



Effect of Aging Heat Treatment on Corrosion Behavior and Mechanical Properties of 6061 Aluminum Alloy

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Abstract

Aluminum-magnesium-silicon alloys are widely used in wide range of engineering applications because they have moderate corrosion resistance, excellent formability, and high specific strength. The combined effect of quenching media and aging time on corrosion behavior, mechanical properties, and microstructure of 6061 Al alloy was investigated. Potentiodynamic polarization technique was employed to study the corrosion behavior of 6061 Al alloy in 3.5 %NaCl solution. The microstructure, phases and mechanical properties were examined via optical microscope, XRD and tensile and hardness testers respectively. The results of microstructure and X-ray diffraction analyses showed that the formation of (CuAl₂) and (Mg₂Si) phases improved the hardness and strength. The mechanical properties and corrosion resistance of treated 6061 Al alloy were progressively increased with increasing aging time.

Keywords: 6061 Al alloy, corrosion, aging time, mechanical properties.

الخلاصة: سبائك الألومنيوم والمغنيسيوم والسيليكون تُستخدم على نطاق واسع من التطبيقات الهندسية لأنها تتمتع بمقاومة تآكل معتدلة وقابلية تشكيل ممتازة ومقاومة نوعية عالية. تمت دراسة التأثير المشترك لوسائط التبريد و زمن التعتيق على سلوك التآكل ، والخصائص الميكانيكية ، والبنية المجهرية لسبائك الألومنيوم 6061. تم استخدام تقنية استقطاب الجهد الساكن لدراسة سلوك التآكل لسبائك 6061 Al في محلول كلوريد الصوديوم بنسبة 3.5٪. تم فحص البنية المجهرية والمرحل والخواص الميكانيكية بواسطة المجهر الضوئي ، XRD واختبار الشد والصلابة على التوالي. أظهرت نتائج تحليلات البنية المجهرية وحيود الأشعة السينية تكوين أطوار (CuAl₂) و (Mg₂Si) اللذان يعملان على تحسين الصلابة ومقاومة المادة. تمت زيادة الخواص الميكانيكية ومقاومة التآكل لسبائك الألومنيوم المعالجة 6061 بشكل تدريجي مع زيادة زمن التعتيق.

1. INTRODUCTION

Aluminum is the second most widely used metal in industrial applications in the world. The 6XXX series alloys denoted as is heat treatable, medium-strength alloys, moderate corrosion resistance, and excellent formability characteristics [1]. The 6061 alloys are used in general works (structure, handling instruments) and also for frameworks assembled by welding processes [2]. Magnesium (Mg) and silicon (Si) can produce various degrees of properties (such as strength) of alloys by heat-treated precipitation of the main solutes [1, 3]. In other words, the strength of the 6XXX series can be greatly increased by performing two or more stages of heat treatment. The tempering around 175°C (T6) is called the as-obtained microstructure of the material. So the treatment process of the 6XXX series can be classified into, artificial aging treatment and solution heat treatment. The 6XXX series alloys is including T6 temper that includes, solution treatment and follows with artificial aging treatment. The quenching treatment is a good method to improve some mechanical properties such as the strength

