Effect of Heat Treatment on the Corrosion Behavior of AA6061 Aluminum Alloy in Highly Acidic Media

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ABSTRACT

This study investigated the effect of heat treatment on the corrosion behavior of commercially purchased AA6061 aluminum alloy in highly acidic media. The alloys were subjected to three heat treatment conditions: solution heat treatment (homogenization), precipitation hardening (artificial aging), and annealing, with as-received samples serving as baseline. Corrosion behaviors were evaluated using the gravimetric weight loss method in 0.1M H_2SO_4 solution fpr 168 hours. Microstructural analysis were performed on the samples using optical microscopy before and after corrosion testing to state the type of corrosion associated with each processes. Results revealed that the as-received (non-heat treated) samples exhibited the best corrosion resistance with an average corrosion rate of 1.049 mm/yr. Precipitation hardening showed improved resistance (1.291 mm/yr) compared to solution heat treatment (1.554 mm/yr) and annealing (1.750 mm/yr). The high corrosion resistance of the heat-treated samples were attributed to elevated iron (0.72%) and lead (0.34%) impurities that formed cathodic intermetallic particles and segregated at grain boundaries. Pitting corrosion was the dominant mechanism in acidic media, with intergranular corrosion observed in heat-treated samples. The study established that non-heat treated AA6061 provides optimal corrosion resistance in highly acidic environments.

Keywords: AA6061, heat treatment, corrosion, acidic media, weight loss, microstructure

INTRODUCTION

Aluminum is one of the most abundant elements on Earth, constituting approximately 8% of the Earth's crust and rated third in the metal market [1]. The demand for aluminum continues to increase rapidly due to its unique combination of properties, making it one of the most versatile materials used in engineering and construction [2]. Aluminum is relatively lightweight compared with copper and steel, while some of its alloys possess strengths comparable to or even greater than those of certain structural steels [3][4][5]. The 6xxx series of aluminum alloys primarily contains magnesium and silicon as the principal alloying elements. These alloys have been extensively researched due to their significant technological applications and their ability to achieve enhanced strength through precipitation hardening [6][7]. AA6061 is a precipitation-hardenable alloy that combines low weight, good mechanical strength, weldability, and corrosion resistance, making it widely used in structural and engineering applications including transportation, marine structures, pipelines, and architectural components [5].

Aluminum naturally forms a thin, adherent oxide film (Al_2O_3) that provides passive protection against corrosion. However, this protective film can be compromised in aggressive environments, leading to localized or generalized corrosion [8]. The susceptibility of AA6061 to corrosion depends on factors such as microstructure, alloy composition, and environmental conditions [9]. Highly acidic media tend to accelerate uniform and localized corrosion, especially by dissolving the passive oxide film and promoting pitting [10].

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Heat treatment procedures such as solution heat treatment, aging, and annealing are used to alter the microstructure of AA6061 and customize its mechanical properties [11]. However, these microstructural modifications also influence corrosion behavior, as they alter the distribution and composition of precipitates, grain boundaries, and intermetallic phases [12]. Kumar et al. [14] investigated the corrosion behavior of precipitation-hardened AA6061-T6 aluminum alloy in acidic, alkaline, and salt environments. Their investigation showed that the corrosion rate of AA6061-T6 varied significantly with the corrosive medium. The alloy exhibited a higher corrosion rate in alkaline solutions than in acidic solutions. Prabhu and Rao [15] investigated the corrosion behavior of 6063 aluminum alloy in different concentrations of phosphoric acid and sodium hydroxide at varying temperatures. Their results showed that the alloy experienced more severe corrosion in sodium hydroxide than in phosphoric acid. Kassouha,A and Entakly,S [16,17] investigated the effects of heat-treatment temperature and quenching media on the mechanical properties and corrosion behavior of AA6061 aluminum alloy. The results showed that heat treatment influenced the hardness and tensile strength of the alloy, while the corrosion tests indicated improved corrosion resistance following heat treatment. The lack of comprehensive knowledge concerning the relationship between heat treatment and corrosion resistance limits the effective optimization of AA6061 for demanding applications.

This study assessed how solution heat treatment, artificial aging, and annealing heat treatment affect AA6061's corrosion behavior in highly acidic media. The specific objectives were to heat-treat AA6061 by annealing, homogenization, and precipitation hardening; evaluate corrosion rates in highly acidic media by weight loss and micrographic analysis; and from the results, determine which heat treatment condition will best improveS corrosion resistance [13].

