EFFECT OF HEAT TREATMENT ON THE MICROSTRUCTURE AND PERFORMANCE OF HIGH-VELOCITY AIR-FUEL SPRAYED WC-10Co4Cr COATINGS

VPLIV TOPLOTNE OBDELAVE NA MIKROSTRUKTuro IN LASTnostI WC-10Co4Cr PREVLEK, IZDELANIH Z ZELO HITRIM NAPRŠEVANJEM V PLINSKI ATMOSFERI MEŠANICE PROPANA IN ZRAKA

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In this study a high-velocity air-fuel (HVAF) flame-sprayed WC-10Co4Cr coating was heat-treated at (240; 300; 400) °C for 2 h in an air atmosphere. The effect of the heat treatment on the hardness, fracture toughness, wear resistance, corrosion resistance, phase composition and microstructure behaviour of the coatings was investigated. It could be concluded from the X-ray diffraction (XRD) pattern that the phase of the coatings was mainly composed of tungsten carbide, an amorphous phase, a small amount of W,C and trace metal tungsten. However, the heat-treated coating had a small increase in W,C compared to the original coating, although the amount of amorphous phase did not decrease significantly. Results indicated that as the heat-treatment temperature increased, the hardness of the coating first increased and then decreased, while the fracture toughness increased. The polarization test confirmed that the heat-treated coating had higher corrosion resistance than the original coating. In addition, the results of the reciprocating friction and wear test indicated that small amounts of W,C strengthening phases were formed in the WC-10Co4Cr coating after heat treatment at 400 °C. This process did not eliminate many of the tougher Co and WC phases. Therefore, this coating had the best wear resistance among all the comparative coatings.

Keywords: heat treatment, WC-10Co4Cr coatings, abrasion resistance, corrosion resistance.

1 INTRODUCTION

WC-Co coatings are widely applied as wear-resistant layers for a variety of applications due to their excellent wear resistance; such applications include the metalurgy, energy and other industries.1–7 Higher particle velocities were achieved through the HVAF spray process at lower particle temperatures.8 High particle velocities have interesting possible applications in various processes, because they have a positive effect on the coating density and increased lamellar cohesion, and high particle temperatures are generally avoided due to increases in the carbon loss with increasing temperature and the formation of brittle structures in the coating.9–13 However, W2C phases and other amorphous phases could inevitably be exhibited in the sprayed coatings because decarburization would be generated by WC during spraying.14 The generation of these phases decreased the mechanical properties of the WC-Co coatings, limiting their applications.15 Some researchers have found that a heat treatment could significantly improve the hardness and wear performance of WC-Co coatings coupled with a transformation in the phase composition.16,17 Nerz et al.18 reported that when WC-12Co coatings were treated at 875 °C for 1 h under argon gas, they recrystallized the matrix phase to form Co3W,C and Co2W6C carbides. The wear resistance of HVOF-sprayed WC-12Co coatings was increased after 5 min of heat treatment at 900 °C as a result of the formation of new carbide phases. Sohi et al.19 also observed a similar phenomenon. Li et al.20 re-
ported that the complex carbide Co₆W₆C was transformed through crystallization of the amorphous phase at 600 °C for 6 h. In general, the composition and phase of the coatings led to a change in the mechanical properties, which mainly affected the wear resistance of the heat-treated coatings. When the heat treatment temperature was over 450 °C, in a previous study of WC-Co coatings, the coating began to appear as a new oxide phase, CoWO₄. A new phase formed in the coating after heat treatment at temperatures higher than 550 °C. WC and Co were oxidized into new phases, such as CoWO₄, C₂CoO₄, WO₃, and C₆W₆O₁₆. As the temperature increased, the amount of WC, which gradually decreased in the coating, transformed into these new brittle structures, and the brittle phase was harmful.

Nitesh Vashishtha et al. used steel as a coating carrier that could withstand a high heat-treatment temperature. The temperature of a 2A12 aluminium alloy became too high at approximately 530 °C, and the heat-treatment range of the substrate was limited, so this alloy is only suitable for heat treatment at lower temperatures. There have been many studies on the heat-treatment temperature of WC-Co coatings higher than 500 °C and relatively few studies at temperatures lower than 500 °C. However, there have been fewer studies on the heat treatment of WC-Co-Cr coatings, and there are almost no data on the microstructure, mechanical properties, wear and corrosion behaviour of the coatings after low-temperature heat treatment. The properties of the WC-Co and WC-Co-Cr powders are relatively similar. Therefore, the 2A12 aluminium alloy was selected as the substrate and WC-10Co₄Cr as the coating to study the effect of heat treatment on the overall performance of the coating. The purpose of this paper is to study the effect of a low-temperature heat treatment on the microstructure, mechanical properties, wear and corrosion behaviour of WC-10Co₄Cr coatings.

