International Journal of Engineering

Journal Homepage: www.ije.ir

Effects of Various Ageing Heat Treatments on Microstructural Features and Hardness of Piston Aluminum Alloy

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PAPER INFO

Paper history:
Received 03 November 2018
Received in revised form 19 November 2018
Accepted 03 Januray 2019

Keywords:
Aluminum Alloy
Piston
Heat Treatment
Microstructure
Hardness

ABSTRACT

Piston aluminum alloys have different intermetallic phases, such as Cu_3Al, Mg_2Si ,and AlNi phases. The morphology and the distribution of such phases have important roles on mechanical properties of the piston material. Therefore, in this research, various ageing heat treatments on the mentioned material were done and the microstructural feature and the hardness were studied. Obtained results showed that solutioning at 515 °C for 7 hours and ageing at 205 °C for 7 hours, was the superior heat treatment process, since such treatment led to increase the hardness value to its highest value (153 BHN) for the piston aluminum alloy. This heat treatment caused to increase the size of Si particles obviously and caused to precipitate other intermetallic phases of Al (Ni,Cu) and Ni-Si. Additionally, solutioning at 500 °C for 5 hours and ageing at 180 °C for 9 hours resulted in coarsening Si and Al-Ni participates in the longitudinal direction, which was caused to increase the hardness value to 137 BHN. Energy dispersive X-ray spectroscopy (EDS) results indicated that when the specimen aged at 230 °C for 5 hours, other intermetallic phases such as Al (Ni,Si) and Mg_2Si appeared in the matrix.

doi*: 10.5829/ije.2019.32.01a.12*

1. INTRODUCTION

Aluminum-silicon cast alloys have been widely used for the production of piston parts and cylinder heads, according to the high corrosion resistance, the low coefficient of the thermal expansion and the high ratio of the strength to the weight [1-3]. Besides, in recent years, it has been demonstrated that the mechanical properties of aluminum-silicon alloys could be enhanced by applying suitable heat treatments [4]. This was due to the existence of different phases and intermetallics, in various shapes and distributions, which depended on corresponding process parameters of casting or applied heat treatments [5]. Since the wear phenomenon is a major problem in different industries [6], increasing the wear resistance of the material can be an economical method to decrease the cost. One way to enhance the wear resistance is to increase the hardness of the material. In the following paragraph, some of the researches which were focused on changing the microstructure of various piston aluminum alloys were reviewed:

Zeren et al. [7] demonstrated that the solutioning treatment at 500 ºC for 5 hours and the aging process at 180 ºC for 9 hours resulted in increasing the hardness value to 127 BHN. Haque et al. [8] studied the casting parameters such as the chill and sand solidification mold, which were affected properties of such alloy. It was figured out the optimum heat treatment procedure was solutioning at 510 ºC for 4 hours and aging at 180 ºC for 6 hours to reach the hardness value to 140 BHN [9]. Sheik et al. [10] showed that for piston aluminum alloy with 2.2 wt% nickel content, the heat treatment, which contained solutioning step at 495°C for 5 hours and aging stage at 180 °C for 8 hours, led to increase the hardness value to 145 BHN. Shikolaev et al. [11] reported that the hardness increasing of piston alloy was due to the reducing of casting temperature, and

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Please cite this article as: M. Azadi, S. Rezanezhad, M. Zolfaghari, M. Azadi, Effects of Various Ageing Heat Treatments on Microstructural Features and Hardness of Piston Aluminum Alloy, International Journal of Engineering (IJE), IJE TRANSACTIONS A: Basics Vol. 32, No. 1, (January 2019) 92-98

increasing of the cooling rate after the alloy solidification. Zainon et al. [12] demonstrated that the solutioning step at 500 °C for 5 hours and the aging stage at 170 °C for 2 hours caused to increase the hardness about 44 % with respect to the as-cast alloy.

Thus, due to limited researches, the aim of the present study was to investigate effects of various new heat treatments to increase the hardness of piston aluminum alloys. Besides the microstructural feather and chemical analysis of such alloy were studied by the optical microscopy (OM), the scanning electron microscopy (SEM) and the energy dispersive spectroscopy (EDS), respectively.

