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Enhancement of Corrosion Resistance and Electromagnetic Wave Absorption in Aluminium 6061 through Plasma Electrolytic Oxidation Coating with Ethylenediaminetetracetic Acid

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Abstract

Aluminium 6061 is well known for its good tensile strength and high corrosion resistance due to the natural protective oxide layer formed on its surface. However, the phenomenon of corrosion can still occur, particularly in aggressive environments, leading to material degradation. To further enhance corrosion resistance, a coating using the Plasma Electrolytic Oxidation (PEO) method with a concentrated solution of Na2SiO3, KOH, and EDTA was applied for 4 minutes. The addition of EDTA plays a crucial role not only in improving corrosion resistance but also in influencing the dielectric properties of the material, which subsequently affects the absorption of electromagnetic waves. Corrosion testing using the Tafel Polarization method revealed that the PEO coating with EDTA resulted in a more positive corrosion potential and a lower current density compared to untreated Aluminium 6061. Furthermore, EDTA enhances the porosity of the oxide layer, promoting the formation of micro-pores on the surface, which can trap corrosive agents and mitigate corrosion phenomena. Testing with a Vector Network Analyzer (VNA) at frequencies ranging from 8 GHz to 12 GHz demonstrated that the material exhibits an electromagnetic wave absorption of -1 dB. Overall, the application of PEO coating with EDTA significantly improves both corrosion resistance and electromagnetic wave absorption, making it suitable for various applications in the automotive, electronics, and energy industries.

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Abstrak

Aluminium 6061 terkenal dengan kekuatan tarik yang baik dan ketahanan korosi yang tinggi karena lapisan oksida pelindung alami yang terbentuk di permukaannya. Namun, fenomena korosi masih dapat terjadi, terutama di lingkungan yang agresif, yang menyebabkan degradasi material. Untuk lebih meningkatkan ketahanan korosi, pelapisan menggunakan metode Plasma Electrolytic Oxidation (PEO) dengan larutan pekat Na2SiO3, KOH, dan EDTA diaplikasikan selama 4 menit. Penambahan EDTA memainkan peran penting tidak hanya dalam meningkatkan ketahanan korosi tetapi juga dalam mempengaruhi sifat dielektrik material, yang kemudian mempengaruhi penyerapan gelombang elektromagnetik. Pengujian korosi menggunakan metode Polarisasi Tafel menunjukkan bahwa pelapisan PEO dengan EDTA menghasilkan potensi korosi yang lebih positif dan kerapatan arus yang lebih rendah dibandingkan dengan Aluminium 6061 yang tidak diberi perlakuan. Selain itu, EDTA meningkatkan porositas lapisan oksida, mendorong pembentukan pori-pori mikro di permukaan, yang dapat menjebak agen korosif dan mengurangi fenomena korosi. Pengujian dengan Vector Network Analyzer (VNA) pada frekuensi mulai dari 8 GHz hingga 12 GHz menunjukkan bahwa bahan tersebut menunjukkan penyerapan gelombang elektromagnetik sebesar -1 dB. Secara keseluruhan, aplikasi pelapisan PEO dengan EDTA secara signifikan meningkatkan ketahanan korosi dan penyerapan gelombang elektromagnetik, sehingga cocok untuk berbagai aplikasi di industri otomotif, elektronik, dan energi.

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1. Introduction

Aluminum, particularly in alloy forms such as 6061, has become an essential material in the defense sector due to its unique combination of properties that meet the stringent requirements of military applications. Its lightweight nature significantly enhances the performance of military vehicles, aircraft, and naval vessels by improving fuel efficiency, increasing payload capacity, and boosting maneuverability (Dursun & Soutis, 2014; Hatch, 1984). Furthermore, the high strength-to-weight ratio of aluminum alloys makes them ideal for structural components, offering durability without adding excessive weight—an essential attribute in aerospace applications, where every kilogram saved can lead to substantial improvements in operational efficiency and cost-effectiveness (Davis, 1999). In addition to its mechanical advantages, aluminum exhibits excellent corrosion resistance derived from the natural oxide layer formed on its surface. This characteristic is critical in defense applications, where equipment is frequently exposed to harsh environmental conditions such as moisture, salt, and other corrosive agents.

