MATEC Web of Conferences **135**, 00013 (2017) DOI: 10.1051/matecconf/201713500013
ICME'17

Solid-State Recycling of Light Metal Reinforced Inclusions by Equal Channel Angular Pressing: A Review

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Abstract. Solid-state recycling of light metals reinforced inclusions through hot Equal Channel Angular Pressing (ECAP) is performed to directly recycle metal scraps and reduce cost of material in engineering applications. The ECAP is one of the most important method in severe plastic deformation (SPD) that can convert light metals into finished products. This paper reviews several experimental and numerical works that have been done to investigate the effects of the ECAP parameters such as die angles, material properties, outer corner angle, friction coefficient, temperature, size of chips, pressing force, ram speed and direct effects of number of passes on the strain distributions. It also includes the performance enhancement of aluminium matrix composite reinforced ceramic-based particles that derived from direct recycled aluminium chips for sustainable manufacturing practices.

1 Introduction

Recycling aluminium and its alloys by solid-state recycling method is relatively simple, consume lower energy, and not to have harmful impact on the environment. It is significant to study the direct aluminium recycling in order to reduce the energy consumption and emissions level that causing global warming [1]. Chips can be directly recycled and formed by ECAP, one of the most promising severe plastic deformation (SPD) techniques for fabrication of bulk ultrafine grain materials [2]. The common steps associated with this method are pulverizing the chips, cleaning, drying, cold compaction and hot/cold pressing the chip-based billet. The process depends on the design methods and the factors affecting the mechanical properties of aluminium chips such as size of chips, cold pressing

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parameters, extrusion temperature, extrusion rate and ratio [3]. Enhancing mechanical properties of the recycled light metal alloys and decreasing the recycled part porosities are the primary aimed. The ECAP can apply design with an internal angle of 90° and 20° of the outer angle. The ECAP dies and billet can be heated to decrease porosity during the process. The decrease in porosity was due to the compressive force applied through the interaction of the billet material with die and container [4]. In metal matrix composites (MMCs), silicon carbide, alumina oxide and boron carbide are the most commonly used particulates in fibre reinforced metal matrix composite. The boron carbide (B_4C) particulate is a superior ceramic reinforced material for MMCs than silicon carbide (SiC) and alumina (Al_2O_3) due to its high hardness, low density, high strength, high wear and impact resistance, high melting point, low coefficient of thermal expansion and good chemical stability [5, 6]. However, MMCs showed the superior plastic properties in the SPD [7]. While boron carbide (B_4C) is widely common reinforced metal matrix composites that has a low density value, good hardness, excellent thermal stability and remarkable chemical inertness [8]. This paper presents a review on solid-state recycling of aluminium alloys reinforced ceramic particles in metals matrix composites (MMCs). It also covers design variations of the ECAP dies and the processing parameters. The review considers how ultra-fine grained material through the ECAP technique can affect the microstructure, mechanical and physical properties as well as the overall performance of the consolidated chips.

2 Experimental Factors Influencing ECAP Material

2.1 Inner Angle

The inner angle Φ, is one of the important factor that enhance the strain in each pass. The factor of inner angle presented is directed to have influences on the microstructure development. The researchers proposed that angles should be selected between 90° to 120° and this supported the evidence from the results of finite element analysis and microstructure investigations [6, 10]. Die angle, Φ contributed to direct effect on strain distribution of ECAP under ideal conditions. An inner angle of 90° is the most significant angle because of its effectiveness of achieving an ultrafine-grained microstructure development [2]. The influence of processing routes is an alternative way to consider between consecutive numbers of passes and angle [6].

2.2 Outer Angle

A direct effect of an outer angle, ψ on the extruded billet through the ECAP process can become important. The outer angle proposed to be $\psi = 20°$ to cause an impact on the better strain homogeneity that is very effective on the grain refinement. If $\psi = 0$ was taken, the arc curvature leads to be dead zone where the billet is no longer contacted to the die wall and the problem could be eliminated or removed by having movable ECAP dies. Increasing in ψ will lead to less strain as it is obtained from the derived equation [12, 13]. Smaller corner angles maximize the homogenous of the billet while the friction reduced at the corner gap. ECAP channel and angles have the influence on generating the average equivalent plastics strain. The friction causes an important effects to the required punch load to extrude the billet and maximum strain is obtained by the following parameters with $\varphi = 90^o$, $\psi = 15^o$ and $\mu = 0.3$ [2, 13].