2. MATERIALS AND METHODS

The chemical composition of the used material was measured as Si: 12.5, Ni: 2.2, Cu: 2.4, Fe: 0.41, Mg: 0.74, Zn: 0.07, Mn: 0.03 and Al was balanced. Such material was similar to A332.0 aluminum alloy [13]. Different ageing heat treatment procedures were conducted on as-cast aluminum specimens. Details of such procedures are shown in Table 1. For better comparison of results, the specimen without any heat treatment, which was called as blank, was also used.

Then, metallographic samples were prepared by mechanical grinding with SiC papers, up to the 2000 grit. In addition, specimens were polished by the 0.3 μm alumina paste. The Keller's reagent was also used to detect constituents of the aluminum alloy. Microstructural feathers were performed by the optical microscopy (OM: Olympus model) and the field emission scanning electron microscopy (FESEM: MIRA3-TSCAN). Detecting of various phases was done by using an energy dispersive X-ray spectroscopy (EDS) with the accelerating voltage of 30 keV. Brinell hardness testing was conducted, using 30 kg load and 2.5 mm indenter diameter. Results of the hardness were averaged from three determinations.

3. RESULTS AND DISCUSSIONS

The microstructure of the as-cast alloy is shown in Figure 1.

TABLE 1. Heat treatment procedures

Heat treatment conditions	Solutioning temperature and time (°C, hours)	Ageing temperature and time (°C, hours)
Procedure 1	480, 6	220, 6
Procedure 2	500, 5	180, 9
Procedure 3	515, 7	205, 7
Procedure 4	-	230, 5

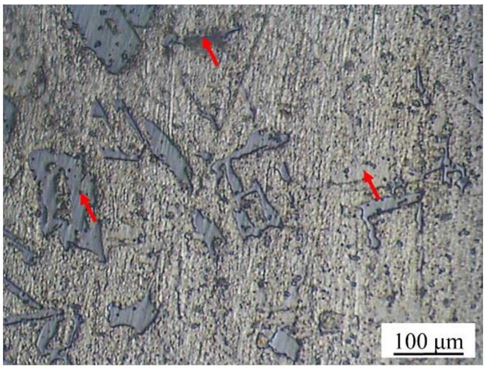

Figure 1. The microstructure of the as-cast aluminum alloy

Aluminum alloy contained various phases which were distributed in the α-Al matrix. The similar microstructure was also seen in the other research [14]. The mean size of the polygonal morphology for the Si phase (gray-colored areas) was about 100 μm. Such phase was observed by other researchers [1, 2, 15, 16].

When Procedure 1 was done, the length of the Si phase increased obviously and reached the higher value than 150 μm, as shown in Figure 2. Besides, the size of the intermetallic phase (brown-colored areas) increased in the flake morphology. In addition, the amount of another intermetallic phase increased which was appeared in black-colored areas. Such behavior led to enhance the hardness value of 2%, with respect to the as-cast specimen. Besides, hardness results for all specimen are reported in Figure 3.

When Procedure 2 was performed, the polygonal morphology of the Si phase changed to the flake shape, which was distributed homogeneously in the α-Al matrix, as shown in Figure 4. Additionally, the amount of the intermetallic phase (brown-colored areas) increased obviously, with respect to the as-cast (blank) specimen. Such heat treatment led to increase the hardness value, to 137 BHN.

Procedure 3 of heat treatment caused to increase the size of Si obviously to higher than 200 μm. Besides, the shape of Si and the brown phases changed to the rounded morphology, as shown in Figure 5.

