

Effect of Equal Channel Angular Pressing on the Microstructure and Mechanical Properties of Hybrid Metal Matrix Composites

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Abstract

Objectives: The objective of the present study is to prepare Al6061-Gr-SiC hybrid composites by stir casting route and the effect of Equal Channel Angular Pressing (ECAP) on the microstructure and mechanical properties of Al6061-Gr-SiC hybrid composites will be evaluated. **Methods:** In the present study, Al6061 is selected as matrix material. The reinforcement materials chosen are graphite (Gr) and Silicon carbide (SiC) particles of 10-30 μm size. The hybrid composites have been prepared by stir casting route in which the amount of Gr particles are kept at 3wt% and SiC particles are varied from 2-10wt% in steps of 2wt%. The cast hybrid composites are subjected to annealing treatment at 400°C for 4 hours and specimens have been prepared from these composites for ECAP process. The ECAP process was carried out at room temperature using a die with channel angle of 120° and Bc route was adopted for successive passes. The influence of ECAP on microstructure and mechanical properties of Al-Gr-SiC hybrid composite was evaluated. **Findings:** The microstructural study revealed that the composites are free from defects and also the distribution of reinforcement particles in the matrix are fairly uniform. Significant improvement in micro hardness and tensile strength was observed as the wt% of SiC_p increases in as cast Al6061-Gr-SiC hybrid composites. After ECAP process, the size and distribution of the reinforcement particles are not changed but significant reduction in the grain size of the matrix alloy was observed. The micro hardness and tensile test results revealed that, there is a significant improvement in the micro hardness and the Ultimate tensile strength of ECAP processed hybrid composites. The enhancement in mechanical properties are mainly attributed to the grain refinement of the matrix alloy and strain hardening of hybrid composite materials by ECAP process. **Applications:** The ECAP process had a profound effect in enhancing the mechanical properties of hybrid composites. These composite materials have great impact in automobile, military and aerospace industries.

Keywords: Al6061, ECAP, Hybrid Composites, Mechanical properties, Stir Casting, Silicon Carbide

1. Introduction

In the recent years, research has been shifted to composite material system from monolithic materials to convene global demand for light weight and better performance materials. In particular Aluminium base particle reinforced MMC's are finding wide spread acceptance due to light weight, high specific strength, stiffness and higher wear resistance, hence finds applications from general engineering industries to Aerospace applications¹⁻³. The

Hybrid composites are latest group of composites consists of more than one reinforcement and employed for numerous applications due to their excellent mechanical and tribological properties. Among the various aluminium alloys, the Al6061 is better choice for a matrix material because it has good mechanical properties, formability and the strength of this material can be altered by doing the heat treatment^{3,4}. Reinforcement of aluminium alloy with SiC particulates has generally been observed to

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improve the yield strength, ultimate tensile strength and wear behavior of the composite material⁴⁻⁷. Aluminium graphite particulate MMCs have been recognized as a high-strength, low-density material and finds applications in automotive components due to their superior tribological properties⁸. The stir casting method is found to be easier and the low cost manufacturing method when compared to other processing methods, particularly when discontinuous reinforcements are used^{9,10}.

Ultra-fine grained materials are emerged as a potential materials due to their remarkable mechanical and physical properties, hence these materials have great impact in biomedical, electronics, military, aerospace, and automotive industries. Severe plastic Deformation (SPD) process are a group of metal working process that uses extreme strains to produce exceptional grain refinement in metals and alloys¹¹. Amongst these various SPD process, Equal Channel Angular Pressing (ECAP) is more popular and attractive due to its simplicity, ease of operation, tooling and cost effectiveness and possibility of scale-up to produce ultra-fine grained materials for structural applications¹²⁻¹⁴. Most research work on ECAP was carried out on pure metals and metallic alloys¹⁴⁻¹⁶. Unlike in case of metals and alloys, not much work has been carried out in the case of MMCs¹⁷⁻¹⁹. However, the reinforcement materials used in these composites are Al_2O_3 , SiC_w , SiC_p and Gr_p . ECAP of these MMC's results in the uniform distribution of the particles in the matrix and also it reduces the matrix grain size to submicron level. In addition, significant enhancement in strength and hardness of the composite was observed¹⁹⁻²². A major work has not been carried out on ECAP of composites and very few reports are found on ECAP of Aluminium hybrid composites. The main objective of the present investigation is to prepare Al-Gr-SiC hybrid composite by stir casting technique and the prepared samples were subjected to ECAP. The influence of ECAP on microstructure and mechanical properties of Al-Gr-SiC hybrid composite will be evaluated. The obtained results are compared with the base Al6061 alloy and as cast Al-Gr-SiC hybrid composites.

