Mechanical Characterization of Equal Channel Angular Pressed Al6061

Aishwarya Jadhav, B. Ankitha, Shreya Guddin,
2nd year, B.E, Mechanical Engineering,
R.V. College of Engineering, Mysore Road
Bangalore–560059,Karnataka,INDIA

Dr.Shanmukha Nagaraj
Professor, Department of Mechanical Engineering,
R.V. College of Engineering, Mysore Road
Bangalore–560059,Karnataka,INDIA

***Abstract*— Equal Channel Angular Pressing (ECAP) is currently being widely investigated because of its potential to produce ultra-fine grained microstructures in metals and alloys. The objective of this work is to study the effect of ECAP on the mechanical properties of Al 6061 alloy. Fabrication of the ECAP components for the processing of severely plasticized samples using die channel angles of 90º, 120º and 140º has been carried out. Mechanical behavior of the ECAP processed materials were investigated along with the hardness measurements to assess the improvement. Experimentation has revealed that the yield strength, ultimate tensile strength and the hardness of ECAP'ed samples showed tremendous improvement and proves the usage of ECAP for increasing the mechanical strength by modifying the grain structure, thereby producing ultrafine grained (UFG) materials.**

Keywords— Severe Plastic Deformation (SPD), Equal Channel Angular Pressing (ECAP), Al 6061 Alloy, Mechanical Performance (YS, UTS, Elongation and Hardness)

I. INTRODUCTION

Hall-Petch relationship [1, 2] describes that the grain refinement process improves the strength of metallic materials. But in Al-based alloys, it is generally difficult to reduce the grain size below 10 micrometer by the conventional recrystallization methods because the stacking fault energy in Al-alloys is relatively large, which assists the recovery of the dislocations [3]. Despite the difficulty in grain refinement through the recrystallization methods for Al alloys, it has been shown that the grain sizes of less than 1micrometer can be produced by a technique of equal channel angular pressing (ECAP) [4]. It consists of pressing test samples through a die containing two channels, equal in cross-section and intersecting at an angle $\phi\left(0<\phi\leq 90^{0}\right)$. It's also termed as equal channel angular extrusion (ECAE).

The sample is simply pressed through the channel and a shear strain is introduced in the sample when it passes through the bending point of the channel [5-7] and retains the same cross-sectional area so that it is possible to repeat the pressing for several cycles. A high total strain is imparted in the sample because of repetitive pressing wherein the sub-grain boundaries evolve into high-angle boundaries through the absorption of dislocations, thereby producing arrays of ultrafine grains separated by high-angle grain boundaries [8, 9]. Hence, ECAP is a very interesting method for modifying microstructure/grain structure, thereby producing ultrafine grained (UFG) materials.

UFG materials are characterized by higher strength and higher toughness at ambient temperature. If the UFG microstructure is retained to elevated temperature too, there is also a potential for achieving superplastic formability [10]. In fact the microstructure and mechanical properties of the deformed materials are directly related to the degree of plastic deformation and to its homogeneity [11]. The plastic deformation behavior is controlled by both die design parameters [7, 12] and parameters related to material properties, strain rate sensitivity and hardening exponent [13].

It is well known that alloys of 6000 series of Al-alloys are widely used in automotive and aerospace industries as a result of their good physical and chemical properties [14, 15]. Hence, the objective of this research work is to analyze experimentally the effect of ECAP on the mechanical properties of Al 6061 alloy for its strength enhancement and grain improvement. The experimental results are detailed in this paper. But, the improvement is because of the grain structure modification and the micrographic study of these is attempted in the up-coming paper.

II. EXPERIMENTATION

A. Fabrication

ECAP has three important parts: Die, Billet and Plunger. ECAP components were fabricated based on the drawing created in AutoCAD using Wire Electro Discharge Machining (WEDM. The dimensions of all the components are mentioned in Table 1. The ECAP was performed at room temperature, wherein material gets extruded in the Universal Testing Machine (UTM) and to keep friction away, Graphite-Grease mixture is used as a lubricant during the process. Two dies - male and female (Fig. 1(b)), clamped by bolts and guide pins complete the assembly. The male die has two guide pins to position both the die accurately. When both are packed together, square hole is formed (Fig. 1(b)), through which the plunger extrudes the billet. The channel was bent through an angle of 60°, 90° and 120° in the vicinity of the center of the die and an arc of curvature.

