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A Review on the Severe Plastic Deformation of Al-Zn-Mg Alloy Using Equal Channel Angular Pressing (ECAP)

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ABSTRACT

Because of its potential to produce nano/ultrafine grained microstructures and improve the mechanical properties, Equal Channel Angular Pressing (ECAP) is widely used now-a-days in almost all manufacturing sector as a severe plastic deformation process. In this process, a load of appreciable magnitude is applied on the material thereby subjecting it to deformation, and plastic flow to get the desired shape and size. The variations in strain path directions during deformation have significant effect on the physical and mechanical response of the distorted metals/alloys.

Key words: ECAP, microstructure, severe plastic deformation, strain path

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INTRODUCTION

Various industrial metal forming processes are characterized by a complex deformation history, which is made up of successive strain paths that may vary in their orientation. Today, aluminium is used not only because of the reduced weight it possessed, but it's also easy to machine, cast, extrude, roll, etc [1]. For the numerous application found in these alloys, it is reasonable to understand their mechanical behaviour when subjeccted to different loading conditions, strain rates and temperatures.

In recent times, there are a lot of methods that are employed for the refinement of the structure of metals/alloys by severe plastic deformation (SPD), with some of the methods permitting grain refinement even to a nanometer scale. Investigations show that the metals/alloys having such a structure exhibit a number of specific properties including significantly higher yield point than those produced by other conventional deformation methods like drawing and rolling [2].

One of today's research frontiers in advanced materials is seeking to actively design materials with tailored physical, chemical and mechanical properties suitable for high-end applications. The effective way to manipulate material's properties to reach a specific high performance is microstructural modification. In this pattern, grain size refinement of crystalline materials to produce ultra-fine grained (UFG) or nanocrystalline materials has been shown to be an effective technique to increase their strength [3-4]. Such refined microstructure can be achieved through processes involving severe plastic deformation [5-6] or through consolidating ultra-fine or nano-sized powders into bulk materials using various powder metallurgy processes [7-8]. Research in this field has been increasing in the past ten years, with the main focus towards scaling up the processes and to understand the deformation mechanisms of such materials.

However, the production of these materials is through the application of severe plastic deformation to conventional coarse-grained metals/alloys and typically they have grain sizes within the ultra-fine or even the nanometer range. Recently, many industrial fields has focuses their attention on ultra-fine grained (UFG) materials with nano-crystalline structures. These materials possess a wider range of exceptional properties that result from a large volume fraction of their grain and/or interphase boundaries [9-10]. For example, as well described by the Hall-Petch (HP) relationship [11], in spite of the fact that the mechanical and physical properties of all crystalline materials are determined by several microstructural parameters, the average grain size of the material generally plays a very important, and often a prevailing role. It is well known that the strength of polycrystalline materials is typically related to the grain size through the Hall-Petch (HP) equation [12-13] which states that the yield stress, σ_y is given

$$\sigma_y = \sigma_o + k_y d^{-1/2} \quad (1)$$

where σ_o is friction stress, k_y is constant of yielding and d is grain size. It follows from Eq. (1) that as the strength increases, there is a decrease in the grain size and this has led to a soaring interest in fabricating materials with extremely small grain sizes.

In addition, UFG materials display the super plastic behaviour that is available for forming parts with complex shapes. This super plastic behavior is normally found in polycrystalline materials with grain sizes that are less than 10 mm at above 0.5Tm (the melting temperature) and relatively low strain rate [14], that is, smaller grains lead to the superplasticity at lower temperatures and/or higher strain rates [15]. These UFG materials have been produced by an expanding variety of processing techniques, such as mechanical alloying (MA), crystallization of amorphous precursors and severe plastic deformation (SPD) [16-19]. Especially, there has been increasing interest in the SPD processes, such as equal channel angular pressing (ECAP) [16-17], high-pressure torsion (HPT) [18] and accumulative roll bonding (ARB) [19]. In these processes, grain refinement occurs as a consequence of dynamical recovery and recrystallization through the rearrangement of dislocations which are generated in large quantities within materials by very large plastic strains [17].