of the alloy [1, 4]. In general, the success of the cooling process depends mainly on the possibility of heat transfer to the cooling medium in order to obtain, a supersaturated solid solution. The heat treatment temperature of the solution must be between 460 and 530°C[5]. Therefore, Quenching hardening is the most common method of use as heat treatment in the manufacturing industry, which leads to increased service reliability of the metal alloy components. Heating to about 175°C (for 6000-alloys in general between 160-200°C, will produce “age-hardening”, “Artificial aging” or simply “aging” [1] leads to precipitation of various phases at various amounts of time [3]. Based on that, when the alloys are exposed to a solution heat treatment followed up by quenching treatment and tempering, their mechanical properties up to their highest grade. The heat treatment and precipitation hardness was studied by several groups [5]. Guanxia X., Gu Z. et al. , 2020 [6], studied the possibility of producing new aluminum alloys and studying the mechanical properties for the purpose of using them in industrial applications. The new alloy product under an aging state showed mechanical properties ranging from 15~18% for ductility, yield strength and tensile strength were 310 MPa and 380 MPa, respectively. Abdulwahab, et al. 2013 [7], Al-Si-Mg alloys modified with antimony, and type A356 were examined. The mechanical properties and microstructure studied and the effect of aging treatment. They found that heat treatment of the solution at a temperature of 540°C/h for the prepared alloys and then subjecting them to heat aging at 180°C for 1 to 5 hours will lead to an increase in the hardness and tensile properties with the aging treatment. Also, the elongation and impact energy will decreased. They used the stirring casting method to prepare two different composites of AA 6061 alloy as matrix reinforced with different ceramic additives Al₂O₃ and B₄C. Pin-on-disk technology was used to calculate the wear rate for each addition of Al₂O₃ and B₄C particles. In this research, the hardness test was used in the analysis and evaluation of the addition of solid particles. Krishna P. Ch. 2017 [9], studied in this paper the effect of heat treatment on the mechanical properties of 6xxx series alloys. The study showed that the alloys in the 6xxx series have the potential to form magnesium silicate (Mg₂Si), which makes the heat treatable. It was also found that the 6xxx series alloys have good formability, mechanical ductility and weldability. Fahimpour, et al. 2012 [10], investigate examined the corrosion parameters of 6061 alloy joined by friction stir welding and gas tungsten arc welding methods under difference conditions. Finally, the temperature and duration rate of cooling can vary the type, amount, size, and division of both insoluble and soluble particles. The aim of the present work is to study, corrosion resistance and mechanical properties for treated aluminum 6061 alloys. The improving its corrosion resistance and mechanical properties carrying out the solution treatment and following it with the aging process and studying the effect of changing the media of the solution treatment, as well as studying the change of aging factors.

2. METHODOLOGY

2.1. Materials

The chemical composition of 6061 Al alloy shown in Table 1, was in form plate with 4mm thickness. The plate was sectioned to 15×15 mm square specimens using electrical discharge machine EDM.

Table 1 Chemical composition of 6061 Al alloy.

Element	Cu	Ti	Fe	Si	Mg	Cu	Mn	Cr	Zn	Al
Wt%	0.28	0.05	0.34	0.72	0.92	0.28	0.03	0.019	0.14	Bal.

2.2. Sample preparation

The specimens were mechanically ground in standard manner starting from 400 P emery paper and finished with 1200 P emery paper. The ground specimens were mechanically polished using 1 μm colloidal silica to ensure the best possible surface finishing with minimum residual stress.

2.3. Aging treatment

The heat treatment process of the prepared samples was done using a carbolite box furnace (GLM3 model). After completed the heating and holding alloy at temperature the treatment that must be below the temperature of the eutectic reaction, the prepared samples were quenched in various media (oil and water). Table 2 shows the types of quenching media (water and oil) used during the experiments. The prepared samples were treated with

water and oil at 520°C for 2h, then aged at the different aging times (2, 3 and 4)h at temperature 175°C as shown in Figure 1.

Table 2 Physical properties of media.

Quenching Media	Temp (°C)	Specific Gravity	Specific Heat Capacity (JKg ⁻¹⁰ k)	Density (Kg/m ³)	Viscosity (Ns/m ²)
water	25	1.035	4188	1000	0.9 x 10 ⁻³
Oil	25	0.874	1890	890	45 x 10 ⁻³

