

## **MECHANICAL CHARACTERIZATION AND FRACTOGRAPHY OF 100-125 MICRON SIZED SILICON CARBIDE PARTICLES REINFORCED Al6061 ALLOY COMPOSITES**

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### **Abstract**

In the current exploration, the impact of the 100 to 125 micron size addition of silicon carbide (SiC) on the mechanical performance of Al6061 alloy has been studied. The Al6061 alloy dispersed with 6, 9, and 12 wt. % of SiC particles were synthesized by a two-step stir cast route. Two-step addition of the preheated particles into the melt helps avoid the agglomeration of the particles, which further contributes to enhancing the properties of composites. The orchestrated composites were exposed to microstructural examines and mechanical properties evaluation. Microstructural portrayals of acquired examples were completed by SEM microscopy, EDS, and XRD patterns. The event of SiC particles were affirmed by the XRD patterns. The density of the Al6061-SiC composites was increased with the addition of high-density silicon carbide particles. The hardness, ultimate, and yield qualities of metal composites have been improved with the increase in the content of SiC support. The ductility of SiC reinforced composites decreased with hard ceramic particles' incorporation in the Al matrix alloy. Various fracture mechanisms were observed in the Al6061-SiC composites using SEM.

**Keywords:** Al6061 Alloy; SiC Particles; Microstructure; Tensile Strength; Fractography

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## Introduction

Metal matrix composites (MMCs) with aluminium (Al) as the matrix are used for light weight structural applications and electronic enclosures. Metal network composites had ascended as an indispensable class of materials for fundamental primary, wear, and electrical applications, essentially on account of their ability to show preferred quality over weight-solidarity to cost extents when stood out from indistinguishable solid materials. Among MMCs, aluminum metal matrix composites (AMMCs) are considered newly moved materials for their light weight, high strength, high modulus, low coefficient of warm extension, and extraordinary wear resistance properties [1, 2].

Al6061 alloy is a wrought alloy with magnesium (Mg) and silicon (Si) as the major alloying elements. Al6061 alloy is an average strength Al alloy selected in this study due to its practical usages and good mechanical properties, and its ability to cast, extrude, roll and machine, etc. Aluminium 6061 has higher corrosion resistance and is therefore used in industries like marine, automobile, and construction. Automobile applications, especially engine parts, pushed researchers for improvements in the properties of Al alloys [3, 4]. At room temperature, Al6061 alloy possesses excellent properties; however, it shows poor high-temperature behavior. Further, it is necessary to improve the tribo-mechanical properties of aluminium alloys by adding conventional reinforcements to form aluminium matrix composites (AMCs). The monolithic aluminum alloys can be added in different compositions by suitable manufacturing methods to develop composite materials with novel properties. Further, literature reviews on the previous investigations reveal that only a very few studies have been made on the use of silicon carbide (SiC), alumina ( $Al_2O_3$ ), and graphite as reinforcement to synthesize aluminum-silicon carbide, alumina, and graphite composites by two stage liquid melt technique. An optimized two stage stir casting technique is developed for the composite preparation. Prepared aluminum- silicon carbide, alumina, and graphite composites are evaluated for their physical, mechanical, and wear properties [5]. *Manish et al.* [6] reviewed the mechanical behaviour of various metal matrix composites reinforced with  $Al_2O_3$ ,  $B_4C$ , TiC, graphite, SiC, and  $TiB_2$  particles. Further, *Nagedra et al.* [7] evaluated the density, hardness and tensile behaviour of SiC particles reinforced Al6061 alloy composites with varying 1, 2, 3, and 5 weight percentages. The prepared composites reinforced with SiC particles exhibited superior mechanical properties.

It is also evident from the earlier research that several investigators processed MMCs by using different matrices and reinforcement combinations. These MMCs are processed by the liquid metallurgy route and powder metallurgy techniques [8-10]. Their work noted that it is challenging to mix these hard or soft non-metal or ceramic reinforcements into the aluminium alloy. An optimized process is required to fabricate aluminum-based MMCs, enhance the wetting behaviour, and have uniformity of particulates in the matrix. The stir casting process is the most common method to produce metal-based composites. This process has several advantages over other manufacturing processes; in this, the wettability of reinforcement can be achieved by proper stirring speed. Also, the stir casting process helps to fabricate very complex geometries and large-sized samples [11, 12]. Further, a literature review on the previous investigation reveals that only a very few studies have been made on the use of silicon carbide (SiC) as reinforcement to synthesize aluminium-silicon carbide composites by two stage liquid melt technique [13]. An optimized two stage stir casting technique is developed for the

composite preparation [14]. Prepared aluminium-silicon carbide composites are then subjected to evaluation of their physical, mechanical, and wear properties.

Al6061 is an alloy with low density and moderate strength. The alloy is dispersed with 100 to 125 micron sized SiC particles to improve strength. The composites with 6, 9, and 12 weight % of SiC particles reinforced were developed and evaluated for density, ultimate tensile, and yield strength; further percentage elongation and fractographic studies were carried out. The composites were synthesized by a novel stir casting method that includes adding reinforcement in two stages into the molten metal, enhancing the wettability between reinforcement and the Al6061 alloy matrix.