2.3 Pressing Speed

Pressing speed is a significant factor of ECAP process. Pressing force could be validated by using the FEM software and to be compared with the experimental work. Furthermore, the punch force of experimental and simulation have the same conditions so that, the results of FEM assumed as agreeable [14]. However, when the temperature is low the need for high straining is required to avoid the problems associated with ductility and durability of the material and die set of ECAP processing [3]. High capacity hydraulic press is required to generate high ram speed between the ranges from 1 to 20 mm/s. The investigations confirmed that the pressing of pure Al have not influences on the equilibrium of ultra-fine grain formed by ECAP process [6].

2.4 Pressing Force

Pressing force is an important factor of ECAP die. However, the pressing force could be validated by using the FEM software and to be compared with experimental work or theory relations. The punch force of experimental and simulation have the same conditions so that the results of FEM simulation assumed to be agreeable as the pressing force simulated values are 121.5kN and 113kN. On the other hand, for the first pass when ψ =15˚, Φ = 60˚ where the effective strain values obtained between the whole and the plan of the ECAP metal. In improvement of the ECAP tool was noted throughout the mechanical and physical properties and the grain size was reduced about 8 times [15].

2.5 Pressing Temperature

Temperature effect is one of the most important parameter in SPD processing methods such as ECAP processing. Metallic powder of aluminium and steel were investigated. The process of was proposed that the consolidation was performed at room temperature. Furthermore, the tensile strength decreases by increasing the temperature of ECAP processing and the total elongation is also increased [17]. The researcher proposed that when the temperature is increased from 120°C to 180°C, it can cause decreases of mechanical properties while the precipitate and grain size are increased. On the other hand, temperature is effective to cause decreasing on high angle boundaries and transformation on metal phase. The die was heated up until 15 minutes to desire temperature furnace [16]. Higher temperatures of 200°C, 250°C, 450°C result in decreasing the size of grains and the microstructure during continues ECAP process [18]. Lower temperature may cause new systematic recovery, recrystallization, twining, and mechanism of dislocation climb become impossible. By lowering the temperature values the need for straining force is required avoid problems emerged that associated with ductility of the material and durability of the die-set of the ECAP process [19, 20].

2.6 Processing Routes of ECAP

The theory of deformed billet routes were introduced by rotating billets throughout 0◦, 90◦ and 180◦ degree along each ECAP extrusion pass [5]. The process was proceeded repetitively to obtain the strain distribution along crossing area and there are four main processing routes that have been used to study the microstructural development during ECAP. It is recognized that after pressing, the characteristics within material crystalline would be changed due to the pressing and possible to carry the main processing routes definition [21].

Route A: The sample is pressed with no rotation.

DOI: 10.1051/matecconf/201713500013

Route B_A:The sample is rotated with 90◦ alternatively, clockwise or counter clockwise
Route B_C:The sample is rotated 90◦ clockwise between the passes.
Rout C: The sample to be rotated with an angle of 180◦.
The principle of ECAP processing routes influence on the light metal compression including mechanical properties, microstructure, deformation and strain distribution [55]. Figure 1 illustrated the basics routes of ECAP process.

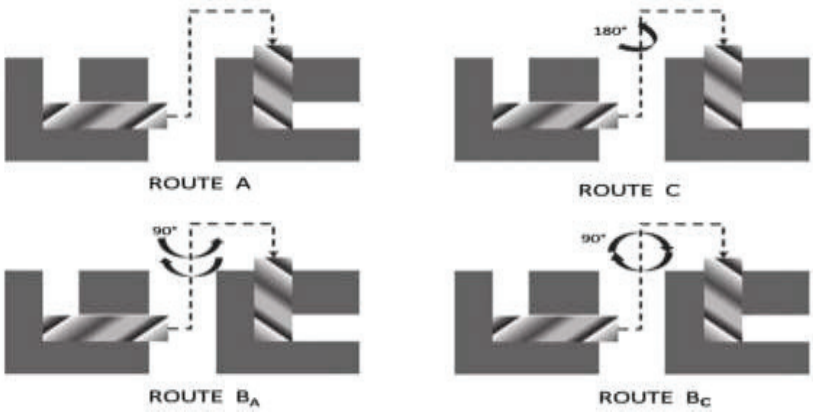

Fig. 1. Illustrated The Basics of ECAP Processing Routes [22]