2. Materials and Methods

2.1 Materials Selection

In the present study, Al6061 is selected as the matrix material, Gr and SiC particles of 10 to 30 μm size were employed as reinforcing materials for preparing composite. The chemical composition of Al6061 alloy by

weight percent Si = 0.72, Mg = 0.89, Cu = 0.21, Fe = 0.23, Cr = 0.22, Zn = 0.10, Ti = 0.01 and Al = Balance. The amount of Gr particles is maintained at 3wt% constant, while SiC particles are varied from 2 to 10wt% in steps of 2wt%.

2.2 Preparation of Composites

Figure 1 show the experimental set up used to prepare the hybrid composites. The hybrid composite was synthesized by stir casting method in which Al6061 alloy ingots were charged into electric resistance furnace and melted to 750°C, followed by degassing using pure nitrogen. The preheated Gr and SiC particles are incorporated into the melt and stirred using zircon coated steel impeller. The composite melt was solidified in the steel mould of round rods of 15 mm diameter x 150 mm length. The detailed procedure adopted during composite preparation has been explained in our earlier paper⁴.

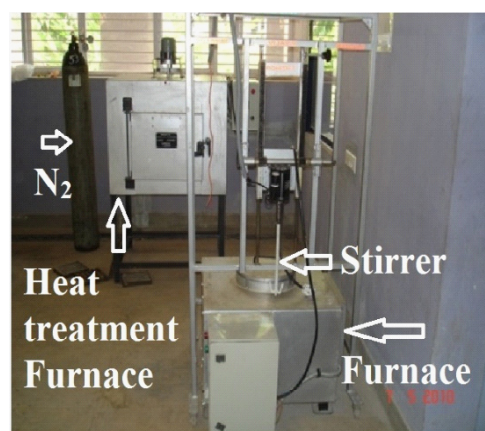


Figure 1. Stir casting set up.

2.3 ECAP Process

The samples of 10 mm diameter and length 80 mm were machined from cast hybrid composite for ECAP. Prior to ECAP, the surface of the samples was polished using SiC abrasive papers to reduce friction between the sample and die wall. The samples were annealed at temperature of 400°C for 4 hours to homogenize the microstructure. The annealed composite samples were subjected to ECAP using a die with two channels having an equal circular cross section with diameter of 10 mm. The two channels of the die intersect at angle of $\phi = 120^\circ$ and $\psi = 12^\circ$ as shown in Figure 2. The theoretical effective strain according to

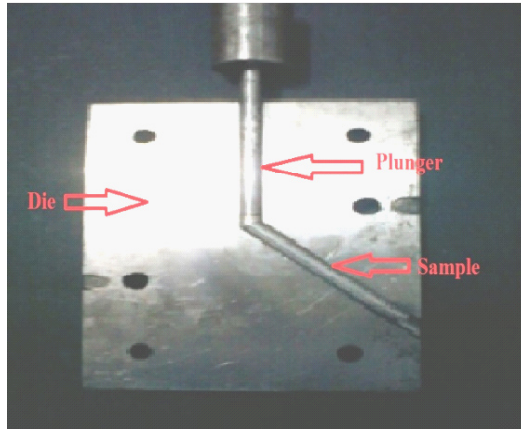


Figure 2. ECAP die with plunger

the die geometry is given by the equation as formulated by Nakashima et al.¹³,

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

From the above equation it was calculated that the strain introduced was ~ 0.7 for each pass of sample through the die. In order to reduce the friction between the die walls and sample, MoS_2 lubricant was used. B_c route was employed in the present study in which sample is rotated by 90° in one direction after each successive pass. ECAP experiments were carried out at room temperature and repeated three times to verify the results. The specimen was taken for characterization after each pass of ECAP process.

