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The effects of precipitation hardening on corrosion behavior of AA6082 aluminum alloys

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Abstract

Aluminum alloys are now widely preferred in industrial applications due to their low density and high strength values. The properties of these alloys can be further improved by precipitation hardening heat treatment. For this purpose, the temperature and time used in the precipitation hardening process plays a very effective role on the performance of the material. Therefore, in this study, the effects of artificial aging heat treatment on mechanical properties and corrosion behavior of AA6082 alloy were investigated. The effects of artificial aging time on microstructure and mechanical properties of alloy were analyzed and at the same time corrosion behavior was tried to be determined by corrosion tests. For experimental investigations, the alloy samples prepared in appropriate sizes were heated to 540°C (± 0.5°C) with heating rate 10°C/min. by electrical resistance ceramic furnace. For the solution heat treatment, samples were kept in the furnace at this temperature for 4 hours. The samples taken from the furnace were firstly poured into iced water at 10°C and then subjected to artificial aging at 190°C for 2, 4, 6, 10, 12 and 24 hours. Finally, the samples taken from the furnace were left to cool down in stagnant air. The results show that the mechanical properties and the corrosion resistance of the alloy increase with the increase of artificial aging time. The best value of corrosion resistance was obtained at a temperature of 190°C at 10-hour aging period. The hardness of commercial alloy of 43 BHN is increased to 98 BHN and the corrosion resistance of the commercial alloy increased from 6.91 mpy to 0.49 mpy at a temperature of 190°C at 10-hour aging period.

Keywords: AA6082 aluminum alloy, T6 heat treatment, artificial aging, mechanical properties, corrosion behavior

Introduction

Aluminum is the second most used metal in the world. Due to its high specific strength (strength/weight ratio), easy formability, high thermal conductivity, compatibility with surface treatments and resistance to corrosion, aluminum and its alloys are used in a wide range of applications from automotive, building and packaging sectors to high voltage-electricity transmission lines to construction applications [1-3].

6XXX series aluminum alloys, containing Mg and Si as main alloy elements have generally good extrusion and rolling capabilities. These alloys also have good corrosion resistance, especially in atmospheric environments. In addition to these favorable properties, the maintenance of the gloss of the anodized surface of the 6XXX series aluminum alloys also increases the amount of commercial use day-by-day [4-6]. At the same time, the strength of this alloy group can be substantially increased by a two-stage heat treatment [6, 7].

This two-stage heat treatment consists of solutioning and ageing process. The solutioning process, holding the alloy in temperature below eutectic reaction, is used to dissolve the precipitates of Mg_2Si, homogenize the chemical elements concentration on the cross-section of dendrites of the α phase and the change in the silicon precipitations morphology. The solutioning process is usually performed at 460-540 ° C for aluminum alloys of the 6XXX series.

The ageing process can be applied as natural aging at room temperature and the artificial aging at moderate temperatures. The ageing (soaking of the supersaturated alloy to separate strengthening phases from the supersaturated solid solution) the precipitation strengthening is obtained as a result of the phases precipitation of Mg_2Si, Al_2CuMg and Al_2Cu [8].

Artificial ageing (holding the alloy at constant temperatures during predetermined period) results in the improvement of the mechanical properties such as tensile strength and hardness and in simultaneous worsening of plasticity. Because of the growth of alloy's strength after heat treatment is very often accompanied with the reduction of the plasticity, their optimal relation should be selected depending on a given application of the alloy [8].

In the aging phase, which provides increased strength in the material, the precipitation process of the oversaturated melt takes place:

$$\alpha \rightarrow GP \rightarrow \beta^{II}\,(Mg_5Si_6) \rightarrow \beta^{I}\,(Mg_9Si_5) \rightarrow \beta\,(Mg_2Si) \qquad (1)$$

The maximum hardness is possible by obtaining the phase β^{II} during aging. On the other hand, the conversion of the β^{II} phase to the β phase is defined as over-aging, and the Face-Centered Cubic FCC crystal structure of the equilibrium phase β results in a reduction of the hardness of the alloy [9, 10].

Depending on the temperature and duration of the applied artificial aging heat treatment, the type, size and quantity of the precipitated phase play an active role on the mechanical properties of the aluminum alloy and corrosion behavior [3, 6].

