Investigation on the Mechanical Properties of A356 Alloy Reinforced AlTiB/SiC\textsubscript{p} Composite by Semi-Solid Stir Casting Method

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Abstract. Employing the semi-solid stir casting method to strengthen MMCs by SiC\textsubscript{p} particle was the simplest way in the casting process. The strength and toughness of a composite material can be obtained through a combination of the A356 / Al7Si composites and SiC\textsubscript{p} particle. The purpose of this study was to investigate the difference in the mechanical properties of Al\textsubscript{7}Si\textsubscript{1}Mg\textsubscript{1.5}TiB/SiC\textsubscript{p} and Al\textsubscript{7}Si\textsubscript{1}Mg/SiC\textsubscript{p} composites, as well as the changing effects on the extra level of SiC\textsubscript{p} particle. Al-Si was used as matrix strengthened by SiC\textsubscript{p} with the percentage variations of 10, 15, 20 wt%. The additional level of 1.5 wt% AlTiB aimed for increasing the matrix grain refinement. The semi-solid stir casting method was performed to spread the SiC\textsubscript{p} particles evenly in the liquid matrix. The results of the study were the tensile strength value of as much as 143 MPa or the increase of 22.16%. The biggest yield strength on the Al\textsubscript{7}Si\textsubscript{1}Mg\textsubscript{1.5}TiB/SiC\textsubscript{p} composite was averagely as much as 106 MPa. The highest impact toughness was averagely amounted to 4.74 J/mm\textsuperscript{2}. The lowest porosity value was averagely 2.10%. The morphology of the composite between the reinforcing particle and the matrix was able to unite and to be dispersed evenly. The present study was conducted through density test, tensile test, impact test, microstructure test, and SEM.

Keywords: Mechanical properties, A356 Alloy, Semi-solid stir casting

1. Introduction
Recently, the development of Metal Matrix Composites (MMCs) in science and technology is considered a critical need. The Al-Si composite has a major role in the field of aluminum composite casting. The material has been widely used in the production of automotive, planes, outer space materials and industrial construction because of its excellent resistance. The composite material can be welded easily, and it is resistant towards high corrosion, and it also has other superior properties [1-2].

The production of MMCs combines the aluminum composite of A356 / Al-Si as matrix and the particle of ceramics silicon carbide (SiC\textsubscript{p}) as the reinforcement. The addition of the composite of Titanium Diboride (TiB) as the grain refiner is performed because its property could increase the metal strength and toughness [3]. SiC\textsubscript{p} is employed as the reinforcement because it has an excellent mechanical property with the density of 3.2 g/cm\textsuperscript{3}, the yield strength of 600 MPa, the hardness of 2480 Knop (2170 HB), and the modulus of elasticity of 400 GPa, and it does not cause oxidation on metal
The A356 composite has several strengths such as having light property (density of 2.7 g/cm³), the yield strength of 172 MPa, and the corrosion resistance. Nevertheless, it has low level of hardness of as much as 60 HB [5]. Moreover, Mg (1 wt%) is added to improve the wettability of Al-Si matrix towards SiCₚ particle. The function of improving the wettability is to wet the entire surface of the reinforcing particle that may affect an increase on the strength of matrix bond with the SiCₚ particle [6-7].

The results of the study about AlSi₃Mg₂ matrix reinforced by SiC (5-15 wt.%) indicated the attained maximum tensile strength on SiC (10 wt.%) was as much as 280MPa. The hardness value increased on SiC (15 wt.%), i.e. that was 98HB, was increased of as much as 48% [8]. The employment of A356 matrix, the reinforcing SiC particle and the graphite with the SiC (0-9 wt.%) could cause the maximum hardness value on SiC (9 wt.%) of as much as 144VH. However, in this case, the hardness increased, but the elongation decreased [9]. In the case of Al6062 Matrix with the reinforcing particles (5, 10, 15, 20 wt.%), the results of the study showed that the highest hardness value was attained on SiC (20 wt.%), that was 83 HRB [10]. A study about the employment of 98.41% Matrix with the SiC reinforcing particles (5, 10, 15, 20, 25, 30 wt.%) indicated that the best hardness value was obtained on the SiC percentage of 25%; that was 45.5 BHN [11]. A study investigating AlTiC and AlTiB with variations of 0.2%, 0.5%, and 1% showed that the addition of 1% TiB caused the grain size to become smaller [12]. The Al7178 composite with the variations of TiB (1, 2, 3, 4 wt.%) indicated that, with the addition of TiB between 1-4 wt.%, the grains underwent a significant decrease with the addition of 1 wt.% TiB; that was as much as 140 µm, on 4 wt.% to be 55 µm [13]. A study employing the AlTiB master alloy with the variation from 0.03% to 0.15% indicated that the smallest grain size was 50 µm, attained on the variation of 0.13 % TiB [14].