## Experimental Details

### Materials and Composites Preparation

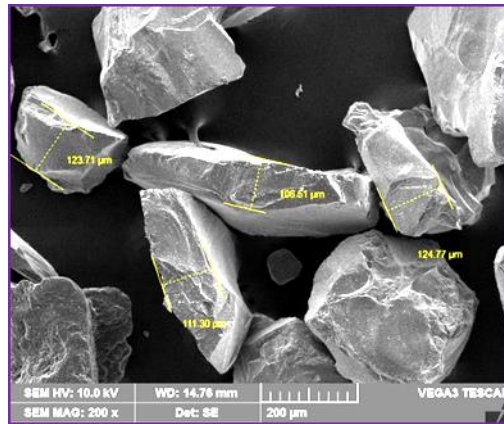


Fig.1. SEM micro-photograph of 100-125micron sized SiC particles.

Table 1. Chemical configuration of Al6061 alloy.

Elements (wt. %)	Al6061 (actual)
Mg	0.89
Si	0.64
Fe	0.23
Cu	0.17
Ti	0.10
Cr	0.07
Zn	0.03
Mn	0.07
V	0.01
Al	Balance

Metal composites with 6, 9, and 12 wt. % of SiC particulates with 100-125 micron size were produced by the stir method of casting. Aluminum 6061 alloy (Fenfee Metallurgical Pvt. Ltd., Bangalore) is preferred as a matrix due to its greater casting properties, strength, formability, heat treatment nature, good corrosion resistance, machinability, and wide applications in several sectors, while SiC particles with a size of

100-125 microns were utilized as reinforcements (Fig.1). Table 1 shows the chemical configuration of the Al6061 alloy utilized in the current studies.

SiC particles of range between 100 to 125 microns (Supplied by Bioaid and Scientific Industries, Bangalore, Karnataka, India) are used in the present study. The SEM analysis of SiC particulates is carried by using SEM. The composition of SiC particles is shown in Table 2. Some critical physical, mechanical and thermal properties of SiC particles are shown in Table 3.

*Table 2. Chemical composition of SiC particles.*

<i>Elements</i>	<i>Composition wt. %</i>
<i>Silicon (Si)</i>	<i>64.78</i>
<i>Carbon (C)</i>	<i>35.22</i>

*Table 3. Properties of SiC particles.*

Density (g/cc)	3.10
Melting Point (°C)	2990
Poisson's Ratio	0.14
Modulus of Elasticity (GPa)	410
Hardness (HV)	2550
Compressive Strength (MPa)	2950
CTE $\mu\text{m}/\text{m}^\circ\text{C}$	4.5
Thermal Conductivity W/mK	34

An estimated amount of Al6061 alloy ingots are placed in the furnace for melting. The melt is heated to 750 °C. By the utilization of a thermocouple, the melt temperature is measured. Once the melt reaches 750 °C, degassers (solid hexachloroethane-C<sub>2</sub>Cl<sub>6</sub>) are introduced into the melt. Vortex is created by using the chromium steel stirrer, which is coated with zirconia. The impeller speed is kept constant at about 300 rpm, while the impeller immersion depth is 60% of the height of the molten material. Once the vortex is made, the preheated SiC particles in two stages are introduced into the melt by a constant feed rate, which includes distributing the whole weight mixture of reinforcements in two equivalent weights. At each stage, vigorous stirring is carried out before and after incorporation of alumina particles to prevent particle clustering and ensure that the microparticles are homogeneously dispersed in the melt. With continuous stirring, the melt is discharged into preheated die (made of cast iron). The Al6061-SiC composite specimens with 15 mm dia and 120 mm in length are obtained after casting. The Al6061 with 6 to 12 weight percentages of SiC composites are prepared by the same procedure.

#### *Testing of Composites*

The size, shape, and distribution of SiC particles present in Al6061 compound composites are known utilizing SEM instrument (TESCAN VEGA 3 LMU, Czech Republic). The machine is connected with JED 2300 examination software program for EDX investigation. For SEM, specimens are machined to a dimension of 15 mm in dia and a height of 5 mm. The cut samples are made to have a flat surface using a belt grinder. Later the samples are polished by utilizing emery papers (made of SiC) with a grit size of 300 to 1000. Finishing is carried out by hand on micro cloth by fine cerium oxide. Produced samples are etched to reveal the proper granular structure using Kellers reagent. The etching solution consists of 95 ml of H<sub>2</sub>O, nearly 2.5 ml HNO<sub>3</sub>, 1.5 ml HCl and 1 ml HF. After etching, the samples are washed and thoroughly dried.

For XRD studies, Al6061 with 6 and 12 weight percentages of SiC composites were selected. For this purpose, prepared composite samples are cut to 15 mm diameter and 2 mm height in size specimens, and the same polishing method is carried as in the case of SEM. XRD studies are carried out by a PANALYTICAL XRD using Cu-K alpha radiation. The  $2\theta$  range is selected such that all the intense peaks of the material phases predictable are covered.

