

Corrosion resistance improvement of 6061 aluminum alloy using anodizing process

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Abstract. Aluminum alloy is a material that is frequently used in the aerospace and transportation industries due to its high mechanical and corrosion resistance qualities. Unfortunately, aluminum alloys are prone to corrosion, limiting their application in some harsh situations such as when submerged in aqueous environments. The purpose of this study is to investigate how anodizing can increase the corrosion resistance of 6061 Aluminum alloy. The anodizing process was carried out using two different parameters which are voltage (5V, 10V, 15V) and electrolyte sulfuric acid (H₂SO₄) concentration (0.3M, 0.5M) for 1 hour. The anodized samples were performed using several analyses such as X-ray diffraction (XRD) analysis, morphology analysis, and corrosion test. From this study, it is found that the difference in anodizing parameters affects the corrosion resistance of the samples. Sample anodized at 15V, 0.5M gives the best corrosion resistance.

Keywords: 6061 aluminum alloy; anodizing; corrosion resistance

1. Introduction

Aluminum (Al) is a silvery-white lightweight metal, with a density of 2.7 g/cm³, soft and malleable with excellent thermal and electrical conductivity. Because of that Al and its alloys have varied engineering applications (Adediran *et al.* 2021). Aluminum is the most widely used non-ferrous metal, primarily in alloyed forms rather than pure metal. Alloying elements like copper, magnesium, and zinc are added to create alloys with tailored properties for various industries such as aerospace, automotive, construction, and electronics. Its recyclability and natural oxide layer also contribute to its extensive use (Ardelean *et al.* 2018).

6061 aluminum (6061 Al) alloy belongs to the 6xxx series of aluminum alloys which are primarily alloyed with magnesium (Mg) and silicon (Si). 6061 Al alloy is a widely used material known for its excellent combination of strength, corrosion resistance, and versatility. The alloys are celebrated for their broad-spectrum applications across various industries, including aerospace,

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automotive, construction, marine, and consumer goods (Rodrigues *et al.* 2017, Afaf *et al.* 2021, Sun *et al.* 2023).

The corrosion resistance of 6061 aluminum alloy is not as high as some other materials, so anodizing can indeed be an effective way to improve its corrosion resistance. Anodizing creates a protective oxide layer on the surface of the aluminum, which enhances its ability to withstand corrosive environments. Anodizing also offers additional benefits beyond corrosion resistance such as increased surface hardness, the ability to introduce colors for aesthetic purposes, and electrical insulation properties (Yu *et al.* 2023, Adyono and Lestari 2020).

Aluminum anodization is an electrochemical technique that produces stable oxide (Al_2O_3) in the presence of an electrolyte, it is a widely researched and acknowledged approach in the industry for corrosion and abrasion protection (Zubillaga *et al.* 2008). Anodizing aluminum involves using either alternating or direct current along with various electrolytes such as chromic acid, sulfuric acid, oxalic acid, borates, citrate, and carbonates (Hou and Chung 1997). Among these, a sulfuric acid solution is the most commonly used electrolyte for anodizing due to its widespread effectiveness (Bouchama *et al.* 2013). The surface properties of 6061 Al alloy can be improved electrochemically by anodization, which results in the formation of metal oxide on its surface. The resulting layer is known as aluminum anodic oxide. Potential (voltage), current density, electrolyte, temperature and time, surface preparation, and post-treatments are parameters that will influence anodized aluminum properties. Thus, parameter optimization is vital for achieving desired outcomes in corrosion resistance, color, and other qualities.

The protective oxide layer produced on the surface of the anodized Al alloy, which enhanced its ability to withstand corrosive environments. Thus, the influence of voltage and concentration of acid sulfuric was studied to improve the corrosion resistance of anodized 6061 Al alloy.

2. Experimental

2.1 Experimental materials and preparation

The round bar samples of 6061 aluminum alloy with a dimension of 13 mm diameter with chemical composition listed in Table 1 were cut into 7 mm lengths.

The samples were ground using a series of metallographic abrasive papers (#400, #600, #800, and #1000) until no visible scratches remained on any surface. Then the specimens were polished with diamond paste to a mirror-like surface. After an acetone degreasing, the specimens were rinsed with distilled water.

