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Influence of Grain Refinement by Al-5Ti-1B on the Microstructure and Mechanical Properties of Aluminium Alloy A356

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Abstract

An investigation was carried out to understand the effect of grain refinement on the microstructure and mechanical properties of Al-alloy A356 by addition of varying weight percentage of Al-5Ti-1B. Grain refinement and modification of α- phase in Al-Si alloys are considered as important task resulting from solidification process. Two different approaches to grain refinement by solidification process have been pursued physically induced and chemically stimulated. The physical relies mainly on the use of external field, such as ultrasonic vibration, while the chemical approach depends primarily on addition of grain refiner, which is the subject of this research work. The effect of grain refiner on the solidification of the A356 alloy was studying and the obtained samples were characterized by optical microscopy. The mechanical properties (σ_{uts}, $\sigma 0.2$ and δ) of the refined A356 alloys were investigated as a function of the addition level of Al-Ti-B master alloy (0, 1, 3,5 wt.%). The results indicated that the primary α- phase aluminium are significantly refined and the microstructures changed from coarse dendrites to fine equiaxed α-Al dendrites, without any change in the morphology of the eutectic Si particles. Additionally, the tensile strength, yield strength and elongation are increased noticeably with addition of grain refinement. The tensile strength, yield strength and elongation of the A356 with 3 wt % grain refine of (Al -5Ti-1B) are 156.3 MPa, 104.3 MPa and 4.9%, i. e., the percentage of improvement was 12 %, 6 % and 8.9 %, respectively.

Keywords: *Aluminium alloy-A356, Grain refinement, Modification of α- phase, Microstructure, Mechanical properties*

1. Introduction

Aluminium alloys are known to have excellent strength to weight ratio compared with other conventional metals like steels. A356 is one of the most widely used aluminium alloys in many industrial applications because of its excellent castability, corrosion resistance and good mechanical properties. It has lower production cost, fast machining rate and good recyclability [1]. Grain refinement plays an important role to determine the quality and integrity of aluminium alloys. Grain refinement is considered to be an important melt treatment during the casting of aluminium alloys, and introduce of inoculating particles into melts is the most effective way to achieve small uniformly distributed equiaxed grains, which leads to high toughness, high yield strength, excellent formability and improved machinability. Al–Ti–B ternary master alloys, particularly Al–5Ti–1B, have been widely used as aluminium grain refiners over the past several decades. The Al–5Ti–1B master alloy offers a remarkable performance in the continuous and semi-continuous casting of wrought alloys, but fails to meet the expectations in the case of cast aluminium alloys, especially for the Al–Si [2,3]. The effects of addition of Al-5Ti-1B grain refiner on the microstructure, mechanical properties and the acoustic emission characteristics of Al-5052 aluminium alloy have been studies [4]. Microstructural analysis showed the presence of primary α- solid solution and the absence of Al-Mg phase. The results indicated that the addition of Al–5Ti–1B grain refiner into the Al-5052 alloy caused a significant improvement in mechanical properties. The main mechanisms behind this improvement were found to be due to the grain refining during the solidification and segregation of Ti at primary α- grain boundaries. In another previous study [5], commercial A356 alloy was refined with Al–5Ti–0.25C–2RE master alloy, and the microstructure and macrostructure of the refined alloy were investigated. The results show that the grain refining effect of A356 is poor by the addition level of 0.5 wt% master alloy, but when the level reaches 3.0 wt% the grain can get a satisfactory refining effect. Few researchers have made an attempt on various grain refiners with their mechanism, such as Al-10Sr on A356 alloy. The results indicated that a size decrease of α-Al dendrites, change in eutectic Si and enhancement in the mechanical properties. The change of grains from eutectic Si to rounded particles explained the mechanical properties improvement [6, 7]. The main objective of present research work is to study the effect of Al-5Ti-B on the microstructure and the influence of the structural refining on the mechanical properties of aluminium alloy-A356.

2. Experimental Work

2.1 Materials

A commercial Aluminium – Silicon based alloy, A356, was used in this investigation with chemical composition as provided by the supplier “ASTM” shown in Table 1.

Table 1. Chemical composition (wt. %) of A356 “ASTM”.