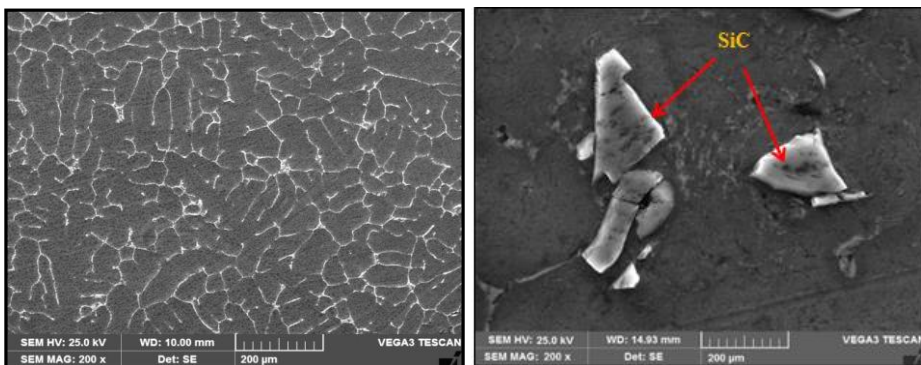
ASTM D792 [15] procedure is used for density evaluation with circular pieces of size 12 mm in dia., and 30 mm in length with an allowance of  $\pm 0.15$  mm. Purified water at room temperature is utilized as the drenching fluid, and the mass is estimated using a digital balance with a 0.001 g resolution. Experimentally, the composite density is acquired by displacement methods utilizing a physical offset with a measuring kit according to the ASTM: D792-66 details. Further, theoretical densities were estimated by using the standard rule of the mixture formula.

Vickers hardness tester (Model: Olympus) having a load range of 25 to 1000 g is used for hardness measurement. The ASTM E384 [16] standard is used for testing. Loads are applied by dead weight. A precision diamond indenter is used, and a load of 100 g is applied over the specimen of 15 mm dia, 10 mm length, and duration of 30 seconds. Then, the indentation is measured microscopically, and the applied load is used to estimate the Vickers hardness number (VHN) value. Three readings have been recorded on each sample at various locations, and the mean value has been noted.

Tensile tests are performed using computerized universal testing machine (UTM) of Instron make, with 60 kN capacities and least count of 4 N. The tensile specimens having a dimension of 9 mm gauge dia. and a gauge length of 45 mm respectively as per ASTM E8 [17]. All the experiments are carried out at a rate of 0.1 mm/min in a displacement mode. Three tests are carried out, and the best results are considered. Tensile behaviour of the matrix and its composites viz., UTS, YS, and ductility are evaluated. After the test, fracture surfaces are presented for microstructural studies using SEM to understand the fracture mechanism.

## Results and Discussion

### *Microstructural Examination*



(a)

(b)

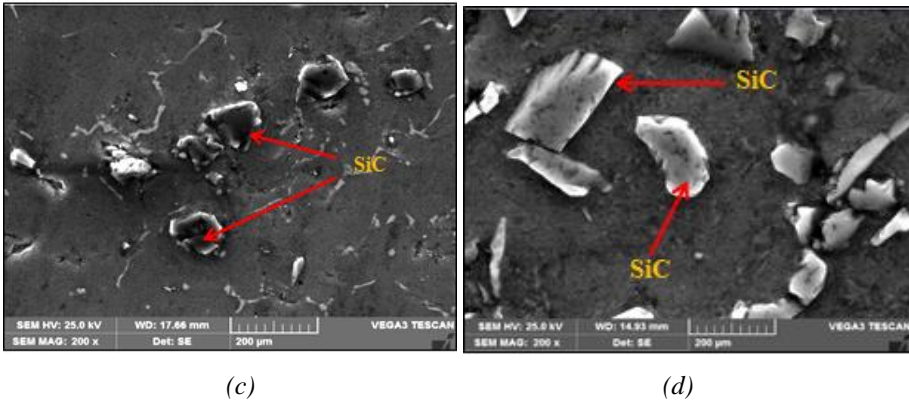


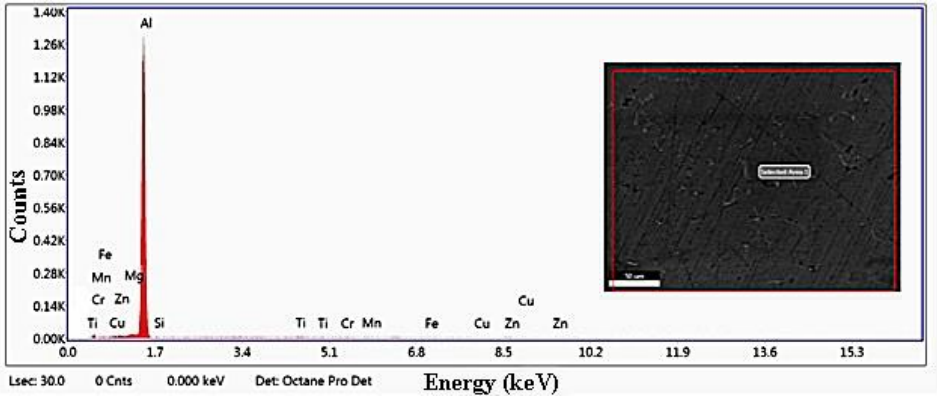
Fig. 2. SEM microphotographs of (a) Al6061 alloy (b) Al6061- 6 wt.% SiC (c) Al6061-9 wt.% SiC (d) Al6061-12 wt.% SiC composites.

