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Enhancement of Mechanical Properties of AA 6351 Using Equal Channel Angular Extrusion (ECAE)

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Abstract The Equal Channel Angular Extrusion (ECAE) process is a promising technique for imparting large plastic deformation to materials without a resultant decrease in cross-sectional area. The die consists of two channels of equal cross section intersecting at an angle of 110°C. The work piece is placed in one channel and extruded into the other using a punch. In the present study, Influence of equal channel angular extrusion on room temperature, the mechanical properties of Aluminum Alloy AA 6351 alloy was investigated. The results show that, the mechanical properties of Aluminum AA 6351alloy, such as yield strength, ultimate tensile strength and elongation, can be improved heavily by equal channel angular extrusion. Processing routes, processing temperature and extrusion passes have important influence on room temperature mechanical properties of processed Aluminum AA 6351alloy by equal channel angular extrusion. The mechanical properties such as yield strength and ultimate tensile strength can be enhanced when Aluminum AA 6351 alloy was processed by equal channel angular extrusion for single pass at route A at 303 K.

Keywords: *equal channel angular extrusion (ecae), yield strength, ultimate tensile strength, hardness, microstructure*

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1. Introduction

Although the mechanical and physical properties of all crystalline materials are determined by several factors, the average grain size of the material generally plays a very significant, and often a dominant role. Thus, the strength of all polycrystalline materials is related to the grain size, d, through the Hall–Petch equation which states that the yield stress, σy, is given by:

$$\sigma y = So + ky\, d - 1/2 \qquad (1)$$

where So is termed the friction stress, ky is a constant of yielding and d is the grain size. It follows from Eq. (1) that the strength increases with a reduction in the grain size and this has led to an ever-increasing interest in fabricating materials with extremely small grain sizes. The grain sizes of commercial alloys are generally tailored for specific applications by making use of pre-determined thermo-mechanical treatments in which the alloys are subjected to specified regimes of temperature and mechanical testing. However, these procedures cannot be used to produce materials with sub micrometer grain sizes because there is invariably a lower limit, of the order of a few micrometers, which represents essentially the minimum grain size readily attained using these procedures (5). Accordingly, attention has been directed towards the development of new and different techniques that may be used to fabricate ultrafine-grained materials with grain sizes in the sub micrometer and the nanometer range.

To place these terms in the right context, it is first necessary to provide a formal definition of ultrafine-grained materials (UFG) (12). With reference to the characteristics of polycrystalline materials, UFG materials are defined as poly crystals having very small grains with average grain sizes less than 1μm. For bulk UFG materials, there are the additional requirements of fairly homogeneous and reasonably equiaxed microstructures and with a majority of grain boundaries having high angles of disorientation (8). The presence of a high fraction of high-angle grain boundaries is important in order to achieve advanced and unique properties.

Two basic and complementary approaches have been developed for the synthesis of UFG materials and these are known as the ''bottom-up'' and the ''top-down'' approaches. In the ''bottom-up'' approach, UFG materials are fabricated by assembling individual atoms or by consolidating nano-particulate solids (9). The ''top-down'' approach is different because it is dependent upon taking a bulk solid with a relatively coarse grain size and processing the solid to produce a UFG microstructure through heavy straining or shock loading. This approach avoids the small product sizes and the contamination which are inherent features of materials produced using

the ‘‘bottom-up’’ approach and it has the additional advantage that it can be readily applied to a wide range of pre-selected alloys (4).

2. Problem Definition

The first observations of the production of UFG microstructures using the ‘‘top-down’’ approach appeared in the scientific literature in the early 1990s in several publications dealing with pure metals and alloys. It is important to note these early publications provided a direct demonstration of the ability to employ heavy plastic straining in the production of bulk materials having fairly homogeneous and equiaxed microstructures with grain sizes in the sub-micrometer range and with a high fraction of high-angle grain boundaries (10). In order to convert a coarse-grained solid into a material with ultrafine grains, it is necessary both to impose an exceptionally high strain in order to introduce a high density of dislocations and for these dislocations to subsequently re-arrange to form an array of grain boundaries (5). Aluminum and its alloys are being widely used as a predominant material in various engineering applications. More significantly, ultra fine grained (UFG) high strength aluminum alloy AA 6351 is in great demand to be used in various applications. But due to its moderate strength, it is not preferred for applications requiring high strength.

3. Objective

The main objective of this work is to improve the properties of AA 6351 alloy and to investigate the effect of Equal Channel Angular Extrusion (ECAE) on microstructure and mechanical properties.

