Original Article

Strain path effects on the development of shear bands during shear tests in aluminum alloy processed by ECAP

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\textbf{ABSTRACT}

ECAP (Equal Channel Angular Pressing) involves the pressing of a prismatic specimen through two channels with the cross-section identical to that of the specimen and intercepting at a certain angle. The specimen undergoes shearing over a single plane but no dimensional changes, leading to a possible anisotropy in the mechanical properties of the processed specimen. In addition, multiple ECAP passes lead to a severe refinement of the material structure, which is a function of the angle between the channels and the rotation of the sample in successive passes (the so-called "processing route"). An analysis is presented of the mechanical and microstructural anisotropy along three orthogonal axes in an aluminum alloy specimen processed along three different processing routes. The mechanical properties were evaluated through shearing tests, and the stress–strain curves thus determined indicated that the mechanical behavior of the commercial purity aluminum after ECAP depends on the processing route. The analysis of the specimen surfaces after testing revealed the presence of shearing bands whose orientation also depended on the processing route.

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1. Introduction

Severe plastic deformation (SPD) of metals leads to grain refinement down to nanometric sizes, with consequent strengthening and high strain rate superplasticity of the processed material \[1\]. According to Figueiredo and Langdon \[2\], Equal Channel Angular Pressing (ECAP) is one of the most effective SPD techniques in order to obtain ultra-fine grains (UFG). ECAP involves the passage of the material through two intersecting channels with identical cross-sections and a fixed angle between them. There is no change in the dimensions of the processed material, allowing the indefinite repetition of the processing up to extremely large deformations \[3\]. ECAP involves the shearing of the material along the plane corresponding to the intersection of the two channels, which may...
lead to the anisotropy in the mechanical properties of the products [4,5]. For successive ECAP passes, the position of this shearing plane varies according to the so-called "processing routes" [6]. In route A the specimen undergoes no rotation around its axis for the successive ECAP passes; route B_A involves the rotation of the sample by 90° either in the clockwise or anti-clockwise directions, with successive inversions in the rotation direction, whereas route B_C is similar to route B_A, but with no inversion in the rotation direction for successive passes. Finally, in route C the sample is rotated 180° between successive passes. During Route A the shearing plane and direction are the same in even and also in odd numbered passes; the shearing plane is always the same in the successive passes of route C, but the shearing direction is inverted after each pass. For route B_C, shearing occurs at different shearing planes for each pass, which however are repeated after 2 successive passes and involving an inversion of the shearing direction. The situation is similar for route B_A, but the shearing planes are repeated only for each 4 successive passes, without any inversion in the shearing direction. The present paper discusses the heterogeneity of deformation of commercial purity aluminum after ECAP processing following various routes, followed by pure shearing along specific directions.

2. Material and procedures

The material used in the experiments was an Al-1.34% Fe-0.64% Mg-0.44% Zn-0.14% Si-0.11% Cu alloy. Bars with square cross-section of 16 mm were cut to provide billets of 100 mm length. The billets were annealed at 513 K for 90 min followed by furnace cooling.

ECAP processing was conducted at room temperature in a compression machine (Kratos) with capacity of 500 kN. The die used had an angle of 90° between channels and no external curvature. Molybdenum disulfide was used as lubricant and the punch speed was set at approximately 1 mm/s.
Tensile tests were performed in the annealed material and after 1 ECAP pass. The tensile specimens had a circular cross-section with 5 mm diameter and 30 mm of gauge length; its orientation was such that the tensile strain axis coincided with the pressing direction. The tests were performed at constant cross-head velocity, corresponding to an initial strain rate of $10^{-4}$ s$^{-1}$, utilizing an INSTRON model 5582 machine. Two specimens were used for each material condition.

