

STUDY ON THE INFLUENCE OF ANODIZATION
PARAMETERS ON MICROHARDNESS, THICKNESS,
AND CORROSION RESISTANCE OF ALUMINIUM
ALLOY 6063-T6

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Received on August 11, 2025

Presented by V. Bankova, Member of BAS, on October 30, 2025

Abstract

This study investigates the influence of anodization parameters on the surface microhardness and corrosion resistance of aluminium alloy 6063-T6. The alloy was anodized in 1 M H₂SO₄ with or without 10 wt.% oxalic acid, using current densities of 3 and 5 A/dm², electrolyte temperatures of 10 °C and 20 °C, and anodization durations of 30 and 60 min. Surface microhardness was measured using the Knoop method, and corrosion resistance was evaluated via potentiodynamic polarization in 3.5 wt.% NaCl solution. Lower current density (3 A/dm²) and reduced electrolyte temperature (10 °C) enhanced corrosion resistance. Microhardness was primarily governed by oxide compactness rather than thickness, with some thin but dense layers exhibiting high hardness values. The optimal combination of high hardness, and superior passivation was achieved without oxalic acid at low current density and temperature. These findings provide practical guidelines for tailoring anodization processes to improve both mechanical durability and corrosion performance of aluminium alloys.

Key words: aluminium alloy 6063-T6, anodization, passivation, microhardness, corrosion resistance

Introduction. Anodization is a widely employed electrochemical process used to enhance the surface properties of aluminium alloys, particularly to improve

<https://doi.org/10.7546/CRABS.2025.11.05>

their corrosion resistance, wear resistance, and aesthetic appeal [1–3]. This process involves the controlled oxidation of the aluminium surface within an electrolyte bath, which is most commonly sulphuric acid, though other electrolytes can also be used depending on the desired properties. The electrochemical reaction results in the formation of a porous oxide layer that adheres strongly and uniformly to the underlying metal substrate, creating a protective barrier [4]. The characteristics of this anodized oxide layer, such as its thickness, porosity, and hardness, can be carefully tailored by adjusting various anodization parameters, including current density, electrolyte composition, temperature, and duration of the anodization process. These processing variables significantly influence the microstructure and morphology of the oxide layer, thereby affecting the final functional properties of the treated alloy [5, 6].

The anodized surface plays a crucial role in determining the overall performance and durability of the material, especially in applications where the aluminium alloy is exposed to harsh or aggressive environments, including marine atmospheres, industrial pollutants, or mechanical wear scenarios. The thickness and density of the oxide layer are particularly important factors that govern the alloy's resistance to corrosion and its ability to withstand prolonged exposure to challenging conditions [7]. Furthermore, the hardness and mechanical integrity of the anodized coating directly impact the material's resistance to surface damage, including scratching, abrasion, and plastic deformation under load, thereby extending the service life of components made from anodized aluminium alloys [8, 9].

In addition to sulphuric acid, organic acids such as oxalic acid are frequently employed as anodizing electrolytes because they promote the development of ordered pore structures and influence oxide crystallinity. Oxalic acid is particularly relevant for applications where surface morphology, dye adsorption, or functional coatings are required, as it enhances porosity and modifies the microstructure of the anodic layer. However, these structural modifications may also affect corrosion resistance, making it important to evaluate the trade-offs between improved surface functionalization and protective performance.

The present study is centred on a comprehensive investigation of the functional and mechanical properties of anodized aluminium alloy 6063-T6, a material widely used in structural and architectural applications due to its favourable combination of strength and corrosion resistance. This research places particular emphasis on understanding how variations in anodization parameters, specifically, current density, bath temperature, anodization time, and electrolyte composition affect critical surface characteristics, microhardness, and corrosion resistance of the anodized layer.