SEM examines the microstructural characterizations of specimens with EDS attachment. Fig. 2 (a-d) shows the SEM micrographs of Al6061 and SiC reinforced composites. Fig. 2 (a) shows the SEM of pure Al6061 alloy. It confirms that there is less porosity and grains are visible properly. Fig. 2 (b-d) shows the SEM images of Al6061 with 6 to 12 weight percentages of SiC, respectively. It confirms that most SiC particles are mixed uniformly in Al6061 alloy. Further, these figures reveal the homogeneity of the prepared composites. The microphotographs also clearly indicate the increased reinforcement contents in the Al6061 alloy composites. As seen from Fig. 2 (d), the introduction of SiC microparticles in two stages into the Al6061 matrix has led to significant progress in composite microstructure [18]. This improved wettability of the SiC in the matrix will further help in enhancing the properties of Al6061 alloy composites [19]. It is also noted in Fig. 2 (b-d) that the SiC particle is distinct and shows the good bonding between the aluminium 6061 matrix.

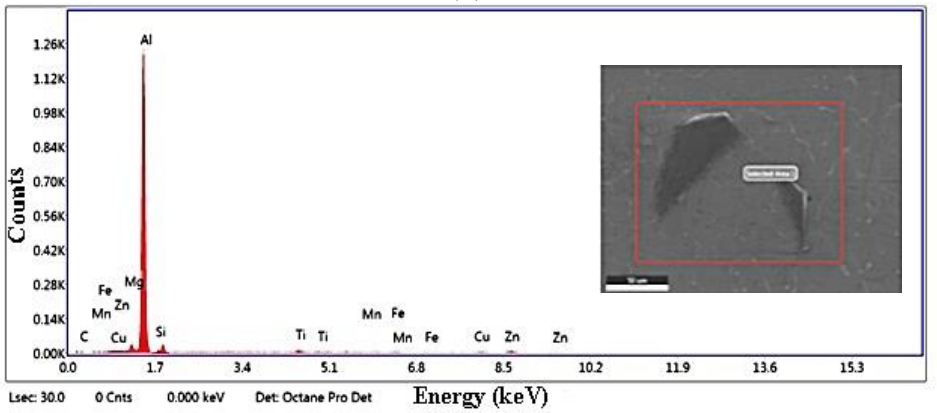
Fig. 3 (a) indicates the EDS spectrum of pure Al6061 alloy, which confirmed the elements like Mg, Si, Ti, Mn, Fe, Cu, and Zn in the Al matrix. Table 4 represents the alloying elements in as-cast Al6061 alloy in wt.% which is determined by EDS analysis. Fig. 3 (b) shows the analysis of Al6061 with 6 wt.% of SiC composite using EDS, which confirms the elements like C, Mg, Si, Mn, Fe, and Cu in the Al alloy matrix as shown in Table 4.

Table 4. Composition of Al6061- SiC composites in weight % by EDS analysis.

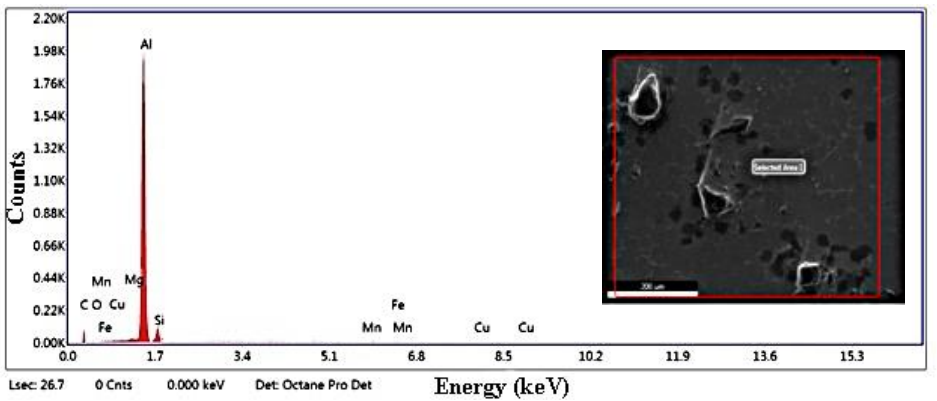
Element	Weight percentages		
	Al6061	6 - SiC	12 - SiC
C	--	1.21	1.90
O	--	--	0.27
Mg	1.11	1.12	0.94
Al	96.89	88.29	85.13
Si	0.71	7.23	10.71
Mn	0.20	0.15	0.12
Fe	0.41	0.62	0.51
Cu	0.35	0.39	0.42
Ti	--	0.12	--
Zn	0.20	0.17	--



