Fabrication of WO$_3$/Al$_2$O$_3$ Composite Ceramic Coatings on 6063 Aluminum Alloy by Ultrasound-enhanced Micro-Arc Oxidation

Yupeng Guo$^{1,*}$, Zhenguo Wei$^1$, Dongbo Wei$^2$, Daqiang Ma$^1$, Xiaofeng Lu$^1$, Xiaolei Zhu$^1$

$^1$ School of Mechanical and Power Engineering, Nanjing tech university, Nanjing 211816, China
$^2$ School of Mechatronic Engineering, Harbin Institute of Technology, Harbin150001, China
*E-mail: guoyupeng@njtech.edu.cn

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WO$_3$/Al$_2$O$_3$ composite ceramic coatings were prepared through ultrasound-enhanced MAO technique on 6063 aluminum substrates. The hardness and corrosion performance of the substrate were improved. The diameter of micropores on the surface of the coatings decreased with increasing Na$_2$WO$_3$ concentration. X-ray diffraction results showed the coatings consisted of $\gamma$-Al$_2$O$_3$, $\alpha$-Al$_2$O$_3$, and WO$_3$. The amounts of $\gamma$-Al$_2$O$_3$ and WO$_3$ increased with increasing Na$_2$WO$_3$ concentration. The roughness decreased from 2.00$\mu$m to 1.67$\mu$m. The corrosion current density reduced from 32.59$\mu$A/cm$^2$ to 0.29$\mu$A/cm$^2$, and the hardness increased from 1025HV to 1465HV. The vibration amplitude of the electrolyte increased with increasing ultrasonic power and reached 144$\mu$m at 700W, which changed the microstructure of the coatings.

**Keywords**: Ultrasound enhanced micro-arc oxidation, ceramic coatings, corrosion performance

1. INTRODUCTION

Aluminum and aluminum alloy are widely used in aviation, naval, and other fields due to their low density and high strength[1, 2]. However, the surface property[3, 4] and hardness of these materials limit their application[5]. Ultrasonic-enhanced micro arc oxidation (MAO)[6, 7], as a new surface treatment technology, has gained increasing attention for preparation of ceramic coatings. He[8] studied the effect of ultrasonic composite MAO on the growth of A96061 aluminum alloy coatings; the method improved the growth behavior and anti-vibration performance of the coatings. Shen[9] evaluated the effect of ultrasonic composite MAO on 6061 aluminum alloy coatings. Ultrasound effectively promoted the formation of $\alpha$-Al$_2$O$_3$, reduced the formation of larger discharge micro pores, and increased the coating thickness. Qu[10] investigated ultrasound-MAO treatment of magnesium alloys for medical use, the polarization resistance was the optimal 120W ultrasound power. However, the vibration of ultrasound
at low power was small, and the effect on the MAO discharge process may be limited. Quantitative analysis of the relationship between ultrasonic power and the vibration of electrode was found to be a key factor for analysis of ultrasonic process. Quantitative measurement of ultrasonic vibration has not been evaluated yet. Na$_2$WO$_4$ is typically used to improve the friction and corrosion properties of coatings in MAO[11, 12]. Chen[13] determined the effect of Na$_2$WO$_4$ on the MAO coatings of the Al-Ti double component. Na$_2$WO$_4$ enhanced the intensity of the reaction and increased the thickness of the coatings. Chen[14] used Na$_2$WO$_3$ to improve the polarization resistance of MAO-coated Mg-Zn-Ca alloy; the optimal combination comprised 0.5 g/L Na$_2$WO$_4$ and other additives. Hakimizad[15] studied the pulse current mode on the plasma electrolytic oxidation of 7075 Al in Na$_2$WO$_4$-containing solution; the hardness of the coatings was improved to 1900HV. Bayati[16] studied the characteristics and coating formation mechanism of WO$_3$ and TiO$_2$ nanocomposite coatings produced by different treatment voltages; the band gap energy of the coatings was estimated to be 2.87eV, and the degradation rates were 2.210$^{-2}$ and 0.910$^{-2}$ min$^{-1}$, respectively.

Considering the successful application of Na$_2$WO$_4$ to MAO, Na$_2$WO$_4$ was used to prepare WO$_3$/Al$_2$O$_3$ ceramic coatings through ultrasound-enhanced MAO; this method could be used to expand the applications of MAO technology in corrosive environments. In the current work, WO$_3$/Al$_2$O$_3$ ceramic coatings were prepared with different Na$_2$WO$_4$ concentrations under ultrasound. The relationship among ultrasound power, concentration of Na$_2$WO$_3$, microstructure, morphology, corrosion property, hardness of the coatings was studied.

