

# Strengthening of Aluminum by SiC, Al<sub>2</sub>O<sub>3</sub> and MgO

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## Abstract

The objective of this experimental investigation is to produce a metal matrix composite (MMC) using pure aluminum as a base material reinforced with one of the following ceramic additives each time (alumina Al<sub>2</sub>O<sub>3</sub>, silicon carbide SiC, and magnesium oxide MgO) with different volume fractions. Liquid state mixing technique was employed for the different constituent. Temperature was checked frequently while mixing using a thermocouple. Degasser was added to the content of the composite while mixing to minimize gas bubbles at the final cast. After melting and mixing, melts were poured in metallic mould then we got a cast from which specimens for various tests were prepared. Complete mixing between the Al matrix and the additives was checked by taking specimens from different parts from the cast (from the upper middle and the upper edge, and from the middle, then from the lower middle and lower edge then subjected to microscopic observation. Microstructure examination and microanalysis were carried out using optical microscope and scanning electron microscope equipped with energy dispersive x-ray analysis, moreover tensile mechanical properties were determined in each case. The addition of SiC, MgO & Al<sub>2</sub>O<sub>3</sub> particulates into the matrix alloy increased the yield strength, the ultimate tensile strength & the hardness, & decreased elongation (ductility) of the composites in comparison with those of the matrix. Increasing wt% of SiC, MgO & Al<sub>2</sub>O<sub>3</sub> increased their strengthening effect but SiC is the most effective strengthening particulates, for higher strength, hardness, & grain size reduction. On the other hand, it decreases ductility & toughness.

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*Key words:* Composite materials; Liquid state mixing; Mechanical properties; Microstructural examinations

## 1. Introduction

It is very important to study the composite materials because it is the material for advanced technology, high temperature application where high strength / stiffness to-weight ratio is required. Composite Technology combines the most important properties of the components together in order to obtain a material with overall properties suitable for the design of the engineering part required. So it is a technology where you can tailor the material for the purpose set up. Composite materials consist of two or more physically and / or chemically distinct phases, suitably arranged or distributed. It has the characteristics that are not depicted by any of its components in isolation. Generally the continuous phase is referred to as the matrix, while the distributed phase is called the reinforcement.

A lot of work was done in this subject for the last decades since the production advances was highly affected by composites where you can tailor material properties as you need by mixing two different materials without chemical reaction. Some of composites are of metallic matrices with ceramics additives to have what we call metal matrix composite (MMC), and some polymeric matrices (PMC) and others are of ceramic matrices (CMC).

Most of the studies on metal matrix composites (MMC) has focused on aluminum (Al) as the matrix metal. The combination of lightweight, environmental resistance and

adequate mechanical properties has made Al and its alloys composites very popular. The melting point of aluminum is high enough to satisfy many application requirements, yet low enough to render composite processing reasonably convenient. It can accommodate a variety of reinforcing agents [1].

Particulate Al-MMCs are reinforced usually with SiC and Al<sub>2</sub>O<sub>3</sub>. Conventional processing methods include powder metallurgy and molten metal methods [1]. Discontinuous Al/SiC-MMC and Al/Al<sub>2</sub>O<sub>3</sub>-MMC have found widespread applications in aerospace, transport, military energy and electric industries, for example, they have been used in electronic packaging aerospace structures, aircraft and internal combustion engine components and a variety of recreational products [2-5].

A number of other reinforcing materials such as graphite, illite clay, Zirconia etc have been incorporated in Al using molten metal method. The basic limitation of this method is the poor wettability of ceramic particles with liquid Al alloys, [6-8]. Wettability can be defined as the ability of a liquid to spread on a solid surface, and it represents the extent of intimate contact between a liquid and a solid [24], and this enhances the tendency of reinforcement agglomeration. This represents a great challenge of producing cast metal matrix composites. This would normally result in poor distribution of the particles, high porosity content, and low mechanical properties. For that we need improve the wettability of matrix with additives. For improving wettability of SiC and Al<sub>2</sub>O<sub>3</sub>

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studies proved a high efficiency of wettability improvement by addition of silicon or magnesium.

The retention & distribution of the particulates are very important in production of composites materials. MgO addition improves the retention and distribution of Al<sub>2</sub>O<sub>3</sub> within the matrix [8],[9]. Stirring was useful to obtain a range of particulate percentages [10].

J. Hashim et al. studied the improvement of wettability by using clean SiC particles and magnesium as a wetting agent, and stirring continuously while the MMC slurry is solidifying were found to promote wettability of SiC with A359 matrix alloy. Decreasing this solidification time was also found to improve the wettability whereas increasing the volume fraction of SiC particles present will give the opposite effect [23].