2 EXPERIMENTAL PART

2.1 Materials and Thermal spray

In the experiment, a commercial thermal spray powder (WC-10Co₄Cr) was selected as the spray material. The base material was 2A12 aluminium alloy, which was machined in a plate sample with a size of 100 mm × 80 mm × 10 mm. Before spraying the sample, the sprayed surface was sandblasted (coarsened) with 16# brown corundum. After sandblasting, the surface of the substrate, which was blown with compressed air, was decontaminated with acetone and ethanol. A Kermetico AK HVAF supersonic flame-spraying system was used for the test. Propane was used as fuel, air was used as the oxidant, and nitrogen was used as the powder feeding gas. The spraying parameters of the AK-07 spray gun are shown in Table 1. Compressed air was used simultaneously to cool the back of the aluminium alloy substrate. After many tests and comparisons, it was proven that a spraying distance of between 180 mm and 300 mm was a more appropriate spraying distance. In this paper, 200 mm was selected as the spray distance for subsequent research on the performance of the coating. Finally, the sprayed sample sheet was cut into a square with a size of 10 mm × 10 mm × 10 mm for subsequent tests.

Table 1: Thermal spraying parameters employed during deposition of the WC-10Co₄Cr coatings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Fuels</td>
<td>Propane</td>
</tr>
<tr>
<td>Nozzle</td>
<td>AK-07</td>
</tr>
<tr>
<td>Spray distance (mm)</td>
<td>200</td>
</tr>
<tr>
<td>Powder feed rate (min⁻¹)</td>
<td>4</td>
</tr>
<tr>
<td>Nitrogen carrier gas (kPa)</td>
<td>172.3</td>
</tr>
<tr>
<td>Air pressure (kPa)</td>
<td>627.4</td>
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</tr>
<tr>
<td>Porosity of the coatings</td>
<td>0.95 %</td>
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2.2 Heat treatment

The square sample was subjected to heat-treatment tests at different temperatures, and the heating equipment was a Nabertherm P300 box-type resistance furnace. The resistance furnace was equipped with a temperature-regulating device, and the temperature-error range was no more than 3 °C. The samples were placed in a resistance furnace with test temperatures of (240; 300; 400) °C for 2 h and then air-cooled to room temperature.

2.3 Material characterization

Scanning electron microscopy (SEM: SU5000, Japan) was used to characterize the powder morphology, the top surface of the coating, the cross-section and the wear trajectory. The samples were polished first with P400, P800 and P2000 silicon carbide sandpaper and then with diamond suspensions of 2.5 μm and 1 μm. The microhardness of the cross-section of the coating was measured using a Vickers microhardness tester (VMH-002VM, Germany). The average value of 10 indentation tests was obtained on the cross-section of the coating polishing, in which the load was 2.94 N and the pressure holding time was 15 s. The indentation method was used in combination with the Evans & Wilshaw formula to calculate the fracture toughness of the coating. The equipment used was a VMH-002VM Vickers microhardness tester. The indenter was a diamond Vickers indenter, and the load was 19.61 N. The average value of 10 indentation cracks for each coating was measured to calculate the crack length from the centre of the indent (μm).

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\[ K_c = 0.079 \left( \frac{P}{a} \right)^{3/2} \log \left( \frac{45a}{c} \right) \]  

where \( P \) is the applied indentation load (mN), \( a \) is the indentation half diagonal (μm), and \( c \) is the crack length from the centre of the indent (μm).
In the WC-Co-Cr coating material, the crack prepared by the indentation method satisfied $0.6 < c/a < 4.5$ ($c$ was the length from the centre of the indentation to the end of the crack, and $2a$ was the length of the diagonal length of the indentation). The load was maintained at 19.61 N for 15 s. The phase composition of the sprayed powder and coating was analysed by XRD (Rigaku, Japan), a copper cathode was used ($\lambda = 0.15406 \text{ nm}$), the scanning angle was $10^\circ < 2\theta < 90^\circ$, and the step size was 0.01°. Finally, JADE software was used to analyse the phase of the diffraction peak.

