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Hardness and Microstructure of Al6061 Alloy after Severe Plastic Deformation

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Abstract—*The processing of metals through the application of severe plastic deformation (SPD) techniques provides the potential for achieving exceptional grain refinement and improvement in mechanical properties. The Equal Channel Angular Pressing (ECAP) is the most efficient SPD solution for material nanostructuring as material billet undergoes severe and large deformation. Billets of Al6061 alloy were processed by ECAP for channel angle* $\phi = 90^0$ *at room temperature and the readings were recorded both on the top and bottom surface indicating that after ECAP the hardness value exhibits an increase of 40%. Also, three different cross-sectional planes (A, B and C) were identified to record different readings. Microstructure of the three specimens at sections A, B and C were also analysed using SEM, which indicates that the grain size reduces from 60 µm to 15 µm. The findings in the present study help in developing high strength materials in automobile and aerospace industry on account of its ability to change the microstructure of materials.*

Keywords: *Severe Plastic Deformation, ECAP, Al6061, Hardness, Microstructure.*

1. INTRODUCTION

Severe Plastic Deformation (SPD), a top down grain refinement approach, is used for producing nanostructure in the material. An important features of SPD Processing is that the high strain is imposed without any significant change in the overall dimension of the workpiece [1].This makes it possible to repeatedly deform the work piece so that large strains can be introduced in the specimen for obtaining nanostructure. SPD technology has become the focus of attention of many research groups and individual researchers and an analysis was conducted by Langdon [2] to evaluate the impact of the broad publications appearing over the last decade within the discipline of material science indicating it to be the most popular research area.Several techniques based on SPD, such as equal channel angular pressing (ECAP) [3–7], high-pressure torsion (HPT) [8, 9], dynamic plastic deformation (DPD) [10], and accumulative roll bonding (ARB) [11], have been widely developed to produce ultrafine-grained (UFG) or nano-crystalline (NC) materials.Among these different Severe Plastic Deformation (SPD) processesthat have been developed in the last few years for obtaining materials with sub micrometer or even nanometer grain size, one of the most widely used is the processing technique called Equal Channel Angular Extrusion (ECAE) or Equal Channel Angular Pressing (ECAP). The ECAP technique was invented in 1972 by a scientist from the former Soviet Union, V.M. Segal and it uses the principle of repeated shear deformation to refine the grain size in metallic materials.

The ECAP has a number of advantages first, very large deformation strain can be obtained after repeated passes without changing the shape of billet. Second, very uniform and homogeneous deformation can be applicable throughout the cross section of the billet. Third, no residual porosity is found in the deformed billets.

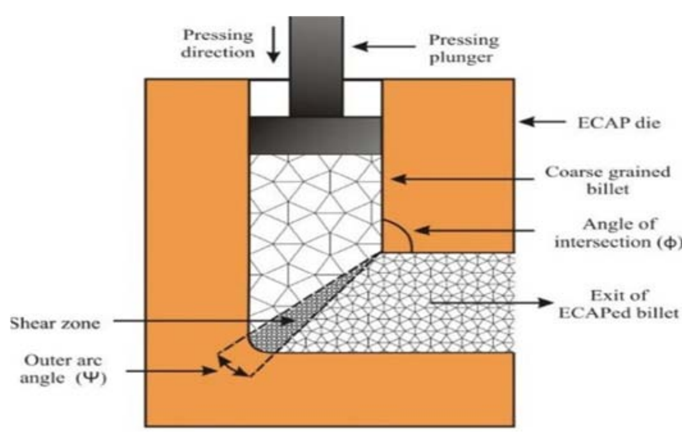

Fig. 1: Principle of ECAP technique

Fourth, since the size of the billets is only limited by the size of the die and the pressing facility, it is possible to produce large number of samples. Fifth, the area exposed to tensile stresses are limited during deformation. Figureure.1 explains the basic principle of the ECAP process, to press a sample through a die having two intersecting channelswhere the two channels have identical cross-sections so that the cross-section of the sample experiences no change during pressing.

