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Twin intersection mechanisms in nanocrystalline fcc metals

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ABSTRACT

Deformation twins have been reported to produce high strength and ductility. Intersections of deformation twins may affect the microstructural evolution during plastic deformation and consequently influence mechanical properties. However, the mechanisms governing twin-intersection behavior remain poorly understood. In this study, we investigated twin intersection mechanisms by observing twin transmission across the boundary of another twin using high-resolution transmission electron microscopy. Based on the experimental observations, mechanisms were proposed for twin–twin intersections and associated dislocation reactions in nanocrystalline fcc materials.

1. Introduction

When one twin meets another twin, what mechanism governs their intersection? This problem is interesting because deformation twinning in nanocrystalline (NC) materials is of both fundamental and technological significance. Experimental observations [1–4] and molecular dynamics (MD) simulations [5,6] reveal that deformation twins will interact with gliding dislocations, which simultaneously increases the strength and ductility of NC materials [2,7]. In NC face-centered cubic (fcc) metals, deformation twinning has been observed under various deformation conditions, including low temperature [8], high strain rate [9], high-pressure torsion [10–12], uniaxial tensile testing [13] and cryogenic ball milling [14]. Moreover, it has been reported that for NC fcc metals, twinning becomes a major deformation mechanism within a range of grain sizes [15–19].

When multiple twinning systems are activated in fcc metals, interactions between various twinning systems become inevitable. This not only affects the microstructural evolution but also is expected to affect the mechanical behavior of the material during deformation. Twin intersections have been observed in fcc stainless steel [20] and Hadfield steel single crystals [21]. These experimental observations raise a critical question: what is the dislocation mechanism associated with the observed twin intersections?

To answer the above question, we studied intersections of twins in NC Cu film and Cu–30 wt% Zn–0.8 wt% Al alloy (Brass 260, Cartridge Brass) samples using high-resolution transmission electron microscopy (HRTEM). These two material systems were selected because NC Cu has been reported to easily form deformation twins [22–24], and the Brass 260 alloy has lower stacking fault energy than Cu and also easily forms deformation twins and twin intersections [25]. To study the intersection mechanism of twins, we have obtained clear HREM images at locations where one twin transmits across the coherent boundary of another twin. This requires a low dislocation density around the observed region to reduce lattice distortions. Detailed sample preparation procedures to meet this requirement are described in the next section.

2. Experimental procedure

Both an NC Cu film and NC Brass 260 alloy samples were used in this study. The NC Cu film was deposited on a coarse-grained Cu substrate using pulsed laser deposition (PLD). The coarse-grained Cu substrate was used so that it deformed evenly with the NC Cu film under uniaxial tension to a designated strain. The PLD processing parameters can be found in a previous paper [26]. The NC Cu film was strained under tension together with the substrate at a strain rate of $2.5 \times 10^{-4}\ s^{-1}$ to a plastic strain of 1.5%. Such a small tensile strain was chosen to reduce the density of accumulated dislocations at twin boundaries so that clear HREM images can be obtained from the area of twin intersections.

The NC Brass 260 alloy was processed by cryo-milling and spark plasma sintering (SPS). The SPS serves two purposes: to consolidate the alloy powder for easier HRTEM sample preparation and to reduce dislocation density for higher quality HRTEM images. Dislocations formed during cryo-milling are mostly annihilated during

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the high-temperature SPS process so that the deformation twin boundaries become more coherent and straight [25]. The detailed processing parameters can be found in a previous publication [25].

Special care was taken during the sample preparation so that no extra dislocations were introduced into the final TEM sample. TEM specimens were prepared by mechanical grinding and dimpling, followed by ion milling. Low-energy ion beam was used for ion milling to minimize the irradiation damage by the ion beam and to remove the deformed surface layer on the TEM sample. HRTEM investigations were performed on JEOL analytical electron microscopes operating at 200 kV, with point to point resolution of 0.18 nm. Details on HRTEM sample preparation can be found in our previous publications [25,26].