Sajjad et al. employed a new method for uniform distribution of very fine SiC particles with average size of less than 3 µm was employed. The key idea was to allow for gradual in situ release of properly wetted SiC particles in the liquid metal. For this purpose, SiC particles were injected into the melt in three different forms, i.e., untreated SiCp, milled particulate Al-SiCp composite powder, and milled particulate Al-SiCp-Mg composite powder. The resultant composite slurries were then cast from either fully liquid (stir casting) or semisolid (compocasting) state. Consequently, the effects of the casting method and the type of the injected powder on the microstructural characteristics as well as the mechanical properties of the cast composites were investigated. The results showed that the distribution of SiC particles in the matrix and the porosity content of the composites were greatly improved by injecting milled composite powders instead of untreated-SiC particles into the melt. Casting from semisolid state instead of fully liquid state had similar effects. The average size of SiC particles incorporated into the matrix was also significantly reduced from about 8 to 3 µm by injecting milled composite powders. The ultimate tensile strength, yield strength and elongation of Al356/5 vol.%SiCp composite manufactured by compocasting of the (Al-SiCp-Mg)cp injected melt were increased by 90%, 103% and 135%, respectively, compared to those of the composite manufactured by stir casting of the untreated-SiCp injected melt [25].

W. Zhou et al. studied a composites based on two aluminum alloys (A536 and 6061) reinforced with 10% or 20% volume fraction of SiC particles were produced by gravity casting and a novel two-step mixing method was applied successfully to improve the wettability and distribution of the particles. The SiC particles were observed to be located predominantly in the inter-dendrite regions, and a thermal lag model is proposed to explain the concentration of particles [21].

K. R. Suresh et al. studied tensile and wear properties of aluminum composites fabricated by squeeze casting method and checked uniform particulate distribution. The squeeze cast composites show peak strength of 216 MPa showing an increase of 11.6% in tensile strength. The new composites also have improved wear resistance when compared to gravity cast composites. [22]

Elimination of casting defects such as pores and non-uniform distribution of the particulates is essential in improving the properties of the composite materials [10], [11].

The matrix should bond strongly with the reinforcement but should not be chemically affected by adverse reactions. Proper matrix and reinforcement selection will promote part formability by various processes [13].

Reinforcement, as either continuous or discontinuous may constitute 10 to 60 vol % of the composite [14].

The aim of this study was to investigate the production of Al-MMC using a modified liquid state mixing called stir casting method. The technique was examined by employing the ceramic particulates of SiC, Al<sub>2</sub>O<sub>3</sub> and MgO to aluminum in the liquid state where heating temperature and casting temperature was determined after some trials to achieve two targets:

- High enough to add the additives and mix it properly and then cast before the aluminum starts to solidify.
- Not too high so that it may burn the most of the additives before mixing them with the matrix and not to take a lot of time to solidify after casting so that the particulates may settle in the bottom of the mould due to gravity.

After mixing properly and casting, specimens subjected to various mechanical tests and micro-structural observation.

## 2. Experimental Procedure

Melting was carried out in an electric resistance furnace and heated to the temperature of 900°C (220°C higher than melting point of Al). This temperature was found convenient to compensate for the temperature drop during transferring the crucible and mixing the particulates. It was determined after making many trials at various temperatures. The ceramic particles were heated to 300°C before addition into the molten Al to avoid high drop of temperature just after addition of particulates in case of adding them in the cold state. It found that it gives time for impeller to stir the mixture & cast the aluminum before solidifying.

As reinforcement particulates, the following ceramic powders were added into the molten Al after separating a particle size using cylinder mill grinding and sieving:

- SiC powder of 50 µm particle size.
- Al<sub>2</sub>O<sub>3</sub> powder of 60 µm particle size.
- MgO powder of 50 µm particle size.

Before addition of Al<sub>2</sub>O<sub>3</sub> or SiC, the furnace was opened & 10 wt %Si was added to the melt & stirred then furnace was closed & reheated to 900°C, where Si addition was not needed for MgO addition due to its high wettability with aluminum. After addition of particulates with different constituents for each cast stirring process was employed to make the ceramic powders uniformly dispersed through the matrix (the liquid Al) before casting into the metallic mould. The apparatus used during the composite mixing are shown in schematic figure 1 which consists of: a drilling machine, a steel rod fixed to the drill grip welded from the other side to a steel impeller to be inserted in the graphite crucible containing the liquid

aluminum through a hole in the center of the steel cover that was added to avoid splashing of the liquid metal during the impeller rotation while mixing. Also, we needed a stand of a steel plate to hold the graphite crucible firmly on the table of the drilling machine during mixing. Operating the drill at 450 RPM for mixing, where the temperature of the melt during mixing was monitored by a thermocouple every minute until temperature becomes 700°C, then the degassing powder was added to remove gasses from the melt & stirred for seconds then cast carefully in a metallic mould of dimensions (15x8x1cm) ensuring that it is completely full. After 10 min cooling the mould was opened. Details of the melts are shown in table 1.

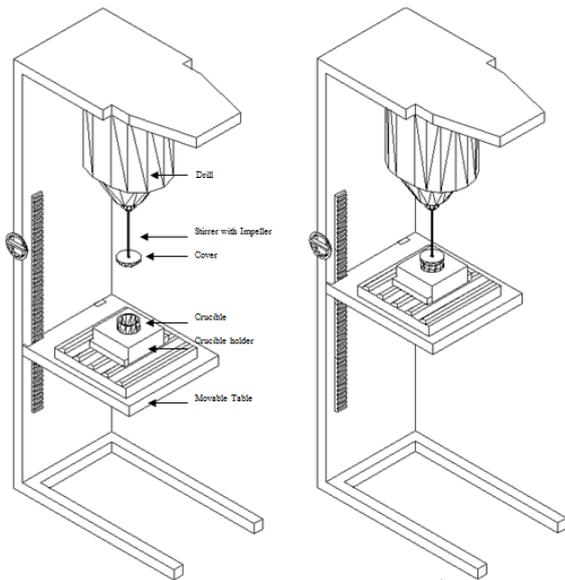


Figure 1: Schematic presentation of mixing process.

