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ARTICLE

Effect of Current Density on Microstructure, Corrosion Resistance, and Wear Resistance of Micro-arc Oxidation Coatings on 2195 Al-Li Alloy in a Silicate-Phosphate Electrolyte Solution

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Abstract: Ceramic coatings were prepared on 2195 Al-Li alloy by micro-arc oxidation (MAO) in a silicate-phosphate electrolyte solution under different current densities. The effect of current density varying from 200 A/m² to 800 A/m² on the microstructure, corrosion resistance, and wear resistance of MAO coatings was investigated. The surface and cross-sectional morphologies, composition, and roughness of MAO coatings were analyzed by scanning electron microscope, energy disperse spectrometer, X-ray diffractometer, X-ray photoelectron spectroscopy, and surface roughness tester. The results show that with the increase in current density, the roughness and thickness of MAO coating increase. MAO coatings are mainly composed of γ -Al₂O₃ and a small amount of α -Al₂O₃. MAO coatings prepared under the maximum current density is the densest. Potentiodynamic polarization tests indicate that the corrosion resistance of coatings increases with the increase in current density. When the current density is 800 A/m², MAO coating exhibits the best corrosion resistance, with a corrosion potential of -0.536 V and a corrosion current density of 4.32×10^{-7} A/cm², which is two orders of magnitude lower than that of the substrate. Electrochemical impedance spectroscopy results indicate that, at a current density of 800 A/m², the sample possesses the largest capacitive arc radius and the highest impedance magnitude in the low-frequency region. The wear resistance of MAO coatings increases with the increase in current density. When the current density is 200 A/m², the wear mechanism is dominated by abrasive wear. With further increase in current density, the wear mechanism remains abrasive wear. MAO coatings prepared at 800 A/m² show the best wear resistance with a wear rate of 1.355×10^{-4} mm³/(N·m).

Key words: Al-Li alloy; micro-arc oxidation; microstructure; corrosion resistance; wear resistance

1 Introduction

Under the background of the continuous development of science and technology, the requirements for lightweight materials in the fields of automobile, ship, and aviation are becoming more and more urgent. In addition, environmental problems, such as carbon emissions from vehicles, aircraft, and other means of transportation also guide people to choose quantities of lighter materials to lose weight and achieve the goal of reducing emissions. Aluminum-lithium (Al-Li) alloys have superior specific strength and specific elastic modulus, in

which lithium is the lightest metal element. The density of lithium is only 0.53 g/cm³, which is added to aluminum to form Al-Li alloy. Al-Li alloy has high specific strength and stiffness, good corrosion resistance, and excellent low-temperature fatigue performance^[1]. Therefore, Al-Li alloys have become one of the best materials to replace the traditional aluminum alloys. However, the hardness of Al-Li alloys is low, and the presence of amorphous and extremely thin natural oxide film on the surface makes their wear resistance and corrosion resistance weak, which restricts their applications.

Micro-arc oxidation (MAO) is a relatively new efficient and

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environmentally friendly modification technique. Micro-arc discharge occurs on the sample surfaces during MAO process with a series of complex reactions, such as electrochemical reaction, thermochemical reaction, plasma chemistry, and high-temperature phase transition, resulting in the formation of dense ceramic coatings^[2-4]. The thickness of the coatings ranges from tens to hundreds of micrometers, with excellent corrosion resistance, wear resistance, bionic property, and thermal insulation property. MAO is a promising technique in surface engineering because it can generate thick, dense, and hard ceramic coatings on valve metals and their alloys^[5-7]. The performance of MAO coatings is affected by many factors, such as electrolyte^[8], electrochemical parameter^[9-10], and power supply type^[11]. Kalkanci et al^[12] found the thickness of ceramic coating increases with rising current density within a certain range for all solutions. The higher the current density, the faster the growth rate of the coating. Xiang et al^[13] investigated the microstructure and properties of the ceramic layer obtained after MAO of 6063 aluminum alloy with different current densities, and found that the pore density of the coating decreases with the increase in current density. When the current density is 1500 A/m², the coating shows the best mechanical properties and corrosion resistance.

However, MAO technique still has many problems. For example, MAO coatings often exhibit loose and porous surface due to the presence of discharge micro-holes and some small cracks^[14]. In particular, the inhomogeneity of the arc discharge, as well as the subsequent rapid cooling and repetitive discharge, leads to the inhomogeneous growth of MAO coatings as well as the formation of porous structures^[15]. This will lead to a decrease in corrosion resistance of the oxidized alloy.

In recent years, many methods have been used for MAO to improve the corrosion resistance of the oxidized alloy, such as ultrasonic-assisted machining^[15] and adding SiO₂ nanoparticles to the electrolyte^[16].

However, there are few reports available on the effect of current density on the properties of MAO coatings^[12-13], especially for Al-Li alloys. In the present study, MAO coatings were prepared on 2195 Al-Li alloy by varying the current density using alkaline silicate-phosphate electrolyte. Their structure, morphology, and roughness were characterized. The electrochemical corrosion behavior of the coatings has been studied by potentiodynamic polarization tests. The wear resistance and corresponding mechanism of MAO coatings prepared at different current densities were also investigated.

