Effect of Silicon Carbide and Graphite Reinforcements on Mechanical Properties of Al6061 Based MMCs

Deepika.C
Lecturer, Department of Mechanical Engineering, Govt Polytechnic
Kustagi-583277, Karnataka, India.

Abstract

This paper reports on mechanical properties of a novel hybrid composite material based on Al6061 as matrix material and SiC and graphite as reinforcements. Weight percentage ofSiCwas varied while graphite was kept constant.An economical technique of stir casting was used to fabricate the hybrid composites.The cast alloy and hybrid composites have beenput throughthe microstructure studies, hardness test and tensile test. Microstructural characterization was performed usingoptical microscopy. It's reported that multiple reinforcing content has an impact on mechanical properties including hardness, yield, and ultimate tensile strength.It was found that addition of SiC and graphite particles enhanced the hybrid Al6061 composites' mechanical properties. Reduction in grain size, dislocation strengthening, and precipitation strengthening mechanisms all contributed to the increased hardness, yield, and ultimate tensile strength of hybrid composites.Fractured surface analysis was carried out to identify the failure tensile failure mechanisms in hybrid composites.

Keywords: Aluminium alloy; Hybrid composites; Stir casting; Microstructure; Mechanical properties;

1.0 Introduction

A monolithic aluminium alloy or monolithic aluminium can be improved mechanically, physically and tribologically in a variety of ways.Second phase particles, heat treatment, or secondary processing techniques can be used to enhance the properties.In addition to these, hard ceramic compounds or organic materials are one of the most preferred methods [1-2]. Here the basic question is why there is need for composites when compared to monolithic aluminium or its alloy. Metals in general are isotropic which means there are properties are same in all directions while in case of composites it can be anisotropic which means properties are excellent in the direction of axial direction or they can be quasi-isotropic which means they have properties nearly isotropic. The aluminium composites reinforced with ceramic particulates possess nearly isotropic properties compared to continuous fiber composites. One can see that the composites differ in many ways like there stiffness and strength can be tailored according of needs of loading conditions, they possess greater resistance to fatigue damage, absorb radar microwaves, improved wear resistance and very low thermal expansion. Fascinated by their promising properties many attempts have been made to use in numerous structural and non-structural applications [3-4].

Monofilament, continuous fibers, whiskers, and particulate ceramic reinforcement are some of the most commonly used forms.The reinforcements of such kinds which is either carbides such as SiC, TiC, B_4C, oxides like Al_2O_3, TiO_2, nitrides like Si_3N_4, AIN or borides like TiB_2, ZrB_2[5-7]. Liquid metallurgy techniques such as casting and liquid infiltration can be used to develop aluminium alloy composites, thermal spraying or physical vapor deposition are gaseous state techniques used in conjunction with solid state techniques such as powder metallurgy or roll bonding. There are many factors to consider when selecting the processing technique for composite materials, such as load requirements, application type, as well as the matrix and reinforcement composition.Due to its simplicity and low processing costs, stir casting is preferred by many. Kumar and Murugan et al [8] developed Al6061/AlN (0 – 20%) composites by stir casting technique with bottom pouring arrangement. As cast microstructure of alloy depicted α-Al dendritic structure along with Mg_2Si precipitates resulted due to supercooling. Composites showed uniform dispersion of AlN particles along with refined α-Al grains in the Al6061 metal matrix. In another work, Moses et al [9] developed Al6061/TiC composites by stir casting route by feeding 15% mass fraction of TiC into the molten metal at 30 g/min.The microstructure studies showed that the composites developed at 100 rpm stirring speed showed poor distribution of TiC particles while 500 rpm showed uniform dispersion of TiC particles.

Hybrid composites incorporate multiple reinforcements into mmc’s, which are the latest evolution of the family [10-11]The incorporation of hard ceramic particulate reinforcements increases the wear resistance of composite material but in turn causes significant damage to counterface material leading to poor wear performance of overall tribo-system. In addition to this the ceramic particulate reinforced composites are hard to machine to required shape due to high hardness of ceramic reinforcements which in turn causes the tool wear. On the other hand the carbon material like graphite particulates are not recommended for strength related requirements owing to their soft nature. They tend to decrease both fracture toughness and strength of composite materials due to which it is not suggested for load bearing applications. On the contrary the lubricating properties and chemical inertness of graphite make it a popular material due to its layered structured is used as lubricant material.