The mixing process of the SiCₚ ceramic particle in the liquid matrix of aluminium composite has two main weaknesses. First, the SiCₚ particle of which surface is not usually wetted by liquid matrix. Second, the SiCₚ particle tends to settle or float on the liquid matrix surface. It may cause an uneven distribution of SiCₚ particles on the matrix surface [6]. The study conducted by employing the semi solid stir casting was aimed to ease the mixing process of SiCₚ particle into the liquid matrix [15]. The purpose of this study was to investigate the differences in the mechanical properties of Al-Si₃Mg/SiCₚ composite and Al-Si₃Mg₅₄TiB/SiCₚ composite as well as the changing effects toward the addition of SiCₚ particle. This present study employed the semi solid stir casting method.

2. Experimental Method

The experiment of composite Al₃Si₃Mg/SiCₚ and Al₃Si₃Mg₅₄TiB/SiCₚ composites was done by employing the semi solid stir casting method. In this case, the A356 / Al₃Si alloy played a role as matrix. Besides, 1 wt.% Mg was used to incerase the wettability. Then, 1.5 wt.% of TiB was added to refine the grains on the matrix. Next, The SiCₚ played a role as the reinforcement on the Al₃Si matrix. The variations of SiCₚ employed are 10, 15, 20 wt.%. Table 1 below shows the compositions of chemical materials used.

| Materials               | Chemical composition (%) |
|-------------------------|--------------------------|
|                         | Al  | Si  | SiCₚ | Fe  | Ti  | B   | Mg  | Mn  | Other |
| Al₃Si / A356 (ingot)    | 92.39| 7.26| -    | 0.147| -   | -   | 0.07| 0.008| 0.125 |
| Mg (ingot)              | 0.022| 0.013| -    | 0.003| -   | -   | 99.93| 0.012| 0.02  |
| AlTiB (ingot)           | 93   | 0.16| -    | 0.16 | 5.00| 0.98| -   | -   | 0.05  |
| SiCₚ (powder)           | 0.03 | -   | 98.6 | 0.1 | -   | -   | 0.03| -   | 1.24  |

There were several steps conducted during the casting process. First, preparing the materials to be casted, including Al₃Si, Mg, and AlTiB. Then, those materials were cut by machine according to the variations of the casting compositions. After that, the materials were set aside to get the wt.%
composition set. The variations of the casting compositions could be seen on Table 2. Then, the Al\(_7\)Si, Mg, and Al-TiB were added to the electric furnace stir casting shown in Figure 1a.

| Composition (wt.%)          | Al\(_7\)Si (gram) | Mg (gram) | AlTiB (gram) | SiC\(_p\) (gram) | Total (gram) |
|-----------------------------|-------------------|-----------|--------------|------------------|--------------|
| Al\(_7\)Si\(_7\)Mg/SiC\(_p\) 0% | 990               | 10        | -            | -                | 1000         |
| Al\(_7\)Si\(_7\)Mg/SiC\(_p\) 10% | 890               | 10        | -            | 100              | 1000         |
| Al\(_7\)Si\(_7\)Mg/SiC\(_p\) 15% | 840               | 10        | -            | 150              | 1000         |
| Al\(_7\)Si\(_7\)Mg/SiC\(_p\) 20% | 790               | 10        | -            | 200              | 1000         |
| Al\(_7\)Si\(_7\)Mg\(_{1.5}\)TiB/SiC\(_p\) 0% | 975               | 10        | 15           | -                | 1000         |
| Al\(_7\)Si\(_7\)Mg\(_{1.5}\)TiB/SiC\(_p\) 10% | 875               | 10        | 15           | 100              | 1000         |
| Al\(_7\)Si\(_7\)Mg\(_{1.5}\)TiB/SiC\(_p\) 15% | 825               | 10        | 15           | 150              | 1000         |
| Al\(_7\)Si\(_7\)Mg\(_{1.5}\)TiB/SiC\(_p\) 20% | 775               | 10        | 15           | 200              | 1000         |

