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TECHNICAL PAPER

Structure–Property Correlation of Al–SiC–Al_2O_3 Composites: Influence of Processing Temperatures

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Abstract This paper deals with the change in the mechanical behaviour of aluminium alloy 6061 with different weight percentage of Silicon Carbide (SiC) and Alumina (Al_2O_3) ceramic powders and change in processing temperature. The crucial properties of this aluminium alloy are relatively light in weight, better corrosion resistance, wear resistance and have low production cost. These properties make them pleasant for different applications such as aerospace, defense, automotive sectors. The purpose of designing Metal Matrix Composite is to figure the desired qualities of metals and ceramics. The fabrication of the MMC was done by stir casting process. The tensile test, hardness test and impact test were performed on these composite samples to study the mechanical behaviour. The result shows that there is a significant increase in tensile strength for the samples that are processed at the temperature of 750 °C with a higher weight fraction of SiC. Also, the samples made at 850 °C exhibit better hardness and impact strength with increased content of alumina. The internal microstructure of the composites was analyzed by scanning electron microscope.

Keywords Metal matrix composites · Aluminium alloy · Silicon carbide · Alumina · Scanning electron microscope

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1 Introduction

Nowadays for the modern development and economic utilities, need of advanced engineering materials for various engineering applications keep on increasing. To handle such demands, metal matrix composite is one of the important reliable sources. The MMC's are made with carbide reinforcements because of better mechanical properties such as high strength to weight ratio, hardness and wear resistance. The effect of SiC on aluminium alloy was analyzed by Kalkanli et al. [1] and found that there was an increase in hardness with the increase of SiC content [1]. Baradeswaran et al. [2] worked on the wear performance of aluminium alloy with carbide reinforcements and revealed that tensile strength and wear resistance were improved for the hybrid aluminium alloys with B_4C and graphite used as reinforcement.

Fly ash and rice-husk ash can also be added along with reinforcements to fabricate MMC's with better mechanical properties. Industrial waste of these ashes influences the properties such as tensile strength, hardness and porosity with the increase in volume fraction of reinforcements [3]. David Raja Selvam et al. [4] studied the effect of fly ash particles in the metal matrix composites and stated that there was an improvement in tensile and hardness properties with the increase in weight percentage of SiC particulates with fly ash content. The fabrication of metal matrix composites is carried out by different techniques such as stir casting, double stir casting, squeeze casting, combo-casting, liquid pressing, high-pressure direct casting [5] and powder metallurgy process [6] based on the reinforcements and applications. Among the various techniques, stir casting is simple, less expensive and suitable for mass production [7]. Nowadays the use of nano-sized reinforcement particles in MMC is increased for better influence in mechanical and microstructural properties. Ezatpour [8] investigated the influence of nano-alumina particles in Al6061 alloy and the effect of the extrusion process on the mechanical and microstructural properties of the composites. The results showed that extruded samples had high strength and ductility values than as-cast samples. Also found that increase in the amount of alumina increased the tensile and yield strength but decreased the elongation. The distribution of reinforcements can be improved by varying the process parameters or incorporating some additional setup with the primary stir casting setup. An additional setup by may include Al/nanoAl_2O_3 powder along with the injection of pure argon gas into the aluminium alloy for better distribution [9].

Also in squeeze casting technique, when the addition of reinforcement increases, more agglomeration forms in the composite structure leading to good mechanical characteristics. The Al–Si base composites reinforced with different mixtures of Ni and nano-alumina particles fabricated by Squeeze casting process shows the results as improvement in tensile strength and ductility by increasing Ni and nano-Al_2O_3 powder content [10]. High squeeze pressure in squeeze casting results in the increase of refinement of the microstructure and decrease of the percentage of porosity [11]. The processing parameters in all the methods such as melting temperature, processing time, processing speed and pre-treatment of reinforcements play a crucial role in mechanical characteristics of the MMC. Increasing the melting temperature, processing time and pre-treatment of reinforcements by thermal oxidation improves the properties of the composites in the liquid pressing method. The results show a low coefficient of thermal expansion and high thermal conductivity [12]. In the stir casting process, the increase in stirring time leads to a significant decrease in the tensile strength as the porosity in the casting increases [13, 14]. Changes in milling time of nano-sized reinforcement particles lead to a gradual variation in the mechanical performance of the composites [15, 16]. Heat treated alumina particles influences the properties of MMC's in hardness, compression and wear behaviours [17]. Sajjadi et al. [18] compared the microstructure and mechanical properties of A356 Al alloy/Alumina composites fabricated by stircasting and compocasting. The results revealed that the addition of alumina (micro and nano) led to an improvement in hardness, yield, tensile and compression strength. The type of fabrication process and the particle size were the effective factors influencing the mechanical properties. They also found that the compocasting process with a decrease in alumina particle size led to the better mechanical properties.

