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The Effect of Scandium (Sc) onto Mechanical Properties and Morphologies of Aluminium-Silicon (Al-Si) Alloy

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ABSTRACT

Aluminium-silicon (Al-Si) alloy is the metal matrix composite (MMCs), widely used in constructions and transports requiring high strength and ductility. This research focused more on the Al-Si as the base alloy which act as matrix component, while Scandium (Sc) act as the reinforcement and inoculants that helps to reduce the grain size of the base alloys, in order to investigate the effect of Sc onto mechanical properties and wear behaviour of Al-Si alloy. In this research, Al-Si was reinforced with 0.2 to 0.8 wt.% Sc. Al-Si and Sc were melted at 720 °C in high temperature furnace. Al-Si-Sc composite then were poured to stainless steel mould and solidified at room temperature. From results obtained, the increment of Sc increased the value of mechanical properties to Al-Si. The ductility of Al-Si was observed much lower in the absence of Sc. The tensile strength of unrefined Al-Si and Al-Si with 0.6 wt.% Sc were 325 and 377.3 MPa. The hardness value for the unrefined Al-Si also shows less compared with Al-Si with 0.8 wt.% Sc, which were 70 and 85 Hv. Results show that 0.6 wt.% Sc gave the lowest wear rate which was 0.7 x 10^{-4} at 100 N, while for 150 N, the wear rate was 1.25 x 10^{-4} g/min. Microstructure of Al-Si-Sc composite alloy has much finer compared to unlined Al-Si alloy. Increased Sc in Al-Si alloy influenced the grain refinement and mechanical strength of that composites.

1. Introduction

The aluminium matrix composites (AMCs) have tremendous applications in automobiles, automotive, space shuttle and aeronautics manufacturing in these recent generations. These predominant metal successes can be achieved by having great mechanical properties such as rigid, good dimensional stability, chemically inert, low density, high performance in low temperature, corrosion resistance, wear resistance and lower fatigue strength better than pure aluminium [1].

The properties of AMCs will be tailored with suitable mixture of matrix and reinforcement to produce desired properties in different applications. Previous studies had been adding ceramic elements as reinforced particles to maintain the request from the industries and also increase the

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performance of the AMCs [2]. Titanium diboride (TiB_2), silicon carbide (SiC) and titanium carbide (TiC) act as great reinforcements for AMCs that can produce good materials for building constructions for their wear resistance and great toughness [3]. However, the addition of TiB_2 particles gives out the highest level of modulus and interfacial bonding better than SiC and TiC [4]. Moosa [5] studied that the addition of ceramic elements into the metallic alloy can fabricate good results because of the ceramic properties themselves.

Despite that, excellent mechanical properties are strongly associated with the microstructure, specifically with grain size itself. A refine microstructure has a lot of improvement in the properties better than the course one in cast condition. Coarser grain size can weaken the mechanical characteristics of the composite. The refining process produces more lower porosity, high fatigue strength and also excellent mechanical properties with respect to more uniform microstructure of the cast Al alloy [6]. Former researchers did some improvements on the performance of Al alloy by adding different inoculants in the aspects of grain refinement [7]. Generally, different metal elements addition will produce different results of microstructure modification depending on the properties of the element itself [8]. In the effort to produce more equiaxed and smaller grain sizes of AMCs with the addition of ceramic particles, researchers added some amount of grain refiner which is strontium (Sr) that eventually gives out a good refinement resulting in more long lasting and higher durability [9].

This research focused more on the Al-Si as the base alloy which acts as matrix component, while Sc act as the reinforcement and inoculant that helps to reduce the grain size of the base alloys in order to investigate the effect of Sc onto mechanical properties and wear behaviour of Al-Si alloy.

2. Methodology

2.1 Composite Fabrication

The initial Al–7wt.% Si alloys were prepared in an electrical resistance furnace by melting and diluted it with Al (99.99% pure). The composition of Sc was chosen in ranging of 0.2 to 0.8 wt.% and mixed with Al-Si master alloy. The samples of Al-Si with addition of Sc were prepared according based to the formulation listed in Table 1.