3. Results and discussion

3.1. TEM and HRTEM observation of twin transmission across twin boundary

Fig. 1(a) is a typical HRTEM image showing a twin transmitting across the boundary of another twin in the NC Cu film that was fabricated by PLD and subsequently deformed to plastic strain of 1.5% by uniaxial tension. Fig. 1(b) is an HRTEM image enlarged from the twin transmission area in Fig. 1(a) and is marked for the convenience of description. The ITB and TTB stand for the incident twin boundary and transmittal twin boundary, respectively. BTB and MTB represent the barrier twin boundary and the migrated twin boundary of the barrier twin, respectively. ω is the angle between the TTB and MTB, and θ is the angle between the BTB and MTB. The d_{IT} and d_{TT} are the twin thicknesses of incident twin (IT) and transmittal twin (TT), respectively. Suppose the upper section of BTB is the original BTB before twin transmission and IT is the twin to whose side that BTB migrates. As shown in Fig. 1(b), the IT penetrates the BTB from the right side of BTB and after reactions with the BTB, it transforms into a TT on the left-hand side of the BTB. The twinning planes for IT and TT are different {111} planes so that the ITB forms an angle of $\sim 141^{\circ}$ with the TTB. The BTB, ITB and TTB are coherent twin boundaries on {111} slip planes, while MTB deviate from the original BTB. As shown in Fig. 1(b), the reaction between IT and BTB caused the migration of the BTB towards the IT side to form MTB when IT transmitted across the BTB. The MTB in Fig. 1(b) is a straight line lying between the IT and TT, and is also the bisector of the angle between BTB and TTB, which in this case means $\omega = \theta = 35.25^{\circ}$. d_{IT} and d_{TT} were measured from the HRTEM micrograph as 6.3 ± 0.5 nm and 3.6 ± 0.5 nm, respectively, which leads to a ratio of $d_{IT}/d_{TT} \cong 1.7$.

Fig. 1(c) is a typical TEM image showing twin transmission in Brass 260 alloy processed by cryo-milling and spark plasma sintering. An incident twin (IT) first penetrates the BTB from the top left corner of the image and after reacting with the BTB, transforms into a TT along another {111} plane. The TT then meets and reacts with another BTB, but does not transmit across the second BTB. Fig. 1(d) is an HRTEM image enlarged from the MTB area in Fig. 1(c). Unlike the situation shown in Fig. 1(b), the MTB here can be divided into two sections. In the upper section (marked as MTB1), no migration of BTB occurred and therefore MTB1 coincide with the BTB. Both d_{TT1} and d_{IT1} were measured from the HRTEM micrograph to be 3.8 ± 0.3 nm, which indicates that the thickness of the IT is maintained as it transmitted across the BTB to form TT. In the second section, the MTB2 deviates from the BTB by an angle of $\theta \approx 43^{\circ}$. We measured d_{IT2} and d_{TT2} from

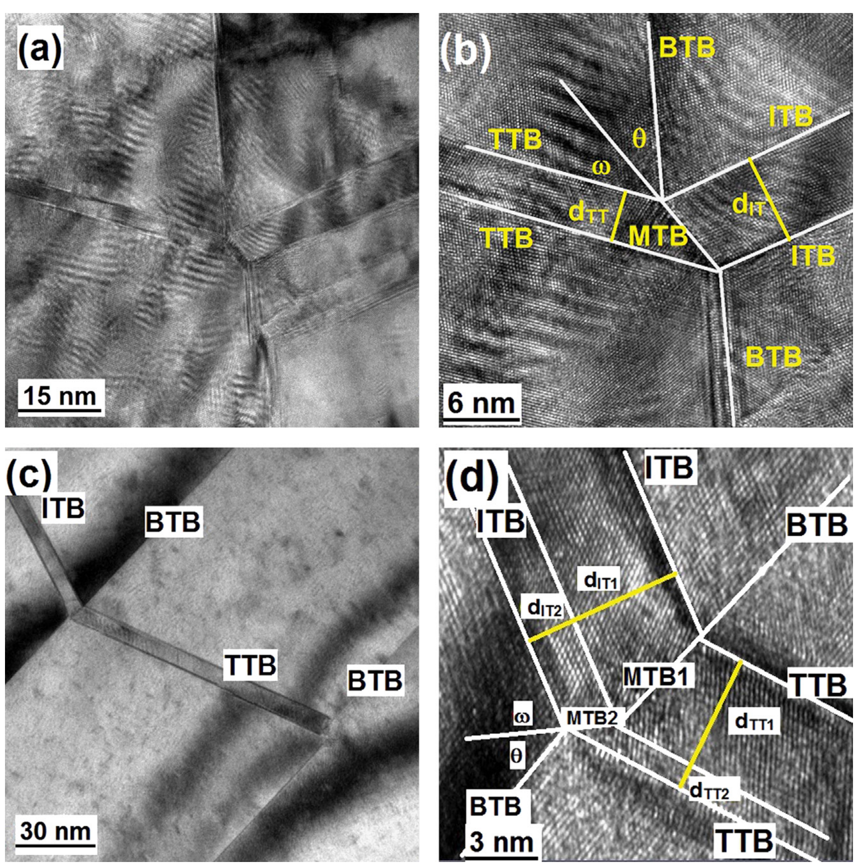

Fig. 1. (a) A typical HRTEM image showing twin transmission phenomenon in NC Cu films processed by PLD and the subsequent uniaxial elongation; (b) the HRTEM image showing the transmission area shown in (a) with marks added; (c) a typical TEM image showing twin transmission phenomenon in NC Brass 260 alloy processed by cryo-milling and the following SPS; (d) the HRTEM image showing the twin transmission area in (c) with marks added.