Effect of Medium Quenching and Temperature on Corrosion Behavior of Aluminum Alloy 6061

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Abstract

In the present work the effect of heat treatment processes at different temperatures and in different quenching media on mechanical properties in addition to corrosion behavior in different pH solutions of aluminum alloy 6061 was achieved.

The alloy was received as fabricated and the solution heat treatment processes was achieved at temperatures (490,530,570 °C), then quenching for every degree was done in two media (water, oil) to obtain on six samples. The artificial aging was done on every sample at temperature (160°C) for one hour.

The microstructure was examined to show Mg_2Si in every sample.

The results of hardness test showed that the hardness of alloy increased with increasing heat treatment temperatures, and at the same temperature the quenched specimens in oil had higher hardness.

On the other hand, the tension tests showed that the strength of alloy increased with increasing of heat treatment temperature, and at the same temperature the quenched specimens in water had higher hardness.

The results of corrosions test showed that the heat treatment operations improved corrosion resistance, and the lower value was get upon treating at 530°C.

Keywords: Aluminum Alloys, Corrosion, Heat treatment.

1-Introduction:

The aluminum is considered as the second used metal on the world while consumption 25 million tons after steel, because of the light of weight make it important for commercial use in many ranges such as transport, space, ships, building, and in car manufacturing. The other property of aluminum is good corrosion resistance, and this explains its importance in constructions, civil engineering and heat exchangers [1].

The aluminum alloys are divided into two essential groups: cast aluminum alloys, and wrought aluminum alloys. The world consumption of cast alloys is 15%, and there are many ways to casting of aluminum alloys, the most famous ways are sand casting, mold casting, or casting in pressure chambers [2].

The wrought aluminum alloys form 85% of overall used aluminum, and the shape of this alloy rolled plates with thickness bigger than 6mm, and sheets with thicknesses (0.15-6)mm. While the thickness of stripes is lower than (0.15)mm. Also these alloys are produced as extruded piped and bar and wire…etc.

The wrought aluminum alloys are consisted of number of series that differ from each other by alloying elements and quantity of these elements [2].

Table1 shows the essential composition of wrought aluminum alloys.

Table 1: Wrought Alloy Designation System [2].

Alloying series	Description or Major Alloying Element
1xxx	99.00 Minimum Aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other elements
9xxx	Unused Series

Series 1xxx, 3xxx, 5xxx, and 8xxx aren't heat treated and strengthen with strain hardening during formation processes, strain hardening is the major way to strengthening un heat treatable aluminum alloys [1].

Series 2xxx, 6xxx, and 7xxx are heat treatable alloys, where it is possible to get required properties by control heat treatment parameters that depend on principle of heating to temperature of solid solution then rapid cooling to low temperature to save this solution, after that the alloy is left to get its properties by precipitations processes of strengthen elements " artificial aging" or the alloy is heated to relatively low temperatures to precipitate strengthen elements from solid solution within the structure [1].

Most of aluminum alloys have good corrosion resistance to most environments, and this rely on the nature of self-protection of aluminum which form a very invisible thin layer of aluminum oxide (Al_2O_3) with 50 angstroms thickness, and it has the following properties:

- Perfect Coherence and bonding between oxide layer and metal.
- The layer of oxide has no defects.
- The layer of oxide is formed as soon as exist in circumference conditions.
- The possibility of forming new layer of oxide in the case of failure or cracking the first layer [3].

In spite of good resistance of aluminum and its alloys against corrosion in many media, but in some alkaline and acidic or even chloride salt when aluminum be in contact with wet aggressive materials that prevent the oxygen to get aluminum surface, in these conditions it is better unused it at all [3].

2- The Importance of Research and its Aims:

The alloys of series 6000 (Al-Mg-Si) are used as moderate strength construction material, in addition to good welding ability, and these alloys have good resistance against corrosion in original environment and have good resistance against stress corrosion cracks [3].

One from most important of these alloys is aluminum alloy 6061 that contain on Silicon and Magnesium as essential alloying elements, where the quantity of added Silicon and Magnesium is sufficient to form metastable phases such as Mg_2Si, and the added Chromium is for strength increasing and control size of granules, also added Copper to increase the strength [3].

This alloy has high strength, good extrusion ability, good welding ability, and good corrosion resistance, and has wide applications in ships building and containers maker [2].

The Aluminum and its alloys are passive metals and resist corrosion in aqueous solutions except mediums that contain active particles such as Chloride. Therefore, the factors that changes corrosion properties are alloying elements that play role in changing mechanical properties, or precipitates that result from heat treatment, or formation processes that change microstructure [3].