An MFT-4000 multifunctional material surface performance tester was used to test the wear on the polished coating surface. The indenter was made of SiC, the friction length was 5 mm, the friction speed was 50 mm/min, the load was 50 N and 70 N, and the abrasion of the coating was tested by scratch friction with a load of 70 N.

All the measurements were carried out at $(25 \pm 1) ^\circ C$ in a water bath using a CHI660e electrochemical workstation. The electrochemical test involved a three-electrode system. The samples were used as the working electrode, a saturated calomel electrode (SCE) was used as the reference electrode, and a platinum counter electrode was also used. Before the test, the samples were polished and cleaned. The surface of the samples was washed with deionized water and then cleaned with an acetone alcohol solution. The noncoated surface was coated with epoxy resin adhesive to prevent the corrosion solution from infiltrating, exposing the working surface (coated surface), which had an area of 100 mm². The samples were immersed in a 3.5 w/% NaCl acetic acid solution with $\text{pH} = 3$ for 60 min until the open-circuit potentials (OCPs) became almost stable. Potentiodynamic polarization tests were conducted at a scan rate of 10 mVs⁻¹ from $-500 \text{ mV} \text{ vs. OCP}$ to $2 \text{ V} \text{ vs. OCP}$. Electrochemical impedance spectroscopy (EIS) tests were performed at the OCPs in the frequency range from 100 kHz to 10 mHz. The data were analysed with ZSimWin software.

3 RESULTS AND DISCUSSION

3.1 Structure of the powders and coatings

WC-10Co4Cr is an agglomerated and sintered powder with a common micron structure. Scanning electron microscopy (SEM) images of the sprayed powder are shown in Figure 1. The morphology of the sprayed powder is regular spherical particles with a size of approximately 5–45 μm. It can be seen that the powder is loose and porous. This structure enables it to fully melt during the spraying process. The spray particles were not blown away due to their small size.

Figure 2 shows that the phase structures of the micron- and submicron-coatings were prepared by the WC-10Co4Cr thermal spray powder in this experiment. It can be seen from the XRD spectra that the powder and coatings have similar characteristic peaks, specifically those of WC, W₂C, Co, and Cr, but the intensities of the peaks are different. The characteristic Co and Cr peaks of the coatings are broad to different degrees than the powder. During the spraying process, the metallic phase can first dissolve a certain amount of W and C. After being sprayed on the surface, the metallic phase cools quickly and becomes amorphous.

The heat treatment of WC-12Co4Cr coatings was conducted in an air atmosphere. The powder and coating composition were tested by XRD (Figure 2). A diffraction peak was observed at 40° to 45°, where W₂C, W and amorphous phases were all present. Coating A was the unheated coating, coating B was heat treated at 240 °C, coating C was heat treated at 300 °C, and coating D was heat treated at 400 °C. There was no significant change in the XRD results of coatings A and C, except that a small amount of the W₂C phase increased after heat treatment at 240 °C and 400 °C.

SEM images of the WC-10Co4Cr coating heat treatment are shown in Figure 3. These SEM images show
the uniform distribution of WC within the ductile Co and Cr matrix. The SEM images also show that WC particles have block-like and angular shapes; these shapes are shown in Figure 3b (not specified in Figure 3b, 3f and 3h). Because the three heat-treatment temperatures were relatively low, there was no significant change in the size of the WC. Figure 3i shows the WC-10Co4Cr coating after heat treatment at 400 °C, indicating that the coating did not oxidize during the heat treatment. The energy spectra of the other coatings were similar, so they are not shown in this Figure 3i.

Figure 3 shows that the microstructure of the coating is homogeneous and dense, with a few pores, but no cracks are found. Table 1 shows the results of porosity tests on the coating. The pores in five cross-sectional pictures of the coating were counted and calculated with related software. The porosity of the coating is the ratio of the black pore area to the entire area. The calculated results show that the porosity of the coating was approximately 0.95 %. HVAF technology has a low flame temperature, high particle-flight speed, and short residence time in the flame (oxidizing atmosphere). The porosity of the coating was reduced.