The anodizing experiment was designed with a basic anodizing setup equipped with a DC power source, and the electrodes selected for both cathode and anode are 6061 Al alloy. In this study, the anodizing process took 60 minutes at room temperature with different voltages (5V, 10V, and 15V) and different concentrations of sulphuric acid (H_2SO_4) which are 0.3M and 0.5M. Following the anodizing process, the anodized 6061 Al alloy was thoroughly rinsed with distilled water and dried

Table 1 Chemical composition of 6061 aluminum alloy (wt.%)

Element	Cu	Si	Mg	Mn	Zn	Fe	Cr	Ti	Al
Weight percent (%)	0.22	0.62	0.98	0.13	0.16	0.45	0.11	0.03	Balance

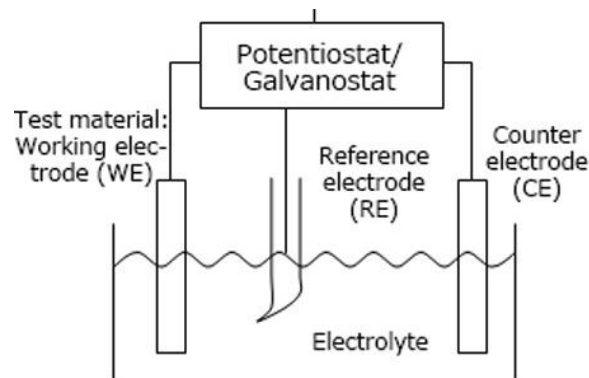


Fig. 1 Schematic diagram of corrosion test

using an air blower for further analysis.

2.2 Corrosion test

NOVA software and AUTOLAB PGSTAT 204 were both implemented for the linear polarization test. A three-electrode was used in the electrochemical measurements, in which the anodized sample acts as the working electrode, a platinum electrode acts as the counter electrode, and a saturated calomel electrode (SCE) acts as the reference electrode. A 3.5 % sodium chloride (NaCl) solution was used as an electrolyte and a 100 mm² exposed sample area. Potentiodynamic polarisation testing would take place at room temperature using a potentiostat connected to a computer. The scanning was performed at a rate of 1 mV/s. Fig. 1 shows the schematic diagram of the electrochemical corrosion test setup.

2.3 Phase and morphology analysis

The phase analysis was done by using an X-ray Diffractometer (XRD) Shimadzu Lab 6000X. This XRD pattern was obtained in the range of 20 to 90 degrees with a 2°/min scan rate. Scanning electron microscopy (SEM) was used to analyze the surface morphology of anodized samples after a corrosion test.

3. Result and discussion

Fig. 2 shows the Tafel polarization curve of anodized samples with different voltages and different H₂SO₄ concentrations. Meanwhile, the results of the Tafel polarization test of the anodized samples in 3.5% NaCl are summarized in Table 2. Extrapolating the polarization curve in Fig. 2 yields the corrosion potential (E_{corr}) and corrosion current density (i_{corr}). E_{corr} evaluated the likelihood of corrosion during the test, while i_{corr} calculated the severity of the corrosion. The E_{corr} values of an anodized 6061 Al sample immersed in 0.3M H₂SO₄ at 5 V and 15 V have been changed from -1.5019 V to -1.2944 V, respectively. The E_{corr} values show the same trend for samples anodized in 0.5M of H₂SO₄ at 5 V and 15 V. It is seen that the value changed from -1.4656 V to -1.0709 V. The corrosion rate indicates a higher rate for samples anodized at 5 V for both concentrations. This is

