PERIODICA POLYTECHNICA SER. MECH. ENG. VOL. 48, NO. 2, PP. 145–150 (2004)

INFLUENCE OF ECAP ROUTES ON MECHANICAL PROPERTIES OF A NANOCRYSTALLINE ALUMINIUM ALLOY

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Received: March 8, 2004

Abstract

Equal-Channel Angular Pressing (ECAP) is an effective tool for producing ultra fine grained materials. In repeated application of ECAP, the rotation of the sample along the longitudinal axis of the billet allows to carry out different routes of deformation. The applied route has a strong influence on the texture, microstructure and mechanical behaviour of ECAP processed metals. In the present study ECAP was successfully applied to produce ultra fine-grained microstructure in a commercial Al-Mg-Si alloy (Al 6082). The mechanical investigations of the ECAP deformed specimens revealed that after 4 ECAP passes the material had a very high strength but a significantly decreased ductility. Further ECAP processing to 8 passes by route *C* increased ductility dramatically and strength slightly. The diameter ratio of the ellipse shaped cross-section of the compressed specimens was the highest for the sample deformed by route *C* for eight passes. This indicates that the anisotropy of the structure of ECAP deformed materials may play an important role in achieving good ductility. The quality of the ultra-precision finished surface of the processed sample improved dramatically after eight passes.

Keywords: Equal channel angular pressing, high strength and ductility, nanosized microstructure, surface quality.

1. Introduction

Equal-channel angular pressing (ECAP) is a processing method in which a metal is subjected to intense plastic straining through simple shear without any corresponding change in the cross-sectional dimensions of the sample [1]–[2]. This procedure may be used to create ultra fine grain sizes in bulk polycrystalline materials. The principles of the ECAP process have been examined with reference to the distortions introduced into a sample as it passes through an ECAP die with special attention to the effect of rotating the sample between consecutive passes. Significant distortions of the grain structure occurred when a sample passed through a standard ECAP die, so when a sample is pressed repetitively through the die, it has been recognized that the overall shearing characteristics within the crystalline sample may be changed by a rotation of the sample between the individual passes [3]. The repetitive pressing of the same sample is generally carried out in order to attain very high imposed strains. At the same time there is an opportunity to rotate the sample between consecutive pressings in order to activate different shear planes and directions, thus enhancing the mechanical properties at room temperature by applying different routes [4].

It is well known that plastic deformation induced by conventional forming methods can significantly increase the strength of metals. However, this increase is usually accompanied by a loss of ductility. It has been found recently that materials processed by ECAP after certain number of passes show high ductility along with high strength [5]. Such unusual behaviour of materials, which is in contradiction with 'classic' tendencies to lost ductility with increased strength, needs to be understood deeper. In this paper the effect of different routes of ECAP techniques on the strength and the ductility of an Al-based alloy is investigated. The mechanical behaviour is related to the characteristic features of the nanocrystalline microstructure formed during ECAP deformation.

2. Producing of ECAP Specimens

The material used in this study was a commercial Al-Mg-Si alloy (Al 6082). The main components of the alloy are Al (97%), Si (0.7–1.3%), Mg (0.6–1.2%) and Mn (0.4–1%). Before the ECAP deformation, the material was annealed at 420 °C for 40 minutes. Specimens in this condition were regarded as the as-received material. Cylindrical billets of 15 mm in diameter and 145 mm in length were pressed through the ECAP die with 90 °C intersecting channels [6]. Four and eight passes were completed by the following routes: B_C (rotation of the billet around its longitudinal axis after each pass by 90 °C clockwise), B_A (rotation of the billet around its longitudinal axis after each pass by 90 °C clockwise and counterclockwise, alternatively) and C (rotation of the billet around its longitudinal axis after each pass by 180 °C, clockwise). The temperature of deformation was 293 K and the displacement rate of the billet was 8 mm/min.