2 Experiment

2.1 Materials preparation and MAO process

Commercially available 2195 Al-Li alloy with dimensions of 20 mm×15 mm×2 mm was used as a substrate for MAO process. Its composition consists of 1.07wt% Li, 3.97wt% Cu, 0.4wt% Mg, 0.15wt% Zr, 0.25wt% Ag, 0.10wt% Ti, and balanced Al. Prior to MAO process, samples were ground using emery abrasive papers up to 2000#, followed by deoiling with acetone for 10 min and then rinsing with

deionized water. MAO process was conducted in a constant current mode for fixed 60 min at different current densities of 200, 400, 600, and 800 A/m², separately. MAO technique was performed using an alkaline silicate-phosphate composite electrolyte system (Na₂SiO₃–(NaPO₃)₆–NaOH) as the basic electrolyte. The composition of the electrolyte is shown in Table 1. All reagents used in this experiment were of analytical grade. The variation of voltage with respect to treatment time was recorded. After MAO treatment, the samples were rinsed with deionized water and dried for further studies. The schematic diagram of the experimental device is shown in Fig.1.

2.2 Coating characterization

After MAO, the surface roughness of the samples was measured by surface roughness tester TR200. Five points were selected on both sides, and the average value was recorded. The surface and cross-sectional morphologies, thickness, and elemental composition of MAO coatings were analyzed by scanning electron microscope (SEM, Nova Nano 450) equipped with energy dispersive spectroscopy (EDS, INCA 250X-Max5). To ensure the integrity of MAO coatings, a Ni-P electroless plating was deposited on samples before the cross-sectional SEM observation. The basic formula of the Ni-P electroless plating solution is shown in Table 2. The phase analysis of the coatings was conducted by X-ray diffractometer (XRD, D8ADVANCE) with Cu K α ray ($\lambda=0.154\ 056\ \text{nm}$), and the scanning range was 10°–80°. The surface element composition and chemical state of coating was analyzed by X-ray photoelectron spectroscopy (XPS, Model Axis Supra) equipped with a monochromatic Al and Ag dual-anode X-ray source, with a maximum power of 400 W.

2.3 Electrochemical test

The potentiodynamic polarization tests of MAO coatings were conducted using an electrochemical workstation of PGSTAT302N in 3.5wt% NaCl solutions at 25 °C. The electrochemical tests used a conventional three-electrode cell. Meanwhile, the samples with an exposed area of 1 cm² to the

Table 1 Composition of the electrolyte (g/L)

Reagent	Concentration
Na ₂ SiO ₃	8.0
(NaPO ₃) ₆	6.0
NaOH	0.5

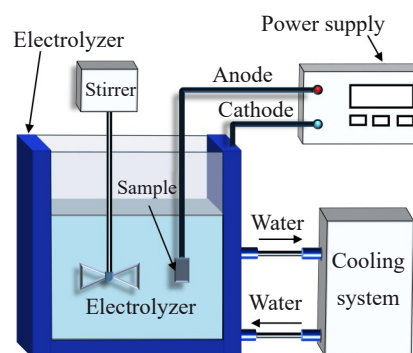


Fig.1 Schematic diagram of MAO experimental device

Table 2 Basic formula of the Ni-P electroless plating solution (g/L)

Reagent	Concentration
NiSO ₄	30
NaH ₂ PO ₂	26
Na ₃ C ₆ H ₅ O ₇	5
C ₄ H ₆ O ₄	15
C ₃ H ₆ O ₃	15
C ₂ H ₃ O ₂ Na	20

solution were used as the working electrode, a platinum foil acted as the counter electrode, and the saturated calomel electrode served as the reference electrode. Before the tests, the electrochemical testing system was stabilized at open circuit potential (OCP) for 30 min. The experiments were conducted in triplicate for all samples to ensure reproducibility.

Electrochemical impedance spectroscopy (EIS) of MAO coatings was performed using a PGSTAT302N electrochemical workstation in 3.5wt% NaCl solution at 25 °C. Before the test, the system was stabilized at OCP for 30–40 min. All samples were tested in triplicate to ensure the reproducibility of the results.

2.4 Wear test

Using the HT-1000 ball-on-disk friction and wear tester to test the wear resistance of the coatings, the friction pair was GCr15 balls with a diameter of 4.976 mm, and other wear parameters were the load of 365 g, the friction radius of 6 mm, the rotational speed of 224 r/min, and the friction time of 10 min. The section profile curve was obtained using the TR200 surface roughness tester, and the wear volume V (mm³) was calculated. The wear rate (K) of the coating was calculated according to the formula:

$$K = V/SF \quad (1)$$

where V is the wear volume (mm³), S is the total glide distance (m), and F is the load (N).

3 Results and Discussion

3.1 Voltage-time curves

The curves of voltage with respect to time under different current densities of 200, 400, 600, and 800 A/m² for 60 min during MAO process are shown in Fig.2. It can be seen that

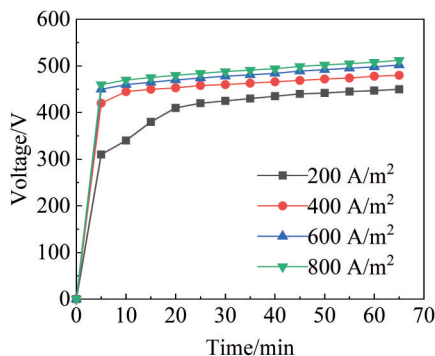


Fig.2 Voltage variation of MAO coatings with time at different current densities

the voltage at each current density in the initial 5 min rises rapidly, numerous small bubbles are observed on the surface of Al-Li substrate. These bubbles are mainly O₂ produced at the anode and a small amount of water vapor, which is corresponding to the conventional anodic reaction process^[17]. After that, the voltage increases slower, and sparks begin to emerge and grow on the surface of sample. The higher the current density, the higher the voltage at the same MAO treating time. Xiang et al^[13] have reported the similar phenomenon. The terminal voltages of the coatings prepared under the current densities of 200, 400, 600, and 800 A/m² are 468, 503, 522, and 532 V, respectively.