2. MATERIALS AND METHOD

2.1. Preparation of MAO coatings

Circular aluminum alloy sample with a diameter of 15 mm and a thickness of 2 mm was used. The chemical element composition of the samples was AlMgSi (Wt %): Mg 0.45 %–0.9 %, Si 0.2 %–0.6 %, Cu ≤ 0.1 %, Fe ≤ 0.35 %, Mn ≤ 0.1 %, Zn ≤ 0.1 %, Cr ≤ 0.1 %, Ti ≤ 0.1 %, and Al. The samples were polished with 800× 2000 # SiC sand paper and washed with ethanol. The experiments were carried out after drying. The MAO equipment was composed of 10 kW MAO power supply (independently developed by Nanjing tech university), stainless steel sink, and cooling system. The sample was connected to the positive pole of the power supply as the anode. Stainless steel sink was used as the cathode. The ultrasonic equipment was JH-10000, the power was 900W, and the frequency was 28kHz. The electrolytic cell was placed inside the ultrasonic cell, and the ultrasonic cell, which was filled with water. The ultrasonic vibration was transmitted to the steel sink through water. The working solution was composed of Na$_2$SiO$_3$, KOH, Na$_2$WO$_3$, and deionized water. The concentration of Na$_2$SiO$_3$ was 4g/L, and that of KOH was 4g/L. The power supply and process parameters for preparing the coatings are shown in Table 1. The substrate was AlMgSi and the coatings were defined as AlMgSi-1, AlMgSi-2, AlMgSi-3, AlMgSi-4, AlMgSi-5, AlMgSi-6. The temperature of the electrolyte was maintained at 30°C–35°C by using a stirring pump. According to previous experiments[17-19], the frequency, duty
cycle, and time were set to 500 Hz, 50%, and 35 min, respectively. In constant voltage mode, the processing voltage was 520 V.

Table 1. The chemical composition, electrical conductivity and pH of the electrolyte under 500 Hz, 50% duty cycle, and 35 min

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Ultrasound Power (W)</th>
<th>Na$_2$SiO$_3$ (g/L)</th>
<th>KOH (g/L)</th>
<th>Na$_2$WO$_3$ (g/L)</th>
<th>Electrical conductivity (mS/cm, 24°)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlMgSi-1</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td>10.08</td>
<td>12.1</td>
</tr>
<tr>
<td>AlMgSi-2</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>10.74</td>
<td>12.1</td>
</tr>
<tr>
<td>AlMgSi-3</td>
<td>700</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>10.74</td>
<td>12.1</td>
</tr>
<tr>
<td>AlMgSi-4</td>
<td>700</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>10.93</td>
<td>12.1</td>
</tr>
<tr>
<td>AlMgSi-5</td>
<td>700</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>11.25</td>
<td>12.1</td>
</tr>
<tr>
<td>AlMgSi-6</td>
<td>700</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>11.56</td>
<td>12.1</td>
</tr>
</tbody>
</table>

2.2. Analysis of structure and composition of the coatings

The microstructure of the coatings was analyzed using JSM-6480A scanning electron microscope (SEM) and EDS. The phase structure of the specimens was detected using D/max-r B X-ray diffraction (XRD, Cu Kα radiation). The scattering angle 2θ was set from 10° to 90° with a step of 0.041°, an acquisition time of 1 s/step, energy of 40 kV, and current of 40 mA. PHI5700ESCA System X-ray photoelectron spectroscopy (XPS, twin anode, X-ray source, using Al Kα α¼1 486.6eV) was employed to probe the surface chemical composition and valence of the samples. The surface roughness of the coatings was measured using a roughness tester (TR200, cut-off length 0.8 mm). The surface hardness of the coatings was evaluated using a digital micro-hardness tester (HVS-1000) in HV mode at a load of 25 g for 5 s. The electrochemical workstation CHI604C was employed to detect the corrosion property of the specimens through Tafel testing with an initial potential of −2V, a final potential of 1V, a quiet time of 200 s, and a scan rate of 1mV/s. Three-electrode cell set-up was used in which the prepared sample was the working electrode and a platinum sheet and a saturated calomel electrode were used as the counter and reference electrodes, respectively. The experiments were performed in 3.5 wt.% NaCl solution at room temperature. Ultrasonic vibration was used displacement detection system (independently developed by Nanjing tech-university), the laser displacement sensor was HG-C1000, with a measurement range of 3mm and an accuracy of 1μm. Vibration signal was collected by UPO2104CS oscilloscope.

