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Characterization of Aluminum Alloy-Based Nanocomposites Produced by the Addition of AL-TI5-B1 to the Matrix Melt

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ABSTRACT

The present study is an attempt to produce aluminum matrix nanocomposites using a certain aluminum alloy (which its melt has high fluidity) as a matrix material and reinforced with hard and stable fine (nano-sized) precipitates. Therefore, Al-Ti5-B1 master alloy and Al-Si alloy of high silicon content were proposed for preparation of such nanocomposites. Three nanocomposites were prepared by adding Al-Ti5-B1 of three different percentages (1, 2 and 3 wt. %) to the melt of aluminum alloy at 710°C for a holding time of 10 min and application of mechanical stirring at this temperature. Finally, the treated melt was squeeze cast. The microstructures were investigated using optical and scanning electron microscopes. Phases and different constituents were analyzed with the aid of EDX and XRD analyzers. The addition of Al-Ti5-B1 master alloy with any percentages (even 1 wt. %) to the melt of aluminum alloy, led to remarkable decrease of the matrix grain size. Moreover, many fine precipitates were detected within the Al-Si matrix such as $TiAl_3$ phase in the form of flaky and blocky morphology and TiB_2 phase in the nano-sized particles. These precipitates act as heterogeneous sites for nucleation during solidification. The addition of Al-Ti5-B1 master alloy to the Al-Si base metal led to remarkable increase in the average hardness. As the added percentage of Al-Ti5-B1 master alloy is increased, the average hardness value is increased. The average hardness of addition of 3 wt. % Al-Ti5-B1 master alloy reached 130 HV, which was almost twice as high as the hardness of the Al-Si base metal.

Keywords: Aluminium Grain Refinement, Al-Ti5-B1 Master Alloy, TiB_2 Particles, $TiAl_3$ Intermetallic Compounds, Aluminium Matrix Nanocomposites, Hardness, Wear Resistance

1. INTRODUCTION

For a long period, aluminum alloys were some of the most widely used materials as the matrix of metal matrix composites MMCs, both in research and development and in industrial applications. This is mainly due to the low density of aluminum alloys (the first requirement in most application). Moreover, they are inexpensive in comparison with other low density alloys (such as Mg or Ti) (Feng and Froyen, 2000). Nowadays, Aluminum Metal Matrix Composites (AMMCs) are one of the advanced engineering materials that have been developed for weight critical applications in the aerospace, defense, marine and more recently in the automotive and transport industries due to their excellent combination of high specific strength and superior wear resistance. In the automobile sector, AMMCs are used for making various components such as pistons, cylinder heads, connecting rods, where the tribological properties of the materials are very important (Sajjadi *et al*., 2012; Yadav *et al*., 2011; Storjohann *et al*., 2005). MMCs with uniform dispersion particles in the range of 10 nm -1 µm are termed “Metal Matrix Nano-Composites” (MMNCs). These nano-

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composites exhibit more outstanding properties over ordinary MMCs and are assumed to overcome the shortcoming of MMCs such as poor ductility, low fracture toughness and machinability (Sathyabalan *et al*., 2009; Srinivasan *et al*., 2012).

The widely used particle for reinforcing Al alloys is SiC. Besides its low density and low cost, SiC enhances an increase in the Young's modulus, hardness and tensile strength. However, these composites suffer from a great loss in ductility and toughness due to the undesirable reactions between SiC particles and aluminum, yielding Al_4C_3 interfacial product, which limits their applications to a certain extent (Mahmoud *et al*., 2008). On the other hand, Titanium diboride (TiB_2) has distinct advantages over SiC because of its inertness to aluminum matrix (Shackelford and Alexander, 2001). In other words, formation of brittle intermetallic products at the interface between the reinforcement and matrix can be avoided using the TiB_2 particles. Moreover, TiB_2 particles exhibit high elastic modulus and hardness, high melting point and electrical conductivity as well as good thermal stability. On the other hand, there was a great limitation on the amount of TiB_2 particles added to the matrix due to the higher viscosity of the resultant MMCs. Accordingly; several studies have been conducted to syntheses the in situ TiB_2 particulate reinforced Al-based composites with enhanced mechanical properties (Salvador *et al*., 2003; Tjong and Huo, 2009; Boopathi *et al*., 2013; Sivaprasada *et al*., 2008).