Experimental. The material analyzed in this study was aluminium alloy AA6063-T6, with a composition of Al $\leq$ 97.5 wt.%, Mg 0.45–0.9 wt.%, Si 0.2–0.6 wt.%, Fe $\leq$ 0.35 wt.%, and minor elements including Cr, Cu, Mn, Ti, and Zn (each $\leq$ 0.1 wt.%), along with other elements limited to $\leq$ 0.05 wt.% each

and ≤ 0.15 wt.% in total [10]. Prior to anodization, the samples underwent a cleaning procedure to eliminate contaminants. Surface preparation involved degreasing with acetone and isopropyl alcohol, followed by rinsing with deionized water and drying under ambient conditions. Anodization was performed using a two-electrode setup, where the aluminium sample served as the anode and a pure aluminium sheet as the cathode. The electrolyte consisted of 1 M sulphuric acid (H_2SO_4), with 10 wt.% oxalic acid incorporated under specific experimental conditions. Anodization parameters were systematically adjusted to investigate their influence on the properties of the oxide layer (Table 1).

T a b l e 1
Experimental conditions for the anodization experiment

Sample	Current density (A/dm ²)	Oxalic acid (%wt.)	Temperature (°C)	Time (mins)
S01	3	0	10	30
S02	5	0	20	60
S03	5	0	10	30
S04	5	10	10	60
S05	5	10	20	60
S06	3	10	10	30
S07	5	10	20	30
S08	3	0	20	60
S09	5	0	20	30
S10	3	0	10	60
S11	5	10	10	60
S12	3	10	20	30

To ensure uniform oxide growth and thermal stability, the electrolyte was continuously stirred and cooled throughout the process.

Surface microhardness (HK) was evaluated with a DVK 1-AT semi-automatic microhardness tester (EBPu Electromechanical Equipment Co., Ltd.). Cross-sectional analysis was performed on samples prepared using a DTQ-5 low-speed cutting machine. These samples were embedded in transparent resin, ground with alumina sandpaper, and polished using a 0.25 μm diamond suspension to achieve a smooth finish. Microstructural observations were conducted with an LM-308 upright metallurgical microscope, equipped with a digital camera and specialized software for image acquisition and analysis.

Corrosion resistance was assessed using a Corrtest CS350 single-channel potentiostat/galvanostat in a three-electrode configuration, comprising a platinum (Pt) counter electrode, a silver/silver chloride (Ag/AgCl) reference electrode, and the anodized sample as the working electrode. Prior to testing, samples underwent thorough cleaning with isopropanol, followed by rinsing with deionized (DI)

water and air drying. The anodized samples were then immersed in a 3.5 wt.% sodium chloride (NaCl) solution until a stable open circuit potential (OCP) was established. Potentiodynamic polarization measurements were subsequently performed, with the exposed surface area limited to 1 cm² for consistency. All experiments were conducted at room temperature using freshly prepared solutions, and analytical-grade reagents were employed in all procedures.

Results and discussion. Microhardness and oxide thickness. The influence of anodizing parameters on microhardness and anodic oxide layer thickness is shown in Fig. 1. In general, a thicker oxide layer is expected to increase hardness due to the formation of a denser and more protective anodic film. However, the quality of the oxide layer – particularly its porosity and structural compactness – also plays a decisive role in determining microhardness values.