METHODOLOGY

The AA6061 aluminum alloy was purchased from Alibaba online store (Gwningen store, China). Chemical reagents NaOH, H_2SO_4, HNO_3, and distilled water were purchased from Cybex Nigeria Limited, Kaduna . Composition test was carried out on the sample procured to ascertain the chemical composition of the purchased AA6061 was verified using a Spectromax machine according to ASTM B209 standards [17]. The result of the test are presented in Table 1.

Table 1: Chemical composition of the AA6061 aluminum alloy used.

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Ag	B	Be	Bi
0.42	0.72	0.18	0.148	0.85	0.06	0.269	0.27	0.152	0.029	0.008	0.011	0.019
Ca	**Cd**	**Co**	**Li**	**Na**	**P**	**Pb**	**Sn**	**Sr**	**V**	**Zr**	**Al**	
>0.0048	0.04	0.002	0.001	0.0053	<0.0046	0.34	0.002	0.01	0.058	0.063	96.3	

Sample Preparation

The AA6061aluminium alloy was cut into 20 cylindrical pieces of 10mm × 10mm dimensions. The total surface area of each sample was 1.257 x 10^{-3} m^2. All samples for heat treatment received surface finishing using emery paper of increasing grit size (400, 600, 800, 1200). For microstructural analysis, samples were further polished to mirror finish using diamond paste (1-6 μm), cleaned in acetone, dried, and stored in a desiccator [17].

Heat Treatment Process

Samples were divided into four groups and two samples were used for each group:

Group A (As-received): No heat treatment (baseline)

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Group B (Solution Heat Treatment): The samples were heated in a muffle to 530°C for 1 hour and left at this temperature for another hour after which it was cooled to room temperature water[26][29].

Group C (Precipitation Hardening): The samples in this group were heated to 530^0C in a muffle furnace and left at this temperature for one hour after which it was quenched in room temperature water. After cooling they were removed and subjected to a temperature of 175^0C, in an aging furnace for eight hours. The furnace was not opened during this period to maintain temperature stability. Samples were removed after the holding time was completed and allowed to cool in still air to room temperature.

Group D (Annealing): These samples were heated to 415^0C in a muffle furnace and left at this temperature for 3 hours, they were finally left to cool slowly in the furnace.

After the various heat treatment procedure, the oxide on their surfaces were removed with emery paper and cleansed in acetone. Each was finally weighed and weight recorded.

Corrosion Test

Gravimetric method according to ASTM G31 was used. Samples were immersed in 200ml of 0.1M H_2SO_4 (pH 2) for 168 hours. Weight loss was recorded every 24 hours. After exposure, samples were cleaned according to ASTM G1 standard with concentrated HNO_3, rinsed, dried, and re-weighed. Corrosion rate was calculated using [20]:

$$C_R \text{ (mm/year)} = \text{Rate of corrosion} = \frac{(KxW)}{(AxDxT)}$$

Where K = 87.6 (constant), W = weight loss (mg), A = surface area (cm^2), D = density (2.7 g/cm^3), T = time (hours).

Microstructure Analysis

Samples were etched with Keller's reagent (2 mL HF, 3 mL HCl, 5 mL HNO_3, 190 mL H_2O) according to ASTM E407. Micrographs were captured at 500x magnification using a microstructure analysis machine.

RESULT AND DISCUSSION

Chemical Composition

Chemical composition of the AA 6061 used is shown in Table 1. The analysis revealed that iron (0.72%) and lead (0.34%) exceeded ASTM B209 specifications. The elevated iron content promotes formation of cathodic intermetallic particles (Al-Fe-Si phases), while lead segregates at grain boundaries, increasing intergranular corrosion susceptibility [21][22][23].

Corrosion Behavior in Acidic Medium

The corrosion behavior in acidic medium is shown in Table 2 and presented graphically in Figure 1 to 3

Table 2: Corrosion results in 0.1M H_2SO_4

S/N	Exposure time(hrs)	Corrosion rate (mm / yr)			
		A	B	C	D
1	0	0	0	0	0
2	24	1.150	0.861	0.287	1.722

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3	48	0.861	1.435	0.861	2.583
4	72	0.957	1.818	1.531	2.009
5	96	1.363	1.650	1.650	1.722
6	120	0.976	1.550	1.492	1.433
7	144	1.052	1.722	1.578	1.394
8	168	0.984	1.845	1.640	1.394
AVR/CR		1.049	1.554	1.291	1.750