3.2 Surface roughness of MAO coatings

The surface roughness of the MAO coatings under different current densities is shown in Fig. 3. The surface roughness increases almost linearly with the increase in current density, which is attributed to the presence of more and larger inevitable cavities, open-pores, and pancake-like structures under higher current density^[18]. The roughness values of the coatings under the current densities of 200, 400, 600, and 800 A/m² are 0.75, 1.41, 3.25, and 4.01 μm, respectively. Zhang et al^[19] also found that during the MAO process, the size of ceramic micropores and oxide particles increases, which leads to the increases in surface roughness.

3.3 Surface and cross-sectional microstructures of MAO coatings

Fig. 4 shows the surface and cross-sectional morphologies of MAO coatings prepared at different current densities. It is evident that the variation in current density affects the morphology of MAO coatings. As the current density increases, the surface of the coating becomes coarser and rougher, and its thickness also increases.

When the current density is 200 A/m² (Fig.4a), the surface of the coating is relatively uniform, but there are many open-pores. In addition, there are many micro-cracks on the surface caused by thermal expansion and cold shrinkage during melting and solidification of the molten oxides^[20]. The thickness of MAO coating is about 10 μm from the cross-sectional morphology in Fig.4b, and it is uneven, which is also related to the scattered formation of the molten oxides on the surfaces.

When the current density increases to 400 A/m², the

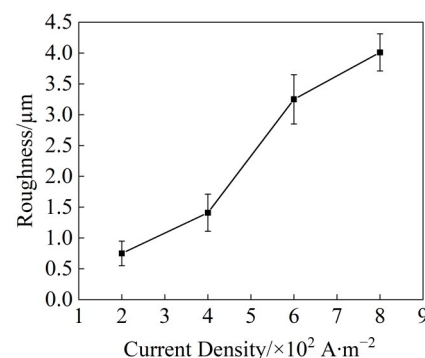


Fig.3 Roughness of MAO coatings under different current densities

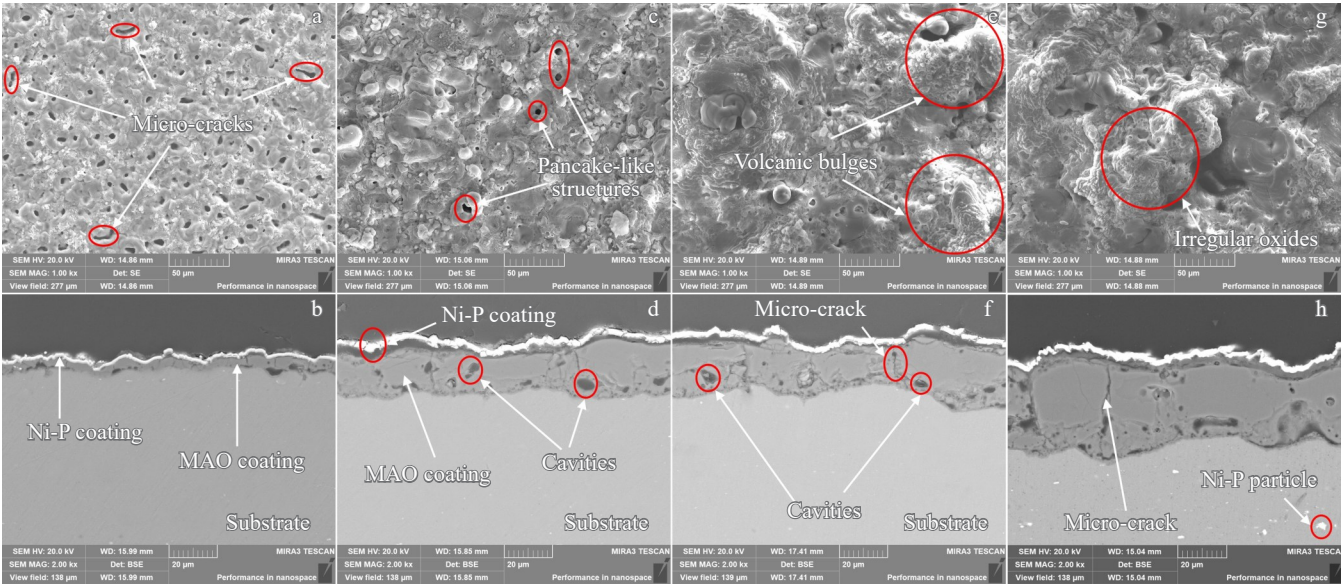


Fig.4 Surface (a, c, e, g) and cross-sectional (b, d, f, h) morphologies of MAO coatings prepared on Al-Li substrate at current density of 200 A/m² (a–b), 400 A/m² (c–d), 600 A/m² (e–f), and 800 A/m² (g–h) for 60 min

quantity of the open-pores on the coating surface decreases, compared with that in Fig. 4a. Many larger pancake-like molten oxides are formed, as shown in Fig. 4c. The pancake-like structures are caused by molten oxide ejected from the discharge channels owing to the rapid solidification under the cooling electrolyte^[21]. The similar results have been reported by Ezhilselvi et al^[22]. They found that the size of the pore increases with the increase in current density, while the pore density reduces. The corresponding cross-sectional morphology is shown in Fig. 4d. The upper layer of MAO coating becomes relatively denser and is well combined with the substrate. However, several cavities exist in the lower region of the MAO coating, which reduces its compactness.