The present work is to study the effect of different weight percentages of two reinforcements, SiC and alumina with different processing temperatures in aluminium alloy 6061 when most of the research works focus on the effect of single reinforcement MMC.

2 Material Details

In this research work, metal matrix composite is prepared by stir casting process. Materials used in the composite are Al6061 aluminium alloy, silicon carbide and aluminium oxide (alumina). Here Al6061 is the base material and SiC and alumina are the reinforcements in the metal matrix composite. 50 µm grain size powders of SiC and alumina are used as reinforcement.

2.1 Aluminium Alloy

Al6061 is the medium-to-high strength, light weight and an economic material used in aerospace and automotive applications. This alloy have good machinability and weldability. It is one of the most common alloys of aluminium for general purpose use. This alloy has the melting point of 650 °C and the density of 2.70 g/cm^3.

2.2 Silicon Carbide

Silicon Carbide is a well known abrasive material having silicon and carbon with chemical formula SiC. It has excellent thermal conductivity, hardness, corrosion resistance and stiffness. The density of silicon carbide is 3.21 g/cm^3 and the melting point is 2730 °C. Silicon carbide powder has been mass-produced for the use as an abrasive. Grains of silicon carbide can be bonded together by sintering to form very hard ceramics that are widely used in applications requiring high endurance, such as car brakes, car clutches and ceramic plates in bulletproof vests.

2.3 Aluminium Oxide (Alumina)

Aluminium oxide is a chemical compound of aluminium and oxygen with the chemical formula Al_2O_3. It is the most common occurrence of several aluminium oxides and is specifically identified as aluminium oxide. It is commonly called alumina, and may also be called aloxide, aloxite, or alundum depending on particular forms or applications. Alumina has the density of 4.1 g/cm^3 and the melting point of 2072 °C. It has great hardness, stiffness and thermal conductivity. It is used as an abrasive owing to its hardness and used as a refractory material owing to its high melting point. It resists strong acid and alkali attack at elevated temperatures. It is also used in high-temperature electrical insulators, grinding media, gas laser tubes and wear pads.

2.4 Experimental Procedure

The experimental set up (Fig. 1a) has the components such as the main furnace, preheating furnace and steel stirrer blades. Preheating of aluminium alloy and the mixer of the ceramic powders silicon carbide and alumina is the initial step of the experiment. Here the aluminium alloy ingot was preheated for 1 h at 550 °C. At the same time, silicon carbide and alumina powder mixer were preheated to 300 °C in the preheating furnaces. Then the aluminium alloy 6061 ingots were melted in the graphite crucible in the main furnace. The crucible with aluminium alloy was heated to 750 or 850 °C and maintained at the same temperature based on the sample requirement. The stirring mechanism was lowered into the crucible and stirring was continued for 15 min with a stirring speed of 600 rpm. After initiation of stirring, preheated ceramic powders were poured into the crucible and mixed with aluminium alloy, so that the reinforcement powders uniformly dispersed in the matrix phase. The temperature range of the furnace was maintained at 750 ± 10 or 850 ± 10 °C in final mixing process based on the sample requirement. This experiment was repeated by varying the compositions of the silicon carbide and alumina. After 15 min of stirring, the crucible was taken out and molten material was poured into the mould cavity of platen die. Each sample was made from a total of 1 kg (1000 g) material mix. Totally four compositions were made with two different temperatures (750 or 850 °C).

In this work, sample A and B were fabricated with the furnace temperature of 750 °C. Sample C and D were fabricated with the furnace temperature of 850 °C. Sample A and C contain aluminium alloy 6061-95%, silicon carbide-3%, alumina-2% and sample B and D contain aluminium alloy-95%, silicon carbide-2%, alumina-3% (Table 1).