(a)



(b)

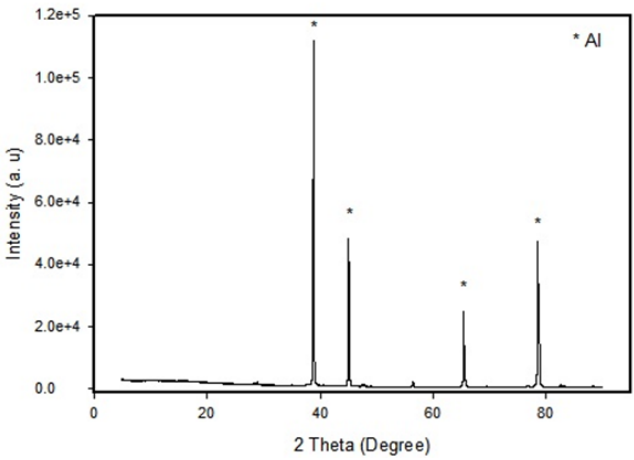


(c)

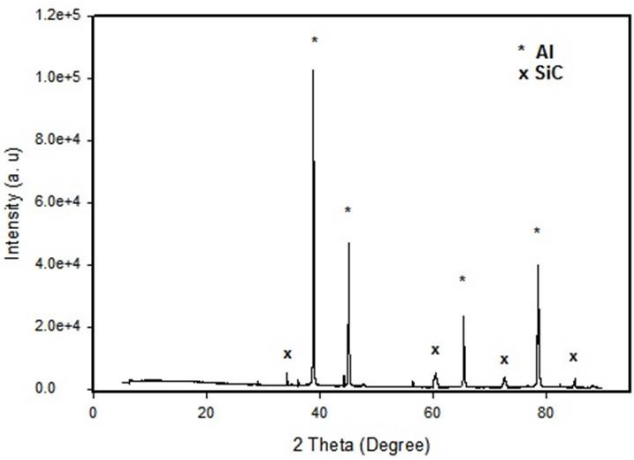
Fig. 3. EDS spectrum of (a) Al6061 alloy (b) Al6061-6 wt. % SiC and (c) Al6061-12 wt. % SiC composite.

Fig. 3 shows the elemental analysis of Al6061 with 12 wt.% of SiC composite using EDS, which confirms the C, Mg, Si, Mn, Fe, and Cu in Al alloy matrix as shown in Table 4. The distribution of silicon carbide in Al6061 alloy is confirmed by the presence of silicon and carbon elements. The presence of oxygen (O) indicates the oxide formation, which is low in percentage (0.27 weight percentage).

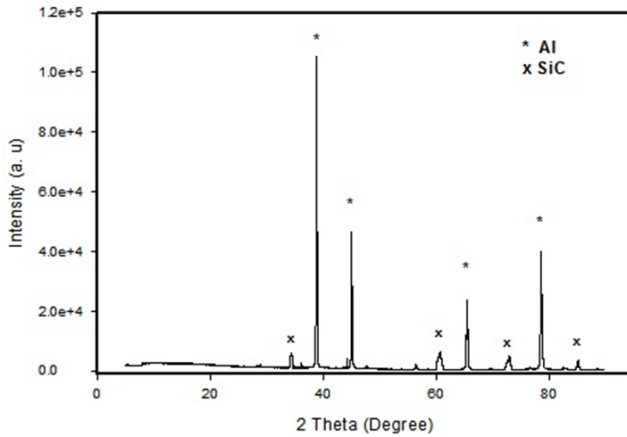
Fig. 4 (a-c) shows the X-ray diffractograms of Al6061 alloy (Fig. 4a), 6 wt.% of SiC (Fig. 4b), and 12 wt.% of SiC (Fig. 4c) reinforced composites. The XRD is carried out in a  $\theta$ - $2\theta$  diffractometer Panalytical using Cu K $\alpha$  radiation, a voltage of 35 kV, and a current of 50 mA. In Fig. 4 (a), the  $\alpha$  Al peaks are more clearly identified in as-cast Al6061 alloy. The peak observed for the Al6061 alloy is at 38°, 45°, 65° and 78° approximately, similar observations were made by Knowel *et al.* [20].



(a)



(b)



(c)

Fig. 4. X-ray diffractograms of (a) Al6061 alloy (b) Al6061-6 wt. % SiC and (c) Al6061-12 wt. % SiC composite.

Further, SiC phase peaks can be seen in the 6 and 12 wt.% of SiC composites as shown in Fig. 4 (b) and 4 (c), respectively. The SiC reinforcement peaks are observed in the Al6061 alloy composite is at 34°-36°, 44°, 60°, 72° and 84°. Al6061 alloy with 12 weight percentage SiC composite shows higher peak intensities than 6 wt.% of SiC particulates reinforced composites. Similar observations on XRD analysis were made by Keneshloo [21] in SiC/Al alloy composites.

