Comparison of the Annealing Heat-Treated Microstructure and Hardness of the AA2024-T4 and AA6061-T6 Alloys

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Abstract

Precipitation Hardenable Aluminum Alloys are suitable alternatives in electric vehicle bodies due to their lower specific weight compared to steel. Therefore, the development and understanding of the properties of aluminum alloys help to develop electric vehicles, reduce greenhouse gas emissions, and control global warming. In this research, we investigated the heat treatment of AA2024-T4 and AA6061-T6 alloys at a temperature of 453 °C for 210 minutes in a tube furnace with a heating rate of 5 °C/min in a vacuum (7.5×10^{-13} Torr). The alloys were assessed by optical microscopy (OM), scanning electron microscopy (SEM), and hardness test. The effect of heat treatment was investigated on the particle size as well as the phases. The particle diameter and hardness value of AA2024-T4 decreased after heat treatment. The number of precipitates in AA2024-T4 increased after heat treatment. Precipitates size in AA6061-T6 alloy remained almost unchanged after the heat treatment.

Keywords: Aluminum alloys, AA2024-T4, AA6061-T6.

1. Introduction

Aluminum is one of the most abundant metals on earth's crust that is usually used to reduce the weight of industrial products, particularly in the aerospace industry, automotive industry, and construction industries [1]. In modern aircraft construction, there are many pieces, such as props, Aircraft fittings, gears and shafts, bolts, computer parts, couplings, fuse parts, hydraulic valve bodies, nuts, pistons, rectifier parts, worm gears, fastening devices, veterinary, etc. [2]. Due to the solubility nature of copper in aluminum, with appreciably higher solubility at higher temperatures in comparison to lower temperatures, one can expect precipitation of an Al-Cu secondary phase during solidification [3]. Age hardening (T4) is very common for AA2000 group alloys, and (T6) is for AA6000. T6 operation is known as precipitation hardening operation and it is obtained by cooling the completely dissolved solidified alloy in water and then returning it to 175ºC and holding it for 9 h [4]. The dissolution temperature depends on the material of the base alloy. In T6 process, the holding temperature determines the holding time, there is also a definition of 18 hours at 160°C and 8 hours at 177°C [5]. T4 heat treatment is a method to increase the yield strength of alloys capable of precipitation hardening. The T4 heat treatment results from cooling the completely dissolved solidified alloy in water and keeping the alloy at room temperature (23ºC) [6]. Due to the limited solubility of Cu–Mg elements in the Al matrix, the highest strength attainable in the peak aging condition, through precipitation strengthening, is limited in the Al–Cu–Mg alloys [7]. AA2024 is known as a corrosion-resistant alloy with a Cu content of 4wt.%. With a density of 2.7 g/cc, this alloy has exhibited precipitation-hardening potentials,Its yield strength is also equal to 75.8 MPa and solidus temperature of AA2024 is 502ºC [8]. Beyond this temperature, the solubility of copper deposits will be enhanced which may affect the heat treatment capability of the alloy. Noteworthy, the eutectic temperature of Al-Mg and Al-Cu are 450 and 548ºC, respectively. Exceeding the eutectic temperature of Al-Mg will enhance the Mg solubility which can contribute to the formation of ɣ deposits in the interlayer after the junction formation process [9,10]. AA2024 alloy is prone to hot cracking. Transient Liquid Phase (TLP) bonding has been employed for joining the alloys with high susceptibility to hot cracking [11]. Moreover, the tensile yield strength and solidus temperature of AA6061 are 55.2 MPa and 582ºC, respectively [12]. Successive TLP bonding of Al2024 to Ti-6Al-4V was also reported utilizing Sn-5.3Ag-4.2Bi interlayers (thickness of 50 µm) which led to the bond strength of 62 MPa in the second stage at 453oC [13]. TLP bonding of AA2024-T4 to AA6061-T6 was also reported at 453oC [14]. The annealing temperature of AA2024-T4 is 413oC [2]. We estimated the average solidus and annealing temperature as the eutectic temperature, and this temperature for Al2024-T4 alloy is equivalent to 457.5oC. Temperatures higher than 457.5°C may impair the precipitation hardening of AA2024 alloy. It is possible that after cooling the alloy, brittle

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compounds will be formed in the boundary of the aluminum grains over time. Regarding the importance of this temperature in the joining process of Al2024-T4 and AA6061-T6 alloys, the effect of heat treatment at 453ºC is assessed on these alloys in this technical article.

