Microstructural and Thermal Properties of Piston Aluminum Alloy Reinforced by Nano-particles

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Abstract. Aluminum alloys have been widely utilized in engine pistons of automotive industries. Under such loading conditions, thermal stresses were applied to the piston material, due to the combustion process. Knowing the thermal behavior and microstructural properties of the material has an important rule for designers. Besides, the used material should withstand these thermal expansions and one way to increase this thermal strength is to add nano-particles for reinforcing the material. In the present article, the thermal behavior of piston aluminum alloys has been analyzed. This objective has been performed by thermal dilatometric measuring to find the thermal expansion coefficient. Then, the effect of adding nano-particles for reinforcing the aluminum alloy has been also investigated. In addition, the distribution of nano-particles in the aluminum matrix was also studied by the field emission scanning electron microscopy (FE-SEM). Besides, the microstructure of the piston aluminum alloy, with and without SiO_2 nano-particles, was investigated.
Keywords. Microstructural properties; Thermal properties; Piston aluminum alloy; Nano-particles reinforcing; Dilatometric measuring; Thermal expansion coefficient.

INTRODUCTION

Pistons are an important component in engines, which are exposed to thermal and mechanical loadings. For design engineers, it is better to strengthen the material for such high loads. Besides, they tend to reduce the weight and therefore, aluminum alloys have been widely utilized in piston industries. This selection of aluminum alloys is according to their high ratio of the strength to the weight. One way for strengthening aluminum alloys is to reinforce the material by nano-particles to make a metal matrix composite (MMC).

For such objective, researchers have recently investigated thermal and mechanical properties of such aluminum alloys, reinforced by different nano-particles. In order to study mechanical properties, a high number of articles has been published. However, studies on the reinforcement of aluminum alloys by nano-articles and also thermal properties of aluminum alloy nano-composites are still rare. A literature review on these researches can be found in following paragraphs.

In several articles [1-6], SiC nano-particles have been added to different aluminum alloys. Jiang and Wang [1] evaluated the microstructure and mechanical properties of the rheoformed cylindrical part of the 7075 aluminum matrix composite reinforced with nano-sized SiC particles. In another similar article, they [2] reported the microstructure and mechanical properties of semi-solid slurries and the rheoformed component of the nano-sized SiC/7075 aluminum matrix composite, prepared by ultrasonic-assisted semisolid stirring. Jiang et al. [3] performed the microstructure evaluation of the semi-solid billet of the nano-sized SiC_p/7075 aluminum matrix composite during the partial remelting process. Mazahery and Ostad Shabani [4] reinforced a commercial casting aluminum alloy matrix with nano-sized silicon carbides by experimental and novel modeling evaluations. Reddy et al. [5] reviewed researches about silicon carbide reinforced aluminum metal matrix nano-composites. Yang et al. [6] studied the bulk aluminum matrix nano-composite fabricated by the ultrasonic dispersion of nano-sized SiC particles in the molten aluminum alloy.

In other cases [7-13], some other nano-particles have been added to aluminum alloys. Yolshina et al. [7] evaluated the synthesis and properties of novel aluminum-graphene and aluminum-graphite metallic composite materials. Liberini et al. [8] investigated nano-TiO_2 coatings on aluminum surfaces by the aerosol flame synthesis. Nassar and Nassar [9] studied properties of aluminum matrix nano composites prepared by powder metallurgy processing. Lu et al. [10] performed the WC nano-particle surface injection via laser shock peening onto the 5A06 aluminum alloy. Sadreddini and Afshar [11] studied the corrosion resistance enhancement of Ni-P-nano SiO_2 composite coatings on aluminum. Shi et al. [12] found electro-chemical and mechanical properties of super-hydro-phobic aluminum substrates, modified with nano-silica and fluorosilane. Issa et al. [13] developed an aluminum/amorphous nano-SiO_2 composite using powder metallurgy and hot extrusion processes.

For the dilatometric analysis on aluminum alloys, the number of researches is still rare. Hadjadj et al. [14] characterized the precipitation and phase transformations in the Al-Zn-Mg alloy by the differential dilatometry. Hadjadj and Amira [15] studied the effect of the Cu addition on the precipitation and the redissolution in the Al-Zn-Mg alloy by the differential dilatometry.

In this research, the effect of the addition of SiO_2 nano-particles on the microstructure and thermal properties of piston aluminum alloys has been investigated. In addition to the microstructure investigation, thermal dilatometric measuring was performed to find the thermal expansion coefficient of materials.

