A Review: Plastic Deformation through Equal Channel Angular Pressing

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Abstract**—**In most manufacturing processes, objects of the required shape and size are produced through plastic deformation; sometimes by deforming the product itself through rolling, extrusion, drawing etc, and by deforming the metal removed through grinding, milling and cutting operation. In these processes, a load of appreciable magnitude is applied on the material subjected to deformation, and the plastic flow thus produced is suitably restricted to get the desired shape and size. Equal Channel Angular Pressing (ECAP) is very capable of producing ultrafine grained microstructures and improves the mechanical properties of the deformed materials. The variations in strain path directions during deformation have significantly effect on the physical and mechanical response of distorted metals.

Keywords**—** ECAP, microstructural evolution, severe plastic deformation, strain path

I. Introduction

Most of the industrial metal forming processes is characterized by a complex deformation history, which is composed of successive strain paths that may vary considerably in their orientation. Today, Aluminium is used due to reduced weight it possessed, but it has always been popular because it is easy to machine, cast, extrude, roll, etc [1]. Because of the widespread use of these alloys, it is important to understand their mechanical behaviour when exposed to different loading conditions, strain rates and temperatures, and to be able to model the behaviour and later, to predict the behaviour for any of these conditions. In order to improve mechanical properties of these alloys many processing routes can be applied. During the last decade, the equal-channel angular pressing (ECAP) route proved to produce ultrafine-grained bulk samples in a fully dense condition without changing the cross-sectional dimensions of the samples. During ECAP, significant grain refinement occurs together with dislocation strengthening, resulting in a significant enhancement in the strength of the alloys [2]. During plastic deformation of metals, the dislocation density increases and form heterogeneous structure characteristics due to the deformation conditions of the deformed material. The resulting structure influences the mechanical properties of the metal and as such, it is of great interest to understand the origin and evolution of the dislocation structures [3]. Ultrafine grained material has allowed the design and manufacture of aluminium components to require fewer manufacturing steps. ECAP is capable of producing ultrafine grained microstructures in Al alloy and this will practically depend upon the advantages obtained when this process is combined with conventional forming techniques [4]. Deformation is, of course, a continuous process and at any particular point in a deforming body, the state of strain changes from one instant to the next and the sequence of these states of strain are called the strain path, or strain history. The difference between the states of strain at two points in the strain path is called finite strain if however; the interval between the two points is finite. Thus, if the interval is infinitely small, then the strain path is known as an incremental strain. In many engineering tests and manufacturing processes the strain paths are not coaxial [5]. The changes in strain path directions have a significant effect on the mechanical response of metals. The effect of a certain pre-strain becomes manifested by an increase in re-loading yield stress, transient hardening, hardening recovery and failure shift. However, the effect is toughly anisotropic and is dependent on the extent of pre-strain [6]. The improvement in the strength properties of polycrystalline metallic materials with preservation of sufficient toughness can be achieved by refining of grains. Equation (1) shows the Hall-Petch relationship between the grain size and the level of yield strength. This relationship can be used in extensive interval of grain sizes, up to several dozens of nanometres.

$$\sigma_y = \sigma_0 + kd^{-\frac{1}{2}} \tag{1}$$

Where $[\sigma_y]$ is flow stress, $[\sigma_0]$ and [k] are constants, [d] is grain size.

The possibilities of efficient refining of structure of technical materials lead to important modification of technology of thermo-mechanical treatment. However, this has enabled the grain size at the level of several micrometres to be obtained. Further grain refinement requires extreme value of plastic deformation of material. Many methods have been developed which have enabled the achievement of severe plastic deformation. The equal channel angular pressing (ECAP) is one of methods that has been used often by researchers.

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The principle of this method consists of severe deformation of massive samples realised by shear without change in the cross section. The sample is usually pressed through a die, in which two channels intersect, forming an angle usually of 90º. The pressing is conducted either at room or at increased temperature. Equivalent deformation can be achieved with a value of 10 or even higher. The most critical for the development of microstructure and the resulting properties of experimental samples is above all number of passes and selection of deformation route which is determined after each passes. In the analysis of shear characteristics at various deformation routes, samples turned at 90º has been regarded as optimal. The ECAP method makes it possible to obtain the grain size of several hundreds of nanometers [7].