3. RESULTS AND DISCUSSION

3.1 SEM

The ultrasonic power and concentration on the microstructure of the coatings are shown in Figure 1. Uniform MAO coatings were obtained on the substrates (Figure 1a). The surface of the coatings contained micro pores and molten regions which were formed due to the heating, melting, and quenching.
of the molten oxides[20]. Smooth areas appeared on the coatings under 1 g/L Na$_2$WO$_3$ (Figure 1b). WO$_3^{2-}$ in the electrolyte participated in the MAO reaction and changed the morphology of the coatings. A dense “stack” was generated under ultrasonic-enhanced MAO (Figure 1c). The ultrasonic waves produced high-frequency oscillations in the electrolyte, which caused the oscillation of electrolyte around the spark discharge channel.

Figure 1. The ultrasonic power and concentration on the microstructure of the coatings (a) AlMgSi-1; (b) AlMgSi-2; (c) AlMgSi-3; (d) AlMgSi-4; (e) AlMgSi-5; (f) AlMgSi-6;

The high oscillation frequency of the electrolyte induced the production of cold quenching by the spark discharge channel of MAO, which generated a dense “stack” and promoted the reduction of diameter on the generated small holes. With increasing Na$_2$WO$_3$ concentration, the “stack” of the coatings gradually decreased, the smooth areas appeared, and the number of micropores decreased. WO$_3$
was distributed more evenly on the coatings, and their morphology was smooth under ultrasonic treatment. However, the dense “stack” on the surface of the coatings indicated the high concentration of Na\textsubscript{2}WO\textsubscript{3} at AlMgSi-6 (Figure 1f), which may affect the performance of the coatings.

### 3.2 Cross section

The cross section of the coatings is shown in Figure 2. The thickness of the coatings increased from 35 μm to 39 μm with increasing Na\textsubscript{2}WO\textsubscript{3} concentration under ultrasound treatment (Figure 2b). Ultrasonic vibration promoted the process of MAO and increased the thickness of the coatings. The WO\textsubscript{3}\textsuperscript{2-} ions moved to the anode under the action of electric field and participated in micro arc discharge, leading to the formation of WO\textsubscript{3}. The content of WO\textsubscript{3} and the thickness of the coatings increased with increasing concentration of WO\textsubscript{3}\textsuperscript{2-} ion.

![Figure 2. Cross section of the coatings under different preparation conditions (a)AlMgSi-1; (b)AlMgSi-2; (c)AlMgSi-3; (d)AlMgSi-4; (e)AlMgSi-5; (f)AlMgSi-6;](image)

### 3.3 EDS

The EDS results of the coatings under different preparation conditions are shown in Table 2. The coatings were composed of O, Mg, Al, Si, and W. Si was obtained from Na\textsubscript{2}SiO\textsubscript{3}, and W was derived from Na\textsubscript{2}WO\textsubscript{3}. Al and Mg were obtained from the Al substrates, and O was derived from the Al\textsubscript{2}O\textsubscript{3} ceramic coatings. The W content was 1.14 % at AlMgSi-2, which generated WO\textsubscript{3}. WO\textsubscript{3}\textsuperscript{2-} in the electrolyte participated in the MAO reaction and entered into the coatings. The W content was 1.36 % under ultrasonic addition, which promoted the MAO and increased the content of W. The content of W was increased from 1.14 % to 2.30 % with increasing Na\textsubscript{2}WO\textsubscript{3} concentration.
Table 2. the EDS of surface scanning results under different preparation conditions