Kalkanli et al [12] showed that with the addition of SiC particles in AA7075 resulted in increase in flexural strength and tensile strength. The composites before heat treatment showed minimal increase in flexural strength up to 10 wt.% of SiC content while in case of heat treated ones the increase was significant. On the other hand similar trend was observed in case of ultimate tensile strength values. As cast composites showed small increment in tensile strength values which when made a comparison to unreinforced AA7075 alloy. In case of heat treated, the composite with 10 wt.%SiC showed highest strength of about 350 MPa. The increase in flexural strength was attributed to strain hardening due to inhibition of motion of dislocations by SiC particles. But in case of composites with SiC content up to 30 wt.% showed decrease in flexural and tensile strength in as cast conditions. This was attributed to clustering of SiC particles in the metal matrix which forms weak zones leading to poor strength values. Mobasherpour et al [13] Nanoalumina particles were added to AA7075-Al_2O_3 composites in order to study their effect on tensile strength.An UTM with a capacity of 50kN was used to measure the tensile properties of the material. A 5 mm/min of crosshead speed was used for all composites in all tests conducted at room temperature.The tensile strength of unreinforced AA7075 alloy was found to be 276 MPa while that of composites with 5%Al_2O_3 showed tensile strength of 443 MPa. All composites have been observed to have higher tensile strength with higher alumina content than unreinforced alloys when alumina content is increased.The increase in strength had been ascribed to high stiffness of nano alumina particles which contributes via strain hardening. With increasing alumina content, composites' ductility decreased.Out of all unreinforced alloy had higher elongation of about 9% while least elongation of about 2.1% was observed for composite with 5% alumina content. Shen et al [14] examined the mechanical characteristics of composites, such as their bending and compression strengths by subjecting them to compression test and three-point bending test respectively. The three-point bending test showed that as compared with non-reinforced AA7075 alloy, composites were stronger in bending. The highest bending strength of about 813 MPa was observed for composite with 7.5% B_4C particles. However significant drop in bending strength was observed for composite with 12.5% B_4C particles which was attributed weak interfacial bonding between particles and matrix material. The fractured surface showed particle debonding was not a predominant mechanism for failure of composites. Meanwhile, a thin layer of aluminium was present on B_4C particles on the fractured surface, indicating a good interfacial bond.The compressive stress strain curves for compositesdisplayed the composites' fracture and yield strength with 7.5% B_4C had values of 895 and 600 MPa respectively. All the composites had higher bending and fracture strength in comparison to AA7075 alloy without reinforcement.

Komai et al [15] AA7075 composite materials reinforced with SiC whiskers were studied for tensile and fatigue properties. The composite was developed using powder metallurgy technique followed by heat treatment as according to T6 temper conditions. The composites obtained after hot extrusion displayed orientation of whiskers in the direction parallel to that of extrusion. It was further observed that the SiC whiskersdistribution throughout the matrix was uniform but clusters of whiskers were still found at few regions. To verify the mechanical characteristics, the tensile samples were machined along the extrusion direction. Compared to unreinforced alloys, composites had 75% higher elastic modulus and 40% higher tensile strength.The fracture analysis displayed that the failure of the composite was due to whisker pull out. Composites also had a higher fatigue strength than alloys without reinforcement.The fracture analysis after fatigue failure was due to the crack nucleation at the whisker clustered region. However, at different regions the crack was found to be initiated at composite surface where there were no whisker clusters leading to unstable failure of composites.

The main goal is to produce high-quality MMCs with little porosity and uniform graphite (Gr) and silicon carbide particle dispersion, drawing inspiration from earlier investigations.Here, it is discussed how Al6061 alloy and its hybrid composites' ultimate tensile strength, microstructure, elongation, yield strength and hardness are affected by the content of reinforcement.

2.0 Experimentation

Stir casting was used to create hybrid composites from Al6061 by melting it in graphite crucibles maintained at 760°C while melting it.The Al6061 alloy's composition is displayed in Table

1.This was accomplished using an electrical resistance melting furnace with a stirrer.As soon as the melt is melted, hexachloroethane tablets are used to degas the melt (molten Al6061).At 400 rpm, molten metal is stirred with preheated particles' graphite and SiC after degassing.In order for the reinforcement to dissolve evenly in the molten metal, they are added one by one, while the stirring is continued.After stirring for 15 minutes, the melted Al6061 melt is dispersed with graphite and SiC particles.Metallographic analyses, hardness and tensile tests are performed on the as cast A6061 alloy and hybrid composites after machining.This investigation was conducted on a tensile specimen of the dimensions shown in Fig.1.