A finer grain size increases the strength and the fracture toughness of a material and provides the potential for superplastic deformation at moderate temperatures and high strain rates. Traditional thermo-mechanical processes generally lead to a grain size above 10 µm or, exceptionally, a few microns in diameter. Thus, several techniques such as vapour deposition, high-energy ball milling, fast solidification and severe plastic deformation are also required to obtain submicrons or nano-size grains [8].

This paper presents a review on the achievements and possibilities of the techniques that have been explored on equal channel angle pressing of a deformable plastic material. Large plastic deformations can in principle be obtained by classical forming techniques like cold rolling wire drawing and extrusion.

II. Method for Severe Plastic Deformation (SPD)

The process of severe plastic deformation is defined as metal forming process in which a very large plastic strain is forced on a bulk process in order to make an ultra-fine grained metal [9]. The ECAP is also known as the “Equal Channel Angular Extrusion”. This technique was originally developed by [10]. Fig. 1 shows a die with a billet pressed in between.

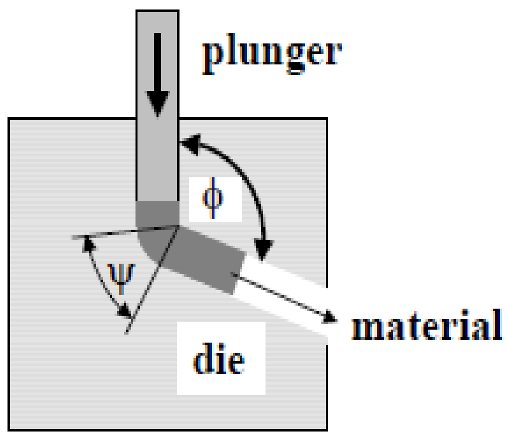

Fig.1 A laboratory scale ECAP die [10]

The billet is pressed through the die consisting of two channels with identical cross sections and intersecting at an angle $\emptyset$, usually 60º < $\emptyset$ < 135º. Often $\emptyset$ = 90°. Due to the identical cross section of the channels, the dimensions of the billet remain unchanged, and the process can in principle be repeated any given number of times [10]. In this method, some drawbacks of the ECAP are also taken into consideration. The ECAP is a discontinuous process with some limitations in up-scaling potential. Moreover, a low volume fraction of the useful material produced with uniform microstructure and without cracks can be established because only the portion of the billet that passed through the shear zone will receive the desired deformation and grain refinement [11].

In the last ten years, a large number of investigations regarding a severe plastic deformation (SPD) technique called the ECAP have been published [12] [25]. The justification for this interest lies in the fact that the ECAP of deformed metals and alloys exhibit a very small grain size and subsequently their tensile strength is remarkably improved.

III. Microstructural Evolution During (SPD)

The microstructural evolutions of metals and alloys subjected to low and medium plastic deformation have been discussed severally [13] [14]. The outcome of their studies is a model describing severely the deformed metals with high to moderate stacking fault energy and grain subdivision which takes place by the formation of cell blocks separated by arrays of geometrical dislocations. Within these cells, there are regions relatively free from dislocations and bounded by low angle boundaries. The more severe the deformation, the narrower the cell blocks become and continue until the cell boundaries transform into high angle boundaries. This pattern has been often observed in ECAP of deformed metals and alloys and characterized with the formation of very small grain microstructures [15]. Fig. 2 shows the micrographs and the grain size distributions for the as received and ECAP treated samples.