Moreover, the titanium aluminides; $TiAl_3$ and TiAl, have been considered one of most important reinforcement candidates due to their low density, excellent mechanical properties, especially at high temperatures and high wear resistance (Adamiak *et al*., 2004; Sathyabalan *et al*., 2009). These unique properties of Al based MMCs reinforced with titanium aluminides make them a good candidate to substitute traditional high temperature alloys, such as nickel super alloys, in the aerospace industry, especially in turbine elements (Salvador *et al*., 2003).

Regarding the aluminum matrix, grain refinement is a common way to increase both strength and toughness of the material at ambient temperatures (Wang *et al*., 2004). Fine grain structure can be produced by various methods: Using grain refiners, rapid solidification, mechanical milling/alloying of powder metals and severe plastic deformation (SPD).

It is expected that addition of Al-Ti5-B1 master alloy to the melted aluminum during casting can achieve almost all the previous advantages by one step. Al-Ti5-B1 master alloy is one of the main grain refiners (Yi *et al*., 2006). In situ aluminum aluminides (Al_3Ti) and TiB_2 particles can be formed during solidification by the reactions between Al and Ti and between Ti and B elements (Nagli *et al*., 2008). The present study has been undertaken to present the feasibility of adding Al-Ti5-B1 master alloy to the melted Al-Si base alloy and to reveal the grain refinement and any resultant in situ reactions formed during solidification.

2. MATERIALS AND METHODS

In this study, Al-Si alloy was used as a base material. The chemical composition of this base material is shown in **Table 1**. Al-Ti5-B1 master alloy was added in different percentages (1, 2 and 3 wt. %) to the melted Al-Si alloy at 710°C, for a holding time of 10 min. Mechanical stirring was applied at this temperature and then squeeze casted. The microstructures of the matrix material (Al-Si alloy) and the resultant intermetallics were investigated using optical and scanning electron microscopes equipped with EDX analyzer. The resulted microstructures were analyzed by X-Ray Diffractometer, (XRD) to identify experimentally the new phases that were in situ formed inside the Al-Si matrix. The microhardness of the product was also measured with Vickers hardness tester at 200 g load for 15 s.

3. RESULTS

3.1. Microstructure Analysis

Macroscopic appearance of the Al-Si base metal without any addition together with that produced after addition of Al-Ti5-B1 master alloy with different concentrations, are shown in **Fig. 1**. Generally, there was a great reduction in α-Al grain size after the addition of Al-Ti5-B1 master alloy to the Al-Si base metal (compare **Fig. 1a-c**. On the other hand, the addition of different concentrations of Al-Ti5-B1master alloy to the Al-Si base metal has almost no significant changes in the grain size (compare **Fig. 1b** with **Fig. 1c**). **Figure 2 and 3** show the scanning electron micrographs for the microstructures of Al-Si base metal treated by the addition of Al-Ti5-B1 master alloy with concentration of 1 and 3%, respectively. At lower magnifications (**Fig. 2a and 3a**), both microstructures show fine dendritic eutectic morphology structure inside α-Al grains.

Table 1. Chemical composition of the base aluminum alloy; (wt.%)

Al	V	Pb	Cr	Ti	Ni	Mg	Mn	Cu	Fe	Si
Bal.	0.02	0.01	0.02	0.02	0.13	0.51	0.40	2.06	0.41	7.22