2. Materials and Methods

A temperature of 453ºC (near the eutectic temperature of Al-Mg) was selected as the optimal temperature for the experiments. Table. 1. denoted the chemical composition of the alloys. The wire-cutting method was employed to cut the 16×25×3 mm^3 pieces for SEM, and OM analyses and hardness test. The alloys were polished using 80-grit SiC. Then, the alloys were ultrasonically cleaned (10 min, 35 kHz, and 0.5 A) in acetone. The heat treatment process was applied by a high-temperature horizontal carbonate tube furnace. The alloys were heat treated in a tube furnace at a heating rate of 5ºC/min under vacuum ($7.5×10^{-13}$ Torr) and a temperature of 453ºC for 210 min (Fig. 1). The samples are slowly cooled to room temperature in a vacuum furnace. The etching process was conducted for 12 s using an etchant solution comprising 1.5ml HCl, 2.5ml HNO_3, 1ml HF, and 95ml distilled water. AA2024 and AA6061 alloys were explored by optical (YJ-2006B) and scanning electron (AIS2300C) microscopic methods. Depending on the imaging site, voltages of 15, 20, and 30 kV were employed to determine the samples .the hardness test carried out by HMV brinell hardness machine test according ASTM E10 standard.

Table. 1. Chemical composition of the applied metals.

Alloys	Elements (wt.%)						
	Al	**Cu**	**Mg**	**Mn**	**Cr**	**Fe**	**Si**
AA2024	Bal.	4.1	1.4	0.5	0.02	0.31	0.29
AA6061	Bal.	0.23	0.92	0.05	0.23	0.26	0.62

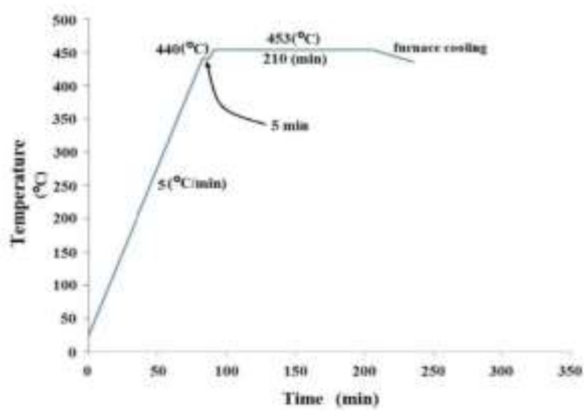


Fig. 1. Heat treatment diagram of AA2024 and AA6061.

3. Results and Discussion

Microstructure of AA2024-T4 and AA6061-T6 alloys, before heat treatment process is shown in Fig. 2. and Fig. 3. along with the type of applied heat treatment. The microstructure of the alloys is also presented in Fig. 4., and Fig. 5. after the heat treatment process. Before heat treatment, the size of the precipitates in the AA2024-T4 reached a maximum value of 30 µm. After the heat treatment process, however, the diameter of the precipitates did not exceed 15 µm and generally remained below 10 µm. In AA2024-T4 alloy, precipitate phases of $(Al, Cu)_6(Fe, Cu)$, Al_2Cu, Al_2CuMg, and Al_7Cu_2Fe can be formed in alpha (α) aluminum [15].

Precipitate size remained almost unchanged (mostly below 11 µm) in the AA6061 alloy. In AA6061-T6 alloy, the precipitation phases of $(Al, Cu)_6(Fe, Cu)$ and Al_3Fe can be formed in alpha aluminum (α) [16]. According to multi-element diagrams, $(Al, Cu)_6(Fe, Cu)$, Al_2Cu, and Al_3Fe phases dissolve some amounts of other alloying elements [17]. The $(Al, Cu)_6(Fe, Cu)$ phase is quasi-stable and tends to convert to the Al_7Cu_2Fe phase [17].

Mg-containing oxide deposits appeared black. Regarding the higher percentage of Mg in AA2024 alloy, the higher density of these precipitates can be observed in AA2024 alloy compared to the AA6061 alloy (Fig. 6.). The equilibrium-phase diagrams (Fig. 7.) were used to interpret the phases in Fig. 2. to Fig. 6. The percentage of precipitation area compared to the solid aluminum solution is presented in Table. 2. and Table. 3. As the eutectic temperature is not exceeded in the AA2024 alloy, the reinforcement precipitates germinate and start to grow again in the alloy AA2024 over time up to 72 h [15]. The number of precipitates decreases, and their size increases by enhancing the retention time [18].

The formation of precipitates is associated with an increase in the hardness of the alloy that quickly brings the structure of the alloy closer to the microstructure of the AA2024-T4 alloy [15, 16]. The greatest changes in the hardness and strength of AA2024 alloy occur in the first days after the dissolution of the precipitates when the speed of changes becomes very slow [15, 16].

At temperatures higher than the eutectic temperature of the alloy, these precipitates will be concentrated and continuously formed in the grain boundaries of aluminum and reduce the strength of the alloy [15,19]. The letter (O) after the alloy code means not heat treated. The comparison of the hardness of heat-treated and non-heat-treated alloys is presented in Table. 4. The average number of precipitates and the percentage of deposits in the structure of the alloys are presented in Fig. 8. Brinell hardness alloys are mentioned in the diagram of Fig. 9.

Table. 2. The percentage of the area of the precipitation.