4. Severe Plastic Deformation Techniques

As a consequence of these limitations, attention has been devoted instead to the development of alternative processing techniques, based on the application of severe plastic deformation, where extremely high strains are imposed at relatively low temperatures without incurring any concomitant changes in the cross-sectional dimensions of the samples. Formally, processing by severe plastic deformation (SPD) may be defined as those metal forming procedures in which a very high strain is imposed on a bulk solid without the introduction of any significant change in the overall dimensions of the solid and leading to the production of exceptional grain refinement so that, typically, the processed bulk solids have 1000 or more grains in any section.

In these techniques, metals were subjected to large deformation under high applied pressures in attempts to improve the mechanical properties of materials that were inherently fairly brittle. These techniques include equal-channel angular pressing (ECAP), high-pressure torsion (HPT), multi-directional forging, friction stir processing (FSP). All of these procedures are capable of introducing large plastic straining and significant micro structural refinement in bulk crystalline solids.

4.1. Equal Channel Angular Extrusion

The various procedures, equal-channel angular pressing is an especially attractive processing technique for several reasons. First, it can be applied to fairly large billets so that there is the potential for producing materials that may be used in a wide range of structural applications. Second, it is a relatively simple procedure that is easily performed on a wide range of alloys and, except only for the construction of the die, processing by ECAP uses equipment that is readily available in most laboratories. Third, ECAP may be developed and applied to materials with different crystal structures and to many materials ranging from precipitation-hardened alloys to intermetallics and metal–matrix composites. Fourth, reasonable homogeneity is attained through most of the as pressed billet provided the pressings are continued to a sufficiently high strain. Fifth, the process may be scaled-up for the pressing of relatively large samples and there is a potential for developing ECAP for use in commercial metal-processing procedures. These various attractive features have led to many experimental studies and new developments in ECAP processing over the last decade. Interest in the field of nano-structured materials has grown tremendously in recent years. The potential of improving mechanical properties by reducing the grain size to the nano-structured regime has been aggressively addressed in the past decade. Over the past several years there has been considerable interest in the phenomena that take place at nanometer length scales and that may lead to novel mechanical properties in structural materials. Severe plastic deformation may be used as a processing tool to achieve a refinement in grain size in metallic alloys to the sub micrometer or nanometer range.

4.2. Working Principle

The process of equal channel angular extrusion involves pressing a billet through a die, consisting of two channels of identical shape and cross-sectional dimension that are positioned under a predetermined angle Φ and an additional angle of Ψ that defines the arc of curvature at the outer point of intersection of the two channels. As the billet is extruded through the die, it is deformed at the point of intersection of the two channels along the shear plane indicated by the two lines. If an outer corner angle of $\psi 0 = 0°$ is used, the shear plane is stationary, whereas if non-zero angles are used the shear plane gradually rotates, following the shape of the corner.

When comparing the construction of the die for equal channel angular extrusion with that for conventional extrusion, the essential difference is that the cross-sectional shape and dimension remain the same for the inlet and the outlet channel of the equal channel angular press. On the other hand, there is a drastic change in the shape and dimension between the “inlet channel” and the “outlet channel” of a conventional extruder. It is because of this difference that deformation by means of convention extruder can only be applied once.

On the other hand, it is possible to conduct an infinite number of pressings on a material when using equal channel angular extrusion. Hence the total effective deformation equals the deformation of the single pressing in the case of conventional extrusion and the accumulated deformation per pressing in the case of equal channel angular extrusion. The schematic of the ECAE die is

shown in Figure 1. The amount of equivalent strain depends upon the two angles, Φ and Ψ, and given through a relation, developed analytically, that depends on the geometry of the process. channel" and the "outlet channel" of a conventional extruder. It is because of this difference that deformation by means of convention extruder can only be applied once.

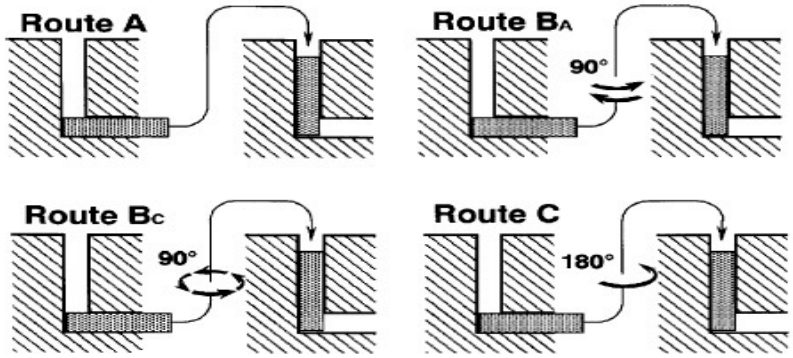

Figure 1. Processing routes in ECAP

4.2.1. ECAE Processing Parameters

The homogeneity and the amount strain induced depends on the various parameters of the tool which are described below.