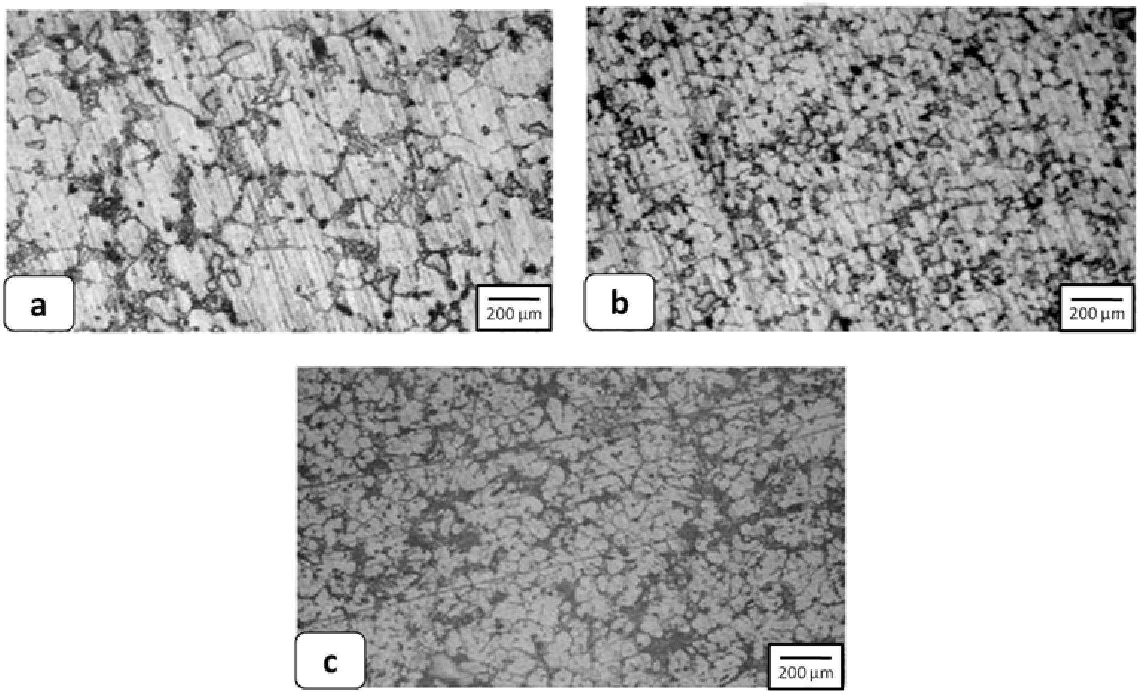

Fig. 1. Optical microscopic appearances of: (a) Al-Si base metal without any addition, (b) and (c) base metal with addition of 1 and 3% Al-Ti5-B1 master alloy, respectively

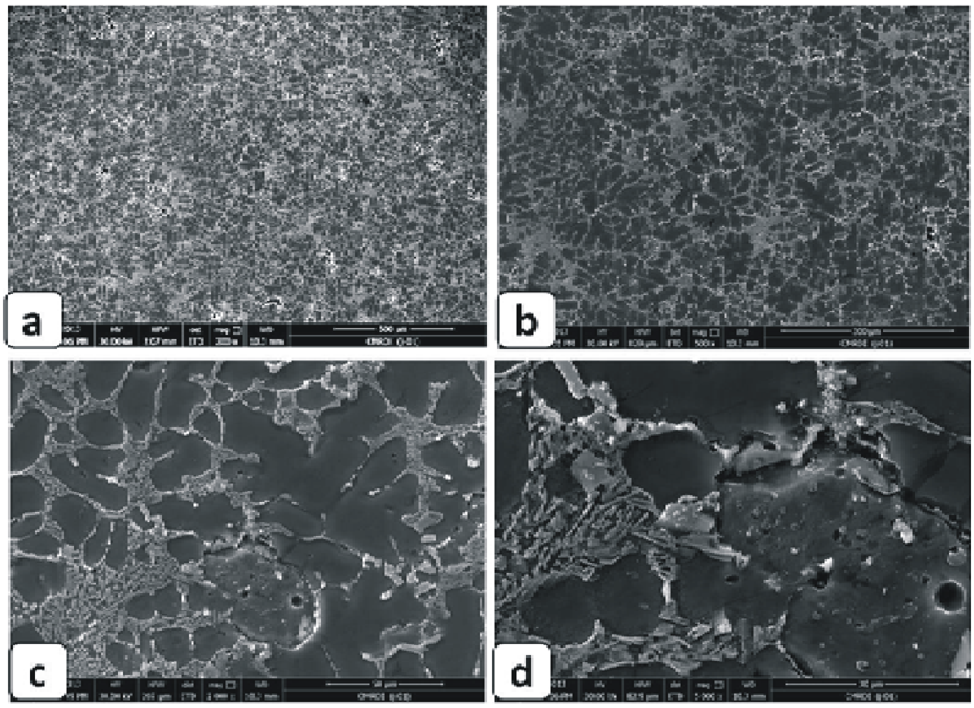

Fig. 2. Different magnified SEM micrographs of Al-Si base metal with addition of 1% Al-Ti5-B1 master alloy