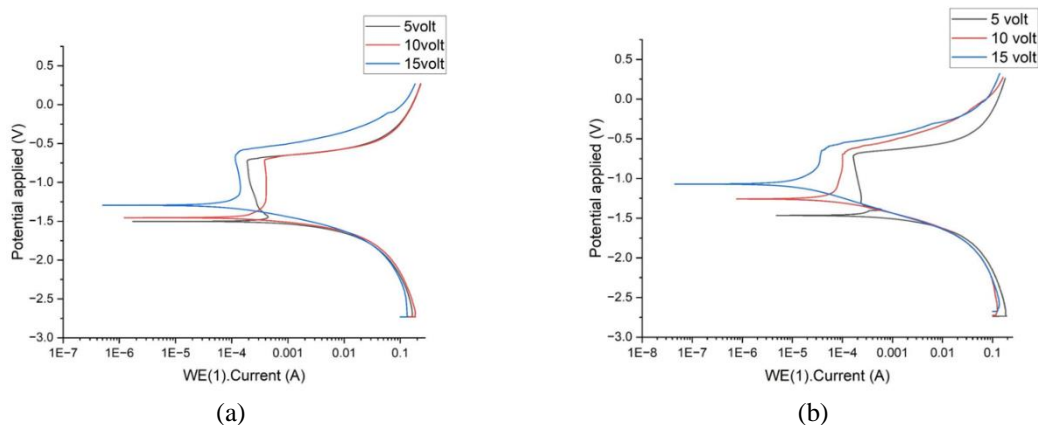


Fig. 2 Tafel polarization curve of 6061 Al anodized samples at different potentials (voltage) and different H_2SO_4 concentrations (a) 0.3M H_2SO_4 and (b) 0.5M H_2SO_4

Table 2 Result of polarization test for the anodized 6061 Al sample with different concentration

Samples	E_{corr} (V)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	Corrosion Rate (mpy)
5V, 0.3M	-1.5019	318.43	136.86
10V, 0.3M	-1.4551	150.85	64.84
15V, 0.3M	-1.2944	57.51	24.72
5V, 0.5M	-1.4656	354.81	152.50
10V, 0.5M	-1.2576	32.90	14.14
15V, 0.5M	-1.0709	8.98	3.86

due to the porous oxide layer formed (Starostin *et al.* 2015).

According to the results of Fig. 2 and Table 2, with the increase of potential (voltage), the i_{corr} of the oxide layer decreases gradually for samples anodized in different concentrations of H_2SO_4 . The oxide layer was obtained at the condition of 0.5M H_2SO_4 at 15 V and possesses optimal corrosion resistance with a minimum corrosion current density equal to $3.86 \mu\text{A}/\text{cm}^2$. It was clearly shown that the E_{corr} values for both 15 V of 0.3M and 0.5M H_2SO_4 anodized samples were shifted to a more positive E_{corr} value compared to the other samples as presented in Fig. 2. Thus, this sample enhanced corrosion resistance and it attributed to the formation of a porous oxide layer on their surfaces (Prado *et al.* 2021).

Fig. 3 shows the surface morphology of the anodized 6061 Al sample after a corrosion test using scanning electron microscopy (SEM). The corrosion products play an important role in the corrosion sensitivity of 6061 Al during the corrosion process. A compact and adherent corrosion product film can effectively prevent the penetration of the corrosive ions. The oxide or hydrate layer forms during the anodizing process. In the case of anodized 0.3M H_2SO_4 with different anodizing voltages expresses different corroded surface morphologies. Fig. 3(a) presents the interconnected pores distributed on the surface and a lot of small and bigger pores are found on a sample surface. Fig. 3(b) shows that smaller pores are found on the samples compared to Fig. 3(a). The sample in Fig. 3(c) shows the well-distributed pores. The intermetallic precipitation reveals a white spot on the surface. The corroded surface looks more stable in the case of anodized 6061Al using 0.5M H_2SO_4 .

