Characterization of Aluminium-Silicon (Al-Si) cast alloy refined with Titanium Diboride (TiB_2) and Scandium (Sc)

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ABSTRACT

The aluminium-silicon (Al-Si) alloys, based on the Metal Matrix Composites (MMCs) system are widely used in light-weight constructions and transport applications requiring a combination of high strength and ductility. A grain refinement plays a crucial role in improving characteristics and properties of Al-Si alloys. In this investigation, titanium diboride (TiB_2) and Scandium (Sc) elements were added to the Al alloys for grain refinement of the alloy. Sc is the most widely used and a very effective element for modifying the morphology of eutectic silicon, while TiB_2 was commonly present in the commercial grain refiners used for Al-Si alloys. The TiB_2 content was fixed at 6wt.% while 0.2-0.8wt.% Sc contents were chosen in this investigation. The Instron Universal Tensile Strength (UTS) machine and Vickers hardness tester were used to characterize the tensile strength and hardness of Al-Si alloys respectively. Optical microscope and x-ray diffraction (XRD) were used to observe the microstructure and to determine the phase distribution in Al-Si alloy. From the results obtained, increased Sc in Al-Si/TiB_2 composite alloys has influenced on the grain refinement and improves the mechanical strength of this composite. At the composition of 0.8 wt.% Sc gave the highest value for hardness and tensile strength. The optical microscope showed that the finer microstructure observed when increased the Sc contents to Al-Si-TiB_2 composite alloy. From this investigation that has been done, we can conclude that the addition of modifier and grain refiner, TiB_2 and Sc will increase hardness and tensile stress of Al-Si cast alloy.

Keywords: *Aluminium-silicon, titanium diboride, scandium, mechanical properties, microstructure,*

INTRODUCTION

In order to meet the demands of the aerospace, automotive and military industries, the necessity of lightweight and high-performance structural

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materials has provided. The necessary momentum required for the development and emergence of Metal-Matrix Composites (MMCs). Further, these MMCs are attractive and viable alternatives to the traditional engineering alloys, with the majority of them having metallic matrices reinforced with high strength high modulus and brittle ceramic phases [1]. Particulate reinforced MMCs appear to be the most popular choice because they can offer relative ease in processing, lower fabrication cost, and nearly isotropic properties in comparison to fiber reinforced materials. High strength to weight ratio, excellent formability, good corrosion resistance, good castability and weldability are few of the properties which made Al alloys as most promising engineering materials. The strength and hardness of Al are mainly depended on their microstructure, a lot of efforts have been done for refining microstructure of castings in order to improve the mechanical properties of Al [2].

Grain refinement is an important practice to improve the microstructural uniformity and mechanical properties [3]. It plays a crucial role in improving characteristics and properties of cast and wrought Al alloys. Generally grains refinements are added to the Al alloys to grain refine the solidified product [4]. Grain refinement has been associated with the formation of casting defects. It is generally assumed that an increase in the level of grain refinement is beneficial for castability. Grain refinement during solidification involves the formation of fine equiaxed grains at the expense of dendrites [4].

However, Al and its alloys will have the coarse grain size in as- cast condition. Mechanical properties of Al are strongly connected to their microstructure obtained after heat treatment. These coarse grain size of as-cast alloys results in low Al mechanical properties. These low mechanical properties make it unreliable for the further advance application. To overcome this, Al with smaller grain size must be produced. A finer grain sizes promote improved casting soundness by minimizing shrinkage, hot cracking, and hydrogen porosity. This fine equiaxed grain structure is normally desired in Al final product. In cast house applications, the control of grain size is absolutely essential in maintaining product consistency and quality, in reducing costs and maintaining high levels of productivity. The type of size and grain formed are determined by the composition of the alloy, solidification rate, and the addition of master alloys (grain refiners).

Rosmamuhamadani et. al., [5] have investigated the mechanical properties of aluminium-copper (Al-Cu) alloy that was reinforced with 1 to 6wt.% TiB_2. From the results obtained, they found increased of TiB_2 contents will increase the value of tensile and hardness properties of Al-Cu alloy. The composites synthesized using *in-situ* techniques exhibit the presence a uniform distribution of reinforcement that tends to be fine and associated with a clean interface with the metallic matrix. In order to achieve a good mechanical and wear properties, it is important to control Al_3Ti phase formation during the synthesis of in-situ Al/TiB_2 composites.