Table 1
Sample compositions of Al-Si alloy reinforced with Sc by weight percentage (wt.%)

Samples	Al-Si (wt.%)	Sc (wt.%)
1	100.0	0
2	99.8	0.2
3	99.6	0.4
4	99.4	0.6
5	99.2	0.8

After that, this material was heated in a furnace until the melting temperature reached approximately 720 °C. The maximum weight of molten aluminium alloy and Sc is 5 kg. The stainless steel mould was then pre-heated up to 200 °C before all the metals were poured into the mould cavity [10].

2.2 Characterization of Composite Alloy

Sample characterization is a process of identifying the physical and mechanical 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 which is an ultimate tensile (UTS) machine, Vickers hardness tester, pin-on-disc and field emission scanning electron microscope (FESEM).

During the tensile test, the Instron tensile test is performed to determine the sample strength. The samples will be subjected to forces. The tensile strength data will be gathered as the testing progresses. For each sample, the same rate is chosen. The data gained from the testing will be automatically distributed by the machine. The average result will be determined using the data collected [11]. The Vickers hardness method is used to determine the hardness value of a certain material. The hardness value of a material is determined by indentation using a diamond indenter under a variety of loads, which is then transformed into the hardness value [12].

Wear characterization involved wear tests carried out by pin-on-disc machine. The tests include measuring the weight loss, wear coefficient and wear rate of Al-Si alloy reinforced with Sc. The test was done in Characterization Laboratory, Industrial Technology Department, Agensi Nuklear Malaysia, at Kajang, Selangor. Wear is quantified by measuring the wear groove with a profilometer and measuring the amount of material removed. Users specify the turntable speed, the load, and any other desired test variables such as friction limit and number of rotations [13]. The wear factor, defined as the ratio of wear volume (in mm^3) to the product of applied load (in N) and sliding distance (in meter), is an important parameter, which quantifies the wear resistance. Figure 1 shows a pin-on-disk machine that used to measure the wear properties of Al-Si-Sc composite alloys.

Fig. 1. Pin-on-disc wear machine

FESEM is a microscope that uses electrons, which have a negative charge, to create pictures rather than light. It has a large depth of field, allowing a large number of samples to be focused at the same time, can produce high-resolution images, and samples are simple to prepare. The electrons will be liberated by the field emission source, and then the conductive object that will be characterised will be scanned in a zig-zag pattern.

3. Results

3.1 Effect Sc on Mechanical Properties

Figure 2 shows that refined Al-Si with 0.8 wt.%Sc produced the highest value which is 347 MPa, compared to unrefined Al-Si and other compositions (0.2, 0.4 and 0.6 wt.%Sc). The increment of tensile strength values is increasing proportionally along with the increment of Sc addition [14]. The improvement in tensile strength of the composite is due to the strong bonding between the reinforcement and matrix [15]. Good interfaces and wettability between Sc and Al matrix alloy formed a very good interfacial bonding. The load is properly transferred to the reinforcing material by the matrix and becomes more effective along with the increment in the capability of the matrix's load bearing [16]. The presence of grain refiner also acted on the obstacles which prevent the probability of the occurrence of dislocation [17].

The tensile strength of Al-Si, and with different Sc contents can be seen from the data obtained in Table 2 and Figure 2(a). It can be concluded that the Sc particles were homogeneously dispersed in the matrix alloy which increases the dislocation resistance during the deformation of the composites. This phenomenon can enhance the tensile properties of the composite itself. The increment in tensile strength resulted in the increment in grain refiner. Results from grain refiner increments will increase the tensile strength. As Sc act as the grain refiner, it can also strengthen the grain boundaries in Al-Si and with different Sc contents. Finer grain size resulted in the increment of tensile strength. The addition of grain refiners is also capable of producing great tensile strength outcomes because of the significant reduction in stress concentration that developed through the process of uniforming the distribution of finer second stages.