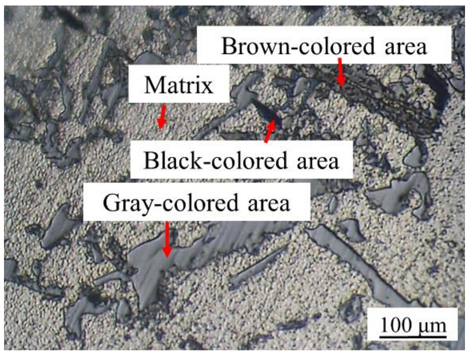

Figure 2. The microstructure of the alloy after Procedure 1

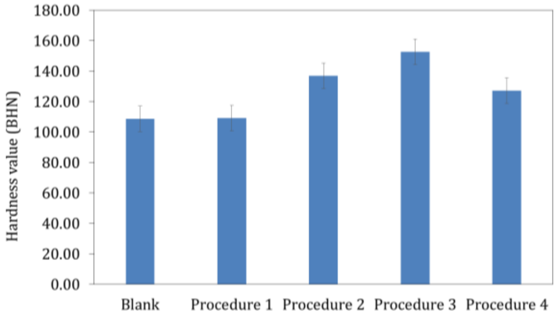

Figure 3. Hardness test results for all specimens

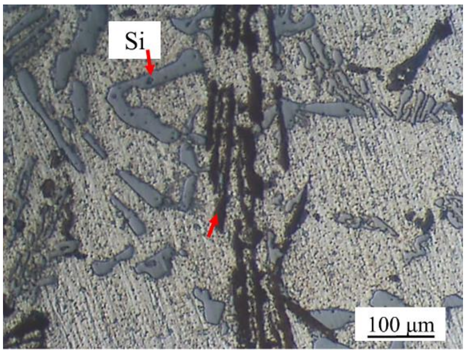

Figure 4. The microstructure of the alloy after Procedure 2

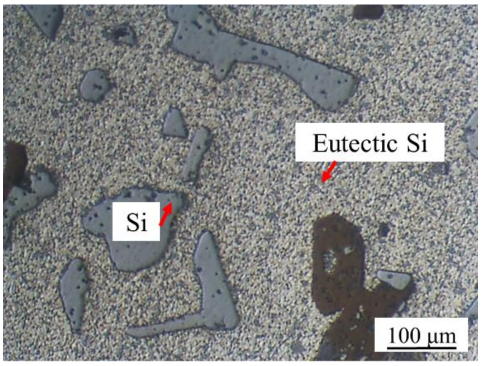

Figure 5. The microstructure of the alloy after Procedure 3

Such event raised the hardness value to 153 BHN (the highest value). It was noticeable that the primary Si has a rounded form and the eutectic mixture appeared in separated flakes. Such observation was reported by other researches [17 , 18].

As shown in Figure 6, when the ageing process was applied without the solutioning step (Procedure 4), the intermetallic phase and Si particles were arranged almost in grain boundaries, with the flake morphology. Such heat treatment caused to enhance the hardness value about 20%, comparing to the as-cast alloy.

As shown in Figure 7, the Si phase exhibited the gray-colored area in the matrix and other intermetallic phases were also shown in white-colored areas. The intermetallic phases appeared in the feather-like morphology in some areas for the blank sample. The X-ray diffraction (XRD) result for the blank specimen is reported in the other research [19]. Azadi et al. [19] reported that the same alloy contained two intermetallic phases of Ni-Al and Cu_3Al plus the Si and Al-Si (eutectic mixture) phases.

For detecting of more details, SEM images of various specimens were also seen in Figures 7-9.

Two SEM images after procedure 3 in different magnifications were seen in Figures 8 and 9. As the solution temperature was the highest among other procedures with the value of 515 ºC, the smaller size of Si and other intermetallic phases were disappeared in the matrix.

