Mechanical and Fatigue Properties of Gravity Die-Cast A356 Aluminium Alloy with Addition of Scandium

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Abstract. A356 is widely used for the casting of high strength components in automotive, aerospace and other industrial applications. This is due to its high achievable strength, castability, light weight, good thermal and electrical conductivity. However, the as-cast A356 exhibits relative poor mechanical properties due to the presence of coarse acicular eutectic silicon morphology. In this study, Sc-modified-A356 and the effect of heat treatment have been studied and compared with unmodified A356. Various amounts of Sc ranging from 0.2 wt% to 0.6 wt% were added into the mixture of A356 aluminium alloy and the specimens were produced by using gravity die-casting. Next, the ultimate tensile strength, Vickers hardness and fatigue behaviour of the cast samples are examined. The results revealed that by adding 0.4 wt.% of Sc, the heat treated sample is able to achieve ultimate tensile strength of above 300 MPa and Vicker’s hardness of 118 HV. Furthermore, the fatigue properties of the 0.4 wt% Sc-A356 with T6 heat treatment was found to be improved as compared to the unmodified A365 samples.

1. Introduction
Aluminium alloy has a wide range of properties and it is a favorable material for many engineering applications [1]. Among them, A356 aluminium alloy has received numerous attention particularly in automotive and aerospace industries. The presence of silicon (Si) in the aluminium can enhance the fluidity of casting alloys and help in heat treatable properties in balanced combination of Magnesium [2]. Although A356 has been reported to have good castability, good thermal, electrical properties and integrated strength, the as-cast A356 exhibits relative poor mechanical properties due to the presence of coarse flake-like eutectic silicon morphology [3,4]. To enhance the mechanical properties, modification of Si eutectic structure is necessary. The 3 common methods for the eutectic Si modification are; (i) chemical modification, (ii) quench modification and (iii) ultrasonic vibration [5]. In respect to chemical modification, small amount of rare earth (RE) elements are often added to the alloy to modify microstructure and improve the mechanical properties [6]. While some literatures reported significant improvement after chemical modification with heat treatment have been performed to the alloy [6,7]. In general, T6 heat treatment process is often applied for strengthening of aluminium alloy. The process involves two steps, there are namely solution heat treatment and artificial aging. Si particles in aluminium alloy will undergo significant changes in shape and size during the solution treatment. The eutectic silicon will first fragmented then individual particles will coarsen and slowly becoming round in shape with time [8,9].

On the other hand, the addition of Scandium (Sc) in aluminium has been reported to enable the formation of Al3Sc and improve the mechanical properties. It was found to be one of the most effective
grain refiners on cast grain structure in aluminium alloy [3]. Pramod et al. [14] have studied the microstructure and wear properties of A356 with Sc. Prukkanon et al. [15] have investigated the effect of Sc on the fluidity and castability of A356. As the study for influence of Sc on mechanical and fatigue of A356 is rarely reported in the literature, present work aims to investigate beneficial effect in terms of the mechanical and fatigue properties of A356 aluminium alloy with small amount of Sc addition and heat treatment.

2. Methodology
2.1. Sample Preparation
In this work, the A356 aluminium alloy with different amount of Sc were prepared using gravity die casting method. The composition produced for this experiment are namely pure A356, 0.2wt% Sc + A356, 0.4wt% Sc + A356, and 0.6wt% Sc + A356. The temperature of furnace was set to 850°C and hold for 90 minutes to ensure the A356 alloy has fully melt. Then, the Al2Sc master alloy was inoculated to the molten A356 alloy. The melt was stirred from time to time to ensure the homogenous mixing of Sc in the melt. Next, the molten alloy was poured into pre-heated die that has cavity design as shown in Figure 1.

![Design of die](image)

2.2. Heat Treatment
The cast samples were heat-treated in a furnace at temperature of 540°C with duration of 8 hours and subsequently quenched into 60°C water. The samples were dried and artificially aged at 185°C for 8 hours then followed by naturally aged for 20 hours at room temperature.