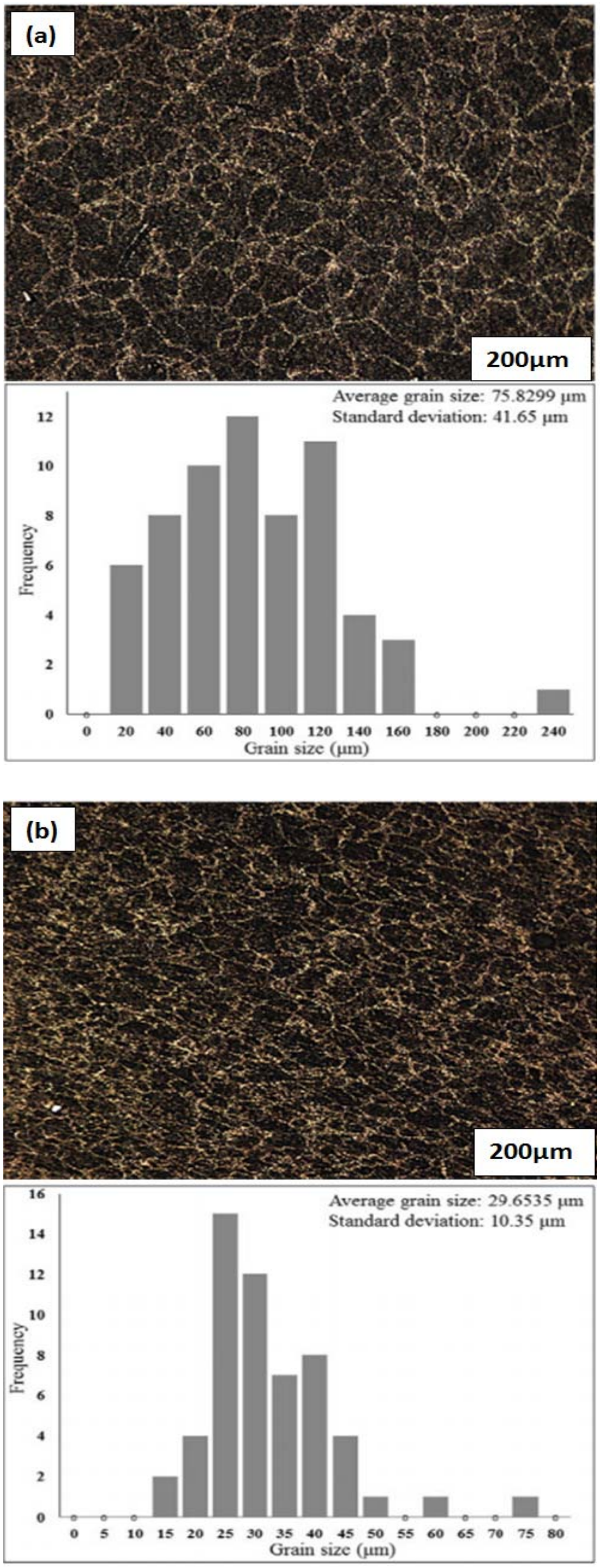

Fig. 2 Optical micrographs and grain size distributions, (a) As Received (b) ECAP treated sample [16]

Fig. 2 (a) depicts the microstructure of the as-received sample of Aluminium 6061 (AA 6061). A free grains deformation was observed due to annealing process. An average grain size with standard deviation of 76±42 µm was calculated from their observation. Equiaxed structures with coarse grains were reported to be homogeneously distributed in the both the normal and the extrusion direction. In the ECAP treatment of Fig. 2(b), few grains were observed which is about 2.6 multiply by the grain sizes obtained for the as received sample. From their result, elongated lamellar morphologies were observed in the ECAP treated samples in the shear direction. It was also reported that the induced plastic strain led to the grain refinement [16]. Grain refinement by severe plastic deformation implies that there is creation of new high angle grain boundaries. This can be accomplished by three mechanisms. The first is the elongation of existing grains during plastic deformation, causing an increase in high angle boundary area. The second is the creation of high angle boundaries by grain subdivision mechanisms and the third is an elongated grain which can be split up by a localization phenomenon such as a shear band [17].

IV. INFLUENCE OF STRAIN PATH

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 [15]. Fig. 3 represents the interactions of subsequent shear deformations in the first and second ECAP passes.