The specially-designed die which is used in ECAP has two internal angles Φ and Ψ associated with the two channels where Φ corresponds to the angle between the two intersecting channels and Ψ is the angle at the outer arc of curvature of the two intersecting channels.

On passage through the die, the sample undergoes straining by simple shear as illustrated schematically in Figure2. The simple shear is imposed at the shearing plane of the sample between two adjacent segments labeled 1 and 2. Simple shear is considered a "nearly ideal" deformation method for structure and texture formation in metal working and it enables the sample to be subjected to a large amount of strain without the damage that occurs in conventional metal working such as rolling. Also, the unchanged cross-section of the sample makes it possible for the sample to be processed by ECAP repetitively and thus to accumulate very large shear strain.

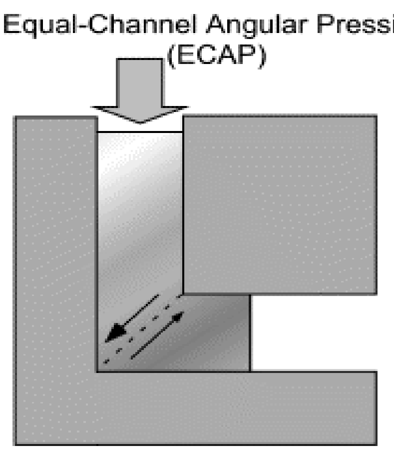

Fig. 2: The principle of shearing in the sample during ECAP

The magnitude of shear strain after one pass ECAP in the frictionless condition is determined with [12]:

$$\gamma = 2\cot\left(\frac{\emptyset+\Psi}{2}\right) + \Psi\mathrm{cosec}\left(\frac{\emptyset+\Psi}{2}\right)$$

Also, the magnitude of equivalent effective plastic strain (ε_{eq}) after N passesisgivenbythefollowingrelationship:

$$\varepsilon_N = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\emptyset}{2}+\frac{\Psi}{2}\right) + \Psi cosec\left(\frac{\emptyset}{2}+\frac{\Psi}{2}\right)\right]$$

The UFG materials processed by ECAP often exhibit an enhanced strength, but the ductility is also decreased [13].

However, various materials with high strength and ductility have been obtained after ECAP processing [14, 15].In contrast, data on toughness of the UFG materials are very limited, because the dimension of the samples processed by ECAP is usually so small that it is difficult to carry out the fracture toughness test.

In this study, Hardness and Microstructure tests on Al6061 alloys after ECAP is observed and carefully examined.Billets of Al6061 alloy were processed by ECAP for channel angle $\phi = 90^0$ at room temperature and microhardness measurements were recorded on the longitudinal and cross-sectional planes. The readings were recorded both on the top and bottom surface indicating that after ECAP the hardness value exhibits an increase of 40%.

2. EXPERIMENTAL PROCEDURE

The ECAP dies as shown in Fig. 3 (a) was designed based on die angles ($\phi = 90^0$, $\psi = 20^0$) and length of vertical channel around 120mm. Proper lubrication of dies, billet (length 80 mm), plunger is done using molybdenum disulphide (MoS_2). The dies were then placed between the rams of hydraulic machine of 50 T capacity with billet inside it. The plunger is then placed on the top of the billet and the load is applied with constant velocity of 1 mm/sec. The experiment was performed at room temperature.