Table 1: Specimens groups & their constituents.

Melt number	Alloy
1	Al Pure
2	Al- 10 wt% Si, 5.0 wt %SiC
3	Al- 10 wt% Si, 7.5 wt %SiC
4	Al- 10 wt% Si, 10.0 wt %SiC
5	Al- 10 wt% Si, 15 wt %SiC
6	Al- 10 wt% Si, 20 wt %SiC
7	Al- 5 wt %MgO
8	Al- 10 wt %MgO
9	Al- 15 wt %MgO
10	Al- 20 wt %MgO
11	Al- 10 wt% Si, 5.0 wt %Al <sub>2</sub> O <sub>3</sub>
12	Al- 10 wt% Si, 10.0 wt %Al <sub>2</sub> O <sub>3</sub>
13	Al- 10 wt% Si, 15.0 wt %Al <sub>2</sub> O <sub>3</sub>
14	Al- 10 wt% Si, 20 wt %Al <sub>2</sub> O <sub>3</sub>

Specimens for various tests were prepared from each melt. For microstructure observations, the constitutional metallographic technique was utilized. The volume fractions of the particulates and their distribution, and the grain size of the Al matrix were determined.

For tensile test samples was prepared according to ASTM-E8-95a and impact test samples were prepared according to the ASTM E23.

Chemical analysis of the samples was done using EDX system attached to SEM, Model XL-30W/TMP Philips.

### 3. Results and Discussion

#### 3.1. Mechanical properties:

##### 3.1.1. Tensile test:

All tensile tests were carried out on Universal Tensile Testing Machine (Dartic). Figures 2, 3, and 4 show the stress-strain curves for various composites studied in this work. These curves are shown from load-elongation curves obtained from the tensile testing machine.

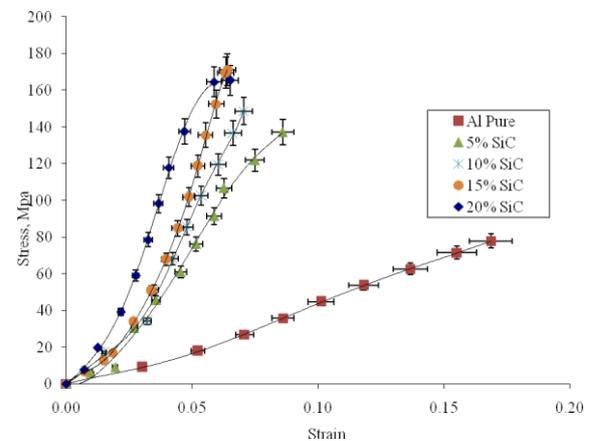


Figure 2: Stress strain diagrams for Al-SiC MMC.

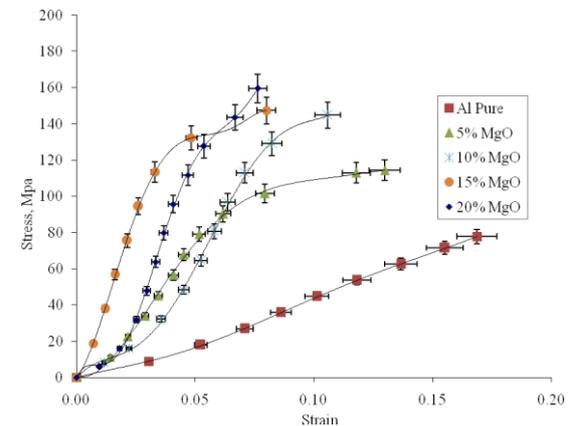
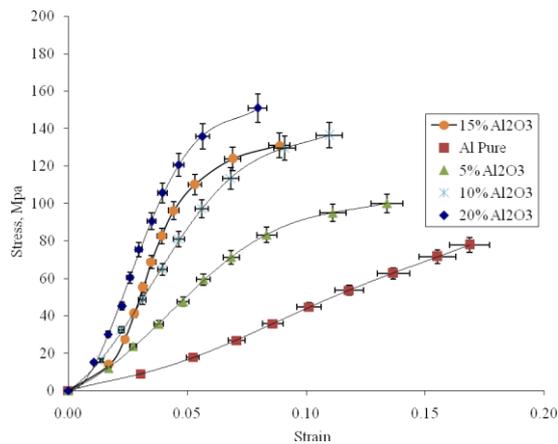


Figure 3: Stress strain diagrams for Al-MgO MMC.

Figure 4: Stress strain diagrams for Al-Al<sub>2</sub>O<sub>3</sub> MMC.

To show the effect of various ceramic particulates at different percentages on the ultimate tensile strengths (UTS), figure 5 was drawn for comparison. The results show that the UTS increase in all cases with increasing wt% of the ceramic particulates, the largest increase being in Al-SiC MMC, and the least being in Al-Al<sub>2</sub>O<sub>3</sub> MMC. These results indicate the effectiveness of the particulates in strengthening of the Al.