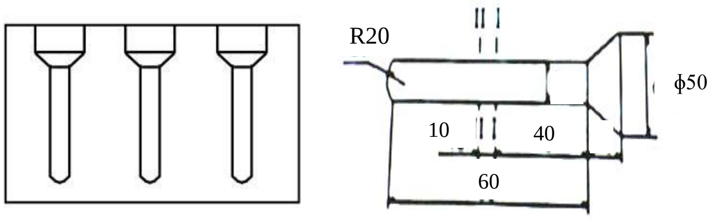
In the research done by Ibrahim et. al., [6] they found that the microstructure of Al-Si with TiB_2 has much finer microstructure compared to unfine Al-Si alloy. It showed that the eutectic silicon microstructure in Al-Si alloy changed from needles-look or acicular to fine grain size or globular when the added of TiB_2. The mechanical studies showed that the ductility of Al-Si alloy was much lower in the absence of grain refiner, TiB_2. The tensile strength of unrefined Al-Si and Al-Si with 6 wt.%TiB_2 as grain refinement were recorded 275 and 312 MPa respectively. The hardness value for the unrefined Al-Si alloy also shows less compared with Al-Si with grain refiner, 6 wt.%TiB_2, which are 74 and 78 MPa. This showed the results were significant improvements in mechanical properties have been obtained with the use of TiB_2 as grain refiner to Al-Si alloy.

This research was planned to study the effect of grain refiner TiB_2 and Sc onto the properties of Al-Si cast alloys. By adding boron to titanium, it will dramatically increase its strength, stiffness, and microstructure stability. Ti-B nucleant released particles that will promote equiaxed, fine grain structures all the way through the cast alloy, thus avoiding the formation of columnar crystals. Grain refiner improves homogeneity and allows for a uniform distribution of alloying elements. It can also reduce porosity and eliminates hot tearing in cast structures which will simultaneously improves the responsiveness to subsequent heat treatment thus enhances its mechanical properties and machinability in the fabrication process.

METHODOLOGY

Mould pattern

While in casting, the materials were first melted and heated to a proper temperature. The metal mould that has a desired shape suitable for standard testing. The molten material was then poured into a cavity or mold that holds it in the desired shape during cold-down and solidification. While pouring, its important to reduce overflow. Next stage was solidification of the sample for a few minutes to solidify. The important parameters in this processing were to control the cooling rate and cooling time. It's because these parameters that were chosen will determine the structure of materials produced. It's important to avoid defects occur in sample produced [7]. The mould design used in this investigation as illustrated to the Figure 1(a) below. Permanent stainless steel mould that used will be able to produce three samples at one pouring and the dimension (in mm) of the pattern is mentioned in as in Figure 1(b).



(a) (b)

Figure 1: Dimension of pattern and the cross-section of die steel mould

Casting alloy

Al-7wt.% Si and 6wt.% TiB_2 were respectively melted at 720 °C in an induction furnace. The furnace temperature with an accuracy of ±1 °C was monitored and well maintained. Al-Si-TiB_2-Sc composite alloys were prepared through conventional melting and casting route. While in casting, all the alloys were melted in an induction furnaces and the liquid metal was poured into permanent standard mould and the compositions of the alloys. The melts are homogenized for 15 minutes before adding Sc according to the percentage of weight. A melt then poured into a stainless steel mould and let them cool within 24 hours. The permanent mold casting is produced in tight dimensional tolerances with high surface quality.

Characterization

Sample characterization is a process of identifying the physical, mechanical and chemical properties of the sample. Characterization of the sample being investigated in this study will undergo phase investigation and physical testing. A few instruments are used in making the analysis of the sample is Universal tensile strength (UTS) Instron, Vickers hardness tester, optical microscope and x-ray diffraction (XRD).

To measure the tensile strength, the Instron tensile test was used. The sample was reached to forces being applied in tension. This testing done to obtain the data based on the tensile test. All samples were tested at the same rate which was 2 min/mm. The data then automatically produced by the machine. All data were recorded and calculated to obtain the average result. Figure 2 shows the specimen dumb bell shape for tensile test according to ASTM E-92 [8].