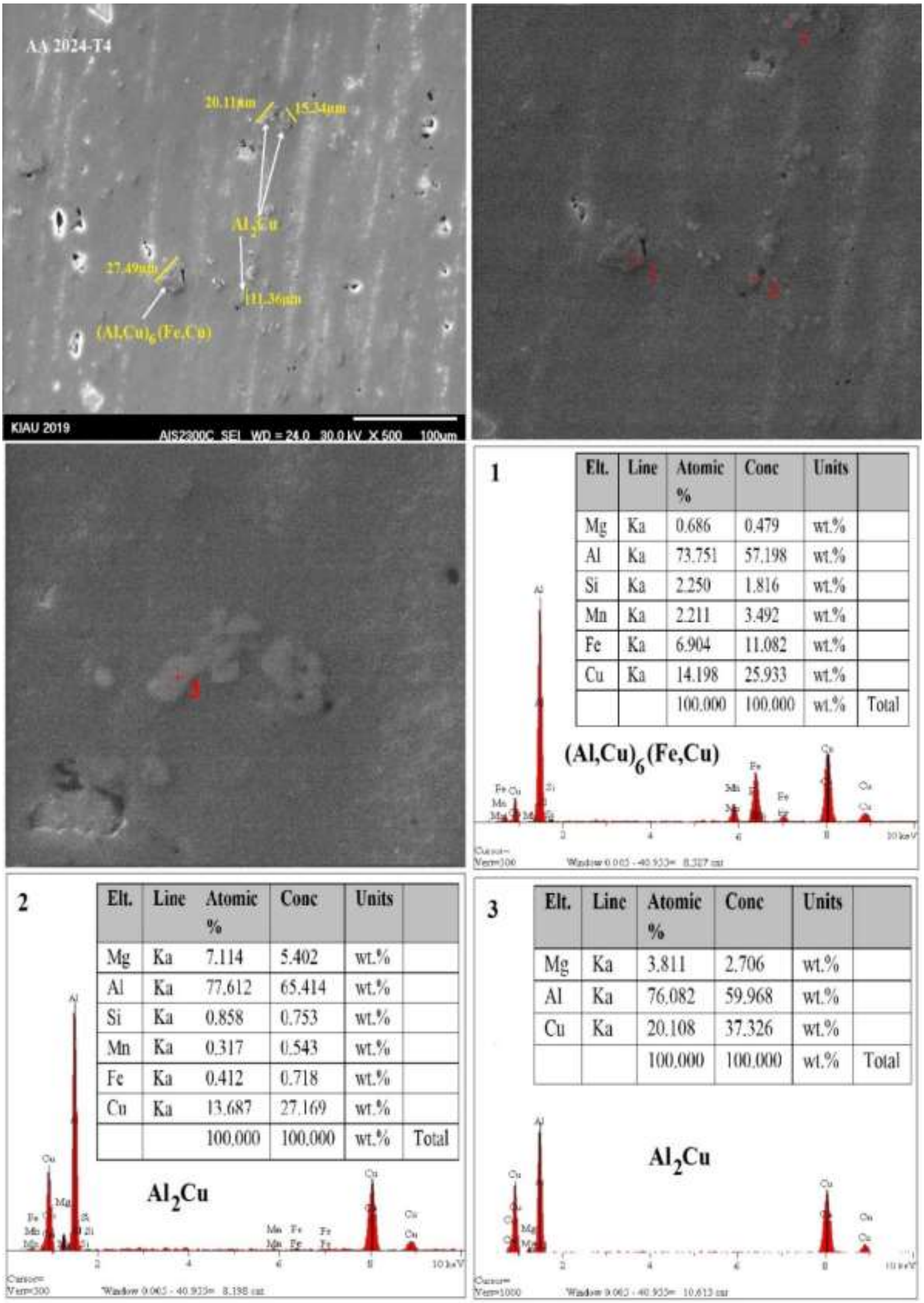
Base metals	Area under investigation (μm^2)	The area of the precipitates in the image (μm^2)	Average area percentage of precipitates in the background	Number of precipitates
AA6061-T6	441025	5287	1.19 ± 0.1	22
AA6061-T6	441792	5854	1.32 ± 0.1	57
AA2024-T4	441792	24332	5.51 ± 0.1	43
AA2024-T4	442559	23651	5.34 ± 0.1	60

Table. 3. The percentage of the area of the precipitation (after heat treatment at 453 degrees Celsius).

Base metals	Area under investigation (μm^2)	The area of the precipitates in the image (μm^2)	Area percentage of precipitates in the background	Number of precipitates
AA6061	159572	1888	1.18 ± 0.1	29
AA6061	441792	5115	1.16 ± 0.1	27
AA6061	44160	5369	1.22 ± 0.1	35
AA2024	441792	14588	3.30 ± 0.1	138
AA2024	441792	14584	3.30 ± 0.1	169
AA2024	442559	14758	3.34 ± 0.1	156

Table. 4. Comparison of the hardness of heat-treated and non-heat-treated alloys.

