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Characteristics of Al-Si-Mg Reinforced SiC Composites Produced by Stir Casting Route

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Abstract. Al-Si-Mg alloy that is strengthened by silicon carbide particles has the potential to have excellent mechanical properties with lightweight. In this study, metal matrix composites reinforced silicon carbide from 2 vol-% to 15 vol-% and magnesium amounted to 10 wt-% as an external dopant were fabricated by stir casting route. The magnesium was added to promote the wetting between Al matrix and reinforced SiC. The process involved SiC blended inside the molten Al by a stirrer with a rotational speed of 500 rpm at 800 °C for 2 minutes and degassed with Ar gas for 4 minutes to remove all of the gas content in the molten Al. The molten composite was then cast into the plate and tensile test sample molds. The effect of SiC addition on the mechanical properties and microstructure of the composites was investigated. The result showed that the optimum tensile strength was reached at 8 vol-% SiC with the value of 175 MPa, while the elongation was 9.1%. The maximum hardness and wear rate were achieved at 10 vol-% SiC with the values of 57 HRB and 0.0022 mm$^3$/m, respectively. Such increase was related to the microstructures dominated by the presence of Chinese script, primary and eutectic Mg$_2$Si which were contributed to the mechanical properties of the composites.

Keywords: Al-Si-Mg alloy, SiC, composites, stir casting, mechanical properties

1. Introduction
The recent development of technology requires material properties that cannot be found in metal, polymer, and ceramic. Such properties cover high specific strength, high-temperature creep resistance, and better fatigue strength. Therefore, a composite is made [1,2]. This material will be used for applications that need a high-performance material such as automotive, military, aerospace, and electric industry [3]. To satisfy this need, the demand for Al composites for automotive application has increased from time to time. Therefore, particulate reinforced composites are one of the most common materials used for many industrial applications at this moment. Aluminum is the most favorable materials selected as a matrix to produce aluminum matrix composites (AMCs) in the last two decades [4]. Many applications of AMCs have been established and one of the largest AMCs applications is in the ground transportation sector, such as automotive engine, brake shoe, train brake-lining, etc. Instead of having high wear resistance, it must be lightweight, has a high ultimate strength, hardness, high toughness and low thermal conductivity. Aluminum is the most popular metal that used as matrix due to its low density (2.7 g/cm$^3$) – almost 0.3% of the density of steel (7.83 g/cm$^3$), cuprum (8.93 g/cm$^3$) or bronze (8.53 g/cm$^3$) [5]. Pure aluminum has a low strength with a high ductility, so aluminum must be alloyed with another element such as Cu, Zn, Si, Mg or Mn. Among the aluminum based casting
alloys, Al-Si-Mg alloys are most widely used in automotive industries because of their excellent casting properties accompanied by their superior mechanical properties [6]. Therefore, reinforcing aluminum alloy with SiC particles could considerably enhance their hardness and the ultimate tensile strength but decrease their ductility [7,8]. The strength of composites is also expected to be influenced by the dislocation density, dislocation-to-dislocation interaction and constraint of plastic flow due to the resistance offered by the reinforced particles [9].

Stir casting method is one of the most economical methods to cast Al-SiC composites utilizing Al-SiC liquid stirred by a straight-blade mechanical stirrer [10]. However, there are some disadvantages of stir casting method, such as segregation due to particle settling during casting. This matter could occur because of a different density between the particle and matrix. It is also hard to make homogenous dispersion due to its poor wettability, and the materials tend to agglomerate and result in high porosity content in the final product [11]. Degasification with argon and stirring with correct speed and time will minimize the possibility of a porous content.

The objective of this study was to characterize the microstructure, and mechanical properties of Al-Si-Mg aluminum reinforced SiC composites produced by stir casting method and to observe the effect of various of Vf-% SiC on microstructure and the mechanical properties of the composites was also studied.

2. Experimental Method

2.1 Making of Al-Si-Mg/SiC composite
Aluminum alloy with a chemical composition in Table 1 was used as a matrix, and SiC particles with different sizes from 25-98 μm were used as particles reinforced with various amounts from 2 to 15Vf-% and commercially pure magnesium as a wetting agent with the content of 10 wt-%.