**Figure 1.** (a) Electric furnace stir casting, (b) Temperature vs. time semi solid stir casting process

Then, they were heated to the temperature of 800 °C to get a liquid state. On the other hand, the temperature was lowered to 590 °C to get a semi solid state. Meanwhile, the SiC\(_p\) particle was heated separately inside an electric oven at a temperature of 400 °C for 120 seconds. After that, the SiC\(_p\) was added to the electric furnace stir casting and stirred thoroughly by using a mechanical mixer. The mixing speed of the mixer was 500 rpm for 180 seconds. The metal mold was also heated to the temperature of 300 °C. After all materials were mixed and stirred in semi solid state, the temperature was increased to 750 °C to get a casting condition. The casting product was refrigerated at room temperature of 36 °C which could be seen in Figure 1b, the graphic of semi solid temperature vs. time. After that, the composite was cut according to the test specimen. The composite specimen was tested by employing density test, tensile test, impact test, and microstructure photo and SEM. Figure 2 below illustrates the specimen of casting product.
3. Results and Discussion

3.1. Density and Porosity

The specimens for the density test had the size of 2 x 2 x 2 cm by using a VIBRA digital balance. The density test results and its measurement on the porosity of Al$_7$Si$_1$Mg/SiC$_{p}$ and Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_{p}$ composites are shown on Table 3.

| Composites (wt.%) | $\rho_{\text{actual}}$ (g/cm$^3$) | $\rho_{\text{theoretical}}$ (g/cm$^3$) | Porosity |
|-------------------|-----------------------------|---------------------------------|-----------|
| Al$_7$Si$_1$Mg/SiC$_{p}$ 0%  | 2.63                        | 2.66                           | 1.50      |
| Al$_7$Si$_1$Mg/SiC$_{p}$ 10% | 2.65                        | 2.71                           | 2.58      |
| Al$_7$Si$_1$Mg/SiC$_{p}$ 15% | 2.66                        | 2.72                           | 2.57      |
| Al$_7$Si$_1$Mg/SiC$_{p}$ 20% | 2.69                        | 2.76                           | 2.89      |
| Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_{p}$ 0% | 2.64             | 2.68                           | 1.49      |
| Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_{p}$ 10% | 2.65             | 2.73                           | 2.19      |
| Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_{p}$ 15% | 2.67             | 2.76                           | 2.22      |
| Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_{p}$ 20% | 2.70             | 2.78                           | 2.51      |

The graphics of the density and porosity of the Al$_7$Si$_1$Mg/SiC$_{p}$ and Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_{p}$ composites are shown on Figure 3.

![Figure 2. Casting Product Composite](image)

![Figure 3. Graph (a) composite density, (b) composite porosity](image)

The density graphic indicated that the Al$_7$Si$_1$Mg/SiC$_{p}$ composite underwent an average increase of 1.2%. Whereas, the Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_{p}$ composite went through a decrease on the variation of SiC$_{p}$.
of 15 wt.%, and increased of as much as 1.4% on the variation of SiC_p of 20 wt.%. Figure 3b showed that the porosity of the Al_7Si_1Mg/SiC composite increased averagely of as much as 28 %. Whereas, the Al_7Si_1Mg_1.5TiB/SiC_p composite decreased on the variation of SiC_p (15 wt.%), and then, increased of as much as 10.9% on the variation of SiC_p (20 wt.%). On the process of stir casting, the porosity might potentially occur. This occurrence may be caused by the chemical reaction between matrix and reinforcing particle, so that it may result in the trapped gas during the mixing process. Consequently, the more the number of SiC_p, the more the gas reaction occurs leading to the porosity tendency to increase. These results, according to the results of previous research, indicated that porosity may potentially occur in the process of stir casting because of the chemical reaction between the reinforcing particle and matrix which caused gas, as well as gas which was trapped during the stirring process [6]. The addition of 1% Mg could reduce the porosity. Therefore, Mg would reduce the layer of SiO_2 on the surface of SiC_p, and form MgAl_2O_4 with high wettability on the interface [16]. The porosity formed on the interface of matrix and reinforcing particles would disappear or get reduced [17].

### 3.2. Tensile Test

The tensile strength was acquired from the measurement of maximum load divided by cross-sectional area of tensile test specimen. The tensile test was conducted according to the testing standard of ASTM E 8M-04 [18]. The following Table 4 presents the result of the tensile test.

| Composites (wt.%) | \(\sigma_u\) (MPa) | \(\sigma_y\) (MPa) | %EL |
|-------------------|-------------------|-------------------|-----|
| Al_7Si_1Mg/SiC_p 0% | 77                | 64                | 1.01|
| Al_7Si_1Mg/SiC_p 10% | 106               | 94                | 1.21|
| Al_7Si_1Mg/SiC_p 15% | 116               | 102               | 1.64|
| Al_7Si_1Mg/SiC_p 20% | 125               | 107               | 2.41|
| Al_7Si_1Mg_1.5TiB/SiC_p 0% | 93              | 82                | 1.16|
| Al_7Si_1Mg_1.5TiB/SiC_p 10% | 120             | 94                | 1.86|
| Al_7Si_1Mg_1.5TiB/SiC_p 15% | 134             | 116               | 2.46|
| Al_7Si_1Mg_1.5TiB/SiC_p 20% | 143             | 132               | 2.98|