Although aluminum naturally forms an oxide layer that offers basic corrosion protection, its performance in extreme defense environments is often insufficient. Therefore, prior to the introduction of Plasma Electrolytic Oxidation (PEO) technology, several alternative surface treatment methods were developed to improve aluminum's corrosion resistance, including organic coatings, anodizing, and composite layer applications. Research has shown that organic coatings can provide additional protection against corrosion, while anodizing forms a thicker, more durable oxide layer that enhances corrosion resistance (Kamil et al., 2020). Furthermore, composite coatings incorporating nanoparticles have also proven effective in improving the corrosion performance of aluminum alloys (Rogov et al., 2022). Despite these advancements, PEO technology offers unique advantages by creating a thicker and harder oxide layer, which not only improves corrosion resistance but also enhances the mechanical properties of aluminum.

The PEO process operates by applying high-voltage electrical discharges in an electrolyte solution, resulting in a ceramic-like oxide layer that is thicker, harder, and more wear-resistant—characteristics that make it suitable for demanding military applications (Li et al., 2019). Recent studies indicate that PEO can also significantly improve aluminum's ability to absorb electromagnetic waves, addressing one of its main limitations in defense applications (Zhang et al., 2018). Moreover, the incorporation of additives such as Ethylenediaminetetraacetic acid (EDTA) during the PEO process has shown promising results in further enhancing the performance of aluminum alloys. Acting as a corrosion inhibitor, EDTA reinforces the oxide layer and potentially increases its capability to absorb electromagnetic waves (Liu et al., 2019).

By combining PEO with EDTA, this study aims to optimize the functional properties of aluminum for defense-related applications. Previous research demonstrates that EDTA contributes to the formation of a denser and more uniform oxide layer, which is crucial for improving both corrosion resistance and electromagnetic wave absorption (Zhang et al., 2020). This innovative approach is expected to overcome the inherent limitations of aluminum, making it more competitive for use in the defense sector. As military technology advances, such developments will ensure that aluminum remains a vital material in modern defense applications.

2. Research Methods

2.1. Materials

The substrate material selected in this study is the 6061aluminum alloy with the nominal chemical composition presented in **Table 1**. All specimens used in this study and subjected to PEO treatment are in the rectangular shape of 3 cm x 4 cm.

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

Si	Mg	Fe	Cu	Cr	Zn	Ti	Other Elements	Al
0.63	0.98	0.19	0.18	0.05	0.10	0.08	0.15	Balance

2.2. Coatings Preparation and Process Parameters

Before the PEO treatment, the main surfaces of the 6061 aluminum alloy samples were ground using abrasive papers with grit #500 to #1500, then cleaned with ethyl alcohol, rinsed with distilled water, and dried. The samples were then treated with PEO in 1 L of electrolyte solution containing 15 g/L sodium metasilicate (Na2SiO3), 6.1721 g/L potassium hydroxide (KOH), and 1 g/L Ethylenediaminetetraacetic acid (EDTA). Special attention was given to maintaining the electrolyte temperature around 28°C during the PEO treatment.