Table 1 Compositions of MMC's

Samples	Furnace temperature in °C	% of Al6061	% SiC	% Alumina
A	750	95	3	2
B	750	95	2	3
C	850	95	3	2
D	850	95	2	3

3 Results and Discussion

3.1 Tensile Test

The material strength can be found by testing it under tension or compression. The tensile test specimens have been prepared according to ASTM E08 standard, each specimen is about 25 mm gauge length. The tensile test specimen is shown in Fig. 1b. The specimen is loaded in Hounsfield Universal Testing Machine until the failure of the specimen occurs. The tests are conducted on composites of different combinations of reinforcing materials and the ultimate tensile strength and ductility have been measured. Simultaneous readings of load and elongation are taken at uniform intervals of the load. The Uniaxial tensile test is conducted on the fabricated specimen to obtain the information regarding the behavior of a given material under gradually increasing load conditions. The results obtained are furnished in Table 2.

The tensile test result shows that the sample A has a tensile strength of 181 MPa which is the highest value compared to other samples. It is noted that sample A is produced at 750 °C temperature and it has higher amount of SiC. From the results, it is observed that sample A has failed at the highest value of breaking load 6.66 kN. Sample D has the low tensile strength of 109 MPa with high percentage of elongation. It is noted that sample D is made at 850 °C temperature and has more amount of alumina. The tensile stress–strain curve for aluminium Metal Matrix Composite with various weight percentages of SiC and Alumina is shown in Fig. 2. This result shows that, processing the composite at 750 °C has increased the strength by improving bonding or intimacy of Aluminium with ceramic particles. Sample D results in the decrement of tensile strength due to clustering and agglomeration of ceramic particles which is shown in Fig. 5d.

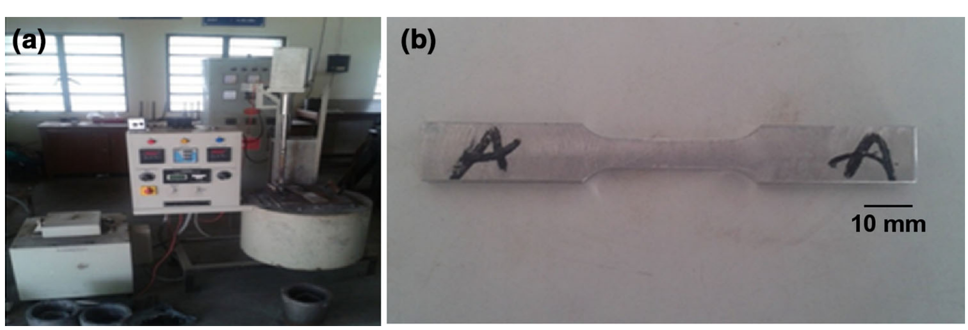

Fig. 1 **a** Stir casting setup. **b** Tensile test specimen

Table 2 Tensile properties of MMC's

Sample name	Sample description	Tensile strength (MPa)	Yield strength (MPa)	Breaking load (kN)	% Elongation
A	95% Al6061 + 3% SiC + 2% alumina at 750 °C	181	169	6.66	2.8
B	95% Al6061 + 2% SiC + 3% alumina at 750 °C	153	139	5.59	3.1
C	95% Al6061 + 3% SiC + 2% alumina at 850 °C	134	120	4.96	3.3
D	95% Al6061 + 2% SiC + 3% alumina at 850 °C	109	93	3.9	3.5