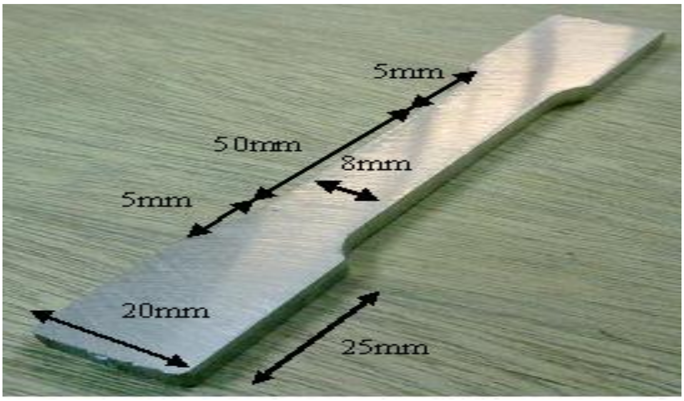


Figure 2: Dumbell shape specimen for tensile test

Vickers hardness tester was one of a method to measure the hardness of a material. The correlation between various hardness scales and tensile strength has been compiled from a variety of metals and alloys. Vickers test procedure as per [9] standard specifies making an indentation with a range of loads using a diamond indenter which is then measured and converted to a hardness value.

Figure 3 shows the Vickers hardness tester instrument used for measuring the hardness of specimens. After the force has been removed, the diagonal lengths of the indentation are measured and the arithmetic mean, *d*, is calculated. The Vickers hardness number, H_V, is given according to equation (1) and (2):

$$H_V = \frac{\text{Constant} \times \text{Test force}}{\text{Surface area of indentation}} \tag{1}$$

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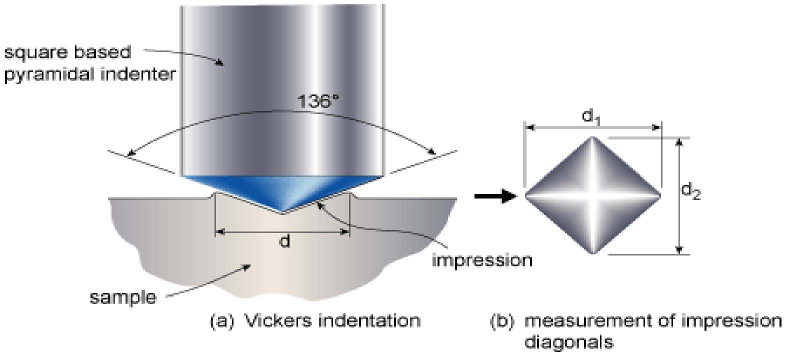

Figure 3: Vickers indentation and measurement

To characterize microstructures, the samples were grinding surfaces, polished and etched. Microstructures were obtained by etching with Keller's reagent to reveal the microstructure of as-cast composite alloys. Microstructure and data from the experiment were analyzed by Carl Zeiss optical microscope. Table 1 shown the weight percentage (wt%) of composition alloys that used in this investigation.

Table 1 : The composition of metal used in investigations (wt.%).

Alloys	1	2	3	4
Aluminum	93	93	93	93
Silicon	7	7	7	7
TiB_2	6	6	6	6
Sc	0.02	0.04	0.06	0.08

RESULTS AND DISCUSSION

Tensile Strength

Table 2 shows the tensile strength of Al-Si-TiB_2 refined with different Sc contents. The tensile strength of Al-Si alloys refined with TiB_2 and Sc with different Sc contents which were 0.2, 0.4, 0.6 and 0.8 wt.% were summarized in the histogram below (Figure 4). Based on Figure 4, by comparing Al-Si-6 wt.%TiB_2 cast alloy, the optimum value of tensile was achieved at the composition at 0.4wt.%Sc. The values were 391.0 and 386.9 MPa respectively. This is due to the particles size of the Sc were well dispersed in the Al-Si-TiB_2 matrix. The hard Sc particles pin down the dislocation line and favor the formation of dislocation loops around the particles. The loops reduce the distance between the particles and thus provide more resistance to further dislocation movement in the composite during deformation. This enhances the strength of the composites. Besides that, in addition, grain boundary strengthening is also expected because the Sc can act as a grain refiner in Al-Si-TiB_2 alloys.

Table 2: Tensile strength of Al-Si alloy reinforced with TiB_2 and Sc

MMCs	Tensile Strength (MPa)
Al-Si	332.7
Al-Si-TiB_2	379.0
Al-Si-TiB_2-0.2Sc	386.2
Al-Si-TiB_2-0.4Sc	390.8
Al-Si-TiB_2-0.6Sc	385.4
Al-Si-TiB_2-0.8Sc	381.2