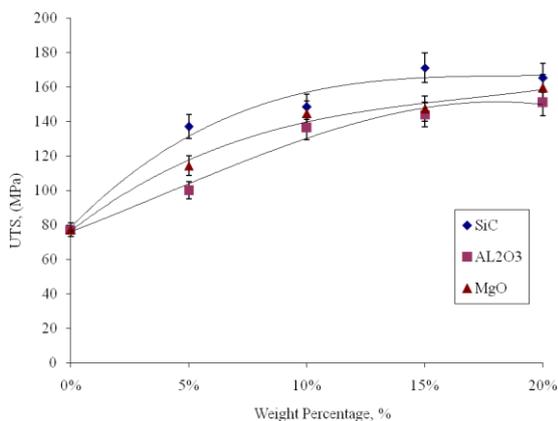


Figure 5: Ultimate tensile strength vs. particulate weight percentage.

The UTS of the composites represent an increase of 121%, 108% and 92% over the corresponding values of the as cast pure Al at ambient temperature for Al-SiC, Al-Al<sub>2</sub>O<sub>3</sub> and Al-MgO respectively.

The increase in UTS of the composites is accompanied by a decrease in strains (ductility) with increasing wt% of the ceramic particulates. The lowest strain was observed in case of Al-SiC MMC, as shown in figure 6. So the retention of the particulates confers an overall embrittling effect on the composites. The increase of UTS of the composites over the pure Al matrix can be related to the interaction between the particulates and dislocations within the matrix, and to the grain refinement of Al with increasing addition of the particulates.

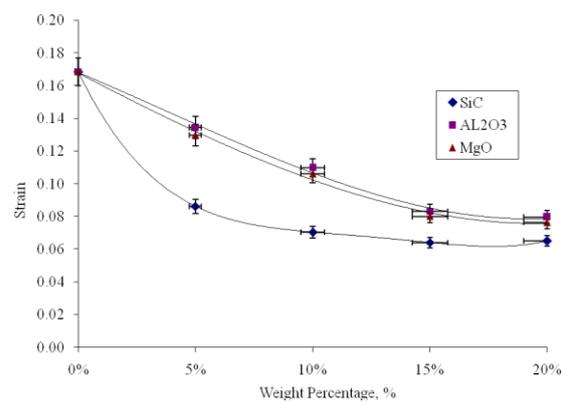


Figure 6: Strain vs. particulate weight percentage.

### 3.1.2. Impact test:

Figure 7 shows the variation of the impact strengths (ak) in Joules (J) for various Al-MMCs with different wt% of the particulates. The results show that the ak value for Al-Al<sub>2</sub>O<sub>3</sub> and Al-MgO MMCs increase slightly in general by increasing wt% of the particulates while in case of Al-SiC MMC the ak decreased slightly by increasing wt% of SiC particulates.

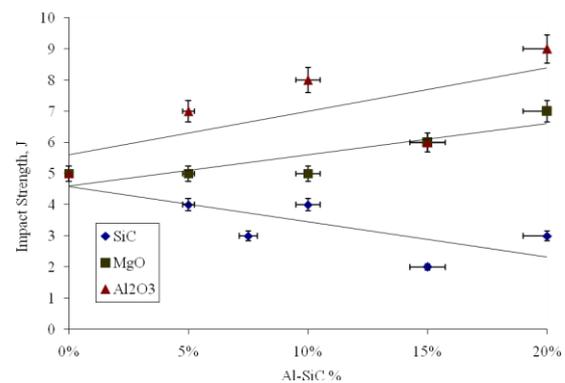


Figure 7: Impact strength vs. particulate weight percentage.

### 3.1.3. Hardness test:

The results of the Brinell hardness measurements are shown in figure 8. It increases with increasing wt% of the particulates used in this work. These increases can be related -as mentioned before- to the interaction of the dislocations with the particulates and grain refinement with increasing wt% of the particulates.

3.2. Microstructure:

Optical microscope was utilized to determine the particulate volume fractions ( $V_f$ ), their distribution in the casting and the grain size of the Al matrix. 1 mm square grid attached to the eye piece of the microscope at a magnification of x50 was used for  $V_f$  determination [16].  $V_f$  was calculated from various parts of the cast and the results are shown in table 2. The results indicate that the  $V_f$  across the casting, horizontally and vertically are quite uniform at various parts of the cast, and the variation of  $V_f$  in horizontal direction is less than that in vertical direction as shown in figures 9 and 10. These results indicate that the method used in the composite preparation was successful and this was reflected in the morphology and relatively uniform distribution of the particulates within the matrix as shown in figures.

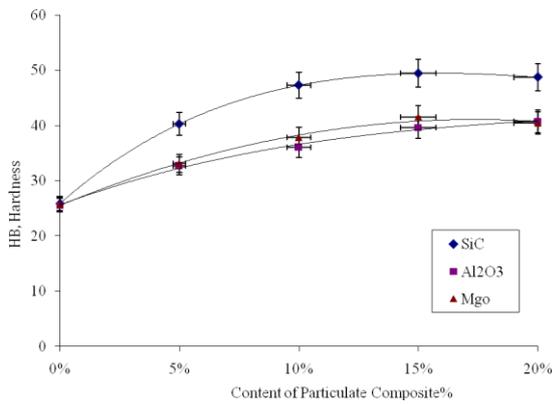


Figure 8: Brinell hardness vs. particulate weight percentage.