Alloy	HB
AA2024-O	47
AA2024-T4	120
AA2024-T4 + 210min at 453ºC	67.45
AA6061-O	30
AA6061-T6	95
AA6061-T6 + 210min at 453ºC	40



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Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	0.686	0.479	wt.%	
Al	Ka	73.751	57.198	wt.%	
Si	Ka	2.250	1.816	wt.%	
Mn	Ka	2.211	3.492	wt.%	
Fe	Ka	6.904	11.082	wt.%	
Cu	Ka	14.198	25.933	wt.%	
		100.000	100.000	wt.%	Total

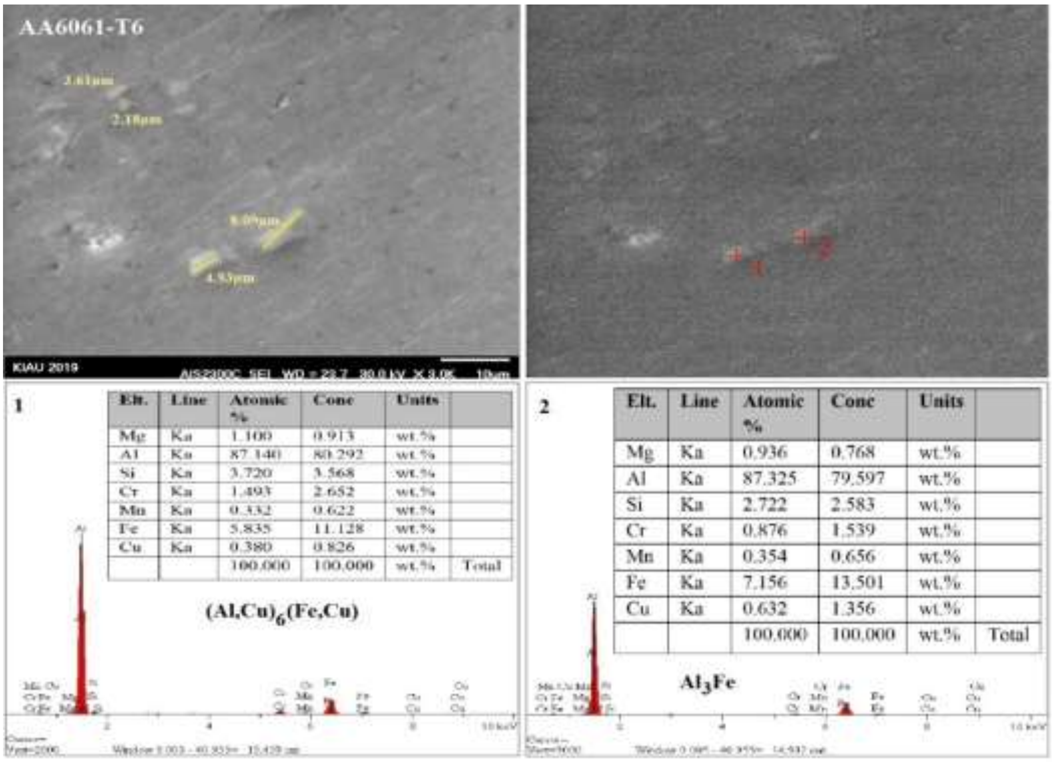
2

Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	7.114	5.402	wt.%	
Al	Ka	77.612	65.414	wt.%	
Si	Ka	0.858	0.753	wt.%	
Mn	Ka	0.317	0.543	wt.%	
Fe	Ka	0.412	0.718	wt.%	
Cu	Ka	13.687	27.169	wt.%	
		100.000	100.000	wt.%	Total

3

Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	3.811	2.706	wt.%	
Al	Ka	76.082	59.968	wt.%	
Cu	Ka	20.108	37.326	wt.%	
		100.000	100.000	wt.%	Total

Fig. 2. Microstructure of the AA2024-T4.



