IOP Conf. Series: Materials Science and Engineering **433** (2018) 012055 doi:10.1088/1757-899X/433/1/012055

Enhancement of the Mechanical Properties of Al-Pb Alloy using an Equal Channel Angular Pressing Process

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Abstract. Aluminium-lead alloys are considered to be vital materials for the 21st century, and applications of these alloys are used in a great many heavy-duty roles such as boring mills, presses, lathes, milling machines, and hydraulic pump bushings. In this work, an equal channel angular pressing (ECAP) process was used to enhance the mechanical properties of Al-Pb bearing alloy prepared using a mechanical alloying method. This work is divided into two main parts: Part I deals with the production of rectangular billets of 15 × 15 × 45 mm^3 in size constructed by mixing powders of Al-10%Pb-4.5%Cu by weight for two hours using a ball milling process. The mechanical properties obtained for these alloys were 191 MPa compressive strength and 50 HV micro hardness. Part II is concerned with the design and manufacture of an ECAP die for a channel angle of 135° with multi passes using rout B^C radius of curvature with inner radius R equal to 15 mm and outer radius r equal to 5 mm suitable for the chosen alloy. The billet produced in part I was then preheated and pressed through the ECAP die. The results obtained from the experimental work showed an increase in mechanical properties: the enhancement of compression strength reached 38%, and that of micro hardness 28% in the first pass; further enhancements of compression strength and micro hardness were 44% and 36% respectively in second pass, without any reduction of ductility in the alloy.

1. Introduction

Severe plastic deformation (SPD) is a unique process that has grown in importance in the last decade due to its potential application in developing significant deformations in a variety of materials and alloys, as well as its production of ultra-fine-grained microstructures. The processes related to fulfilling the operation goals are equal-channel angular pressing (ECAP), and high-pressure torsion (HPT) [1]. To produce the ultra-fine grain structure, ECAP is considered to be the prime technology. One important advantage of ECAP is that it retains the dimensions of the billet while exposing it to a large amount of shear strain [2]. The ability to repeat the ECAP process several times with no change in dimensions while increasing the applied strain to the required level is one of the important benefits of the process. Applying severe strains and simple shear mode enhances the properties of the produced material, which offers an important advantage [3]. Materials including metals, polymers, ceramics, and composites have been tested using the ECAP process [4], also known as equal channel angular extrusion (ECAE) in work by Segal et.al in the 1980s in USSR formerly [3]. Figure 1 shows a schematic diagram for the die commonly used in the ECAP process.

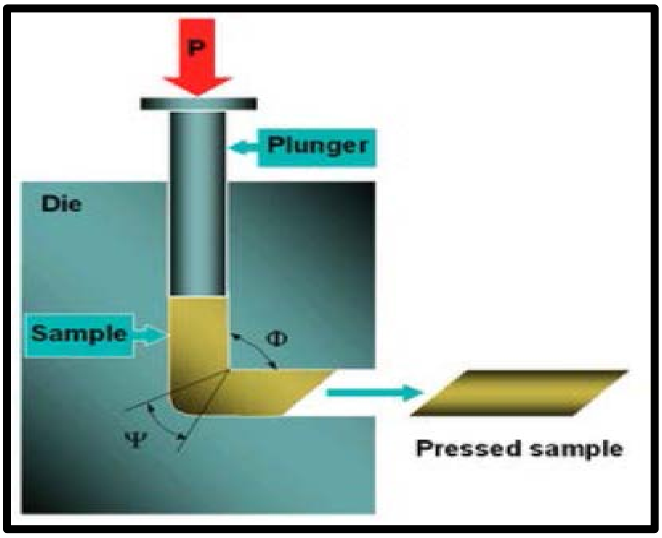

Figure 1. Conventional ECAP process [5].

Figure 2 shows a schematic diagram of four different routes used in the ECAP process. In path (A), the billet is pushed with no rotation, while in path (B_{A}) the billet can be rotated by 90° following each sequential pass. In path (B_C), the billet can be rotated 90° in its original direction (either clockwise or anti-clockwise), while in path (C), the billet can be rotated 180° along all passes [6].