#### Density Measurements

Fig. 5 depicts the theoretical and experimental values of densities of the Al 6061 with SiC particulate composites for various weight percentages of SiC particles. Density is determined experimentally and compared with the theoretical values, which have been evaluated by the rule of mixture [22, 23]. The experimental densities are measured using the water displacement technique (Archimede's principle) [24, 25]. The densities of the Al6061 with SiC MMCs linearly increased with the increase in the percentage of SiC. The experimental and the theoretical densities are almost in line with each other, concluding the uniform distribution of reinforcements in the Al alloy matrix. A very small variation is observed between the experimental and theoretical densities.

The density of Al6061-SiC composites increased when compared with the base alloy. The theoretical density of as-cast Al6061 alloy is 2.7 g/cm<sup>3</sup> and the corresponding experimental density is 2.66 g/cm<sup>3</sup>. Al6061 alloy with 6 to 12 wt. percentage SiC reinforced composites shows 2.72 g/cm<sup>3</sup>, 2.73 g/cm<sup>3</sup> and 2.74 g/cm<sup>3</sup> densities respectively. The increases in densities of the composites are credited to the fact that silicon carbide's reinforcement material has a higher density [26]. According to several authors [27, 28], the increase in density of the composite compared to that of the matrix is mainly due to a higher weight percentage of high-density reinforcement in a low-density base matrix.

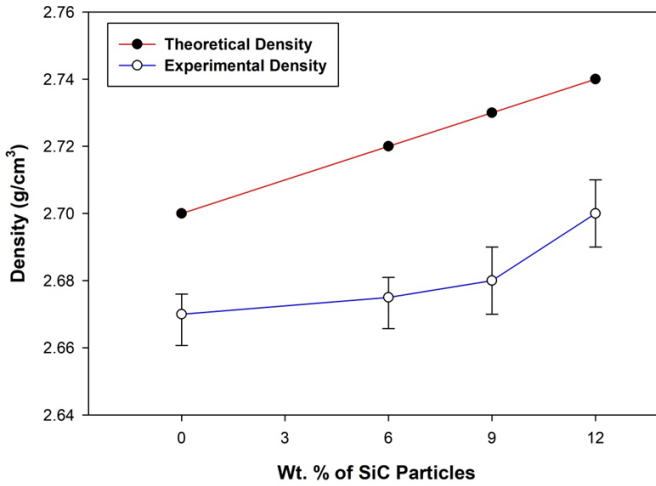


Fig. 5. Variation in density of Al6061- SiC composites.

Hardness Measurements

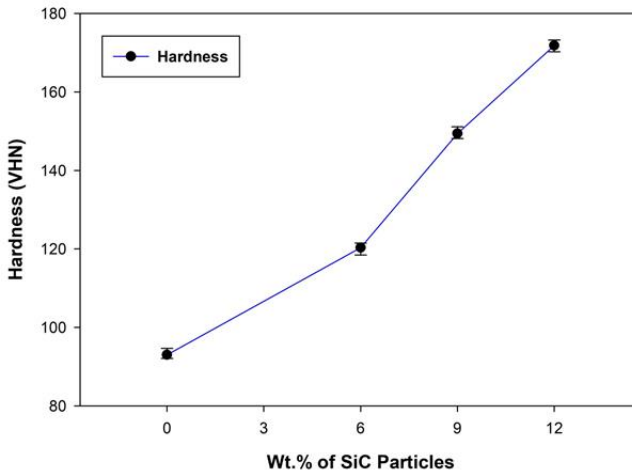


Fig. 6. Variation in hardness of Al6061- SiC composites.

Fig. 6 shows the plot of variation in micro Vickers hardness of Al6061 alloy-based composite with increasing SiC particle content in the matrix alloy. It can be observed from the above figure, hardness of the composites increased as wt.% of SiC content is increased from 6 to 12 wt.%. The improvement is about 84.7% in Al6061 with 12 wt.% of SiC composites compared with the matrix. The same trend is found with the output of other researchers [29]. Usually, after adding the particles, the strain energy at the peripheral of particles is increased, so in composites, enhanced hardness is obtained. The results obtained are consistent with the results of other workers [30, 31]. Increases in the

hardness of Al alloy composites contain hard particles or fibers have been reported by several investigators [32, 33].

*Tensile Properties*

The tensile behavior of as-cast Al6061, Al6061 with 6 to 12 wt.% of SiC composites is determined to measure the UTS, YS, and ductility in elongation (%). The Al6061 alloy and SiC reinforced composite specimens are prepared based on ASTM E8 standard and are subjected to tension test in a universal testing machine. The influence of micro SiC particles on the ultimate and yield behaviour of Al6061 alloy is depicted in Fig. 7.