3. Characterization of Composites

The samples of 10mm diameter and 10mm thick were cut from the specimens and these samples were polished with SiC abrasive papers up to 1000 grit size followed by polishing with Al_2O_3 paste on velvet cloth. Finally, the samples were polished with diamond paste, etched by Keller's reagent and examined using metallurgical microscope. The micro hardness of as cast and the ECAP processed composites were measured using Vickers's micro hardness tester with a load of 1kg for 15 seconds. Averages of 6 indentations were considered on each sample for data presentation. The tension test was conducted using computerised UTM as per ASTM E8M standard. Three specimens were tested on each composite and average values of ultimate tensile strength and ductility (% elongation) was measured.

4. Results and Discussion

4.1 Microstructural Studies of as cast and ECAP processed Hybrid Composites

Figure 3 shows the micro photographs of as cast aluminium alloy Al6061 and their composites. It was observed that the reinforcements are uniformly distributed in the matrix and there is a significant difference in the microstructures of as cast Al6061 and their composites containing Gr and SiC particles. In as cast Al6061, grain boundaries are well defined, on the other hand in Al6061-Gr-SiC hybrid composites grain boundaries are not well defined rather poorly defined and irregularly shaped. Further, these micrographs revealed homogeneity of cast composites, whereas the micrograph with 10wt%SiC particles showed little clusters and porosities in the hybrid composites.

Figure 4 presents the microstructure of ECAP processed Al6061 alloy and their composites. The average grain size of as cast Al6061 alloy was observed to be $54\mu\text{m}$. After first ECAP pass, the grain size was reduced to $21\mu\text{m}$, $12\mu\text{m}$ after second ECAP pass as shown in Figure 4a and further ECAP passes reduces the grain size to $3\mu\text{m}$ (4 pass). Figure 4(b) shows the micro photographs of Al6061-3wt%Gr-2wt%SiC composite after 1st ECAP pass, grain refinement achieved was less. There was no change in the size and distribution of reinforcement particles after ECAP process. After 3rd ECAP pass, the grain size of Al6061-3wt% Gr-2wt%SiC hybrid composite was reduced to $6\mu\text{m}$. Figure 4(c) shows the micro

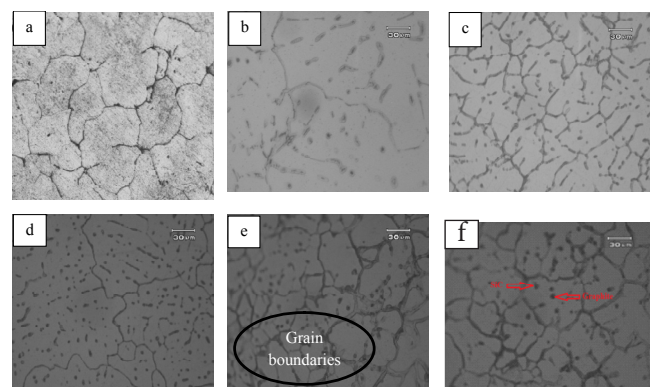


Figure 3. Microstructure of as cast Al6061 and their composites: a) Al6061 matrix alloy b) Al6061-3wt%Gr-2wt%SiC c) Al6061-3wt%Gr-4wt%SiC d) Al6061-3wt%Gr-6wt%SiC e) Al6061-3wt%Gr-8wt%SiC and f) Al6061-3wt%Gr-10wt%SiC.

photographs of Al6061- 3wt% Gr-4wt% SiC after 2 ECAP passes. Similar kind of microstructure was observed for Al6061-3wt% Gr-4wt%SiC hybrid composites. For Al6061-3wt%Gr-6wt% SiC and Al6061-3wt%Gr-8wt%SiC composites only two ECAP passes was possible, the grain size achieved was $9\mu\text{m}$.