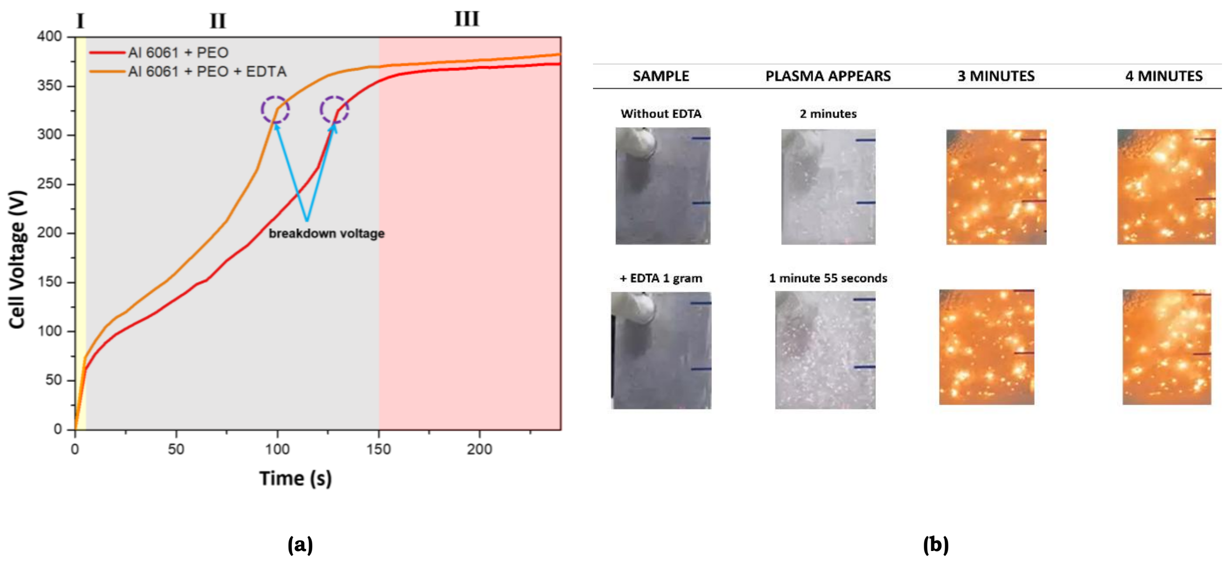

Figure 1. (a) Cell voltage-time response and optical observation of plasma discharge behavior during plasma electrolytic oxidation (PEO) of aluminum alloy in the absence and presence of EDTA additive, (b) Sequential optical images comparing plasma appearances at different times: plasma initiation occurs slightly earlier with EDTA addition

2.3. Coatings Characterization Methods

The corrosion resistance of PEO-treated and untreated 6061 aluminum alloy substrates was evaluated using electrochemical measurements in a 1M NaCl test solution. The electrochemical behavior of the samples was analyzed using the EIS Analyzer Parstat 4000 A galvanostat/potentiostat system, equipped with a three-electrode cell. This cell consisted of (1) the sample being analyzed as the working electrode, (2) a platinum (Pt) as the counter electrode, and (3) Ag/AgCl (saturated with KCl) as the reference electrode. Several methods were used in this study, including: (i) Open circuit potential (OCP) measurements, conducted during the immersion test, where the sample was placed in the test solution, and the potential was recorded every second for 30 minutes, (ii) Tafel extrapolation, which was used as a mathematical technique to determine the values of corrosion current density and corrosion potential and (iii) The behavior of the surface oxide layer was also studied using electrochemical impedance spectroscopy (EIS). The coating characterization method using a Vector Network Analyzer (VNA) aims to assess the ability of the oxide layer formed on 6061 aluminium through the Plasma Electrolytic Oxidation (PEO) process to absorb electromagnetic waves. The VNA is a device used to measure S-parameters (scattering parameters) of materials, providing information on the reflection and transmission of electromagnetic waves at specific frequencies. The VNA is configured to measure the reflection coefficient (S11) and transmission coefficient (S21) within the frequency range of 8 GHz to 12 GHz. An antenna or probe is used to connect the sample to the VNA. The measurements are taken by sending electromagnetic wave signals to the sample and recording the reflection (S11) and transmission (S21) coefficients at various frequencies.

3. Results and Discussions

3.1 Transitory reactions amid the arrangement of the inorganic layer

The cell voltage-time profiles during plasma electrolytic oxidation (PEO) of aluminum alloy, with and without EDTA additive, are presented in **Figure 2**. The graph is divided into three characteristic regions: initial passivation (Region I), plasma discharge development (Region II), and coating growth stabilization (Region III). In this figure, the critical points corresponding to breakdown voltage are highlighted, offering deeper insight into the plasma initiation behavior in both systems.

The discovery of breakdown voltages and the faster transition to softer plasma behavior in the EDTA-modified PEO process provides useful insights into how the electrolyte affects the overall results of plasma electrolytic oxidation (PEO). Specifically, the EDTA-treated system shows breakdown voltages occurring earlier and more uniformly. This helps optimize plasma characteristics, resulting in an oxide layer that offers better protection and higher quality. These findings demonstrate the potential of complexing agents like EDTA in enhancing the PEO process by helping to better control plasma discharge behavior. In the initial stages of PEO, both systems—standard and EDTA-modified—experience a quick rise in cell voltage. This voltage increase happens because of the growing electrical resistance from the formation of a thin oxide film. This is in line with previous research on the PEO mechanism (Kamil et al., 2020). However, there's a key difference in the EDTA-modified system: the voltage increases slightly more than in the standard process. This suggests that EDTA helps form a more uniform and denser passive oxide film, which stabilizes the interface between the substrate and electrolyte, improving early-stage resistance. The way EDTA binds with Al^{3+} ions likely contributes to the creation of a more stable and consistent oxide layer (Zhang et al., 2020).

