Chapter from the book *Aluminium Alloys - Recent Trends in Processing, Characterization, Mechanical Behavior and Applications*

Chapter 14

Equal Channel Angular Extrusion Characteristics on Mechanical Behavior of Aluminum Alloy

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http://dx.doi.org/10.5772/intechopen.71019

Abstract

Materials strengthened by conventional methods such as strain hardening, solute additions, precipitation and grain size refinement are often adopted in industrial processes. But there is limitation to the amount of deformation that these conventional methods can impact to a material. This study focused on the review of major mechanical properties of aluminum alloys in the presence of an ultrafine grain size into polycrystalline materials by subjecting the metal to an intense plastic straining through simple shear without any corresponding change in the cross-sectional dimensions of the sample. The effect of the heavy strain rate on the microstructure of aluminum alloys was in refinement of the coarse grains into ultrafine grain size by introducing a high density of dislocations and subsequently re-arranging the dislocations to form an array of grain boundaries. Hence, this investigation is aimed at gathering contributions on the influence of equal channel angular extrusion toward improving the mechanical properties of the aluminum alloys through intense plastic strain.

Keywords: equal channel angular extrusion, strain hardening, severe plastic deformation

1. Introduction

1.1. Deformation processes

Solid materials transforms from one shape to another through a process called deformation. Solid materials can be plastically deformed into complex shapes to obtain a material having the desired geometry and properties required [1]. Deformation processes are commonly used with other unit operations such as casting, machining, grinding and heat-treatment. These unit operations occur during the transformation of raw materials to finished parts [2]. Deformation process generally can be classified into two; (1) bulk forming process and (2) sheet forming process. Rolling, extrusion and forging are examples of bulk forming process while stretching, flanging, drawing and contouring are sheet forming process. Input materials for bulk forming processes are usually in form of billets, rods and slabs while the input in sheet forming processes are usually in sheet blank form [2]. Deformation processes work by stressing metal sufficiently to cause plastic flow into desired shape. The processes also alter the grain sizes of the materials and induce plastic strains into the materials. Some deformation processes used mostly are rolling, extrusion, forging, extrusion and wire drawing. Extrusion process is considered for the purpose of this study.

Hall-Petch relation shows that the yield stress increases as refinement of grain size increases. It implies that the mechanical behavior of a metal will not be the same if its grain size changes. In order to improve properties of metal, methods of changing grain size is very important. There has been reported limitation of conventional metallurgy processes (such as rolling, forging, drawing and extrusion) in that they cannot supply metals whose grain sizes are substantially smaller than engineering micro-components in dimension [3]. In conventional metal forming operation the amount of plastic strain produced is often limited. Recently, materials with grain structures in the nanoscale range are of high interest. Nanomaterials' ability to decrease the geometrical dimensions of different mechanical devices makes nano structural materials attractive in engineering world. Successful shaping methods of engineering nanocomponents are required for building nanodevices, this can be achieved through bottom-up approach method where the building blocks are in atomic and molecular levels [3, 4]. Merging the manufacturing process of nanomaterials with material fabrication is highly challenging in terms of cost of making many of the raw components for functional nanomaterials. Time required for performing any engineering work at nano scale is also a considerable challenge. These challenges often reduced mechanical response and electrical properties; likewise caused spatial distortions, suboptimal thermal behavior, which weakens the general system performance [3, 4]. Another way is to use top down approach where bulk materials are restructured to nanoscale level using traditional shaping methods while constructing systems and devices at the micro and nano scales.

Severe plastic deformation (SPD) process has been shown as one of the major ways of fabricating bulk nanostructured samples and billets out of different metals and alloys [5]. The first developments and investigations of nanostructured materials processed using SPD methods were fulfilled by Valiev and his co-workers over than 10 years ago.

1.2. Severe plastic deformation (SPD)

Severe plastic deformation was defined as the intense plastic straining under high imposed pressure [6, 7]. Severe plastic deformation methods are used to convert coarse grain metals and alloys into ultrafine grained (UFG) materials [8, 9]. The ultra-fine grain materials obtained possesses improved mechanical and physical properties which impart on them a wide commercial use. Severe plastic deformation is a new metal forming process capable of

http://dx.doi.org/10.5772/intechopen.71019

generating very large or severe plastic deformation in a material without a major change in the billet geometry [5]. The method covers all metal forming processes which are based on simple shear and/or repetitive reversed straining and tend to preserve the initial shape of the billet. Different SPD processes are shown in **Figure 1**. Where ε is the strain; t is the torsion; n is the number of passes; φ is half of the inner die angle; D is the initial diameter; d is the final diameter; H is the height; W is the width; T is the initial thickness; t is the final thickness and r is the radius.