In addition, for Al6061-3wt%Gr-10wt%SiC hybrid composite only one ECAP pass was possible due to high hardness of the composite. Further ECAP pass resulted in the formation of cracks on the specimen (inner radius). This is due to high strain rate sensitivity of composite material than Al6061 alloy due to ECAP process and also due to non-uniform stress distribution across the sample²¹. In addition, as the wt% SiC particles increases, the hardness of the material increases which results in the loss of ductility which leads to the formation of cracks on samples (Figure 4f). Similar observations are made by other researchers^{22,23}.

The **Figure 5**. shows the EDAX taken on the interface of matrix and reinforcements. There were no interfacial

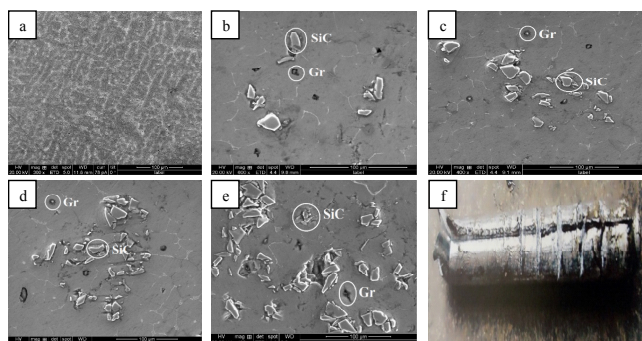


Figure 4. Microstructure of ECAP processed Al6061 and their composites: a) Al6061 matrix alloy b) Al6061-3wt%Gr-2wt%SiC c) Al6061-3wt%Gr-4wt%SiC d) Al6061-3wt%Gr-6wt%SiC e) Al6061-3wt%Gr-8wt%SiC and f) Cracks on the ECAP processed specimen.

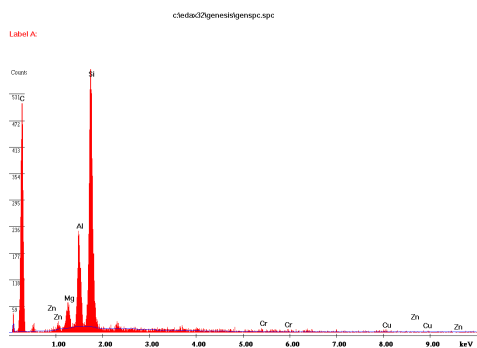


Figure 5: EDAX of Al6061-Gr-SiC Hybrid composite

reactions between the matrix and reinforcements and the bonding between them was good, figure 5 confirms this.

4.2 Hardness and Tensile behavior of ECAP processed Al6061 and their composites

The Vickers hardness of Al6061 alloy and Al6061-3wt%Gr-2-10wt% SiC hybrid composites were evaluated in the as cast and after ECAP process. The hardness of studied hybrid composites is higher than that of Al6061 alloy in the as cast condition and hardness increases with the increasing SiC content into Al6061-3wt%Gr hybrid composites. This improvement in hardness of the composites was mainly attributing to high hardness of the SiC particles. Further, the hardness of the composites was improved after ECAP process, compared to as cast composites. This is due to the fact that, the ECAP resulted in the formation of fine grains of the matrix alloy in composites, also the material become strain hardened due to ECAP process²².