Table 2: The volume fraction of different constituents through the specimen horizontally & longitudinally.

	Optimal	Up Edge	Up Center	Mid Edge	Mid Center	Low Edge	Low Center
Al Pure	5.00%	4.41%	4.28%	4.17%	4.20%	3.68%	3.64%
Al-10 wt% Si, 5.0 wt %SiC	7.50%	6.60%	6.47%	6.29%	6.32%	5.81%	5.88%
Al-10 wt% Si, 7.5 wt %SiC	10.00%	8.77%	8.66%	8.29%	8.32%	7.53%	7.35%
Al-10 wt% Si, 10.0 wt %SiC	15.00%	13.35%	13.08%	12.55%	12.59%	11.17%	11.50%
Al-10 wt% Si, 15 wt %SiC	20.00%	17.53%	17.09%	16.81%	16.84%	15.77%	15.14%
Al-10 wt% Si, 20 wt %SiC	5.00%	4.47%	4.34%	4.13%	4.16%	3.88%	4.04%
Al-5 wt %MgO	10.00%	8.87%	8.57%	8.41%	8.45%	7.98%	7.65%
Al-10 wt %MgO	15.00%	13.15%	12.97%	12.47%	12.51%	11.70%	11.80%
Al-15 wt %MgO	20.00%	17.67%	17.47%	16.66%	16.71%	15.37%	15.89%
Al-20wt %MgO	5.00%	4.45%	4.35%	4.17%	4.17%	3.64%	3.77%
Al-10wt% Si, 5.0wt% Al <sub>2</sub> O <sub>3</sub>	10.00%	8.95%	8.67%	8.47%	8.47%	7.35%	7.45%
Al-10wt% Si, 10.0wt% Al <sub>2</sub> O <sub>3</sub>	15.00%	13.13%	12.77%	12.43%	12.43%	11.34%	11.66%
Al-10wt% Si, 15.0wt % Al <sub>2</sub> O <sub>3</sub>	20.00%	17.51%	17.44%	16.66%	16.66%	14.92%	15.74%
Al-10wt% Si 20.0wt % Al <sub>2</sub> O <sub>3</sub>	20.00%	17.67%	17.47%	16.66%	16.71%	15.37%	15.89%

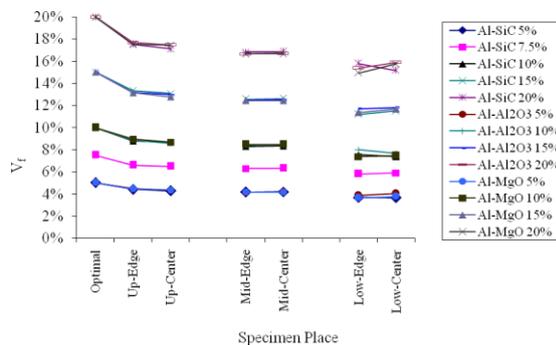


Figure 9: Longitudinal variation of  $V_f$ .

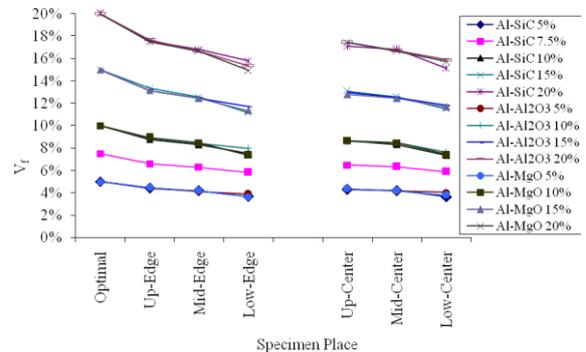


Figure 10: Horizontal variation of  $V_f$ .

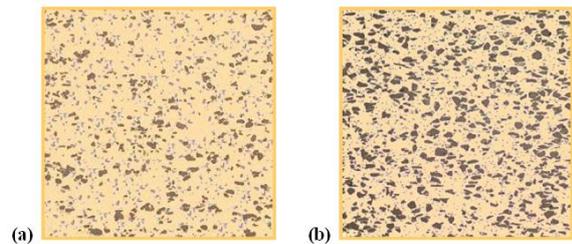


Figure 11: Photographs of MMCs microstructure at X50; (a) Al-10%SiC, (b) Al-20% SiC.

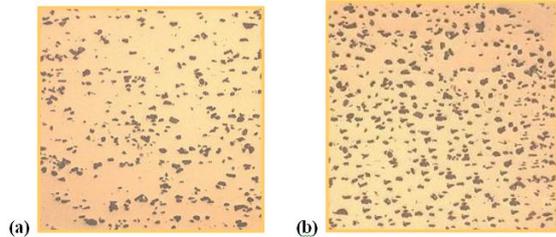


Figure 12: Photographs of MMCs microstructure at X50; (a) Al-10% Al<sub>2</sub>O<sub>3</sub>, (b) Al-20% Al<sub>2</sub>O<sub>3</sub>.

