Experimental investigation on the performance of an improved equal channel angular pressing die

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Abstract. A major problem in Equal Channel Angular Pressing is die design. Friction plays an important role in the extrusion process. In the present work, Aluminium 6082 alloy was processed through a modified ECAP die originally proposed by Mathieu et al. in 2004 [1] and the performance of the die was analyzed. The channel angle was $\phi = 90^\circ$ and corner angle $\psi = 20^\circ$. Mechanical properties, micro hardness measurement and crystalline size ($D$) were measured from the extruded specimen for both the conventional and new die designs. It has been found that the new die samples displayed better results than the conventional ones. The newly designed die reduced the effect of friction on the work piece, it increased the tensile strength, the hardness of the material and achieved better grain refinement.

Keywords: ECAP, AA 6082 alloy, Mechanical properties, crystallite size

1. Introduction

In the last four decades, researchers studied predominantly aluminium alloys in Equal Channel Angular Pressing (ECAP). ECAP was developed by Vladimir Segal and his co-workers in 1977. This process imposes large plastic strain on the material by simple shear. The most important advantage of SPD processes is to produce high strength materials. In ECAP considerable grain refinement occurs without any dimensional changes of the sample. High yield strength is possible to obtain by ECAP through the Hall Petch relation [2,3]. The aluminium alloy AA6082 is a high strength and good corrosion resistance material among the 6xxx series. In many applications 6082 alloys are used instead of 6061 alloys, generally in structural applications [4,5]. Different ECAP die configurations were proposed in [6-8]. Segal
et al. [6] developed a new die assembly especially for high strength and brittle alloy materials. In that die the ingoing extrusion channel has two walls opposite to each other which move together with the sample during extrusion, thus a reduction in friction is achieved. At the same time, the bottom plate of the outgoing channel also has a moving wall which further reduces the friction. Semiatin et al. [6] also developed moving walls on the basis of Segal's work of 1995. Mathieu et al. [1] developed another design in which the sample is simply inserted into the punch so that there are three walls which move together with the sample in the ingoing channel. This die configuration is adopted in the present work. Fig. 1 shows the conventional die and Fig. 2 the modified die designed similar to [1] available in our laboratory.

El-Danaf and Baig [9] reported results obtained for high temperature deformation of Al-Mg-Si alloy processed by ECAP through Route C up to six passes. Super plastic ductility was obtained after ECAP with an elongation of 173 % at a strain rate of $6 \times 10^{-1}$ 1/s at a temperature of 823 K. Baig et al. [10] investigated over aged 6082 Al alloy processed by ECAP up to six passes through Route C. The micro hardness measurements showed a gradual increase in hardness and yield strength with increase in the number of passes. Dadbakhsh et al. [11] investigated ECAP of 6082 aluminium alloy before and after aging process in various conditions. Strength and ductility were improved by a post-ECAP aging treatment. Shear-type rupture was observed in the ECAP-ed tensile test specimens.
The present work is mainly focusing on the evolution of the mechanical properties of AA6082 alloy processed by ECAP up to three passes in Route Bc and C using both the conventional and the new die. The results obtained on the ECAP deformed specimens were compared with the as-received condition.

2. Die design

The modified die design was originally developed by Mathieu et al. [1] and shown in Fig. 2. The main objective of this die design is to minimize the friction of the sample with the die walls. The new die is composed of two parts, one is the punch which contains the sample, and the other part is the fixed one, see Fig. 3a. The experimental realization is shown in Fig. 3b. The lower part of the fixed die has a small platform which is equal to the cross sectional area of the specimen. The sample is turning on that surface during extrusion. The specimen is placed inside the punch and surrounded by three lateral sides of the plunger. Only one side of the sample is in contact with the fix die. After an extrusion process, the fixed die can be split and the specimen can be removed. Another new sample can be also used to eject the first sample.

![Fig.3. (a) Schematic diagram of the new die; (b) The experimental die](image)

3. Experimental details

The as-received Al6082 alloy was annealed at 450°C for 1 hour and then furnace cooled. The specimens were machined from the annealed rod with the dimensions of 25 x 25
mm × 80 mm for conventional die and 22.15 mm × 22.15 mm × 80 mm for new die. The specimens were pressed at room temperature with a ram speed of 1 mm/s using a 100 ton hydraulic press. Molybdenum disulfide was used as lubricant for reducing friction between the work piece and die inner wall. In the new ECAP die, the load reduction was about 10 to 15% with respect to the conventional die.