The cross-sectional microstructure of the coating in Figure 3 shows that the white block WC was distributed in the grey binder, and the local binder dissolved into more W and C, resulting in a brighter colour, as shown in the box in Figure 3d, while those in Figure 3b, 3f and 3h are not shown. The coatings keep the original WC particle size of the powder. Some WC particles in the coating hit the substrate and were embedded in the surrounding binder phase. Some of the micropores in the coating were distributed around the larger WC particles with a polygonal structure, as shown in the circle in Figure 3f, while others were distributed around the WC particles that were broken by the impact.24,25 It is considered that the fragmentation of WC particles during spraying may have been caused by the low melting point of the binder phase and the weakness of the particles.

3.2 Effect of heat treatment on coatings’ hardness and fracture toughness

Figure 4a shows the microhardness of the coating. When the heat-treatment temperature was increased to 240 °C, the hardness increased. The hardness decreased at 300 °C. It starts to increase again at 400 °C. However, the hardness of all the coatings changed slightly, and the range of the change was within 10 %. The hardness of the intermediate coating was higher for the same coating, and the hardness of the coating at the interface with the substrate was slightly higher than that of the surface coating. It was higher because the porosity of the interface and intermediate coatings was low, and the degree of crushed WC particles in the intermediate coating was low. The diffraction peak appeared at 2θ = 38° for coatings B and D but not for coatings A and C. Coatings B and D were slightly harder than coatings A and C because a small amount of the W2C phase is beneficial for increasing the hardness. Many researchers have also reported that the microhardness of WC coatings can reach above 1000 HV.26–28 The fracture toughness of the coating is shown in Figure 4b. Compared with coating A, coatings B, C and D show greater fracture toughness. The fracture toughness of the WC-10Co4Cr coatings was similar after heat treatment at 240 °C and 300 °C, and the maximum fracture toughness was at 400 °C. The fracture toughness of the coatings decreased because more brittle carbide phases formed in the coating after high-temperature heat treatment. The fracture toughness in this paper was measured using coatings that were heat treated at low temperature. The trends in change were slightly different from those observed by...
earlier researchers. The change in fracture toughness is related to the change in residual stress caused by heat treatment and the mismatch of the thermal expansion coefficient between the coating and the substrate. During heat treatment at (240; 300; 400) °C, the heat-treatment temperature increased and the residual stress decreased. The thermal expansion coefficients of the coating and the substrate were better matched, and the WC phases and the adhesive further merged, possibly due to the increase in the fracture toughness.

3.3 Coefficient of friction and abrasive loss of the coatings

Figure 5a shows the relationship between the coefficient of friction (COF) and the heat treatment temperature of the coating. When the load was 50 N, the COF of coating A was 0.142. The COF of coatings B, C and D were 0.128, 0.133, and 0.125, respectively. The results show that the wear rate of the coating after heat treatment was lower than that of the original coating. The coating material had the best wear resistance after heat treatment at 400 °C. The COF showed a downwards trend, and the value dropped by 6–12 % as the heat treatment temperature was increased to 400 °C, but it fluctuated slightly at 300 °C. The COF of all the coatings increased with increasing load when the load was 70 N. However, the overall trend was the same, and the COF showed a downwards trend as the heat treatment temperature was increased. When the heat treatment temperature was 300 °C, the COF of the coating differed by approximately 35 %. These differences were mainly related to the hardness of the coating and the additional load. The adhesion due to surface roughness and ploughing play an important role in the change in the COF. With reciprocating movement, the friction increased with increasing load, which caused some particles in the coating to peel off, leading to a higher friction coefficient. Figure 5b shows that the wear of the coatings varied with the heat treatment temperature at an initial load of 70 N. The wear of the coating is similar to the trend in the COF. The overall trend is downwards, and there is a slight fluctuation at 300 °C. After heat treatment, the

Figure 4: a) Microhardness, b) indentation fracture toughness of as-sprayed and heat-treated WC-10Co4Cr coatings

Figure 5: a) Coefficient-of-friction response at loads of 50 N and 70 N, b) coefficient-of-abrasion loss at a load of 70 N
Wear of the coating was approximately 8–15% lower than that of the coating without heat treatment.

The wear mechanisms were investigated using the SEM images, as shown in Figure 6a to 6d. The worn-out surfaces of the A, B, C and D coatings at a load of 70 N are shown. The brighter areas in the image of coating A are the WC-rich areas, while the darker areas are the cobalt-rich bonding phases that are preferred for wear. During the wear process, the reciprocating friction of the indenter gradually exposes the carbide particles in the coating until they become particles that are completely separated from the adhesive.