1.3. Equal channel angular extrusion (ECAE) process

Equal channel angular extrusion (ECAE), also called equal channel angular pressing (ECAP) has been used to produce ultrafine-grained materials [10–12]. ECAP is a convenient forming procedure to extrude material by the use of specially designed channel dies without a substantial change in geometry [13]. Extrusion by ECAP method enables obtaining of a fine-grain structure in larger volumes. There has been a significant progress in the use of ECAP from ordinary metal processing method to well establish procedure for ultrafine grain refinement. This ultrafine grain refinement improved the strength and toughness in metal and alloy. At present, ECAP is the best developed of all severe plastic deformation (SPD) processing techniques [14–16]. Industrial significance is given to production by processing bulk materials through ECAE. Furthermore, useful tools that can be made use of in the development of new SPD techniques and improving on the existing ones can be formed through the basic principles of ECAE, dealing with the mechanics of setal flow and the microstructural evolution. 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. One of the most promising SPD processes is equal channel angular pressing (ECAP) [10]. Large plastic deformation is involved in ECAP for the deformation of work-piece in a deforming work-piece. This required moving the work piece through two intersecting channels—usually at an angle of 90° or 120°—of identical cross sections in a die as shown in **Figure 2**. ECAE is an effective method of producing a large amount of simple shear deformation in a material by passing it around a corner of two intersecting channels with equal cross-sections as seen in **Figure 2**. The major advantage of ECAE over normal extrusion is that the cross section of the material undergoing ECAE remains the same after the process. The material can be passed through the same die to repeat the process and accumulate higher plastic deformation [17]. Segal, in order to change the texture of material processed metals by method of equal channel angular pressing [10, 18, 19]. The microstructural analysis carried out on materials that passed through the process showed that grain size was refined to nanometer level [20]. Different strain rates during the process of ECAP has been employed to investigate the evolutional characteristics of the material microstructure [21].

The deformation during the ECAP is a mixed form of shearing deformation and bending deformation which affect the orientation of grain crystal of the microstructure [22]. Apart from orientation of grain crystal, low-angular boundary and critical angle of partition grain have significant effect on the flow stress during ECAP [23]. A schematic diagram of ECAP showing its geometry is shown in **Figure 3** where P symbolizes the deformation force.

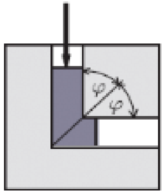
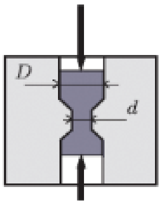
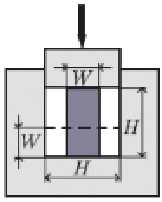
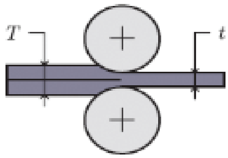
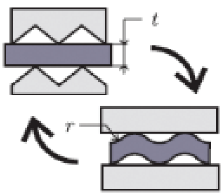
Process name	Schematic representation	Equivalent plastic strain
High-pressure torsion (HPT), Valiev, 1997		$\varepsilon = \frac{\mathrm{tg}\gamma}{\sqrt{3}}$
Equal channel angular processing (ECAP), Segal, 1977		$\varepsilon = n\frac{2}{\sqrt{3}}\cot\varphi$
Cyclic extrusion-compression (CEC), J. and M. Richert, Zasadziński, Korbel, 1979		$\varepsilon = n4\ln\left(\frac{D}{d}\right)$
Multiaxial forging (MF), Ghosh, 1988		$\varepsilon = n\frac{2}{\sqrt{3}}\ln\left(\frac{H}{W}\right)$
Accumulative roll-bonding (ARB), Saito, Tsuji, Utsunomiya, Sakai, 1998		$\varepsilon = n\frac{2}{\sqrt{3}}\ln\left(\frac{T}{t}\right)$
Repetitive corrugation and straightening (RCS), Zhu, Lowe, Jiang, Huang, 2001		$\varepsilon = n\frac{4}{\sqrt{3}}\ln\left(\frac{r+t}{r+0.5t}\right)$

Figure 1. SPD processes developed for grain refinement [4].