3. Experimental Studies

3.1. Mechanical Testing

The mechanical attributes of the specimens processed by ECAP were studied by tensile and compressive tests. The specimens for the tensile and compression tests were cut from the pressed material along the longitudinal axis. The tensile tests were carried out at ambient temperature at 2 mm/min crosshead velocity in order to collect information about dependence of the yield stress, ultimate tensile stress, area reduction and elongation on different process routes and number of passes. The results of the tensile tests are indicated in *Figs.1* and *2*. In *Fig. 1* the area reduction and elongation vs. the number of passes are shown for each ECAP route. In *Fig.2* the yield stress and ultimate tensile stress as a function of the number of passes are depicted for each route. Some ECAP processed specimens were investigated also by compressive testing. During compression, the shape of the cross-section of the specimens tended to change from circular to oval. In order to investigate the influence of process routes on the developing anisotropy, the ratio of the largest and smallest diameters of the cross-section was measured for each process route after the fourth and eighth passes of ECAP (*Fig. 3*).

3.2. *Microstructural Investigation*

The microstructure of the as-received and ECA pressed materials deformed by route C was studied by X-ray diffraction peak profile analysis. The peak profiles were measured on the cross-section of the specimens by a high-resolution double-crystal diffractometer (Nonius, FR 591) using Cu $K\alpha_1$ radiation. The parameters of the microstructure were determined from the peak profiles by the Multiple Whole Profile (MWP) fitting procedure described in detail in [7, 8].

It was found that nanosized microstructure (mean crystallite size $\sim$ 80 nm) with high dislocation density (3×10^{14} m^{-2}) was achieved even after the first pass. The microstructure was refined only slightly during further ECAP passes. At the same time the dislocation density increased with the increase of ECAP deformation up to 4 passes. The dimensionless dislocation arrangement parameter, M, has a value of 4.0 ± 0.4 for the as-received specimen and it decreased to 2.2 ± 0.3 after 8 ECAP passes. This indicates that the dipole character of the dislocation structure became stronger with increasing deformation.

3.3. *Surface Integrity Measurement*

The effect of crystal size and the ECAP process on the surface integrity was investigated by making mirror-like cylindrical and flat surfaces, using turning. An ultra-precision lathe (Csepel UP.1) and Winter mono-crystalline diamond tool were used in these experiments.

The turning process has been applied to every specimen with the same cutting conditions, i.e. cutting speed -78 m/min, while feed rate -1 μm/rev. Surface roughness was measured using an Atomic Force Microscope. The results are very interesting and very promising: surface finish of the cut raw part had the same value

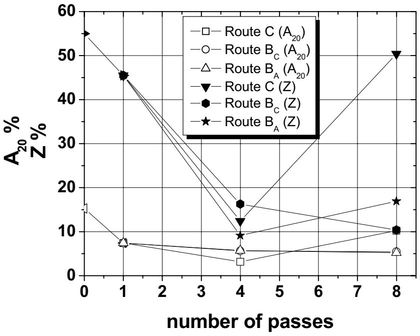

Fig. 1. Elongation (A_{20}) and area reduction (Z) at ambient temperature vs. the number of ECAP passes for different routes

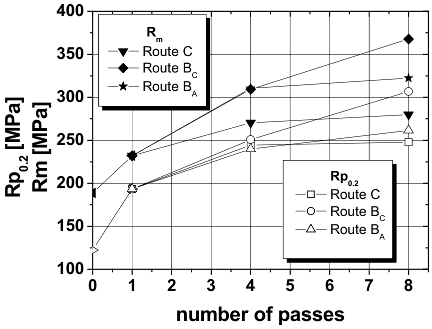

Fig. 2. Yield strength ($R_{p0.2}$) and ultimate strength (R_m) at ambient temperature vs. the number of ECAP passes for different routes

($Ra \approx 55$ nm) for the specimens after 1 or 4 passes of ECAP process. At the same time after 8 passes Ra dramatically reduced to 10 nm.