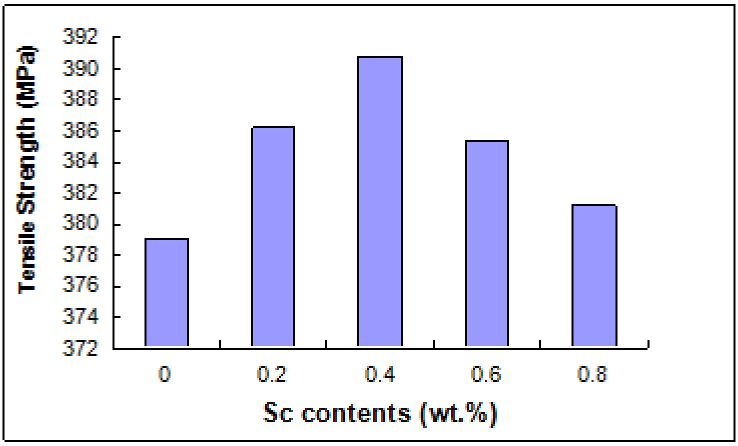

Figure 4 : Tensile strength (MPa) of Al-Si-6 wt.%TiB_2 refined with different Sc contents

Hardness Properties

Table 3 below shows the hardness of Al-Si cast alloys refined with TiB_2 and with different Sc contents. The hardness results of Al-Si alloys refined with TiB_2 and Sc with different Sc contents which were 0.2, 0.4, 0.6 and 0.8 wt.% were summarized in the histogram below (Figure 5). The result showed that the hardness of Al-Si refined with TiB_2 and 0.8 wt.%Sc gave the highest value which was 95.8 Hv. From the result obtained, the hardness value of 0.2, 0.4, 0.6 and 0.8wt.% of Sc were 77.2, 91.9, 93.6 and 95.8 Hv respectively. It is shown that the hardness value increased by increasing of Sc contents. It was because of the structural differences between the grains refined, modified and combined effect of modifier in these alloys.

Table 3 : Hardness value of Al-Si and it's cast alloys.

Alloys	Hardness (Hv)
Al-Si	75.0
Al-Si-6TiB_2	81.8
Al-Si-6TiB_2.0.2Sc	83.8
Al-Si-6TiB_2.0.4Sc	91.9
Al-Si-6TiB_2.0.6Sc	93.6
Al-Si-6TiB_2.0.8Sc	95.8

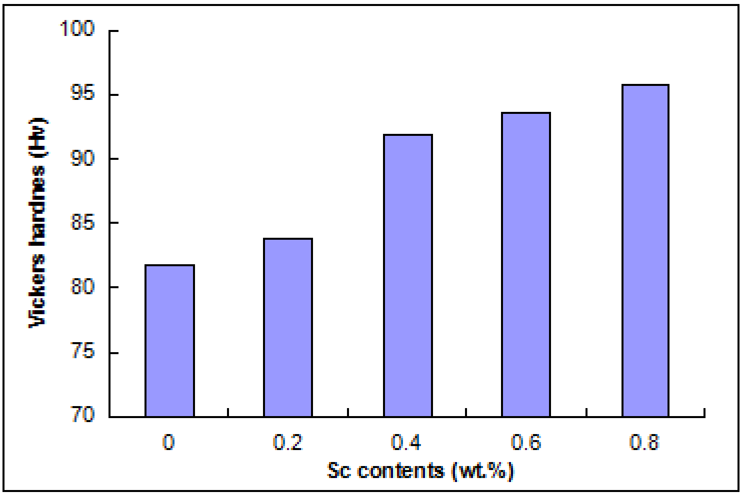

Figure 5: Vickers hardness of Al-Si-6 wt.%TiB_2 refined with different Sc contents

MICROSTRUCTURE OBSERVATION

Figure 6 below shows the microstructure observation for Al-Si-TiB_2 composite alloys with 0.2 and 0.8 wt% of Sc observed by an optical microscope with 50 X magnification. Optical micrograph with 0.2 wt% of Sc showed dendrites with black second phase particles within inter-dendritic spaces. Increasing the percent of Sc to the base alloy showed a diminution in a number of dendrites phase particle. The appearance of dendrite arm spacing was decreased in 0.4, 0.6 and 0.8 wt% of Sc with the consequent refinement of dendrites. The structural fined was seen increased with increasing of Sc content. The alloy with 0.8wt% of Sc showed the dendrite arm spacing becomes rounded and small. The Al-Si-TiB_2-Sc alloys were seen to have refined remarkably.

The dendrites of the cast binary alloy were seen to have refined significantly with the addition of Sc. Kaiser et. al, [10] proved that alloy with 0.2 wt% Sc does not provide much grain refinement, but refines the primary dendrites of α with consequent diminution of dendrite arm spacing. The arm spacing in Sc treated alloys were found to lie within a range of 20 to 40 μm against a value of around 45 μm in case of base alloy. This is ascribed to the modification of solidification speed by Sc during the growth of the dendrite structure.