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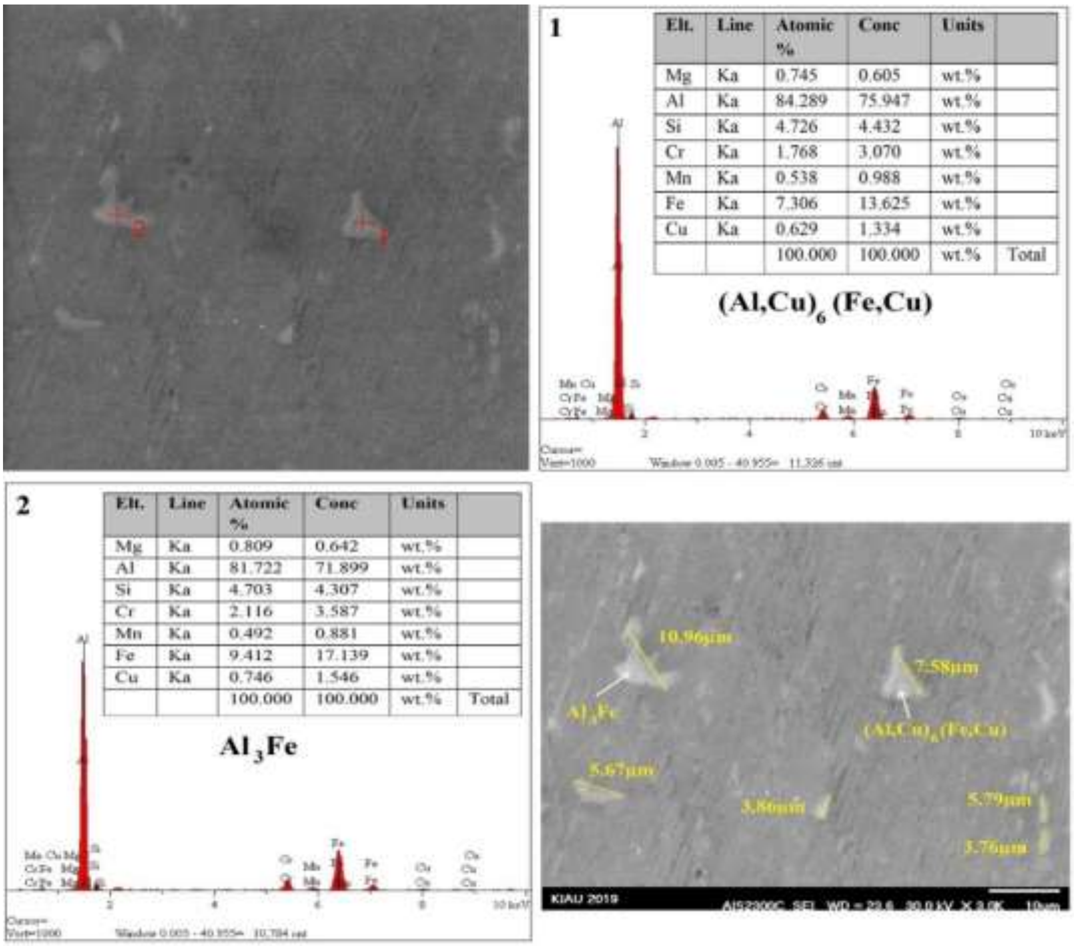
Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	1.100	0.913	wt.%	
Al	Ka	87.140	80.292	wt.%	
Si	Ka	3.720	3.568	wt.%	
Cr	Ka	1.493	2.652	wt.%	
Mn	Ka	0.332	0.622	wt.%	
Fe	Ka	5.835	11.128	wt.%	
Cu	Ka	0.380	0.826	wt.%	
		100.000	100.000	wt.%	Total

2

Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	0.936	0.768	wt.%	
Al	Ka	87.325	79.597	wt.%	
Si	Ka	2.722	2.583	wt.%	
Cr	Ka	0.876	1.539	wt.%	
Mn	Ka	0.354	0.656	wt.%	
Fe	Ka	7.156	13.501	wt.%	
Cu	Ka	0.632	1.356	wt.%	
		100.000	100.000	wt.%	Total

Fig. 3. Microstructure of the AA6061-T6.