When the current density increases to 600 A/m², large annular volcanic bulges are formed, as shown in Fig. 4e. The surface becomes rougher. From the cross-sectional image in Fig. 4f, it can be seen that there are obvious thermal cracks, even crossing the coating, which may deteriorate the corrosion resistance of the coating.

Further increasing current density to 800 A/m² leads to the ceramic oxides with irregular shape appearing on the coating surface (Fig. 4g). The discharge energy increases as the current density increases during the MAO process, and the reactions become intense. More molten oxides are ejected outward, resulting in severe splashing^[21]. Interestingly, the compactness of the coating (Fig. 4h) is much better than the other three coatings from the cross-sectional morphologies, and its thickness reaches about 60 μm when the current density is 800 A/m².

3.4 Elemental analysis of MAO coatings

3.4.1 EDS analysis

Table 3 shows the surface composition of the MAO coatings prepared at different current densities analyzed by EDS. It can be seen that the main elements of the coatings are Al, O, Si, and a small amount of P, Mg, and Na, in which, Al and Mg are mainly from the substrate, and Si, P, and Na are from the

Table 3 Surface EDS analysis results of MAO coatings prepared under different current densities

Current density/ A·m ⁻²	Al/ wt%	O/ wt%	Si/ wt%	P/ wt%	Mg/ wt%	Na/ wt%
200	35.18	62.71	1.27	-	0.85	-
400	32.02	63.04	4.12	-	0.81	-
600	25.36	66.06	6.82	1.02	0.74	-
800	20.02	63.38	13.07	1.66	-	2.94

electrolyte. In addition, the Si content in the coating increases with the rising current density. With the increase in current density, the discharge channels decrease in number but grow in size. And more intense discharge reactions occur, which results in more anions (e. g., SiO₃²⁻) from the electrolyte accumulating near the coating surface by adsorption and electrophoresis^[22], thus increasing their content within MAO coating^[23]. P and Na also remain on MAO coating surface because of spark sintering.

However, no Li is detected in MAO coatings by EDS, and the similar results are also confirmed by Qin et al^[24]. By XPS, they concluded that the Li did not participate in the reaction during MAO process. Considering the poor stability of Li in an aqueous solution at high temperature, the precipitation of Li compounds in the substrate results in a large number of defects in the anode coating at the beginning^[25-26]. Besides, the bubbles expand with the growth of the coating, and the generated gases are released when the cracks occur. This further leads to increased coating thickness and the emergence of dielectric breakdown. These effects provoke the enhancement in electric field and strong micro-discharge, which has an immediate impact on the defects in the cross-section of MAO coatings^[27-28], as shown in Fig. 4.

3.4.2 XPS analysis

Fig.5 presents XPS results of MAO coating surface of Al-Li alloy prepared at a current density of 800 A/m². The chemical composition of the coating was investigated and elucidated with the binding energy of carbon (284.8 eV) adopted as the reference peak.

Fig.5b–5d present the high-resolution XPS binding energy spectra of Al 2p, O 1s, and Si 2p for MAO coating on Al-Li alloy, respectively. Specifically, the two characteristic peaks in the Al 2p spectrum (Fig.5b) are assigned to the Al-O bonds in γ -Al₂O₃ and α -Al₂O₃^[29]; the Si 2p spectrum is depicted in Fig.5d, and the Si signal corresponds to the silicon species in the Si-O bonds of SiO₂^[30]; the O 1s spectrum (Fig. 5c) corresponds to the oxygen species in the Si-O bonds of SiO₂ and the Al-O bonds of Al₂O₃.

XPS analysis results demonstrate that the ceramic coating formed by MAO on the Al-Li alloy surface is mainly composed by SiO₂ and Al₂O₃. Then, no characteristic peak of Li is detected. The same results are also obtained in samples prepared at current density from 200 A/m² to 600 A/m². Combined with EDS results, it can be reasonably concluded that Li does not participate in MAO reaction process^[24].

3.5 Phase composition

For comparison, XRD patterns of the MAO coatings prepared at current densities from 200 A/m² to 800 A/m² are exhibited in Fig.6. It is found that the main phases of the coatings are γ -Al₂O₃ and a small amount of α -Al₂O₃, and the diffraction peaks of the γ -Al₂O₃ are stronger than those of the α -Al₂O₃. Similar results are also reported in Ref. [8,31]. Xiang et al^[13] studied the formation mechanism of metastable phase Al₂O₃, and found that the nucleation rate of droplet melting γ -Al₂O₃ phase is higher than that of α -phase at a high degree of

undercooling. The melted Al₂O₃ of the outerlayer of MAO coating being directly in contact with the electrolyte has a large cooling rate, which is beneficial to the formation of γ -Al₂O₃ phase. With the increase in current density, the peaks corresponding to α -Al₂O₃ are enhanced, indicating more γ -Al₂O₃ transformation to α -Al₂O₃. And the reason can be attributed to more heat generated at higher current density and the low thermal conductivity of aluminum oxide^[21]. High temperature causes the Gibbs free energy of α -Al₂O₃ to be significantly lower than that of γ -Al₂O₃. The oxide film will be spontaneously transformed into the more stable α -Al₂O₃ crystal phase. The higher the temperature, the stronger the transformation tendency. This ultimately leads to an increase in α -Al₂O₃ content of the oxide film layer as the current density increases^[21]. For MAO coatings, the diffraction peaks of Al corresponding to the substrate are detected.