The effect of SiC_p percentage to the tensile strength of Al_7Si_1Mg/SiC_p and Al_7Si_1Mg_1.5TiB/SiC_p composites is shown in Figure 4.
Figure 4. Graph (a) Tensile strength, (b) Yield strength, (c) Elongation of Al7Si1Mg/SiCp and Al7Si1Mg1.5TiB/SiCp Composites

Figure 4a The graphic of tensile strength of Al7Si1Mg/SiCp composite was bigger than Al7Si1Mg1.5TiB/SiCp composite with the difference of average of 16.18%. The strength of Al7Si1Mg1.5TiB/SiCp composite increased on the variation of SiCp of 10 wt.% of as much as 120 MPa and on variation of SiCp of 20 wt.% became 143 MPa, or improved of as much as 22.16%. For the Al7Si1Mg/SiCp composite, the tensile strength was increasing on the variation of SiCp of 10 wt.% of as much as 106.84 MPa, and on the variation of SiCp of 20 wt.% became 125 MPa, or as much as 19.01%. The addition of 1.5% TiB could increase the tensile strength. Figure 4b indicates that the biggest yield strength was on the Al7Si1Mg1.5TiB/SiCp composite, which was as much as 106 MPa. The difference on the yield strength of the Al7Si1Mg/SiCp and Al7Si1Mg1.5TiB/SiCp composites was of as much as 14 MPa. The yield strength of the Al7Si1Mg1.5TiB/SiCp composite was bigger than that of the composite with Al7Si1Mg/SiCp matrix. It could be concluded from Figure 4c that the strain between the Al7Si1Mg/SiCp and Al7Si1Mg1.5TiB/SiCp composites increased with the difference of as much as 0.55%EL. The strain on the Al7Si1Mg/SiCp composite was averagely 1.56%EL, whereas the strain of the Al7Si1Mg1.5TiB/SiCp composite was averagely 2.11%EL. The force on the Al7Si1Mg1.5TiB/SiCp composite was bigger than that on the Al7Si1Mg/SiCp composite. It was based on the discovery of the previous researchers that the extra level of TiB with certain percentage would repair the grain structure of the composites [10,19].

3.3. Impact Test
The impact test was conducted according the standard of ASTM E-23 02a [20]. The test results could be seen on Table 5.
Table 5. Results of impact test

| Composites (wt.%) | Load of hitter (Kg) | Impact value (J/mm²) |
|-------------------|---------------------|----------------------|
| Al₇Si₁Mg/SiCₚ 0%  | 1                   | 4.43                 |
| Al₇Si₁Mg/SiCₚ 10% | 1                   | 3.93                 |
| Al₇Si₁Mg/SiCₚ 15% | 1                   | 4.93                 |
| Al₇Si₁Mg/SiCₚ 20% | 1                   | 5.46                 |
| Al₇Si₁Mg₁.₅TiB/SiCₚ 0% | 1 | 4.56               |
| Al₇Si₁Mg₁.₅TiB/SiCₚ 10% | 1 | 6.06               |
| Al₇Si₁Mg₁.₅TiB/SiCₚ 15% | 1 | 4.73               |
| Al₇Si₁Mg₁.₅TiB/SiCₚ 20% | 1 | 5.63               |

The graphic of relationship between the impact value and the percentage variation of SiCₚ is shown in Figure 5.

The impact value of Al₇Si₁Mg₁.₅TiB/SiCₚ composite was higher than that of Al₇Si₁Mg/SiCₚ composite. On the Al₇Si₁Mg₁.₅TiB/SiCₚ composite, the impact value for the variations of SiCₚ of 10, 15, and 20 wt.% increased averagely of 4.74 J/cm². On the Al₇Si₁Mg/SiCₚ composite with 10, 15, 20 wt.% variations of SiCₚ, the impact price increased averagely of 4.68 J/cm². The difference between Al₇Si₁Mg/SiCₚ and Al₇Si₁Mg₁.₅TiB/SiCₚ composites was of as much as 0.06 J/cm². The highest impact value was found on the Al₇Si₁Mg₁.₅TiB/SiCₚ composite. The extra level of TiB could bear a bigger impact load.