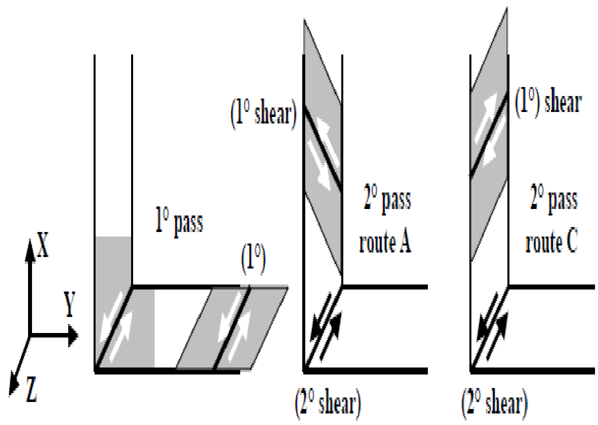

Fig. 3 Interactions of consequent shear deformations in the first and second ECAP pass [8]

A cubic element in the initial billet is elongated into a rhombohedral shape during the first ECAP pass. The elongation is visible in the (XY) plane. The first shear plane is active as indicated in Fig. 3 (a). When the second passage through the die is carried out without rotation (route A), a further elongation in plane (XY) occurs. A second shear plane, perpendicular to the first (when φ = 90°) is now active as shown in Fig. 3 (b). In further passes, the 1º and 2º shear plane are alternating active and further elongation occurs in each pass. When route C is applied as shown in Fig. 3 (c), deformation always occurs along the same shear plane, but alternating in shear direction. The shape of an initial cubic element is restored after each 2N passes. Where 'N' is an integer.

The [α] parameter in equation 2 was used by [18], and it was introduced by Schmitt to quantitatively express the change of strain path from one pass to another:

$$\alpha = \frac{\varepsilon_p . \varepsilon}{\|\varepsilon_p\| . \|\varepsilon\|} \quad (2)$$

Where $\dot{\varepsilon}$ and ε_p are the strain rate tensors of the consecutive passes.
For the most drastic 'orthogonal' change in strain path. $\alpha = 0$. For a monotonous strain, $\alpha = 1$, and for strain reversal $\alpha = -1$. Fig. 4 shows the influence of ECAP-billet rotation on the α -parameter defined for route A, B and C respectively.

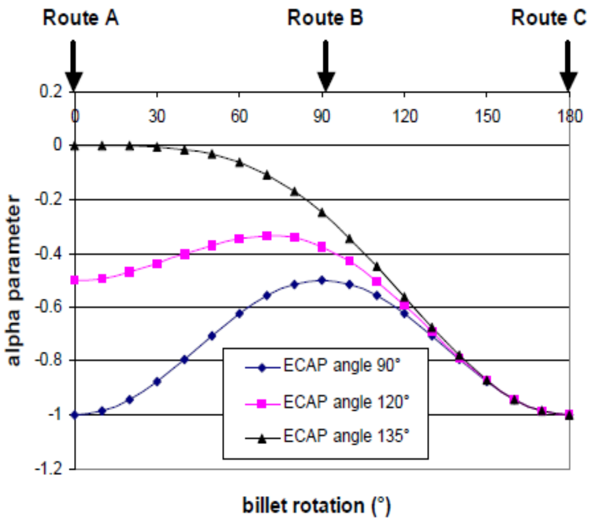

Fig. 4 ECAP-billet rotation on the α -parameter [8]

The graphs show the trends for ECAP with die angles at 90º, 120º, and 135º. The α -values shown from the trend. As shown in Route A, α is strongly dependent on the ECAP die angle. route B is nearly orthogonal and has a relation: –0.5 < α < -0.25 while in all cases, route C corresponds to strain reversal. In route B from the shear deformation, the cubic volume element is elongated in each orthogonal plane after the 2° pass. For route BA, the distortion will increase after each pass, but for route BC the restoration of the cubic element is observed after each 4N passes. In both routes BA and BC, shear occurred on the shear planes intersecting at 120°. Several experimental results published in the literature seem to be in agreement with Fig. 4. For a die angle of 90°, it was reported that route B is more efficient than A and C [19] [20]. For a die with φ = 120°, route A and B are nearly as effective but C is clearly less effective [21].