Component	**Material**	**Dimensions (mm)**
Die	Steel	110 × 80 × 50
Billet	Aluminium 6061	9.5 × 45
Plunger	High Speed Steel	10.4 × 80
Bolts	Steel	M8 × 38
Guide Pins	Mild Steel	ϕ 8 × 50

Table 1. Specimen Details

Two halves of the Die

Assembly

Fig 1. ECAP dies

B. *ECAP Process*

First the upper arm of the Universal Testing Machine (Fig.2) is lowered at a very low speed till the contact is made between the upper arm of Universal Testing Machine and the die placed above the plunger. Care is to be taken during this process to provide adequate support to die so that it doesn't fall off from the set up. Once this criterion is satisfied the set up is ready to apply load. The load has to be applied for the plunger to push the billet through the channel.

A gradual load is applied to the billet and the extrusion takes place. Some graphite powder is placed at the top of die so that the plunger takes along with it graphite powder during its movement in to the die channel, this ensures a separation between plunger and the die wall so that they don't weld during the process and removal after extrusion is easier. As the load is applied to the billet at some point the material starts to yield. As the loading continues the billet continues to extrude and the process of loading is continued till the plunger goes inside the channel till the mark previously made on the plunger coincides with the upper surface of the die. This completes extrusion process. The load at the end of extrusion process is noted down.

After completion of extrusion process the compression arms are retracted and the assembly is taken, the plunger can be removed from the die easily by pulling it. The bolts are unscrewed using Allen key. The die is slightly tapped along its sides so that it slightly opens. A screw driver is then used to open up the two die halves and the billet is removed and can be used for further extrusion process. The above mentioned steps are repeated to get billets extruded by one pass, two pass, three pass, four pass etc., but the specimen is rotated counterclockwise 90° around its longitudinal axis between each pass, since large total strains can be introduced without changing the initial shape and refined the grain size of face centered cubic (FCC).

Fig 2. Schematic showing the assembled view on UTM ready for load to be applied

C. *Mechanical Testing*

Cylindrical tensile specimens were machined from the as-ECAP pressed rods with dimensions as shown in Fig. 3. For comparison, additional tensile specimens were prepared with no ECAP pressing in order to evaluate the influence of ECAP pressing on the tensile properties of the alloy. All of the tensile testing was performed at room temperature in a test machine operating at a constant rate of cross-head displacement to an initial stain rate of 0.004/s using 10T UTM.

D. *Hardness Testing*

After ECAP, billet's cross section is rubbed against various grades of emery paper (D100, C180, 400, C600, C1000 grades) in a uniform manner with continuous 90° rotation starting with D100 grade emery paper and finishing with C1000 respectively. Further, the specimens are polished using polishing machine with fine powder of magnesium oxide paste. The specimen is then subjected to hardness tests using Rockwell hardness machine with cone indenter.

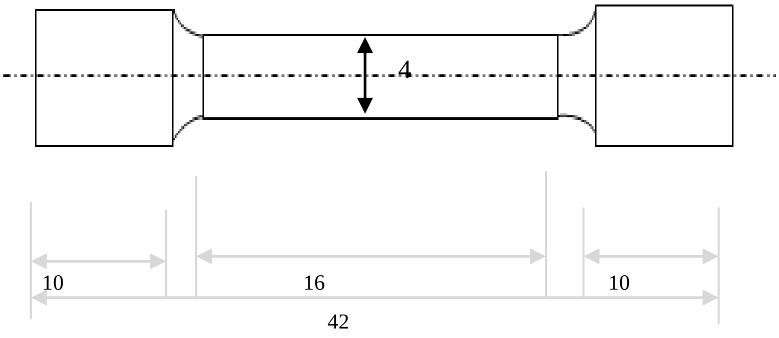

Fig 3. Tensile specimen specifications (all dimensions are in mm)