A tool was specially designed for simple shear tests in sheet samples; it displayed two separate grips with only one possible direction of relative movement provided by sliding, as illustrated in Fig. 1. The movement of the grips provides simple shear in a region of the sample between them, and the distance between the grips is 3 mm. Molybdenum disulfide lubricant is applied in the contact parts of the tool to reduce friction and the apparatus is attached to a tensile test machine (INSTRON model 5582). The displacement of the grips and the load were measured during the tests and converted into shear stress and shear strain using Eqs. (1) and (2), which can be converted into effective stress and effective strain using the von Mises yield criterion (Eqs. (3) and (4)).

\[
\frac{\Delta y}{d} = \frac{dy}{dx} = \varepsilon_{\text{shear}} \tag{1}
\]

\[
\frac{F}{A} = \sigma_{\text{shear}} \tag{2}
\]

\[
\sigma_{\text{ef}} = \sqrt{3}\sigma_{\text{shear}} \tag{3}
\]

where $\Delta y$ is the displacement of the grips in the direction $y$, $d$ is the distance between the grips in the direction $x$ (3 mm), $\varepsilon_{\text{shear}}$ is the shear strain, $F$ is the force applied by the test machine, $A$ is cross-section area of the specimen in the YZ plane and $\sigma_{\text{shear}}$ is the shear stress.

After one ECAP pass, sheets 1.5 mm thick were cut from the billets oriented parallel to the axial direction and to the shearing direction that would be observed in a second ECAP pass following routes A and C or B, as illustrated in Fig. 2. Cutting was performed with a Buehler Isomet 1000 Precision Saw with a Buehler Diamond wafering blade 12.7 mm in diameter and 0.5 mm thick. As routes A and C demand $0^\circ$ and $180^\circ$ rotations of the billet between successive passes, respectively, the shear testing direction of these routes are in the XZ plane while the shear directions corresponding to route B are set in the XY plane. Specimens for the shear tests were then extracted from the prepared sheets with pre-determined orientation that matched the shear direction in the second ECAP pass, following the principal processing routes: A, B and C. The shearing direction in the shear tests was the same as in the second ECAP pass and 3 specimens were tested for each situation. There is no difference between routes $B_A$ and $B_C$ in the second pass so only the letter B will be used to describe both routes. However, since the specimen rotation in route B can be either clockwise or anti-clockwise there are two possibilities of shear direction and both of them are described in Fig. 2.
The extracted longitudinal sheets were ground to approximately 1 mm thickness in SiC paper and polished with diamond paste to a mirror like finishing. The specimen surfaces were observed after shear testing with a Leitz optical microscope and scanning electron microscopy-SEM, utilizing a JEOL JSM 6360 LV microscope operating at 15 kV.

3. Results

3.1. Mechanical properties

Fig. 3a shows the effective stress-effective strain curves (SS curves) determined by tensile tests in the annealed material and after 1 pass of ECAP. It can be seen that both specimens tested for each situation yielded very similar results. Fig. 3b shows the SS curves (average of the 3 performed tests) determined by shear tests for the various directions of the aluminum billet processed by ECAP (the graph scale was changed to facilitate the observation of differences in the results for the various shear directions). The experimental error in these shearing tests was of about ±3%; the stress levels in Fig. 3b are thus within the experimental error. On the other hand, there is a clear difference in the final strain to fracture for shearing along Routes A, B and C, which were respectively ≈0.28, ≈0.1 and ≈0.35.

3.2. Surface analysis

Optical microscopy was used to evaluate the distribution of second phase particles in the specimen prior and after ECAP processing. Fig. 4 shows that the second phase particles were preferentially oriented along the billet axis and this orientation continued after processing.

After the shear test the specimen surfaces were analyzed with a SEM and different patterns of shear bands were observed depending on the shear direction. Fig. 5 shows the surface of the sample sheared in a direction corresponding to route A. At smaller magnification just shear bands almost perpendicular to the shear direction are observed while at higher magnifications shear bands parallel to the shear test direction are also observed.

The shear bands observed at the surface of the sample sheared in a direction corresponding to route B exhibiting a different pattern. At smaller magnifications a chessboard like shear band pattern is observed where the main bands are parallel to the shear direction. At higher magnifications inclined shear bands are also observed between the main ones as seen in Fig. 6.

When the shear test is conducted in a direction corresponding to route C shear bands are hardly observed at smaller magnifications. However shear bands parallel to the shear test direction are observed at higher magnifications as shown in Fig. 7. It is also observed that the shear bands do not cross the whole sample surface, but seem to be constrained at the interior of some grains while other regions are free from shear bands.

Fig. 8 shows the backscattered electrons image of the different samples surface after testing, to ease the observation of the second phase particles and their orientation. It is shown that the second phase particles are preferentially oriented at the extrusion direction of the billets. The extrusion direction makes an angle of 45° with the shear direction before testing but this angle decreases after testing due to the sample shearing. The preferential orientation is clearly observed at the samples sheared in directions corresponding to routes A and C and is not well defined at the sample sheared in a direction corresponding to route B. As the surface of the samples corresponding to routes A and C are parallel to the plane XZ of the billets and the surface of the sample corresponding to route B is parallel to plane XY (Fig. 2), the difference is
attributed to a higher preferential orientation of the second phase particles at the former than the latter.