	Si	**Fe**	**Cu**	**Mn**	**Mg**	**Zn**	**Ti**	**Other**	**Al**
Min	6.5	-	-	-	0.20	-	-	-	
Max	**7.5**	**0.6**	**0.25**	**0.35**	**0.45**	**0.35**	**0.25**	**0.15**	**Balance**

This alloy was supplied from Aluminium Company of Egypt in the ingot form of A356-1, the delivered alloy of A356 was chemically analyzed (actual analysis) with the help of optical immersion process and the result is shown in Table 2.

Table 2. Chemical composition (wt %) of the A356 Al-alloy used in this study.

Si	Fe	Cu	Mn	Mg	Zn	Ti	Other	Al
7.36	**0.15**	**0.0462**	**0.00129**	**0.329**	**0.00229**	**0.136**	**0.012**	**Balance**

The Aluminium – Silicon phase diagram shows that the equilibrium eutectic constitution is about 12.6 wt% silicon. Figure 1 shows that the aluminum-silicon eutectic can form as follows:

- Directly from the liquid in the case of a silicon concentration of 12.6%, for a eutectic aluminum-silicon alloy.
- In the presence of primary aluminum in the case of silicon contents less than 12.6%, for hypoeutectic aluminum-silicon alloys), and
- In the presence of primary silicon crystals in the case of silicon content greater than 12.6%, for hypereutectic aluminum-silicon alloys.

The chosen aluminium alloy in this study consider as in a hypoeutectic Al-Si alloy. Its liquids temperatures started at 614°C and solidification ended at 577°C (eutectic temperature). The microstructure comprises both primary Fcc- aluminium solid solution containing 1.65wt% silicon and eutectic containing silicon enriched aluminium and pure silicon [8].

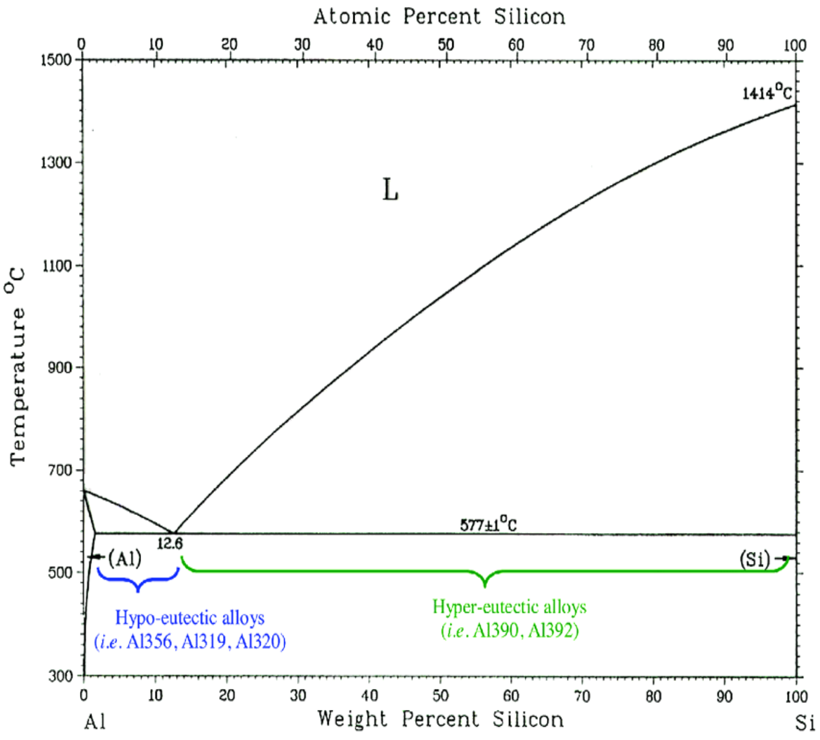


Figure 1. Al-Si phase diagram showing hypo-and hyper-eutectic alloys.

2.2 Addition of Grain Refiner

An amount of 1.5 Kg of A356 alloy was melted in a heat resistance furnace with using of a steel crucible coated from inside with graphite. After complete melting of the alloy, the temperature of the molten metal was kept at a temperature of 740 °C± 10 °C, which is higher than its liquidus temperature by about 125 °C to allow the complete dissolution of the silicon particles. Aluminium alloy Al–5Ti–1B was used in this investigation as grain refiner, then treated with addition different amounts of grain refiners, 0%, 1%, 3%, 5 wt. %, respectively. After addition of the grain refiner, the melt was manually stirred with a steel rod coated with a graphite and was maintained at 740 °C for 5 minutes for homogenization. The thermocouple type K (chromel–alumel) is accurate, inexpensive and has a wide temperature range, this type of thermocouple was used in measuring the temperature during melting process, and in addition, calibration was done before and after each series of melts.