The as cast samples were machined to subject them to metallurgical procedures like polishing and etching. Optical micrographs were taken on etched surface of all samples using the Olympus metallurgical microscope, fitted with a camera. The dispersion of reinforcements and microstructural features and tensile fractured surfaces are studied in more detail using scanning electron microscope (Model: JSM 840a Jeol) and EDAX at BMS college of Engineering, Bengaluru, India.

Table: 1

Composition of Al6061 alloy

Chemicals	Si	Ti	Fe	Mn	Zn	Cu	Mg	Cr	Other	Al
Wt. (%)	0.4-0.8	0.15	0.7	0.15	0.25	0.40	0.8-1.2	0.35	0.05	Balanced

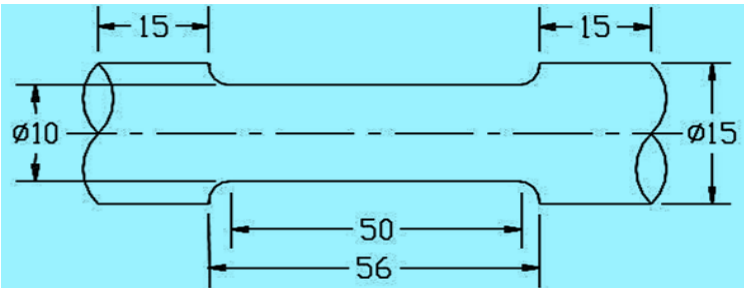
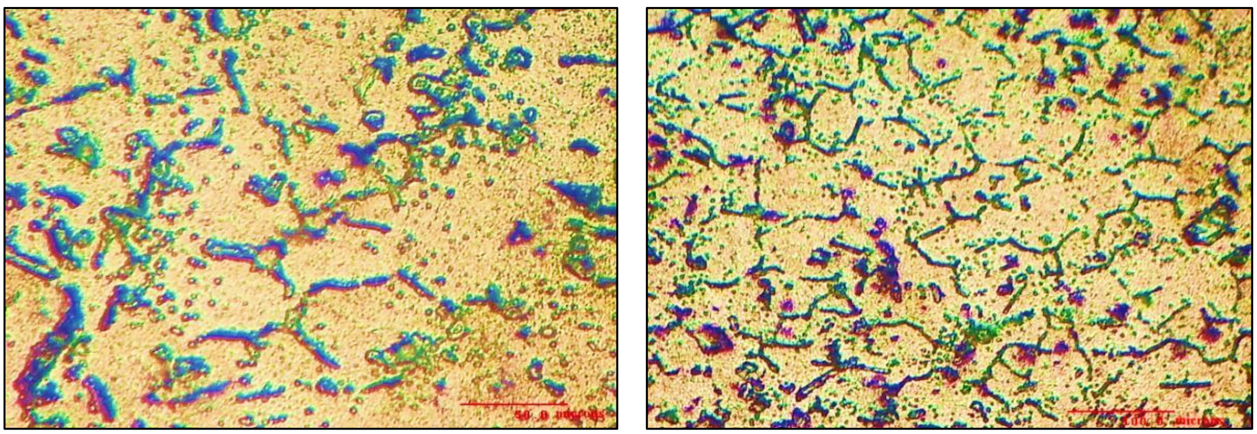


Fig.1 Schematic diagram of tensile test specimen

3.0 Results and Discussions

3.1 Microstructure analysis

Optical images of polished as cast hybrid composites are shown in Figure 2 (a) – (b) with different composition of hybrid reinforcements. During stirring the gas from the atmosphere can get entrapped in the molten during stirring and form as pores in the microstructures which are seen in the optical microstructure. Fig 1(b) depicts the location of the particles' SiC and graphite at the α-Al grain boundaries. Graphite particles were observed as dark gray phases in microstructure, whereas SiC particles were gray.There was no dispersion of reinforcements in both reinforcements, and the grain boundaries of α-Al were mostly present within the dispersion of both reinforcements. Figure 1 (b) shows clustering at various regions in hybrid composites.A very good interface bond between α-Al grains and reinforcement could be observed in the laboratory. It mainly involved mechanical interlocking between the two.