<table>
<thead>
<tr>
<th>No.</th>
<th>O (At%)</th>
<th>Mg (At%)</th>
<th>Al (At%)</th>
<th>Si (At%)</th>
<th>W (At%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlMgSi-1</td>
<td>30.97</td>
<td>0.31</td>
<td>61.79</td>
<td>6.93</td>
<td>0</td>
</tr>
<tr>
<td>AlMgSi-2</td>
<td>30.59</td>
<td>0.16</td>
<td>60.92</td>
<td>6.71</td>
<td>1.14</td>
</tr>
<tr>
<td>AlMgSi-3</td>
<td>31.89</td>
<td>0.52</td>
<td>58.10</td>
<td>7.55</td>
<td>1.36</td>
</tr>
<tr>
<td>AlMgSi-4</td>
<td>30.48</td>
<td>0.43</td>
<td>56.57</td>
<td>10.55</td>
<td>1.65</td>
</tr>
<tr>
<td>AlMgSi-5</td>
<td>32.87</td>
<td>0.30</td>
<td>54.52</td>
<td>9.89</td>
<td>1.91</td>
</tr>
<tr>
<td>AlMgSi-6</td>
<td>31.66</td>
<td>0.29</td>
<td>57.09</td>
<td>8.16</td>
<td>2.30</td>
</tr>
</tbody>
</table>

3.4 XRD

The XRD patterns of the coatings obtained under different preparation conditions are shown in Figure 3. The coatings consisted of $\gamma$-$\text{Al}_2\text{O}_3$, $\alpha$-$\text{Al}_2\text{O}_3$, and WO$_3$. X-rays penetrated the coatings because they were thin. $\gamma$-$\text{Al}_2\text{O}_3$ appeared in the XRD diffraction peak at AlMgSi-2, illustrating that Na$_2$WO$_3$ increased the thickness of the coatings. The $\gamma$-$\text{Al}_2\text{O}_3$ peak value of XRD was further increased at AlMgSi-3, and ultrasound promoted the MAO reaction, as discussed in section 3.9. The peak intensities of $\gamma$-$\text{Al}_2\text{O}_3$ and WO$_3$ gradually increased with increasing Na$_2$WO$_3$ concentration which illustrated the WO$_4^{2-}$ participated in the formation of the MAO coating[21]. A trace of $\alpha$-$\text{Al}_2\text{O}_3$ appeared on the coatings. The diffraction peak of WO$_3$ coincided with the diffraction peak of Al$_2$O$_3$ [22], and the peak intensity gradually increased, indicating that WO$_3$ entered the coatings during the MAO process. However, the peak intensity of WO$_3$ at 23.966° was lower due to the low content of WO$_3$ given that the highest content was 2.30 % in the EDS analysis. Na$_2$WO$_3$ was separated into Na$^+$ and WO$_4^{2-}$ in the electrolyte, and a chemical reaction was carried out during the process: 2WO$_4^{2-}$ −4 e$^-$ =2WO$_3$ +O$_2$↑. WO$_3$ was obtained by the MAO treatment.

![Figure 3](image-url)  

**Figure 3.** XRD of the coatings prepared under different ultrasonic power and concentration: (1) AlMgSi-1; (2) AlMgSi-2; (3) AlMgSi-3; (4) AlMgSi-4; (5) AlMgSi-5; (6) AlMgSi-6.

3.5 XPS

XPS analysis was conducted to determine the valence and chemical composition of the coatings (Figure 4). A core-level binding energy of 285.0 eV for electrolyte Cls was used as reference to explain
the results. The wide-scanning results show that the coatings were composed of Al(2p), O(1s), Si(2p), and W(4f) (Figure 4a); this finding is consistent with the results of XRD and EDS analyses. The core-level binding energy of Al(2p) is depicted in Figure 4b. The peak at binding energy of 70.7 eV, corresponds to Al-O bonds in Al₂O₃ [23]. The O(1s) core-level binding energy is depicted in Figure 4c, which is represented by two distinct peaks. Peak A at binding energy of 529.2 eV corresponds to Al-O bonds in Al₂O₃ [24], Si-O bonds and W-O bonds. Peak B, at binding energy of 528.2 eV corresponds to oxygen in O–H groups [25, 26]. The peak at binding energy of 32.68 eV corresponds to W-O bonds in WO₃. Peak B at binding energy of 34.69 eV corresponds to some non-stoichiometric tungsten oxides WₓOᵧ [27]. W tended to appear primarily in the outer and inner regions of the coating, and originated from the electrophoresis and diffusion of the electrolyte solution through the pores in the coatings. These experimental results were in good agreement with the XRD analysis.

![Figure 4. XPS of the coatings at AlMgSi-5 (a) Wide (b) Al(2p) (c) O(1s) (d) Si(2p) (f) W(4f)](image)

3.6 Roughness

The surface roughness of the coatings obtained under different preparation conditions are shown in Figure 5. The surface roughness decreased from 1.34μm to 1.25μm at 1 g/L Na₂WO₃. The SEM results show the coatings had smooth area after the addition of Na₂WO₃. After ultrasonic treatment at AlMgSi-3, the roughness was increased to 2.00μm, because the stack increased. With increasing Na₂WO₃ concentration, the roughness of the coatings decreased from 2.00μm to 1.67μm. The content of Na₂WO₃ increased, and a smooth region appeared on the surface of the coatings, which reduced the roughness.