Kalenda Mutombo studied effect of Intermetallic Particles-Induced Pitting Corrosion in 6061-T651 Aluminum Alloy in Council for Scientific and Industrial Research (CSIR), the results showed that Al-Fe-Si containing rich-particles acted as cathodes and promoted the dissolution of the Aluminum surrounding matrix in the Aluminum alloy 6061-T651. The cathodic behavior of Al-Fe-Si intermetallic depended on the pH of the solution and Chloride-containing environment. Pitting associated with constituent-particles was attenuated in acidic and alkaline solution [4].

Mohammed A. Amin has studied Influence of the Alloying Elements on uniform and pitting Corrosion events induced by SCN^- Anions on Al-6061 and Al-Cu alloys surfaces. The results showed that the Al-6061 alloys presented the highest corrosion resistance towards uniform and pitting corrosion processes in KSCN solutions [5].

In 2007 a work about effects of pH and chloride concentration on pitting corrosion of AA6061 has been achieved by B. Zaid et al. The results showed that The corrosion behavior of the AA6061 Aluminum alloy was found to be dependent on the pH and chloride concentration (NaCl) of solution [6].

Aluminum alloy 6061 is considered a common alloy in manufacturing parts of machines and suffers from corrosion naturally in machines that work in marine environments because of its existence in salt mediums with different degrees of pH.

So, the importance of research comes from improving the properties in addition to decreasing the corrosion.

Where, the change of times and temperatures in addition to quenching media during heat treatment of aluminum alloy 6061 would give other mechanical properties in addition to new corrosion properties resulting from structure changes.

3- Experimental Procedure:

3-1-Sample Preparation and Chemical Composition:

AA6061was used in this study, the percentages of alloying elements were measured by spectrometer XMF 104 with operation parameters (A= 30mA, V= 40KV, 2ϴ =20°-100°), this apparatus was showed in Fig(1).

Figure 1: XRF Analyzer (XMF 104) for determine alloying elements percentage.

Table 2 showed the measured chemical composition by XRF.

Table 2: Chemical composition (wt%) of used Aluminum alloy 6061

Element	Al	Mg	Si	Fe	Cu	Mn	Zi	Cr	Ti	Others total
AA6061	REM	1	0.65	0.28	0.08	0.23	0.05	0.02	0.04	<0.01

3-2- Heat treatment Processes:

The solution heat treatment was applied by heating the specimens to three temperatures (490,530,570°C) and the hold time was (55 min) then cooling by two different media (water, oil), and to avoid the natural aging, artificial aging was applied by heating to temperature (160°C) , the hold time is 1 hour.

The used furnace was Kelvin for Digital Electronics. Table 3 showed different samples of specimens with different heat treatment parameters.

Table 3: Parameters of heat treatment

Sample	Temperature of solution heat treatment (C°)	Medium of quenching	Temperature of artificial aging (C°)	Period of artificial aging (min)
1	490	Water	160	60
2	490	Oil		
3	530	Water		
4	530	Oil		
5	570	Water		
6	570	Oil		

3-3- Mechanical tests:

3-3-1- Static tension test:

The static tension test was applied by Tinius Olsen apparatus, that showed in Fig(2), to show strength, according to DIN standard that achieve the formula:

$$L_0 / \sqrt{A_0} = 11.3 \qquad ....(1)$$

Where:

L_0: active length of specimen.

A_0: initial cross section of specimen [6].

3-3-2- Hardness test:

The hardness test was applied by ERNSl apparatus according to Brinel standard.
Where:
Applied force: 125 Kg.
Steel ball diameter: 5mm [7].

3-4- Corrosion test:

The corrosion tests were carried out in 3.5wt% NaCl solutions with different values of pH(2,7,12) which was prepared using standard procedures, by adding high pure NaCl to reagent water (3.5%gr NaCl with 96.5% H_2O), and the salt was dissolved in the water by using the magnetic mixer GD503. This concentration is approximate to salts concentrations in sea water and this percentage causes the higher corrosion of aluminum because of the quantity of dissolution Oxygen and ion conductivity at higher values. This solution was divided into three groups. First group, HCl was added to obtain on acidic solution. NaOH was added to second group to obtain on alkaline solution. Third group was without adding to obtain on neutral solution. The value of PH for three groups were controlled by PH Meter P11 [8].

Figure 2: Tension test machine.

Figure 3: Hardness test machine.