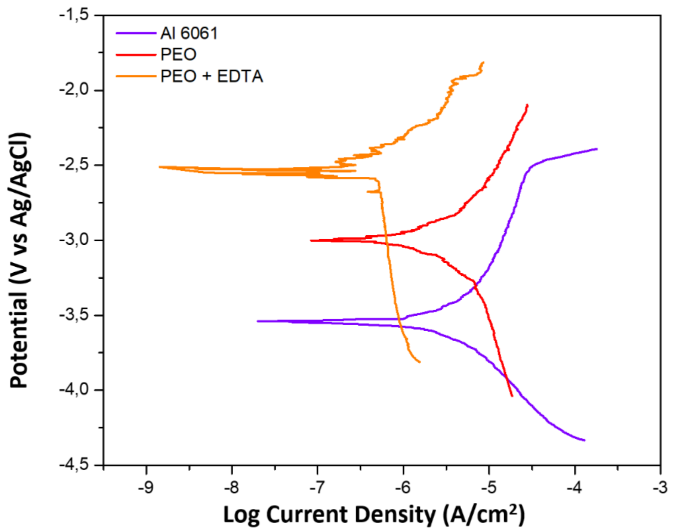

Figure 2. Potentiodynamic polarization curves of Al 6061, PEO-coated aluminum, and PEO + EDTA samples in 3.5 wt.% NaCl solution

As the process moves into Region II, where plasma discharges begin, we notice that the breakdown voltage happens earlier in the EDTA-assisted system. This indicates that EDTA is influencing the electrochemical environment in a way that facilitates dielectric breakdown at a lower voltage. Essentially, EDTA helps stabilize the electrical double layer (EDL) and spreads the electric field more evenly across the substrate surface. As a result, plasma discharges are triggered more uniformly and at slightly lower voltage thresholds (Kamil et al., 2020). This earlier breakdown results in softer plasma discharges, which is a significant contrast to the more intense, localized discharges seen in the standard PEO process. In conventional PEO, these intense plasma discharges can lead to larger pores and microstructural defects in the oxide layer. However, with the softer plasma behavior brought on by EDTA, the oxide layer becomes more uniform and compact. This is further confirmed by the sharper voltage rise after the breakdown point in the EDTA-modified system, suggesting that the plasma-assisted oxide growth is more efficient. By reducing severe discharge channels and preventing localized overheating, EDTA helps produce a more stable and uniform oxide layer (Kamil et al., 2020). This improvement in oxide layer quality is crucial for its overall strength and durability.

When the process enters Region III, where coating growth stabilizes and voltage levels off, both systems follow similar trends. However, the EDTA-modified system reaches a slightly higher stabilized voltage, suggesting that the oxide layer formed with EDTA is thicker and more compact. This aligns with findings from Kamil et al. (2020) and Zhang et al. (2020), who showed that adding complexing agents like EDTA enhances the thickness and compactness of the oxide layer. A thicker oxide layer generally offers better electrical insulation, higher corrosion resistance, and stronger mechanical integrity, making it ideal for applications in harsh conditions. Using EDTA as an electrolyte modifier not only boosts the quality of the oxide coating but also promotes a more controlled plasma discharge process. This control is essential for forming oxide layers with the best possible properties. By encouraging softer and more uniform plasma discharges, EDTA helps avoid the creation of large pores or defects, leading to a denser and more robust oxide layer. This has significant practical implications, especially in industries where high resistance to corrosion and wear is essential (Kamil et al., 2020; Zhang et al., 2020).

3.2 Surface Topography Analysis

The 3D surface profilometry images shown in **Figure 3** vividly illustrate the morphological differences between oxide layers produced by conventional plasma electrolytic oxidation (PEO) and those formed with the addition of ethylenediaminetetraacetic acid (EDTA) to the electrolyte. More than just a comparison of visuals, these images offer a deeper understanding of how modifying the electrolyte composition influences surface roughness, topography, and ultimately the overall coating performance.