III. RESULTS AND DISCUSSIONS

A. Experimental Results

1. Mechanical Properties

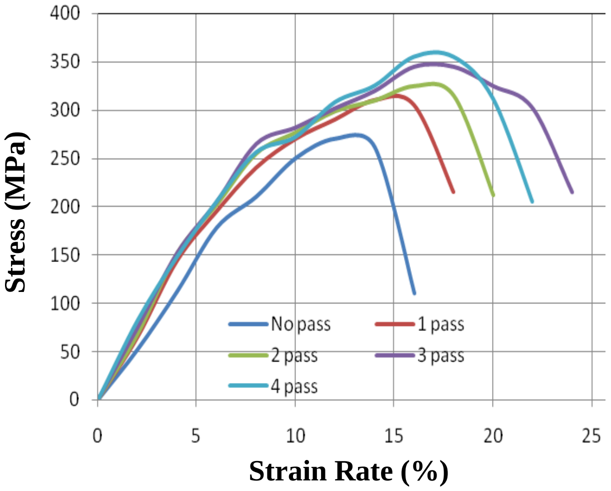

Fig 4 (a). Typical engineering stress and strain curves of the ECAP Al 6061 alloys

Tensile tests were carried out on as-cast alloy and ECAP'ed samples. Fig 4(a) illustrates the engineering stress and strain curves of the as-cast alloy and four ECAP'ed samples. As shown in this figure, both the maximum stress and the maximum strain significantly increased after ECAP process. Tensile strength, particularly the yield strength, noticeably increased after the first passes. Then the yield strength, in particular the yield strength of the forth passed ECAP, noticeably increased and then decreased gradually as the number of ECAP passes increased. The ultimate tensile strength (UTS) however increased as the number of ECAP passes were increased up to four passes (Fig 4(b)).

Fig 4(c), illustrates the elongation to failure as a function of the number of ECAP passes. The elongation to failure remarkably increased with increasing the number of ECAP passes, and finally reached 15% after passes than that of the as-cast alloy's 13.5 % elongation. It is seen that the hardness (Fig 4(d)) and the ultimate tensile strength (Fig 4(b)) of the specimens after ECAE are higher than that of the specimen without ECAE. The hardness and the ultimate tensile strength increases remarkably with a significant decrease in elongation after one pass of ECAE. However, the hardness, ultimate tensile strength and elongation increase with the increase of the pass number after two passes of ECAE. The improvement of the mechanical properties is attributed to the difference in microstructures between as-received and extruded aluminium specimens. Grain size decreased and grain was refined during the progress of ECAE. Grain refinement can affect mechanical properties of polycrystalline materials [7]. The classical effect of grain size on hardness can be explained by the Hall–Petch model [12].

The microstructure of the as-cast Al alloy usually consists of large aluminium dendrites and large eutectic silicon elements. In addition, some casting defects exist such as micro-shrinkage, small gas porosity etc. These are the primary reasons for the low tensile properties of this alloy. During ECAP, the large aluminium dendrites and eutectic zinc elements were broken and the casting defects were eliminated.

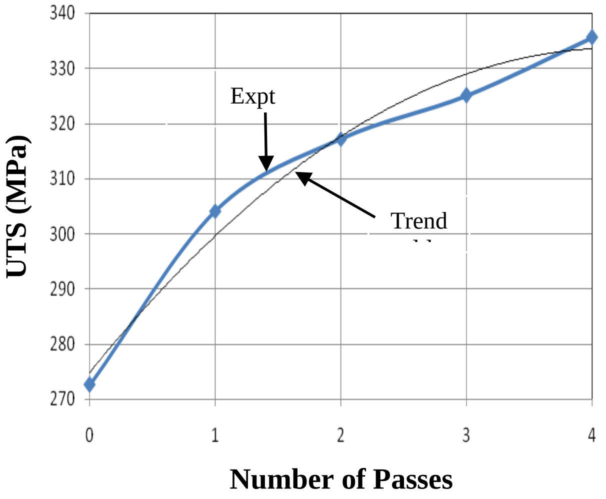

Fig 4 (b). Ultimate tensile strengths of the aluminum specimens with various pass numbers

This is the reason for this alloy pressed for only four passes of ECAP exhibiting much higher tensile strength and much better ductility compared with the as-cast alloy. As is well known, the strength depends on both the grain size and the state of the second phase in the alloy i.e. size and morphology of the grains. While the as-cast samples exhibit mainly a brittle fracture behavior, the processed alloys show a typical ductile fracture behavior compressing of well-developed dimples (morphology study, which is not in the scope of this paper) over the entire surfaces, which means that the brittle as-cast alloy was transformed into the ductile alloy by multi-pass SPD.