3.6 Corrosion resistance

3.6.1 Potentiodynamic polarization test

Potentiodynamic polarization curves obtained for MAO coatings and the substrate alloy are shown in Fig. 7, and the results of self-corrosion potential (E_0) and corrosion current density (I_0) of each sample are also displayed in Table 4. The bare Al-Li substrate initially shows a steep increase in anodic potential from about -0.834 V up to -0.536 V, indicating a passivation process. After that, the current density is evidently enhanced, corresponding to the dissolution process of the formed passive film. E_0 and I_0 of the substrate are -0.834 V and 2.359×10^{-5} A/cm², respectively. The lower potential and larger corrosion current imply the weak corrosion resistance of the substrate in NaCl solution.

It can also be seen from Fig. 7 that with the increase in MAO current density, the self-corrosion potential increases,

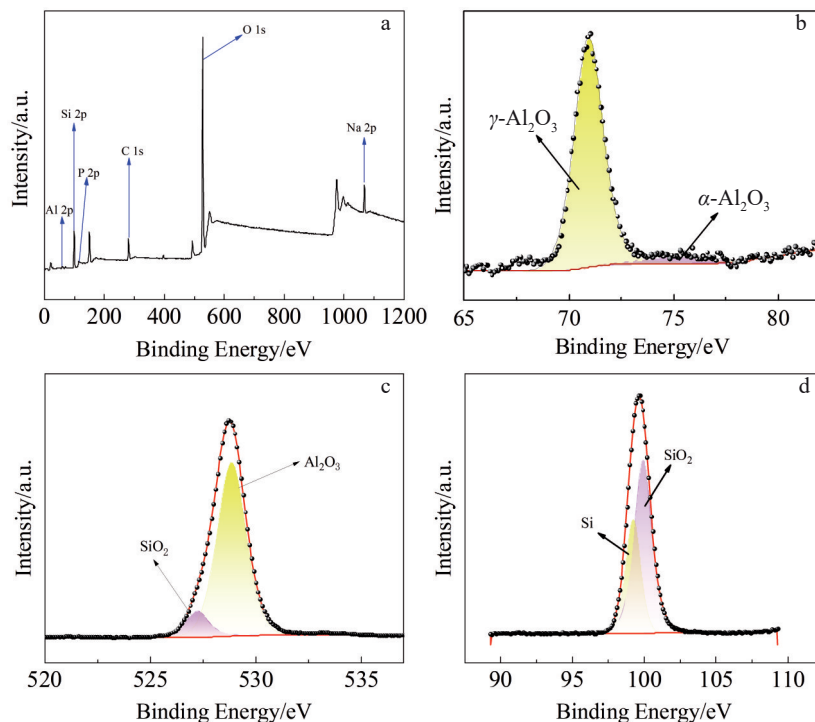


Fig.5 XPS spectra of MAO coatings prepared at current densities of 800 A/m²: (a) whole, (b) Al 2p, (c) O 1s, and (d) Si 2p

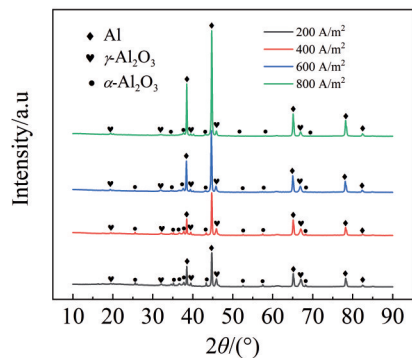


Fig.6 XRD patterns of MAO coatings prepared at different current densities

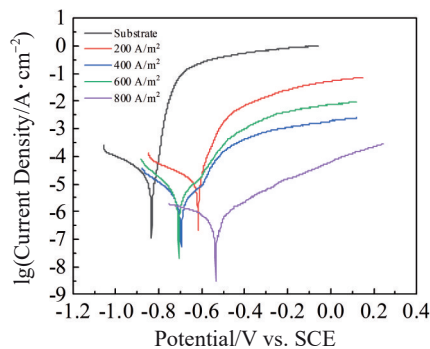


Fig.7 Potentiodynamic polarization curves of the substrate and MAO coatings prepared at different current densities

and the corrosion current density decreases, indicating enhanced corrosion resistance of MAO coatings^[32]. When current density is 200 A/m², the coating surface is uniform, but it contains many holes, even adjacent holes connected together, which increases the corrosion area, resulting in poor

corrosion resistance of the coating. As the current density increases, the thickness and density of MAO coatings increase. When the current density is 800 A/m², the E_0 is -0.536 V, which is shifted positively by about 0.298 V compared with the substrate, and the I_0 is the lowest of 4.32×10^{-7} A/cm², which is two orders of magnitude smaller than that of the substrate. The corrosion resistance of ceramic layer is mainly related to the thickness of coating and its surface quality^[24]. When the current density is 800 A/m², the surface and cross-sectional morphologies of the coatings (Fig.4) are more uniform and denser, and the holes are less, which improves the corrosion resistance.

3.6.2 EIS test

EIS can quantitatively evaluate the corrosion resistance of MAO coatings. Fig.8 presents EIS spectra of MAO coatings prepared at different current densities after immersion in 3.5wt% NaCl solution for 1 h.