4. Discussion

The stress-strain curves determined by tensile testing (Fig. 3a) indicates that ECAP processing increases the material strength remarkably, but the specimen work hardening is much lower than for the annealed samples up to a strain of about 0.2. At higher strain levels, the work hardening rates are similar under both conditions. The behavior of the annealed material in Fig. 3a corresponds to a work hardening coefficient of $n \approx 0.2$, whereas for the ECAP processed material, $n \approx 0.03$; care should be taken in the use of these “$n$” values, since they could suggest that the work hardening in the annealed or “ECAPed” material differ along the full straining range, which is not true.

Since the experimental error in the shearing tests was of about ±3%; the stress levels in Fig. 3b are thus within the experimental error and do not allow accurate quantitative analyses. The low fracture strain ($\approx 0.1$) for shearing following Route B was caused by early strain concentration along a shearing band, in opposition to the situations for the shearing corresponding to Routes C and A, where fracture occurred for a strain of $\approx 0.35$ and $\approx 0.28$, respectively. This is connected to
the more pronounced initial softening of the material sheared along Route C than for the other cases. The qualitative analysis of the stress levels for the three situations in Fig. 3a suggest that shearing along Routes A and B involves a somewhat higher initial flow stress than for the shearing along Route C. This could be connected to the pronounced change in shearing direction for Routes A and B, in relation to the shearing direction in the previous ECAP pass, possibly leading to a high initial flow stress followed by a restructuring of the dislocation structure established in the previous ECAP pass and consequent softening, especially for Route B. On the other hand, shearing along Route C involves only a shear reversal in the same plane, leading to a “Bauschinger” effect. Similar transients in the stress strain curves were observed in copper processed by ECAP and tested along different directions in compression [7], where the material exhibited higher flow stress followed by work softening when the new slip direction was not coplanar to the slip in the previous direction. This is probably also at the root of the widely known fact that Route B leads to a faster grain refinement than Routes A and C. It is also clear from Fig. 3b that the material lacks any work hardening capacity during shearing along Routes A, B and C.

Surface analysis of the specimens after shear tests showed the occurrence of shear banding during straining. Despite the presence of second phase particles preferentially oriented at the extrusion direction, the surface of the various sheared samples presented very different features due to the shear bands orientation. Shearing in directions corresponding to routes A and C led to shear bands preferentially aligned with the directions of the interception between the specimens and the shear plane at the previous ECAP processing as shown in Fig. 9.

Although the main shear bands observed at the sample sheared in a direction corresponding to route B are parallel to the shear test direction, in disagreement with the direction

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**Fig. 8** – Backscattered electrons image of the surface of the samples after shear tests at directions corresponding to routes A (a), B (b) and C (c).

**Fig. 9** – Illustration of the shearing plane during ECAP processing and the orientation of the shear test specimens corresponding to routes (a) A and (b) C.

**Fig. 10** – Illustration of the shearing plane during ECAP processing and the orientation of the shear test specimen corresponding to route B.
of the interception between the specimen and the previous ECAP processing shear plane, Fig. 6 shows that, at higher magnification, some inclined shear bands are observed between the main shear bands. Fig. 10 shows an illustration of the specimen for shear test corresponding to route B and its geometrical relation with the previous ECAP shearing plane.

5. Conclusions

Shearing of the material after an ECAP pass, along the shearing directions corresponding to further ECAP processing following Routes A, B and C led to stress–strain curves with stress levels similar to each other.

Shearing along Route B led to early fracture caused by strain concentration along a shearing band, in contrast to the fracture observed in the shearing along Routes A and B. This is connected to the higher initial softening in the shearing curve along Route B.

Shearing along Routes A, B and C led to profuse shear banding in the samples. Shear bands along routes A and C were preferentially aligned with the directions of the interception between the specimens and the shear plane at the previous ECAP.

The only shear bands in the shearing along Route C were parallel to the shear test direction in disagreement with the situation observed for shearing along Routes A and B where shear bands in different directions were observed.

Conflicts of interest

The authors declare no conflicts of interest.

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References