2.3 The Microstructure Analysis

Metallographic samples were cut from the same position for all experiments, the distance was 15mm from the bottom of casting, as shown in Figure 2, and the samples were prepared according to used procedures development of aluminum alloys. The specimens were obtained under different condition with adding the (0, 1, 3, 5 wt. %) of Al-5Ti-1B master alloy. The specimens were taken from each cast sample for microstructure analysis by sectioning the cylinders parallel to its longitudinal axis, three specimens for microstructure analysis were made from one section. The samples were cut and grinding using standard metallographic procedures. The grinding was done by using 240, 320, 400, and 600 grit papers. Then, the samples were polished using 1 µm, and 0.05 µm Alumina suspension in water. A final polishing was done using silica suspension. The samples were thoroughly cleaned after each step.

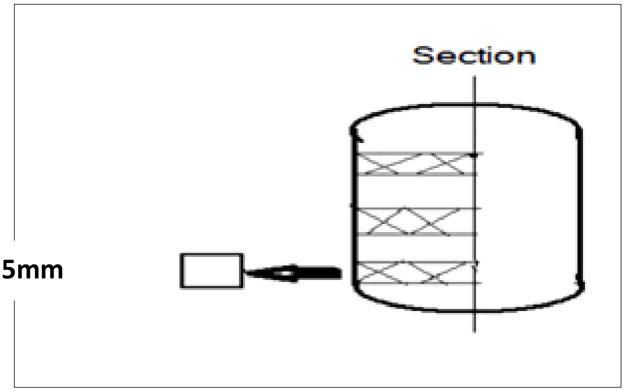


Figure 2. Location of specimens from bottom of cast cylinder of Aluminum Alloy-A356.

2.3.1 The Optical Microscopy and Quantitative Characterization

The samples that used for characterization optical microscopy were etched using 0.5% HF solution to reveal the resulting microstructure [9]. Grain size, length, and width of both eutectic silicon and α - aluminium are measured by linear intercept method applied to the microstructure obtained from polarized light in optical microscope at 400X. Six digital micrographs are processed using image C-software. The average of ten readings is taken from the results.

2.4 Tensile Test

The tensile tests of samples were carried out at ambient temperature of 25 °C using UH-F1000KNI/Shimadzu universal testing machine with a strain rate of 5 mm/min. The stress and strain curves were provided as a computer output by the control unit of the test machine. The samples were taken from each cast piece by sectioning the cylinders parallel to its longitudinal axis for tensile testing, three tensile test specimens were fabricated from one section, the location for tensile test is shown in Figure 3, the gauge length of the tensile test specimens was 36 mm and 6mm diameter as described in ASTM E8M [10].

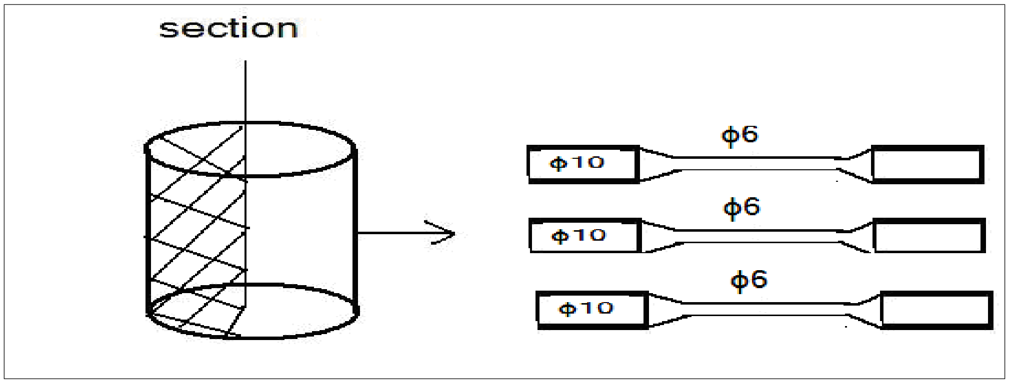


Figure 3. Schematic drawing of tensile test specimen and their location in the mould with ASTM E8.