2. Hardness values as a function of number of ECAP passes

Vickers micro hardness tests were taken on both 6061 aluminum samples in order to determine the mechanical properties across their surface of interest, as well as quantify the change in hardness as ECAE passes increased.

The hardness of each specimen is found and they are compared as in Fig 5(a), wherein the hardness value of the ECAP'ed Al6061 has increased as the number of passes increased. Also in [16], its been shown that the hardness values in case of 90º die channel angle was found to be maximum when compared to 120º and 140º die channel angle. Also, Fig. 5(b) gives the plot of percentage increase in hardness as a function of number

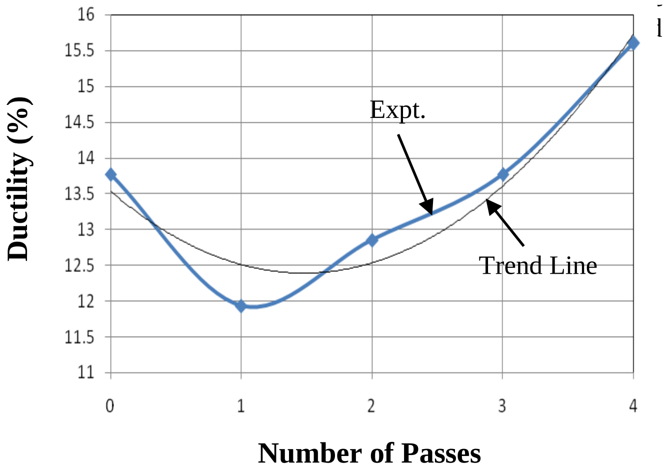

Fig 4 (c). Ductility of the aluminum specimens with various pass numbers

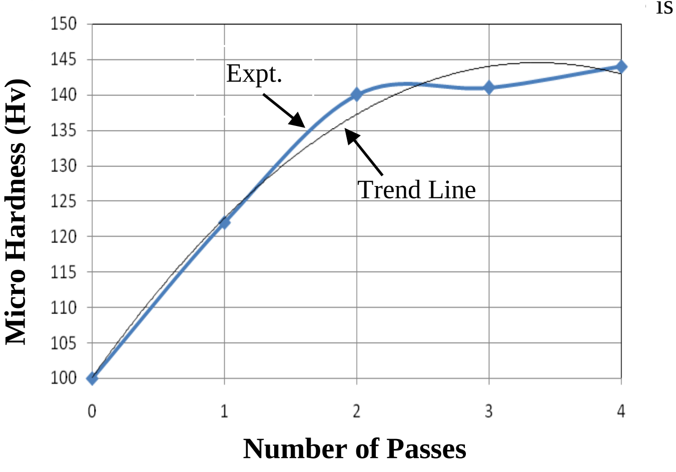

Fig 4 (d). Micro-hardness of the aluminium specimens with various pass numbers

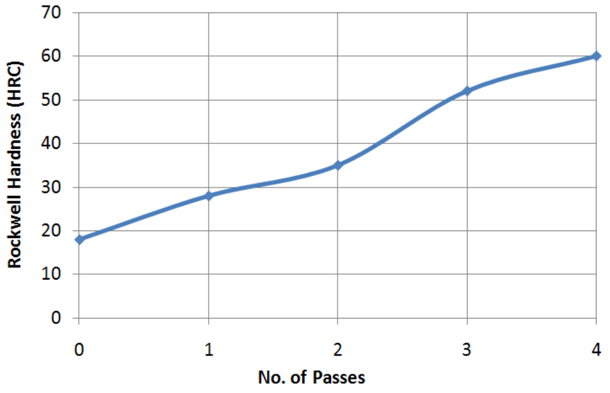

Fig 5(a). Hardness of the Al 6061 as a function of Number of ECAP passes

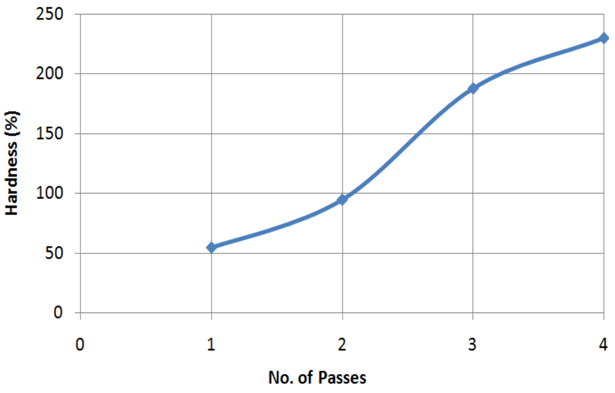

Fig 5(b). Percentage increase in Hardness vs. Number of ECAP passes

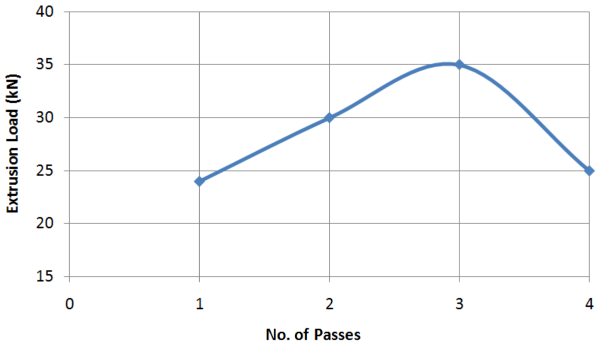

Fig 6.

to as-cast alloy specimen. This shows that there is an improvement in the mechanical properties of the aluminium as the number of passes increases.

3. Load required for extrusion

It is also observed that the load required for extrusion of aluminium billet goes on increasing up to some extent and then decreases as shown in Fig 6. The reason for this behavior being the strength during the deformation at later stages is chiefly controlled by complex dislocation

decrease in load requirement, after the third pass. Also, the effect of grain boundary on plastic deformation is vital because deformation must be transmitted through the grain boundaries. During deformation, dislocations pile up along slip planes at the grain boundary. As the stresses are increased, more and more dislocations pile up and higher shear stresses are developed at the head of dislocations and piles up, which eventually leads to dislocations movement in the neighboring grain across boundary.