4.2.2. Channel Intersection Angle Φ

The Angle between the two intersecting channel refers to the channel intersection angle (Φ). The channel angle, Φ, is the most significant experimental factor since it dictates the total strain imposed in each pass and thus it has a direct influenceson the nature of the as-pressed microstructure.

4.2.3. Outer Corner Angle (Ψ0)

The angle of curvature, Ψ0, denotes the outer arc where the two parts of the channel intersect within the die. This angle plays only a minor role in determining the strain imposed on the sample**.**

4.2.4. Inner Corner Angle (Ψi)

The angle of curvature, ψi, denotes the inner arc in the inner corner where the two parts of the channel intersect within the die. The inner corner angle (ICA) is one of the major factors affecting deformation homogeneity in work pieces during equal channel angular pressing. Corner angle (ICA) is one of the major factors affecting deformation homogeneity in work pieces during equal channel angular pressing.

4.2.5. Inner Corner Radius (Ri)

The radius, Ri given to the inner curvature in the inner corner is termed as inner corner radius.

4.2.6. Outer Corner Radius (Ro)

The radius, Ro given to the outer curvature in the outer corner is termed as outer corner radius. Outer corner has a significant influence on the strain distribution in the body of work-piece. Based on in homogeneity and average strain criteria, there is an optimum outer corner radius.

4.2.7. Temperature of Billet and Die

The pressing temperature is a key factor in any use of ECAP because it can be controlled relatively easily. it is generally experimentally easier to press specimens at high temperatures, optimum ultrafine-grained microstructures will be attained when the pressing is performed at the lowest possible temperature where the pressing operation can be reasonably conducted without the introduction of any significant cracking in the billets. By maintaining a low pressing temperature, this equilibrium grain size and the highest fraction of high-angle boundaries.

4.2.8. Friction

The friction between the die and the material has significant influence on the strain homogeneity and the force applied.

4.2.9. Force

Processing by ECAP is usually conducted using high-capacity hydraulic presses that operate with relatively high ram speeds. Typically, the pressing speeds are in the range of 1–20 mm/s. The pressing speed or force has significant influence on strain homogeneity.

4.2.10. Number of Passes

The number of passes represents the total strain induced in the material.

4.2.11. Deformation Route

When the sample is pressed through several consecutive passes, the shearing characteristics may be changed by rotating the sample between each pass. Thus the route with which the sample was re-entered to the ECAP die in each pass had an influence on the microstructure achieved due to successive change of the shear plane.

There are four basic processing routes in ECAP.

Route A: 0°, all passes; the billet is not rotated between successive passes.

Route B Or BA: (90°), N even, 270° N odd; the billet is rotated 90° clockwise and counterclockwise alternatively.

Route C: (180°) All passes; the billet is rotated 180°

Route D or BC: (90°), All passes; the billet is rotated 90° clockwise.

5. Die Design

The Die dimensions are specified below. H13 tool steel is used as the die material and the channel intersection angle is 110^0