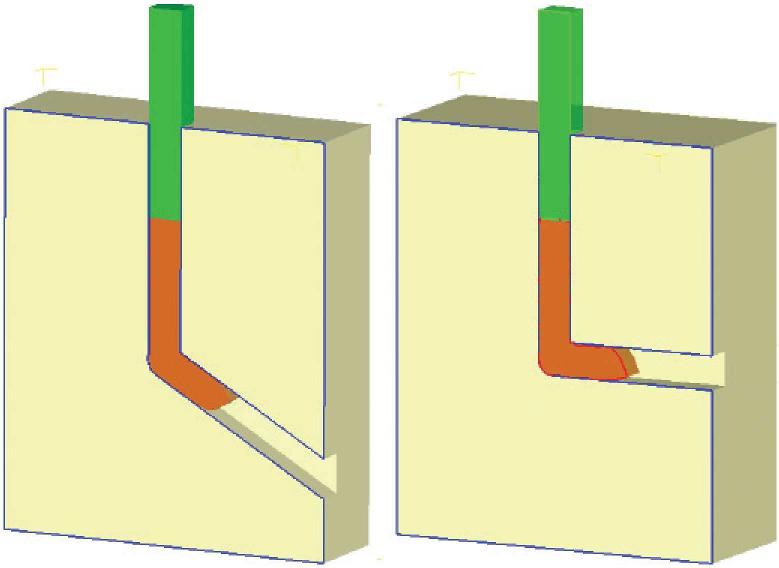


Figure 2. ECAP principles (channel intersecting at 120° and 90°, respectively) [10].

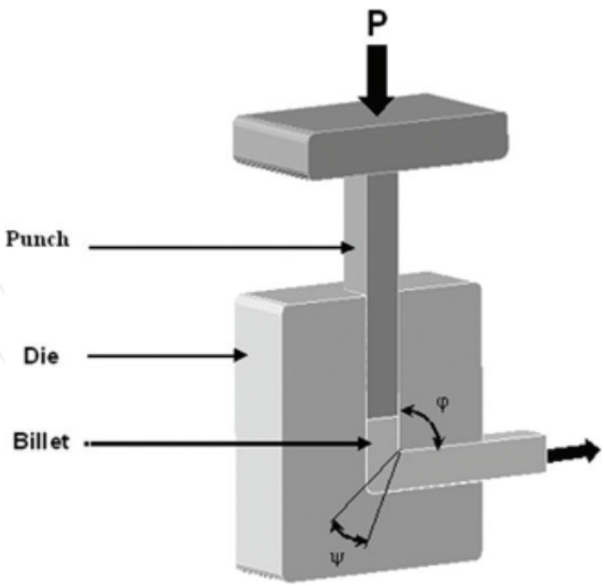


Figure 3. Schematic diagram of an ECAP die showing the inner die angle (∅) and the outer die angle (Ψ) [26].

The properties of materials processed by ECAP are strongly dependent on the plastic deformation behavior during pressing [16, 24]. These properties are governed mainly by the inner die angle ∅ and outer die angle y, the material properties like strength and hardening behavior [11], and process variables such as lubrication and deformation speed [25].

As the billet moves as a rigid body in the vertical channel, all deformation is restricted to a small area about the channel's meeting line. The metal is subjected to a simple shear strain under relative low pressure compared to the traditional extrusion process [25].

During ECAP, the work-piece cross-sectional area remains unchanged; this ensures process repeatability until the deformation reached a required grain size level. As a result of cumulative nature, high strain can be achieved with multiple passes. In multiple pass, different paths may be employed, such paths include:

i. Path A: the work-piece orientation remains unchanged in successive passes

ii. Path B: the work-piece is rotated by 90° about its longitudinal axis

iii. Path C: the work-piece is rotated by 180° about its longitudinal axis.

2. Aluminum 6063 alloy

Pure aluminum is a ductile and weak material; however the presence of a relatively small percentage of impurities in aluminum considerably increases its tensile strength and hardness properties [27]. The mechanical properties of aluminum and its alloys also depend on the amount of work it has been subjected to and not only its purity. The major purpose of working is to fragment the grains in the aluminum alloy resulting in an increase in tensile strength and hardness but decrease in ductility [27].

The 6000 series alloys have recently found increased application in automotive and construction industry. Therefore, several research works have been undertaken to strengthen the alloys either by small addition of copper, magnesium, zinc and/or silicon or by a pre deformation treatment [35]. There is a great increase in market for extrusion intricate shape, medium strength and good toughness as a result of development of Al-Mg-Si alloys for light structures. These developed alloys are required to meet precise tensile properties and fatigue strength, welding characteristics and formability [28].