In this study, the effects of artificial aging on the hardness and corrosion resistance of AA6082 alloy were investigated.

Experimental Studies

The chemical analysis of commercial AA6082 aluminum alloy used in this study and in rod form is given in Table 1.

Table 1: The chemical analysis of AA6082 aluminum alloy (wt.%)

Si	Mg	Mn	Fe	Cu	Cr	Zn	Ti	Al
0.96	0.66	0.49	0.204	0.02	0.004	0.014	0.016	97.63

The specimens, have dimensions of 12.09 mm in diameter and 15 mm height, were heated to 540 ± 0.5°C with heating rate 10°C/min. in an electric resistance ceramic? furnace. They were subjected to a solutioning treatment process for 4 hours at this temperature. The samples taken from the furnace were first put into iced water at 10°C for 15mins. and then subjected to artificial aging at 190°C for 2, 4, 6, 10, 12 and 24 hours. Finally, the samples taken from the furnace were allowed to cool down in stagnant air.

The heat-treated samples were prepared metallographically to examine their microstructural properties. For this purpose, the samples passed through the emery papers of 400, 600, 800, 1000 and 1200 mesh respectively were polished using 3 μm diamond paste solution and etched for about 30 seconds in Kellers Etch. Microstructure studies were performed using a JEOL JSM-6060LV brand SEM microscope.

The hardness measurements of the samples were carried out on a Brinell hardness tester using a 2.5 mm diameter hardened steel ball and a load of 62.5 kg. Hardness values were determined by taking the arithmetic average of at least 5 measurements for each sample.

Potentiodynamic polarization (Tafel) method was used to determine the corrosion behavior of the samples. Three electrode techniques were used in the experiments performed in the Gamry potentiostat/galvanostat device, using saturated Ag/AgCl as the reference electrode and graphite electrodes as the auxiliary electrode. Experiments were performed at room temperature and 3.5% NaCl solution, and potentiodynamic polarization measurements were carried out at 5 mV/s for 3600 seconds with a voltage between -1 and 1. Prior to the corrosion tests, the surfaces of the specimens, 12.09 mm in diameter and 5.16 mm in dimensions, were passed through standard metallographic sample preparation steps up to 1200 mesh emery paper.

Results and Discussion

The change in hardness values according to the aging time of samples subjected to artificial aging at different times at 190°C after solutioning treatment for 4 hours at 540°C is given in Figure 1.

The commercial hardness value of AA6082 aluminum alloy was 43 BHN and after solutioning treatment the hardness reduced to 40 BHN. As can be seen in Figure 1, the hardness value of the samples increases with increasing artificial ageing time. The highest hardness value (98 BHN) was obtained at 10 h aging time at 190ºC. The hardness tended to decrease again with the prolongation of the aging period and the hardness value fell to 89 BHN in 12 hours and 78 BHN in 24 hours respectively.

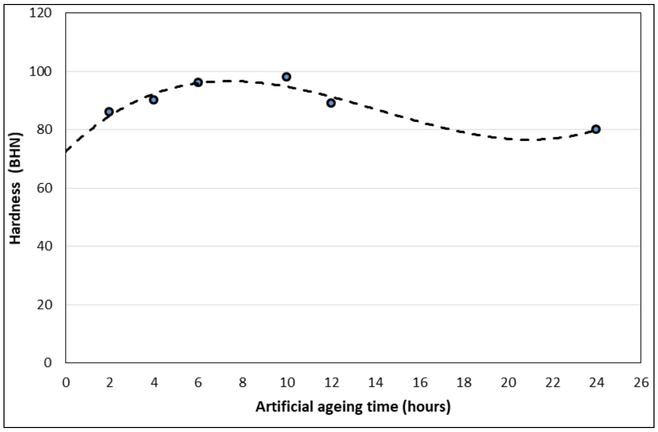

Fig 1: The effect of the artificial aging time on the harness value of AA6082 alloy

Based on the results of the performed investigations, a mathematical relationship between the hardness of the alloy and the heat treatment parameters can be established. Pezda, J. [8] informed the mathematical dependence of the effect of heat treatment parameters on the change of the alloy BHN hardness as second order polynomial.