3.7 Corrosion property

The anticorrosive performance of the coatings is shown in Figure 6 and Table 3. The corrosion current density was reduced from 32.59μA/cm² to 1.88μA/cm² after MAO treatment. Because of the
The effect of ultrasonic wave, the loose layer was removed and the dense layer was more compact, the polarization resistance of ultrasonic MAO coatings were better than that of single MAO coatings[28].

**Figure 5.** Roughness of the coatings under different preparation conditions (1) AlMgSi-1; (2) AlMgSi-2; (3) AlMgSi-3; (4) AlMgSi-4; (5) AlMgSi-5; (6) AlMgSi-6;

The treatment improved the polarization resistance of the AlMgSi. The corrosion current density of the MAO coatings was improved to 1.70μA/cm² by Na₂WO₃, indicating Na₂WO₃ improved the anticorrosive performance. The increase in the coating thickness and γ-Al₂O₃ content improved the anticorrosive performance. With increasing Na₂WO₃ concentration, the corrosion current density gradually decreased from 2.50μA/cm² to 0.29μA/cm². Under the effect of ultrasonic vibration, the content of WO₃ on the coatings was increased, which improved the polarization resistance. The anticorrosive property of the ceramic coatings was decided by microstructure and chemical composition, etc.[10]. The ultrasonic was improved the SEM and EDS as shown in Figure 2 and table 2. The increase in the Al₂O₃ content improved the polarization resistance of the coatings. The thickness of the coatings was increased, leading to difficulty of the corrosion solution in penetrating the coatings. However, the corrosion current density was increased to 0.41μA/cm² at AlMgSi-6, the concentration of Na₂WO₃ was too high, which influenced the SEM morphology (Figure 1f).

**Table 3.** Corrosion potential, corrosion current density and polarization resistance of the coatings tested in 3.5% NaCl solution

<table>
<thead>
<tr>
<th>NO.</th>
<th>Corrosion potential (V)</th>
<th>Corrosion current density (μA/cm²)</th>
<th>Polarization resistance (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlMgSi-1</td>
<td>-0.598</td>
<td>1.88</td>
<td>21798.9</td>
</tr>
<tr>
<td>AlMgSi-2</td>
<td>-0.384</td>
<td>1.70</td>
<td>30816.3</td>
</tr>
<tr>
<td>AlMgSi-3</td>
<td>-0.238</td>
<td>2.50</td>
<td>17376.5</td>
</tr>
<tr>
<td>AlMgSi-4</td>
<td>-0.128</td>
<td>0.22</td>
<td>210612.6</td>
</tr>
<tr>
<td>AlMgSi-5</td>
<td>-0.195</td>
<td>0.29</td>
<td>127665.1</td>
</tr>
<tr>
<td>AlMgSi-6</td>
<td>-0.110</td>
<td>0.41</td>
<td>75119.5</td>
</tr>
<tr>
<td>AlMgSi</td>
<td>-0.871</td>
<td>32.59</td>
<td>1298.8</td>
</tr>
</tbody>
</table>
Figure 6. Potentiodynamic polarization curves of the coatings tested in 3.5% NaCl solution (1) AlMgSi-1; (2) AlMgSi-2; (3) AlMgSi-3; (4) AlMgSi-4; (5) AlMgSi-5; (6) AlMgSi-6.

3.8 Hardness

Hardness of the coatings prepared under different conditions are shown in Figure 7. The hardness of 6063 aluminum alloy substrate is 83 HV [29] and improved by MAO. Na$_2$WO$_3$ increased the hardness of the coatings from 1025 HV to 1097 HV. The element W entered the coatings and generated WO$_3$, similar to the XRD results, thereby improving the hardness of the coatings. Na$_2$WO$_3$ changed the conductivity of the electrolyte (Table 1). More energy was applied to the growth of the coatings, and the Al$_2$O$_3$ content in the coatings increased, which increased the hardness of the coatings.