ECAP is particularly desirable because it is the most cheapest and easier to perform among the SPD processes due to the simplicity of the process and tooling. ECAP allows the metals to undergo severe shearing deformation, breaking the original texture into ultrafine or nanostructured material after a number of passes. The process enforces a high strain on the sample, resulting to a high density of dislocations, which are re-arranged during the numerous passes to form subgrains and subsequently new high-angle grain boundaries [20-21].

There are some limited results showing that high stresses prompted in ECAP does not only results to the ultrafine grain (UFG) microstructure production but also reasonably affect the distributions and sizes of any second-phase particles and precipitates contained within the matrix [22]. However, the results reported to date are limited and, in addition, it is anticipated that the morphology of the precipitates will depend critically on the temperature used for the ECAP processing [23].

This paper presents a review on the achievements and possibilities of the techniques on equal channel angle pressing of a deformable aluminium alloy. Enormous plastic deformations can be obtained by metal forming techniques such as cold rolling, wire drawing and extrusion.

METHOD FOR SEVERE PLASTIC DEFORMATION BY ECAP

The ECAP which is also known as the Equal Channel Angular Extrusion was invented by Vladimir Segal in 1977 and originally developed by Segal [24]. During the ECAP pressing a rod shaped sample is forced through an angular die channel with a uniform cross section but bent into an L-shaped configuration (Fig. 1). The material is subjected to large plastic shear deformation when forced to change the direction by 90º (intersection angel between two channels) [25].

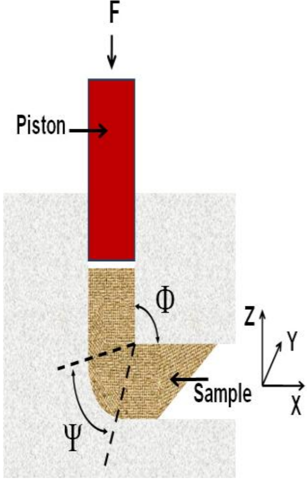


Fig. 1 ECAP Die

The equivalent strain ε, introduced in ECAP is determined by a relationship incorporating the angle between the two parts of the channel ϕ, and the angle portraying the outer arc of curvature where the two parts of the channel intersect ψ[25]. The relationship is given by;

$$\varepsilon = \frac{N}{\sqrt{3}}\left[2cot\left\{\frac{\phi}{2}+\frac{\psi}{2}\right\}+\psi cosec\left\{\frac{\phi}{2}+\frac{\psi}{2}\right\}\right] \quad (2)$$

Where N is number of passes through the die.

Since the cross-section remains the same with the process even after the introduction of the shear strain, repetitive pressing is possible and a large strain is aggregated in the sample.

However, considering some disadvantages of ECAP process, the age-hardenable alloys are not easily processed at room temperature because they normally fail tragically by cracking. This is because there is formation of precipitates in the treated solution of the alloy causing the material to deform. ECAP can also affect the order in which precipitation can occur resulting to disappearance of some phases after heat treatment [26]. To avoid these problems the processing temperature is increased [23], which can also lead to emancipation of other negative issues such as larger grain sizes and further precipitation resulting to the material being over aged.

ECAP also possess a sophisticated effect on the microstructure after precipitation when the aluminium alloys are age-hardened. In as-quenched samples of aluminium alloys at a temperature of 25 °C, ECAP can impede precipitation causing disintegration and disappearance of already existing phases [27]. Despite this difficulty, there is a rising persuasion in processing these alloys by ECAP because aluminium alloys that are age-hardened are of high rendition particularly in aerospace industries. Recently, a scheme developed such that these alloys are processed by ECAP at room temperature has been implemented and it is realized that pressing can be done comfortably without formation of cracks or partitions [28], if it is done immediately after quenching from the solution treatment temperature or at least within a very short pre-aging time [29].