3. Results and Discussion

3.1. Microstructure of A356

Microstructures of the solidified samples taken from the mould without adding the Al-5Ti-1B master alloy are presented in Figure 4(a,b,c), the microstructure exhibits the overall matrix and eutectic Si morphology respectively. The microstructure of the as-cast aluminium alloys A356 is a fully dendritic structure of α solid solution and eutectic silicon. Figure 4a showed also coarse acicular eutectic silicon dispersed among the fully developed dendritic primary α-aluminium (white) and eutectic silicon (dark- gray). One branch of a primary α-aluminium was about 600 μm in length, as shown in Fig. 4a, which indicated that the grain size was about a few millimeters as one grain usually contained several arms. The microstructure of the hypoeutectic aluminium alloys (A356), usually consists of coarse dendritic α-Al solid solution and Al–Si eutectic, where Si usually observed as long plate or big spheres shape. There were a number of researchers reported the presence of intermetallic phases like the eutectic Al_2Cu “Chinese script” shaped α-Al_{15} $(Mn,Fe)_3Si_2$ and long sharp needles of β-Al_5FeSi, which precipitate in the interdendritic and intergranular regions, and strongly detrimental to the alloy mechanical and fatigue properties [11, 12].

3.2 The Microstructure of A356 with inoculated by Al-5Ti-1B

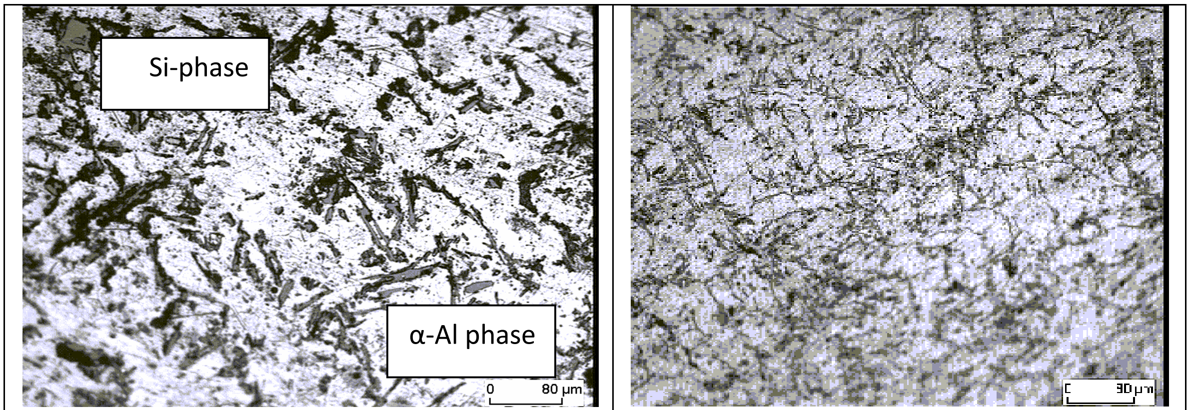
A typical optical microscopy images of the A356 alloy with adding the (1, 3, 5 wt. %) Al-5Ti-1B master alloy are shown in figure 4(d,e,f). It is clearly that in the absence of grain refiner, the cast A356 alloy consists of dendritic primary α-Al and interdendritic needle plate-like eutectic silicon distributing randomly as shown in Figure 4(a). However, after adding the Al-5Ti-1B master alloy, the microstructures changed from coarse dendrites to fine equiaxed α-Al dendrites, without any change in the morphology of the eutectic Si particles. The grain refiner does not modify the eutectic Si as expected, this is shown in Figure 4(d,e,f). On the other hand, it can be seen that the primary α-Al phase that is not treated by grain refinement, was developed obviously into fully dendritic with the average length of its primary arm up to 1400μm as shown in Figure 4(c). After adding the Al-5Ti-1B master alloy, the morphology of the primary α-Al dendritic crystal was changed to a somewhat equiaxed structure or small polygonal as shown in Figure. 4(d,e,f) with reducing the size of the primary α-Al phase obviously. In addition, the average grain sizes at different levels of Al-5Ti-1B master alloy is calculated using quantitatively analyzed software (linear intercept method). The results of these calculation are summarized in Table 3.