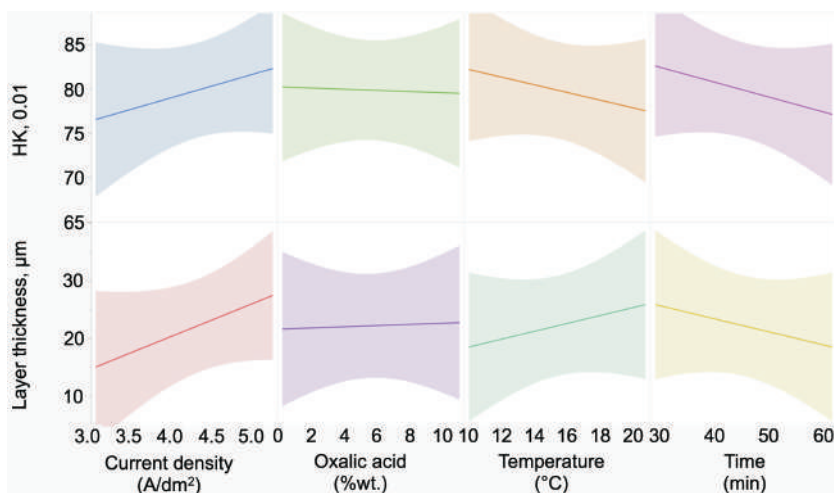


Fig. 1. The influence of anodizing parameters on the microhardness, and anodic oxide thickness

Samples 9, 11, and 12 exhibited the thickest oxide layers (45 μm, 39 μm, and 31 μm, respectively) and moderate-to-high microhardness values (84.6, 76.6, and 67.4 HK, respectively). The relatively high hardness of 9 suggests that its oxide layer is dense and mechanically robust, while the slightly lower hardness of 11 and 12, despite their thickness, may be attributed to increased porosity or reduced oxide density.

Samples with intermediate oxide thicknesses, such as 1, 2, 3, and 4 (20–25 μm), displayed microhardness values ranging from 70.5 to 91.4 HK. Among these, 3 exhibited the highest microhardness, suggesting a highly compact oxide layer with minimal porosity. Sample 1 also showed good hardness, whereas 2 and 4 had comparatively lower values, likely due to less compact oxide structures influenced by their anodizing conditions.

Interestingly, samples 5, 6, and 7, despite having relatively thin oxide lay-

ers (8–12 μm), showed high microhardness values (89.1, 82.1, and 87.2 HK, respectively). This indicates that oxide compactness and structural uniformity can compensate for reduced thickness. In contrast, 8, with a similar thickness (8 μm), displayed markedly lower hardness (67.6 HK), likely due to a porous or non-uniform oxide film.

While a general trend indicates that oxide thickness correlates with microhardness, exceptions clearly exist. Thin but dense oxide layers can achieve high hardness, whereas thick but porous layers may perform less effectively. This underscores that the primary determinant of hardness is oxide quality rather than thickness alone.

As shown in Fig. 1, increasing current density elevated both microhardness and oxide thickness. The addition of oxalic acid did not significantly influence oxide thickness but resulted in lower hardness. Elevated electrolyte temperature reduced hardness but increased oxide thickness, suggesting a trade-off between layer growth and compactness. Increasing anodizing time decreased both hardness and oxide thickness, indicating possible over-anodizing effects that degrade the film's structural integrity.

Open circuit potential. The evolution of open circuit potential (OCP) over 2 h immersion in 3.5 wt.% NaCl is shown in Fig. 2. Considerable differences in potential stability and final steady-state values were observed among the anodized samples, reflecting the intrinsic quality and protective nature of their oxide films.

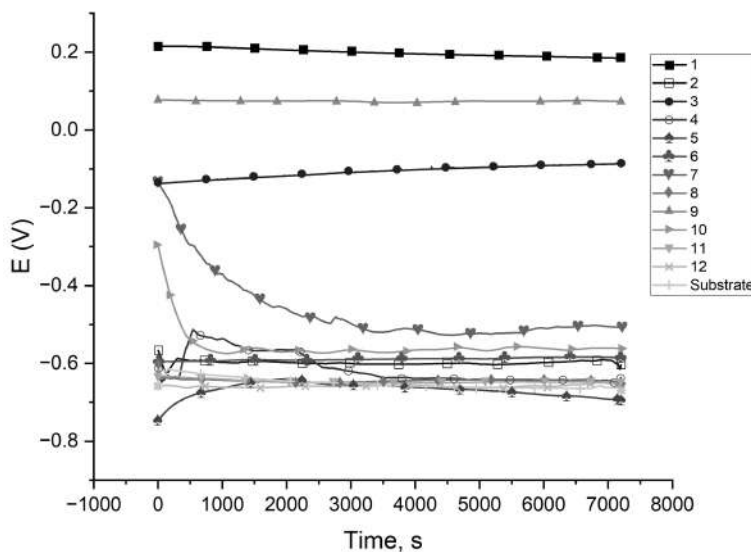


Fig. 2. Open circuit potential (OCP) curves of the anodized samples and substrate