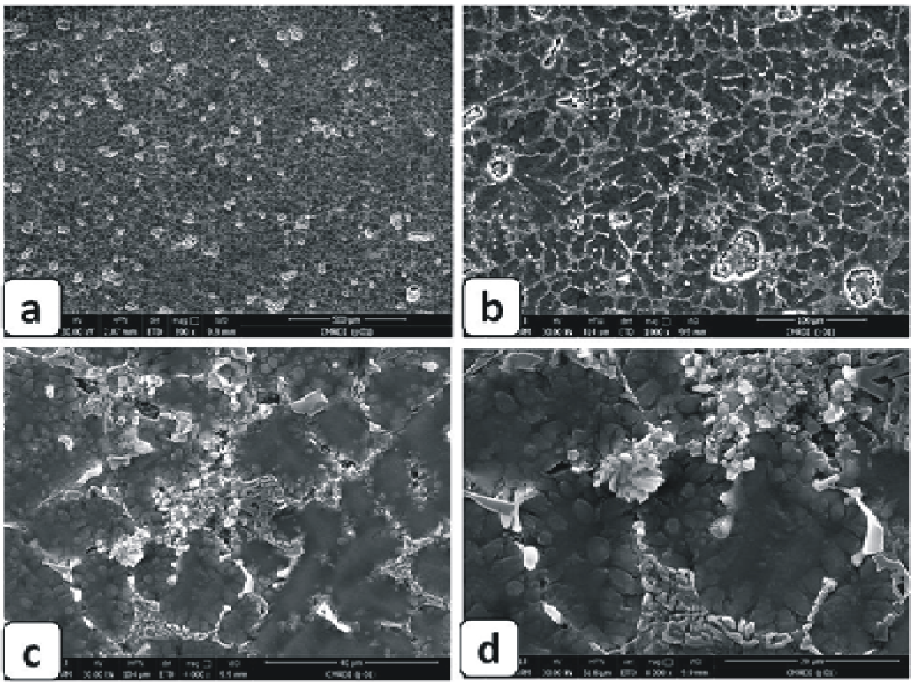

Fig. 3. Different magnified SEM micrographs of Al-Si base metal with addition of 3% Al-Ti5-B1 master alloy

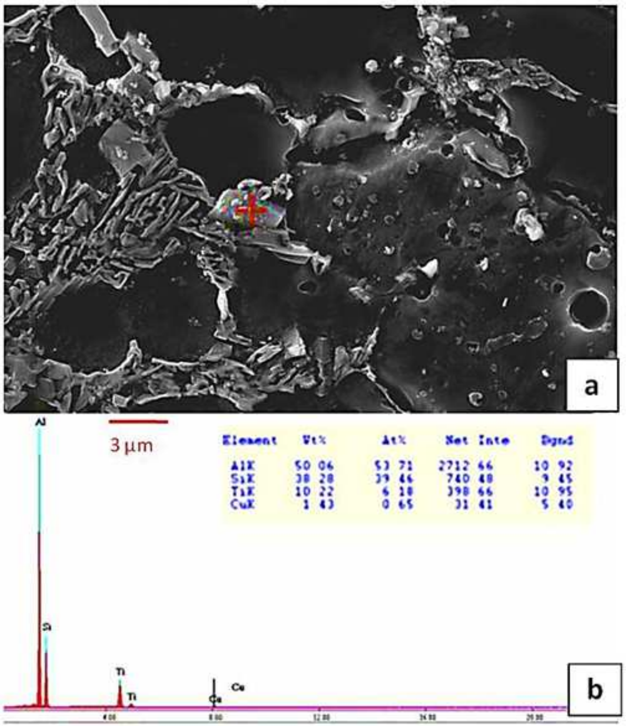

Fig. 4. EDS spectra of the cross mark in SEM micrographs of Al-Si base metal with addition of 1% Al-Ti5-B1 master alloy, indicating that it is $TiAl_3$ intermetallics