Figure 7. Hardness of the coatings prepared under different conditions (1) AlMgSi-1; (2) AlMgSi-2; (3) AlMgSi-3; (4) AlMgSi-4; (5) AlMgSi-5; (6) AlMgSi-6;

Ultrasonic-enhanced MAO increased the hardness of the coatings from 1097 HV to 1140 HV. Ultrasonic vibration promoted the cold quenching of the electrolyte, and the aluminum content in the coatings increased, leading to increased hardness. Under the action of ultrasound, the hardness of the coatings gradually increased to 1465 HV with increasing Na$_2$WO$_3$ concentration; the concentration of
Na$_2$WO$_3$, the content of WO$_3$ in the coatings and the content of γ-Al$_2$O$_3$ increased, thereby increasing the hardness of the coatings. Compared with the CeO$_2$ nano-particles doped in MAO coatings[19], the WO$_3$ was doped into the coatings and produced the WO$_3$/Al$_2$O$_3$ composite coatings, which improved the hardness of the coatings.

3.9 Mechanism of ultrasound enhanced MAO

A laser displacement sensor was used to measure the high-frequency vibration generated by ultrasound and clarify its role in the MAO process. Measurement of ultrasonic vibration under different ultrasound power are shown in Figure 8. As the ultrasonic power was increased, the vibration amplitude of the electrolyte increased, and the peak value caused by ultrasonic waves in the displacement curve increased. The displacement fluctuation was small, with an amplitude of 5μm without applying ultrasound. When the ultrasonic power was 100W, a sharp peak of vibration appeared on the displacement curve. The peak value was 20μm, and it was accompanied by low-frequency vibration. With increasing ultrasonic power, the amplitude of the high-frequency vibration spike increased. The amplitude increased from 45μm at 300W to 144μm at 700W with increasing low-frequency displacement amplitude.

![Figure 8. Measurement of ultrasonic vibration under different ultrasound power (a) 0 W, (b) 100 W, (c) 300 W, (d) 500 W, (e) 700 W](image)

The introduction of ultrasound into the MAO process increased the high-frequency vibration process of the electrolyte, and the vibration frequency was 10 kHz. During the MAO process, electrolyte ions, such as SiO$_3^{2-}$, OH$^-$, and WO$_3^{2-}$, migrated to the anode at the $V_1$ speed under the action of the stirring pump and electric field[30]. The reaction occurred at the end of the workpiece, and spark discharge was carried out. After applying ultrasound, the spark discharge time during MAO was about 1μs[31], and the single wave time of ultrasonic vibration was about 1μs, which effectively promoted the movement of the electrolyte[32]. SiO$_3^{2-}$, OH$^-$, and WO$_3^{2-}$ obtained velocity $V_2$ under ultrasonic vibration, and the velocity toward the anode was $V_1$+$V_2$. Meanwhile, the vibration generated by ultrasonic
treatment on the workpiece was $V_3$, and the total relative velocity was $V_1+V_2+V_3$. The vibration caused the electrolyte to move rapidly to the spark discharge area. The number of ions participating in the MAO discharge per unit time increased, which effectively promoted the spark discharge and improved the microstructure and macroscopic performance of the coatings.

4. CONCLUSIONS

WO$_3$/Al$_2$O$_3$ composite ceramic coatings were prepared under ultrasound-enhanced MAO. The corrosion performance, hardness of the substrate was improved. The major conclusions are as follows:

1. The diameter of micro pores on the surface of coatings decreased with increasing Na$_2$WO$_3$ concentration. Meanwhile, the roughness decreased from 2.00$\mu$m to 1.67$\mu$m, and the coating thickness increased from 28.1$\mu$m to 39.3$\mu$m.

2. The coatings consisted of $\gamma$-Al$_2$O$_3$, $\alpha$-Al$_2$O$_3$, and WO$_3$. The intensities of the peaks of $\gamma$-Al$_2$O$_3$ and WO$_3$ increased with increasing Na$_2$WO$_3$ concentration.

3. The corrosion current density was reduced from 32.59$\mu$A/cm$^2$ to 0.29$\mu$A/cm$^2$, and the hardness increased from 1025 HV to 1465 HV. The corrosion and hardness of the substrate was improved by ultrasound enhanced MAO and Na$_2$WO$_3$, providing a new way for expanding the applications of MAO technology in corrosive environments.

4. The vibration amplitude of the electrolyte increased to 140$\mu$m at 700W, and the ultrasound-enhanced MAO produced a high-frequency oscillation effect on the electrolyte, which promoted spark discharge and changing the microstructure of the coatings.

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No potential conflict of interest was reported by the authors.

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