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The initial stages of formation of low angle boundaries within lamellar bands during accumulative roll bonding of aluminum

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The nature of newly forming lamellar band boundaries was investigated in accumulative roll bonded aluminum. These boundaries initiate as low angle interfaces parallel to the existing lamellar band boundaries irrespective of the crystallographic orientation of the parent lamellar band. The transverse directions of the divided segments were found to rotate at an angle equal to the degree of misorientation between segments. Such a phenomenon is not sustained when the boundaries become high angle.

Keywords: Rolling; Electron backscattering diffraction; Misorientation; Microstructure; Texture

Grain refinement during severe plastic deformation of a metal occurs by continuous fragmentation of the microstructure [1,2]. Any fragmentation process results in the formation of low angle boundaries (LABs), which may eventually turn into high angle boundaries (HAB) through deformation-induced crystallographic rotations [3]. The creation of a large fraction of HABs can considerably refine the microstructure, whereby the mean spacing between the boundaries is reduced to a few hundred nanometers. Such grain refinement can be readily achieved by rolling in an innovative way, whereby two sheets are initially roll bonded followed by cutting, stacking and further rolling. This process can be carried out in successive iterations to generate very large plastic strains without reducing the initial sheet thicknesses. Such a severe plastic deformation method, termed accumulative roll bonding (ARB), was first proposed by Saito et al. [4,5]. It is known that ARB generates complex microstructures, including refined structural features in the form of classical lamellar bands (LB), after 3–4 rolling cycles [3–7]. ARB has also been exploited successfully to fabricate a multilayered composite material consisting of alternating layers of Al and Al(Sc) [8,9]. Similar to other ARB fabricated sheets, the nature of LAB formation in this multilayered composite needs to be understood because these boundaries are argued to be the precursor to the formation of HABs; the latter can eventually occupy a significant fraction of deformation microstructure after several rolling cycles. It is also known that the relative proportions of HABs and LABs, and their spatial distribution, play a major role in the type of static restoration phenomenon operating during subsequent annealing [10,11]. This paper provides new information concerning the nature of formation of LABs within the lamellar bands contained in the severely strained Al layers of the Al/Al(Sc) multilayered composite described in Quadir et al. [8,9].

For ARB sheets of high purity aluminum (Al) and an Al–0.3 wt.% Sc alloy (Al(Sc)) were rolled to 1 mm thickness and fully recrystallized. Here the Al(Sc) alloy was heat treated above the solvus and water quenched to generate a supersaturated solid solution. A sheet of each alloy was cleaned, brushed, stacked and preheated at 200 °C for 5 min before roll bonding, in a single pass, to 50% reduction. The roll-bonded sheet was cut in two and prepared for the next cycle in the foregoing manner. This procedure was carried out for a total of five ARB cycles (including a final 50% rolling reduction) to generate 32 alternating layers of Al and Al(Sc). Within the Al and Al(Sc) layers, respectively, LBs of 0.4 and 0.15 μm thickness were generated, although such features were predominantly separated by either HABs or LABs in the Al and Al(Sc) layers, respectively. The fine scale crystallographic features of the LBs within the as-deformed Al layers were investigated in detail by high

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resolution electron backscatter diffraction (HR EBSD) using a TSL™ EBSD system interfaced to a JEOL 7001F field emission scanning electron microscope.