Aluminum alloy 6063 commonly referred to as an architectural alloy because is a medium strength alloy. It is normally used in intricate extrusions. It has a better surface finish, better corrosion resistance, and better formability than iron, readily suitable to welding and can be easily anodised.

The principal alloying elements in Al 6xxx series alloys are Mg and Si, both having low solid solubility in Al at room temperature [29]. The presence of Fe impurities together with Mg and Si, influences the material microstructure through the formation of intermetallic particles, such as Al (Fe,Mn)Si, Mg_2Si, and Al_3Mg_2. It is known that the Fe-rich particles cannot be re-dissolved during homogenization owing to their high melting point (>700°C) this behavior has helped in improve on the mechanical properties of Al alloy. A range of intermetallic particle phases, with their crystallographic structures, have been identified [30]. Distinguishing between the phases is of importance for aluminum alloy metallurgy, but may be difficult based purely on cross-sectional microscopy [31].

2.1. Properties of aluminum 6063 alloy

Al 6063 alloy is an extrusion alloy that is heat treatable for strengthening; machinability is considered to be average for this alloy; likewise, its forming ability, either hot or cold, is good; the alloy is readily welded by all of the conventional methods; hot working (as with forging) can be done on this alloy; Cold working characteristics 6063 are good for all conventional forming methods; it hardens due to aging heat treatment and cold working; its electrical conductivity is 50% of copper. Al 6063 alloy is called architectural aluminum for two reasons—firstly, it has good surface finish smoother than other available alloys, and secondly, its strength is approximately half the strength of 6061, making it suitable in applications where ultimate strength is not a requirement. This class of Al alloy is classed as "good" for forming and cold working requirements, "excellent" for anodizing, and "fair" for machining. It has a good resistance to general corrosion, including resistance to stress-corrosion cracking in the heat treated condition. The mechanical properties of 6063 aluminum alloy depend greatly on the temper, or heat treatment, of the material. Some of the physical properties and temper designations of Al 6063 are stated in **Tables 1** and **2** respectively.

2.2. Uses of aluminum 6063 alloy

6063 is mostly used in extruded shapes for architecture as discussed above, particularly for window frames, door frames, and roofs making aluminum 6063 an important extrusion alloy. It possesses moderate strength and has excellent finishing characteristics. Al 6063 has become the prime architectural alloy and its response to a wide variety to surface finishes further demonstrates its versatility therefore finding usage in decorative applications. The corrosion resistance is very good and the grade is easily welded and brazed, and is heat-treatable as well. Moreover, Al 6063 is commonly used in decorative applications, pipes and tubings for

Properties	Value
Density	2.71 g/cm^3
Melting point	600°C
Modulus of elasticity	67G Pa
Electrical resistivity	0.035E−6Ωm
Thermal conductivity	180 W/m K
Thermal expansion	23E−6/K

Table 1. Physical properties of Al 6063 alloy [32].

Standard tempers	Temper definition
F	As fabricated. There is no special control over thermal conditions, and there are no mechanical property limits.
O	Annealed. Applies to products that are annealed to obtain the lowest strength temper.
T1	Cooled from an elevated-temperature shaping process and naturally aged.
T4	Solution heat-treated and naturally aged.
T5, T52, T53	Cooled from an elevated temperature shaping process and artificially
T54, T55	Aged.
T6	Solution heat treated and artificially aged.

Table 2. Temper designations and definitions [33].

irrigation systems, lawn furniture, esthetic applications and trim. Alloy 6063 is often used for electrical applications in the T5, T52, and T6 conditions due to its good electrical conductivity (the definition has been shown in **Table 2**).

3. Equal channel angular extrusion of aluminum 6063 alloy

Up till date, 6063 is widely used in the production of extrusions—long constant-cross-section structural shapes produced by pushing metal through a shaped die. These include "L" and "U" shaped channels and angles. The influence of magnitude of plastic deformation on properties of metallic materials is connected with increase of internal energy. Due to the result of non-homogeneity of deformation at ECAE technique the internal energy gain differs at different places of formed alloy [34].

ECAE as earlier defined is a technique using severe plastic deformation to produce ultra-fine grain sizes in the range of hundreds of nanometers to bulk course grained materials [10, 35, 36]. ECAE is performed by pressing Al 6063 alloy billet of material through a die that has two channels which intersect at an angle. The billet experiences simple shear deformation, at the intersection, without any precipitous change in the cross section area because the die does not allow for lateral expansion. This means 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.