(a) Al6061/4%SiC/3%Gr (b) Al6061/8%SiC/3%Gr

Figure 2. Optical micrographs of hybrid composites

3.4 Mechanical properties

3.4.1 Hardness

As shown in Figure 3, Al6061 composites have different Vickers hardness depending on the combination of SiC and Gr content.A Vickers hardness of 62VHN was measured for Al6061, and 66, 74, 81 and 84 VHN values were obtained with the addition of 2%, 4%, 6%, and 8% of SiC.Al6061/8%SiC/3%Gr composite achieved the greatest increase in hardness of 72%.Here composite with highest SiC content of 8% showed highest increment of 73.34% in hardness value. Overall, the hardness was found to increase in increase in SiC and graphite particle content in Al6061 matrix. Comparing SiC and Gr combinations with unreinforced Al6061 alloys, all combinations showed an increase in hardness.Highest hardness value of 84 VHN was recorded for Al6061/8%SiC/3%Gr hybrid composite which surpasses Al6061 alloy by about 73.3%.

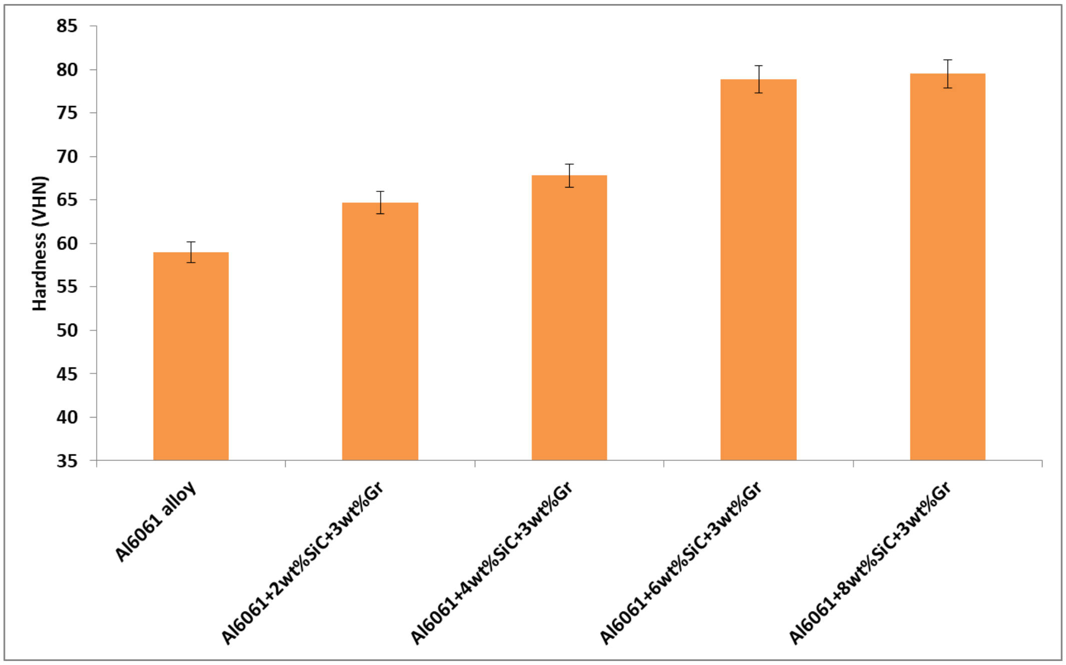


Figure 3. Effect of SiC and graphite content on hardness

The following factors are the main causes of the enhancement in hardness: [16-17],

- In composite materials, dispersion of silicon carbide and graphite particles is uniform.In the light of optical micrographs displayed in Fig 1, it is clear that both reinforcements were dispersed uniformly, which resulted in an increase in hardness.
- SiC particles have a much higher hardness than Al6061.In simple terms, one can expect enhancement in hardness of soft phases when a hard phase is introduced into a soft and ductile phase.SiC particles do impart a high level of hardness to the matrix, but their uniform dispersion contributes to its growth.
- Difference between the coefficient of thermal expansion between Al6061, SiC and graphite particles generate dislocations near to reinforcement/matrix interface. Further raise in reinforcement content increased the density of dislocations which in turn enhanced hardness of all composites.

3.4.2 Yield strength

Figure 4represents yield strength of Al6061 alloy and its hybrid composites as a function of reinforcement content. It’s evident that the yield strength of single reinforcement composite and multiple reinforcement hybrid composite increases with increase in their content. For as cast Al6061 alloy, a 54 MPa of the yield strength had been observed, meanwhile for the composite exhibited 62, 68, 75, 88 MPa for the inclusion of 2%, 4%, 6% and 8% of SiC respectively. It can be seen that the Al6061/8%SiC/3%Gr composite showed an increment of 44.56% compared with Al6061 alloy. Overall,there was an improvement in composites yield strength with the addition of more SiC and graphite. Hybrid composites have a higher yield strength with an enhancement in Gr and SiC combinations.As compared with Al6061 alloy, the hybrid composite Al6061/8%SiC/3%Gr composite recorded a strength value of 88 MPa, almost 44.89 % higher.