At the end of the aging process, the increase in the hardness values of the alloys is due to the variations in the phases, precipitates and grain sizes formed in the microstructure. The increase in hardness is accepted as a sign of the success of the aging process after the dissolution in the literature [11]. The highest hardness value can be achieved by adjusting the optimum aging temperature and time.

When the aging process starts, both magnesium and silicon are beginning to precipitate as Mg_XSi_Y, as indicated by the formula of the solid solution. The precipitate phase formed at the start of aging is in perfect coherence with the aluminum matrix. But at high temperature, the Mg_XSi_Y precipitates become incompatible with the matrix together with increasing duration. Because of the artificial aging process, the maximum hardness value of the samples is obtained by precipitation of β^{II} (Mg_5Si_6) phase in needle form [13]. The β^{II} phase begins to turn into a rod like β^{I} (Mg_9Si_5) phase during the increasing aging process, leading to a decrease in the hardness of the material [14]. As the aging time increases, the precipitation of the β (Mg_2Si) phase becomes more dominant, resulting in a marked decrease in the hardness of the aluminum alloy [10]. In this case, full conformity is required to achieve higher strength and stiffness [12].

At the same time, coarse particles and constantly growing grain sizes are observed due to the combination of increasingly coexisting precipitates in the over aging period. In this period, the factors that prevent dislocation movements being decreasing and consequently the mechanical properties of the material are becoming increasingly smaller? [15]. Corrosion current (I_{Corr}) and corrosion potential (E_{Corr}) values measured from the corrosion experiments of the samples by the potentiodynamic polarization (Tafel) method are given in Table 2.

Table 2: The changes of corrosion test results of AA6082 samples according to artificial aging time

Duration (Hour)	I_{Corr} (µA)	E_{Corr} (V)
2	15.67	-0.714
4	9.13	-0.838
6	8.49	-0.793
10	1.30	-1.140
12	7.64	-0.721
24	5.73	-0.744

The following formulas were used to calculate the corrosion rate (Rcor) of the samples from these results [16]:

$$R_{Corr} = \frac{I_{Corr} \, . \, K \, . \, EA}{d \, . \, A} \qquad (3)$$

Where,

R_{Corr} : Corrosion rate (mpy)
I_{Corr} : Corrosion Current Intensity (µA)
K : Constant
EA : Equivalent weight (atomic weight/valance)
d : Density (g/cm^3)
A : Surface area (cm^2)

When the corrosion rate was calculated, the density of AA6082 alloy specimens exposed to T6 heat treatment, determined using the Archimedes technique, was 2.713 (g/cm^3). The surface area of samples was 1,1499 cm^2 for corrosion test in this study and K constant was taken as 1.288 and EA (equivalent weight) was calculated according to the chemical composition of alloy the by formula given below [16].

$$EA = \frac{1}{\sum \frac{n.fi}{M_A}} \qquad (4)$$

Where;

n: Atomic valance of element
f_i: Chemical composition of element
M_A : Atomic weight of element

When the data of elements of AA6082 alloy are substituted in the formula, the equivalent weight value is found to be 9.0027. The corrosion rate (RCorr) was then calculated according to the formula given above. The change in corrosion rate with the heat treatment time is plotted in Figure 2.