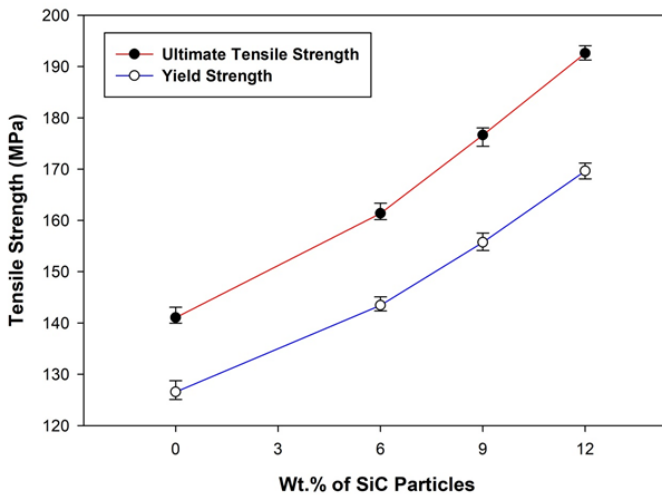


Fig. 7. Variation in ultimate and yield strength of Al6061- SiC composites.

Fig. 7 is the graph of UTS and YS (stress to produce a plastic strain 0.2%) of the Al composites, plotted with the weight percentages of SiC content. The test found that the ultimate and yield strength of base Al6061 alloy is 141 MPa and 126.5 MPa, respectively. The UTS of Al6061 with 6 to 12 wt.% of SiC are 161.3 MPa, 176.6 MPa, and 192.5 MPa, respectively. It has shown an increase in UTS by about 36.53 %, and YS increases by about 34.03 % in 12 wt.% SiC materials. The enhancement in UTS and YS is due to strengthening mechanisms [34].

In the present work, Al6061 with SiC composites are synthesized by the two-step reinforcement addition method, enhancing the bonding between the matrix and SiC particles. Further, this strong bonding improved the tensile properties. Improvement in UTS is due to the Al6061 matrix strengthening following a reduction in grain size and high dislocation density generation in the Al matrix due to the difference in the thermal expansion between matrix and SiC reinforcement. The load transfer from the soft Al6061 matrix to the hard SiC reinforcement during the test, due to good bonding between two systems, Hall-Petch effect is the contribution of grain refinement to the various strength aspects [35]. These incorporate the usual composite strengthening through the load exchange between the soft material and the hard and brittle reinforcement [36]. The increase in UTS is similar to the results obtained by Min Song and co-authors [37], who

recognized the enhanced strength due to the addition of the hard reinforcement. Also, Qiyao Hu [38], who has investigated SiC reinforcements in A356 and Al6061 matrices, has reported enhanced UTS. *Veeresh Kumar et al.* [39] studied the effect of titanium diboride and graphite content on the tensile behaviour of Al6061 alloy. The composites with these particles exhibited superior properties.

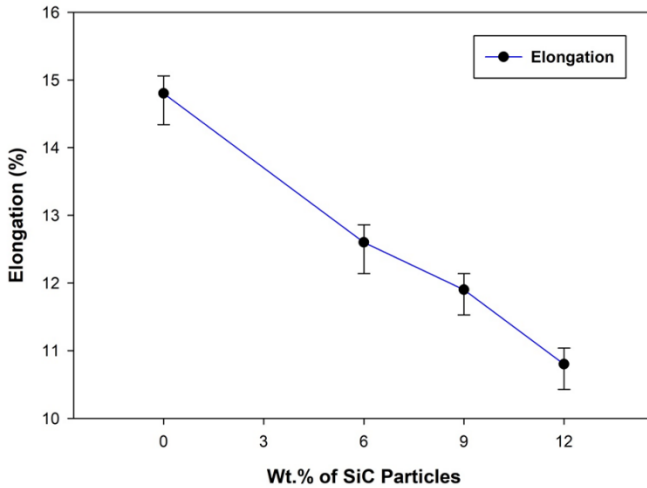


Fig. 8. Variation in ductility of Al6061- SiC composites.

Fig. 8 indicates the ductility of the Al6061 alloy and SiC reinforced composites, and the specimens show a decrease in elongation in terms of percentage. Composites with 12 wt. % of SiC content shows a decrease in ductility by about 27%.

Researchers have accounted for the diminishing malleability of particulate MMCs [40] lower than the base matrix. This is very intriguing in perspective of the perception made in the study that the fracture pursues a brittle process. The outcomes and the trends shown in the present case are like those obtained by different researchers [41], who likewise imparted the insight that the flexibility of the composite declines with increasing reinforcement. This loss in ductility can be credited to the embrittlement impact because of the hard SiC particles, which cause an increment in stress concentration sites. These strengthening particles oppose the passage of the dislocations either by making stress fields in the Al or by actuating large differences in the elastic property between the Al compound and the SiC dispersoid.

#### *Tensile Fractography*

Fig. 9 (a-d) is the fractured SEM images of Al6061 alloy and Al6061 with 6 to 12 weight percentages of SiC composites. It is evident from the SEM; the Al6061 shows greater voids indicating the ductile fracture, whereas Al6061 with SiC composite shows smaller voids and brittle fracture.