Higher OCP values correspond to stronger passivation and improved corrosion resistance, whereas lower or more negative potentials reveal a surface prone

to corrosion. Sample 1, which exhibited one of the densest and moderately thick oxide layers, also demonstrated the highest stable OCP of 0.184 V. This confirms the formation of a compact, protective oxide film contributing to superior electrochemical stability. Similarly, 9, with one of the thickest oxide layers, maintained a relatively noble OCP at 0.0735 V, indicating effective passivation despite its thickness.

In contrast, samples 5, 6, 7, and 12 showed highly negative OCP values (ranging from -0.507 V to -0.694 V), signalling compromised oxide layers that are less protective and more susceptible to corrosion. These findings correlate well with the microhardness data, where these samples either had porous oxide films or higher porosity levels reducing their protective capabilities.

The untreated substrate, with an OCP of -0.669 V, further highlights the beneficial effect of anodization, which generally shifts the potential towards more positive, stable values. These results collectively underscore the importance of anodization parameters, especially, current density and electrolyte temperature in promoting oxide film compactness and electrochemical stability.

Potentiodynamic polarization. The potentiodynamic polarization curves for the anodized samples and the uncoated substrate are presented in Fig. 3. The curves reveal marked differences in corrosion potential (E_{corr}), corrosion current density (i_{corr}), and passivation behaviour, all of which align closely with the previously discussed OCP trends, thereby providing a comprehensive electrochemical characterization of the anodized surfaces.

Corrosion current density (i_0), a key indicator of corrosion rate, was found to be lowest in samples 1 (3.05×10^{-10} A/cm²), 3 (3.90×10^{-10} A/cm²), 5 (1.22×10^{-10} A/cm²), and 9 (1.72×10^{-10} A/cm²), all of which exhibited well-formed, dense oxide layers as confirmed by SEM and microstructural analysis. This low i_0 reflects the formation of highly protective oxide films that effectively act as barriers against aggressive ionic species in the corrosive environment. These results correlate strongly with their favourable OCP values, which remained stable and shifted positively over time, as well as with the enhanced microhardness observed (Fig. 2), suggesting that these anodization conditions promote both mechanical reinforcement and electrochemical stability.

Conversely, sample 11 recorded the highest i_{corr} (7.85×10^{-7} A/cm²) and corresponding corrosion rate (0.00854 mm/y), indicative of a porous, defective oxide layer that compromises corrosion resistance. This compromised oxide film likely results from suboptimal anodization parameters, such as excessive current density or electrolyte temperature, which promote localized dissolution and micro-crack formation within the oxide. Such defects act as initiation sites for corrosive attack, facilitating electrolyte penetration and accelerating substrate degradation.

Corrosion potential E_{corr} trends closely mirror those observed for i_{corr} . Samples with the most positive potentials, such as 1 (-0.117 V) and 9 (-0.226 V), demonstrate enhanced anodic protection characterized by stable passive regions

and delayed onset of pitting. This suggests the formation of a robust passive film that efficiently suppresses active corrosion processes. In contrast, samples 6 (−1.018 V) and 7 (−1.051 V) exhibit highly negative potentials indicative of active corrosion and poor passivation, likely caused by incomplete oxide formation or excessive porosity. These observations underscore the sensitivity of E_{corr} to the integrity and composition of the anodic oxide layer.