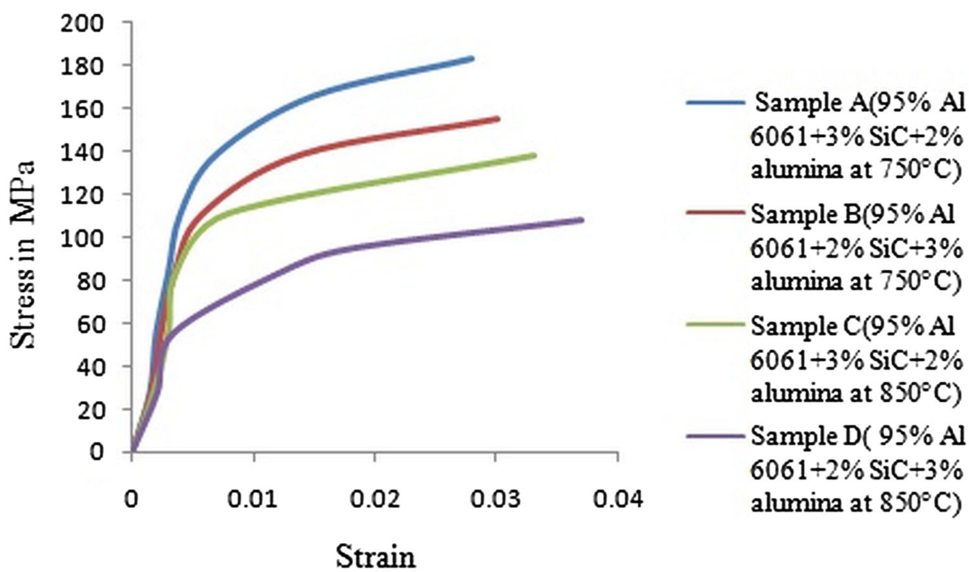

Fig. 2 Stress–strain curve

3.2 Impact Test

The Charpy impact test, also known as the Charpy v-notch test, is a standardized high strain- rate test which determines the amount of energy absorbed by a material during fracture. This test has been carried out on the samples made as per the standard ASTM E23-16b. The absorbed energy by the specimen is noted while fracture takes place during testing. The impact test specimens are shown in Fig. 3a.

The readings have been taken on three specimens for each sample and the average energy is calculated. It is clear from the Table 3 and Fig. 3b, tha the sample B and D absorb more energy than other samples. Sample B and D contain 3% of alumina. So higher alumina content influences the impact properties of the composites. Also, it is noted that the samples fabricated at 850 °C have a comparatively higher impact strength than the samples fabricated at processing temperature of 750 °C.

3.3 Hardness Test

The ability of the material to resist indentation, penetration and scratches can be identified by the hardness of the material. The Rockwell hardness test has been carried out because of its accuracy, simplicity and rapidity. In this test, 1/16 inch steel ball indenter has been used. The total indenting load is 100 kg. Three readings have been taken in different places on each sample and those readings are listed in Table 4 (Fig. 4).

The Rockwell hardness test has been carried out on all the four samples. Three trials have been taken for each sample and the average Rockwell hardness number has been calculated. It is found that sample B and D have the highest HRB of 60 and 64. Samples A and C have the lowest HRB of 57 and 58. The sample A and sample C are made of same composition with 2% of alumina and sample B and D are made of same composition with 3% of alumina. From this, it is clear that the increase in alumina content influences the hardness of the composite. By comparing the sample B and sample D, the sample D has more hardness. It is also noted that the higher processing temperature has further influenced the hardness of the composite.

3.4 Microstructural Studies

In general, SEM is used to observe the topography and morphology of a specimen. A scanning electron microscope is a type of electron microscope that produces images of a sample by scanning it with a focused beam of

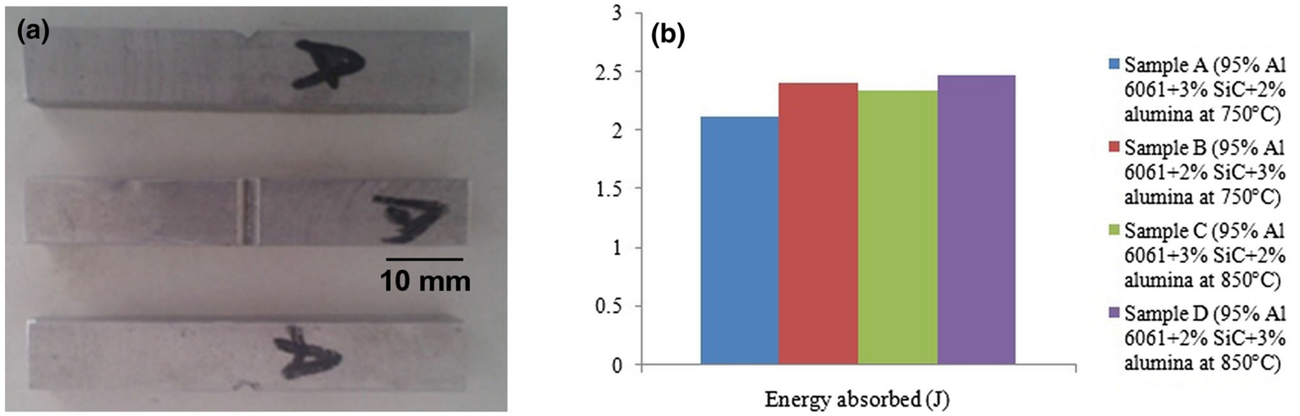

Fig. 3 **a** Impact test specimens. **b** Impact test results

Table 3 Impact properties of MMC's

Sample name	Sample description	Energy absorbed (J)
A	95% Al6061 + 3% SiC + 2% alumina at 750 °C	2.12
B	95% Al6061 + 2% SiC + 3% alumina at 750 °C	2.41
C	95% Al6061 + 3% SiC + 2% alumina at 850 °C	2.34
D	95% Al6061 + 2% SiC + 3% alumina at 850 °C	2.47