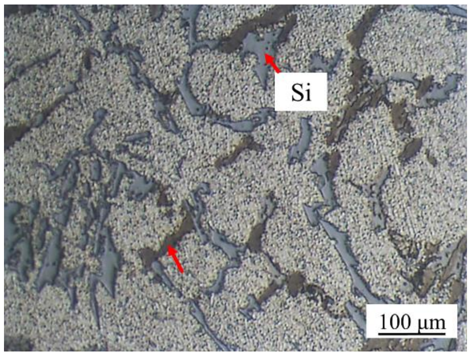

Figure 6. The microstructure of the alloy after Procedure 4

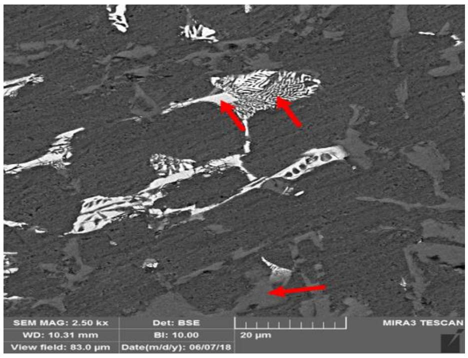

Figure 7. The SEM image of the as-cast (blank) aluminum alloy

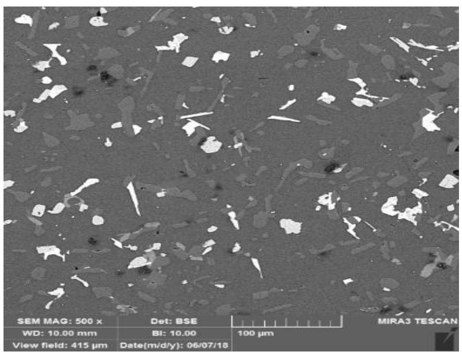

Figure 8. The SEM image of the alloy after Procedure 3

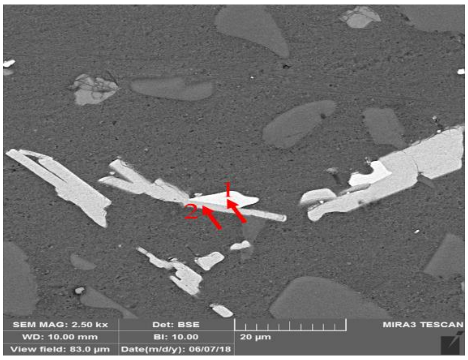

Figure 9. The SEM image of the alloy after Procedure 3 for EDS results

In addition, the large size of the mentioned phases distributed homogeneously in the matrix. The morphology of phases was rounded for both Si and intermetallic phases in most places, inconsistent with the OM image in Figure 5.

Details of EDS results for point 1, which is shown in Figure 9, is reported in Table 2. Point 1 contained Ni, Cu, and Al elements. Due to the phase diagram of Al-Ni-Cu phase [20], such phase was Al (Ni,Cu) or τ-phase. Besides, according to the intensity of related peaks in Figure 10, it was predicted that the chemical composition of this phase could be Al_2CuNi, since Zeren et al. [1] reported the similar phase in the piston aluminum alloy.

TABLE 2. Details of EDS result for point 1 in Figure 9

Element	Wt%	A%
Mg	0.64	2.05
Al	75.08	84.50
Si	2.09	3.34
Ni	12.64	6.02
Cu	9.55	4.09

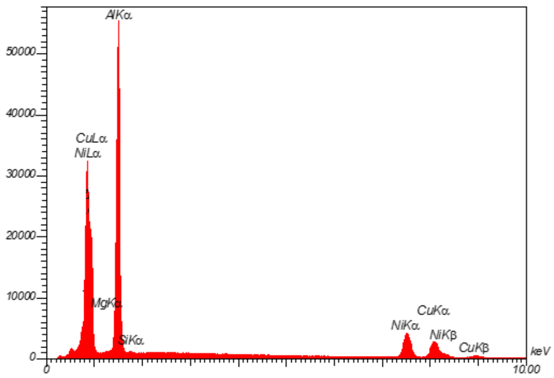

Figure 10. The pattern of EDS result for point 1 in Figure 9

Details of EDS results for point 2 which is shown in Figure 9, is reported in Table 3. Therefore, due to the phase diagram of Ni-Si [21] and the weight percent of related elements in Table 3, the presence of $NiSi_2$ was predictable. It was noticeable that a large amount of Al phase in the EDS result could be related to the low thickness of the Ni-Si phase in Figure 9.

When the solutioning step was eliminated, the feather-like morphology of intermetallic phases was also seen similar to the as-cast sample. The eutectic Si phase exhibited in the flake-like shape as shown in Figure 11.

EDS results for the specimen after Procedure 4 are shown in Figures 12 and 13 and Table 4 to 7.