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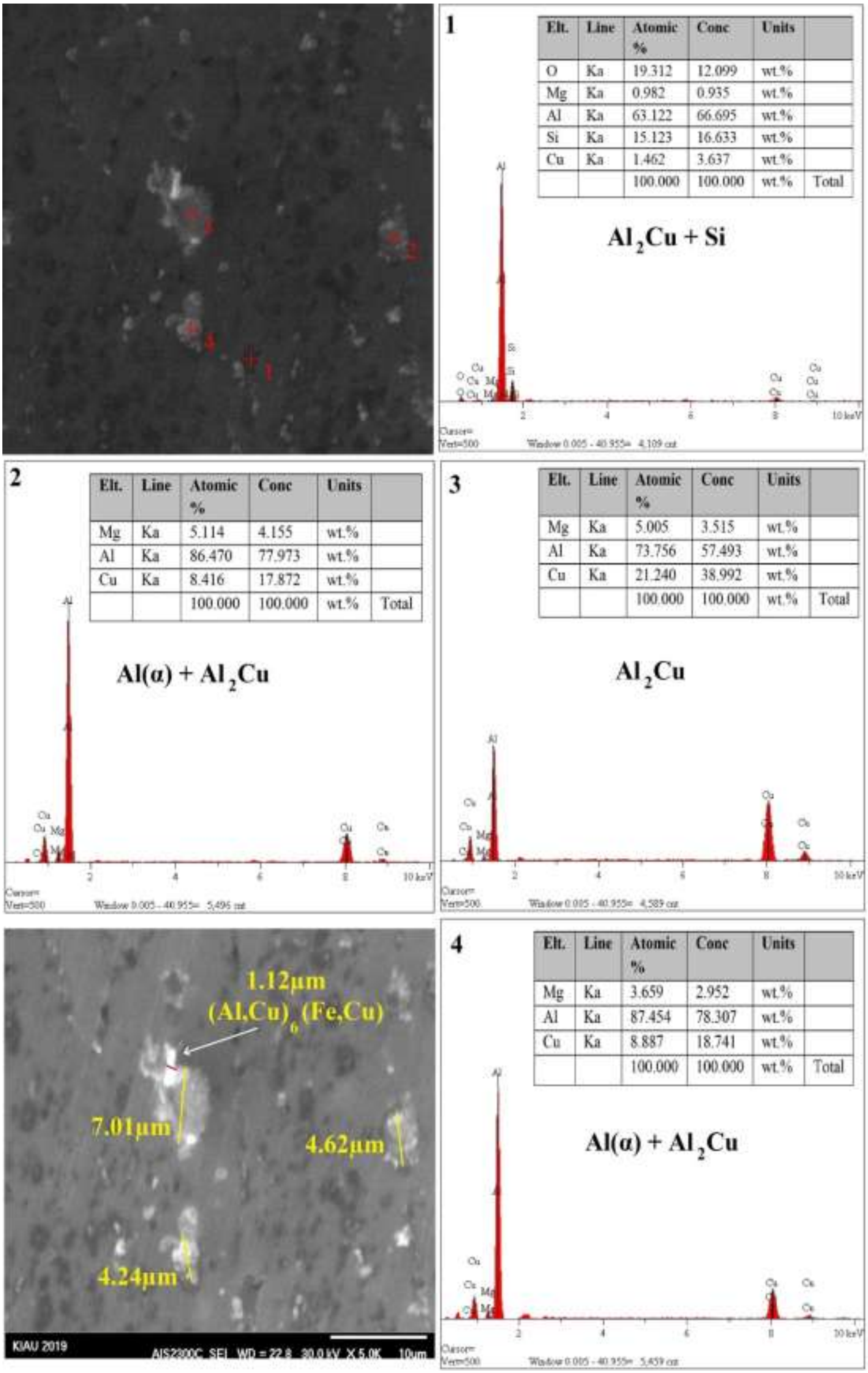
Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	0.745	0.605	wt.%	
Al	Ka	84.289	75.947	wt.%	
Si	Ka	4.726	4.432	wt.%	
Cr	Ka	1.768	3.070	wt.%	
Mn	Ka	0.538	0.988	wt.%	
Fe	Ka	7.306	13.625	wt.%	
Cu	Ka	0.629	1.334	wt.%	
		100.000	100.000	wt.%	Total

2

Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	0.809	0.642	wt.%	
Al	Ka	81.722	71.899	wt.%	
Si	Ka	4.703	4.307	wt.%	
Cr	Ka	2.116	3.587	wt.%	
Mn	Ka	0.492	0.881	wt.%	
Fe	Ka	9.412	17.139	wt.%	
Cu	Ka	0.746	1.546	wt.%	
		100.000	100.000	wt.%	Total

Fig. 4. Microstructure of the AA6061 (Held at 453ºC for 210 minutes).



1

Elt.	Line	Atomic %	Conc	Units	
O	Ka	19.312	12.099	wt.%	
Mg	Ka	0.982	0.935	wt.%	
Al	Ka	63.122	66.695	wt.%	
Si	Ka	15.123	16.633	wt.%	
Cu	Ka	1.462	3.637	wt.%	
		100.000	100.000	wt.%	Total

2

Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	5.114	4.155	wt.%	
Al	Ka	86.470	77.973	wt.%	
Cu	Ka	8.416	17.872	wt.%	
		100.000	100.000	wt.%	Total

3

Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	5.005	3.515	wt.%	
Al	Ka	73.756	57.493	wt.%	
Cu	Ka	21.240	38.992	wt.%	
		100.000	100.000	wt.%	Total

4

Elt.	Line	Atomic %	Conc	Units	
Mg	Ka	3.659	2.952	wt.%	
Al	Ka	87.454	78.307	wt.%	
Cu	Ka	8.887	18.741	wt.%	
		100.000	100.000	wt.%	Total

Fig. 5. Microstructures of the AA2024 (Holding at 453°C for 210 minutes).