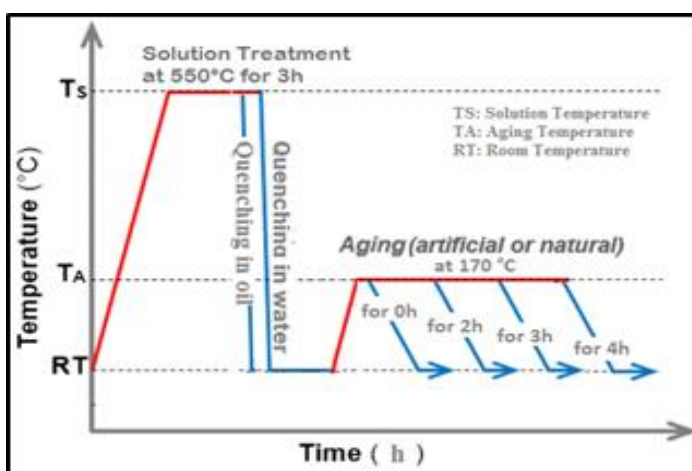


Figure 1 Aging process diagram for 6061 Al alloy, with all aging conditions.

2.4. Corrosion tests

Corrosion tests were performed in 3.5wt% NaCl by adding high purity NaCl to the distilled water. Samples were degreased with acetone and then rinsed in distilled water before being immersed in the test solutions. By using potentiostat device conforming to the ASTM (G-5) Standard, an electrochemical corrosion measuring was applied. By using the following equation the corrosion rate (C.R) can be calculated [1, 11, 12, 13]:

$$C.R (mpy) = 0.13 * icorr * e / \rho \tag{1}$$

Where:

mpy: mils penetration per year.

icorr: corrosion current intensity (A/cm²).

ρ: metal intensity (gm/cm³).

e: atomic weight.

2.5. Mechanical properties

The optical microscope (Nikon.120, Japan) with digital camera and computer was used to examine the microstructure of the samples. vickers hardness device was used to measure the hardness of samples after aging treatment under load 0.5 kg. Vickers hardness value reported was the average of three readings taken at different locations. The equation used to find the vickers hardness (HV) is:

$$H.V = 1.8544 \times [P / (d1 + d2 / 2)2] \tag{2}$$

Where:

H.V: Vickers micro-hardness.

P : Applied load (kg).

d : Sample diameter (mm).

Other prepared samples for tensile testing depended on standard ASTM E8.

3. RESULTS AND DISCUSSION

3.1. Microstructure and X-ray analysis

The microstructure of 6061 Al alloy is shown in Figure 2 and 3. The formation of stable phases of Mg_2Si and $CuAl_2$, which reaches a stable state of the formation of phases due to an increase in the aging time to 4h in water quenching as shown in Fig. 4. The dominant intermediate β phase (Mg_2Si) in 6061 Al alloy (Al-Mg-Si alloys) in the betimes stages of aging was observed as needle-shaped. The second phases of the predominant equilibrium in 6061 alloy are (AlFeSi, $CuAl_2$ and Mg_2Si) results by XRD analysis is shown clearly in Figure 4. The quenched in various media (oil and water) of Al-Mg-Si alloys will refine the precipitate structure and induce the formation of the meta-stable Q' phase ($AlMgSiCu$) and increase the mechanical properties and hardness [1, 12]. The microstructure in Figure 2 and 3 is shown that increasing the quenching followed by aging time leads to an increase in the size of grains. Generally, the structure of samples quenched in water is smaller than that of samples quenched in oil due to the higher cooling rate obtained by water. Increasing the aging time to 4h at 175°C causes the precipitates to coalesce into larger particles [14, 15].

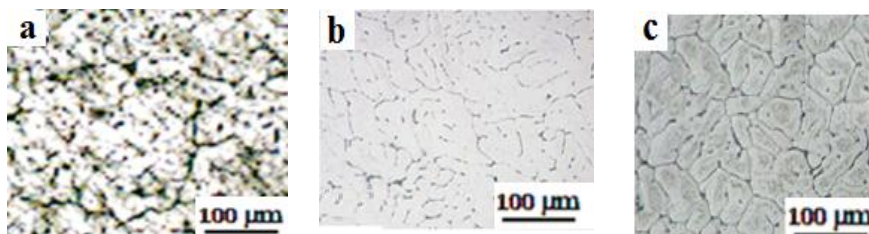


Figure 2 Optical microscopy of 6061 Al alloy, with water quenching and aging time at (a) 2h, (b)3h, and (c) 4h.