Ductility loss appears to be a customary occurrence in some of the materials and this can be attributed to the non-equilibrium state of the grain boundaries such as the boundary sliding and the grain rotation [22].
Variety of materials is available for dies and tooling, each having its own characteristics, applications, advantages and limitations. When selecting materials for the equipment, the mechanical properties such as strength, toughness, machinability, ductility, elasticity, fatigue and hardness should be taken into cognisance. The cost and the availability of processed materials are also required for optimum output.

V. Equal Channel Angular Pressing Procedure

ECAP is performed by pressing a cubic element in the initial billet of material through a die that has two channels which intersect at an angle during the first ECAP pass. The billet experiences simple shear deformation at the intersection without any swift change in the cross sectional area. This is due to the fact that the die does not allow for lateral expansion. This means that the billet can be pressed more than once and can be rotated about the pressing axis during subsequent pressings. A single pass with channels 90° to each other, induces approximately 1.15 equivalent strains in the billet. Based on the regular repetition of such a rotation ϕ around extrusion direction, four commonly applied routes have been defined. Route A has no rotation of the billet, route BA is rotated counter clockwise 90° on even number of passes and clockwise 90° on odd number of passes, route BC is rotated counter clockwise 90° after every pass, and route C is rotated 180° after every pass.
The accumulated equivalent strain value is calculated using the die-channel and relief angles in Equation (3) [23].

$$\varepsilon_N = N.\frac{1}{\sqrt{3}}\left[2\cot\left(\frac{\emptyset}{2}+\frac{\psi}{2}\right)+\psi\operatorname{cosec}\left(\frac{\emptyset}{2}+\frac{\psi}{2}\right)\right] \quad (3)$$

Where N is the number of passes; $\emptyset$ is the channel angle and ψ is the corner angle.
The assumptions in this geometric analysis include simple shear, a frictionless die surface, a uniform plastic flow on a plane, a complete filling of the die channel by the workpiece and a rigid perfectly plastic material (no strain hardening behaviour is included). With these assumptions, Equation (3) doesn't take into account for the effect of friction, strain hardening, strain distribution and deformation gradient, providing a homogeneous value of strain in the whole work piece. During ECAP, significant grain refinement occurs together with dislocation strengthening, resulting in a significant enhancement in the strength of the alloys [24].

VI. CONCLUSION

Cubic element in the initial billet of material is forced through a die with two channels at a specific angle. The extruded sample through the outlet possessed new mechanical properties. ECAP routes have proved to produce ultrafine-grained bulk samples in a fully dense condition without changing the cross-sectional dimensions of the samples. Grain refinement by severe plastic deformation initiates the formation of new high angle grain boundaries. During ECAP, significant grain refinement occurs together with dislocation strengthening and resulted in a significant enhancement in the strength of the deformed alloys.

REFERENCES

[1] R. Sterie, N. Panait, P. Moldovan, “Study and research concerning the quality of cast billets of 6XXX aluminium alloys”, U.P.B. Sci. Bull., Series B, Vol. 70 (2008) pp 85-92.

[2] Z. Horita, T. Fujinami, “Equal-channel angular pressing of commercial aluminium alloys: grain refinement, thermal stability and tensile properties”, Metallurgical and Materials Transactions, A 31A, (2000) pp 691-701.

[3] C. Wejdemann, H. F. Poulsen, U. Lienert and W. Pantleon, “The effect of strain path change on subgrain volume fraction determined from in situ X-ray measurements” IOP Conf. Series: Materials Science and Engineering 3 (2009) 012003.

[4] D. Nagarajan, U. Chakkingal, P. Venugopal, “Influence of col extrusion on the microstructure and mechanical properties of an Aluminium alloy previously subjected to equal channel angular pressing”, Journal of Materials Processing Technology, Vol 182, (2007) pp363-368.

[5] T. C. Hsu, “Velocity and Strain-rates in Plastic Deformation” Journal of strain analysis, vol 2 no 3 (1967).