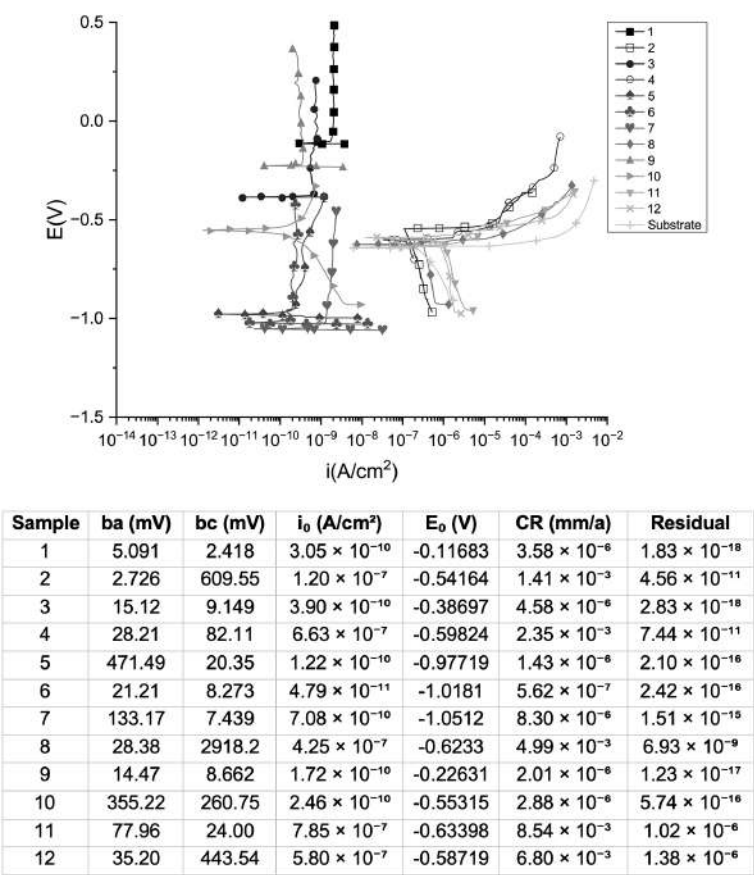


Fig. 3. Potentiodynamic polarization curves and corrosion parameters of anodized samples and substrate

Analyzing these electrochemical data in the context of anodization parameters reveals critical insights into the interplay between process conditions and corrosion behaviour. Specifically, lower current density (3 A/dm^2) combined with lower electrolyte temperature (10°C) favour the development of compact, uniform oxide films with superior corrosion resistance. This is attributed to slower oxide growth rates, which allow for better organization of the oxide matrix and reduced incorporation of impurities or defects. On the other hand, the detrimental impact of oxalic acid, particularly, at higher current densities and longer anodiza-

tion durations is clearly reflected in the higher corrosion rates and more negative corrosion potentials observed in samples such as 7, 11, and 12. The presence of oxalic acid may induce complex ion interactions or localized acidification at the oxide-electrolyte interface, exacerbating film dissolution or porosity.

Elevated electrolyte temperatures also contribute to increased oxide porosity and corrosion susceptibility, as demonstrated in samples 8 and 12. Higher temperatures enhance ionic mobility and oxide dissolution kinetics, thereby compromising the oxide film's protective properties and facilitating localized corrosion. These findings highlight the delicate balance required in anodization conditions to optimize oxide layer morphology, chemistry, and protective function.

Together, these findings emphasize that the best corrosion performance arises from a carefully balanced anodization process that optimizes oxide compactness, thickness, and chemical stability while minimizing defects such as cracks, pores, or non-uniform growth. This synergy between mechanical hardness and corrosion resistance underscores the potential for tailoring the surface properties of aluminium alloy 6063-T6 through controlled anodization parameters, enabling the design of components with enhanced durability for demanding industrial and structural applications. Future work could focus on exploring the influence of additional electrolyte additives, post-anodization sealing treatments, and long-term corrosion testing under varied environmental conditions to further improve the performance and reliability of anodized aluminium surfaces.