The enhancement of yield strength is mainly due to contribution by several strengthening mechanisms namely, load transfer from matrix to reinforcements, grain refinement, dispersion strengthening and dislocation strengthening. There are a number of reasons why composites have increased yield strength and listed below [18-20],

- Grain refinement or grain size strengthening – The direct correlation between the grain size and yield stress is described by Hall-Petch equation where the relationship between grain size and yield strength is proportionally inversed. In most of the cases it is found that the smaller grain size enhances yield strength in metallic materials while it enhances toughness of the ceramic materials. The average grain size for composites was found to decrease with increase in SiC and graphite particle content which is already shown in Figure 10. The Al6061/8%SiC/3%Gr hybrid composite which showed minimum grain size of 27 µm exhibited highest strength of 88 MPa. In this regard one can expect that grain refinement is one of the main contributors for increase in yield strength.
- Dislocation strengthening – Due to thermal expansion coefficient mismatch between the Al6061, SiC and graphite,nucleation of dislocationsis observed in case of composites. Dislocations which nucleate near matrix/reinforcement will keep on increasing with increase in reinforcement content. In order to have plastic flow the dislocations need to move freely in the matrix but due to presence of reinforcements there motion is inhibited and hardens the composites.

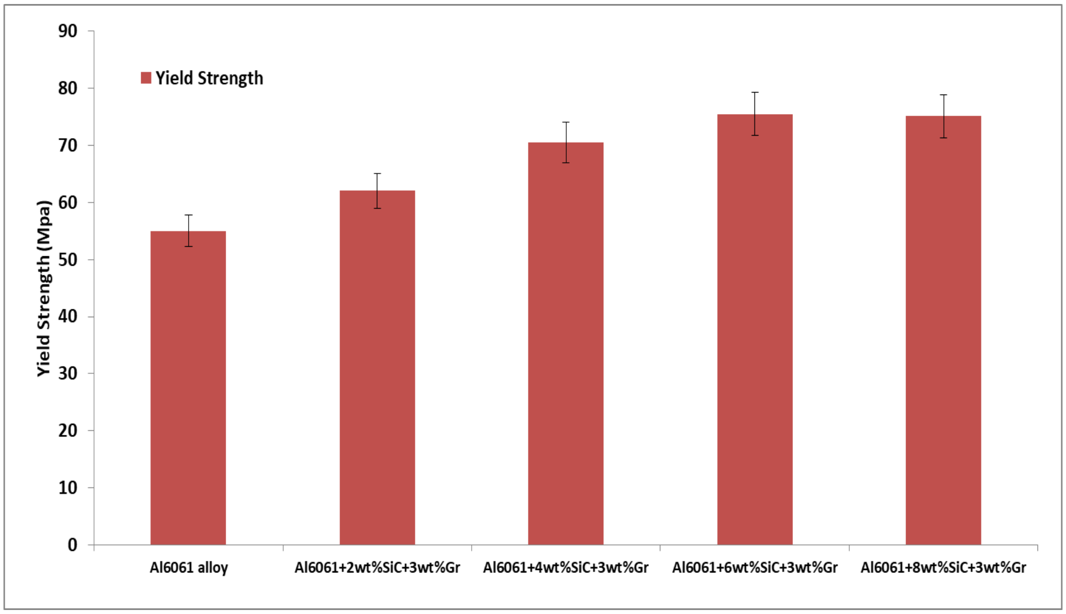


Figure 4. Effect of SiC and graphite content on Yield strength

3.4.3 Ultimate tensile strength

Figure 5 displays the Al6061 and its composites' ultimate tensile strength with varied particle content of graphite and SiC.Hybrid composites' ultimate tensile strengthimproved with increase inreinforcement content. For aluminium 6061 alloy as cast, tensile strength was 112 MPa; for SiC composites inclusion of 2%, 4%, 6% and 8% the tensile strength was 118, 124, 36, and 145 MPa respectively.It's evident that the Al6061/8%SiC/3%Gr composite exhibited highest strength and showed an increment of 68.34% in comparison of Al6061 alloy. Overall, with the increase in both SiC and graphite content the tensile strength of the composites improved. When both SiC and Gr content is increased in hybrid composites, the tensile strength increases. As compared to Al6061 alloy, A6061/8%SiC/3%Gr hybrid composite has the strongest strength of 145 MPa, approximately 68.85% greater.