Different deformation routes can be applied depending on the billet rotation; these routes are shown in **Table 3**. ECAE technique can be applied to commercial pure metals and metal alloys [37]. The schematic diagrams of these routes are shown in **Figures 4** and **5**.

3.1. Superplasticity of aluminum alloys via ECAE

The ability of a material to pull out to a high tensile elongation without the development of necking is termed superplasticity. Superplasticity is usually in the range of 1–10 μm fine grain

Routes	Description
Route A	No rotation of the billet
Route B_A	Rotated counter clockwise 90° on even number of passes and clockwise 90° on odd number of passes [39]
Route B_c	Rotated counterclockwise 90° after every pass
Route C	Rotated 180° after ever pass

Table 3. ECAE routes [38].

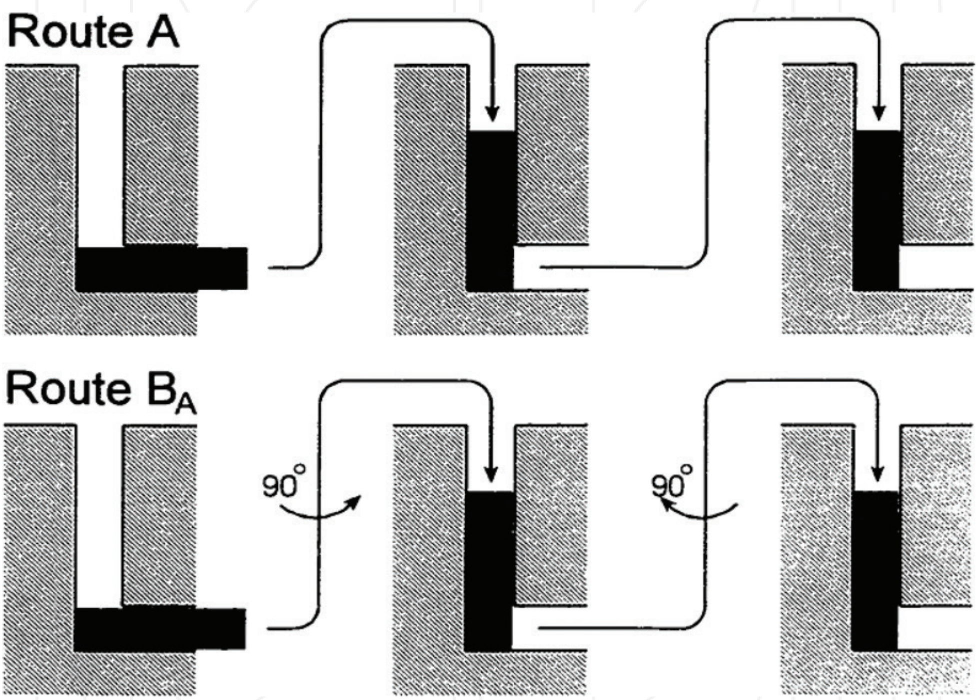


Figure 4. Schematic illustration of route A and route B_A [6].

size. Much finer grain sizes in the near-nanometer range has been achieved in Al-based alloys in experiments by using an intense plastic straining technique such as equal-channel angular pressing (ECAP) [40]. Superplastic properties in Aluminum alloys cannot be achieved under conventional processing conditions. Superplasticity is the ability of a material to undergo very large uniform neckless tensile deformation normally over 500% elongation prior to failure at a temperature well below its melting point (*Tm*) because the deformation mechanisms fall into the grain boundary sliding (GBS) regime [41, 42] fine grain size of 10 μm [43], high operation temperature of 0.9*Tm* and slow strain rate are required as for some Al alloy material. The aerospace industry first developed the AA2004 (Al-6Cu-0.5Zr) alloy, also known as Supral 100, which is a good example for superplastic applications [44]. The alloy composition corresponds to a relatively large addition of zirconium which provides a dispersion of very fine Al_3Zr particles