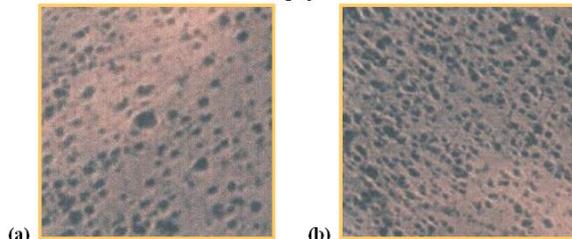


Figure 13: Photographs of MMCs microstructure at X50; (a) Al-10%MgO, (b) Al-20%MgO.

The grain size of the Al matrix was measured by mean lineal intercept method from the same specimens used for  $V_f$  determination. The average grain sizes are given in table 3.

Table 3: The average grain size measured for MMCs.

Alloy	Average Grain Size ( $\mu\text{m}$ )
Al <sub>Pure</sub>	897
Al- 10 wt% Si, 5.0 wt %SiC	107
Al- 10 wt% Si, 7.5 wt %SiC	108
Al- 10 wt% Si, 10.0 wt %SiC	74
Al- 10 wt% Si, 15 wt %SiC	59
Al- 10 wt% Si, 20 wt %SiC	57
Al- 5 wt %MgO	158
Al- 10 wt %MgO	116
Al- 15 wt %MgO	91
Al- 20 wt %MgO	77
Al- 10 wt% Si, 5.0 wt % Al <sub>2</sub> O <sub>3</sub>	179
Al- 10 wt% Si, 10.0 wt % Al <sub>2</sub> O <sub>3</sub>	124
Al- 10 wt% Si, 15.0 wt % Al <sub>2</sub> O <sub>3</sub>	91
Al- 10 wt% Si, 20.0 wt % Al <sub>2</sub> O <sub>3</sub>	86

The average grain size for pure Al in as-cast condition was 897  $\mu\text{m}$ . Addition of the particulates decreased the grain size at rates shown in table 4. the largest decrease was noticed at initial additions of the particulates, namely at 5 wt% in all cases, then the decrease was tapered and at

20 wt% particulate additions the grain sizes were almost constant. The composite grain sizes are finer than that of the monolithic matrix. This refinement is caused by the ceramic particulates acting as nuclei for the grain formation during solidification and at the same time these particulates would inhibit the processes of the grain growth [17]. The greatest effect in refining the grain size was in case of the SiC MMC. Similar observation was seen by [18] where 20% Al<sub>2</sub>O<sub>3</sub> addition produced 90% reduction in the grain size of the composite.

Table 4: Average grain size reduction with increasing different particulate percentages.

%	SiC	Al <sub>2</sub> O <sub>3</sub>	MgO
5%	88%	82%	86%
10%	31%	27%	33%
15%	20%	22%	27%
20%	3%	15%	5%

### 3.3. Effect of Si:

During the fabrication of Al-SiC composite the major problem is the formation of the Al<sub>4</sub>C<sub>3</sub> phase at the SiC/Al interface, because the SiC is thermodynamically unstable in the Al melt. This brittle reactant Al<sub>4</sub>C<sub>3</sub> forms agglomerates at the interface leading to degradation of the composite strength, modulus and corrosion [19],[20]. In this research work, Si was added to the composite to prevent the formation of Al<sub>4</sub>C<sub>3</sub> reactant. The results of the tensile test confirm this statement, although the strains and impact values for Al/SiC are lower than those for Al/Al<sub>2</sub>O<sub>3</sub> and Al/MgO by a small amount as shown in figures 14 and 15 respectively. In general, Si addition reduces the melting point of the alloy, until the eutectic composition of 12.3%Si is reached. This Si addition will increase the fluidity and decrease the viscosity thus enhancing the wettability of the particles which will have positive affect on the particulate distribution and hence on the mechanical properties.

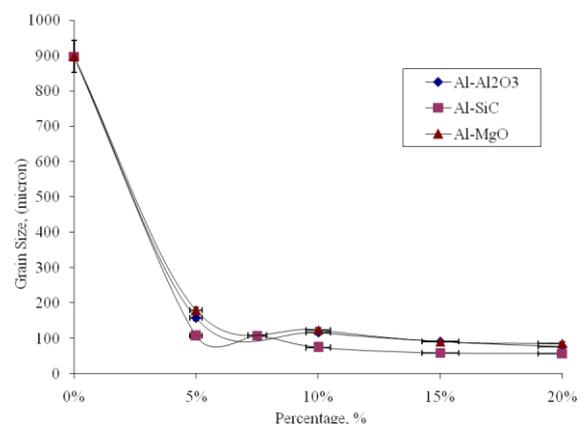


Figure 14: Average grain size of Al-MMCs Al-Si-SiC, Al-Si-Al<sub>2</sub>O<sub>3</sub>, & Al-MgO.