The specimens for the test were cut to rectangular shape (19x15x4.5 mm), after which the sample surface were mechanically polished with emery papers starting from 320 grit up to 1000 grit [9].

The samples were degreased with Acetone and rinsed in distilled water before immersion in test solutions. Electro-chemical experiment was monitored for 8 days. The corrosion test results were evaluated using weight loss and corrosion rate. For this purpose weighting apparatus M-Power [10]. Fig(4) showed theses apparatuses.

Weighting apparatus (M-Power)	Magnetic Sitter (GD305)	pH meter (P11)

Figure 4: Apparatuses of corrosion test.

The weight loss (mg) for each sample was evaluated by finding the difference in weight "final weight initial weight" considering the total surface in accordance with ASTM G311 standard recommended practice ASTM, 1994 [10].

Corrosion rate for each specimen was evaluated from the weight loss measurement following standard procedures as relation down.

$$C_R = \frac{W \times 365 \times 1000}{A \times T \times D} \quad \text{................(2)}$$

C_R: corrosion rate (mm/year).

W: reduction in weight (gr).

A: area (mm^2).

T: time of immersion (hours).

D: density of AA6061 (gr/cm^3) [10].

3-5- Microstructure Examination:

The samples of alloy AA6061 were examined using an optical microscope (B-353 Met Optikal). The etching solution was (2 ml HF, 3 ml HCl, 2 ml HNO_3, 190 ml H_2O)[11].

Figure 5: Optical Microscope B353 for microstructure examination.

4- Result and Descusion:

4-1 Microstructure:

Fig(6) showed microstructure of as fabricated specimen, Mg_2Si precipitates were dispersed in matrix.

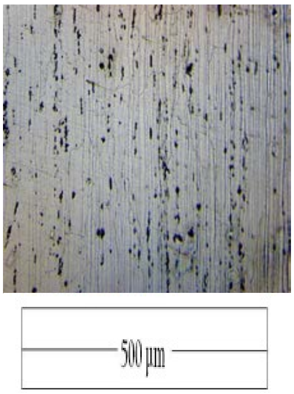
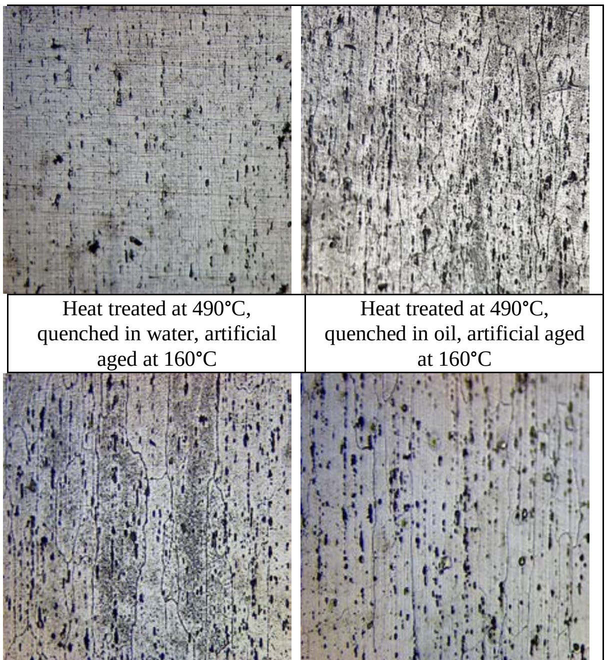
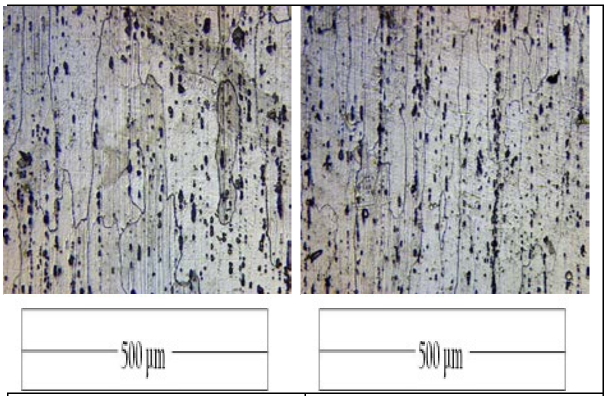


Figure 6: Microstructure of as fabricated aluminum alloy 6061.