2.3. Testing
The uni-axial tensile test was performed by using Instron 5582 universal testing machine with strain rate of 1mm/min. The Vickers hardness test were performed to ASTM E384 whereby the disc samples were prepared and test with a load of 5kgf with 10s of dwell time. Fatigue testing was performed by using Servo-hydraulic Testing Machines. In order to obtain the stress life curve, different stress level ranging from 50% to 85% of 170MPa were applied to the specimens. The frequency of 10 Hz was used for all specimens.

3. Results and Discussion
The mechanical properties are primarily presented in Vickers hardness and ultimate tensile strength (UTS). The influence of Sc on the Vickers hardness of non-heat treated and heat treated samples is shown Figure 2. Based on the result, it shows that Vickers hardness increases as the Sc addition increases. Both heat treated and non-heat treated samples show nearly similar result when the Sc content at 0.4 wt%
and above.

![Figure 2. Vickers Hardness results with variation of Sc addition in A356 Aluminium Alloy.](image)

On the other hand, UTS for non-heat treated and heat treated samples of A356 with addition of Sc is shown in Figure 3. Similar to the Vickers hardness, the UTS increases as the Sc addition increases. Besides that, the heat treated samples were observed to have better UTS as compared to those without heat treatment. The UTS of heat-treated samples were improved significantly from 223.5 MPa to 313.4 MPa when 0.4 wt% Sc added to the A356. Only marginal improvement was observed in heat treated sample that contain more than 0.4 wt% Sc. Present work revealed that addition of Sc in A356 has outperformed other research works which used other alloying elements, for example, Mao et al. [5] obtained UTS of 265 MPa with addition of 0.1 wt% Eu combined with T6 heat treatment. Lee [10] presented a maximum UTS of 213.6 MPa was achieved in heat treated sample containing 0.15 wt% Ti.

![Figure 3. Ultimate tensile strength (UTS) of A356 aluminium alloy with different amount of Sc addition.](image)

Since the Vickers hardness and UTS results have identified marginal improvement in 0.6 wt% Sc-A356, the fatigue test carried out in this study was only based on 0.4 wt% Sc-A356 with T6 heat treatment. Figure 4 shows fatigue evaluation for non-heat treated A356, A356 T6 heat treated and 0.4 wt% Sc-A356 T6 heat treated aluminium alloys. Based on the results, 0.4 wt%
Sc-A356-T6 exhibits higher fatigue behavior as compared to those without Sc addition. Besides that, the results also observed to be better as compared to other research work reported in Lee [11] which their heat treated samples were containing small amount of Strontium (Sr). On the other hand, Ozdes et al. [12] also investigated on the fatigue performance on the heat-treated samples of Sr-A356 samples, their results were close to the fatigue behavior reported in present work. The variation of fatigue performance could be associated with the quality of the microstructure of the cast alloy [11-13]. In general, the improvement of the fatigue behavior observed in present work could be attributed to the better mechanical strength as observed in the UTS and Vickers hardness results. The strengthening of both mechanical and fatigue properties of A356 with small addition of Sc could be beneficial to its application particularly in automotive and aerospace that often subjected to complex loading.

**Figure 4.** S-N Curve of A356, A356-T6 heat treated and 0.4wt% Sc-A356-T6 heat treated aluminium alloy.

4. Conclusion
In this research, the effects of heat treatment and Scandium on mechanical and fatigue properties of A356 aluminium alloy in this research have been investigated. The addition of Sc in A356 was found to be beneficial for improving the Vickers hardness and ultimate tensile strength of the cast alloy. Notable improvement was observed in heat treated samples, particularly in those Sc-modified A356 aluminium alloy. Optimum amount of Sc suitable for the mechanical properties improvement was found to be 0.4 wt%. Only marginal improvement was observed when more than 0.4 wt% of Sc containing in A356 alloy. Similar to the mechanical properties, the heat treatment and addition of 0.4 wt% Sc were found to be able to enhance the fatigue performance of A356 aluminium alloy.

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6. References
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