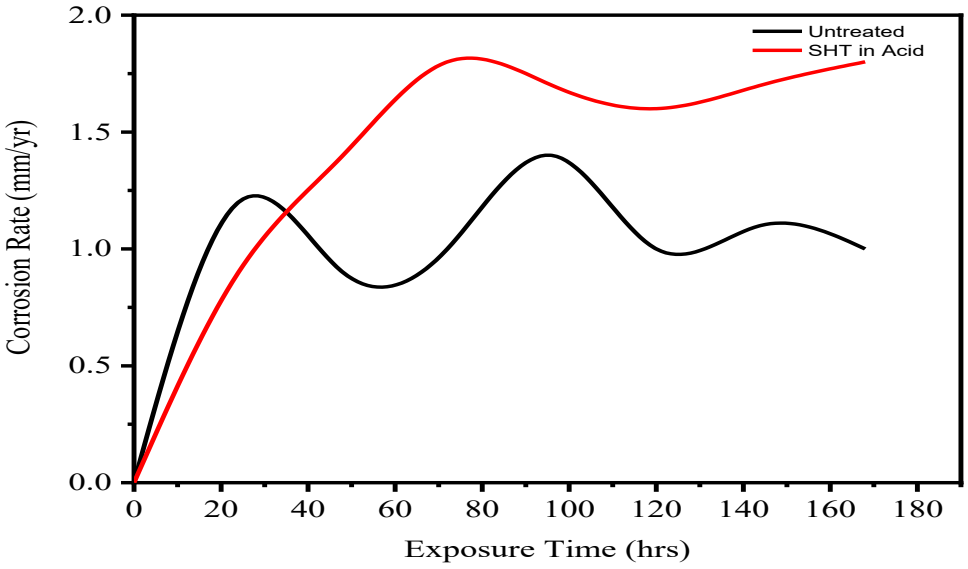


Figure 1: Graph of corrosion rate for control sample and the sample subjected to acidic medium (0.1M of H_2SO4) after solution heat treatment for 1hr

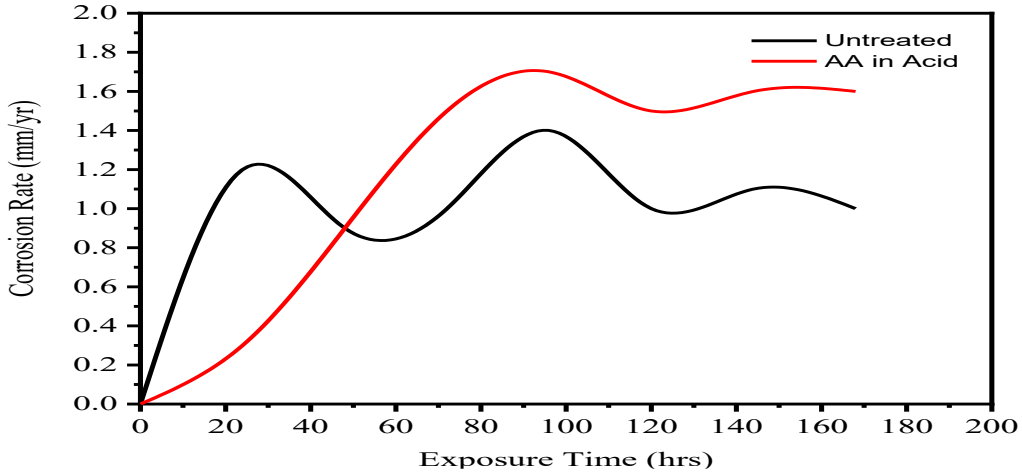


Figure 2: Graph of corrosion rate for control sample and the sample subjected to acidicmedium (0.1M of H_2SO4) after artificial aging for 8hrs.