Starting with the PEO-only sample, we can observe a relatively smooth surface, with the maximum height reaching around 2.55 µm. The color gradients across the image suggest limited topographical variation, with most areas remaining within a low to mid-elevation range. This is quite typical for coatings formed under conventional PEO conditions, where intense yet localized plasma discharges often lead to uneven surface growth, creating moderate roughness and scattered porosity. The moderate height variation seen here reflects the usual behavior for aluminum alloys treated with standard PEO — plasma activity is aggressive at the beginning but tends to stabilize as the oxide layer thickens (Rogov et al., 2022). When we shift our attention to the PEO+EDTA sample, the contrast is striking. The surface becomes significantly rougher and more textured, with maximum height values reaching up to 5.34 µm — more than double that of the untreated PEO sample. The appearance of more pronounced peaks and valleys, evident through the broader color variation, points to a more dynamic plasma discharge process. This aligns well with previous studies reporting that EDTA alters plasma behavior, making it softer and more uniformly distributed across the surface (Yeshmanova et al., 2024).

The underlying mechanism can be traced back to EDTA's role at the electrochemical interface. As a strong chelating agent, EDTA binds with free Al^{3+} ions, helping to stabilize the electrical double layer (EDL) and creating a more even distribution of the electric field at the substrate surface. This promotes finer and more frequent microdischarges rather than violent sparking, resulting in a more homogeneous, textured coating that adheres better and grows thicker over time (Lucas, et al., 2022). Interestingly, the increased peak-to-valley height in the EDTA-assisted PEO layer hints at a thicker, more robust oxide coating, a feature that correlates with improved electrochemical behavior, such as higher voltage stability during processing. In practical terms, a thicker coating often translates into better performance in terms of corrosion protection, wear resistance, and mechanical durability — qualities that are especially valuable for demanding applications like aerospace, automotive, and marine industries (Oh et al., 2023).

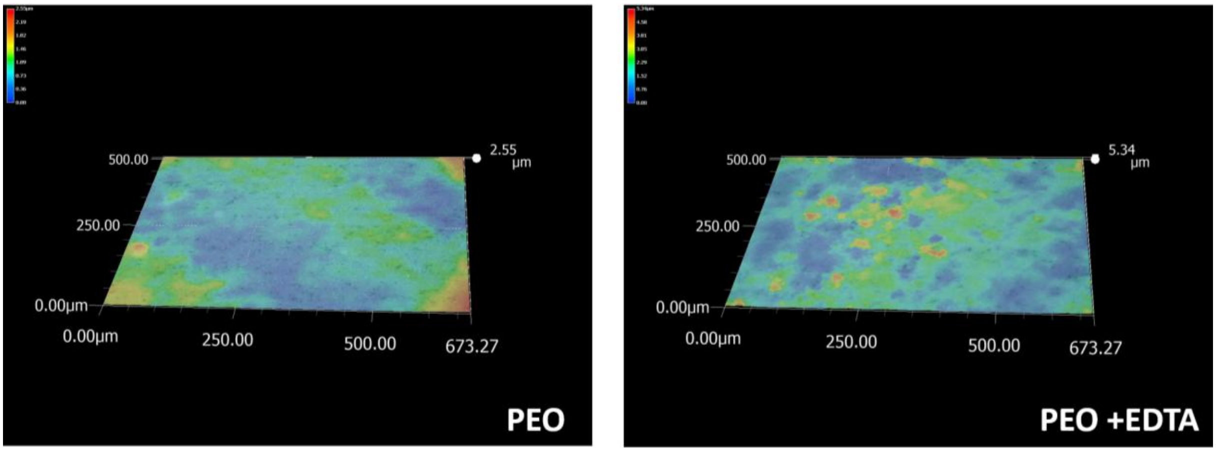

Figure 3. 3D surface profilometry images of oxide coatings produced by plasma electrolytic oxidation (PEO) on aluminum alloy substrates

That said, while increased surface roughness typically enhances mechanical interlocking and improves adhesion, it must be carefully managed. Excessive roughness can become a double-edged sword, introducing localized stress concentrations that may trigger premature failure under mechanical stress. Thus, optimizing the amount of EDTA in the electrolyte is key to achieving the ideal balance between surface complexity and structural integrity. The 3D images provide compelling support for the idea that EDTA facilitates a more controlled plasma-assisted growth mechanism. Unlike traditional PEO, where localized overheating can lead to micro-cracks and coating defects, the softer plasma regime induced by EDTA reduces such risks. This creates a denser, more compact, and defect-free oxide layer — a critical improvement for high-performance surface coatings (Guo et al., 2022). The comparative surface analysis clearly highlights the benefits of incorporating EDTA into the PEO process. Not only does it modify the plasma dynamics to favor more stable coating growth, but it also significantly enhances surface morphology and coating functionality. These insights are in line with current advances in electrolyte engineering aimed at pushing the boundaries of PEO technology for the next generation of protective coatings.