B. Conclusions

This research project has established that ECAP, a type of SPD method, has the potential to significantly reduce the grain size, resulting in superior mechanical properties. The simplicity of the process, lends itself to be easily adopted in the manufacture of miniature shafts, gears and other parts in micro-mechanical systems for defense and space applications.

From the successful experimental study on equal channel angular pressing of Al 6061, every aspect of the mechanical property considered here has been improved in an amplified way:

- Yield strength and the ultimate tensile strength (UTS) noticeably increased as the number of ECAP passes increased.
- The elongation to failure remarkably increased with increasing the number of ECAP passes, and finally reached 15% after passes than that of the as-cast alloy’s 13.5% elongation
- We see 4 times increase in the hardness of the four passed ECAP specimen as compared to as-cast alloy specimen. This shows that there is an improvement in the mechanical properties of the aluminium as the number of passes increases.
- The hardness and the ultimate tensile strength increases remarkably with a significant decrease in elongation after one pass of ECAE. However, the hardness, ultimate tensile strength and elongation increased with the increase in the pass number after two passes of ECAE. The improvement of the mechanical properties is attributed to the difference in microstructures between as-received and extruded aluminium specimens.
- During ECAP, the large aluminium dendrites and eutectic zinc elements were broken and the casting defects were eliminated. This is the reason for this alloy pressed for only four passes of ECAP exhibiting much higher tensile strength and much better ductility compared with the as-cast alloy. Hence, the brittle as-cast alloy was transformed into the ductile alloy by multi-pass SPD.

ACKNOWLEDGMENTS

The authors would take this opportunity to acknowledge the Professor & Head, department of Mechanical Engineeing, RVCE.

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