The differences between both microstructures can be seen clearly. The addition of 0.2% Sc modifier into Al-Si alloy has changed plate-like eutectic into fine particles due to modification of eutectic Al-Si alloy. Fully modified Si particles are dark gray. The fibrous form of eutectic Si enhances the ductility of the alloys. According to Muirhead et. al., [11] the addition of the Ti-B master alloy in near-eutectic Al–Si alloys has a markedly positive influence on the refinement of the dendritic α-Al phase. Furthermore, the addition of Ti leads to an increase in the volume fraction of the α-Al phase and in the primary Si cuboids and a decrease in the size of the grain.

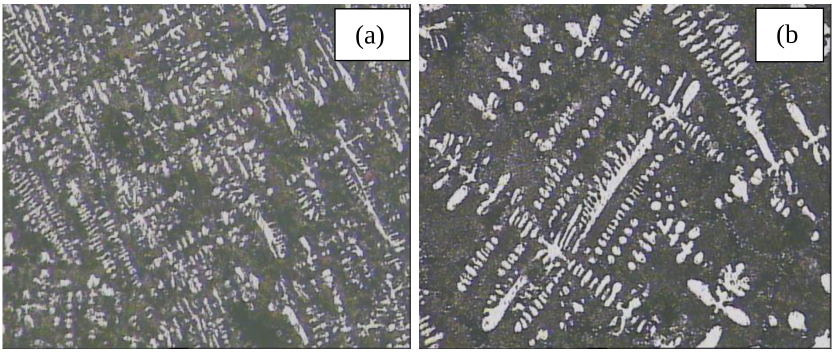

Figure 6 : Morphology of Al-Si-6 wt.%TiB_2 composite alloys with different Sc contents (a) 0.2 , (b) 0.8 wt.% Sc observed by optical microscope with 50 X magnification

X-Ray Diffraction

The XRD analysis of Al-Si-TiB_2-Sc composite was investigated. Refer to Figure 7, the only intensity of Al, Si, and TiB_2 were detected. No evidence was found for the formation of the brittle intermetallic, trialuminide intermetallic (Al_3Ti) in the composites. It is important to eliminate Al_3Ti phase to achieve higher mechanical properties in Al-Si-TiB_2-Sc. Wu et.al., [12] in their research stated to achieved higher mechanical properties and wear behaviour, it is important to eliminate the phase of brittle intermetallic that exit in composites. Kumar et al., [13] stated that this can be achieved by control the reaction temperature and reaction time and also the ratio of Ti:B. Figure 4 below show the XRD pattern of Al-Si-TiB_2-Sc composites.

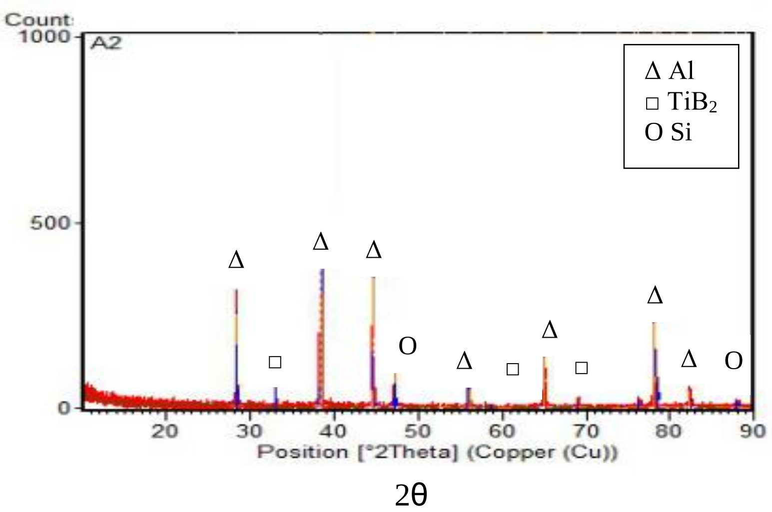

Figure 7 : XRD pattern of Al-Si-6 wt.%TiB_2-0.8 wt.%Sc composites

CONCLUSIONS

From the research have been done, we can conclude that the optical microscope showed the finer microstructure of Al-Si-6 wt.%TiB_2 composite alloy when increased the Sc contents. Grain refining can be successfully done by addition of more percentage weight of Sc modifier into the alloy. For the hardness test, Al-Si-TiB_2-0.8 wt.% Sc cast alloy gave the highest value compared with others composition. Tensile strength of Al-Si-TiB_2-0.8 wt.% Sc gave the highest value compared with other Al-Si-6 wt.%TiB_2 composite alloys.

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