For tensile testing, specimens were prepared from the ECAP samples as per the ASTM E-8 standards with a diameter of 6 mm and a gage length of 24 mm. The testing was carried out using a 30 kN Instron machine at a crosshead speed of 1 mm/min. 3 tests were carried out for each condition. The micro hardness was measured using a Wilson Wolpert hardness tester with a load of 0.3 Kg and the dwell time of 15 s. X-ray diffraction (XRD) analysis were also carried out on the extruded samples. From the XRD peak patterns, the crystalline size (D) and the internal elastic strain of the material (ε) were measured.

4. Results and discussion
4.1 Vickers Micro hardness Measurement

The ECAP deformed samples were cut along the longitudinal direction to measure the hardness values. The hardness values were measured from the top surface of the sliced specimen to the bottom with a gap of 2 mm distance from the edges. The hardness values were found to be quite uniform in all measurement regions. Thus, the hardness mainly depends on the strain imposed on the material. Fig. 4 shows the Vickers micro hardness measurements for both the conventional and the new die ECAP-deformed specimens. Table 1 shows the average hardness values for the different ECAP conditions.

| Table 1. Average Vickers hardness as a function of strain path |
|-----------------|--------|--------|--------|--------|--------|
| Pass 0          | Pass 1 | pass 2, route Bc | pass 2, route C | pass 3, route Bc | pass 3, route C |
| Conventional die| 109    | 120    | 124    | 127    | 131    | 132    |
| New die         | 109    | 125    | 132    | 133    | 136    | 139    |
As can be seen from the data in Table 1, the hardness values are similar in both dies, however, they are slightly higher in all cases for the new die. As the hardness depends on the amount of plastic strain, it means that it is higher in the samples which were processed by the new die. Thus, the reduction in friction leads to an increase in the plastic strain achieved in the ECAP extrusion process.

4.2 Tensile testing

Fig. 5. Tensile strength vs no. of passes

Fig. 6. Percentage of elongation (till failure) vs no. of passes
Fig. 5 shows the tensile test results obtained for both dies. The tensile yield strength is increasing gradually as a function of ECAP passes for both dies. The tendencies are very similar to those observed for the hardness measurements in Table 1.

Fig. 6 shows the percentage of elongation in tensile testing up to failure. The values are very similar for all conditions. Furthermore, as expected, the higher yield stress material shows smaller ductility.

**Crystalline size measurements**

Fig. 7 shows the XRD patterns measured for our aluminium 6082 alloy processed through the conventional and new ECAP dies. The crystalline size (D) was determined using the Williamson-Hall (WH) method. The initial crystalline size was 150 nm. The initial line profile was taken as the base line material.

| Table 2. Average crystallite sizes obtained from XRD analysis in nm unit |
|--------------------------|----------|----------|----------|----------|----------|
|                          | 0 pass   | 1 pass   | pass 2, route Bc | pass 2, route C | pass 3, route Bc | pass 3, route C |
| Conventional die         | 150      | 105      | 65        | 62        | 48        | 44        |
| New die                  | 150      | 78       | 50        | 45        | 31        | 30        |

From the XRD patterns, the individual peaks were analyzed and the the Full Width Half Maxima (FWHM) were calculated as well as the 2*theta values. From the Williamson-Hall equation, the $\beta_{hkl} \cos \theta$ vs $4\sin \theta$ values of all the peaks were obtained. The plotted values were linearly fitted to calculate the slope and the y-intercept. The slope is the elastic lattice strain of the material. From the y-intercept values the crystalline size (D) was calculated. Table 2 shows the results of the measurements. As can be seen, the crystallite size is systematically smaller for the samples processed by the new die.

The peak broadening is in strong relation with the dislocation density while the position of the peak is related to the elastic lattice strain. The latter ($\varepsilon$) was obtained between 0.00116 to 0.0018 in the conventional die samples and from 0.0019 to 0.00232 in the samples of the new die (values are in %). From these results it is clear that the stored dislocation
density and the lattice strain is larger in the new die samples compared to the samples processed by the conventional die.

Fig. 7. XRD analysis of samples deformed by the conventional (a) and the new die (b)

5. Conclusions

AA6082 alloy was successfully processed by a modified die which was proposed originally by Mathieu et al. in 2004 [1]. It has been found that the new die is more efficient in obtaining more plastic strain, higher tensile stress, while there is just a small decrease in ductility. The XRD peak analysis predicted that the crystallite size was systematically smaller and the lattice strain higher in all samples processed by the new die. Therefore, the new die design provides better mechanical and structural properties as a conventional die. These effects can be attributed to the smaller friction in the new design which permits to obtain larger plastic strain in the processed samples.

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