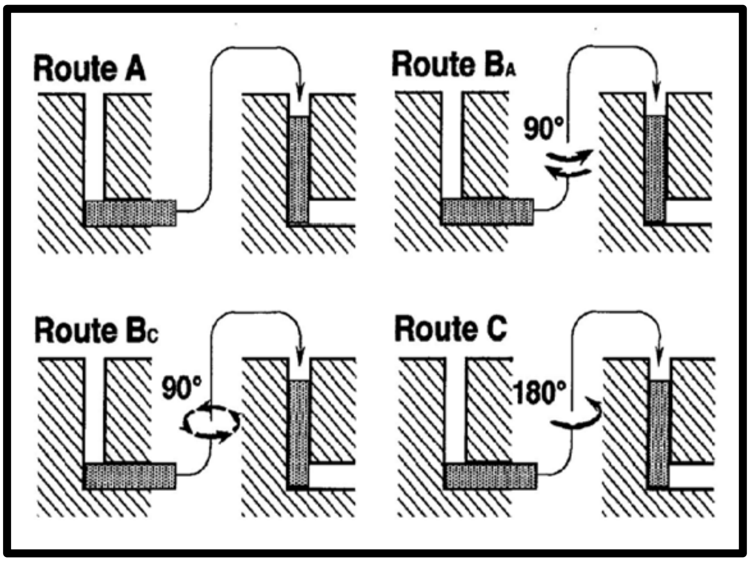

Figure 2. Processing paths (routes) in ECAP [7].

Veeranjaneyulu et al (2016) studied the effective parameters of die design in the equal channel angular pressing process when using different channel angles (90°, 120°, and 135°) with AA6351 billet material. The study concluded that large changes in material properties were achieved in a single pass when using very low values for φ and *Ψ*. It also showed that the greater angle channel, the less

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changeable the levels of stress and strain were [8]. ***Mohammed Hadi Ali (2015)*** used multi pass equal-channel angular pressing with high chromium carbon steel die in four passes using route B with 5 mm/min deformation speed at a temperature of 250 ºC. Different percentages of Mg_2Si and Si contents were thus examined to study the effect on Al-Si/Mg_2Si as the main alloy. Increasing the passes of equal channel angular pressing reduced Mg_2Si particles and achieved a smaller size of dendrite Mg2Si particles. The columnar α-Al phase created equiaxed grains after the deformation was achieved repeatedly [9]. Pure aluminium was used in the study presented by ***Nashith et al (2014),*** which showed an improvement in hardness due to severe plastic deformation using the ECAP process. The grain size refinement was related to the number of passes and suitability of routes. In general, the study concluded that the ECAP process should be regarded as an effective and simple way to improve the mechanical properties of aluminium and aluminium alloys [10]. The influence of the ECAE process on the microstructure and tensile behaviour of materials was further studied by ***Mohan Reddy et al (2013)***. In this study, route A was used, showing that an improvement in the mechanical properties of Al alloys could be achieved by means of severe plastic deformation. The evolutionary rate of microstructure creation during a multi pass ECAE process in aluminium (7075) alloy using die angles 120◦ and 50◦ for Φ and ψ respectively was evaluated using an optical microscope. In this process, two passes were required to obtain an ultrafine-grained structure for this alloy. Increases in strength and hardness are obviously obtained when using the ECAE process, and increasing the number of passes enhanced the effects on strength and hardness because of the fine grain structure obtained [11].

The combined effect of natural aging and severe plastic deformation (SPD) on microstructure, strength, and ductility in equal channel angular pressing was studied by ***Nguyen Q. Chinh et al (2010)***. In this study, AlZnMg alloy was used and the process was carried out at room temperature. The results showed that one or two passes were sufficient to achieve valuable improvements in strength and to reduce microcracks formed during severe plastic deformation. Using equal channel angular pressing with certain numbers of passes increased the ductility of samples used in addition to adding to their strength [12]. The microstructural evolution rate and tensile and impact toughness of an aluminium-zinc copper (Al-40Zn-2Cu) alloy were studied by ***PURCEK et al (2009)*** using ECAE route A or route B_C with not more than four passes. Complete elimination of as-cast dendritic microstructure casting defects such as micro porosities was achieved. The study showed enhancement for both strength and ductility when compared with as-cast condition, and the number of passes and the routes of the process acted as effective parameters on both strength and ductility. After using the ECAE process, the produced alloy behaviours shifted from brittle to ductile [13].

Using lead and tin as additives for aluminium alloys also has a bearing on applications. Tin offers higher friction and scratch features than lead, which is nevertheless regarded as a generally effective additive in soft phase alloying; Al-Pb alloy is considered to be the premium aluminium-based bearing alloy. The homogenized spread of soft phase in aluminium matrix contributes to improving wear properties [14]. The aim of the present work is thus to improve the mechanical properties and microstructure of an Al- Pb–Cu alloy used as bearing alloy.

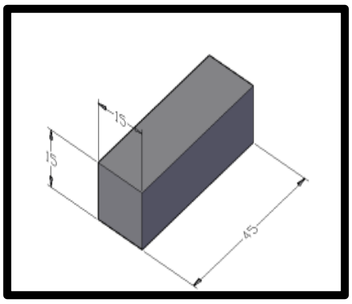
2. Experimental Work

2.1. Preparation of Samples

A mechanical alloying process was used to prepare the samples of Al- Pb –Cu) alloy without any additions. The chemical composition of the alloy was 85.5% Al- 10% Pb- 4.5% Cu, by weight.