Table 3. **Average grain size of α – Aluminium**

Al-5Ti-1B (wt.%)	**0**	**1**	**3**	**5**
Average grain size (µm)	**730**	**270**	**255**	**260**

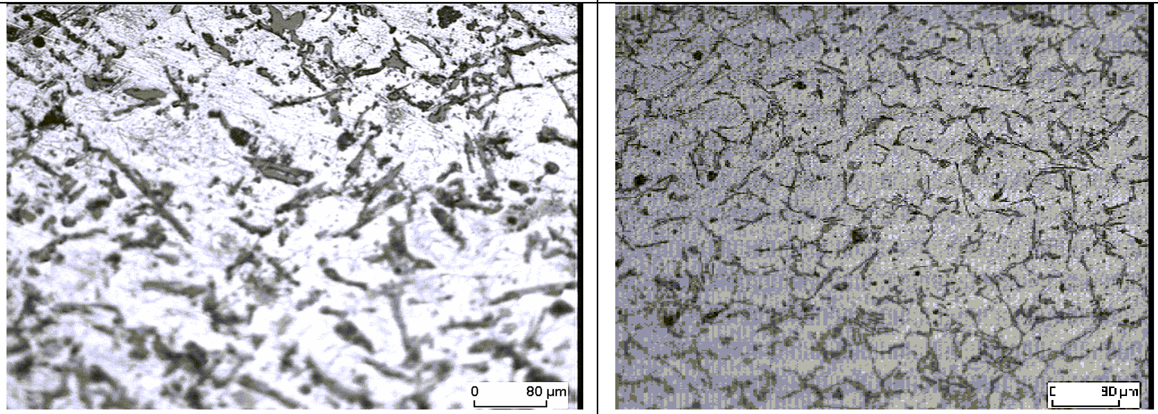
The average grain size of A356 without addition of grain refinement was several micrometers. Upon inoculated by Al-5Ti-1B master alloy, the dendritic structure is divided into a somewhat globular grain structure. When adding an amount of Al-5Ti-1B master alloy from 1 to 3 wt. % lead to a decrease in grain size from 270 to 255 µm. However, when the addition increased to 5 wt.% , the grain size is slightly increase to 260 µm, there is no significant grain size difference between different level of Al-5Ti-1B master alloy was observed.

The effect of various amounts of Al–5Ti–1B grain refiner on the average grain size of the cast specimens is indicated in Table 3. It can be seen that the increase of Al–5Ti–1B master alloy from 1 to 3 wt.% to the alloy resulted a fine microstructure and almost significant reduction of the average grain size. However, by further addition of grain refiner (5 wt.%) to the alloy, the average grain size almost remains constant and the excess addition of the grain refiner does not have a considerable effect on the microstructure of the alloy. Therefore, the optimum amount of 3 wt.% Al–5Ti–1B was selected for refining of the alloy. The grain size bears an inverse relationship to the number of nuclei presented in the liquid state, and will act as nucleation sites during solidification. Since each grain forms from one single nucleus, as great the number of nuclei presented in the melt, as more grains will be formed, thus their size will be reduced. If the number of nuclei is sufficiently high, dendritic structure could not be formed, as they will have no space to grow, and globular grains will preferentially formed. Furthermore, in the previous researches, which have been carried out on the