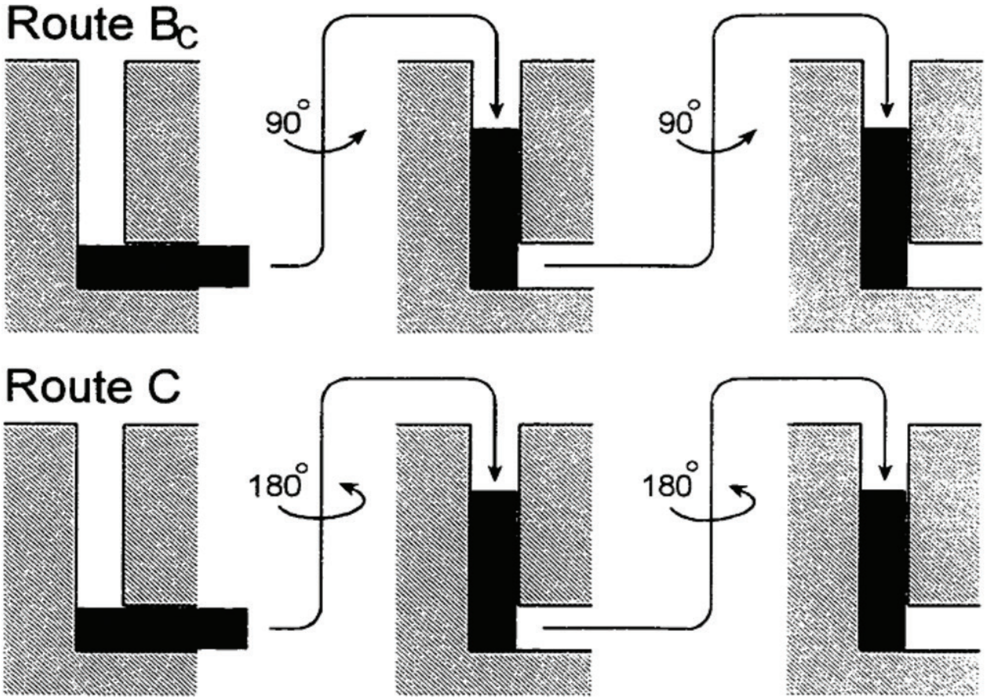


Figure 5. Schematic illustration of route B_C and route C [6].

that stabilize the wrought structure developed during hot/cold rolling and prevent recrystallization until the onset of superplastic forming [45, 46]. This alloy is a medium strength alloy with mechanical properties similar to AA6061 and 2219. It is usually used in lightly loaded or non-structural applications. Automotive industry demands an increasing use of aluminum alloys to reduce weight so as to improve performance and fuel consumption. However, in comparison to steel aluminum alloy sheet materials have lower formability in cold stamping processes. Some aluminum alloy offers an alternative approach which can be deformed to quite a high percentage at elevated temperature by the so-called superplastic forming (SPF) process [45, 46]. Although fine grain size can be achieved in Al alloy through significant thermomechanical process, it is very costly and also the low deformation strain rate results in long forming times [6, 47]. Therefore reduction of the grain size in the sub-micrometer or nanometer scale is usually encouraged by applying Equal-Channel Angular Pressing, or ECAP [48].

Superplasticity has been utilized for the fabrication of complex parts from sheet metal because of the large elongation [49, 50] There is considerable current interest in developing materials with ultrafine grain sizes, since experimental evidences have shown that reducing grain size increases the superplastic strain rate and/or decreases the superplastic temperature [51]. Materials processed by ECAE have the potential for superplasticity, especially at very high strain rates and low temperatures. The validity of this proposal has been demonstrated by several recent reports of high strain rate superplasticity above 10^{-2} s^{-1} and low temperature superplasticity in aluminum and magnesium alloys processed by ECAE [52–55].

4. Conclusions

From the current review, it can be concluded that severe plastic deformation via ECAP is a very useful process on increasing mechanical properties with only partial and acceptable decrease in ductility. Strengthening of material was caused by grains refinement and strain hardening of solid solution. Because the cold-worked material was a normal material that has already been extended through part of its allowed plastic deformation by ECAE, dislocation motion and plastic deformation have been hindered enough by dislocation accumulation, and stretching of electronic bonds. Elastic deformation then reached their limit, a third mode of deformation then occurs faster (i.e. fracture). Strain hardening thus reduces ductility and increases brittleness.

Processing by ECAE led to grain refinement and arrays of ultrafine grains that are significantly smaller than those generally produced using conventional thermo mechanical processing. ECAE is a simple process that can be readily applied to a wide range of materials without the requirement of developing specific and different treatments for each alloy composition. The presence of these exceptionally small grain sizes provides an opportunity for achieving superplastic ductility, and thus a superplastic forming capability at a very fast strain rates (extremely higher than what was used in the experiment).

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