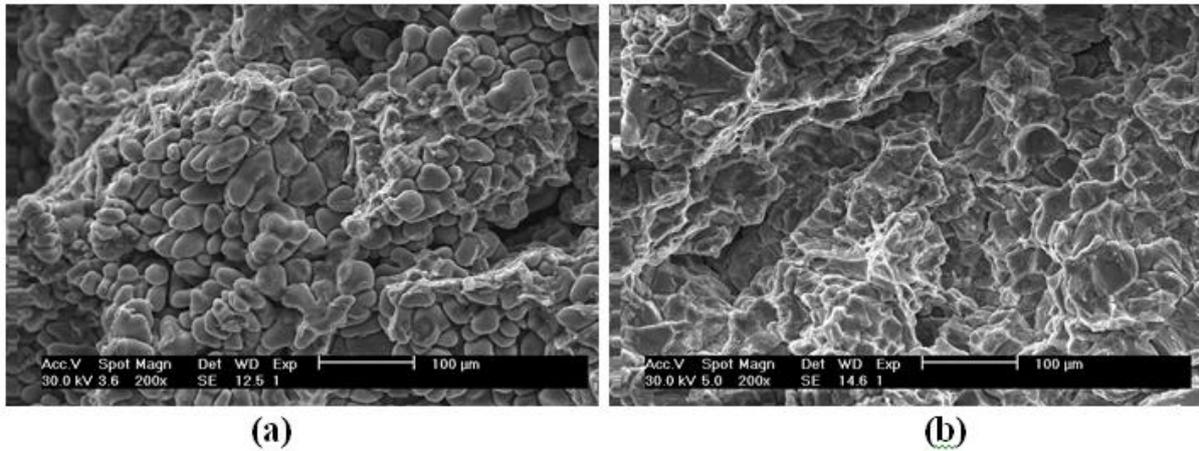


Figure 15: SEM fracture surfaces of pure Al at X200. (a) Tensile. (b) Impact.

### 3.4. Fractography:

SEM observations of fractured matrix of pure aluminum is shown in figure 15. The fractured surface consists of dimpled morphology, revealing ductile fracture of the matrix. However, the fracture surface of the

composites reinforced with SiC, Al<sub>2</sub>O<sub>3</sub>, and MgO particulates essentially consist of a bimodal distribution of dimples, as shown in figure 16, 17, and 18. The micrographs are for 20 wt% of each particulate. The dimples of large sizes are associated with the particulates and the smaller ones are associated with ductile fracture of the matrix.

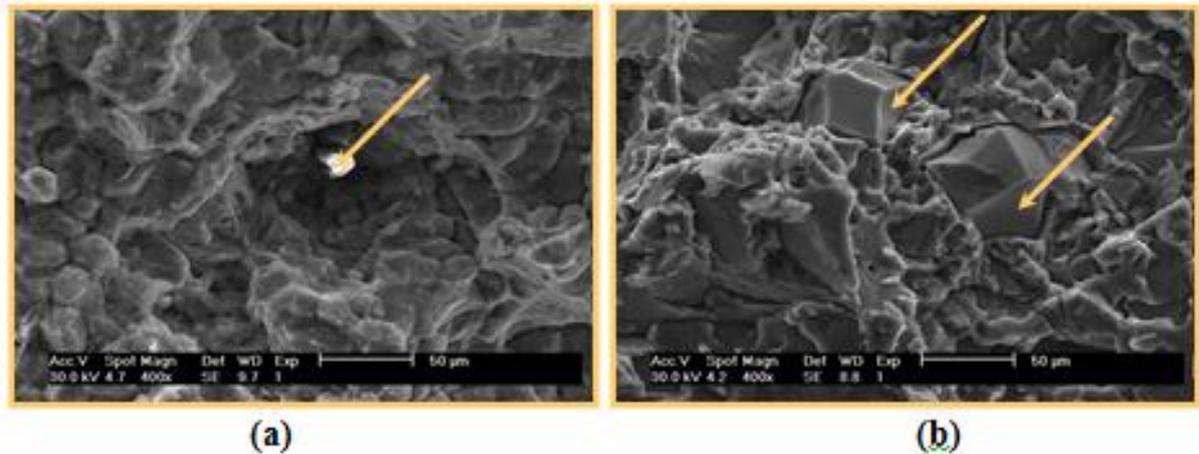


Figure 16: SEM fracture surfaces of Al-20%SiC MMCs at X400. (a) Tensile. (b) Impact.