Two-hour duration ball milling, compacting at 400 MPa, and sintering at 450 °C for 30 minutes in an argon protection furnace was used to produce square cross section billets of 15 mm ×15 mm with 45 mm height. Figure (3) shows a photo of the die used to produce the green compacts (billets), while figure (4-a) shows a schematic diagram and figure (4-b) shows a photograph of the billets.

Figure 3. Die used to produce the billets



(a) **(b)**

Figure 4. (a) Schematic diagram, and **(b) a photograph of billet produced.**

2.2. Die Material and Design

The ECAP die was made from tool steel with two parts. Part one consisted of two grooves with square cross-sections of 15 mm × 15 mm manufactured to form an angle of 135°. The radii for both inner and outer lines, marked as in figure (5) as (R) and (r), were of 15 mm and 5 mm, respectively. A photograph of part one of the die is shown in figure (6).

Part two was a flat plate that acted as a cover for the first part to form the route was formed. Four heaters with K type thermocouples were built within part two of the die to supply the rig with a suitable heat flux to assist the billets passage through the route, and digital controller was connected to control the required temperature for each run. Figure (7) shows the two parts of the die with the plunger.

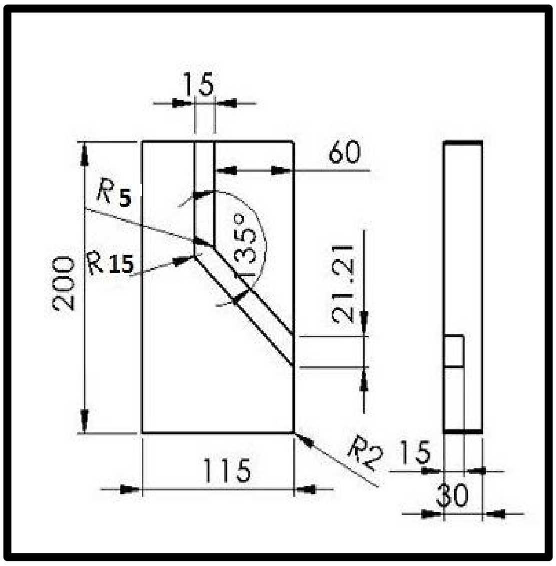


Figure 5. Schematic diagram of ECAP die

Figure 6. Photograph of part one of the die.

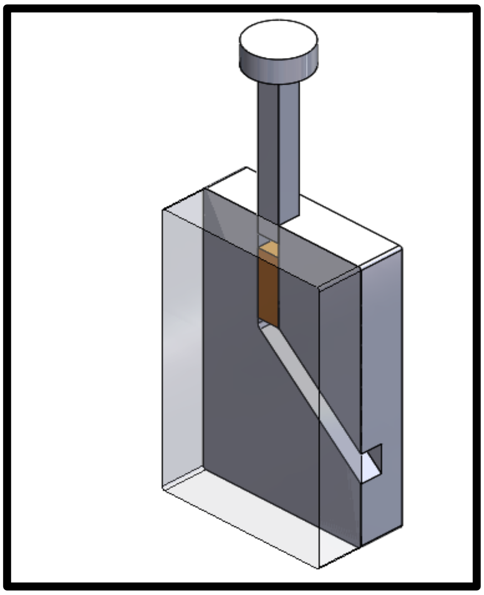


Figure 7. A diagram of both parts of the die with the plunger.

2.3. Procedure

The two parts of the die were assembled inside an adjustable enclosure made of tool steel to withstand the high forces applied, with six bolts and nuts used to fix the two parts tightly together. The assembled rig is shown in figure (8).

Figure 8. ECAP Die with heating system

The first step was to insert the sample inside the die with an adequate quantity of lubricant around the sample and inside surface of the die to reduce the friction generated during pressing. The second step was to heat the sample and die to 250 °C using the electric heaters. Several different runs for temperatures ranging from 50 °C to 250 °C were undertaken; however, any run under 250 °C destroyed the billet inside the die. At 250 ˚C, the billet flow smoothly without any cracks. After the system was heated to a required temperature, the compression test device was used to apply the required pressure. The plunger was used to press the sample into the intersection of the two channels of the die with a ram velocity equal to 0.1 mm/sec and a force of 33 KN. After the sample was pressed into the die channel and exited from the other side, it was reinserted into the die using route $\mathbf{B}_{C}$ for a second pass.

2.4. Examination of the mechanical properties of samples

The deformed billets were prepared for examination of their mechanical properties. According to ASTM standards section E9, the billets were machined to standard dimensions for compressive strength tests. Vickers micro hardness tests were employed for the billets after preparation before they were cut into cubic samples prior to grinding and polishing. The same tests were applied on the billets before and after deformation through the ECAP die to assess the results

3. Results and Discussion

The configuration of the deformed billet after the first and second pass is shown in figure (9).