Fig(7) showed microstructures of heat treated aluminum alloy specimens, also Mg_2Si precipitates were dispersed in matrix, and with increasing of heat treatment temperature, the quantity of precipitates increased, and at every temperature the quantity and the size of precipitates in oil quenched specimens were more than water quenched specimens.



Heat treated at 490°C, quenched in water, artificial aged at 160°C	Heat treated at 490°C, quenched in oil, artificial aged at 160°C
Heat treated at 530°C, quenched in water, artificial aged at 160°C	Heat treated at 530°C, quenched in oil, artificial aged at 160°C



Heat treated at 570°C, quenched in water, artificial aged at 160°C	Heat treated at 570°C, quenched in oil, artificial aged at 160°C

Figure 7: Microstructures of heat treated specimens.

4-2- Mechanical tests:

4-2-1- Hardness test:

Fig(8) showed results of hardness test of aluminum alloy specimens. The base specimen had highest hardness because it was full of dislocations resulting from manufacturing process.

In related with heat treated specimens, the hardness increased with increasing of heat treatment temperature. Also, the specimens that quenched in oil had higher hardness than specimens that quenched in water, this because of quantity and size of precipitates in these specimens.

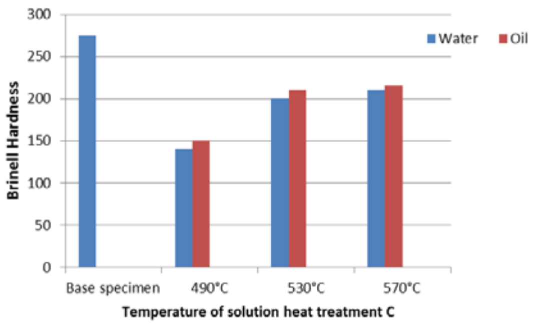


Figure 8: Hardness Values of heat treated specimens

4-2-2- Tension test:

Fig(9) showed results of tension test of aluminum alloy specimens. The specimen that treated at 570°C and quenched in water had the highest strength, and with increasing heat treatment temperatures, the strength increased, and the specimens that quenched in oil had lower strength than specimens that quenched in water because of big Mg_2Si precipitates in microstructure.

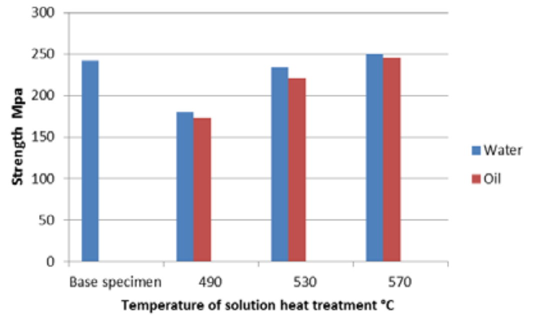


Figure 9: Strength Values of heat treated specimens

4-3- Corrosion Rates:

Table 4 showed values of corrosion rates of specimens samples in different corrosion mediums, and these values redrawn in figures (10-11-12) for comparing.

Table 4: Values of corrosion rates in different mediums

Sample	**Corrosion Rate** (mm/year)		
	Acidic solution pH = 2	Neutral solution pH = 7	Alkaline solution pH = 12
Base specimen	0.061	0.0038	0.029
Heat treated at 490°C quenched in water	0.054887	0.002019	0.026142
Heat treated at 490°C quenched in Oil	0.05055	0.002484	0.027
Heat treated at 530°C quenched in water	0.0496	0.002583	0.024
Heat treated at 530°C quenched in oil	0.050953	0.001698	0.025
Heat treated at 570°C quenched in water	0.042478	0.002167	0.022
Heat treated at 570°C quenched in oil	0.043718	0.002262	0.026068

Fig(10) showed results of corrosion rates of heat treated aluminum alloy specimens in acidic salt solution.

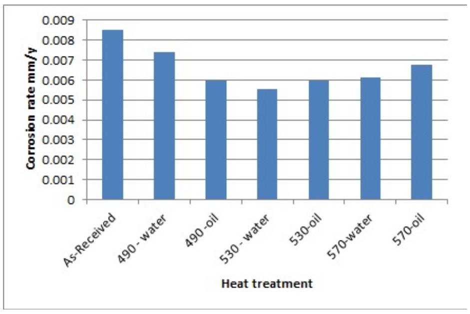


Figure 10: values of corrosion rates in neutral salt solution pH =2

Fig(11) showed results of corrosion rates of heat treated aluminum alloy specimens in neutral salt solution.