Under a load of 50 N, the frictional force of coating A, beginning at the initial stage of wear, shows a downwards trend with time. The friction force is reduced by approximately 25% due to the instability of the transition layer (20 μm away from the coating surface). When the critical sliding distance is reached, the friction stabilizes. Because Co serves as a good binder between the WC particles, the coating stability is further maintained after the critical sliding distance is reached (a certain friction time). The wear mechanisms of coatings B, C

Figure 6: SEM images of the worn-out surfaces at a load of 70 N of the: a) coating A, b) coating B, c) coating C, d) coating D

Figure 7: Force friction response at loads of 50 N and 70 N under different heat treatments: a) room temperature, b) 240 °C, c) 300 °C, d) 400 °C
and D are similar to that of coating A. Under a load of 70 N, the friction first increases, then decreases and finally becomes stable. While the frictional force of coating A increases initially, later it shows a decreasing trend and subsequently stabilizes after sliding some distance. After heat treatment, the critical sliding distance of the coating is relatively short. As shown in Figure 7, during the heat treatments at 240 °C and 400 °C, the increasing load of the coatings has little effect on the variation trend of friction force. However, the friction of coatings A and C has obvious fluctuations when the load is increased. Under a load of 70 N, coating A has more wear than the other coatings because the binder of the unheated coating is relatively easy to break, which causes carbide particles to fall off the surface of the coating. The hard carbide particles that fall off the surface of coating A serve as excess abrasive media, which further wears down the coating. Another cause of high wear may be the peeling of the unstable transition layer of the coating. As the sliding distance increases, the reason for the final stability is that the high temperature due to sliding forms a friction oxide layer, which prevents further wear. Compared with the 50-N load, the critical sliding distance is increased due to the higher load. The wear of coatings A and C is higher than that of coatings B and D. Because coatings B and D have relatively few carbide particles peeled off, the wear of these coatings is also relatively lower. After the surface materials of the coating are removed, the oxides formed by WC, Co, and Cr after abrasion and the harder part of the intermediate coating make the later wear of the coating stable.

3.4 Corrosion properties of the coatings

The potentiodynamic polarization curves for the coatings in 3.5 w%/NaCl acetic acid solution with pH = 3 are presented in Figure 8. The polarization curve of the coatings shows exponential growth with increasing potential and finally flattens and remains basically unchanged. According to Faraday’s law, when one gram equivalent of metal is dissolved at the anode, the amount of electricity passed is 1 Faraday (1 F = 96500 Coulomb). If the atomic weight of the metal is A, the metal valence is n, and the corrosion current density is \( i_{\text{corr}} \), then Equation (2) can be used to calculate the corrosion rate \( V_{\text{corr}} \) of the coating. To calculate \( V_{\text{corr}} \) the following Equation (2) was used

\[
v_{\text{corr}} = \frac{i_{\text{corr}} \cdot A}{nF}
\]

Using the Tafel extrapolation method, the corrosion potential and corrosion current density of the four coatings were calculated, as shown in Table 2. The self-corrosion potentials \( E_{\text{corr}} \) of the four coatings in solution are sorted from high to low as \( D > B > C > A \); the corrosion rate is \( A > C > B > D \). It can be concluded from the experimental results that coating D has the best corrosion resistance because the WC particles in the coating are more uniformly distributed after heat treatment at 400 °C (Figure 3h), as shown in the red circle. In addition, an oxide passivation film is formed on the coating surface in the solution, which further reduces the chance of a corrosive liquid entering the coating/substrate interface, and at the same time, the oxide passivation film slows down the corrosion of the coating surface.