Table 2
Tensile strength and hardness of Al-Si reinforced with Sc contents

Al-MMCs	Tensile (MPa)	Hardness (Hv)
Al-Si	322	70
Al-Si-0.2 wt.%Sc	363	74
Al-Si-0.4 wt.%Sc	353	78
Al-Si-0.6 wt.%Sc	367	81

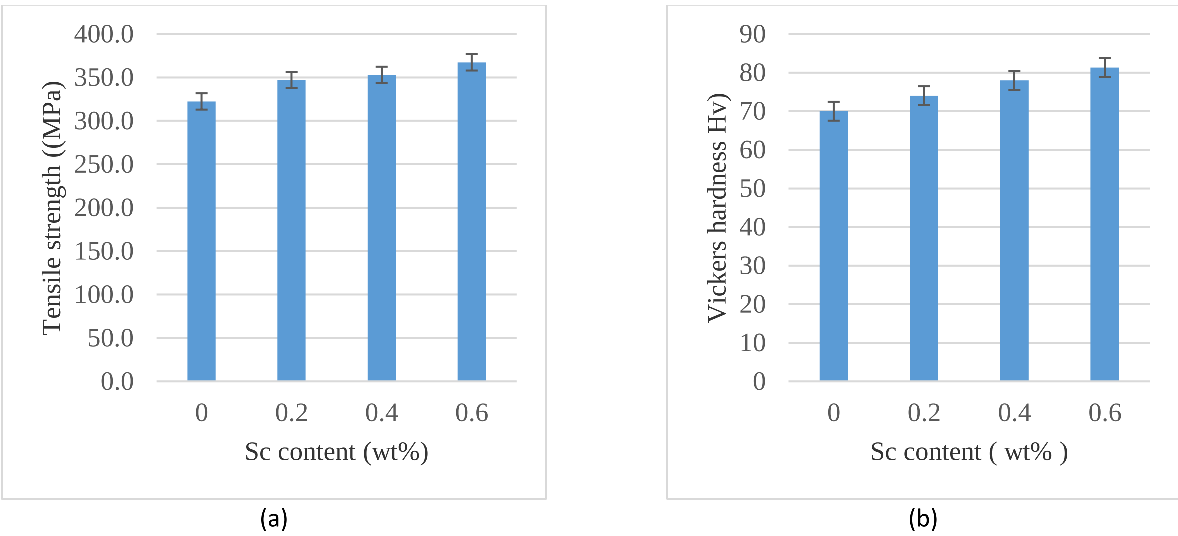

Fig. 2. Al-Si alloy reinforced with different Sc contents (a)Tensile strength (MPa) (b) hardness (Hv)

In hardness characterization, the initial hardness of Al-7Si is 76 Hv for 5N load used. It was observed that the value of hardness increased when Sc contents increased. The hardness of Al-7Si-0.6 wt.% Sc composite was recorded at 89 Hv. The increase of Vickers hardness of Al-7Si-0.6 wt.% Sc composite is 17% compare to Al-Si alloy (without Sc). In conclusion, the addition of Sc increased hardness of Al-7Si alloy. These results are illustrated in Table 2 and Figure 2(b). The increase of hardness value with increasing inoculant contents was supported by Basir [18]. Dhokey and Rane [19] and Kumar *et al*., [20]. Basir *et al*., [18] reported that the increase of strontium (Sr) to Al-Si alloy has increased the hardness value by 10.2% as compared to Al-Si based alloy itself.