Conclusions. This study demonstrated that anodization parameters critically influence the microhardness, thickness, and corrosion resistance of aluminium alloy 6063-T6. Lower current density (3 A/dm^2) and reduced electrolyte temperature (10°C) consistently enhanced corrosion resistance by promoting the formation of a stable, dense oxide layer, as evidenced by lower corrosion current densities and more noble corrosion potentials. The presence of oxalic acid generally increased oxide porosity and corrosion rates, particularly at elevated current densities and longer anodization times. However, its role in enhancing pore structure and modifying oxide crystallinity highlights its importance for applications where tailored surface morphology or functionalization is prioritized over maximum corrosion resistance.

Microhardness was found to depend more on the compactness and quality of the oxide film than on its thickness alone. Several samples with thinner yet denser oxide layers exhibited superior hardness compared to thicker but more porous coatings. Thus, optimizing anodization conditions to produce compact oxide films can significantly improve mechanical durability without necessarily increasing layer thickness.

The optimal combination of corrosion resistance and microhardness was achieved at low current density and temperature without oxalic acid, confirming that controlled anodization can tailor surface properties for enhanced performance. These findings provide valuable practical guidelines for industrial anodiza-

tion processes aiming to improve both mechanical and corrosion properties of the aluminium alloy 6063-T6.

REFERENCES

- [1] GUO F., Y. CAO, K. WANG et al. (2022) Effect of the anodizing temperature on microstructure and tribological properties of 6061 aluminum alloy anodic oxide films, *Coatings*, **12**(3), 314.
- [2] RAZZOUK E., D. KONCZ-HORVÁTH, T. I. TÖRÖK (2024) Microstructure effects on anodizing high-silicon aluminium alloy AlSi12Cu1(Fe) under various surface conditions and power modes, *Crystals*, **14**(4), 352.
- [3] KUSHNIR S. E., M. E. KUZNETSOV, I. V. ROSLYAKOV et al. (2022) Mosaic of anodic alumina inherited from anodizing of polycrystalline substrate in oxalic acid, *Nanomaterials*, **12**(24), 4406.
- [4] STUDENT M. M., I. M. POHRELYUK, V. M. HVOZDETSKYI et al. (2022) Influence of the composition of electrolyte for hard anodizing of aluminum on the characteristics of oxide layer, *Materials Science*, **57**(1), 240–247.
- [5] PAZ MARTINEZ-VIADEMONTE M., S. T. ABRAHAMI, M. D. HAVIGH et al. (2022) The role of anodising parameters in the performance of bare and coated aerospace anodic oxide films, *Coatings*, **12**(7), 908.
- [6] BARA M., M. NIEDŹWIEDŹ, W. SKONECZNY (2019) Influence of anodizing parameters on surface morphology and surface-free energy of Al₂O₃ layers produced on EN AW-5251 alloy, *Materials (Basel, Switzerland)*, **12**(5), 695.
- [7] RAZZOUK E., D. KONCZ-HORVÁTH, T. I. TÖRÖK (2024) Critical challenges in the anodizing process of aluminium-silicon cast alloys – a review, *Crystals*, **14**(7), 617.
- [8] OSSOWSKA A., A. ZIELIŃSKI, J. M. OLIVE et al. (2020) Influence of two-stage anodization on properties of the oxide coatings on the Ti-13Nb-13Zr alloy, *Coatings*, **10**(8), 707.
- [9] CHEN L., Z. LIU, B. WANG et al. (2019) Surface characterization and tribological performance of anodizing micro-textured aluminum-silicon alloys, *Materials (Basel, Switzerland)* 2019, **12**(11), 1862.
- [10] ASM Material Data Sheet, <https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6063T6>, (accessed March 16, 2025).

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