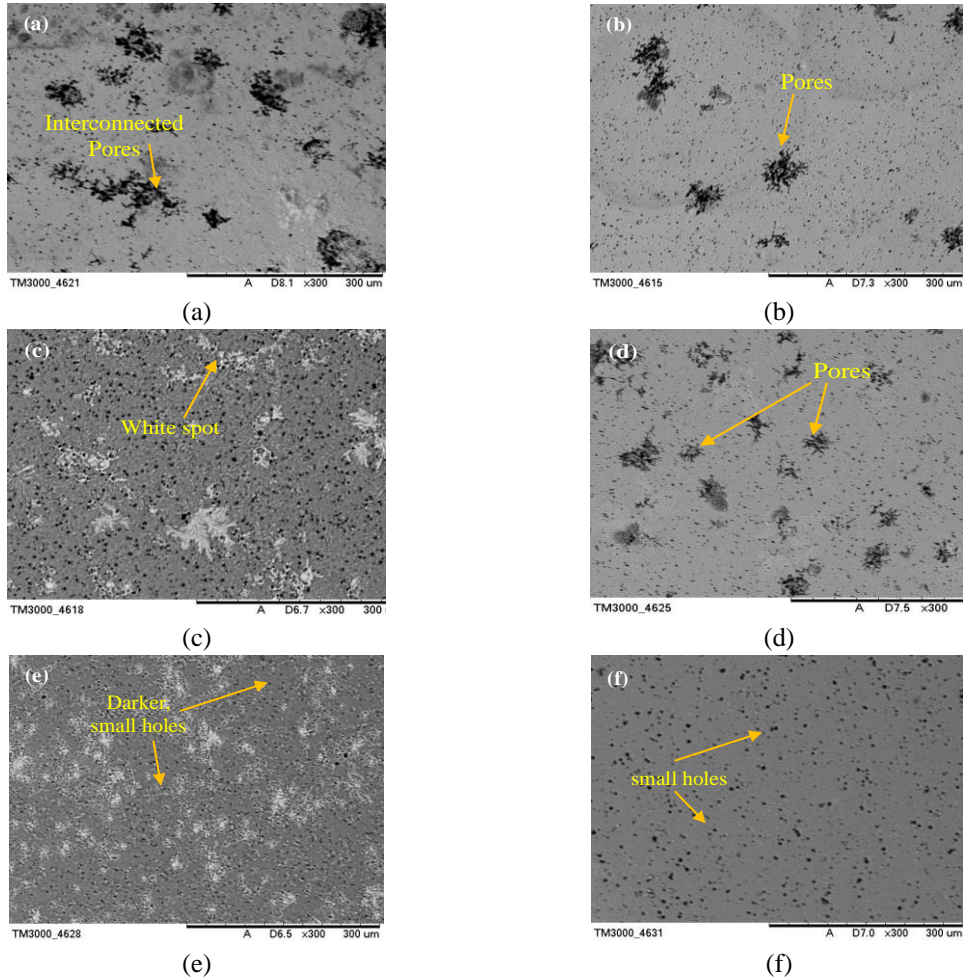


Fig. 3 SEM micrographs of anodized samples after corrosion (a) 5V, 0.3M H₂SO₄ concentration, (b) 10V, 0.3M H₂SO₄ concentration, (c) 15V, 0.3M H₂SO₄ concentration, (d) 5V, 0.5M H₂SO₄ concentration, (e) 10V, 0.5M H₂SO₄ concentration and (f) 15V, 0.5M H₂SO₄ concentration

Fig. 3(d) shows bigger pores with good distribution on the surface. Meanwhile, the surface became darker, and small holes were found in the corroded surface anodized with 6061 Al using a 10V anodizing voltage (Fig. 3(e)).

The small holes with good distribution on corroded surfaces anodized 6061 Al using 15V anodizing voltage as shown in Fig. 3(f). This result expresses the corrosion resistance found on the anodized surface using a 15V anodizing voltage with 0.5M H₂SO₄ concentration. The sample is corroded rather than an anodized sample used 0.3M. Corrosion aggressively attacks the sample of anodized using 0.3M H₂SO₄ with a lower voltage of 5V. With lower molarity and a shorter anodizing period, the sample will have less corrosion resistance. The interconnected pores and bigger pores found on these samples are believed as a localized corrosion phenomenon. This phenomenon also happens in the sample 6061 Al test by Peng *et al.* (2022), which exposed 6061 Al in a simulated marine atmosphere.

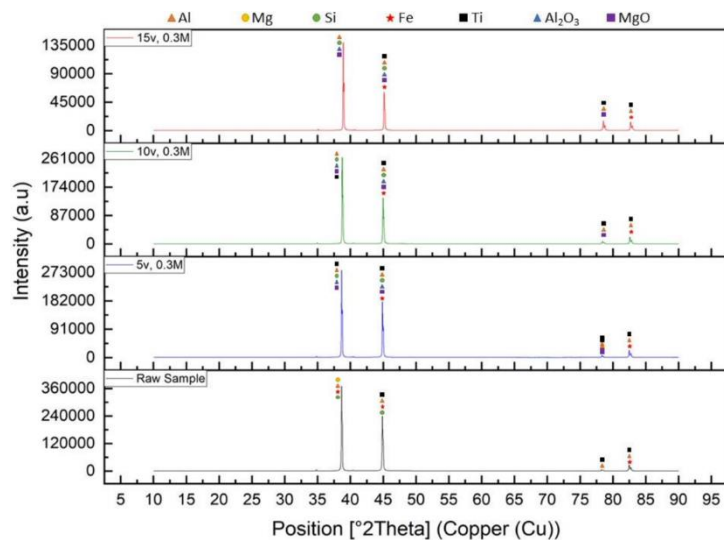


Fig. 4 XRD pattern of anodized 6061 Al samples in 0.3M H₂SO₄ after corrosion testing