As observed from the Nyquist plots in Fig.8a, the samples prepared by MAO at current densities of 400, 600, and 800 A/m² only exhibit capacitive arcs, while the sample prepared at 200 A/m² shows both capacitive arc and weak inductive arc. The appearance of inductive arc in the low-frequency region is attributed to the abundant defects in the coating under low current density, which induces the adsorption or desorption behavior of solution ions at the interface^[33-34]. A larger radius of the capacitive arc in the Nyquist plot indicates superior corrosion resistance of MAO coating^[35]. The radius of the capacitive arc increases with the increase in current density, implying that the corrosion resistance is enhanced with rising current density. At a current density of 800 A/m², the sample exhibits the largest capacitive arc radius, indicating that it possesses the highest corrosion resistance and the lowest corrosion rate.

Table 4 Self-corrosion potential and current densities of substrate and MAO coatings prepared under different current densities

Current density/A·m ⁻²	E_0 /V	$I_0 \times 10^{-6}$ A·cm ⁻²	$R_p/\Omega \cdot \text{cm}^2$	Corrosion rate/mm·a ⁻¹
Substrate	-0.834	23.59	324.9	0.592 50
200	-0.617	13.58	165.5	1.163 20
400	-0.696	2.064	1572.8	0.136 09
600	-0.708	2.050	1550.4	0.114 17
800	-0.536	0.432	34804	0.005 331

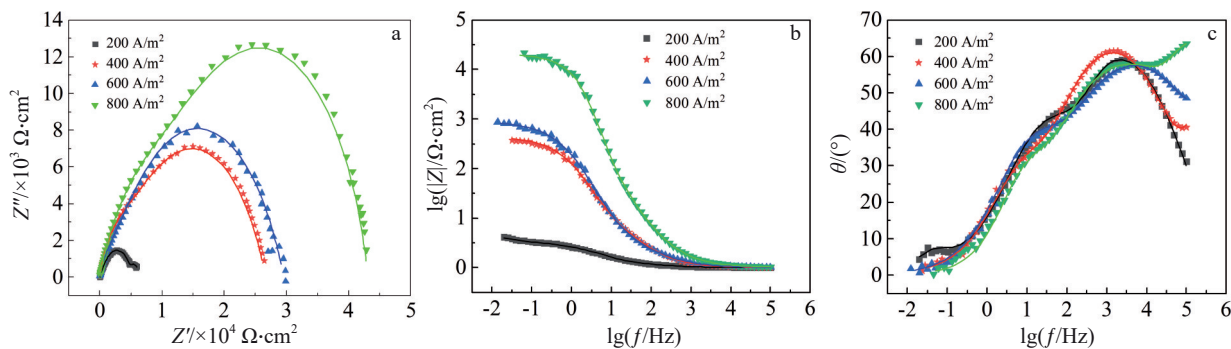


Fig.8 Nyquist plots (a), Bode impedance plots (b), and Bode phase diagram (c) of MAO coatings prepared at different current densities

From the impedance magnitude-frequency plots in the Bode diagram (Fig.8b), all curves show a rapid decrease in impedance magnitude in the high-frequency region, demonstrating that the capacitive behavior of the coating dominates at high frequencies. In the medium-frequency region, the impedance magnitude increases significantly with decreasing frequency, showing typical capacitive characteristics. In the low-frequency region, the impedance magnitude of sample prepared at 800 A/m² is the highest, while that of sample prepared at 200 A/m² is the lowest, which confirms that the protective performance of the coating is improved with the increase in current density. The impedance modulus $|Z|$ of MAO coating prepared at 800 A/m² is higher than that of other coatings, indicating that it exhibits the highest corrosion resistance and the best protective performance.

In addition, the phase-frequency plots in the Bode diagram reveal that MAO coatings have three time constants. The time constant in the high-frequency region corresponds to the loose outer layer, the medium-frequency region corresponds to the dense inner layer, and the low-frequency region corresponds to the electric double layer at the substrate-solution interface. For the sample prepared at 200 A/m², a significant decrease in phase angle appears in the low-frequency region, which is attributed to the poor coating quality at 200 A/m², leading to localized corrosion of the substrate. This result corresponds well to the weak inductive arc observed in the Nyquist plot. Moreover, the sample prepared at 800 A/m² shows the highest phase angle peak, which further verifies that it exhibits the most remarkable capacitive characteristics and the best structural integrity.

Fig.9 shows the equivalent circuit of MAO coating. Table 5 lists the fitting parameters calculated via the ZSimpWin software. R_p and R_b represent the impedance of the outer layer

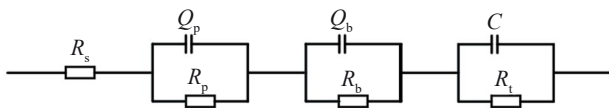


Fig.9 Schematic diagram of equivalent circuit of MAO coating

Table 5 EIS fitting data of MAO coatings prepared at different current densities in 3.5wt% NaCl electrolyte

Current density/A·m ⁻²	200	400	600	800
Solution resistance, $R_s / \times 10^{-5} \Omega \cdot \text{cm}^2$	7.709	4.497	4.142	999.7
n_1	0.8858	0.6919	0.7147	0.6866
$R_p / \times 10^2 \Omega \cdot \text{cm}^2$	2.07	22.18	23.82	1382
$Q_p / \times 10^{-6} \Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^{n_1}$	5.810	6.555	2.832	1.168
n_2	0.6635	0.7879	0.6780	0.8124
$R_b / \times 10^4 \Omega \cdot \text{cm}^2$	0.5018	2.339	2.714	29.27
$Q_b / \times 10^{-6} \Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^{n_2}$	24.14	1.887	5.416	2.462
$R_i / \Omega \cdot \text{cm}^2$	97.19	39.25	21.65	53.70
Double-layer capacitance, $C / \times 10^{-8}$	4.190	1.955	2.070	8.009

and inner layer of the MAO coating, respectively. A higher impedance value corresponds to superior corrosion resistance^[36]. The values of R_p and R_b increase with the increase in current density. When the current density is 800 A/m², the R_p and R_b values are much higher than those of the other samples, indicating that the coating prepared at current density of 800 A/m² possesses the optimal compactness and corrosion resistance.