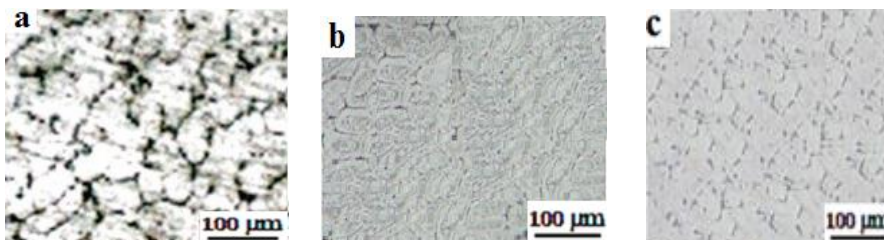


Figure 3 Optical microscopy of 6061 Al alloy, with oil quenching and aging time at (a) 2h, (b) 3h, and (c) 4h.

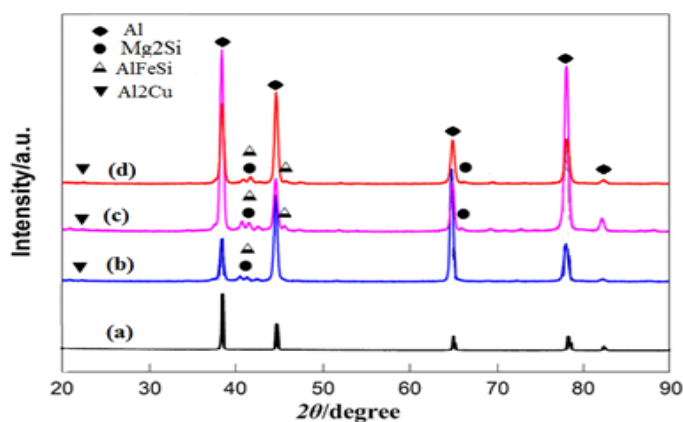


Figure 4 XRD patterns of 6061 Al-alloy at water quenching and aging times at: (a) 0h, (b) 2h, (c) 3h, (d) 4h.

3.2. Characteristic of the electrochemical corrosion test

Potentiodynamic polarization screening was achieved to inspection the effect of different aging time after quenching treatment of 6061 Al alloy on the icorr, Ecorr and the kinetics of cathodic and anodic reactions; the results are shown in Figure 5 and Table 3. As-received 6061 Al alloy samples exhibit the highest corrosion rate. An enhancement in the icorr is observed for all treated samples of 6061 Al-alloy. icorr decreased by about half after 2h aging for the two tested quenching media. Further decreasing in icorr occurred with increasing the aging time up to more than five times lower icorr at 4h aging time. Also from Figure 5 and Table 3 the potentiodynamic polarization curves of oil quenching showed a decrease in values of corrosion current density compared with water quenching at the same aging times that which is evident the corrosion rate reduced. The reduction of current density in oil quenching is probably due to the formation of the Anti-abrasion layer more than water quenching with different aging times which may merely blocks the reactive sites over the surface [16-19].