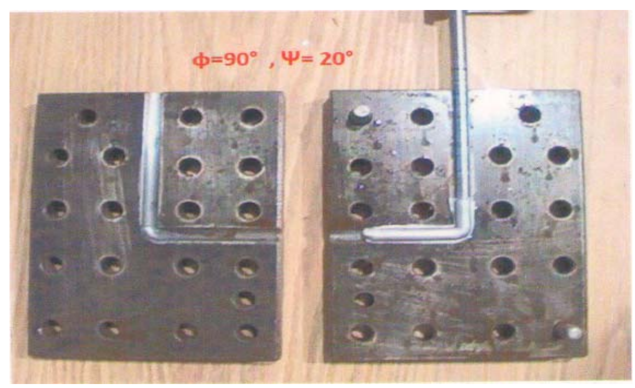

Fig. 3(a): ECAP dies

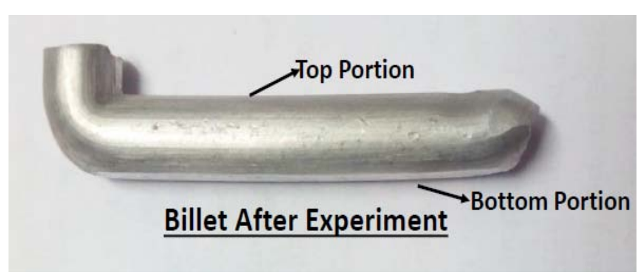

Fig. 3(b): ECAP processed billet

Specification of Al6061 alloy are Aluminium Balance, Magnesium 0.8-1.2 wt%, Silicon 0.4-0.8 wt%, Iron Max 0.7 wt%, Copper 0.15-0.40 wt%, Zinc Max 0.25 wt%, Titanium Max 0.15 wt%, Maganese Max 0.15 wt%, Chromium 0.04-0.35 wt% & others 0.05 wt%.

Hardness measurements were taken after one ECAP pass on thetop and bottom portion (Fig. 3b) of the billet on scale B of the Rockwell hardness tester and then the billet was cut into three parts (part A, part B and part C), Fig. 4, each of 10mm length and the hardness is measured along the three different cross-sections. Finally, polishing was done and the microstructure of all the three parts A, B and C were analyzed using SEM.

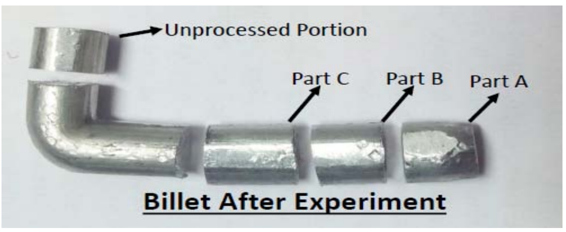

Fig. 4: Billet after experiment

3. RESULTS AND DISCUSSION

I. Hardness Measurements

a) Top Portion and Bottom Portion: The hardness of the Al6061 specimen provided before performing ECAP is 50 HRB and after performing the one pass on ECAP, the average measured hardness of Billet along the longitudinal direction on Top portion (Fig. 3b) is found to be 71.47 HRB and whereas on the Bottom portion it is found to be 65.16 HRB and graph was plotted, Fig. 5, which depicts the variation in the hardness along the Longitudinal Direction. It can be seen that the hardness values increases to 40% along the top portion and nearly 30% along the bottom portion after one ECAP pass.

Fig. 5: Hardness variation on top and bottom surface of ECAPed billet

b) Along the Cross sectional area: After one ECAP pass, the specimen was cut along the cross sectional plain into three different samples (Part A, B, C- 10mm each), Fig. 4, to measure the variation of hardness values along different cross-sections. As depicted in Fig. 6, part C exhibit higher hardness values ascompared to partA &part B.

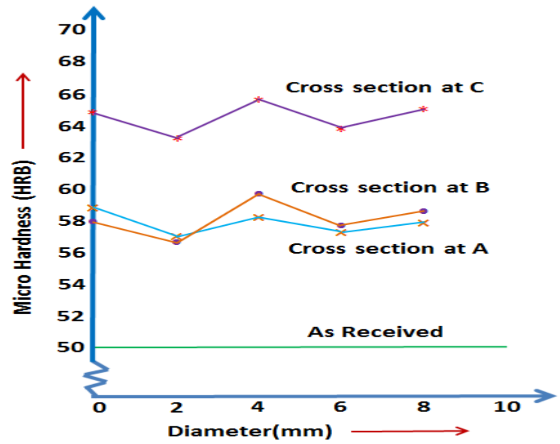

Fig. 6: ariation of hardness values along different cross-sections of the billet

II. Microstructure

The microstructural changes during Equal Channel Angular Pressing are depicted in Fig. 7a, Fig. 7b, and Fig. 7c. The grain refinement from ~60 µm (unprocessed sample) to average grain size of about 15 µm is observed during plastic deformation after one ECAP pass. The microstructure is measured for three different parts A, B and C along the cross-section at two different points, one near the top portion and the other near the bottom portion.