Dhokey and Rane [19] stated that Al alloy with 2.5 wt.% TiB_2 composite indicates 47% improvement in hardness and this goes up with increasing TiB_2 content. It is noticed that the hardness of 5 wt.%TiB_2 is increased almost twice than pure aluminium. Kumar *et al*., [20] stated that the hardness of composites increased by 108% with increase of TiB_2 used in the composite. They found that an increase of 108% in hardness has been achieved when adding 10 wt.% of TiB_2 onto Al-7 wt.%Si alloy. Pramod *et al*., [21] stated that the addition of 0.4 wt.% Sc to A356 and A356–TiB_2 composite increased the hardness from 74 to 88 Hv0.5 and 83 to 107 Hv0.5, respectively. The improvement in the hardness in alloy and composite with the Sc addition is due to grain refinement, eutectic Si modification and the presence of phase containing aluminium, silicon, Sc, and ferum (Fe) [22].

The increase in hardness of Vickers of the composites can be attributed to the decrease in the grain size of Sc particles. It is evident that the addition of inoculant such as TiB_2 leads to significant increment in the hardening by the precipitates, which can be attributed to additional strengthening due to coherency strains and misfit dislocations formed by the precipitation on Sc particles [18].

3.2 Morphology of Al-Si-Sc Composites Alloy

Figure 3 shows the morphology of Al-Si-alloy reinforced with 0.8 wt.% Sc observed by FESEM with 500 X magnification. It can be seen that the shape of particles looks like a needle shape and spherical particles. This statement was supported by Pramod *et al*., [21] observed the change in Si morphology from needle-like to fine spheroidal particles.

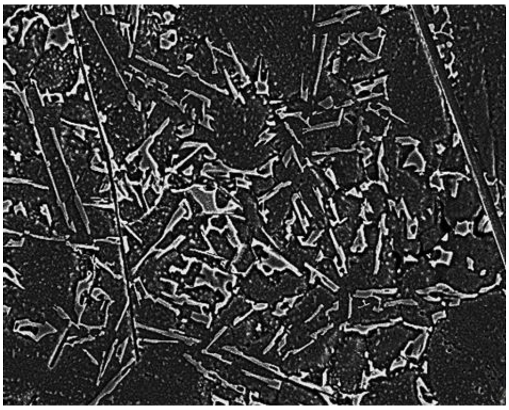

Fig. 3. FESEM morphology of Al-Si alloy reinforced with 0.8 wt.% Sc with 500 X magnification

3.3 Effect of Sc on Wear Characterization

Table 3 shows the weight loss of Al-Si alloys reinforced with different Sc contents. The wear behaviour is measured by weight loss of the specimen at certain sliding distance, with the loads used being 100 and 150 N.

Table 3
Weight loss (in gram) of Al-Si-Sc composite alloy reinforced with different Sc contents

Composition of Sc (%)	Weight loss (in gram)	
	(100 N)	(I50 N)
0	1.05	1.32
0.2	0.80	1.25
0.4	0.45	1.02
0.6	0.41	0.83

By referring to Figure 4, as several Sc contents increases, the ploughing tendency of the abrasive particle is reduced, which is due to the high hardness of Al-Si-Sc composite alloy. The sliding wear due to abrasion is given as in Eq. (1) and Eq. (2),

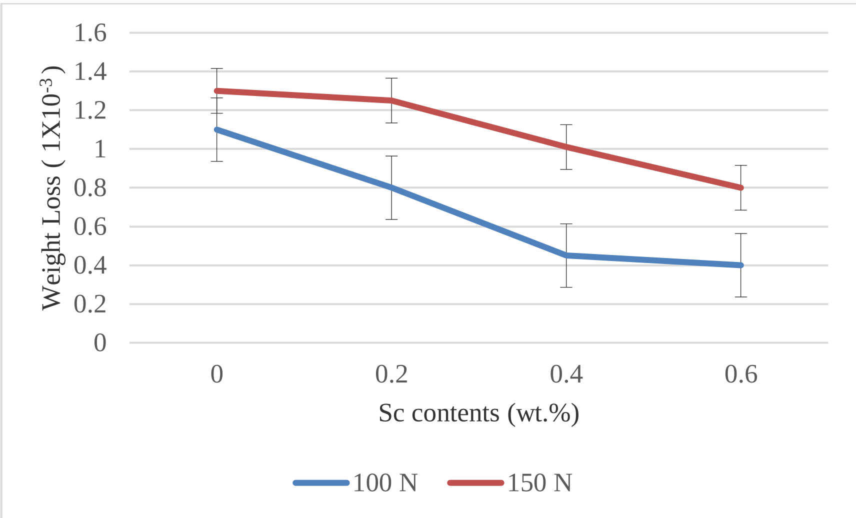

Fig. 4. Weight loss (g) of Al-7Si-Sc in wear test conducted at 1000 m distance with different applied loads (N)