However, the strain for one pass could be calculated by the equation below that developed by Iwahashi [39]

$$\epsilon = \frac{1}{\sqrt{3}}\left(2\cot\left(\frac{\Phi+\psi}{2}\right) + \frac{1}{\sqrt{3}}\left(\psi\, csc\left(\frac{\Phi+\psi}{2}\right)\right)\right.$$

$$\epsilon = \frac{1}{\sqrt{3}}\left(2\cot\left(\frac{\Phi+\psi}{2}\right) + \frac{1}{\sqrt{3}}\left(\psi\, csc\left(\frac{\Phi+\psi}{2}\right)\right)\right.$$

And for multiple no of pass the magnitude effective strain is proposed by [15]

$$\varepsilon_{eq} = \frac{N}{\sqrt{3}}\left[2\cot\left(\frac{\Phi+\psi}{2}\right) + \psi cosec\left(\frac{\Phi+\psi}{2}\right)\right]$$

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3 Reinforced AA6061 Alloy with Metal Matrix Composites

Metal matrix composites (MMCs), especially the aluminium based matrix, have become structural materials that possess light weight, high strength and modulus, low thermal expansion, and good wear resistance. MMCs are promising materials for number of specific applications in aerospace, defence, and automobile industries [23]. The parameters such as ECAP routes, inner angle Φ, outer angle ψ. At the first pass the material deformed to rhombohedral shape and the straining shear plane x, y, z, depends on what a way of the material to be inserted into the ECAP die. The route A yields to increase distortion of in the coordinates of x, y but not with z , the route BA yields for increasing distortion at all sides of orthogonal planes , the route B and C the element is restored after for an every four pressings [24, 20, 9]. Table 1 is showing the particulate properties of the reinforced particles.

Table 1: Properties of Particulate Composites [25]

Properties	WC	SiC	Al_2O_3	B_4C	Si_3N_4
Density g/cm2	13-15.3	3.21	3.7-3.97	2.51	3.31
Compressive Strength MPa	3100-5860	1725-2500	2070-2620	2900	689-2760
Modulus of Rigidity GPa	483-641	476	393	445	317

The corresponding volume friction could be calculated from the relation below:

$$Vp = ((\mathrm{M}\rho)/(\mathrm{P}\rho))/(\frac{M\rho}{P\rho} + \frac{Mm}{Pm})Vp = ((\mathrm{M}\rho)/(\mathrm{P}\rho))/(\frac{M\rho}{P\rho} + \frac{Mm}{Pm})$$

Where, Vp volume fraction of ceramic particles. mρ, Pρ mass and density of the particles mρ, Pρ mass and density of matrix [26].

3.1 Silicon Carbide Reinforced AMC

Saheb investigated Metal Matrix Composites (MMCs) aluminium based particles with SiC, alumina (5%, 10%, 15%, 20%, 25%, and 30%), and graphite of weight fraction 2%, 4%, 6%, 8% and 10%. The findings indicated that the method is successfully developed MMCs materials properties. The observations proposed an increasing of hardness with weight volume friction and the results of maximum hardness is 25% of SiC silicon carbide [27].

Weight friction and 4% graphite. Investigation on the microstructure, wear resistance and mechanical properties of silicon carbide (SiC) reinforced particles reinforcing aluminium matrix composites was also reported. The variations of silicon percentage (0, 5, 10 and 20 wt. %) were proceeded with stir casting process. The findings showed that the maximum hardness obtained was at 20% of SiC addition as long as porosities and wear test were also increased by increasing the volume friction of silicon carbide particles [28]. Other researchers investigated the mechanical properties of hybrid reinforced with groundnut ash and SiC of the volume friction of (10:0, 7.5:2.5, 5.0:5.0, 2.5:7.5 and 0:10) by stir casting process. The results showed with increasing of Groundnut Shell Ash (GSA), the fracture toughness and elongation percentage were improved at 6%wt Al–Mg–Si/SiC–GSA for 15.7% but with 10%wt the fracture toughness reported as 7.33% improvement. Hardness and tensile decreased with the increasing of the GSA volume friction of reinforcing phase [29].