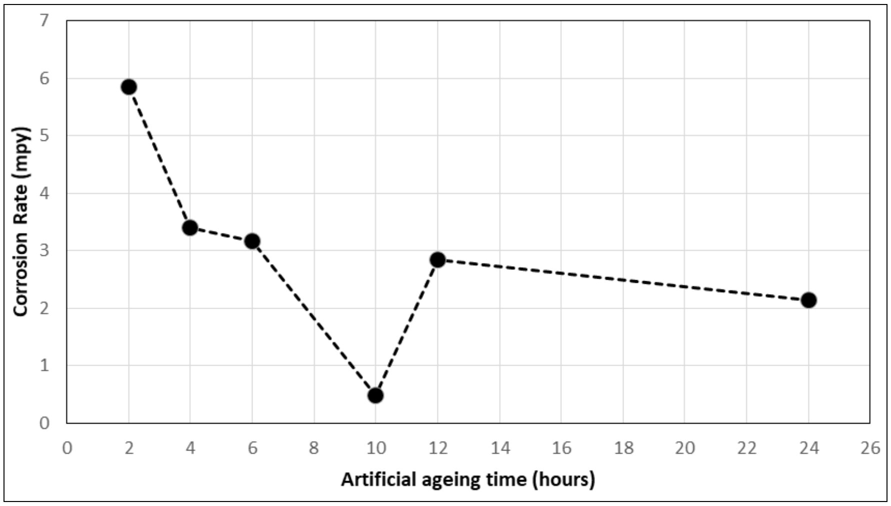

Fig 2: The change of corrosion rate with ageing time

The corrosion rate of commercial alloy samples was detected as 6.91 mpy. As can be seen from Figure 2, the corrosion rate rapidly decreases with aging time and obtained the lowest value of 0.49 mpy in 10 hours, which is the optimum artificial aging time. In the case of over aging, the corrosion rate increases rapidly and reached to 2.85 mpy in 12 hours.

Aluminum and its alloys are highly resistant to corrosion due to the thin, protective barrier oxide layer on their surface. However, in the presence of chloride ions in the environment this protective oxide layer of the region is likely to suffer from corrosion. The most important factors affecting the corrosion resistance of aluminum alloys are the alloying elements they possess. However, temperatures and durations used in heat treatments also play a dominant role in corrosion behavior [17]. After the corrosion test, surface morphologies of the samples were examined on a SEM microscope. A pronounced pitting corrosion was observed on the surfaces of each specimens (Figure 3). Similar results have been obtained in the literature reviews and it has been observed that with increasing aging period, the pitting corrosion also increases [18]. A similar situation has been detected by Yuksel [6] by the corrosion tests performed to AA6063 alloys artificial aged at different temperatures and durations. It has been found that intergranular corrosion decreases with increasing aging time, and with the increase of pitting corrosion and over-aging, pitting corrosion becomes dominant.