4. Discussion

Yield stress ($R_{p0.2}$) and ultimate tensile stress (R_m) grew with the increase of the number of ECAP passes for all the routes investigated. The maximum increment compared to the values before ECAP was reached after the first pass and after eight passes the highest absolute value for yield stress was obtained route B_C, the lowest value by route C. The area reduction (Z) for all routes shows a significant decrease after the fourth pass.

It is interesting to note that after eight passes the sample deformed by route C shows an increase in Z, up to almost the value of the as-received state. Route B_A results in a slight increase of the value of area reduction between four and eight passes. For route B_C, the tendency of decreasing value of Z can be seen even after eight passes but not so drastically as after the fourth pass. For the elongation, almost the same tendency can be observed with increasing number of passes: route C gives the increase of A_{20} after eight passes, while B_C and B_A have the tendency to decrease. These data show that high strength and high ductility exist together after eight ECAP passes applying route C.

The magnitude of the absorbed specific energy [9], which indicates toughness, was also investigated, considering samples produced by different ECAP routes. As shown in *Fig. 4*, it is clear that route C supplied the best results.

During the compressive tests, cross-section of the specimens tended to change from circular to oval, showing the presence of anisotropy caused by ECAP. The ratio of maximum and minimum diameters (a/b) was measured and *Fig.* 3 shows the dependence of this ratio on different process routes and passes. It is worth noting that in some cases the cross-section of specimens has a 'pear-like' shape, thus the measurement of the diameter ratio is somewhat uncertain. It is also worth noting that the diameter ratio for the sample deformed by route C for eight passes is by far the highest among the specimens studied here. This indicates that anisotropy of the microstructure may play an important role in achieving the simultaneous existence of high strength and good ductility in nanocrystalline materials produced by severe plastic deformation. The study of the microstructure of the cross-section does not give any reasonable explanation for the outstanding ductility of the sample deformed in eight passes by route C, therefore microstructural investigations of the longitudinal sections is necessary.

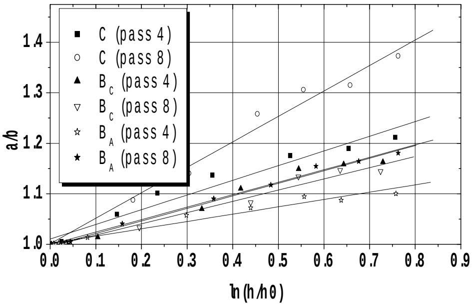

Fig. 3. Diameter ratio vs. compressive strain at ambient temperature for Al 6082 after various ECAP passes

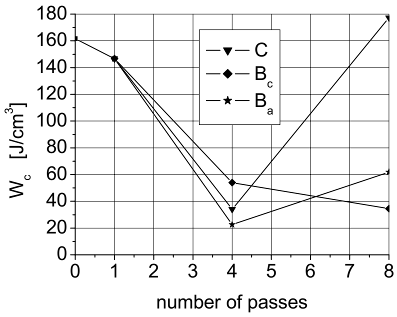

Fig. 4. Absorbed Specific Energy till fracture for Al 6082 after various ECAP passes

The sample surfaces, prepared by ultra-precision machining, demonstrated interesting changes. The original surface quality was nearly identical to that after the fourth pass. After eight passes, however, the surface roughness dropped by a factor of five, further reflecting the effect of the structural changes.

5. Conclusions

Completing the mechanical investigations of the produced specimens by the different routes revealed that route C showed both increasing of strength and ductility owing to the significant changes of the grain structure of the material. In turning experiments after eight steps of pressing – under equal cutting conditions – cut surface roughness reduced by a factor of five on average (from $Ra = 55$ to $Ra = 10$). It is another important impact of structural changes on engineering applications.

Acknowledgement

This work was supported by the Hungarian Scientific Research Fund, OTKA, Grant Nos. T-042714 and T-043247.

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