MATERIALS AND EXPERIMENTS

The studied material in this research is an aluminum alloy, which has been widely used in engine pistons. The chemical composition of this aluminum alloy was measured as 12.5% wt. Si, 0.4% wt. Fe, 2.4% wt. Cu, 0.7% wt. Mg, 2.2% wt. Ni and Al is the remainder. Other elements had values lower than 0.1% wt. in the material. Nano-particles included SiO_2 with the dimension of 20-30 nm. They were coated by aluminum, using the planetary ball mill equipment for 3 times in the time duration of 20 min. Then, the X-ray defractometer (XRD) analysis was carried out in order to check the process.

The production method was gravity and stir casting for aluminum alloys, without and with nano-particles, respectively. Cylindrical specimens were casted in a cast-iron permanent mold. Nano-particles have been added to aluminum alloys with the weight percent of 1%. After the production, the microstructure of materials was examined under the optical microscopy. For the metallography, the etchant was water, HNO_3 nitric acid, HCl hydrochloric and HF hydro fluoric. In addition, to check the distribution of nano-particles in the matrix, the field emission scanning electron microscopy (FE-SEM) was utilized.

Thermal properties of the material were also characterized based on the standard test method for the linear thermal expansion of solid materials, by the thermo-mechanical analysis, according to the ASTM E-831-06 standard. This test has been done by the equipment entitled “Linseis/L75”, shown in “**FIGURE 1**”. The specimen geometry was 20 mm of the length and 5 mm of the diameter. The temperature range was selected as 100 to 350°C with the rate of 10°C/min. The maximum temperature was 350°C, since the maximum temperature in engine pistons would be occurred under this condition during working.

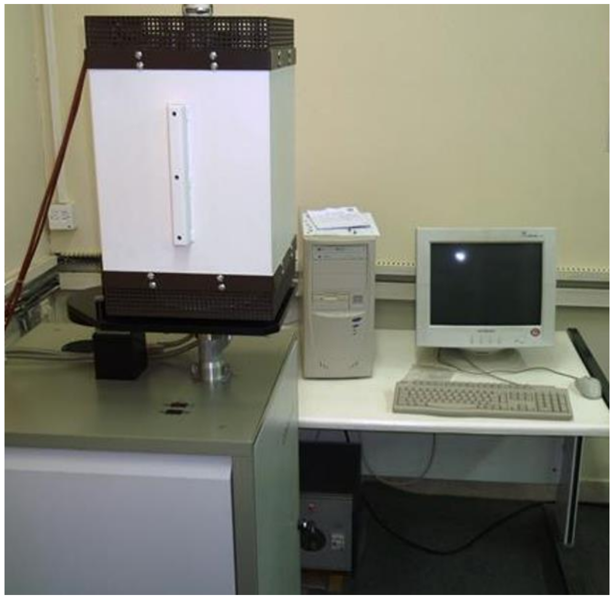


FIGURE 1. The dilatometric equipment for the analysis of thermal properties.

RESULTS AND DISCUSSIONS

As the first result, the XRD result and the FE-SEM image for nano-particles showed that the process of coating by aluminium was properly performed. For checking the distribution of nano-particles in the matrix, "**FIGURE 2**" shows the FE-SEM image. In this figure, it can be seen that a proper distribution was occurred during the stir casting process. The diameter of nano-particles was measured as 26.81 and 32.37 nm, mentioned also on the figure. These results could be confirmed by the literature [11,13] that they were not agglomerated so much.

The material microstructure, which was obtained by the optical microscopy, depicts in "**FIGURE 3**" for both aluminium alloys, with and without nano-particles. Using references [16-17] for a similar aluminium alloy (A332-F), the material (without nano-particles) should have different phases, including the interdendritic network (the α-Al phase), the eutectic Si region (silicons in the medium-gray script), and some intermetallic phases of Mg_2Si (the black script), Cu_3NiAl_6 (the light-gray script) and $NiAl_3$ (dark-gray particles). In this study, all mentioned phases could be observed in the material microstructure, shown in "**FIGURE 3**", except the Cu_3NiAl_6 intermetallic phase. This does not mean that the Cu_3NiAl_6 phase or other intermetallic phases (such as the Fe-rich phase) do not exist. This problem should be solved by more microstructural investigations, plus using the energy dispersive X-ray (EDX) analysis, to determine the exact intermetallic phase.