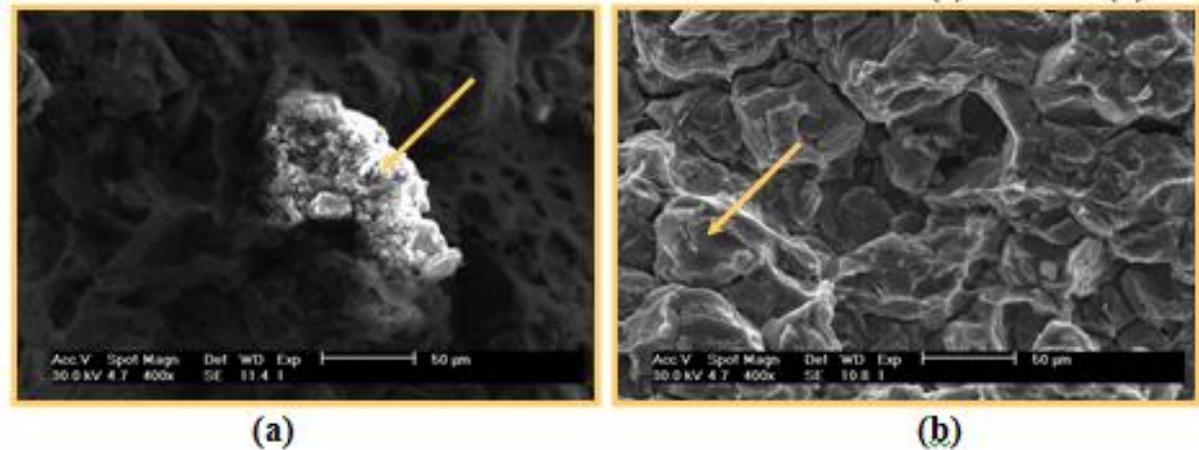


Figure 17: SEM fracture surfaces of Al-20%Al<sub>2</sub>O<sub>3</sub> MMCs at X400. (a) Tensile. (b) Impact.

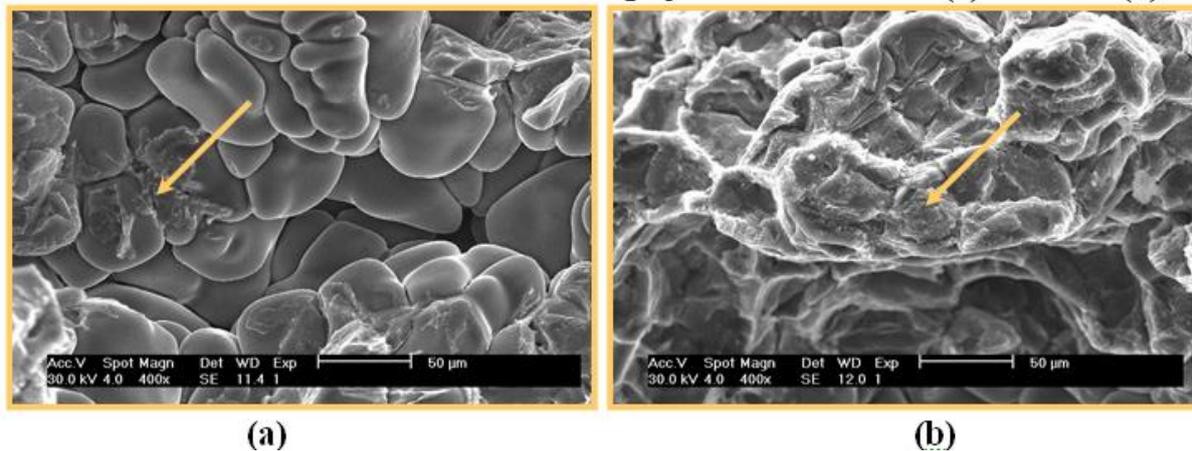


Figure 18: SEM fracture surfaces of Al-20%MgO MMCs at X400. (a) Tensile. (b) Impact.

In most cases the fracture surfaces of the particulates show smooth surfaces indicating that the particulate has fractured rather than decohered, which means that high interfacial strengths dominate in these composites and the composites failed through particulate fracture and matrix ligament rupture, similar observations were reported in the work [17].

#### 4. Conclusion

Addition of SiC, MgO & Al<sub>2</sub>O<sub>3</sub> individually at different percentages to aluminum matrix composite resulted in the following:

- High reduction in grain size of MMCs compared with grain size of the matrix before particulate addition. It is affected by the presence of the particulates in the matrix alloy where they act as grain nucleation sites.
- The addition of SiC, MgO & Al<sub>2</sub>O<sub>3</sub> particulates into the matrix alloy significantly increases the yield strength, the ultimate tensile strength & the hardness, & decreases elongation (ductility) of the composites in comparison with those of the matrix alloy.
- The improvement of mechanical properties by particulate addition & homogeneous distribution depends on wettability of particles with matrix & homogeneous distribution.
- Si addition to matrix before SiC & Al<sub>2</sub>O<sub>3</sub> addition improved wettability & facilitated homogeneous distribution.
- Increasing wt% of SiC, MgO & Al<sub>2</sub>O<sub>3</sub> increases their strengthening effect but SiC is the most effective strengthening particulates, for higher strength, hardness, & grain size reduction. On the other hand, it decreases ductility & toughness.
- The composite reinforced with SiC, Al<sub>2</sub>O<sub>3</sub> & MgO particulates failed mainly through particulate decohesion followed by ductile failure of the matrix, although in some cases particulate fracture was observed.
- One of the important application for Al-SiC and Al-Al<sub>2</sub>O<sub>3</sub> MMC in internal combustion engine, like piston crown, cylinder liners where alumina & carbon

fiber reinforced aluminum have proved a good substitute for cast iron.

- Al-MgO MMC have many applications in structural and industrial purposes, where light weight and high strength-to-weight is needed.

#### 5. Recommendations

Some of the worthwhile investigating parameters:

- Study the effect of stirring speed, stirring time & mixing impeller angle on MMC's homogeneity & mechanical properties. Stirring speed allows vortex formation, & hence penetration of air to the melt increasing oxidation, where low speed decreases stirring efficiency in mixing.
- Study the effect of degasser amount addition on MMC's mechanical properties may be studied.
- The effect of addition of more than one additive on MMC's mechanical properties.
- Study the effect of application of secondary plastic deformation process on the mechanical properties.

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