3.3 Anticorrosion performance study

The presented graph illustrates the relationship between the potential (V vs. Ag/AgCl) and the logarithm of current density (A/cm^2) for three aluminum 6061 samples: untreated pure Al 6061; Al 6061 treated by Plasma Electrolytic Oxidation (PEO), and PEO-treated Al 6061 with the addition of EDTA. This analysis aims to understand how different surface treatments affect the electrochemical behavior of Al 6061, particularly in terms of corrosion resistance and oxidation stability.

For the untreated Al 6061 sample, the graph displays a relatively linear decrease in potential with increasing current density. This behavior reflects the conventional electrochemical response of untreated aluminum, where oxidation occurs unimpeded due to the absence of a protective surface film. Such a linear response indicates minimal resistance to anodic dissolution, aligning with classical electrochemical theory, which describes aluminum's tendency to corrode in aggressive environments due to passive film breakdown (Tu et al., 2023). In contrast, the PEO-treated sample shows a significant increase in potential at equivalent current densities, indicating enhanced resistance to anodic current flow. This is attributed to the formation of a thick, stable oxide layer during the PEO process, which serves as a barrier against electrolyte penetration and slows down the oxidation process. This protective behavior is well documented in the literature, where PEO-treated aluminum alloys demonstrate improved corrosion resistance due to the ceramic-like properties of the oxide layer (Peng et al., 2021).

The most complex behavior appears in the PEO-treated sample with the addition of EDTA. This sample exhibits distinct potential fluctuations over a specific range of current densities, followed by a sharp decline. These fluctuations suggest transient electrochemical phenomena, potentially caused by localized changes in plasma discharge behavior or variations in electroactive species at the electrode–solution interface. As a strong chelating agent, EDTA modifies the ionic environment around the electrode, influencing the energy barrier required to initiate plasma discharges and altering the kinetics of oxide layer formation. Thus, EDTA not only serves as an additive but also actively modulates the electrochemical process during PEO (Kagatikar, 2022). A comparative analysis of the three samples highlights the substantial impact of surface modification on the electrochemical performance of Al 6061. While the PEO process enhances stability and produces a more uniform, corrosion-resistant oxide layer, the inclusion of EDTA introduces additional kinetic complexity. The modulated potential behavior in the EDTA-containing sample underscores the importance of optimizing electrolyte additives to control oxide film characteristics with high precision. Therefore, additives like EDTA may be strategically used to engineer aluminum surfaces with tailored protective properties for specific applications. The results indicate that the PEO process significantly improves the electrochemical stability of Al 6061 through robust oxide layer formation. The addition of EDTA induces complex kinetic phenomena that modulate this process by influencing interfacial dynamics and ion distribution. These insights contribute to a deeper understanding of the PEO mechanism and open opportunities for advanced, adaptive surface treatment technologies in various industrial applications.

Table 2. Electrochemical parameters of Al 6061, PEO-coated, and PEO + EDTA-treated samples derived from polarization tests

Sample	CR (mpy)	i_{corr} (A/cm^2)	β_c (V decade^{-1})	β_a (V decade^{-1})	E_{corr} (V)	R_p (Ωcm^2)
Al 6061	8.1408	6.33 x 10^{-6}	4.91 x 10^{-1}	4.91 x 10^{-1}	-3.519	1.94 x 10^{4}
PEO	6.5249	3.957 x 10^{-6}	7.83 x 10^{-1}	7.83 x 10^{-1}	-3.001	4.95 x 10^{4}
EDTA	1.3062	7.922 x 10^{-6}	1.56	1.00	-2.537	7.69 x 10^{5}

Table 2 presents a comparative summary of key electrochemical corrosion parameters for three Al 6061 samples: untreated, treated with plasma electrolytic oxidation (PEO), and PEO-treated with the addition of EDTA. These data clearly illustrate distinct trends in corrosion behavior across the different surface treatments. The untreated Al 6061 exhibits the poorest corrosion performance, with a relatively high corrosion rate of 8.14 mils per year (mpy) and a corrosion current density (i_{corr}) of 6.33 × 10^{-6} A/cm². Both anodic and cathodic Tafel slopes are nearly identical at approximately 0.491 V/decade, suggesting a balanced but uncontrolled electrochemical process. Moreover, the sample features a highly negative corrosion potential (E_{corr}) of –3.519 V, alongside a low polarization resistance (R_p) of 1.94 × 10^4 Ω·cm², confirming the inherent vulnerability of bare Al 6061 to corrosion in the test environment (Dursun & Soutis, 2014).