In the present work, the fracture behaviour of Al6061, Al6061-6 wt. % SiC, Al6061-9 wt. % SiC and Al6061-12 wt. % SiC composites have been studied. The surface of the monolithic Al sample indicates a ductile mode of fracture (Fig. 9a). It follows from Fig. 9 (b-d) that the multiple shears in SiC particles have been seen in the regions of particles due to the high load-bearing capacity of reinforced composites and strong interfacial bonding between the matrix and SiC particles. The presence of SiC particles in the delicate and malleable Al6061 results in requirements in distortion, along these lines causing triaxial stresses in the delicate and pliable metal, which supports the inception of voids and development in the Al matrix and furthermore debonding at the boundary of the particle and the matrix. It is also clear from Fig. 9 (c-d) and composites with 9 and 12 wt. % of SiC that particle fracture becomes dominant, with the increase in the wt. % of SiC in the Al6061. Many researchers have made the common features on the tensile fractured surfaces [42].

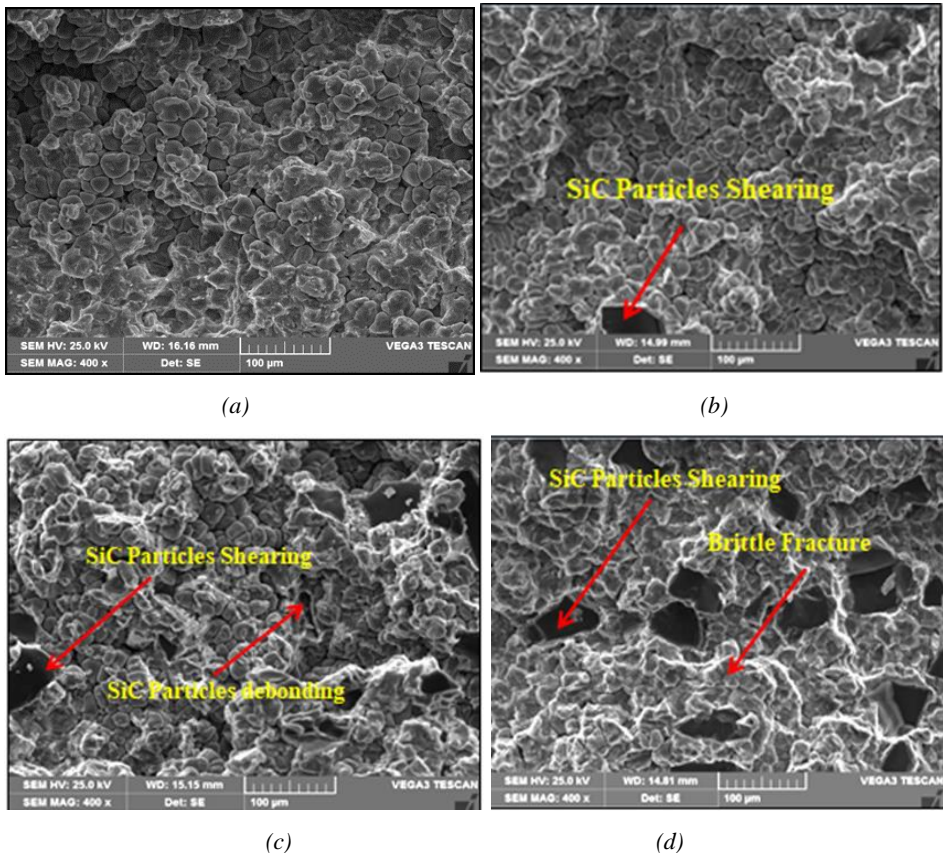


Fig. 9. Tensile fracture surfaces SEM micrographs of (a) Al6061 alloy (b) Al6061- 6 wt.% SiC (c) Al6061-9 wt.% SiC & (d) Al6061-12 wt.% SiC composites.

## Conclusions

The stir-cast technique effectively synthesizes the Al6061-SiC particulate MMCs by varying weight percentages of silicon carbide particles. Further, for all the processed conditions, the microstructure, mechanical properties are studied. The produced composites (Al6061-6, 9, 12 weight percentages of SiC) are effectively synthesized via stir casting with two-stage reinforcement additions.

- Two-stage additions of alumina particles in the Al6061 matrix have resulted in uniform dispersion of reinforcing particles, as shown by SEM studies. The EDS study showed the existence of SiC particles in the produced composites, and the XRD patterns of Al6061-6 and 12 wt.% of SiC composites were analyzed. XRD investigations validate the existence of SiC phases in the Al6061 alloy matrix.
- After including SiC particles in Al6061 matrix alloy, the theoretical and experimental densities of Al6061-6, 9, 12 weight percentages of SiC composites have increased.
- The microhardness, UTS, and YS of SiC reinforced composites have increased with a slight decrease in ductility. Fractographic analysis of tensile fractured surfaces using SEM has indicated the various fracture mechanisms of base alloy (Al6061) and produced composites.

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