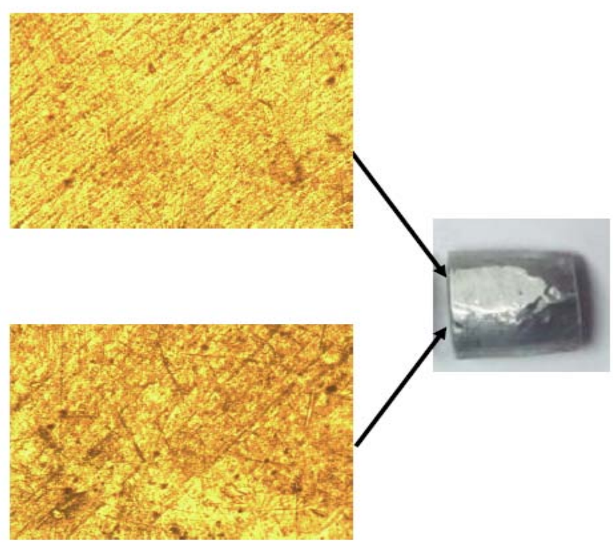

Fig. 7a: Microstructure of part A after ECAP

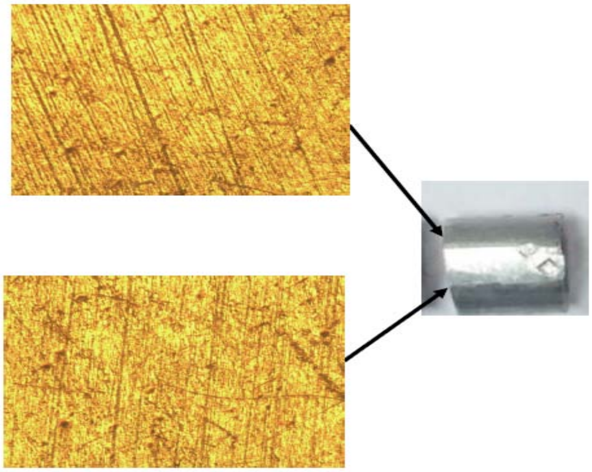

Fig. 7b: Microstructure of part B after ECAP

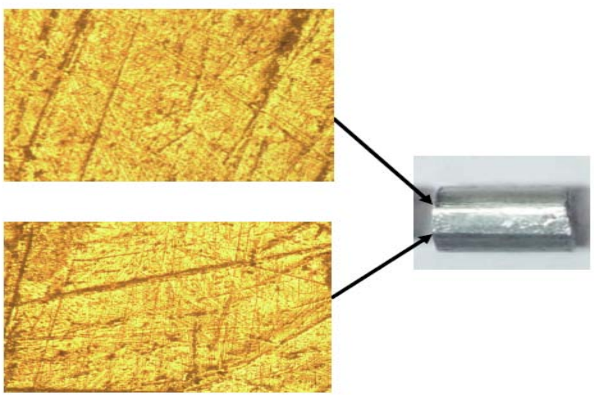

Fig. 7c: Microstructure of part C after ECAP

4. CONCLUSIONS

The Equal Channel Angular Pressing of Al6061 alloy was attempted and the study outlines the following points:

(a) The grain refinement from ~60 µm (unprocessed sample) to average grain size of about 15 µm is observed during plastic deformation after one ECAP pass for $\phi = 90^0$.
(b) Hardness measurements were taken along the longitudinal direction on top and bottom surfaces indicating an increase of about 40% from the unprocessed value.
(c) Specimen C exhibits higher hardness values, an increase of about 30%, as compared to other specimens along the cross-section of the billet.

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