**Table 2: Results of electrochemical corrosion tests**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Corrosion potential (mV)</th>
<th>Corrosion current density (A/cm²)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>–472</td>
<td>7.8×10⁻⁷</td>
</tr>
<tr>
<td>B</td>
<td>–322</td>
<td>4.9×10⁻⁷</td>
</tr>
<tr>
<td>C</td>
<td>–351</td>
<td>4.7×10⁻⁷</td>
</tr>
<tr>
<td>D</td>
<td>–265</td>
<td>2.2×10⁻⁷</td>
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The Cl⁻ in the solution easily exposes the coating surface to pitting corrosion. Once pitting corrosion occurs, the lamellar coating cracks and peels off, which eventually leads to a gradual increase in weight loss of the coating. Some passivation films soon form on the coating surface in a corrosive environment, and the coating enters the passivation area. The self-corrosion current density is also significantly reduced or no longer greatly increased, and the passivation film formed is also in a dynamic equilibrium in continuous dissolution destruction and regeneration. For coating D, when the potential reaches –265 mV, the polarization curve of the coating begins to enter the anode dissolution zone, and the current density increases with increasing corrosion potential. When the potential rises to 95 mV, the polarization curve of coating D enters passivation. The potential continues to rise to 462 mV, and the current density begins to increase sharply with increasing corrosion potential. Similar phenomena are also observed in coatings A, B and C. Compared with coating A, the corrosion resistance of coatings B, C, and D is improved to different degrees. Because the heat treatment may make the coating...
structure more uniform, the Co and Cr in the bonding phase are more likely to generate oxide films, which prevents further corrosion of the coating by the solution. After the coating is heat treated at three different temperatures, the 400 °C-treated coating has a relatively high self-corrosion potential and low corrosion current density, so it has better corrosion resistance and can better protect the substrate. The coating after heat treatment at 240 °C has a relatively high self-corrosion potential and low corrosion current density, so it has better corrosion resistance and can better protect the substrate. Figure 9 shows the Bode plots of the four coatings in 3.5 w/% NaCl acetic acid solution at pH = 3. The Bode magnitude plots (Figure 9a) present the decreased impedance at low frequency with the increased heat-treatment temperature. However, the impedance at a low frequency after heat treatment at 240 °C is slightly higher than that after heat treatment at 300 °C. In theory, the impedance at low frequency reflects the protectiveness of the coating. The impedance of coating A is < 1200 Ω cm², indicating poor corrosion resistance. Bode phase-angle plots (Figure 9b) display the reduced value of the phase angle with decreased heat-treatment temperature, which also signifies a decreased corrosion resistance. For EIS data simulation, a general equivalent circuit model in Figure 10 is proposed to describe the Bode plots based on related research. The specific meanings of these parameters in the equivalent circuit are as follows: \( R_s \) is the resistance of the solution; \( R_1 \) and \( R_2 \) are the charge-transfer resistances, \( R_1 \) is the resistance of the coatings, and \( R_2 \) is the reaction resistance at the metal/coating interface. \( C_1 \) is the capacitance of the coating, and \( C_2 \) is the capacitance of the double layer. The results of the electrochemical impedance spectroscopy show that the \( R_1 \) and \( R_2 \) values of coating D are the largest, followed by those of coatings B, C and A. Based on the results of electrochemical impedance spectroscopy, it can be inferred that the corrosion resistance of the four coatings is D > B > C > A.

4 CONCLUSIONS

The coatings were heat treated at three different temperatures. The effects of the performance were evaluated through microstructure and corrosion-behaviour analyses. Some conclusions can be drawn.

1) No new substances formed in the WC-10Co4Cr coating after heat treatment at (240; 300; 400) °C for 2 h. However, the content of W2C in the coatings increased slightly after heat treatment at 240 °C and 400 °C, and a small amount of W2C was beneficial for increasing the hardness of the coating.

2) The maximum hardness of the coating after heat treatment at 400 °C was 1143 HV; however, the hardness of all the coatings changed slightly, and the range of change was within 10%. The coating had the best fracture toughness after heat treatment at 400 °C, and its value was 8.08 MPa·m^1/2. The mechanical properties of the coating after heat treatment at 240 °C and 300 °C were similar, and both were better than those of the unheated coating.

3) The wear resistance of the coating after heat treatment at 400 °C was preferably slightly higher than that of the coating after heat treatment at 240 °C, and its value was 0.02237 mm². The friction force of coating A and the unheated coating after heat treatment at 300 °C noticeably fluctuated when the load was increased.

4) Electrochemical tests showed that the corrosion rate of the heated coatings was reduced, and it exhibited higher corrosion resistance than the unheated coatings. Based on the electrochemical tests, in the 3.5 w/% NaCl solution.
Acetic acid solution with pH = 3, the coating after 400 °C treatment had a relatively high self-corrosion potential and low corrosion current density, so it had better corrosion resistance.

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Author Contributions
Conceptualization, Writing Review and Editing, X. Z.; Date curation, Methodology, H. L., J. Z., J. J.; Writing Original Draft, W. Z.; Validation, Z. Z., Q. W.; Investigation, Y. X. All authors have read and agreed to the published version of the manuscript.

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