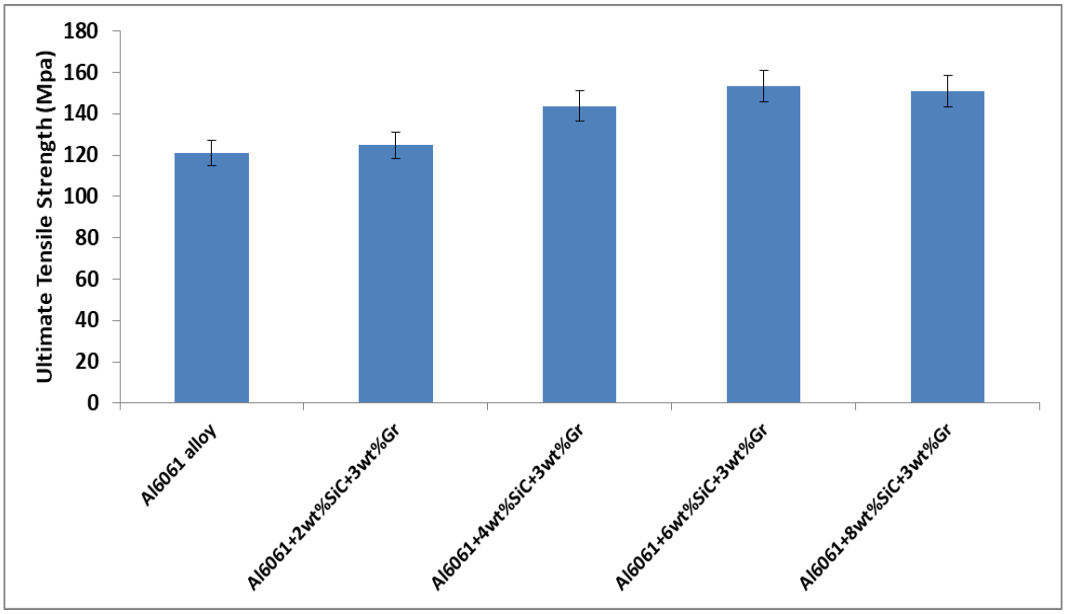


Figure 5. Effect of SiC and graphite content on ultimate tensile strength

The hybrid composite ultimate tensile strength is significantly increased by the impact of reinforcing content.Al6061's matrix should have a uniform distribution of reinforcements, eliminating any zones of particle free space.The SiC and Gr particles' high hardness as well as other various good properties can be utilized effectively for strengthening composites with uniformly dispersed particles.In the absence of reinforcement clusters, weak local regions may form, which could become the primary source of crack initiation under tensile loading.Additionally, it is important that there is no discontinuity in the bonding between the Al6061 and both reinforcements.To a desirable extent, the particles bonding is enhanced by ideal interface between reinforcement and matrix and not just only aids wetting. It is possible for reinforcement particles to prematurely detach if interfacial bonding is weak during force application.Additionally, effective load transfer from the Al6061 matrix to hard and strong reinforcements depends greatly on the quality and strength of the interfacial bonding.Interfacial bond strength determines how much load will be transferred across the bonding surface and therefore how much fracture stress will be transferred to reinforcement particles.The ceramic particles which were distributed uniformly in the Al6061 were very effective in absorbing the load when the composite material was subjected to an external load. Further,due to incorporation of hard reinforcements in ductile Al6061 matrix results is resistance for plastic flow during application of load. Due to restriction to plastic flow of material the tensile strength of composites increases which further increases with increase in reinforcement content. Along with strengthening mechanism mentioned in yield strength section, load transfer mechanism is one more addition to the list of strengthening mechanisms responsible for tensile strength improvement in Al6061 composites.

3.4.4 Ductility

The impact of varying the particles such as SiC and graphite content on Al6061 composites' ductility is depicted in Fig 6.A hybrid composite of Al6061/8%SiC/3%Gr showed the lowest ductility value of 4.8%, while the highest value was 14.9% for Al6061 alloy.SiC particles increased the elongation of Al6061 and decreased its elongation values when SiC particle content was increased.Al6061 is a matrix with a work hardening characteristic that determines the ductility of hybrid composites.Al6061 matrix has undergone high work hardening rates, resulting in lower ductility values in hybrid composites because of the high hardness and strength values.It is also stated that as the reinforcement content increases, particularly with multiple reinforcements, the Al6061 will behave like a yielding low ductility values and brittle material after tensile testing.The increase in reinforcement content is mainly responsible for this increase in porosity percentage.Several regions also were observed to exhibit particle clustering, helping to nucleate voids, especially at the interface between the Al6061 matrix and reinforcement.When hybrid composites are formed, the reinforcement particles' sharp edges can also cause stress concentrations that lead to low ductility values.