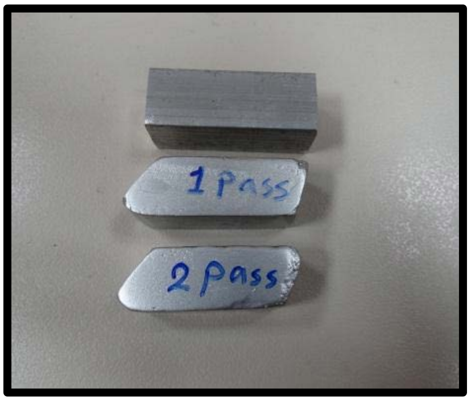


Figure 9. Billet shape after first and second passes.

The mechanical properties of the produced deformed billets showed improvements. Figure (10) shows the micro hardness of the deformed samples after the first and second passes. The figure shows the values of hardness along the width of each sample was not homogeneous due to the variance of strain caused by the radius of curvature on both two sides of the groove which affected the produced mechanical properties; thus, the properties became anisotropic, and the trend of curve agreed with the reference results [1]. Hence, the procedure was performed using a second pass through route B_C, which rotated the sample produced in pass 1 at an angle of 90°, re-entering it into the die and deforming it to make the properties of the sample homogenous.

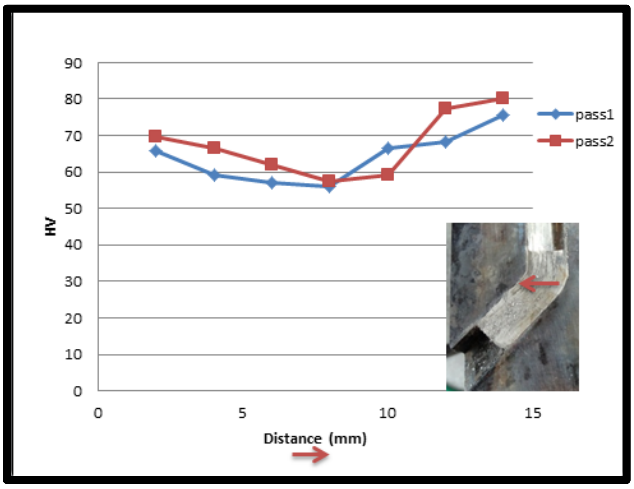


Figure 10. Vickers microhardness (HV) distribution through sample using ECAP die.

The mechanical properties of samples before and after pressing them into the angular die are listed in table 1.

Table 1. The mechanical properties of Al-Pb alloy before and after deformation through ECAP die (135°).

	Vickers Micro Hardness (HV)	Ultimate Compression strength (MPa)	Yield Compression strength (MPa)	Ductility (%)
Before deform	**50**	**191**	**153**	**12.5**
After deform Pass 1	**64**	**264**	**202**	**18**
After deform Pass 2	**68**	**276**	**208**	**18.8**

From table 1, the yield and ultimate compression strength and the magnitude of strength and hardness enhancement were increased during deformation after pass 1, with further enhancement noted after pass 2. The percentage enhancement of compression strength reached 38% and 44% at pass 1 and pass 2 respectively, and the percentage of enhancement of micro hardness reached 28% and 36%. This was due to strain hardening in the material because of the deformation process. In addition, the deformation took place without any significant change in dimensions, strongly enhancing the mechanical properties and improving the ductility. This is an improvement over conventional improving processes which lead to improved hardness and strength but reduced ductility. Thus, one of the characteristics of the ECAP process is retaining ductility of material and improving it, which is

very useful for improving fatigue properties especially where parts produced in this process are used as bearings parts where high fatigue strength is a major property of concern.
In general, in the present work, the enhancement of mechanical properties and microstructure for the Al-Pb bearing alloy was done without an excessive period of ball milling as seen in all previous papers (20, 30, and 40 hours of mixing). The process followed included a reduction in the mixing time to the lowest time necessary for alloying the powder. Nevertheless, the results obtained had good agreement with previous papers, so the costs of power consumed were reduced, and the life time of the required devices extended without negative impact.

4. Conclusions

1. The ECAP process is a more attractive method for enhancing the mechanical properties of Al- Pb alloy.
2. For deformation processes in an ECAP die at 135°, the percentages of enhancement of compression strength reached 38% and 44% in pass 1 and pass 2, respectively, and the percentage of enhancement of micro hardness reached 28% and 36%, respectively.
3. In the present work, in addition to an increase in the mechanical properties of compression strength and micro hardness, increased ductility was observed.
4. The time and power consumed to produce the required characteristics in the alloy by means of mechanical alloying are reduced by use of the ECAP process.

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