Interestingly, ECAP at a very high temperature advances and changes the precipitation kinetics and the morphology of precipitates [27]. Studies have shown clearly that the very high stresses exerted on an Al7034 alloy through ECAP process at 473K, are efficient in leading to partitioning the rod-like structure of $MgZn_2$ precipitates [22] leading to the production of uniformly distributed fine spherical precipitates, which encourage the stability of the structure at a very high temperature [30].

AA7050 aluminum alloy possess a very high strength and is comprised of alloying elements Zn-Mg-Cu with high content. The optimization of this alloy is done in order to obtain better response during artificial ageing through precipitation of η' and η $MgZn_2$phases leading to further commercial condition (T7).

Strength and stress corrosion resistance are the properties acquired by the material in this commercial condition (T7) [31]. However, it is expected that due to various hardening mechanisms that normally occur during ECAP, further strengthening could be obtained such as solid solution, grain refinement, dislocation strengthening and precipitation strengthening which normally depend on initial condition of alloy. There is meaningful improvement of strength compared to the alloy in the commercial over aged condition when ECAP is performed in the as quenched condition; this is due the grain size refining and severe precipitation [32].

MICROSTRUCTURAL EVOLUTION AND INFLUENCE OF STRAIN PATH DURING ECAP

Generally during ECAP, the microstructure produced is in form of a fine-grained structure with high-angle boundaries following a repeated pressing. Investigation was made on the solution treated commercial aluminium alloy of AA7050 series and processed by ECAP at both room and 150°C temperatures [32]. It was established from the findings that, processing by ECAP leads to a refined microstructure as a result of deformation bands formation, which are related to dislocation cells and subgrains of about 200nm within these bands. It further confirmed that, increase of the ECAP temperature led to intense precipitation of η' and η phases, and as a result of precipitation and grain refinement, there is increase in the alloy hardness and tensile yield strength.

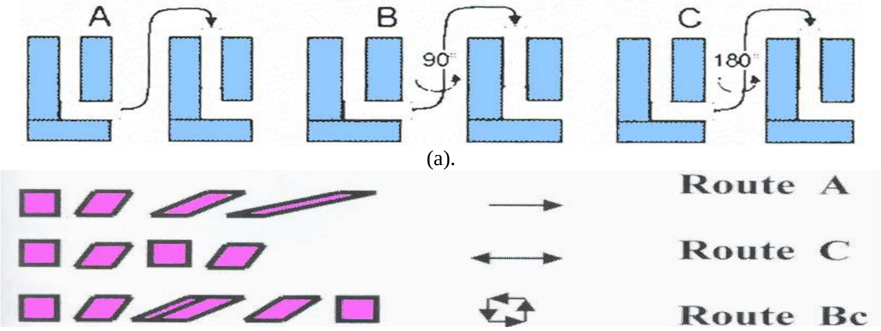
Also studies were made on the microstructural evolution during equal channel angular pressing (ECAP) in an as-cast aluminium alloy of 7475 series that was modified with 0.16% Zr at 673K [33]. From the findings, inhomogeneous deformation characteristics of ECAP for a number of passes lead to transformation of boundaries of deformation bands into high angle grain boundaries with an average size of about 1.7 μm and evolution of new fine grains in high strain. This grain refinement takes place by a continuous reaction that stimulates deformation that is normally similar to continuous dynamic recrystallization.

In most SPD processes, (except high pressure torsion), the deformation is applied with repetitive changes in strain path. Especially in ECAP, several processing routes are available. The implications on the sample distortion have been described in detail [34].

From Fig. 1, it could be seen that after a single pressing a cubic element is deformed into a crystallographic shape having three equal axes and oblique angles, and if the same sample is pressed a second time then the operator has the choice to insert the sample with or without rotation. It has been recognized that, pressing repetitively results in the alteration of the overall shearing properties within the crystalline sample by a rotation of the sample between the individual pressings [35]. Pressing samples repetitively results in the introduction of different slip systems by the rotation of the samples about the X-axis between successive passes through the die.