For the piston aluminium alloy with SiO_2 nano-particles, same phases could be seen, in addition to a new phase including $Si+SiO_x$ (in the light-yellow script), according to add nano-particles [17]. However, the size of grains became smaller than the value in the aluminium alloy without nano-particles. Such behaviour was also reported by the literature [13]. Issa et al. [13] found that the reduction in the aluminium particle size was due to the presence of brittle ceramic particles. They mentioned that adding SiO_2 nano-particles to the aluminium matrix refined grains [13], which showed an agreement with obtained results in this research. Since smaller grains could be observed in the piston aluminium alloy with nano-particles.

Obtained results from dilatometric measuring for both aluminium alloys, with and without nano-particles, can be seen in "**FIGURE 4**". These results contained the expansion of specimens (the thermal strain during the time) versus the temperature. Linear curve fitting was utilized to find the thermal expansion coefficient of materials. As it can be seen, the slope of the curve was lower for the aluminium alloy with SiO_2 nano-particles. In other words, nano-particles affected the aluminium alloy by reducing the thermal strain during a constant temperature. When the temperature increased, this reduction in the thermal strain became more. The thermal expansion coefficient was 14.644×10^{-6} /°C and 11.983×10^{-6} /°C during the temperature range of 100 to 300°C, for aluminium alloys without and with SiO_2 nano-particles, respectively. It means that nano-particles reduced 17% of the thermal expansion coefficient in piston aluminium alloys. Such change could be an improvement for the engine piston application. Since the thermal stress decreased during heating/cooling processes, when the engine is working. Comparing to the ASM handbook [18], the thermal expansion coefficient for the similar aluminum alloy (336.0-T5) is 20.9×10^{-6} /°C, which had about 30% difference with the measured value of the studied material. Since some elements are different, such as the measuring error, the manufacturing process (including gravity and stir casting in this study), the Cu element value, besides existing the heat treatment (T5), for the material in the literature [18]. In this research, since a comparison was performed between two case studies, including piston aluminum alloys, with and without SiO_2 nano-particles; the mentioned difference could not be a problem.

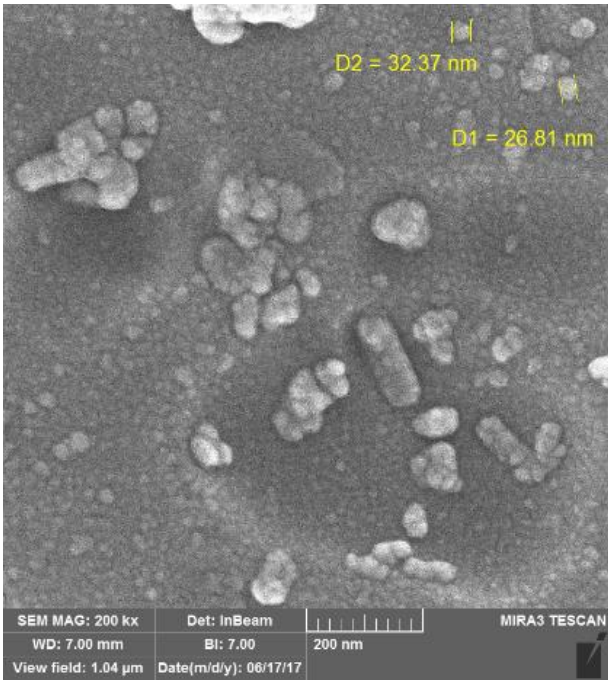
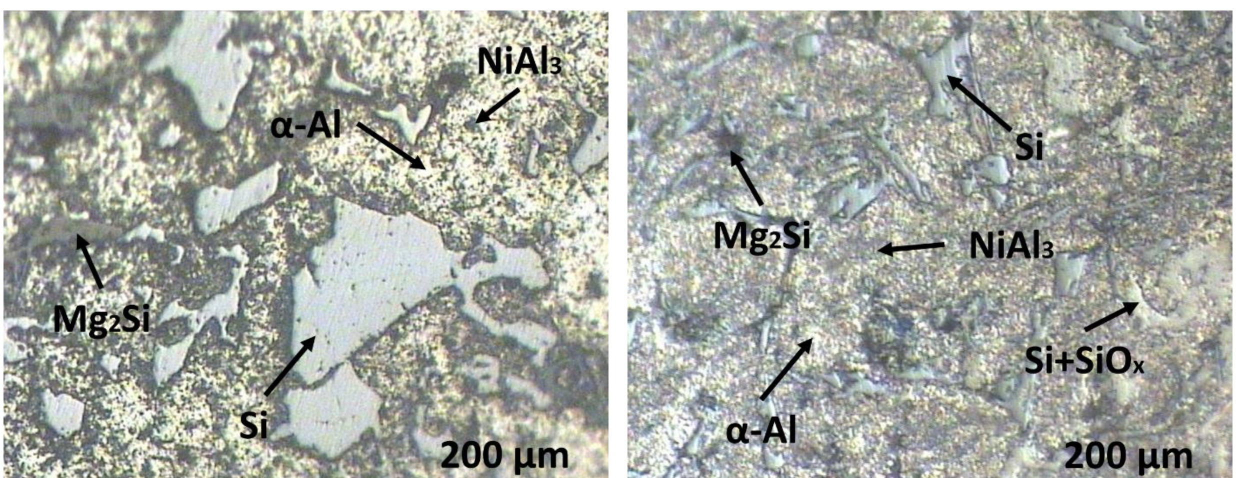