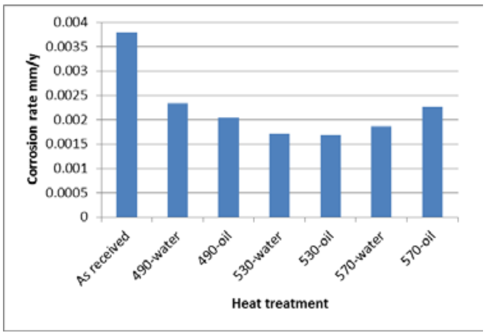


Figure 11: values of corrosion rates in neutral salt solution pH=7

Fig(12) showed results of corrosion rates of heat treated aluminum alloy specimens in alkaline salt solution.

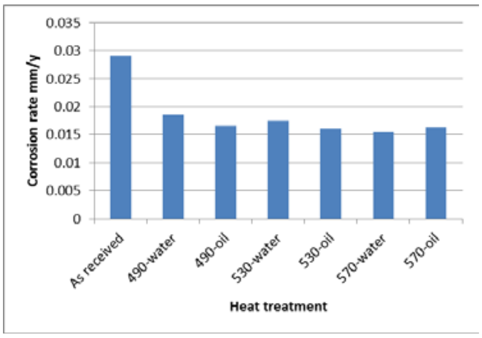


Figure 12: values of corrosion rates in neutral salt solution pH = 12

In the case of acidic solution, the solubility of Al^{+3} facilities the dissolution of the matrix as formula (1):

$$Al \rightarrow Al^{+3} + 3e^{-} \ldots\ldots\ldots\ldots\ldots(3)$$

And reduction of oxygen in water

$$O_2 + 4H^{+} + 4e^{-} \rightarrow 2H_2O \ldots\ldots(4)$$

The acid will dissolve the oxide layer chemically and the precipitates of Mg_2Si will control corrosion, in addition to remaining dislocations.

We note from Fig(10) that corrosion rate of specimen that treated at 490°C and quenched in water was lower than as received specimen because of removed quantity of the dislocation and little precipitates, and corrosion rate became lower with oil quenched specimen because of removing larger quantity of the dislocations and with little precipitates.

In relation to the specimens that heat treated at 530°C, the influence of dislocations was removed, and the precipitates became the essential parameter that control corrosion, so the oil quenched specimens have more precipitates and corrosion rate is bigger, and this is correct for 570°C heat treated specimens.

The formed protective layer in neutral mediums is considered stable and able to resist corrosion attack.

In alkaline solutions the value of corrosion rate for every sample is bigger than value in acidic and neutral solution, because of passivity loss and thining of surface oxide layer, or hydroxide ions attack and alkaline chemical dissolve, or absence of oxide layer.

In fig(12) the corrosion rates were nearly equal but lower than as received specimen which was full of dislocations.

At any rate the mechanism of corrosion of aluminum matrix in acidic and alkaline solutions was related with aluminum hydroxide layer, as shown in formula (5):

$$Al + 3H_2O \rightarrow Al(OH)_3 + H_2 \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Fig (13) showed microscopic images of specimens after immersion.