Figure 1a shows a typical HR EBSD micrograph of an Al layer (rolling direction (RD)–normal direction (ND) section) located at the mid thickness of the multilayered composite. The main feature of the micrograph is the stack of thin, elongated LBs parallel to the RD. They are divided by HABs and LABs, as indicated by the bold black and thin white lines, respectively. In appearance they resemble typical LB structures, as found in a conventionally rolled Al–0.1% Mg alloy after a true stain of 3.9 [12] and in ARB rolled high purity Al alloys after five cycles [13]. It should be noted that ARB rolling can achieve ~20% higher refinement over conventional rolling up to a true strain of 4 [13]. It can be seen that LABs are forming between the existing HABs and these boundaries are aligned both parallel to each other and the RD. It is useful to note the difference between these deformation features and those that form in low to medium rolling microstructures; the latter are comprised of LABs aligned at 25–35° to the RD, as confirmed by both two-dimensional [14] and three-dimensional [15,16] analysis methods. These features are termed microbands and are argued to be crystallographic [14]. Microbands have a systematic change of orientation between the neighboring band in an alternating fashion, which is not present here, even after analyzing a large number of EBSD maps. For the present material the majority of cases show that a single LAB forms between two HABs, although up to three LABs may occasionally form. In Figure 1a 24 HABs and 14 LABs intersect the vertical line drawn on the micrograph, which is a significant proportion of each type of boundary. EBSD data from a larger area gives an average fraction of ~30% LABs, a value comparable to that found in high purity Al after conventional ARB rolling for five cycles [1]. Some variation in this value may arise because of different rolling temperatures and the advancement in EBSD angular resolution allowing better detection of LABs. It was demonstrated by Kamikawa et al. [7] that, because of its higher resolution, transmission electron microscopy (TEM) yields a higher LAB fraction than EBSD on the same area of an ARB sample. In the process of fragmentation during severe plastic deformation it is believed that continued deformation can transform these LABs into HABs, with further LABs forming within the newly created HABs [1]. Therefore, in principle, additional roll bonding cycles should increase the fraction of HABs and result in continual structural refinement. However, the finest achievable distance between HABs is ~200 nm [12]. Therefore, some sort of annihilation of boundaries occurs to restrict the rate of grain refinement at high strains [3]. An ARB microstructure is argued to reach saturation after 5–7 cycles [7], thereby indicating that the present material has not reached saturation, since continuing refinement was observed up to five cycles. Collectively, the LBs generated within the present material consist of orientations along the β fiber, as shown by the ⟨1 1 1⟩ pole figure in Figure 1b (due to symmetry, only half is shown). In Figure 1c the orientations of the LAB-containing lamellar bands are plotted separately to illustrate that they have the same β fiber orientations as the LBs, in general. Therefore, it may be concluded that the formation of LABs is not an orientation-dependent phenomenon of the parent lamellar band. This illustrates another difference between this microstructure and those generated during low to

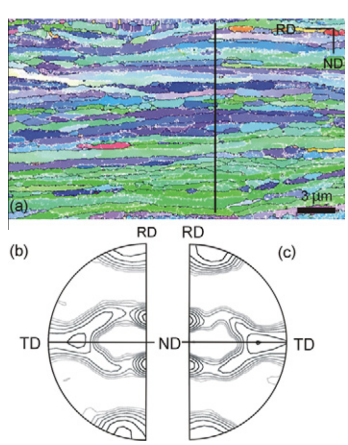

Figure 1. (a) HR EBSD micrograph (50 nm step size) of an aluminum layer of the RD–ND section. High (>15°) and low (0–15°) angle lamellar band (LB) boundaries are shown as bold black and thin white lines, respectively. The orientations of the LBs were measured from 10 separate EBSD scans and shown as half ⟨1 1 1⟩ pole figures in (b) for all the LBs and in (c) for LBs containing LABs.

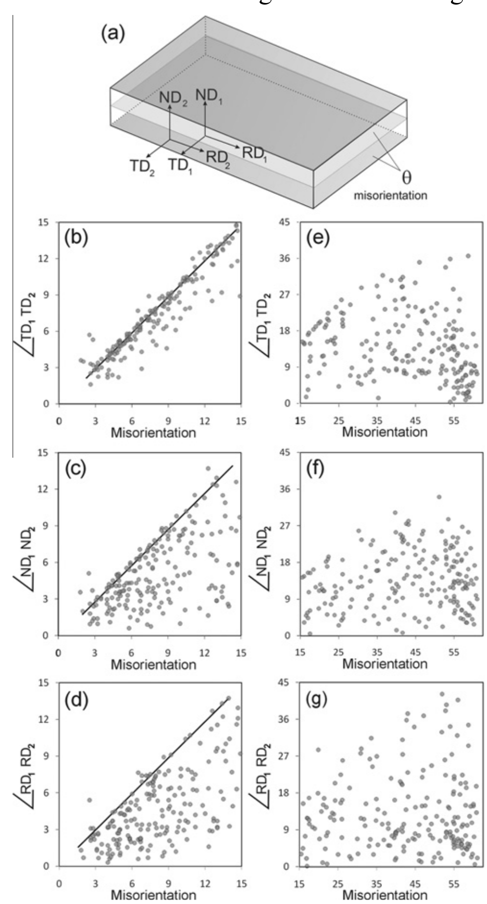

Figure 2. (a) Schematic diagram showing the reference axes of an upper and lower LB separated by a boundary of misorientation θ. The plots show the shift of the reference axes with their respective misorientations across the low angle (b and c) and high angle (e–g) boundaries.