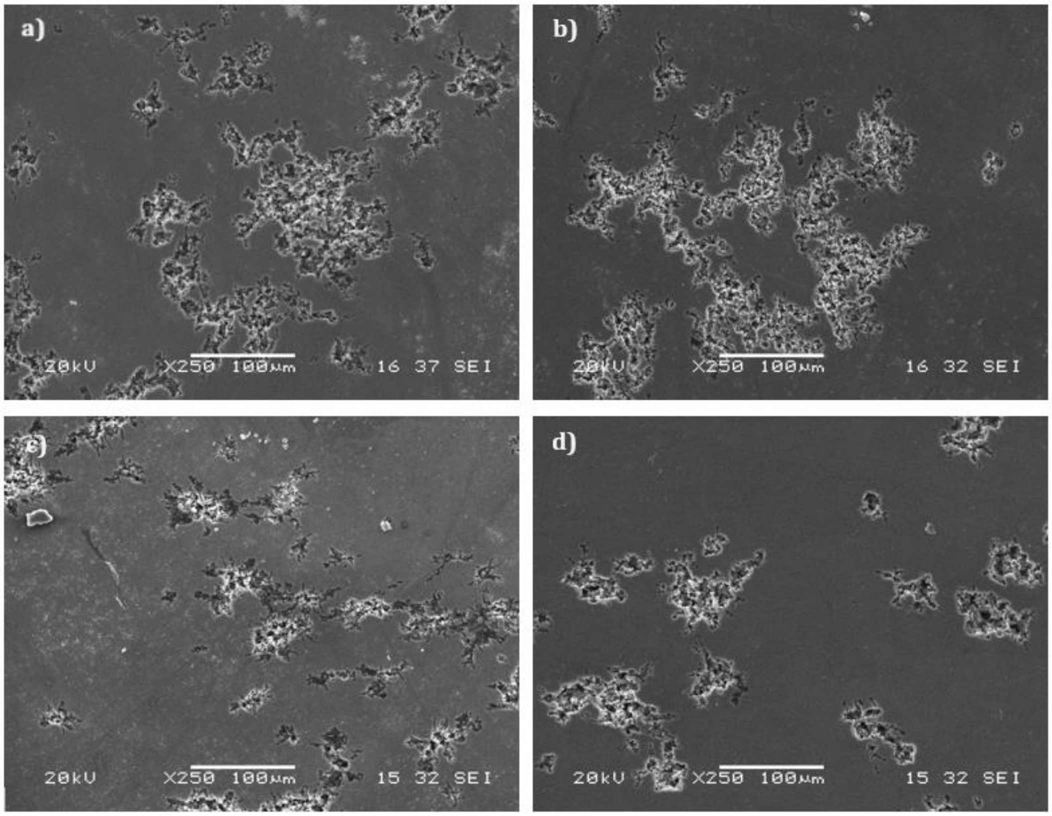

Fig 3: The variations of surface morphology of AA6082 alloy by ageing durations after corrosion tests, a) 2 hours, b) 6 hours, c)10 hours, d) 24 hours

The corroded areas of the material surface were examined by SEM microscopy and the obtained SEM image given in Figure 4. The EDS analysis of the marked corrosion zone (Table 3) (Zone (a)) on the microstructure shows that the concentration of chlorine ions in the corrosive solution is concentrated in this region which show similarity in many studies in the literature [6, 18]

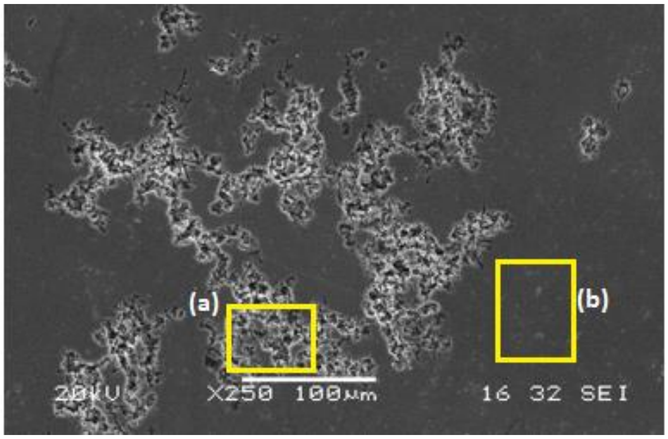

Fig 4: Surface morphology after artificial aging AA6082 alloy after corrosion test and EDS analysis of corrosion products

Table 3: The EDS analysis of the marked corrosion zone on the microstructure (wt.%)

Element	Zone (a)	Zone (b)
Si	2.110	1.090
Mg	1.570	1.312
Mn	0.801	0.560
Fe	0.479	1.031
O	1.534	1.925
Cl	0,657	

When the aging process starts, both Mg and Si are beginning to precipitate in the form of solid solution Mg_2Si and there is an Al matrix around this phase. In this case, electrochemically the Mg_2Si phase is more active than the Al matrix so this situation causes the formation of a micro-galvanic corrosion cell and the intergranular corrosion between the phase bound to the grain boundaries and the matrix [6].

As the selected temperature for artificial aging process increases, the aging time required to achieve optimum properties is shortened. In this case, however, the increasing aging time leads to the transition of the precipitated phase from needle-shaped to rod-like form [9]. The increase in pitting corrosion associated with increased aging time is due to the increase in the physical dimension of the more active precipitate phases compared to matrix. But this is not exactly proven [18, 19].

Conclusions

The obtained results from the artificial aging process applied to AA6082 aluminum alloy at 190°C for 2, 4, 6, 10, 12 and 24 hours and their pertinent discussion allow drawing the following conclusions:

1. The experimental results have revealed that aging between 8 and 10 h at 190°C is the most suitable combination of time and temperature imparting maximum corrosion resistance and hardness to the alloy.
2. Up to the completion of the precipitation of the β^{II} phase, a significant increase in the hardness of the material with increasing aging time was obtained and the highest hardness value (98 BHN) was detected at the 10-hour aging time.
3. With longer aging times, during the transformation of β^{II} phase to β^{I} and β phases (over-aging), the hardness of the alloy decreases rapidly as the sizes and distributions of the precipitates grow out of homogeneity and join with the adjacent precipitates and grow to extreme levels. During 24 hours of aging, the hardness value decreased to 78 BHN.
4. Likewise, the corrosion rate of alloys is reduced with increasing aging time, the minimum corrosion rate (0.856 mpy) was obtained at 10-hour aging time

Acknowledgements

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