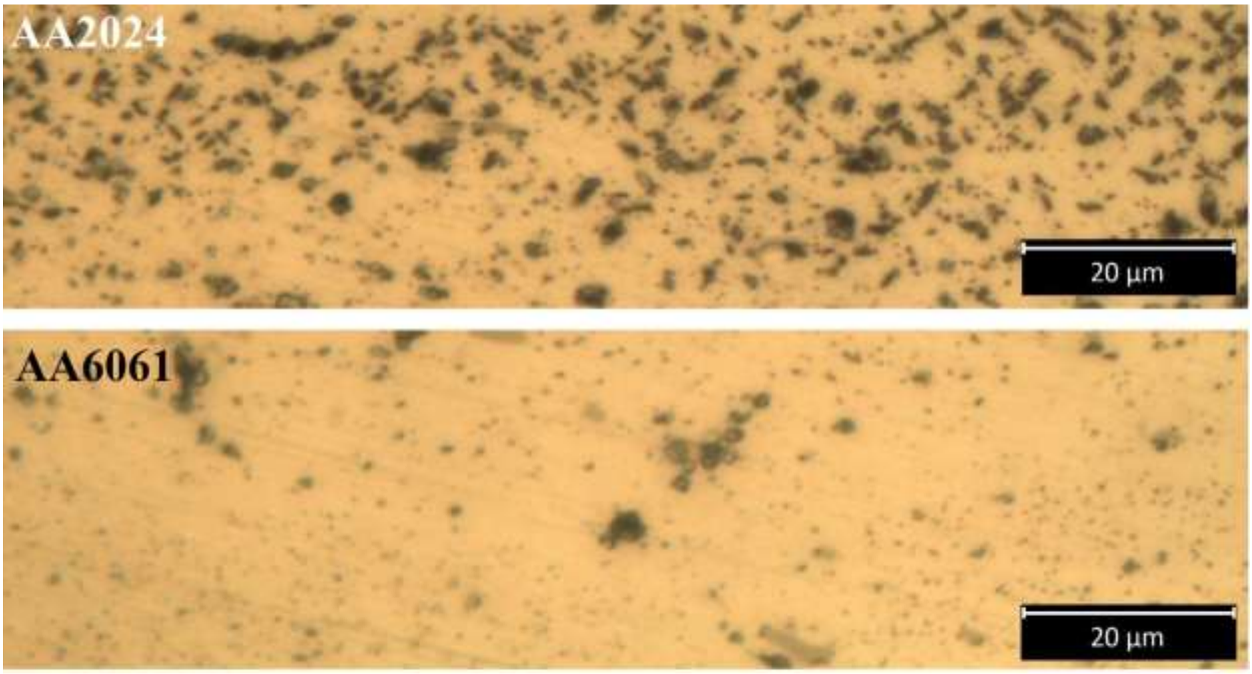
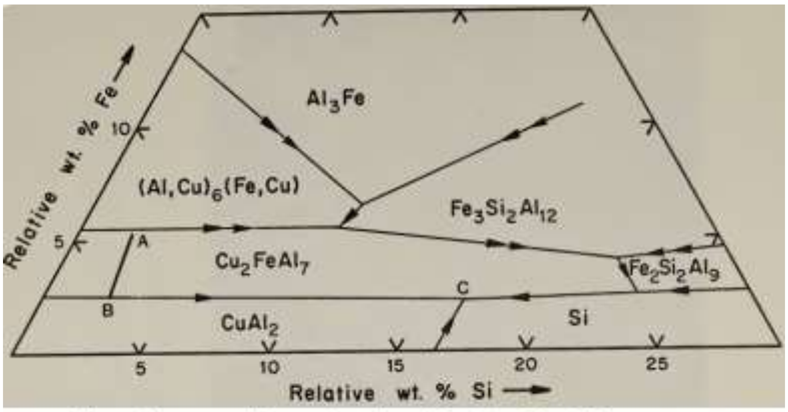
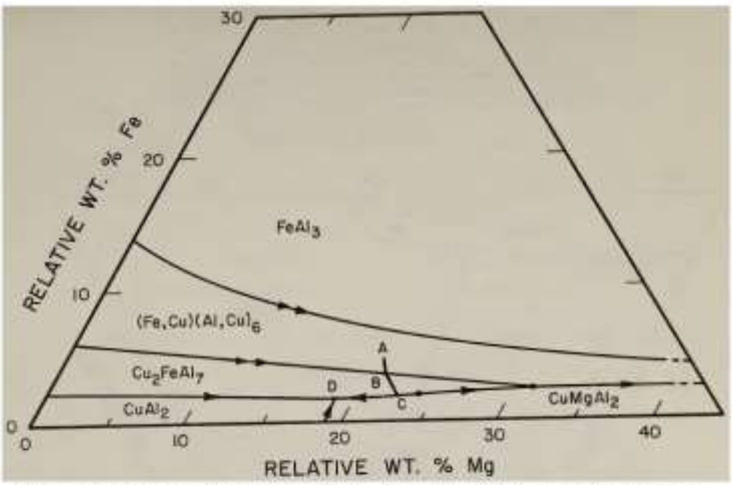


Fig. 6. Microstructure of the alloys (Holding at 453ºC for 210 minutes).



Aluminum alloys in the Al-Cu-Fe-Si system.



Aluminum alloys in the Al-Cu-Mg-Fe system.

Fig. 7. Equilibrium phases diagrams [15].