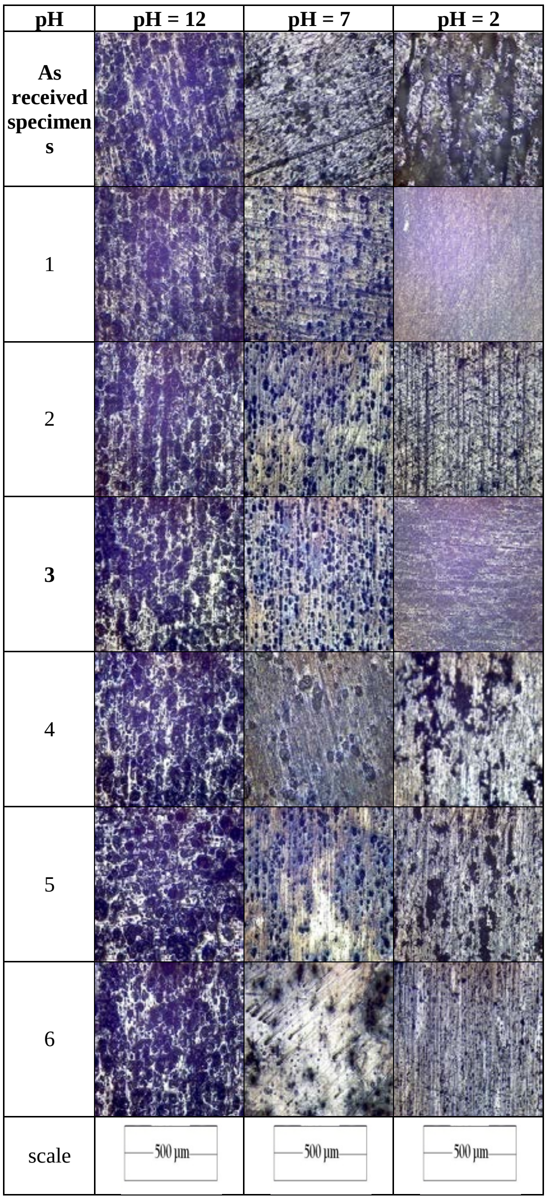


Figure 13: Specimens after immersion

References:

[1] - George E. Tot ten, Handbook of Aluminum, Volume 7, P1-15, Library of Congress Cataloging USA- (2003).

[2] – Mohamad Iz Aldin Dahshan, Handbook of Light Metals and its Alloys, Saoad King University, P.Box2454, (1998).
[3] – Christian Vargel, Handbook of Corrosion of Aluminum, ELSEVIER Magazine, UK, ISBN: 0 08 044495 4, (2004).
[4]- Kalenda Mutombo, Intermetallic Particles-Induced Pitting Corrosion in 6061-T651 Aluminium Alloy, Council for Scientific and Industrial Research (CSIR), South Africa, (2011).
[5] - Mohammed A. Amin, Influence of the Alloying Elements on Uniform and Pitting, Corrosion Events Induced by SCN- Anions on Al-6061 and Al-Cu Alloys Surfaces, Department of Chemistry, Faculty of Science, Ain Shams University, 11566 Abbassia, Cairo, Egypt, (2010).
[6]- ASTM, Standard test methods for Tension Testing of metallic materials, E8-15a annual book of ASTM standards, American Society for Testing and Materials, Philadelphia
[7]- ASTM, Standard test method for Brinell Hardness Testing of metals, E10, American Society for Testing and Materials, Philadelphia.
[8] – ASTM ,Standard Test Method for pH of Aqueous Solutions With the Glass Electrode, ASTM International, West Conshohocken, PA, (2015).
[9]- ASTM, Standard for preparing, cleaning and evaluating corrosion test specimens, G1-81 annual book of ASTM standards, American Society for Testing and Materials, Philadelphia, (1994).
[10]- ASTM, Recommended practice for laboratory immersion corrosion of metals, G-31, Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, (1994).
[11] . E. Cerri, E. Evangelista, Metallography of Aluminium alloys, TALAT Lecture, Italy 1202,(1999)

تأثير وسط ودرجة حرارة السقاية على سلوك التآكل لسبيكة الألمنيوم الطروقة 6061

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الخلاصة

في هذا البحث تمت دراسة تأثير عمليات المعالجة الحرارية عند درجات حرارة وفي أوساط سقاية مختلفة على الخصائص الميكانيكية وسلوك التآكل في أوساط مائية ملحية مختلفة بدرجة الحموضة PH لسبيكة الألمنيوم 6061. تم إحضار السبيكة كما تم تشكيلها وتم إجراء عمليات المعالجة الحرارية المحلولية عند درجات حرارة (490,530,570 °C), وأجريت السقاية عند كل درجة في وسطين مختلفين (الماء, الزيت) للحصول على ستة نماذج. تم التحقق من البنية المجهرية لكل نموذج وتوزع سيليسيدات المغنزيوم ضمن كل نموذج.

أظهرت نتائج اختبارات القساوة أن السبيكة تزداد قساوتها مع ازدياد درجة حرارة المعالجة الحرارية, وعند نفس الدرجة أبدت العينات المسقاة بالزيت قساوة أعلى.

أما نتائج اختبار الشد أظهرت أن السبيكة تزداد متانتها مع ازدياد درجة حرارة المعالجة الحرارية, لكن العينات المسقاة بالماء عند نفس الدرجة كان لها المتانة الأعلى.

أظهرت نتائج اختبارات التآكل أن العينة المعالجة عند 530°C والمسقاة بالماء تبدي أقل معدل للتآكل في وسط مائي ملحي حمضي, بينما العينة المعالجة عند 530°C والمسقاة بالزيت تبدي أقل معدل للتآكل في وسط مائي ملحي معتدل, أما في الوسط المائي الملحي القلوي فالعينة المعالجة عند 570°C والمسقاة بالماء تملك أقل معدل تآكل.