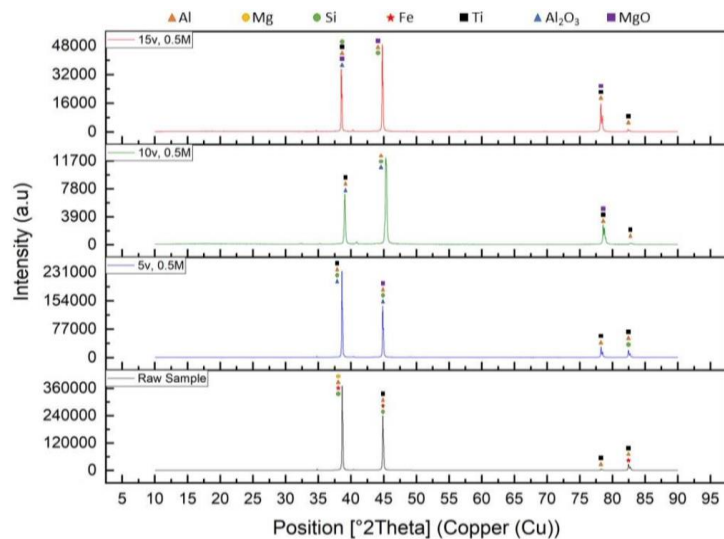


Fig. 5 XRD pattern of anodized 6061 Al samples in 0.5M H₂SO₄ after corrosion testing

Fig. 4 represents the XRD pattern for anodized 6061 Al samples in 0.3M H₂SO₄ after corrosion testing. From this result, the phase of Al₂O₃ and MgO was found in the anodized sample at a peak range of $2\theta=37^\circ$ to 46° . Sample after corrosion test for anodized with 15V has the highest count for Al₂O₃ and MgO phase compared to sample anodized with 5V and 10V. It can be seen that there are Ti and MgO phases in samples 10V and 15V at the positions between $2\theta=37^\circ$ to 40° and $2\theta=77^\circ$ to 80° .

Fig. 5 shows the XRD pattern for anodized 6061 Al samples in 0.5M H₂SO₄ after corrosion testing. The raw sample indicates the non-anodized Al 6061. It can be seen that there are peaks of Al₂O₃ and MgO phase found in anodizing samples at the position between $2\theta=37^\circ$ to 40° . Sample

anodized with 15V has a phase of Al_2O_3 at another peak located at position $2\theta=43^\circ$ to 47° . The phase of MgO was found in samples 5V and 15V after the corrosion testing at a position between $2\theta=44^\circ$ to 47° and the phase of Al_2O_3 was found in sample 5V and 10V but disappeared in 15V at the position between $2\theta=44^\circ$ until $2\theta=47^\circ$.

The XRD patterns of the different samples are shown in Figs. 4 and 5. All the samples show the same pattern. The formation of the anodic coating was confirmed by the presence of the Al_2O_3 and MgO peaks in the anodized sample. The samples were composed of Al, $\text{Al}(\text{OH})_3$, and MgO phases. This corresponds with the products of anodized Al. The Al and $\text{Al}(\text{OH})_3$ contents indicate that the protection reaction occurred on the anodic coating. Therefore, the corrosion does not affect the samples i.e. corrosion attack is not more significant to damage anodized 6061 Al alloy with different anodizing electrolyte concentrations. The presence of elements iron Fe and titanium Ti gives more value to corrosion protection.

4. Conclusions

The 6061 aluminum alloy is anodized and sealed. The surface morphology and corrosion resistance of the anodized aluminum alloy are investigated. According to the results:

- The anodizing parameters such as voltage and electrolyte concentration affect the formation of an oxide film on the sample surface, thus giving different values of corrosion rate.
- The anodized aluminum alloy is composed of a porous layer outside and a barrier layer inside. It is found that the surface of the anodized aluminum alloy possesses a denser and uniform surface morphology.
- The corrosion resistance of the anodized aluminum is the best and possesses the smallest corrosion current density.
- The corrosion rate decreases as the value of voltage for the anodized sample increases. The anodized 6061 Al samples at 15V, 0.5M H_2SO_4 concentration gives the optimum corrosion resistance.

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