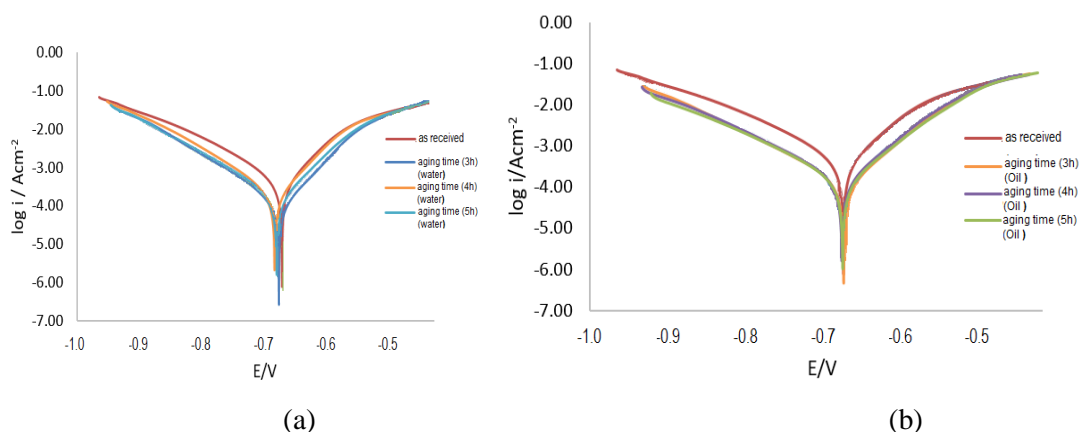


Figure 5 Potentiodynamic polarization curves in 3.5% NaCl for 6061 Al alloy at: (a) quenching in water, (b) quenching in oil.

Table 3 Results the potentiodynamic polarization analysis of 6061 Al alloy.

Mediums quenching	Aging times (h) at temperatur e 175°C	Corrosion potential E _{corr} (mV)	Corrosion current density i _{corr} (µA/cm ²)
As received	0	-773	5.870
Water	2	-783	3.424
	3	-772	1.814
	4	-774	1.110
Oil	2	-779	2.670
	3	-782	1.760
	4	-779	1.000

3.3. Mechanical properties

Heat treatment consists of two-stage: the solution and the aging process. The solution process is used to homogenize the element's concentration and the variation in the silicon depositions morphology. The solution treatment is usually cured out at 460-560°C for aluminum alloys [14]. Figure 6 shows the hardness property as a function of the solution process (aging time) for the samples of 6061 Al alloy. The hardness values were measured by working at least three tests for each state and the average of the results is produced. The hardness of 6061 Al alloy, immediately after solution treatment and aging at 2h is 55 kg\mm² (water-quenching) and 48 kg\mm² (oil-quenching). The results showed that increasing the aging time from 2h to 4h the hardness of the samples will increase. Maximum hardness was reached after 5h of aging at 170°C was 67 kg\mm² (water-quenching) and 59 kg\mm² (oil-quenching). Therefore, increasing the hardness property can be shown by the diffusion mechanism, and also through the obstacle of dislocation by impurity atoms [20]. Tash, et al., 2006 [21], studied the effect of metallic parameters of heat-treated Al alloys. They show that the hardness increased after achieving the aging treatment at 175°C for 2h, this is because of was adhesion of CuAl₂ sheets and β' (Mg₂Si) needles [21, 22]. Therefore, increasing an anomaly in the lattices will lead to a rise in the hardness property of aluminum alloys

[23]. Stress-strain curves shown in Figure 6- a and b for all aging conditions. From the figures, it can be noted that the produce of solute clusters such as precipitates and the subsequent precipitation leads to an increase in the stress-strain. However, the behavior at peak aging will change remarkably, dominated the microstructure by small β - (Mg_2Si) deposits [22]. When the samples aging with longer times, the rate of stress hardening decreases with increasing aging time. This is due to the fashioning of a cluster of β -(Mg_2Si) deposits from the co-clustered Si and Mg [24]. Reduced strain hardening of the β -dominated (Mg_2Si) microstructure was also observed as a result of the cohesion of the loose particles upon continuous annealing. The results when using oil quenching (the stress-strain curves) are smaller than the results when using water quenching solution and this is due to both reducing the rate of strain hardening. The Mg and Si co-assemblies are initially formed. These participate in the increase in yield stress, and the aging peak is connected significantly to the dense cluster with form needle shape deposits in the $\langle 001 \rangle$ Al crystal directions, which are shown to be ideal borders to dislocations [20, 25]. The results indicated that the increased aging time, the increase of ultimate tensile strength, and yield strength, while will decrease the strain hardening rate. Figure 7 shows the samples under quenching and aging treatments, it is indicates that elongation is a function of artificial aging time. This may be due to precipitates incorporation into larger particles causing fewer obstacles to dislocation movement. Generally, the curve of elongation for the samples which are quenching in oil is higher than the curve of samples that are quenching in water as a development of the high cooling rate that can be obtained from water compared with oil.