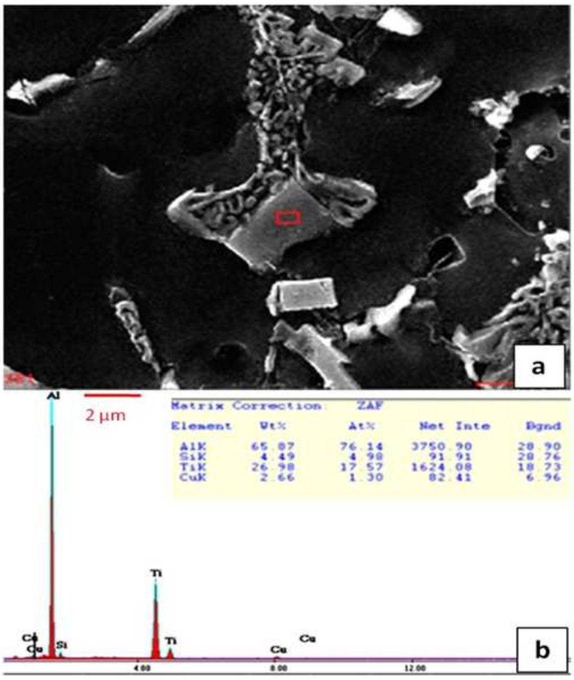

Fig. 5. EDS spectra of the red mark in SEM micrographs of Al-Si base metal with addition of 3% Al-Ti5-B1 master alloy, indicating that it is TiAl3 intermetallics

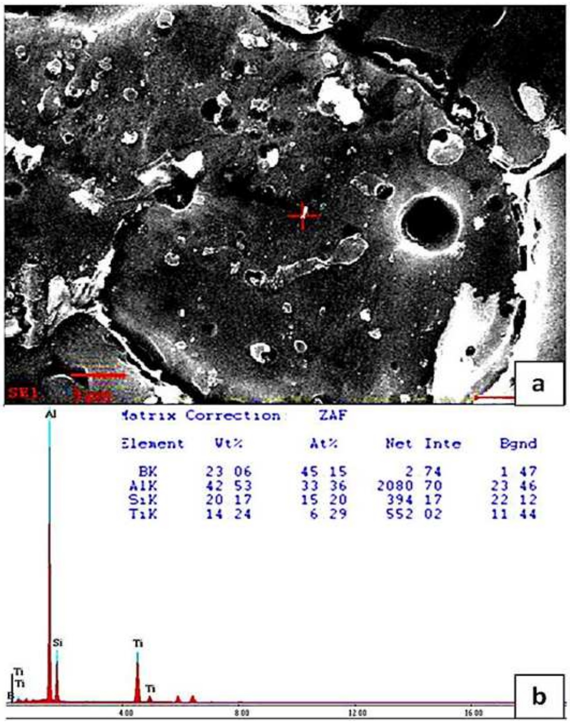

Fig. 6. EDS spectra of the cross mark in a grain center of Al-Si base metal with addition of 1% Al-Ti5-B1 master alloy, indicating that it is TiB_2 particles