3.7 Wear resistance

The friction coefficient curves of MAO coatings prepared at different current densities are shown in Fig.10. It can be seen that when the current density is 200 A/m², the friction coefficient curve firstly goes through a running-in stage, and then rises gradually up to 0.9. When the current density is 400 A/m², the friction coefficient curves first undergo a brief running-in period, with the friction coefficient rising rapidly to approximately 1.05, followed by small-amplitude fluctuations over the subsequent 300 s. After that, the coefficient tends to be stable and increases up to 1.1 in the end of the test. The friction coefficient curves of samples prepared at 600 and 800 A/m² are similar to the curve of sample prepared at 200 A/m². While the friction coefficient curves of samples prepared at 600 and 800 A/m² are more stable and lower, which are 0.45 and 0.50 in the end of the tests, respectively.

The friction coefficients at 200 and 400 A/m² are significantly higher than those at 600 and 800 A/m². This phenomenon can be attributed to the fact that the content of $\alpha\text{-Al}_2\text{O}_3$ in the coating increases with the increase in current density. The increased $\alpha\text{-Al}_2\text{O}_3$ content enhances the coating hardness, which promotes the formation of more wear debris during the friction process. Most of the wear debris exhibits an irregular spherical morphology and acts as rolling particles during sliding, thereby reducing the friction coefficient.

Fig.11 shows wear morphologies of MAO coatings prepared at different current densities and GCr15 small ball, which was used as the friction pair. When the current densities are 200 and 400 A/m², the wear tracks are narrow and flat relatively. At high magnification, obvious wear debris and iron filings can be seen, as shown in Fig.11b and 11e, and the GCr15 small balls have flat and circular wear scars, as shown in Fig.11c and 11f, indicating that the wear mechanism is mainly dominated by abrasive wear. When the current density is

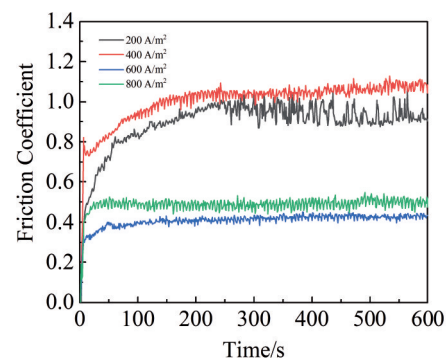


Fig.10 Friction coefficient curves of MAO coatings prepared at different current densities