![Figure 1](image1.jpg)
**Figure 1.** The morphology of reinforced SiC particles.

![Figure 2](image2.jpg)
**Figure 2.** Stir casting equipment (a) tilt furnace and stirrer (b) furnace (c) Ar gas.
Table 1. Chemical composition of Al alloy.

|    | Si  | Mg  | Fe  | Cu  | Mn  | Zn  | Ti  | Al  |
|----|-----|-----|-----|-----|-----|-----|-----|-----|
|    | 6.5-7.5 | 0.25-0.45 | 0.2 | 0.2 | 0.10 | 0.10 | 0.20 | Bal. |

Aluminum alloy and magnesium were melted at 800 °C in an electric furnace while the SiC particles were preheated at 1000 °C for 1 hour in a muffle furnace. After the aluminum was fully melted, a de-sludging process was conducted to remove all slag on the surface layer of molten Al. After molten Al was cleaned, then 10 wt-% Mg was added and continue to be stirred for 10 minutes and degassed for 2 minutes to remove oxygen in the molten Al by flushing argon into the furnace. After matrix phase has prepared, it was followed by pouring the preheated SiC powder into the furnace then continue to be stirred at 500 rpm and degassed to remove the possible oxygen in the molten composites (see Figure 2). Afterward, the molten composite was casted into the tensile test mold.

2.2 Characteristic of Al-Si-Mg/SiC composite
The mechanical properties of composites were measured, including the tensile strength, hardness, and wear resistance. Tensile testing was carried out using GOTECH Al-7000 LA 10 in accordance with ASTM E8M-09. The tensile test was carried out using three specimens for each variable. Hardness testing was carried out using a Rocky machine with Rockwell B method in accordance with ASTM E18-11. For each sample, five hardness readings were taken on the randomly selected regions in order to eliminate the segregation effects and to get a representative value of the matrix material hardness. Wear testing was carried out using Ogoshi method with the following parameter: 12.6 kg load (P₀), 400 m sliding distance (l₀), and 1.97 m/s sliding speed. The samples were then ground using SiC paper #80 before testing. The thickness of disk employed in this testing was 3 mm, with a radius (r) of 10 mm. The metallographic preparation was conducted by grinding using emery paper started from #80, #150, #240, #400, #600, #800, #1000, #1200 to #1500, and was then polished using TiO₂. Keller’s reagent (2 ml HF (conc.), 5 ml HNO₃ (conc.), 3 ml HCL and 190 ml distilled water was used as an etching agent. All sample preparations were observed using OLYMPUS BX41M-LED optical microscope and were further analyzed using Field Emission Scanning Electron Microscope (FESEM) linked to Energy Dispersive Spectrum (EDS) by INSPECT F50 FE-SEM, and phase identification was examined by X-ray diffraction (XRD).

3. Results and Discussion

3.1 Microstructural Observation of Al-Si-Mg reinforced SiC composites
The microstructures of composites with the different volume fraction of SiC are shown in Figure 3. The microstructures were mainly composed of α-Al, eutectic silicon and randomly distributed SiC particles. The dendritic structure in the Al matrix cannot clearly be seen. The SiC particles in the matrix could act as an obstacle for the dislocation movement that will improve the mechanical properties of the composites. When a higher SiC in matrix generated more interface layer in the composite that will transmit the load from the matrix to the reinforcement, the mechanical properties were improved. The second phase particles in the aluminum matrix were also found during the solidification, and according to EDS, the phases which were present in the composites were Mg₃Si and MgO·SiO₂ (Figure 4 and Table 2). The presence of the phases in the composites was also confirmed by XRD results illustrated in Figure 6. The porosity formation in microstructure occurred when the molten composite was stirred for a longer stirring time which can increase the number of air bubbles entrapped into the molten metal and SiC particles which were prone to associate with these bubbles and remaining pores (Figure 5). Porosity or void also occurred at the interface between Al matrix and SiC particles since the wetting system was poor, while the shrinkage porosity took place during the solidification due to the different melting points of the element content in the aluminum matrix [12].
Figure 3. Optical microstructure of Al-Mg-Si /SiC composites with:
(a) 2% SiC; (b) 5% SiC; (c) 8% SiC; (d) 10% SiC; and (e) 15% SiC