Material	:	AA 6351
Diameter	:	16 mm
Length	:	100 mm

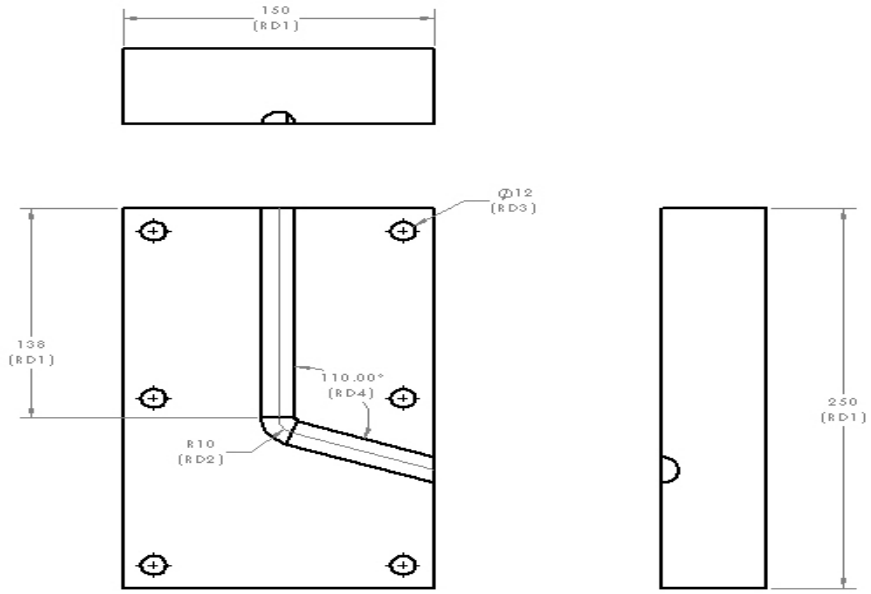

Figure 2. Front, Top and Side Views of the Die

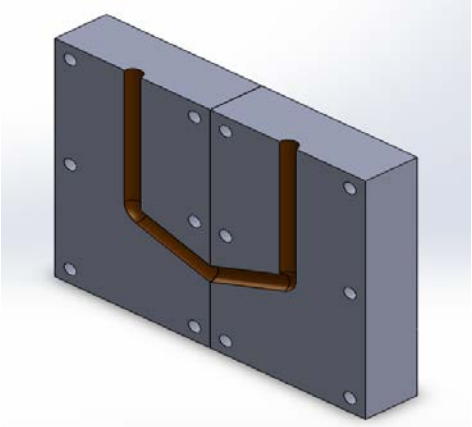

Figure 3. Solid Works Model of the Die

6. Experimentation

Universal Testing Machine (UTM) of 40 tons capacity is used for the purpose of experimentation. Hardened OHNS rod of diameter 16mm and length 120mm is used as pressing rod. The prepared specimen is pressed through Equal Channel Angular Extrusion (ECAE) die upto one pass at room temperature. Molybdenum disulphide is used as lubricant in between the die and the specimen in the process. The processed Sample after one pass is shown below

7. Results and Discussion

The processed sample is subjected to tensile, hardness tests and the properties of the processed sample are compared with the properties of the sample before passing it through the die.

Table 1. Tensile test specimen

S.no	Number of passes	Ys (mpa)	Uts (mpa)	Elongation to failure (%)
1	0	150	250	20
2	1	275.73	385.9	10.66

From the above table it is proved that the yield strength and ultimate tensile strength of the processed sample is increased. In a similar fashion, If the passes are increasing the yield and ultimate tensile strength also increase up to certain limit. From the tensile test result yield strength increases near double times and similarly ultimate tensile strength also increased. The hardness of the processed sample also increases to 100 VHN from 90 VHN.

8. Microstructure

The Microstructure of the specimen taken in Optical Microscope (OM) before pass and after pass is shown below. From the below given diagram, it is clear that the grain sizes of the processed sample has got refined. It shows the clear view of difference between the before and after passing microstructure of equal channel angular extrusions.

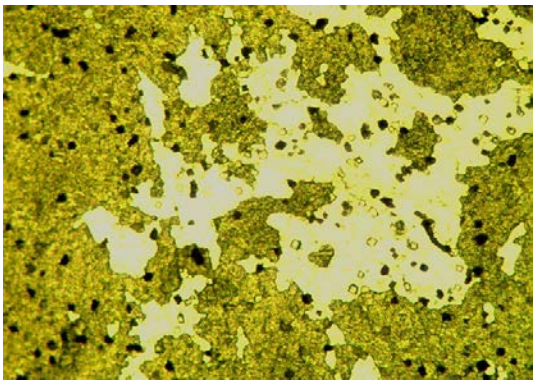

Figure 4. Microstructure of specimen before pass – (400X Magnification-Optical Microscope)

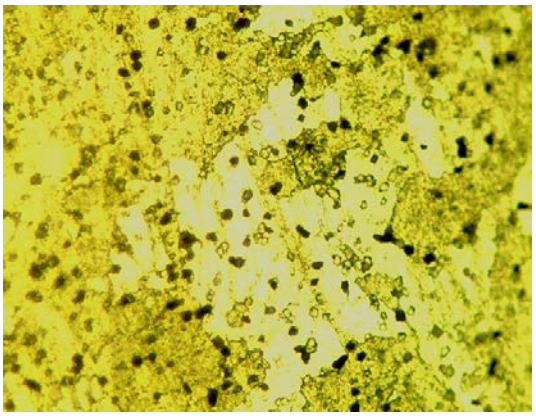

Figure 5. Microstructure of specimen after 1 pass- (400X Magnification-Optical Microscope)

9. Conclusion

The equal channel angular extrusion was carried out on AA 6351 using a suitable die design to improve the properties of the alloy. The main findings and conclusion of this study can be summarized as follows.

• The dendritic structure of the as-cast alloy is replaced with elongated and equiaxed grains after processing by ECAE up to two passes using route BC.

• The micro hardness of the alloy increased with increase in pass number and attains a maximum value of 105 VHN after two passes due to the formation of fine grains and high density of dislocations.

• The tensile strength of the alloy also increased with increase in pass number but there is some reduction in ductility due to the hardening of the alloy.

It can be concluded that processing by ECAE increased the mechanical properties of AA 6351 alloy. The improvement in the properties has made it possible to use the alloy in various engineering applications requiring high strength.

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