Table 4 Hardness test results

Sample name	Sample description	HRB trial 1	HRB trial 2	HRB trial 3	HRB average
A	95% Al6061 + 3% SiC + 2% alumina at 750 °C	57	58	57	57
B	95% Al6061 + 2% SiC + 3% alumina at 750 °C	60	60	60	60
C	95% Al6061 + 3% SiC + 2% alumina at 850 °C	58	58	57	58
D	95% Al6061 + 2% SiC + 3% alumina at 850 °C	63	65	64	64

electrons. The electrons interact with the atoms in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition. Here the fractured impact test specimens have been analyzed using SEM. The samples A and D are used for the SEM Analysis as they have the large variations in the mechanical test results as well as variations in the composition and processing temperature.

The specimens of sample A and sample D are used for the morphological analysis using SEM. Figure 5a shows the microstructure of sample A at 500× magnification. The general arrangements of aluminium alloy matrix molecules, SiC and alumina reinforcement molecules are visible in this picture. It also shows some minor cracks and pits, due to improper stirring which is likely to initiate the fracture during impact load. Figure 5b shows the clear image of the microstructure of the specimen A at 1500× magnification. The light grey portion indicates aluminuium Alloy, the dark grey portion indicates SiC and the white portion indicates alumina. It shows the even distribution of reinforcements, uniform grain boundaries and very few agglomerations of particles of SiC and alumina compared to sample D (Fig. 5d) which results in better tensile strength. Also from Fig. 5b, it is clear that maintenance of processing temperature at 750 °C improves the wettability of the reinforcements compared to the sample D (Fig. 5d), as the temperature is comparatively below the melting points of reinforcements.

Figure 5c shows the microstructure of sample D at 500× magnification. The more visible white portion indicates the presence of higher amount of alumina. Figure 5d gives the clear microstructural view of sample D at 1500× magnification. This picture indicates the tight package of molecules, more agglomeration of reinforcements and ununiformed grain boundaries. The Addition of reinforcement particles in the matrix increases the area of the