A clear improvement is observed in the sample treated with PEO. This surface-modified specimen shows a reduced corrosion rate of 6.52 mpy and a lower i_{corr} of 3.957 × 10^{-6} A/cm², indicating a slower corrosion process. The Tafel slopes increase to about 0.783 V/decade, reflecting a change in the reaction kinetics likely due to the formation of a protective oxide layer. Additionally, the corrosion potential becomes less negative at –3.001 V, and the polarization resistance nearly doubles to 4.95 × 10^4 Ω·cm², all pointing to improved barrier properties provided by the PEO coating (Hatch, 1984).

The most substantial enhancement in corrosion resistance is seen in the PEO-treated sample with EDTA. This sample demonstrates a drastically reduced corrosion rate of just 1.31 mpy, and the Tafel slopes increase sharply to 1.00 V/decade (anodic) and 1.56 V/decade (cathodic). These values suggest that the addition of EDTA significantly alters the electrochemical reaction pathways, likely by modifying the oxide layer's composition and structure. Although the i_{corr} slightly increases to 7.922 × 10^{-6} A/cm², this is offset by a notably less negative E_{corr} of –2.537 V and a dramatic increase in R_p to 7.69 × 10^5 Ω·cm². These changes point to a much more robust and protective oxide film, likely due to the chelating effect of EDTA, which enhances the uniformity and compactness of the coating (Kagatikar, 2022).

Several previous studies have laid the groundwork for understanding the enhancement of corrosion resistance in aluminum alloys through various surface treatment methods. For instance, research by Liu et al. (2019) demonstrated that the application of a hybrid coating combining PEO with a polymer layer significantly improved the corrosion resistance of Al 6061, showcasing the benefits of multi-layered approaches (Liu et al., 2019). Additionally, a study by Wang et al. (2020) investigated the effects of different electrolyte compositions during the PEO process, finding that the inclusion of zirconium ions resulted in a more robust oxide layer with superior protective properties compared to standard electrolytes (Wang & Chen, 2021). These studies illustrate the ongoing efforts to optimize surface treatments for aluminum alloys, emphasizing the importance of both the treatment process and the materials used.

In summary, while the PEO process alone enhances the corrosion resistance of Al 6061 by forming a stable oxide layer, the incorporation of EDTA leads to even greater improvements by modifying the reaction kinetics and optimizing the structure of the protective film. These findings highlight the potential of electrolyte additives like EDTA in developing advanced surface treatments for aluminum alloys used in corrosive environments.

3.4 Absorbing mechanism of organic composite coating

The electromagnetic absorption performance of the samples was thoroughly assessed by measuring their reflection loss across a broad frequency spectrum using a vector network analyzer (VNA). Reflection loss, expressed in decibels (dB), serves as a critical parameter that reflects the efficiency with which a material absorbs incident electromagnetic waves rather than reflecting them (**Figure 4**). In this investigation, three variants of Al 6061—untreated, PEO-treated, and PEO-treated with the addition of EDTA—were compared to evaluate how surface modifications influence their electromagnetic absorption capabilities.

The untreated Al 6061 sample displays relatively modest reflection loss values across the measured frequency range. This behavior is primarily attributed to the metal's high electrical conductivity, which leads to significant reflection of incident electromagnetic waves and minimal absorption. As such, the reflection loss curve for pure Al 6061 features only shallow dips, indicating limited effectiveness in applications that require efficient electromagnetic interference (EMI) shielding. The inherent lack of dielectric loss and impedance mismatch with free space further diminishes the absorption potential of the unmodified surface.

Conversely, the sample subjected to plasma electrolytic oxidation (PEO) demonstrates significantly enhanced reflection loss characteristics. The PEO process forms a ceramic-like oxide layer on the aluminum surface, which not only reduces the electrical conductivity of the material but also improves impedance matching with the surrounding medium. These changes facilitate greater absorption of electromagnetic waves, as evidenced by deeper minima in the reflection loss curve compared to the untreated sample. The improved absorption can be attributed to increased dielectric losses and interfacial polarization effects introduced by the microstructural complexity of the oxide layer formed during the PEO treatment (Tu et al., 2023).