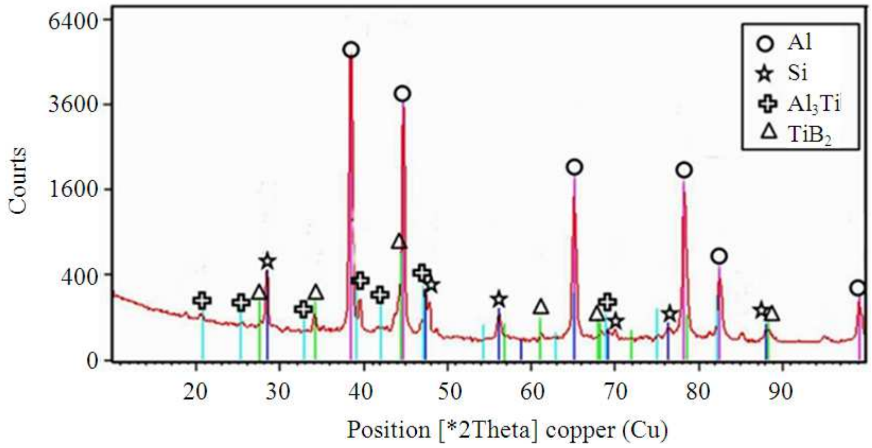

Fig. 7. XRD pattern of the sample that had addition of 3% Al-Ti5-B1 master alloy

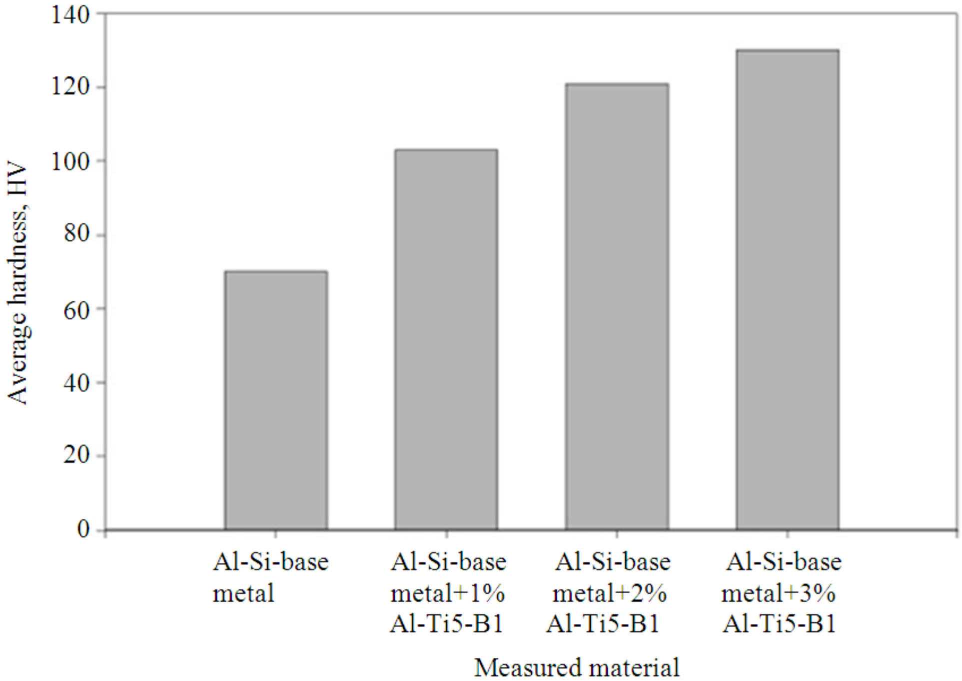

Fig. 8. Average hardness of Al-Si base metal and with addition of 1% Al-Ti5-B1 master alloy with different concentration

These dendrite structures are formed from the Si content of the base metal. Moreover, many precipitates are detected inside the Al matrix. At higher magnifications, these precipitates are appeared in the form of relatively large flakes and blocks in the Al matrix, especially at the grain boundaries, as clearly shown in **Fig. 2c and 3c**. By comparing SEM micrographs of **Fig. 2 and 3**, the percentage of precipitated $TiAl_3$ phase is greater in case of addition 3% Al-Ti5-B1 master alloy (**Fig. 3**) than that of addition of 1% (**Fig. 2**). With the aid of the EDX analysis, these flaky and blocky morphology precipitates are most probably $TiAl_3$ intermetallics (**Fig. 4 and 5**). At the grain center, both TiB_2 and $TiAl_3$ phases can be found as shown in **Fig. 6**. The XRD pattern of the sample that had addition of 3% Al-Ti5-B1 master alloy is shown in **Fig. 7**. It was clear that there were TiB_2 and

$TiAl_3$ phases in addition to that of the base metal; Al and Si, which confirms the microstructure analysis.