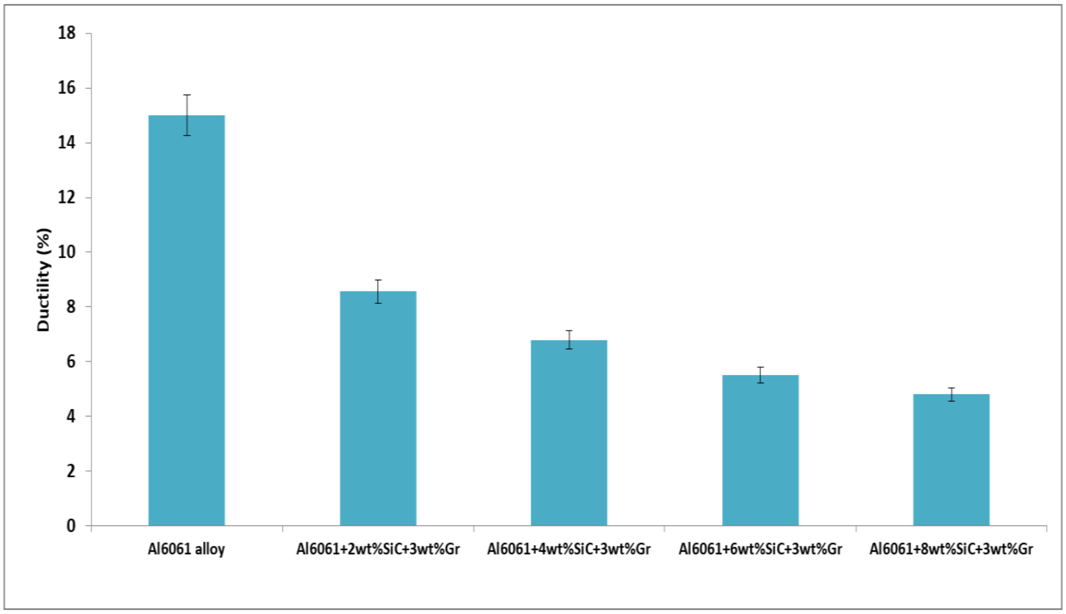
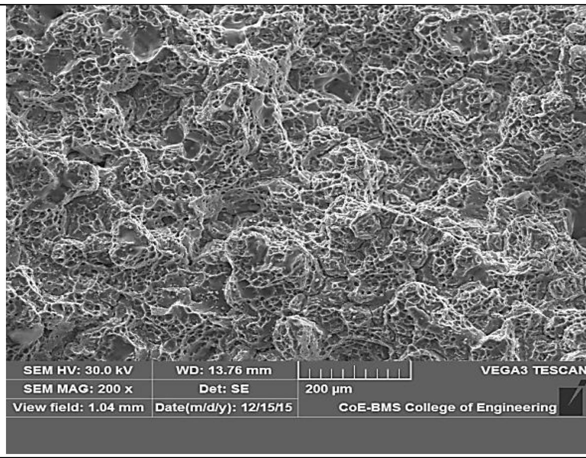


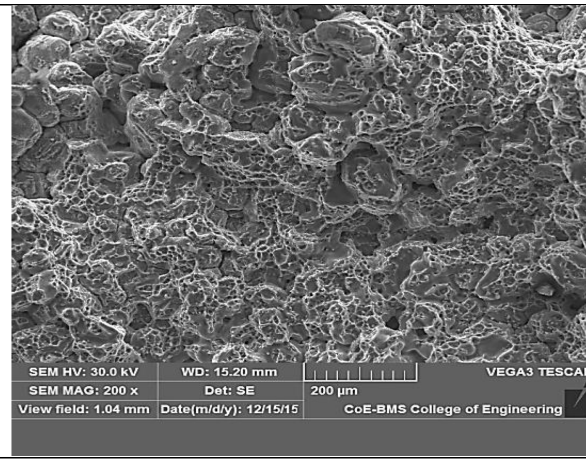
Figure 6. Effect of reinforcement content on ductility