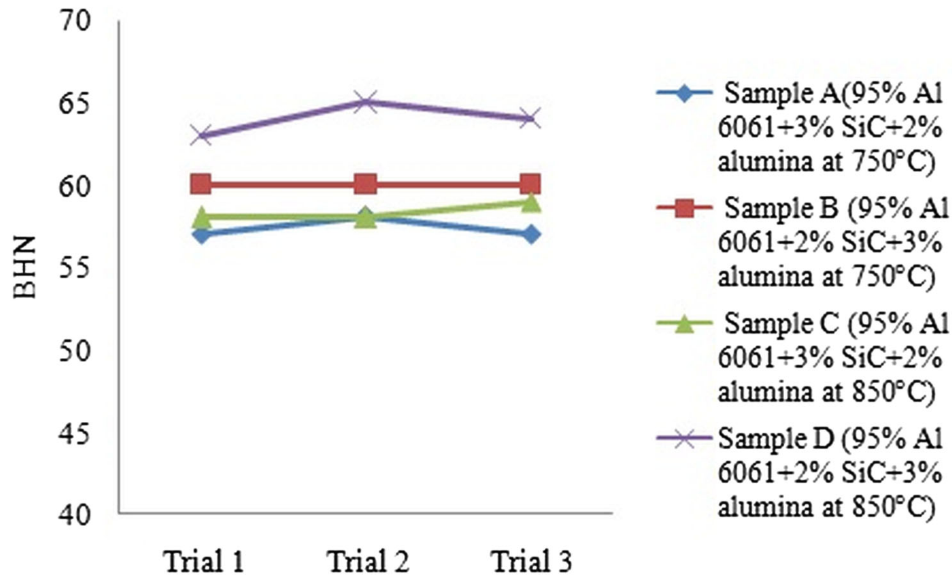

Fig. 4 Hardness test results

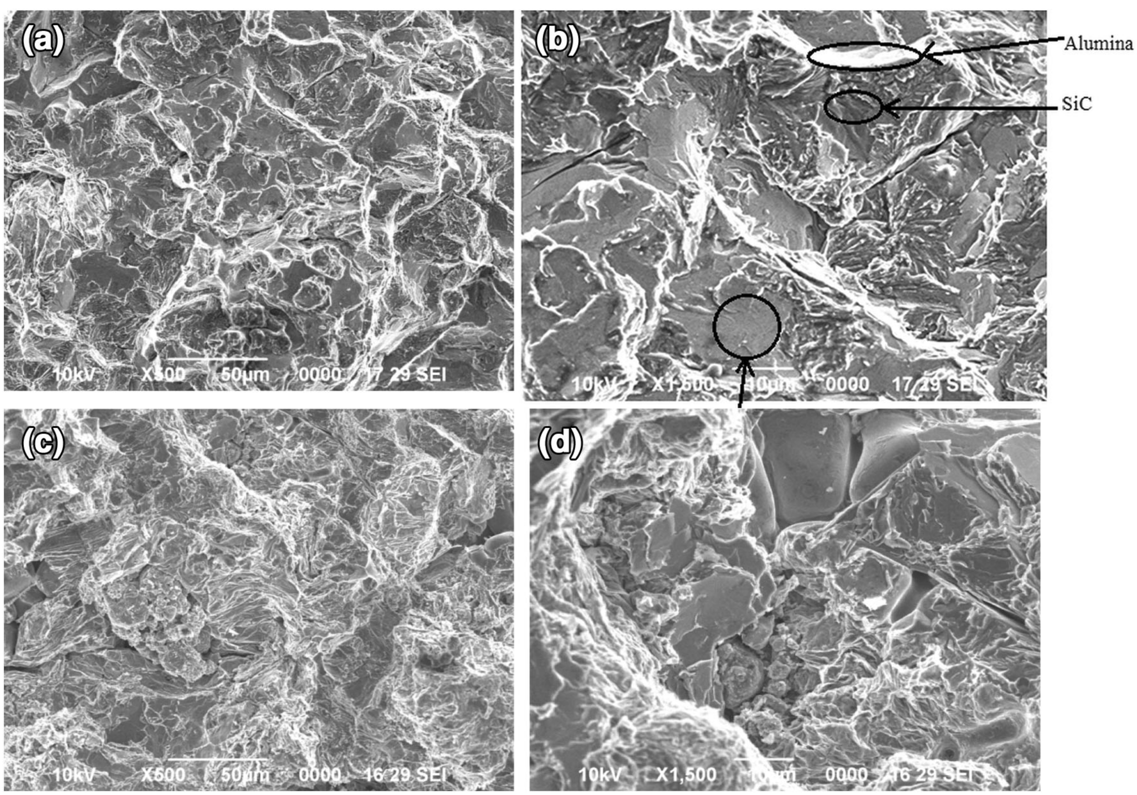

Fig. 5 SEM images of composites **a** sample A at ×500, **b** sample A at ×1500, **c** sample D at ×500, **d** sample D at ×1500

reinforcement and reduces the matrix grain sizes. In sample D, higher alumina content and high- temperature processing with increased solidification time result in the formation of tight package of hard surface that offers more resistance to plastic deformation and in turn increase in the hardness.

4 Conclusions

Al6061–SiC–Alumina Metal Matrix Composites (samples A, B, C, D) are fabricated with different weight percentages of reinforcements (SiC and Alumina) at two different process temperatures (750 and 850 °C) by stir casting process. From the results and evaluation of mechanical properties, following inferences are made.

- Tensile strength value is higher for the samples made at 750 °C. These samples exhibit better wettability and little agglomeration of particles which impede the dislocation of molecules.
- In the samples made at 750 °C, the sample A with more percentage of SiC possesses higher tensile strength (181 MPa). The sample D with more percentage of alumina possesses increased percentage of elongation (3.5%).
- It is also inferred from the results that sample D made at 850 °C processing temperature with 3% of alumina exhibit comparatively higher impact strength (2.47 J) and hardness (64 HRB) than all other samples. It is clear that increased content of alumina influences the hardness and impact strength of the composites.

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