Most notably, the sample treated with both PEO and EDTA exhibits the strongest electromagnetic absorption among all specimens. Its reflection loss curve reveals a pronounced dip—particularly around the frequency band where absorption is maximized—suggesting a synergistic enhancement effect resulting from the addition of EDTA. This additive appears to further modify the oxide layer by introducing more porosity, micro-defects, and heterogeneous nucleation sites. These structural features create a higher density of interfaces and dipolar centers within the coating, which in turn enhance interfacial polarization and dielectric losses. Additionally, the irregular and porous morphology fosters multiple scattering and extends the interaction time of electromagnetic waves within the material, resulting in superior impedance matching and higher absorption efficiency (Peng et al., 2021; Kagatikar, 2022).

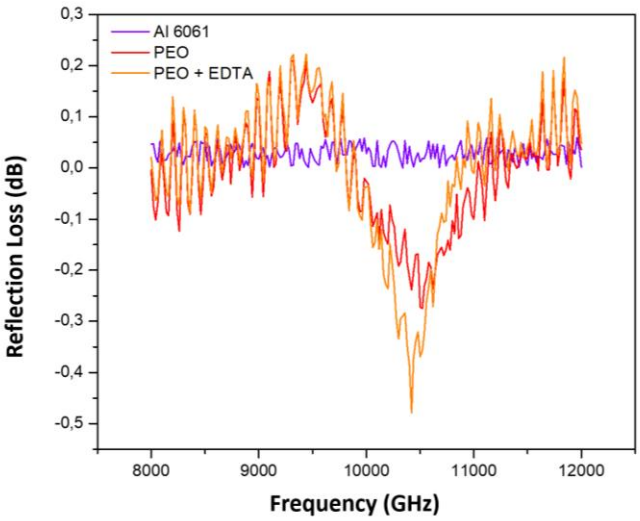

Figure 4. Reflection loss of Al 6061 substrate, PEO-coated aluminum, and PEO with EDTA additive measured across the frequency range of 8–12 GHz

The observed absorption improvements are governed by several fundamental mechanisms. Firstly, better impedance matching reduces the reflection of electromagnetic waves at the surface, allowing greater energy penetration into the material. Secondly, the presence of induced structural heterogeneities contributes to enhanced polarization losses, which dissipate electromagnetic energy as heat. Lastly, the dual-action effect of PEO and EDTA not only enhances these existing mechanisms but introduces new features, such as tailored surface porosity and defect engineering, that significantly improve absorption capacity. These attributes are especially relevant in EMI shielding and stealth technologies, where both signal suppression and wave absorption are essential (Wang & Chen, 2021).

Taken together, these findings underscore the substantial potential of surface engineering in tailoring the electromagnetic wave response of metallic materials. The integration of PEO and EDTA not only enhances corrosion resistance through oxide film formation but also introduces functional properties conducive to wave absorption. This dual benefit opens avenues for aluminum alloys to be used in multifunctional applications that require both mechanical durability and advanced electromagnetic compatibility. Future studies should explore the optimization of electrolyte formulations, treatment durations, and post-processing conditions to further refine the microstructural characteristics of the oxide layers. Advanced characterization tools such as scanning electron microscopy (SEM), transmission electron microscopy (TEM), and broadband dielectric spectroscopy could offer deeper insights into the structure–property relationships that govern electromagnetic absorption (Wang & Chen, 2021).

4. Conclusion

This study successfully addresses the limitations of conventional aluminum alloys in defense applications, particularly their vulnerability to corrosion and limited electromagnetic absorption capability. By incorporating EDTA into the Plasma Electrolytic Oxidation (PEO) process, a thicker, denser, and more uniform oxide layer was achieved. This structural improvement not only enhanced corrosion resistance, as indicated by a more positive corrosion potential and lower current density, but also significantly improved electromagnetic interference (EMI) shielding performance. The optimized coating demonstrated electromagnetic wave absorption of up to −1 dB within the 8–12 GHz frequency range, as verified by VNA testing. These results confirm that the synergistic approach of combining PEO with EDTA can overcome the inherent weaknesses of aluminum, providing a dual-function protective layer that ensures both durability and EMI attenuation. This advancement contributes to the development of multifunctional surface treatments, making aluminum alloys more competitive for next-generation defense applications where lightweight, corrosion-resistant, and stealth-capable materials are critically required.

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