$$V = \frac{kPL}{H} \tag{1}$$

$$k = \frac{VH}{PL} \tag{2}$$

where V is the volume loss (gram), P is the load applied (N), L is the sliding distance (in meter) and H is the bulk hardness of the material. In this case, the load applied was 100 and 150 N and sliding distance were set at 1000 m. The Eq. (1) indicates that the volume loss is inversely proportional to the hardness of the specimen. A similar trend is observed in this study.

Figure 5 shows the dimensionless wear coefficient (k), calculated using the above equation, for the Al-Si-Sc composite alloy at different loads applied. The value of k for composites is lower than the base alloy, Al-Si which suggests better abrasive wear resistance for that composite. For a 100 N load, *k* is 1.10 x 10^{-6} for base alloy, whereas it is 0.40 x 10^{-6} for composition at 0.6 wt.% Sc. When increased load at 150 N, the *k* is 1.3 x 10^{-6} for base alloy and 0.80 x 10^{-6} for composition at 0.6 wt.% Sc. In addition, *k* appears to be insensitive to the load of composites in comparison to the base alloy. In case of composites, the nature of wear is sliding wear and is less sensitive to an applied load.

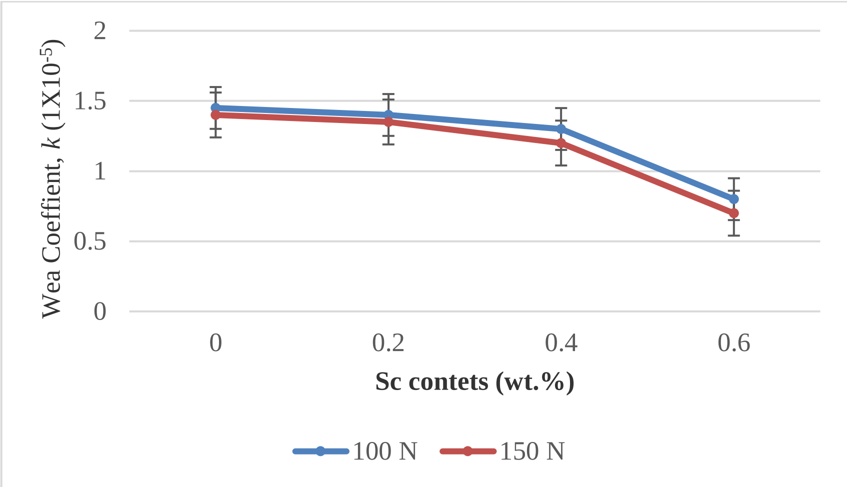

Fig. 5. Wear coefficient of Al-7Si with different Sc contents conducted at 1000 m distance

Thakur and Dhindaw [23] demonstrated that good dispersion and better interface of particles in matrix leads to a lower value of coefficient of friction. Rosmamuhamadani *et al.,* [1] stated the effect of reinforcement used, TiB_2 reduced the weight loss and *k* value of Al-Cu alloy. Besides, it has also been proved that the coefficient of friction is reduced by TiB_2 more effectively than SiC [24]. The lower μ values in composites in comparison to the base alloy could be attributed to the uniformly distributed fine of Sc particles.