Table 2. Element content from points in Figure 4 analyzed by EDS

| Point | Elements content (wt%) | Possible phase |
|-------|------------------------|----------------|
|       | Al  | Si  | Mg  | C  | O  | Sn | N  | Fe |                  |
| 1     | 90.59 | -  | 1.97 | 4.69 | 2.04 | 0.49 | -  | 0.23 | α-Al               |
| 2     | 48.99 | 31.93 | 2.3  | 8.25 | 6.23 | 1.23 | 1.07 | -    | MgO, SiO₂          |
| 3     | 35.74 | 19.31 | 26.88 | 5.25 | 11.4 | 0.42 | 0.99 | -    | Mg₂Si              |

According to SEM-EDS analysis results as demonstrated in Figure 4 and Table 2 which were confirmed by XRD patterns especially for composite with 8 wt-% SiC, there was obtained Mg₂Si phase in composites, besides Al and SiC which were the base materials of sample. In the previous experiment conducted by Pawlik et al. [13], they have shown that many Mg₂Si particles were created around the matrix and SiC. This Mg₂Si precipitated from silicon content in alloy itself reacted with Mg and could also, Mg₂Si precipitate produced by free Si from the reaction product of SiO₂ reacted with an excess of Mg in the Al alloy [14]. During the preoxidized process of the SiC particles, the SiO₂ layer formed on the surface of SiC particles could react with the molten Al-Mg-Si alloy to produce MgAl₂O₄ which was frequently surrounded by the solidification product. Other important compounds that were reported in this alloy were MgAl₂O₄ and MgO.SiO₂ as interface layer products. MgO associated with SiO and MgAl₂O₄ were also formed in Mg-containing alloy, but MgO occurred at a higher Mg concentration and more stable at a higher temperature than that of MgAl₂O₄ [15]. It was also found that other precipitates such as Al₂Cu, MgZn₂ and Al₄C₃ were also influencing the mechanical properties of the composites.
3.2 Mechanical properties of Al-Si-Mg reinforced SiC composites

The effect of Vf% SiC on tensile strength and elongation is shown in Figure 7. The addition of SiC into Al matrix could increase the tensile strength of Al-Si-Mg matrix compared to the matrix without SiC. It could be noted that there were an enhancement strength and an elongation with the addition of SiC particles of up to 8 Vf-% SiC, then gradually decreased with the addition of SiC. Dwidevi et al. [7] and Amirkhanlou et al. [16] reported that an addition of SiC particles would increase the tensile strength continuously until it reached the optimum value and decreased due to the porosity created in the final product. Porosities in Figure 5 generated stress concentration in that spot in a matrix which could act as a source of cracking nucleation and decrease the total loading area [12]. On the other hand, the highest ultimate strength was found at 8 Vf-% SiC due to the uniform particle dispersion that can impede dislocation movement [8]. The uniform distribution of SiC particles in the aluminum matrix will also have a good effect on its mechanical properties.

However, the ductility of the composites which deteriorated significantly with a high SiC particle concentration displayed on Figure 7b, but the elongation increased with a higher SiC content of up to 8 Vf-%, this value was quite odd since the optimum strength generated an optimum elongation in this composites, where both properties should have the opposite correlation. Current research showed an in-line correlation between tensile strength and elongation, see Figure 7a and Figure 7b. It was due to ceramic solid phase addition in a matrix that would resist the dislocation movement. This experiment might be different from a study reported by V. S. Aigboidon et al. [8]. They said that low elongation occurred because of much porosity in a final product that generated a low tensile strength. This matter indicated that a crack at composites could be the main factor which would weaken the mechanical behavior.

Figure 5. Porosity formation in the Al-Mg-Si / SiC composites.
Figure 6. XRD pattern of Al-Mg-Si composites with 8 Vf-% SiC.

Figure 7. Effect of SiC on ultimate tensile strength (a) and elongation (b) of Al-Mg-Si/SiC composite.

