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Extended dislocation boundaries in metals subjected to plane strain deformation

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Abstract

Formation of extended dislocation boundaries is a characteristic feature in metals deformed monotonically. The extended boundaries have preferred orientations both in the crystallographic coordinate system defined by the crystallographic lattice and in the sample system defined by the deformation sample axes. There is an argument in the literature about whether the preferred boundary orientations are dependent on the slip system determined by the grain orientation and deformation mode. In the present paper, this argument is investigated by detailed TEM examination of boundary orientations in grains of selected orientations that constitute a critical test for the argument. The results obtained confirm that the grain orientation plays a key role in determining the boundary plane orientation.

Keywords: Extended dislocation boundaries; Crystallographic orientation; Macroscopic orientation; Grain orientation; Slip system

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1. Introduction

It is well known that dislocations generated during plastic deformation of a variety of metals tend to accumulate into different types of dislocation boundaries. These boundaries are observed as extended boundaries and short cell boundaries in a three-dimensional arrangement [1,2]. The distinctly different appearance of cell boundaries and extended boundaries has been related to different processes of dislocation accumulation during plastic deformation. Statistical trapping of dislocations has been suggested as an origin for cell boundaries. Cell boundaries are thus included in a type of boundary called incidental dislocation boundaries (IDBs) [3]. For the extended boundaries, it has been suggested that they form by different slip activity on each side of the boundary. The different slip activity may have its origins in the operation in neighbouring regions of different sets of slip systems, or a different partition of the total shear among a common set of slip systems. Extended boundaries are thus called geometrically necessary boundaries (GNBs) [3].

A detailed characterization of GNBs can give information whether deformation mechanisms (i.e. slip) are primarily controlled by the grain orientation or by the grain interaction. Also, the characterization gives indirect information about operating mechanisms during plastic deformation. The characterization of GNBs is therefore considered to be an integral part of polycrystal plasticity modeling including microstructural information. GNBs are characterized by several structural parameters, for example, spacing between and misorientation across the boundaries, and boundary plane orientations. Analysis of these parameters has extensively been made [4–6] mainly by transmission electron microscopy. It has been found that the boundary spacing and misorientation depend on the grain orientation in metals deformed in tension [5,6] and by rolling [4,7].

A grain orientation dependence of GNB plane orientations has also been shown in aluminum strained in tension [8,9]. However, in the case of plane strain deformation by rolling or channel die compression, there is still an argument about the grain orientation effect on the alignment of GNBs as it has been suggested [10] that this effect is less significant than an effect of grain interaction in the polycrystalline samples. In the following section, a brief review of the argument is made. In Sections 3 and 4, results obtained from two selected orientations that form a critical test are presented. An analysis of the correlation between the GNB orientation and the slip system is given in the last section (Section 5).

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2. Crystallographic versus macroscopic orientation

Extensive TEM studies have revealed that extended GNBs formed at small-to-medium strain exhibit preferred boundary plane orientations in either of the following two coordinate systems, namely (i) the crystallographic coordinate system defined by the crystallographic lattice and (ii) the sample coordinate system defined by the deformation axes. In the former system, the GNBs are found to align with slip planes or other crystallographic planes depending on the crystal/grain orientation [7,11–13]. For example, in grains/crystals with texture components of the Goss, brass and rotated cube orientations, two sets of GNBs align with active slip planes, while in grains/crystals of copper and *S* orientations, one set of GNBs aligns with the slip plane and the other does not. In cube-oriented grains/crystals, the GNBs deviate significantly from the slip planes. In the sample coordinate system, the GNBs are reported [1,4,10,14–16] to cluster around planes close to the macroscopically most stressed planes resulting from the macroscopic deformation mode, which is at ±45° to the rolling plane in the case of plane strain deformation by rolling (see Fig. 1). However, it is often the case that the GNBs macroscopic orientation exhibits a large spread in the distribution and that the average macroscopic angles of GNBs deviate from ±45° [10,15,16]. A detailed analysis of preferred GNB planes in the two systems has been made by Winther who found that both the crystallographic and macroscopic preferences relate to the slip system determined by the grain orientation and deformation mode [17]. The crystallographic orientation is related to the characteristics of the slip distribution in the active slip systems, although a complete correlation between the boundary plane and the slip system has not been established. The macroscopic orientation is caused by the general directionality of the activated slip systems. This is because the active slip systems are always those close to the planes of maximum shear stress.