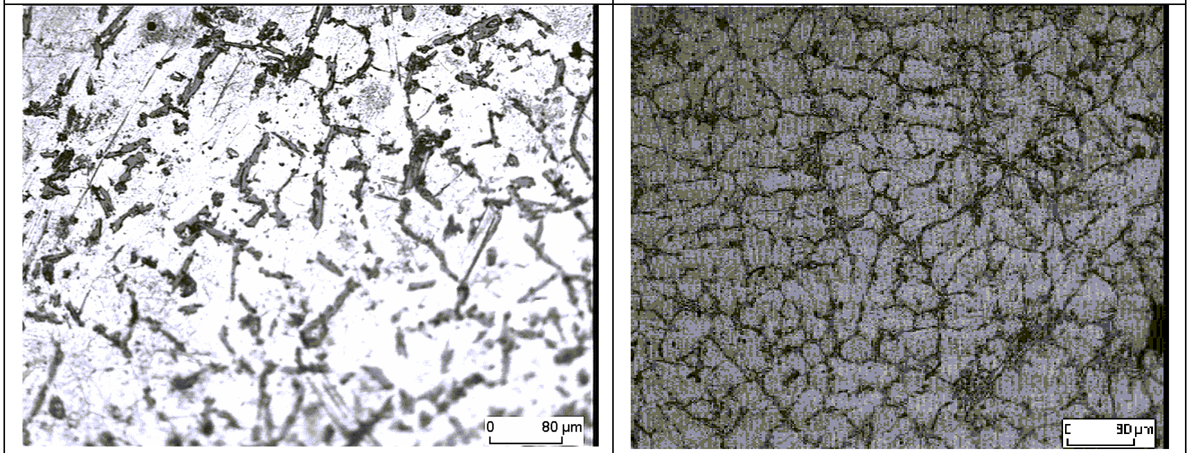
(a) 0 % Al-5Ti-1B

(d) 1 % Al-5Ti-1B



(b) 0 % Al-5Ti-1B

(e) 3 % Al-5Ti-1B



(c) 0 % Al-5Ti-1B

(f) 5 % Al-5Ti-1B

Figure 4. Optical micrograph of A356 with and without addition of Al–5Ti–1B.

effect of the different amounts of Al–5Ti–1B master alloy in thin section casting (Φ6 mm) of aluminium alloy Al–12Zn–3 Mg–2.5Cu, the optimum amount of Al–5Ti–1B was found to be 1 wt.% by Seyed Ebrahimi [13], and 2 wt.% by Alipour [14]. Others researchers recorded the most significant improvement of microstructure of A356, when adding 2.5 wt.% of the Al-5Ti-1B master alloy[15].

3.3 Mechanical Properties

3.3.1 Mechanical Properties of A356 At Different Levels Of Grain Refinement

The mechanical properties of A356 alloy refined with the different amounts of master alloys (0, 1, 3, 5 wt.%) Al-5Ti-1B were determined and the results are shown in Figures 5 and 6. It is clear that the ultimate tensile strength (σ_{uts}), yield strength (σ_y) and elongation (δ) of the A356 alloy without grain refinement are correspondingly lower than those of the refined ones. It can be seen that the tensile strength, yield strength and elongation are increased markedly with addition of grain refinement, the tensile strength, yield strength and elongation of the A356 with 3 % grain refine of (Al-5Ti-1B) are 156.3 MPa, 104.3 MPa and 4.9%, respectively, i.e. improvement occurred by 12 %, 6 % and 8.9 % respectively compared with that one's of non-grain refined. The improvement of tensile properties of the refined A356 alloy can be attributed to the formation of supersaturated solid solution in the solution treatment process and Mg_2Si precipitates during aging [15]. It can be seen that the increase of Al–5Ti–1B master alloy from 0 to 3 wt. % can result in a significant improvement of mechanical properties of the A356 alloy. However, the mechanical properties almost remains constant by further addition of grain refiner (5 wt.%) and the excess addition of the grain refiner does not have any considerable effect on the mechanical properties of the alloy. In the previous work [15], which has been carried out on the effect of the different amounts of Al–5Ti–1B master alloy on the mechanical properties of aluminium alloy. The most significant improvement of tensile properties of A356 was obtained by adding 2.5 wt.% of the Al-5Ti-1B master alloy. The main reason for the improvement of the mechanical properties of A356 with addition of grain refinement (Al–5Ti–1B) may also be due to solid solution strengthening and precipitation hardening. Grain refinement is the key strengthening mechanism for as cast A356 alloys [15]. The increase of ultimate tensile strength, yield strength and elongation values which occurs as a result of grain refinement is due to grain boundary strengthening mechanism that is best described as Hall–Petch equation ($\sigma_y = \sigma_0 + k_y d^{-\frac{1}{2}}$), that demonstrates the yield strength dependence on grain size, d (mm),[16]. These results confirm expectations based on the metallographic results, Figures 5 and 6.