The as cast Alloy Al6061 exhibits a hardness of 45. After the material was subjected to first pass of the ECAP, hardness value was increased to 69 with an increase of 54%. Further ECAP passes increases the hardness to 1.74 times the as cast alloy after 4 ECAP passes. The Vickers hardness of Al6061-3wt%Gr-2wt%SiC hybrid composite increase to 41% after first pass of ECAP, after three ECAP passes, the hardness increases to 59%. Only three ECAP passes are possible for this composite. Further ECAP passes resulted in the formation of cracks in the specimen. Similar observations were obtained for Al6061-3wt%Gr-4wt%SiC hybrid composites. The highest value of the hardness (90) was obtained for 6wt% SiC in the studied composite, but restricted the number of passes to only two. This is due to the hard nature of the composites. But, further addition of SiC (10wt%) in to the Graphite based composites, the hardness of the composites almost remained constant and restricted the pass to only one. The reason is as the wt% SiC particles increases, the hardness of the material increases which results in the loss of ductility which leads to the formation of cracks on samples as shown in Figure 4f with further ECAP process.

The Ultimate Tensile Strength (UTS) of base material Al6061 and SiC reinforced Al6061-3wt%Gr hybrid composites in as cast condition and after ECAP were studied and plotted as in Figure 6(b). In the as cast condition, the hybrid composites exhibit higher strength than the base material. This improvement in strength is due to

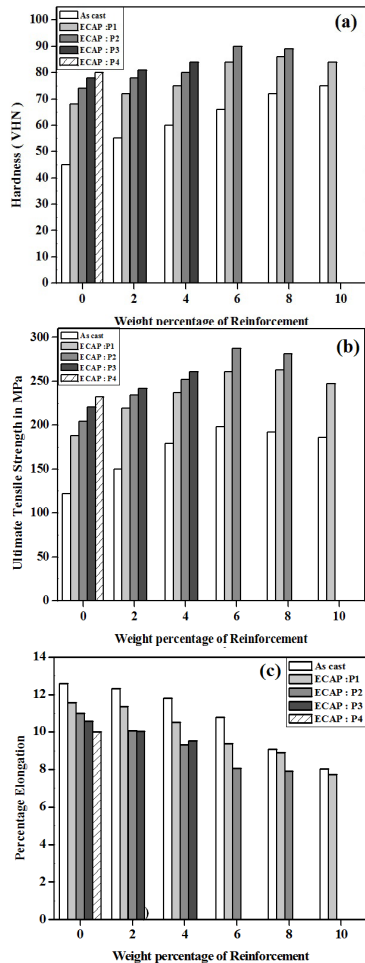


Figure 6. Effect of reinforcements and ECAP process on Al6061 and Al6061- 3wt% Gr – (2 -10wt%) SiC Hybrid composites (a) Vickers Micro hardness (b) Ultimate Tensile strength and(c) Percentage elongation.

the presence of graphite and hard SiC particles and these particles acting as barriers to dislocations, thereby providing increased resistance to tensile stresses. In addition, increased amount of reinforcements in matrix alloy increases dislocation density due to thermal mismatch of the matrix alloy and reinforcements²⁵. The UTS of the hybrid composites increases after each ECAP pass due to grain refinement. It was well known that ECAP process has significant effect in refining the grain size of the composites, which in turn leads to significant increase in UTS of the composites. It is in accordance with the Hall-petch equation. The UTS of matrix alloy Al6061 in as cast condition was found to be 120N/mm². After the first ECAP pass, it is increased to 188N/mm² with 57% increase. Further ECAP passes, increased the UTS of matrix alloy to 1.95 times the as cast alloy. Addition of 2wt%SiC particles into

Al6061-3wt%Gr hybrid composites, the UTS increases by 45% for 1st pass and 63% after 3rd pass of ECAP process. The UTS found to be maximum for 6wt%SiC in the studied composites which is about 198N/mm² in the as cast condition and after 2 ECAP passes, the UTS increases by 45%. For the addition of 8wt%SiC, not much variation was observed in the UTS value of the hybrid composites. Further addition of SiC particles into Al6061-3wt%Gr hybrid composites, decreases the strength due to clustering of SiC particles at some regions in the matrix.

