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Texture development and grain refinement in non-equal-channel angular-pressed Al

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Grain subdivision and texture development in equal-channel angular pressing (ECAP) and in non-equal-channel angular pressing (NECAP) were studied experimentally as well as by modeling in commercially pure Al. The refined grain size was smaller in NECAP than in ECAP. Within one single modeling frame, it was possible to reproduce fairly well texture evolution, intercept lengths and next-neighbor grain misorientation distributions when the flow line approach was used for the strain history in both ECAP and NECAP.

Keywords: Grain refinement; NECAP; ECAP; Al; Polycrystal modeling

Among severe plastic deformation techniques, equal-channel angular pressing (ECAP) is the most often used to transform the initial large grains into an ultra-fine-grained microstructure. The main features of ECAP are: (i) the sample retains its original shape and (ii) the main deformation mode is simple shear in the plane of intersection of the two channels [1]. This process is now being commercialized in its continuous version [2]. However, large numbers of passes are needed to obtain a well-defined and stable microstructure. To improve the manufacturing efficiency, a modified ECAP process – called non-equal-channel angular pressing (NECAP) – was proposed in which the outgoing channel has a reduced diameter in the normal or pressing direction (ND) [3]. It has been shown that ideally the strain mode is the same as in ECAP; simple shear applies at the intersection plane of the two channels [4]. If the reduction of the exit channel is 50%, there is 25% more shear strain in NECAP with respect to ECAP. For a 90° die, the shear strain can be calculated from:

$$\gamma = \frac{p}{c} + \frac{c}{p} \tag{1}$$

where p and c are the inlet and exit channel diameters in the ND [4]. One feature of this process is that the shear plane is nearer to the ND plane, which can be advantageous for increasing the Lankford parameter of Al sheets in order to get better formability [3]. Consequently, it is interesting to investigate this technique in more detail for future developments.

This paper aims to examine the differences between textures and microstructures of commercially pure Al when extruded in NECAP and ECAP. One-pass NECAP and ECAP experiments as well as simulations were conducted. In the simulations, the recent polycrystal grain refinement (GR) model [5] was employed, which is based on a slowing down of the strain-induced lattice rotation near the grain boundaries.

The material studied was commercially pure Al1050 in form of a plate which was heat-treated at 500 °C for 2 h, resulting in an equiaxed grain structure with an average grain size of ~33 μm (Fig. 1a). The annealed Al billet was machined to dimensions of 10 mm × 20 mm × 120 mm, then two samples were put together to obtain a thickness of 20 mm for processing them in 90° angle dies with a section of 20 mm × 20 mm by NECAP and ECAP. The reason for using this split sample configuration is that

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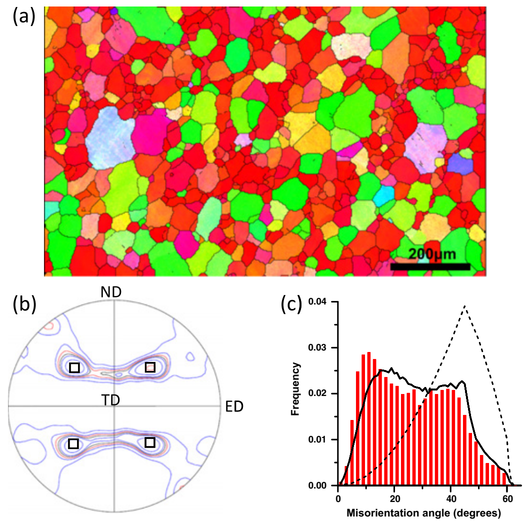

Figure 1. (a) Representative inverse pole figure map of the initial microstructure, (b) {1 1 1} pole figure of the initial texture (isolevels: 1.0, 2.0, 2.5, 3.0, 3.5, 5.0 and 8.0 × random, the squares indicate the cube ideal position), (c) the next-neighbor grain misorientation distribution of the initial sample (bars) together with the simulated non-correlated misorientation distribution (solid line). The non-correlated random Mackenzie distribution is also shown with broken line.