TABLE 3. Details of EDS result for point 2 in Figure 9

Elt	Wt%	A%
Mg	1.67	1.95
Al	80.69	85.19
Si	9.14	8.26
Mn	0.04	0.02
Fe	0.50	0.77
Ni	7.43	3.12
Cu	0.53	0.69

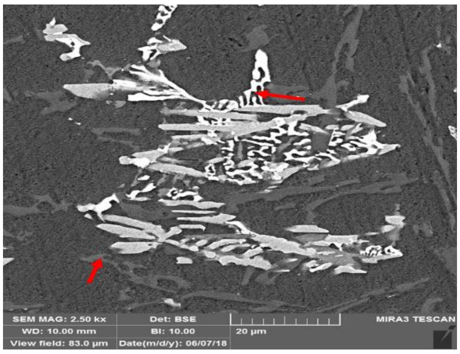

Figure 11. The SEM image of the alloy after Procedure 4

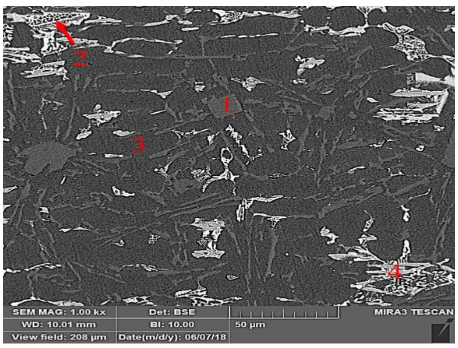

Figure 12. The SEM image of the alloy after Procedure 4 for EDS result (point 1 to 4)

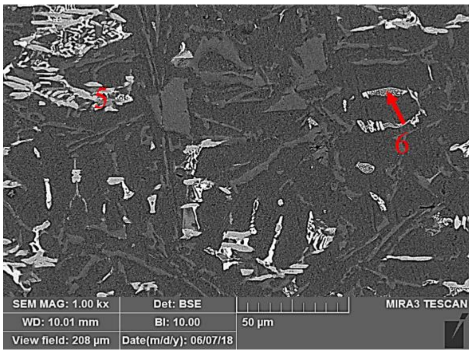

Figure 13. The SEM image of the alloy after Procedure 4 for EDS results (point 5 and 6)

TABLE 4. Details of EDS results for point 1 and point 2 in Figure 12

Elt	Wt%		A%	
	Point 1	point 2	Point 1	point 2
Mg	0.89	0.49	1.02	1.63
Al	2.62	89.91	2.72	91.11
Si	96.49	5.66	96.26	5.41
Ni	0	3.94	0	1.85

TABLE 5. Details of EDS results for point 3 and point 4 in Figure 12

Elt	Wt%		A%	
	Point 3	Point 4	Point 3	Point 4
Mg	1.30	0.31	1.44	1.53
Al	97.14	85.76	97.06	90.39
Si	1.56	0.46	1.50	3.50
Fe	0	0.25	0	0.63
Ni	0	12.25	0	3.51
Cu	0	0.97	0	0.44

TABLE 6. Details of EDS result for point 5 in Figure 13

Elt	Wt%	A%
Mg	21.83	23.38
Al	47.48	48.02
Si	27.53	26.75
Fe	0.13	0.07
Ni	1.69	0.79
Cu	1.34	1.00

TABLE 7. Details of EDS results for point 6 in Figure 13

Elt	Wt%	A%
Mg	6.46	7.26
Al	82.33	83.39
Si	8.29	8.07
Ni	0.83	0.38
Cu	2.09	0.90

As depicted in Figure 12, both white areas were intermetallic phases. Details of weight percent of various elements for point 1 are reported in Table 4. Table 4 shows that the gray-colored area was the Si phase since the weight percent of such phase was about 96.49.

Besides, Table 4 shows that the white-colored area in point 2 was the intermetallic phase, since the weight percent of Ni and Si phases were about 4 and 6, respectively. The related phase was Al (Ni, Si).

Table 5 shows the matrix phase, which was the α-Al phase and other elements such Mg and Si phases were solutionized in the matrix. Besides, Table 5 demonstrates the other intermetallic phase. Due to the phase diagram Al-Ni [22], the chemical composition of such phase was predicted as $NiAl_3$. Such phase was also found in the other piston aluminum alloy [22].

For detecting more details, the other SEM image of the specimen after procedure 4 is seen in Figure 13. EDS results for point 5 which is shown in Figure 13, are reported in Table 6. Table 6 shows the practicable phase was Mg_2Si. Such prediction was also in consistence with the peaks intensity which are seen in Figure 14.

The EDS result for point 6 in Figure 14 is reported in Table 7. Such phase could be Al-Mg-Si-Cu phase. It was found that such a tetrahedron phase would be the metastable phase which would be formed during the artificial ageing [24].