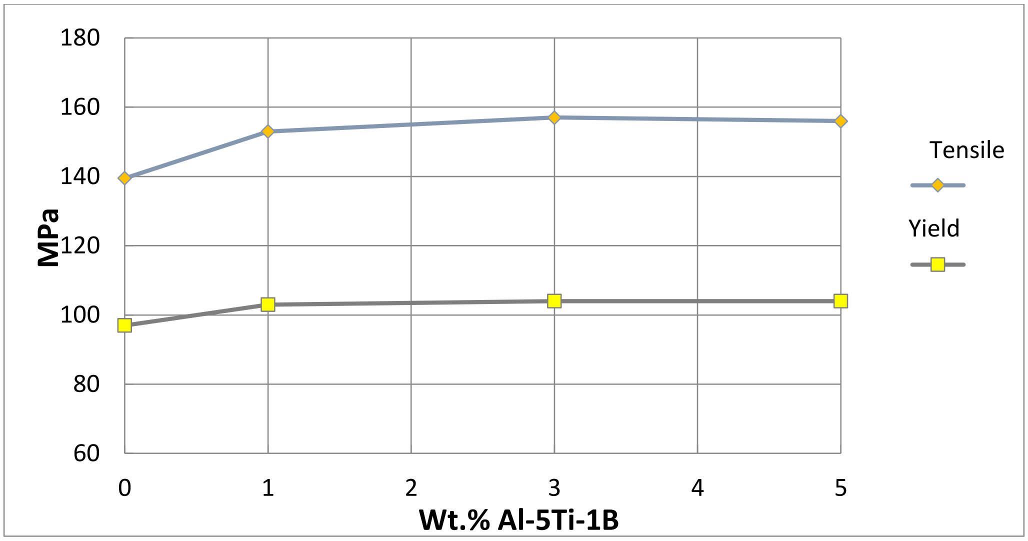


Figure 5. Ultimate tensile strength and yield strength of A356 alloy refined with different levels of the Al-5Ti-1B master alloy.

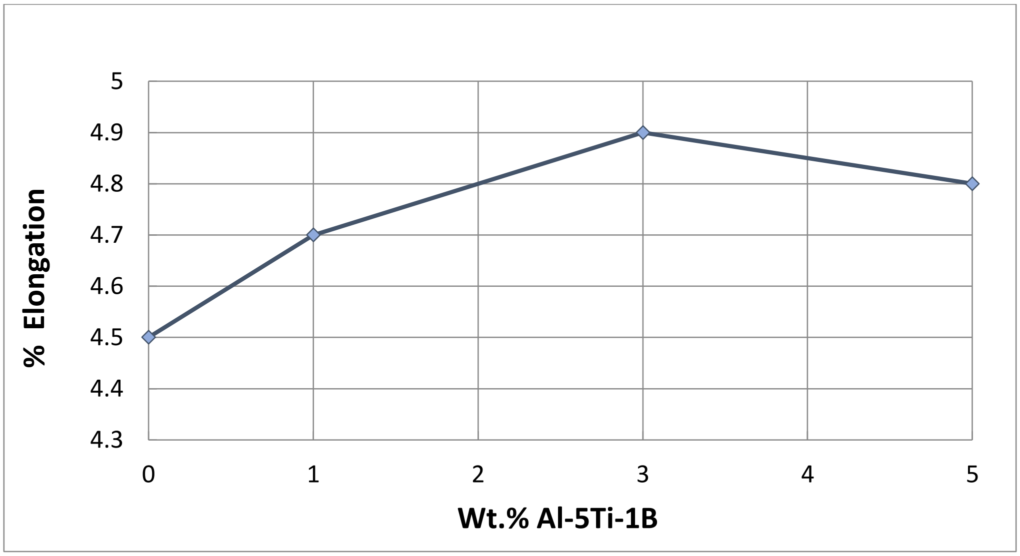


Figure 6. Elongation of A356 alloy refined with different levels of the Al-5Ti-1B master alloy.

4. Conclusions

The microstructures, mechanical properties of the refined A356 alloys were investigated by introducing both titanium and boron in the form of Al-5Ti-1B master alloy and the following conclusions can be drawn:

- At the addition of Al-5Ti-1B in aluminium alloy-A356, α-Al phase can be well refined from coarse dendrites to fine equiaxed grains, having an average grain size of 260 µm.
- At the addition of Al-5Ti-1B in aluminium alloy-A356, the eutectic silicon remains unchanged in the as-cast A356 alloys.
- Enhancement in the mechanical properties such as tensile strength and yield strength were obtained with a significant increase in their values in the case of A356 alloy where grain refiner Al-5Ti-1B were added as compared to that of without grain refinement.
- Elongation of A356 alloy refined with different levels of the Al-5Ti-1B master alloy initially increased then slightly decreased.
- The results indicate that a small amount of Al-Ti5-B1 produces the greatest refinement, while no significant reduction of grain size is obtained with a great amount of grain refiner.

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