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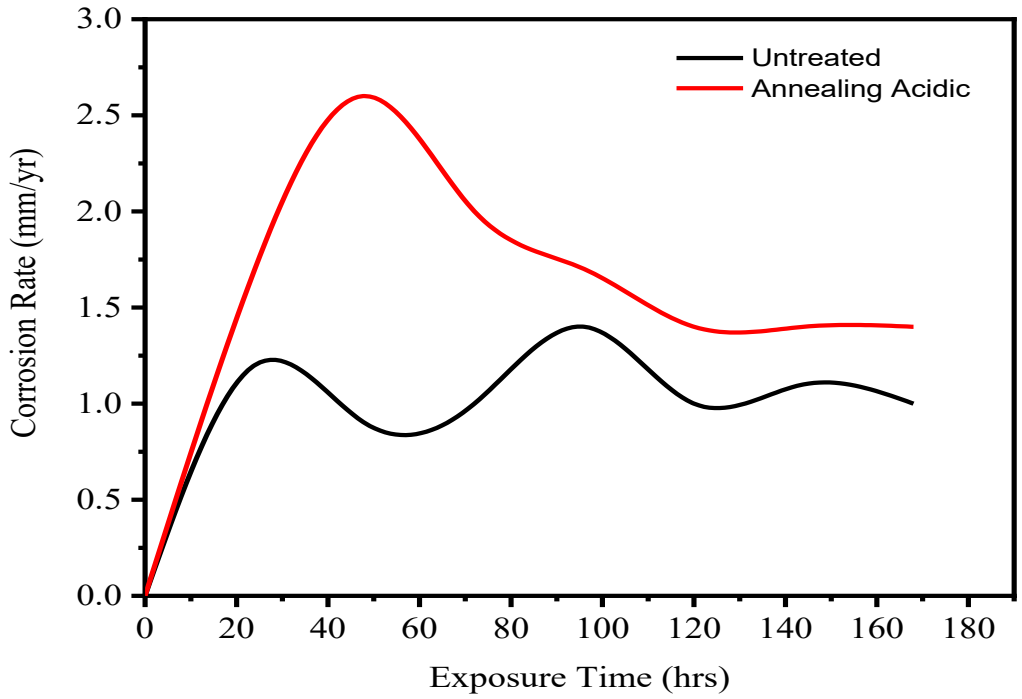


Figure 3: Graph of corrosion rate for control sample and the sample subjected to acidic medium (0.1M of H_2SO4) after being annealed for 3hrs.

Microstructural Analysis

The effect of heat treatment processes and corrosion on the microstructure of AA 6061 aluminum alloy is presented in Plates 1 to 9.

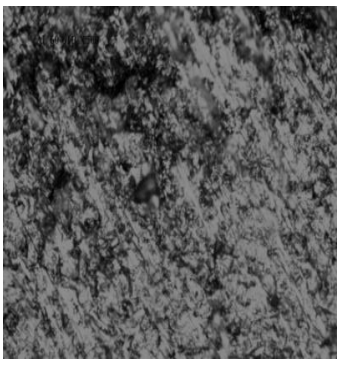


Plate 1: Morphology of non- heattreated showing pitting corrosion sample showing pitting corrosion

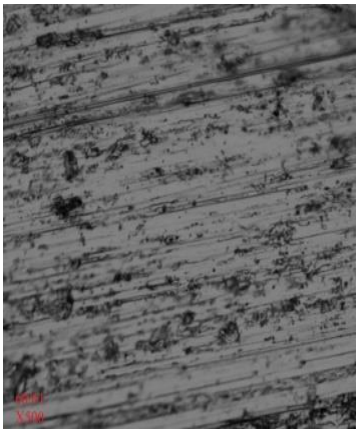


Plate 3: Morphology of solution heat treated sample showing pitting corrosion

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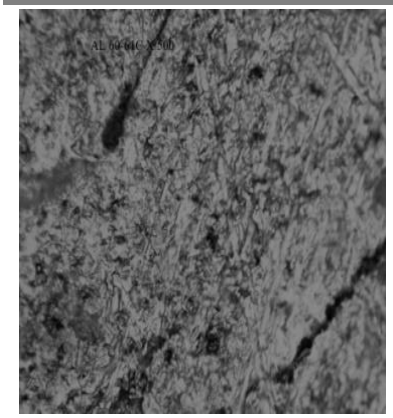


Plate 4: Morphology of artificially aged sample showing intergranular corrosion

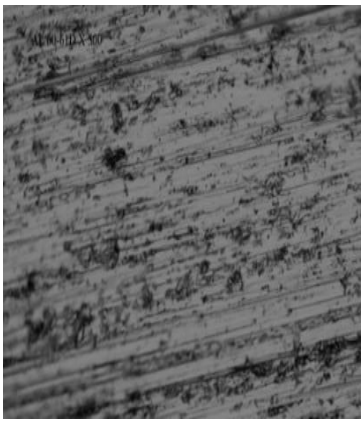


Plate 5: Morphology of annealed sample showing inter-granular

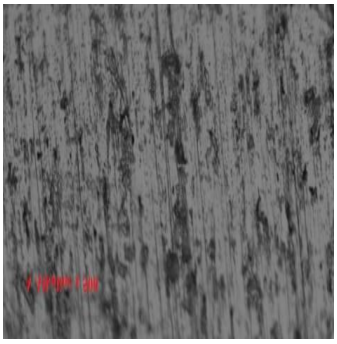


Plate 6: Morphology of non-heat treated sample subjected to acidic medium (0.1M of H_2SO4) for 8hrs showing pitting corrosion