Figure 8. Effect of SiC on hardness (a) and wear rate (b) of Al-Mg-Si/SiC composite.
The hardness increased as the percentage of SiC particles addition in the alloy was increasing, as can be seen in Figure 8a. It was due to the increasing percentage of a hard and brittle phase of ceramic in the matrix [8]. SiC particles acted as an obstacle to dislocation movement so the dislocation density at the interface layer would increase. The difference of CTE (SiC $3 \times 10^{-6}$ °C$^{-1}$ and Al $23 \times 10^{-6}$ °C$^{-1}$[15]) as somehow the source of the step-up of dislocation density result in an elastic and plastic incompatibility between the matrix and the reinforcement. Hence, there was an improvement in the mechanical properties. The weakening factor might be contributed to a decreasing hardness at composites with 15 Vf-% SiC due to the formation of porosity. In the casting process, some SiC particles which were not mixed and wetted completely would stay at the bottom of the crucible. It showed that the shearing action of the stirrer blades to the liquid was weak and the inclining blade slightly generated the rising movement of SiC particles, and the centrifugal movement of SiC particles was tiny, respectively [17].

Figure 8b shows the wear rate of Al-SiC composites with different volume fractions of SiC. It was obtained that the addition of SiC into matrix generated an improvement in wear resistance compared to the unreinforced alloy. Since the interface layer is the most important role in a composite, the reinforcement should be well bonded to the matrix in order to enhance the mechanical behavior [18]. It is known that the wear rate is inversely proportional to the hardness of alloys. In the case of unreinforced Al alloy, the depth of penetration is governed by the hardness of specimen surface and applied load. However, in the case of Al composite, the depth of penetration by the harder asperities of hardened steel disk is primarily governed by protruded hard ceramic reinforcement [19]. In another word, in unreinforced Al alloy, the wear resistance is influenced by stick-formed silicon particles that were created as a result of eutectic reaction during the alloy solidification [20]. A higher wear resistance in the composite was controlled by SiC particles which act to reduce the wear rate by lowering the real contact area [21]. High wear resistance is also influenced by MgOSiO$_2$ [22] and MgAl$_2$O$_4$ [23] spinel at the interface layer. A good spinel layer can minimize particle pull-out that may occur during the preparation and the wear test [24].

3.3 Fractography

The fracture surface of the composites was analysed by scanning electron microscope to investigate whether the material remains ductile since the reinforced particles can change the properties of composites become less ductile. Following the results in Figure 7b, the elongation or ductility or materials increased up to 8 Vf-% SiC as well as the ultimate tensile strength. It is quite strange results where tensile strength and elongation have a reverse correlation. In general, the failure in composites is due to three different sources, namely the matrix/reinforcement interfacial decohesion, reinforcement fracture and matrix failure [25].

The typical SEM micrograph of fracture surface for composites with 8Vf-% SiC is shown in Figure 9. It indicated a combination mode of fracture, between the dimples on the matrix and SiC particles
decohesion. In the center of the sample, it was clearly shown facets which simply indicated a brittle fracture. Furthermore, there were cracked particles that would act as the microcrack initiators during the deformation[26]. It could occur because the interfacial cohesion between the SiC particles and matrix was strong enough. Therefore, it was no wonder for the composite with 8 Vf-% SiC to have the highest tensile strength and good ductility. Strong interfacial cohesion can improve both strength and plasticity of the composite since weak interface will nucleate microcracks at a rather low external applied stress [25]. However, on the edge of the sample, fractography showed dimples which indicated plastic deformation. These dimples may be a result of void nucleation and subsequent coalescence by strong shear deformation and fracture process on the shear plane during a tensile test.

4. Conclusion
It can be concluded that the addition of the reinforced SiC particles improves the mechanical properties of the composites such as strength, elongation, hardness, and wear resistance of up to 8 Vf-%. Furthermore, the ductility of the composites deteriorated significantly with the increase of SiC particles concentration. It was due to the presence of phases in composites contained of MgO, SiO₂ and Mg₂Si in the form of Chinese script and primary Mg₂Si. Meanwhile, the wettability of composite was good enough. It was confirmed by the fractography image that showed the bonding cohesive between particle and matrix was good as the presence of the MgAl₂O₄ or spinel phase in the interface.

5. References
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