive, rendering the incorporation of such dislocations energetically unfeasible [20].

The possible dislocation reactions with $\{10\bar{1}2\}$ twins as derived by Yoo [20] were also discussed by Vallance and Bevis [21] considering the effect of the resolved shear stress on the slip systems in matrix and twin. While for magnesium the direct slip transfer has been established to be cross slip from the basal plane in the matrix onto either the basal or prismatic plane in the twin, the same reaction in zirconium would involve cross slip from the prismatic plane in the matrix onto the prismatic plane in the twin.

The incorporation of slip dislocations in $\{10\bar{1}2\}$ twins in zirconium was studied by Dickson and Robin [22]. They made frequent observations of $(10\bar{1}0)$ slip traces in the matrix to correspond to $(10\bar{1}0)$ slip traces in the $(1\bar{1}02)$ twin, which complies with direct transmission. On occasion, prismatic slip traces in the matrix were also found to correspond to basal ones at the twin boundary with subsequent cross slip from the basal onto the prismatic planes of the twin near the boundary. It is pointed out that this observation was very similar to that made by Yoo and Wei [14] with the role of the basal and prismatic planes reversed, i.e. cross slip in direct transmission seems not to occur necessarily at the twin boundary itself. The authors also observed correspondence between $(10\bar{1}0)$ and $(1\bar{1}00)$ slip traces on either side of a $(1\bar{1}02)$ twin interface, which was explained by indirect slip transmission that required