Several processing routes have been identified for use in ECAP; route A in which the sample is pressed repetitively without rotation, route BC in which the sample is rotated by 90° in the same sense between each pass and route C where the sample is rotated by 180° between passes [36]. More complex combination of these routes could also be performed.

Figure 2 shows that route A markedly increase the distortion of the rhombohedron, route B increases the distortion in the X and Z planes and route C restores the cubic element so that strain has been introduced but with no ultimate distortion of the bulk of the sample [34]. A processing route that will introduce maximum strain in all directions within the sample while recovering its cubic shape after N passes is more appropriate. It is seen that route A is not optimal because it does not restore the cubic structure. In route C the cubic structure is restored or recovered after each $2N$ pressings but no deformation is induced in the Z plane. Therefore, the only optimal route is BC since it introduces strains in each plane while recovering a cubic structure after 4N passes [37].



(a).

(b).

Fig. 2 Features of most processing routes: (a) The modes of successive passes in the ECAP die; (b) Effective deformation of the shape of a billet

APPLICATION OF ECAP TECHNIQUES IN MANUFACTURING INDUSTRIES

ECAP is used to manufacture ultra-fine grained structures for different materials. High-strength semi-finished products produced from Al-Zn-Mg alloy that has undergone ECAP process can find application in the aerospace, power and automotive industries. Such products include screws and rivets for aircraft and other structures, aircraft fuselages elements such as stringers, sections and layers for plants operating in corrosive environments [38] at low temperatures, and skin plates and complex-shaped parts produced by superplastic forming (Fig. 3) [39]. ECAP is also used in fabricating rods of nanostructured titanium materials for medical applications (Fig. 4) [40] in which the process is combined with other techniques such as forging, rolling and extrusion. ECAP is also used in orthopaedics to manufacture devices for the knee, spine and hip etc., dental implants and in oral and cardiovascular surgeries (Fig. 5) [41].

Fig. 3 Pistons produced by superplastic forming

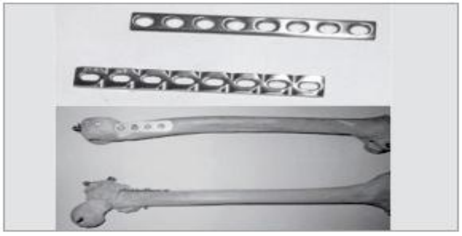


Fig. 4 Medical applications include the manufacture of commercially pure titanium instruments for osteosynthesis

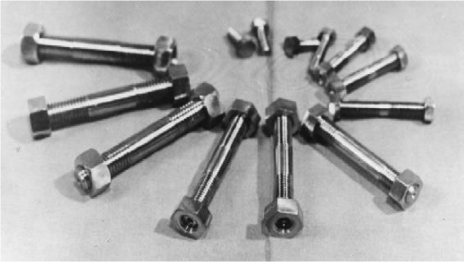


Fig. 5 High-strength thread articles manufactured from a titanium alloy by severe plastic deformation

Also, ECAP technique finds application in the production of materials for microelectromechanical systems and shape memory alloys. ECAP technique is also applied in the production of high-performance mountain bicycles and automotive components where weight consideration is needed. In addition, ECAP reduces waste of material because the material utilization rate is very high in the ECAP process, typically exceeding 90% [42].

CONCLUSION

Cubic element in the initial billet of material is forced through a die with two equal channels at a specific angle. The extruded sample through the outlet possessed new mechanical properties. The various ECAP routes have been found to be of significant importance in the properties of the alloy without change in the cross-sectional area of the samples. Grain refinement by severe plastic deformation initiates the formation of new high angle grain boundaries. For ultrafine or nanostructured materials produced by (ECAP) technique, the workability parameters depend on the number of passes, type of route, and the direction of the specimen's axis and it refers to the relative ease with which the material can be shaped through plastic deformation and it is a function of the material and the process. During ECAP, notable refinement of grains occurs together with dislocation strengthening, which results in a significant enhancement in strength of the deformed alloys.

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