3.4. Micro Structure
The micro structure test was conducted by employing an Olympus optical microscope. The results of micro-photos of Al₇Si₁Mg/SiCₚ and Al₇Si₁Mg₁.₅TiB/SiCₚ composites are shown on Figure 6.
Figure 6. Micro photos of: (a) 0% Al$_7$Si$_1$Mg/SiC$_p$, (b) 0% Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_p$, (c) 10% Al$_7$Si$_1$Mg/SiC$_p$, (d) 10% Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_p$, (e) 15% Al$_7$Si$_1$Mg/SiC$_p$, (f) 15% Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_p$, (g) 20% Al$_7$Si$_1$Mg/SiC$_p$, (h) 20% Al$_7$Si$_1$Mg$_{1.5}$TiB/SiC$_p$ composites

It could be seen in Figure 6 that the higher the level of SiC$_p$ in the composite, the more SiC$_p$ was bound in the matrix. On the Al$_7$Si$_1$Mg/SiC$_p$ composite, the Si was the grey substance with irregular
round grains. Figure 8 b, d, f, and h show the AlSi1Mg1.5TiB/SiCp composite in the form of black-colored fine grain boundaries. Finer grains on that composite were also noticed. The SiCp particle was dispersed randomly and evenly in the Al7Si1Mg/SiCp matrix as well as Al7Si1Mg1.5TiB/SiCp matrix. The more SiCp was dispersed, the harder the composite could be. It was based on the previous study by Hashim et al. (2001) and Lin et al. (2010) that indicated that the employment of semi solid stir casting may help increasing the wettability and dispersing the reinforcing particle homogenously [7].

3.5. Morphology

The test of Scanning Electron Microscopy (SEM) is known to be able to measure the spread of SiCp particle in the Al7Si matrix. The SEM observation result was on the form of morphology with 10.000x magnification in which it produced SEM photos of AlSi1Mg/SiCp and AlSi1Mg1.5TiB/SiCp which are shown on Figure 7 below.

![SEM Composite: The morphology](image)

Figure 7. SEM Composite: The morphology (a) 20 wt.% Al7Si1Mg/SiCp (b) 20 wt.% Al7Si1Mg1.5TiB/SiCp, the spread of SiCp particle (c) 20 wt.% Al7Si1Mg/SiCp (d) 20 wt.% Al7Si1Mg1.5TiB/SiCp

Figure 7a shows the morphology of Al7Si1Mg/SiCp and Al7Si1Mg1.5TiB/SiCp composites between the reinforcing particle and matrix that could be united. On the Al7Si1Mg/SiCp composite, the SiCp particle was found around the interlocking Al7Si matrix. Figure 7b demonstrates the Al7Si1Mg1.5TiB/SiCp composite noticed between the SiCp and Al7Si matrix which was mixed thoroughly. The extra level of TiB changed the particle forms to be finer.

4. Conclusion

In the present study, the researchers derived several conclusions as follow: The morphology of the Al7Si1Mg/SiCp and Al7Si1Mg1.5TiB/SiCp composites between the reinforcing particle and matrix could be united and dispersed evenly. The effect of SiCp wt.% was noticed from the value of tensile strength from two kinds of composites. The Al7Si1Mg1.5TiB/SiCp composite went through an increase on the variation of SiCp of 20 wt.% became 143 MPa or increased of as much as 22.16 %. The biggest yield
strength was found on the Al-Si$_3$Mg$_1$$_5$TiB/SiC$_p$ composite that was averagely amounted to 106 MPa. The difference in the yield strength between those two composites was 14 MPa,%EL in which the highest one was found on the Al-Si$_3$Mg$_1$$_5$TiB/SiC$_p$ composite with the average value of 2.11,%EL. The Al-Si$_3$Mg$_1$$_5$TiB/SiC$_p$ composite had a higher impact value compared to the Al-Si$_3$Mg/SiC$_p$ composite. The highest impact toughness was averagely amounted to 4.74 J/mm$^2$. The porosity value of the Al-Si$_3$Mg/SiC$_p$ composite was averagely 2.38%. On the Al-Si$_3$Mg$_1$$_5$TiB/SiC$_p$ composite, the porosity value was averagely 2.10%. The smallest porosity was found on the Al-Si$_3$Mg$_1$$_5$TiB/SiC$_p$ composite. The difference in the increase of porosity percentage on those two composites was 0.13 %. The extra level of 1.5 wt.% TiB could make the grain refinement to be smoother. The extra level of TiB could result in an increase on the tensile strength value and impact value, and from the different morphology from micro structure and SEM.

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