3.2. Hardness Measurements

Microhardness of the base material and the prepared nanocomposites was measured using microhardness tester and the measured values are presented in **Fig. 8**. It is clear that the addition of Al-Ti5-B1 master alloy to the Al-Si base metal led to remarkable increase in the average hardness. As the added percentage of Al-Ti5-B1 master alloy is increased, the average hardness value is increased. The average hardness of addition of 3% Al-Ti5-B1 master alloy reached 130 HV, which was almost twice as high as the hardness of the Al-Si base metal.

4. DISCUSSION

Coarse columnar α-Al dendritic grains are clearly revealed in the microstructure of the untreated alloy. With the addition of 1 wt. % of Al-Ti5-B1 master alloy, the coarse dendritic structure was transformed into another one of fine and equiaxed grains. The results showed thatthe increase in percentages of Al-Ti5-B1 master alloy (2 and 3 wt. %) has no significant effect on the grain refinement. This is may be due to that the grain refinement needs a very small amount of Al-Ti5-B1 master alloy (normally 0.2 wt. %). The extra amount will be precipitated as reinforcing particles. These particles are fine TiB_2 and $TiAl_3$ precipitates. They can be considered as heterogeneous sites for nucleation during solidification and also as obstacles for grain growth, which lead to grain refinement. In addition to the grain refinement, the dendrite arm spacing of microstructure produced by addition of 3% Al-Ti5-B1 master alloy is finer than that of addition of 1% (**Fig. 2a and Fig. 3a**). This can be attributed to the higher percentage of precipitated $TiAl_3$ phase in case of 3% Al-Ti5-B1 master alloy addition (**Fig. 3**). Moreover, many other fine (nano-sized) precipitates are appeared inside the grains (almost in the grain center). In addition to the grain refining effect of these precipitates, they shorten the eutectic dendrite arms. No normal long needle eutectic silicon is appeared. This means that the formation of in-situ TiB_2 and $TiAl_3$ particles not only refine the matrix grains but also change the eutectic structure into short forms.

As well known, the microstructure features affect the hardness of the material. It was noticed that, the grain refinement is accompanied by an increase in the hardness. In addition, the reinforcing particles strengthen the material. So, in the present investigation, the increment in hardness values by addition of Al-Ti5-B1 master alloy to the Al-Si base metal can be mainly attributed to two reasons. Firstly, the grain refinement of the base metal that can greatly share in this increment. Secondly, the formation of in-situ fineTiB_2 and $TiAl_3$ precipitates inside the Al matrix, which act as reinforcing particles. These fine precipitates are very hard, very stable even at high temperature and they can be considered as reinforcement candidates, as reported by other investigators (Salvador *et al*., 2003). As a final conclusion, the presence of TiB_2 and $TiAl_3$ with high percentages can be considered as grain refining and reinforcing particles.

5. CONCLUSION

In this study, we presented a detailed study on the effect resulted from addition of Al-Ti5-B1 master alloy in different percentages (1, 2 and 3 wt. %) to the melt of considered Al-Si base metal at 710°C for a holding time of 10 min and application of mechanical stirring and squeeze casting. The results obtained can be summarized as follows:

- The addition of Al-Ti5-B1 master alloy with any percentages (even 1 wt. %) to the melt of investigated aluminum alloy, led to remarkable decrease of the matrix grain size
- The addition of Al-Ti5-B1 master alloy to the Al-Si alloy led to fine eutectic dendrites at the boundaries of α-Al grains
- The amount of added Al-Ti5-B1 master alloy to the Al-Si base metal had much less significant effect on the matrix grain size
- Many fine precipitates were detected within the Al-Si matrix such as $TiAl_3$ phase in the form of flaky and blocky morphology and TiB_2 phase in the nano-sized particles
- Addition of Al-Ti5-B1 master alloy to the Al-Si alloy had remarkable improvements in hardness. The hardness was increased to about 130 HV for addition of 3% Al-Ti5-B1 master alloy compared with about 70 HV of the Al-Si base metal

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