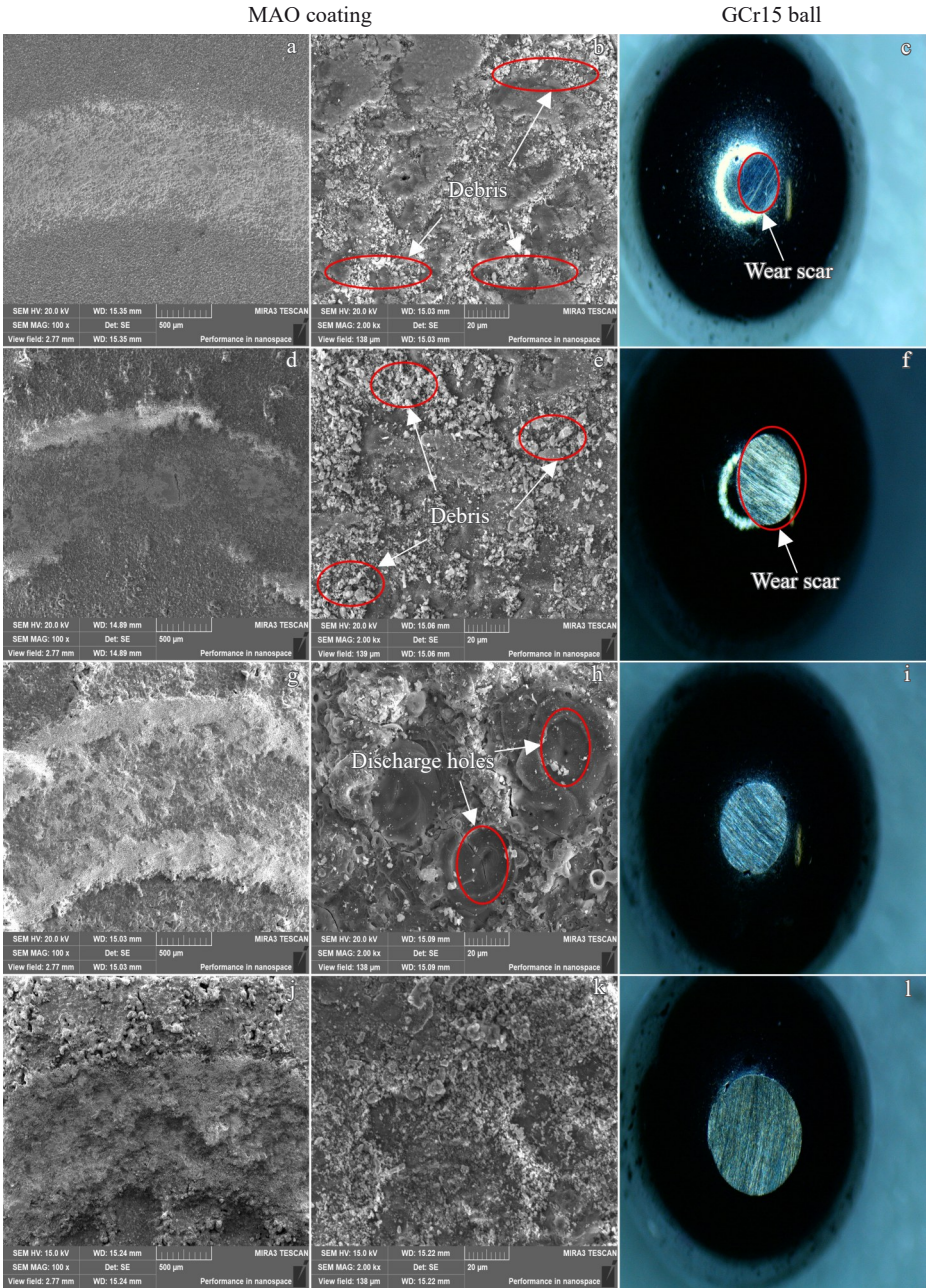


Fig.11 Wear morphologies of GCr15 small ball and MAO coatings prepared at current densities of 200 A/m² (a–c), 400 A/m² (d–f), 600 A/m² (g–i), and 800 A/m² (j–l)

further increased to 600 and 800 A/m², there is also a small amount of wear debris, and the GCr15 small balls are worn severely, which also indicates that the wear mechanism is abrasive wear. The wear area of the GCr15 small balls increases with the increase in current density. This is because both the hardness and the thickness of MAO coatings increase with the increase in current density, which leads to the gradual aggravation of the GCr15 small balls wear^[37].

The wear rate of MAO coatings is illustrated in Fig. 12. With the increase in current density, the wear rate decreases. When the current density is 800 A/m², the wear rate reaches its minimum of $1.355 \times 10^{-4} \text{ mm}^3/(\text{N} \cdot \text{m})$, showing the best wear resistance. Similar results were also reported in Ref.[38–39].

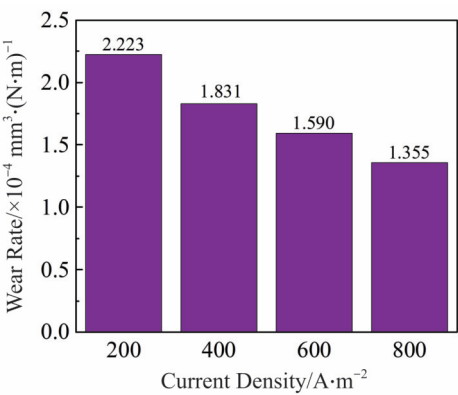


Fig.12 Wear rates of MAO coatings prepared at different current densities

4 Conclusions

1) MAO coatings prepared on 2195 Al-Li alloy at current densities from 200 A/m² to 800 A/m² are uniform and mainly composed of γ -Al₂O₃ and a small amount of α -Al₂O₃.

2) With the increase in current density, the terminal voltages, roughness, and thickness of MAO coatings increase remarkably. The corrosion resistance of coatings increases with the rising current density. When the current density is 800 A/m², the corrosion potential is -0.536 V, which is shifted positively by about 0.298 V compared with the substrate, and the corrosion current is the lowest of 4.32×10⁻⁷ A/cm², which is two orders of magnitude smaller than that of the substrate.

3) The wear resistance of MAO coatings increases with the rising current density. And the wear mechanism is abrasive wear. When the current density is 800 A/m², MAO coatings show the best wear resistance with a minimum wear rate of 1.355×10⁻⁴ mm³/(N·m).

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电流密度对硅磷酸盐电解液中2195铝锂合金微弧氧化涂层 微观结构、耐腐蚀性及耐磨性的影响

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摘 要: 在硅酸盐-磷酸盐电解液中, 采用微弧氧化技术在2195铝锂合金表面制备陶瓷涂层, 研究了不同电流密度(200~800 A/m²)对微弧氧化涂层微观结构、耐蚀性和耐磨性的影响。通过扫描电子显微镜、能谱仪、X射线衍射仪、X射线光电子能谱仪和表面粗糙度仪分析了微弧氧化涂层的表面及截面形貌、成分和粗糙度。结果表明, 随着电流密度的增大, 微弧氧化涂层的粗糙度和厚度均增加。该涂层主要由 γ -Al₂O₃组成, 并含有少量 α -Al₂O₃。在最大电流密度下制备的微弧氧化涂层最为致密。动电位极化测试表明, 涂层的耐蚀性随电流密度的增大而提高。当电流密度为800 A/m²时, 微弧氧化涂层的耐蚀性最佳, 其腐蚀电位为-0.536 V, 腐蚀电流密度为 4.32×10^{-7} A/cm², 较基体降低了两个数量级。电化学阻抗谱结果显示, 电流密度为800 A/m²时, 试样的容抗弧半径最大, 且在低频区具有最高的阻抗值。微弧氧化涂层的耐磨性随电流密度的增大而提高。当电流密度为200 A/m²时, 磨损机制主要为磨粒磨损; 进一步增大电流密度后, 磨损机制仍为磨粒磨损。在800 A/m²下制备的微弧氧化涂层耐磨性最佳, 磨损率为 1.355×10^{-4} mm³/(N·m)。

关键词: 铝锂合金; 微弧氧化; 微观结构; 耐腐蚀性; 耐磨性

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