Figure 6 shows the wear rate conducted for 1 hour and at 1000 m sliding distance with different loads used. The loads used were 100 and 150 N. It clearly shows that when there was an increase in Sc contents to Al-Si alloy that reduced the wear rate of that alloy. From the table, it shows that the highest Sc contents were added to Al-Si alloy giving the lowest value in wear rate. Al-Si-0.6 wt.% Sc composite gave the lowest value of wear rate indicating that the composite is good for wear resistant behaviour. The value of Al-Si-0.6 wt.% Sc was 0.7 x 10 $^{-4}$ at 100 N, while for 150 N the wear rate of that composite was 1.25 x 10^{-4} g/min respectively.

This statement was supported by Kumar *et al*., [20] stated that if the value of *k* for composites is lower than the base alloy suggests better abrasive wear resistance for the composites. In their finding, the *k* is 2 x 10^{-2} for the based alloy and 4 x 10^{-3} for 10 wt.%TiB_2 contents.

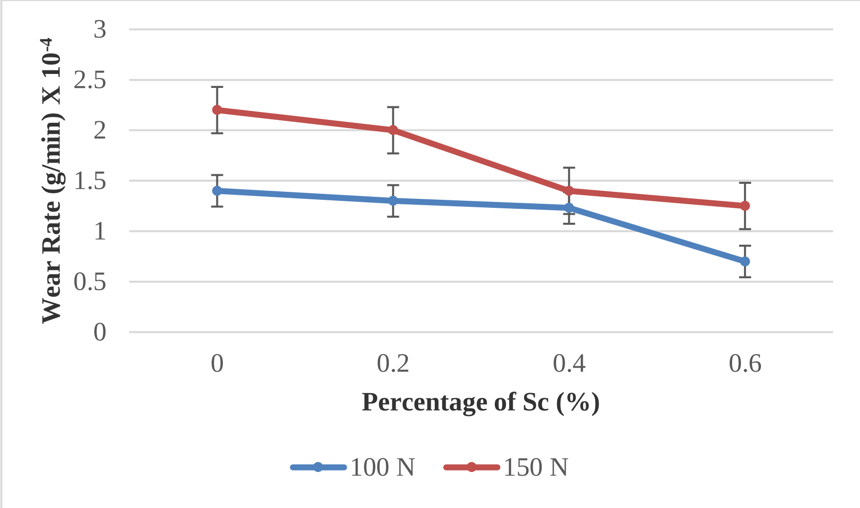

Fig. 6. Wear rate (g/min) of Al-Si-Sc composite alloy in wear test conducted in 1000 m within 1 hour at different loads (N)

Moreover, Sc particles can be formed in metal matrices, thereby promoting a strong particle-matrix bonding. This can reduce the pulling out of particles from MMCs during sliding. In their investigation, Al-based MMCs reinforced with Sc exhibit better wear performance and this statement was supported by Pramod *et al*., [21]. They observed the wear volume of A356 alloy is reduced by the Sc addition by pin-on-disc machine. They conducted a wear experiment for a sliding distance of 2000 m of the alloys and the composite for different normal loads, 75 and 100 N. They proved that the addition of Sc to A356 alloy improved its wear resistance.

4. Conclusions

In this work, tensile strength shows refined Al-Si alloy with the addition of 0.6 wt.% Sc (345 MPa) indicates more ductile than unrefined Al-Si alloy (313 MPa), and unrefined Al-Si alloy also indicates brittle materials compared to refined Al-Si alloy. Vickers hardness shows that Al-Si alloy with addition of Sc at 0.6 wt.%. Sc gave the highest value which was 89 Hv. The FESEM analysis showed that Al-Si with 0.8 wt.%Sc has a much finer microstructure compared to unrefined Al-Si alloy and with small amount of Sc used. There is a definite increase in the wear resistance of Al–Si alloy by the addition of Sc particles. The wear rate decreases with increasing of Sc particles for both applied loads, 100 and 150 N. Hence, the addition of Sc into Al-Si alloy produces finer microstructure alloy with higher values in tensile properties, hardness properties and wear properties.

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