3.2 Aluminium Oxide Al_2O_3 Reinforced AMC

Fogagnolo demonstrated cold and hot press followed by hot extrusion to recycle AA6061 aluminium reinforced with Al_2O_3. The findings proved that cold press and hot extrusion contributed to higher profit compared with primary material produced by conventional casting method [61]. Al-7075 chips reinforced with 10 vol% Al_2O_3 particles by high pressure torsion with 20 turns was investigated by Fogagnolo et al. [30]. The finding showed a grain refinement from 8 μm to 300 nm after the process of HTP has been achieved. The microhardness also improved from 167Hv at initial value to 260Hv after the HTP process and super plasticity of MMC with maximum elongation of 670% was achieved in tensile test when the strain rate reported at 1.0 x 10^{-2} s^{-1}. Besides, investigation on utilizing SiC and Al_2O_3 as reinforced particles in aluminium metal matrix composite have been developed with stir casting process route. The effect of reinforcement volume fraction on microstructure, physical and mechanical properties of the composite have been increased with increasing the volume friction of ceramic particulates. The yield and tensile strengths showed an increases of 19% and 19% with the 20 vol% SiC and 20vol% Al2O3 respectively [31].

3.3 Boron Carbide (B_4C) Reinforced AMC

Boron carbide is a significant hard element that has high elastic modulus and fracture toughness. However it is superior reinforced ceramic particles for enhancing aluminium material composites (AMC) than SiC or Al_2O_3 due to its low density, higher wear resistance, higher strength, higher melting point, higher impact resistance and lower coefficient of thermal expansion and stable chemical stability [32, 9]. The effects of adding micro – nano B_4C particles by using casting process was investigated and the findings proved that 6% vol. nano particles indicate better mechanical properties particularly in tensile, ductility and impact energy than micro B4C reinforcement particles. While the wear resistant gradually increased up to 8% B_4C addition [9]. Ramnath et al. [33] investigated three types of MMC reinforced samples. Sample 1: aluminium alloy 95%, alumina 3% and boron carbide 2%; Sample 2: aluminium alloy 95%, alumina 2%, and boron carbide3 %. ; Sample 3: aluminium alloy only. The findings revealed that the flexural and tensile strength of sample 3 was higher than other two samples because of its aluminium content. The Table 2 is illustrated the amount the type and volume friction of MMCs B_4C particles.

Table 2: Volume Friction of B4C Particles

no	MMCs	Volume Friction % B_4C	Method	Author
1	AA6061/B4C	16 , 30 vol.%	stir casting route	[65]
2	AA6061/B4C	3%, 6% and 9%	stir casting method.	[64]
3	AA6061/B4C	0%,10%,15%,20%	DRAs followed by squeeze casting	[66]
4	AA6061/B4C	0%,2%,4%,6%,8%,10%	ultrasonic cavitation	[18]
5	2024 / B4C	10 vol%B4Cp/2024A	Hot extrusion	[73]
6	Al / B4C + Al2O3	95% AL + 3%Al2O3 + 2%B4C 95%Al + 2% Al2O3+ 3% B4C	stir casting method	[74]