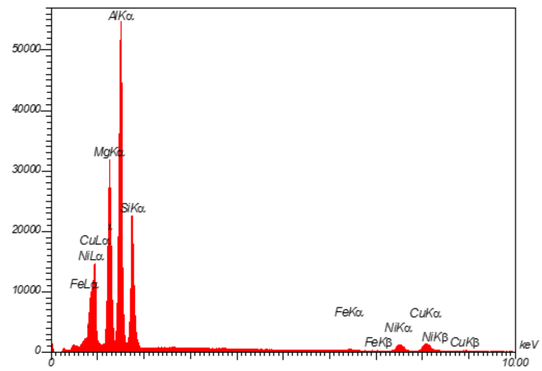

Figure 14. The pattern of EDS result for point 5 in Figure 13

4. CONCLUSIONS

In this article, the effect of various heat treatments was studied on the piston aluminum alloy. Obtained results were summarized as follows:

- The ageing process, which contained solutioning at 500 °C, led to decrease the phase size of Si with the flake morphology and caused to increase the amount of intermetallic phases. Such behavior raised the hardness value to 137 BHN.
- The ageing process with the solutioning step at 480 °C, caused to increase the phase size of Si with the polygonal morphology, to higher than 150 μm, which was distributed in the α-Al matrix phase. However, in this situation, the hardness enhancement was about 2% with respect to the piston aluminum alloy, without heat treatments.
- The solutioning temperature of 515 °C led to increase the phase size of Si obviously and such event caused to increase the hardness to the highest value. Besides, phases of Al (Ni, Cu) and Ni-Si participated in the matrix.
- When the ageing process was applied without the solutioning step, the intermetallic phase arranged almost in grain boundaries and the enhancement in the hardness was about 20%, comparing to the values of the as-cast specimen. Additionally, the presence of Al-Mg-Si-Cu, Mg_2Si, $NiAl_3$, and Al (Ni, Si) phases were predictable.

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PAPER INFO

Paper history:
Received 03 November 2018
Received in revised form 19 November 2018
Accepted 03 Januray 2019

Keywords:
Aluminum Alloy
Piston
Heat Treatment
Microstructure
Hardness

چکیده

آلیاژهای آلومینیومی پیستون دارای فازهای بین فلزی مختلفی همانند Cu_3Al، Mg_2Si و AlNi هستند. مرفولوژی و توزیع چنین فازهایی دارای نقش مهمی بر خواص مکانیکی چنین موادی دارند. بنابراین در این تحقیق، عملیات های حرارتی رسوب سختی مختلف بر ماده موردنظر انجام شد و جنبه های ریزساختاری و سختی مورد مطالعه قرار گرفت.نتایج حاصل نشان داد که عملیات انحلال در دمای ۵۱۵ درجه سانتی گراد به مدت ۷ ساعت و رسوب سختی در دمای ۲۰۵ درجه سانتی گراد به مدت ۷ ساعت بهترین عملیات حرارتی محسوب می‌شود، زیرا که چنین عملیاتی منجر به افزایش سختی به بیشترین مقدار (۱۵۳ BHN) برای آلیاژ آلومینیومی پیستون شد.این عملیات حرارتی موجب شد تا اندازه ذرات سیلیسیم به صورت مشخص افزایش یابد و فازهای بین فلزی Al (Ni,Cu) و Ni-Si رسوب پیدا کند. همچنین، انحلال در دمای ۵۰۰ درجه سانتی گراد به مدت ۵ ساعت و رسوب سختی در دمای ۱۸۰ درجه سانتی گراد به مدت ۹ ساعت سبب افزایش رسوبات سیلیسیم و Al-Ni در جهت طولی شد که این امر موجب افزایش مقدار سختی تا ۱۳۷ BHN گردید. نتایج طیف سنجی متفرق انرژی (EDS) نشان داد زمانی که نمونه در دمای ۲۳۰ درجه سانتی گراد به مدت ۵ ساعت پیرسخت شد، دیگر فازهای بین فلزی مانند Al (Ni,Si) و Mg_2Si در زمینه پدیدار شدند.

***doi**: 10.5829/ije.2019.32.01a.12*