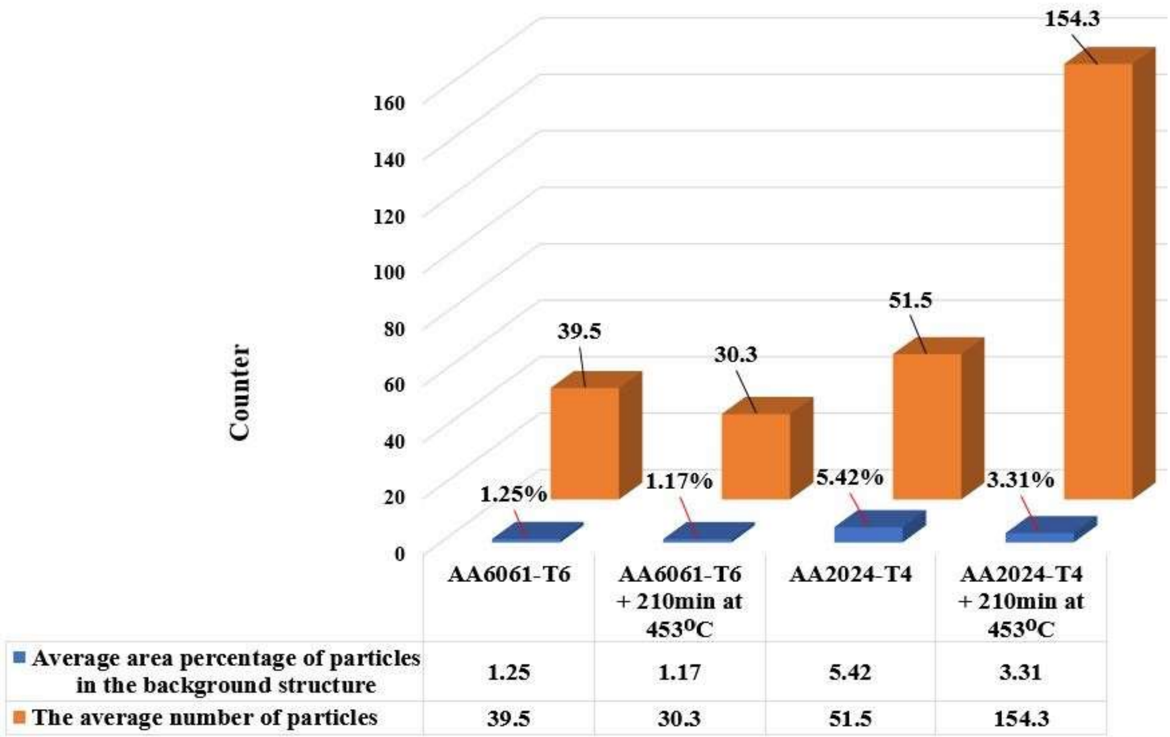


Fig. 8. The average number of precipitates and their percentage in the structure.

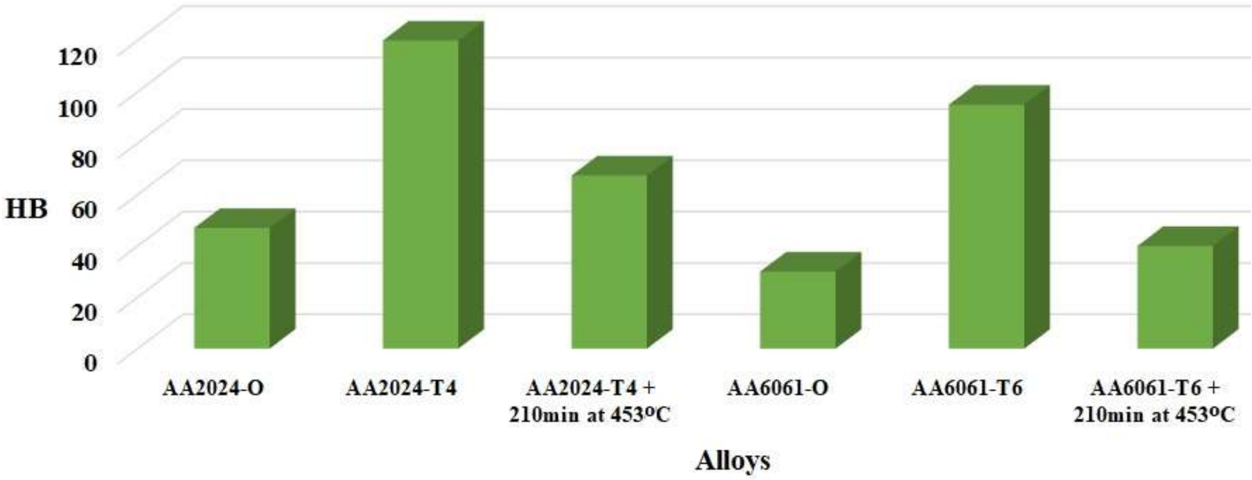


Fig. 9. Brinell hardness of diffent samples.

4. Conclusion

1. Temperatures higher than 457.5°C may impair the precipitation hardening of AA2024 alloy. It is possible that after cooling the alloy, brittle compounds will be formed in the boundary of the aluminum grains over the holding time.
2. After the heat treatment (at 453ºC for 210 minutes) of the AA2024-T4, the diameter of the precipitates is reduced.
3. Precipitate size in AA6061-T6 alloy remained almost unchanged after the heat treatment process at 453ºC for 210 minutes.
4. After heat treatment of AA2024-T4 and AA6061-T6 alloys at 453ºC, the hardness decreases, but the hardness value is higher than the alloy without any heat treatment.

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