Figure 6(c) gives the influence of reinforcement addition on ductility of hybrid composites in terms of % elongation in as cast and after ECAP process. The ductility of as cast matrix alloy Al6061 is 12.6%, after the first ECAP pass, the ductility decreases by 8%. Further ECAP passes decreases the ductility of the base material but after 3 passes it almost remains same¹⁵. The ductility of SiC reinforced Al6061-3wt%Gr hybrid composite is almost same as that of the Al6061 base material up to 4wt%SiC particles. Not much variation in the ductility of the studied composites, this is due to ECAP process and also due to the presence of soft Gr particles in the hybrid composites. After ECAP process the loss of ductility of the composites is less due to formation of equiaxed grains also grain boundaries evolve into arrays of high angle boundaries resulting in better ductility of the composite than the heat treated composites^{26,27}. Further addition of SiC particles (10wt%) in to the composite decreases the ductility of hybrid composites by 30%, due to hard nature of SiC particles.

4.3 Fractography

The fracture surface of the samples after tensile testing was observed under SEM. From SEM picture 7(a), it was observed that larger numbers of small dimples are due to ductile failure of Al6061 alloy after ECAP process. Particle reinforced MMCs fail by mixed mode and which leads to a bimodal distribution of dimples. As it can be seen from Figure 7(b), it was observed that larger dimples are due to the presence of SiC and Gr particles, whereas smaller dimples are due to ductile failure of the matrix. Figure 7(c) shows the fracture surface of Al6061-3wt% Gr – 6wt% SiC after three pass of the ECAP process, the cracks initiated between the matrix and the reinforcement are clearly visible. The Figure 7(d) exhibits that particle debonding has taken place at matrix- particle interface after second ECAP passes, this may be due to large shear strains developed during ECAP process and also the higher wt% SiC

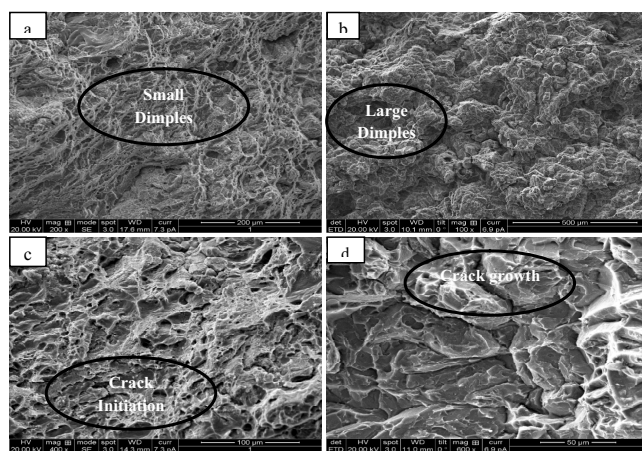


Figure 7. SEM photographs of fractured surfaces of ECAP processed Al6061 and their composites.

(10wt%) particles cause strain hardening during plastic deformation which results in the formation of cracks²⁴.

5. Conclusions

Following conclusions are drawn from the present investigation:

1. Stir casting method was successfully employed to preparation Al6061-3wt% Gr- (2-10 wt%) SiC hybrid composites and microstructural study reveals that the distributions of particulates in the matrix are uniform.
2. The effect of the Gr and SiC_p reinforcements on Al6061 matrix is appreciable in terms of the UTS and also the hardness in the as cast condition.
3. After ECAP process, the size and distribution of the reinforcement particles are not changed but significant reduction in the grain size of the matrix alloy was observed which in turn results in improvement of mechanical properties of the studied composites.
4. For 2 and 4wt%SiC in the hybrid composites, the composites can be processed by ECAP with three passes. Further addition of SiC particles, reduces the number of passes due to increase in the hardness and results in the formation of cracks on the sample.
5. The maximum value of the ultimate tensile strength and Hardness through ECAP Process was exhibited by 6wt% SiC among the studied composites. There is no significant change in the ductility of the studied composites after ECAP process.
6. Al6061-Gr-SiC hybrid composites are the promising engineering materials as they exhibit good mechanical properties.

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