3.5 Fracture analysis

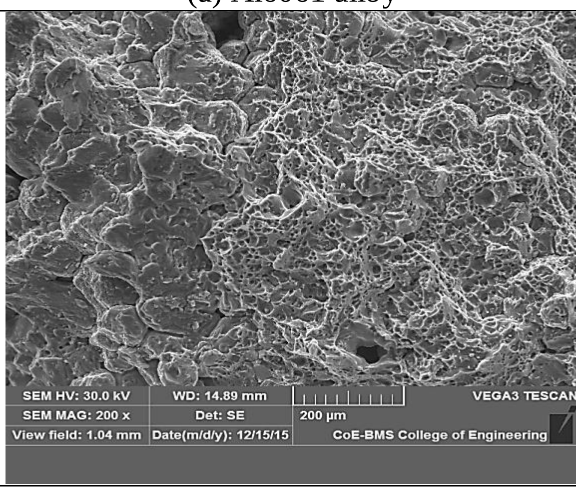
Process conditions, reinforcement morphology, and reinforcement distribution determine the fracture modes of single and multiple reinforcement-based composites.A matrix's density, porosity, precipitation effect and surface roughness can also influence fracture mode.After tensile testing and casting Al6061 alloy, SEM micrographs of composites can be seen in Figure 7.The fracture surface of Al6061 alloy as shown in Figure 7 (a) showed the presence of dimples which is attributed to combine brittle and ductile failure mode. But when a larger magnification of fractured surface of Al6061 alloy is taken, one can see that the voids are full of dendrites. Figure 7 (c) to (d) shows hybrid composite failure modes where brittle is more dominant in comparison to either ductile or brittle.During the process of casting, stirring is used to improve the dispersion and wettability of SiC and graphite particles.But the side effect of this is segregation and formation of porosity in the composite which is high in comparison of Al6061 alloy. It has also been demonstrated that dendritic structure and pores also contribute to fracture since these inter-dendritic spaces provide an ideal nucleation site for cracks.When reinforcements segregate at the inter-dendritic region during solidification, microcracks form during loading as a result.The propagation of these micro-cracks causes the failure of hybrid composites by interconnecting with other interdendritic regions.Further, defects in casting such as entrapped gas pores and shrinkage pores assists the micro-voids formation which grow as loads are applied. [18-21].



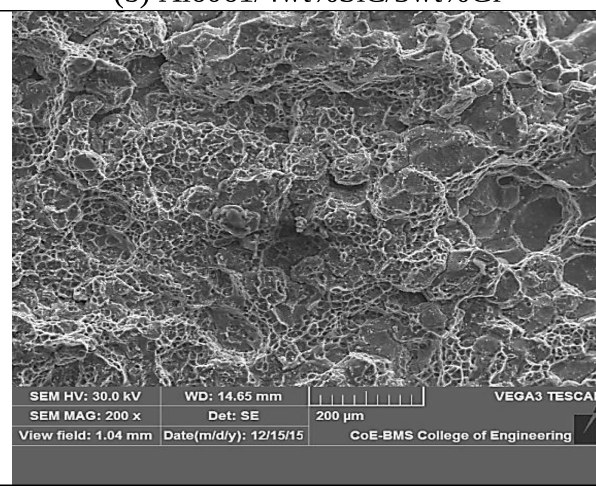
(a) Al6061 alloy



(b) Al6061/4wt%SiC/3wt%Gr



(c) Al6061/6wt%SiC/3wt%Gr



(d) Al6061/8wt%SiC/3wt%Gr

Figure 7. SEM micrographs of Al6061 alloy and hybrid composites after tensile test

4.0 Conclusions

1. A low-cost stir casting technique has been successfully applied to fabricating Al6061/SiC/Gr composites with uniform reinforcement distributions as well as interfacial bonding between SiC/Gr particles and Al6061.
2. Vickers hardness showed highest value of 84 VHN for Al6061/8%SiC/3%Gr hybrid composite while lowest value of 60 VHN for Al6061. Enhanced hardness was due to uniformly distributedSiC and graphite particles, nucleation of dislocations resulted from difference between thermal expansion coefficient of composite constituents.
3. Yield strength studies showed highest value of 88 MPa for Al6061/8%SiC/3%Gr hybrid composite while lowest value of 64 MPa for Al6061 alloy. Tensile strength studies showed highest value of 148 MPa for Al6061/8%SiC/3%Gr hybrid composite while lowest value of 122 for Al6061 alloy.
4. Ductility studies showed highest value of 14.8% for Al6061/8%SiC/3%Gr hybrid composite while lowest value of 4.9% for Al6061 alloy. With increased SiC and Gr content, composites exhibit reduced ductility because of enhanced porosity.
5. In fracture studies of Al6061 alloy and hybrid composites, combined brittle and ductile failure modes were observed.

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