In a recent paper by Hurley et al., alignment of GNBs in an Al–0.13% Mg alloy cold-rolled to a reduction of 20% was studied using electron back-scattered diffraction (EBSD) and scanning electron microscopy [10]. It was concluded that boundaries in grains of all orientations investigated have the same macroscopic alignment and therefore do not exhibit any dependence on the grain orientation. It was also concluded that a lack of dependence on grain orientation indicated that grain interaction effect dominated over grain orientation effect. The finding that boundaries in the Goss orientation were aligned with slip planes was considered incidental since the slip planes in this orientation almost coincide with the most stressed sample planes. These EBSD results show disagreement with the earlier TEM findings [4,7,12,13], raising a debate on the grain orientation effect on the GNB plane orientation.

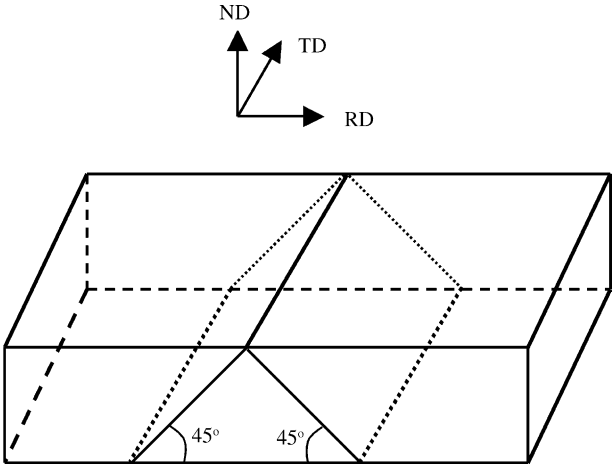

Fig. 1. Sketch showing the most stressed planes in rolling.

This debate was addressed in our recent publication [18]. The principles of TEM- and EBSD-based techniques for boundary plane determination were critically compared, and in particular, the importance of sample section selection for the boundary determination was emphasized. It was also pointed out that the subdivision of orientation space into appropriate subspace and the maintenance of orientation information of individual grains assigned to an orientation subspace during the course of data analysis are crucial for analysing the grain orientation dependence. To settle the discussion key experiments were however refereed and it was suggested [18] to select orientations in which the GNB plane orientations are well defined in the crystallographic system and they substantially deviate from the macroscopically most stressed planes. The brass orientation $\{0\,1\,1\}\langle 2\,1\,1\rangle$ in rolled fcc metals and the γ texture component $\{1\,1\,1\}\langle 2\,1\,1\rangle$ in rolled bcc interstitial free (IF) steels constitute two such critical tests. The identification of GNB planes has been carried out previously [18] for the brass orientation in 25% cold-rolled aluminium and in the present work for the $\{1\,1\,1\}\langle 2\,1\,1\rangle$ orientation in a 30% warm-rolled IF steel. In what follows, the results of the brass orientation in the cold-rolled aluminium [18] are summarized, and new results obtained for an orientation of $(1\,1\,\bar{1})$ $[\bar{2}\,1\,\bar{1}]$ in the warm-rolled bcc IF steel are presented, to demonstrate that grain orientation dependence of GNB planes is a general phenomenon.

3. The brass orientation—critical test 1

In the brass orientation, the two slip planes with which GNBs have been observed to align deviate substantially from the macroscopic planes as illustrated in Fig. 2a. In the RDND section, the trace directions are ±30° to the RD, which deviate by 15° from the maximum shear directions (±45° to the RD, see Fig. 1). In the RDTD section, the traces of the two slip planes coincide and deviate by 35° from the transverse direction.

AA1050 aluminum was cold-rolled to 25% thickness reduction. TEM examination was performed in both the RDND and RDTD sample sections. Fig. 2b and c show examples of TEM images of two brass-oriented grains observed in the two sections. In Fig. 2b, two sets of extended GNBs are seen. They align with the $(\bar{1}\,\bar{1}\,1)$ and $(\bar{1}\,1\,\bar{1})$ planes in the crystallographic coordinate system. This alignment was identified by trace analysis and sequential sample tilting in the TEM [18,19]. In Fig. 2c, a more complicated morphology of GNBs than the one seen in the RDND section is seen, which is caused by the lower visibility in this section caused by their small inclination angle to