FIGURE 2. The FE-SEM image for the distribution of nano-particles in the matrix.



(a) (b)

FIGURE 3. The microstructure of aluminum alloys, (a) without and (b) with nano-particles, by the optical microscopy.

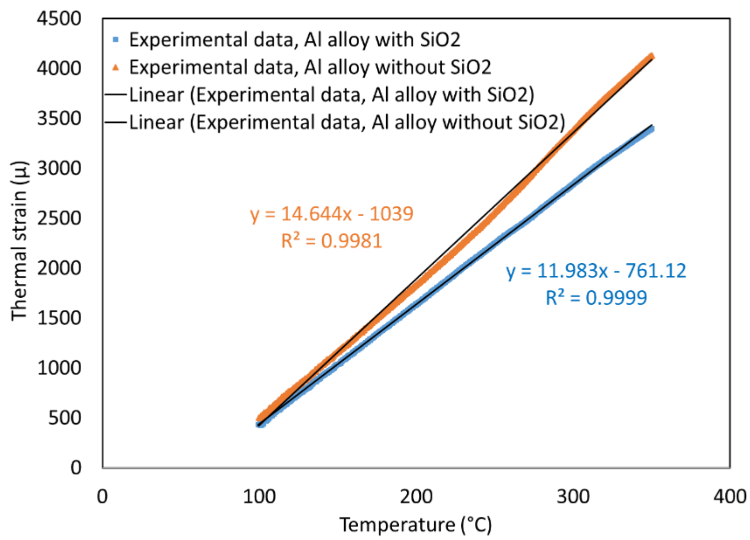


FIGURE 4. Results of dilatometric measuring for aluminum alloys, (a) without and (b) with nano-particles.

CONCLUSIONS

In this article, the microstructure and thermal properties of a piston aluminum alloy (Al-12.5Si-2.4Cu-0.7Mg-2.2Ni), reinforced by SiO_2 nano-particles have been studied. Obtained results can be listed as follows,

- The FE-SEM image showed an appreciate distribution of nano-particles in the aluminium matrix.
- The microstructure of the aluminium alloy without nano-particles included the interdendritic network, the eutectic Si region, and Mg_2Si and $NiAl_3$ intermetallic phases.
- The microstructure of the aluminium alloy with nano-particles included all same phases in the material without nano-particles, in the addition to the Si+SiO_x phase.
- Brittle SiO_2 nano-particles reduced the grains size in the aluminium alloy.
- Dilatometric measuring during the temperature range of 100 to 300°C for both aluminium alloys, with and without nano-particles, showed that the thermal expansion coefficient of the aluminium alloy decreased by adding SiO_2 nano-particles.

For further investigations, more microstructural studies plus the EDX analysis should be performed. In addition, the heat treatment effect such as the T6 process (solutioning at 480°C for 6 hours, water quenching and ageing at 220°C for 6 hours), which was commonly utilized for engine pistons, on microstructural and thermal properties of aluminum alloys.

ACKNOWLEDGMENTS

Authors should thank the Motorsazi Pooya Neyestanak (MPN) Company (located in Neyestanak, Naein, Isfahan, Iran), and also should say an especial thank to Mr. A.A. Sheikhi (the managing director of MPN), for the financial support on this study.

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