3.4 Zircon ZrO_2 Reinforced AMC

Zircon is a hybrid reinforced particles that has superior characteristics of material matric bonding which results better wear resistance compared to other particles such as alumina Al_2O_3 [8]. Hossein et al. [34] investigated the combination of AMCs composites and the addition amount of zircon particles in different percentage (5%, 10 %, 15 %, 20 %, and 25 %). The findings showed an increases of hardness to the maximum value of 75 BHN and density increases up to 92%. By increasing temperature from 600 ˚C to 650 ˚C, the mechanical properties such as yield strength and elongation are improved. The researcher also proposed that the optimum value obtained on compressive strength is 248 MPa with 5% vol. zircon at 650 ˚C. The effects of adding ZrO_3 particles to aluminium at 750 ˚C by stir casting process was studied. The mechanical properties were enhanced with the addition of the ZrO_2 until 2% vol., the strength reported as higher as 197 MPa in this experiment with 64% of the pure Al. The reason of increasing yield strength at the desired temperature 750 ˚C is because of the dislocation density of composites pile-up beyond the zirconium particles, the dislocation occurred during forming metal processing. The mechanical and physical properties were increased as proposed by Ch.V.M.Prasad, when 3 vol% ZrO3. The Table 3 is showing the amount of volume particles proposed by pervious researchers.

Table 3: Volume Friction of ZrO2 Reinforced Particles

No	MMCs	Volume Friction % ZrO_2	Method	Author
1	Al_2O_3/ ZrO_3	5%,10%,15%,20%	Surface modification with aqueous solutions	[67]
2	Al7075/ZrO_3/Fly Ash	0% , 3% ZrO_2 , 6% fly ash 4th 3% ZrO_2+ 6% flyash	stir casting	[11]
3	Al/ ZrO_2	5 – 80 %	Powder technology	[68]
4	Al / ZrO_2	1%, 2% , 3%	Liquid Routing	[69]
5	Al/ZrO2/Al_2O_3/TiO_2	0% - 5 %	stir casting method	[70]

3.5 Fly Ash Reinforced AMC

Mindivan et al. [36] aimed to conduct study on aluminium reinforced composite of aluminium 6082 alloy chips mixed with fly ash by direct conversion. Within the addition of the fly ash results in considerable increase of hardness to superior level and wear properties than those conventionally produced. Aluminium with 10 wt% added fly ash/lead in metal matrix composites was developed using powder metallurgy method. The composites reinforced powder consist of 0, 5, 10, 15 and 20 wt % fly Ash. The experiment was carried out using the mixing chamber component with fixed and rotated at 32 rpm for approximately one hour with changing in direction for every five minutes to ensure homogeneous mixing. The density is directly increased with increasing the percentage of added material content and reached up to 10 wt % [37]. The reinforcement fly ash particles from thermal power plant was also conducted at nano level of reinforcement to form Al matrix materials. The investigation of the nano fly ash particles (1 wt.% to 3 wt.%) causes in increase of AA2024 hardness of which reported as 75 Hv for 1 wt.% to 114 Hv for 3 wt.% [38]. Mechanical property such as compressive strength of nano fly ash/Al composite enhanced with increase in wt. % of nano fly ash. The strength of AA2024 alloy is 289 MPa and it was increased to 345 MPa for 3 wt. % fly ash/AA2024 composite.

4 Conclusion

In this review, direct conversion of aluminium chips reinforced with multiple ceramic particles through the ECAP tool into final products have been presented intensively. An overview of this paper is presented to propose a new approach of improving the performance of aluminium composites made of chips with addition of boron carbide (B_4C)

or zirconium dioxide (ZrO_3). The chip based composite reinforced materials offers an alternative to manufacturing automotive industries of as a way of recycle, reuse the machined materials as a secondary source of metal and to prevent our earth from green house gas for sustainable life. However, B_4C and ZrO_2 are superior ceramic materials that improve the tensile strength, wear resistance, stiffness and microstructure of ultra. Currently ECAP is the most potential tool of all SPD techniques. Due to the mechanical behaviour the ECAP deals with metal flow and microstructure evaluation. More investigations were carried out recently on using ECAP die in direct recycling. The factors that influence the final results such as geometries, die inner and outer angles, backpressure, pressing speed, pressing temperature, and die related accessories were also important to encompass in the ECAP method. Due to the importance of achieving objective to confirm that the aluminium alloy Al6061 reinforced ceramic inclusions can be utilized in engineering applications such as automotive manufacturing.

Acknowledgement

The authors would like to express the deepest appreciation to the Centre for Graduate Studies, Universiti Tun Hussein Onn Malaysia (UTHM). Additional support was also provided by Sustainable Manufacturing and Recycling Technology, Advanced Manufacturing and Materials Center (SMART-AMMC), Universiti Tun Hussein Onn Malaysia (UTHM).

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