straight markers were put on the contact surface between the samples to obtain the shape of the flow lines during extrusion. For this purpose, the extrusion was stopped at half-processing. The long axis of the original plate was the extrusion direction (ED); the extrusion speed was 2 mm s^{-1} and colloidal graphite was used as lubricant. Microstructure characterization was performed by using a JEOL 7001F FEG SEM fitted with a HKL detector with a step size of 0.2 μm. Specimens were cut from the center of the NECAP and ECAP billets along the ND-ED plane. The samples were mechanically polished to 4000 grit by using SiC paper and then electropolished for 15–20 s in an electrolyte of 10% perchloric acid, 20% glycerol and 70% methanol at 30 V, 20 °C, with a current of ~500 mA. From the obtained electron backscatter diffraction (EBSD) maps boundaries were identified using a minimum misorientation angle of 5° between adjacent pixels. In order to have representative data for analyzing the orientation distribution, at least two maps of 80 μm × 80 μm in size were measured for each condition of NECAP-ed and ECAP-ed aluminum sample. Post-analysis of the orientation maps was performed using the EBSDmcf software [6].

A typical strong cube texture comes from the initial samples (Fig. 1b); the next-neighbor grain misorientation distribution (NNMD) of the initial structure displays two peaks, and is thus different from the Mackenzie random non-correlated misorientation distribution (Fig. 1c). This difference can be explained by the strong initial texture. We have generated a grain orientation distribution from the initial texture and calculated the non-correlated misorientation distribution. The so-simulated distribution is close to the measured one (Fig. 1c), proving that little orientation correlation existed between neighboring grains in the initial grain structure.

Both microstructures of the ECAP and NECAP processed samples were elongated, containing a band-like lamellar structure (Fig. 2a and b). For ECAP, the intercept lengths were 2.95 μm and 2.04 μm along the ED and ND, respectively. In NECAP, the intercept lengths were: ED: 2.01 μm, ND: 1.65 μm. These values are in the range obtained in cold rolling of Al and its alloys, reported to be between ~2.0 and 2.6 μm at the same strain levels [7,8].

The experimental textures after ECAP and NECAP are displayed in Figure 3a and e, respectively. The position of the theoretical shear plane is also indicated (broken line) in all pole figures which lie at 45° with respect to the ND in ECAP and at 63.4° in NECAP. The NECAP texture is slightly stronger; the maximum intensity has the value of 5 for NECAP compared to 3.5 for ECAP. The strongest texture component is the C (Fig. 3), which is defined by {1 0 0} ∥ shear plane and ⟨0 1 1⟩ ∥ shear direction; its position is indicated by crosses in the pole figures. The cube component (indicated by squares) also appears in a rotated position (Fig. 3a and e), and its position was estimated in alignment with the simulations but less strong than the cube in Figure 3b and f. The main difference between the experimental textures in ECAP and NECAP is the general position of the texture, which is more rotated in NECAP. Another interesting feature is the shape of the two main reflections that are near the center of the pole figures. In alignment with the simulations, this feature is due to the combined effect of the C component and the differently rotated cube component in NECAP.

For the polycrystal modeling, the initial cubic-type texture was discretized to 496 grains and then grain sizes were assigned to each orientation following a lognormal distribution; the average grain size was 32 μm. The procedure was calibrated in order to reproduce the initial texture by the 496 grain orientations together with their volume fractions defined by the assigned grain sizes.

For modeling the strain paths in both ECAP and NECAP, two approaches, the simple shear model [1] and the flow line model [4], were considered. The simulations were

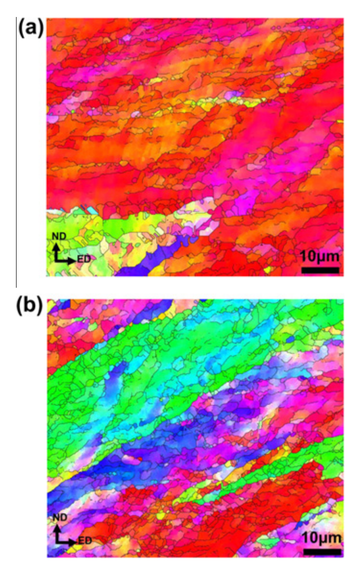

Figure 2. Representative inverse pole figures of the microstructure of (a) ECAP-ed Al and (b) NECAP-ed Al. Grain boundaries with misorientation angle larger than 5° are depicted by black lines.