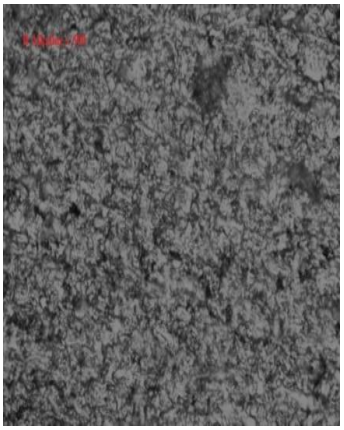


Plate 7: Morphology of solution heat treated sample subjected to acidic medium (0.1M of H_2SO4) showing inter granular corrosion

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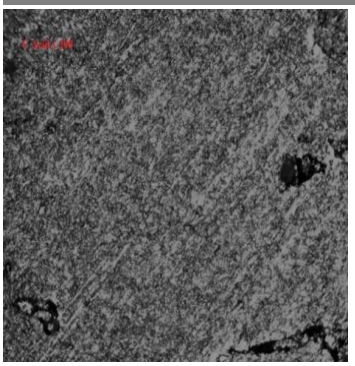


Plate 8: Morphology of artificially aged sample subjected to acidic medium (0.1M of H_2SO4) for for 8hrs showing pitting corrosion.

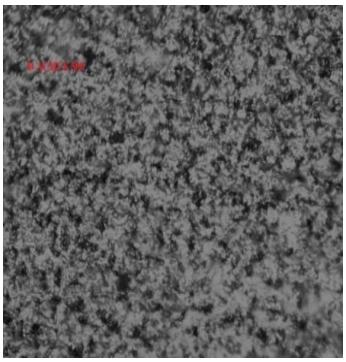


Plate 9: Morphology of annealed samples subjected to acidic medium (0.1M of H_2SO4) 3hrs showing uniform corrosion

DISCUSSION

The corrosion behavior of AA6061 in acidic media is strongly influenced by both heat treatment condition and microstructural changes. The as-received condition exhibited the best acid resistance due to its relatively stable, naturally aged microstructure with less severe lattice strain compared to solution-treated samples [13]. Solution heat treatment caused severe lattice distortion and increased dislocation density, creating high-energy anodic sites susceptible to localized attack. Precipitation hardening produced fine, uniformly dispersed metastable precipitates (β' and β'') that reduced internal lattice strain and created homogeneously distributed micro-galvanic couples, preventing severe localized corrosion channels [17].

Annealing promoted coarsening and continuous precipitation of equilibrium phases (Mg_2Si) along grain boundaries, creating continuous anodic networks that led to severe intergranular corrosion. The elevated lead content (0.34%) further exacerbated this by segregating at grain boundaries and making them more anodic [21][23]. The observed trend, where precipitation-hardened AA6061 demonstrates better corrosion resistance than annealed samples, is consistent with findings reported by Svenningsen e t al. [24], who indicated that discontinuous distribution of precipitates in aged alloys disrupts the anodic corrosion pathway.

CONCLUSION

The as-received (non-heat treated) AA6061 exhibited the best corrosion resistance in highly acidic media with an average corrosion rate of 1.049 mm/yr. Among heat-treated conditions, precipitation hardening offered the best acid resistance (1.291 mm/yr), followed by solution heat treatment (1.554 mm/yr), while annealing was most detrimental (1.750 mm/yr).Elevated iron (0.72%) and lead (0.34%) impurities significantly influenced corrosion behavior by forming cathodic intermetallic particles and segregating at grain boundaries, promoting pitting and intergranular corrosion.

Pitting corrosion was the dominant mechanism in acidic media, with intergranular corrosion observed in heat-treated samples due to grain boundary precipitation. For acidic service conditions, the non-heat treated

condition is recommended for optimal corrosion resistance. Annealing should be avoided as it produced the highest corrosion rates [18][21][23].

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