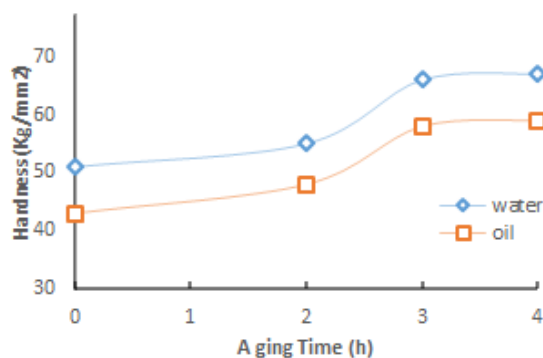


Figure 6 Hardness curve of 6061 Al alloy, at quenching in water and oil.

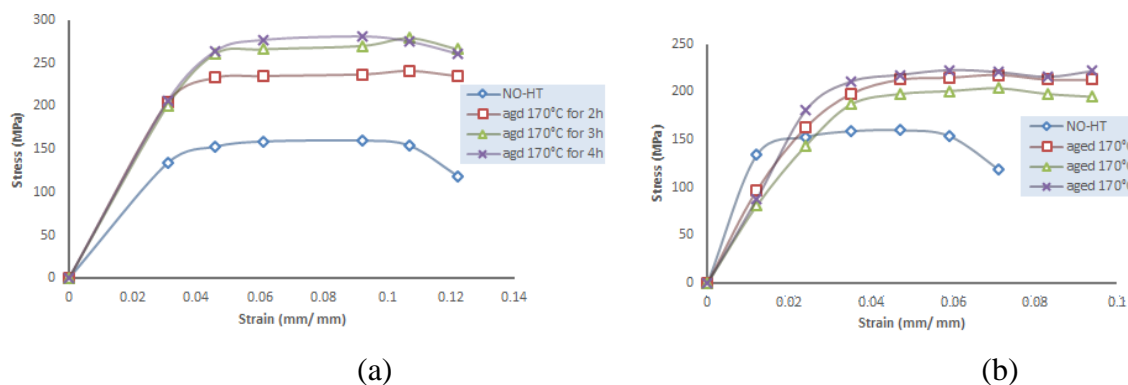


Figure 7 Stress vs. strain curves for 6061 Al alloy, (a) quenching in water, (b) quenching in oil.

4. CONCLUSIONS

In this present work, 6061 Al-alloy standard was solution heat-treated and aging (in water and, oil) with diverse aging times (2, 3, and 4)h. The effect of different solutions of quenching and different aging time on the microstructure and mechanical properties was determined. The following conclusions were obtained:

1. In the heat-treated samples of 6061 Al alloy with various quenching media (oil and water) at the same aging time was corrosion rate in water media was highest in oil quenching. So oil quenching is better for 6061 Al alloy.

2. The aging time has a significant effect on corrosion rate and mechanical properties. As the increases of aging time, the corrosion rate decreases significantly, in addition, to increase in the hardness.
3. The increase in mechanical properties of 6061 Al alloy can be described as a result of the intervention with the dislocation movement as producing the formation of precipitates and the presence of a foreign particle at any phase.
4. Increase in aging time increase the hardness of the 6061 Al-alloy. The hardness of 6061 Al-alloy will raise with increasing the aging time at 175°C.
5. The results from stress-strain curve changes when using oil quenching smaller than the results when using water quenching, this is due to both reducing the rate of strain hardening.

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