[6] E.M. Viatkina, W.A.M. Brekelmans, M.G.D. Geers, “ Strain Path Dependency in Metal Plasticity”, Netherlands Institute for Metals Research, Eindhoven University of Technology, (2001)

[7] M. Greger, V. Vodárek, L. Kander, L. Èí.ek , “Influence of severe plastic deformation by the ECAP method on structure and properties of the P2-04BCh steel “, Archives of Materials Science and Engineering, International Scientific Journal, Volume 37,Issue 1,(2009) pp 13-20

[8] B. Verlinden, “Severe Plastic Deformation of Metals”, Association of Metallurgical Engineers Serbia and Montenegro, Scientific paper AME, Journal of Metallurgy, pp165-182

[9] A. Azushima, R. Kopp, A. Korhonen, D.Y. Yang, F. Micari, G.D. Lahoti, P. Groche, J. Yanagimoto, N. Tsuji, A. Rosochowski, A. Yanagida, CIRP Annals - Manufacturing Technology, Volume 57, Issue 2 (2008) pp 716–735.

[10] V.M. Segal, V.I. Reznikov, A.E. Drobyshevkij and V.I. Kopylov, “Plastic working of metals by simple shear”,Metally, 1 (1981), pp 115-123.

[11] R.E. Barber, T. Dudo, P.B. Yasskin and T. Hartwig, in “Ultrafine Grained Materials III”, TMS, (2004) pp 667-672

[12] R.Z. Valiev, A.V. Korznikov, R.R. Mulykov, “Structure and properties of ultrafine-grained materials produced by severe plastic deformation” Materials Science Engineering A (1993)168 pp 141-148.

[13] Q. Liu, N. Hansen, “Macroscopic and microscopic subdivision of a cold - rolled single crystal of cubic orientation”, Proceedings of the Royal Society (1998) A454 pp 2555-2591.

[14] B. Bay , N. Hansen , D.A. Huges , D. Kuhlmann-Wilsdorf , “Overview no. 96: Evolution of F.C.C. deformation structures in polyslip”, Acta Metallurgica Materialia, 40 (1992) pp 205-219.

[15] M. Furukawa, Y. Iwahashi, Z. Horita, M. Nemoto, T.G. Langdon, “The Shearing Characteristics associated with Equal-Channel Angular Pressing”, Materials Science and Engineering: A, (1998), 257 pp 328-332.

[16] D.M. Jafarlou , E. Zalnezhad, M.A. Hassan , M.A. Ezazi, N.A. Mardi, A.M.S. Hamouda , M. Hamdi , G.H. Yoon, “Severe plastic deformation of tubular AA 6061 via equal channel angular pressing”, Materials and Design 90 (2016) pp 1124-1135.

[17] J. Gill Sevillano, P. Van Houtte and E. Aernoudt, Progress in Material Science, 25 (1980), pp 69-412.

[18] L. Dupuy and E.F. Rauch, “Deformation paths related to equal channel angular extrusion”, Materials Science and Engineering, A337 (2002), pp 241-247.

[19] T.G.Langdon, M.Furukawa, Z.Horita and M.Nemoto, “Investigations and Applications of Severe Plastic Deformation” Kluwer Academic Publisher (2000), pp 149-154.

[20] K. Oh-ishi, Z. Horita, M. Furukawa, M. Nemoto, T.G. Langdon, “Optimizing the rotation conditions for grain refinement in equalchannel angular pressing, Metall Mater Trans, 29A (1998), pp 2011–2013.

[21] A.Gholina, P.B. Pragnell and M.V. Markushev, Acta Materiala 48 (2000), pp 1115-1130.

[22] E. F, Prados , V. L. Sordi , M. Ferrante,M. “Microstructural Development and Tensile Strength of an ECAP - Deformed Al-4 wt. (%) Cu Alloy”. Materials Research, Vol. 11, No. 2, (2008) pp 199-205.

[23] Y. Iwahashi, Z. Horita, M. Nemoto, T.G. Langdon, “An Investigation of Microstructural Evolution during Equal-Channel Angular Pressing”, Acta Materialia, 45 (1997) pp 4733-4741.

[24] Z. Horita, T. Fujinami, “Equal-channel angular pressing of commercial aluminium alloys: grain refinement, thermal stability and tensile properties”, Metallurgical and Materials Transactions, (2000), A 31A, pp 691-701.

[25] V.M. Segal, “Materials processing by simple shear”, Materials Science Engineering A 197 (1995) pp 157-164.