

Article

Microstructure, Wear Resistance and Corrosion Resistance of FeNiCrMo, FeNiCrMo/WC and FeNiCrMo/WC-17Co Coatings Prepared by Laser Cladding: A Comparative Study

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Abstract

FeNiCrMo austenitic stainless steel has good corrosion resistance but a low surface hardness, which limits its wear resistance under high load. FeNiCrMo, FeNiCrMo with 10 wt.% tungsten carbide (WC) (45–106 μm) and FeNiCrMo with 10 wt.% WC-17Co (15–45 μm) were deposited by laser cladding at 1200 W and 480 mm/min, and their phase composition, microstructure, microhardness, wear behaviour and corrosion resistance were compared. Both particle additions promoted a columnar-to-equiaxed transition and the formation of W_2C . The coarse WC particles dissolved only partially and raised the hardness little, from 473 to 475 $\text{HV}_{0.2}$, while the finer WC-17Co particles dissolved more completely and raised it to 550–600 $\text{HV}_{0.2}$. On the worn surfaces, the ploughing grooves of the unreinforced coating were still present but shallower and narrower, indicating that abrasion was reduced in severity rather than replaced. The particles nevertheless impaired the corrosion resistance, most strongly for WC-17Co. FeNiCrMo/WC gave the best overall result. Its specific wear rate was the lowest of the three coatings, $0.73 \times 10^{-6} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$ at 90 N and roughly an order of magnitude below the unreinforced coating, and its mass loss was the smallest at every load, while its corrosion resistance fell far less than that of FeNiCrMo/WC-17Co, with an E_{corr} of -0.393 V against -0.738 V . The coarse, only partly dissolved WC particles provide the most favourable combination of wear and corrosion resistance and are recommended for FeNiCrMo components operating under high load in only mildly aggressive conditions.

Keywords: laser cladding; FeNiCrMo; microstructure; microhardness; wear resistance; corrosion resistance

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1. Introduction

Laser cladding (LC) is an advanced additive manufacturing method that utilizes a high-energy laser beam as a heat source to accurately melt and deposit co-axially fed

powder materials onto a substrate surface [1–3]. This technology can achieve synchronous control of material and energy during the manufacturing process, offering high forming efficiency and material utilization, making it especially suitable for the manufacture of complex structural parts and the remanufacturing of high-performance components [4–6]. By preserving the original properties of the substrate, laser cladding provides a reliable and efficient means of enhancing the surface properties without compromising its overall integrity or functionality [7,8].

FeNiCrMo is an Fe-based austenitic stainless steel, a high-performance alloy enriched with Ni, Cr, and Mo, which exhibits excellent corrosion resistance, high-temperature strength, and good mechanical properties, and is widely used in marine, chemical, and nuclear industries [9–11]. High-quality repairs can significantly extend the service life of FeNiCrMo components, providing substantial economic benefits and considerable research value.

One of the most promising materials for coatings is based on a ceramic reinforcement phase. Tungsten carbide (WC) powder is a commonly used reinforcing phase in metal matrix composites due to its high hardness, high melting point, good wear resistance, and excellent wetting properties [12,13]. The addition of WC into the FeNiCrMo matrix helps to enhance its microhardness and wear resistance, while potentially decreasing its corrosion resistance [14–16].

Adding micron-sized WC particles into the FeNiCrMo alloy can significantly improve the hardness and wear resistance of the material. However, it may reduce its plasticity (even leading to cracking) and corrosion resistance. Since cobalt (Co) has good compatibility with WC phases, it is usually used as the binder phase for WC, thus forming a composite material with both high hardness and excellent wear resistance [17,18]. Therefore, WC-17Co is often used as a protective coating for wear-resistant components in various industrial fields.

WC-17Co offers a novel approach to material design by effectively balancing strength and toughness, making it particularly suitable for manufacturing critical components subjected to complex loading conditions and harsh environments [19,20]. Furthermore, it demonstrates excellent compatibility with advanced manufacturing techniques such as laser cladding. However, the various properties of adding WC or WC-17Co to FeNiCrMo still need to be continuously explored and compared in order to select a more suitable ceramic reinforcement phase according to the actual service environment. The main purpose of adding micron-sized WC particles or micron-sized WC-17Co particles to FeNiCrMo austenitic stainless steel is to enhance its wear resistance while maintaining its good corrosion resistance, which enables synergistic optimization of properties and expands the application range of FeNiCrMo alloys under high loads and harsh environments. To this end, the present work provides a side-by-side comparison of micron-sized WC (45–106 μm) and finer WC-17Co (15–45 μm) reinforcements with respect to both wear and corrosion performance, and clarifies that the larger WC particles provide the most favourable trade-off between these two critical properties for FeNiCrMo coatings.

2. Experimental Procedure

2.1. Powder Materials

In this study, FeNiCrMo powder (Figure 1a) and WC powder (Figure 1b), both with a particle size range of 45–106 μm , were used, along with WC-17Co powder (Figure 1c) with a particle size range of 15–45 μm . The elemental compositions of the three powders, together with that of the Q235 steel substrate, are presented in Table 1. The FeNiCrMo/WC powder and FeNiCrMo/WC-17Co powder were produced by mechanically mixing these powders. The substrate material is Q235 steel.

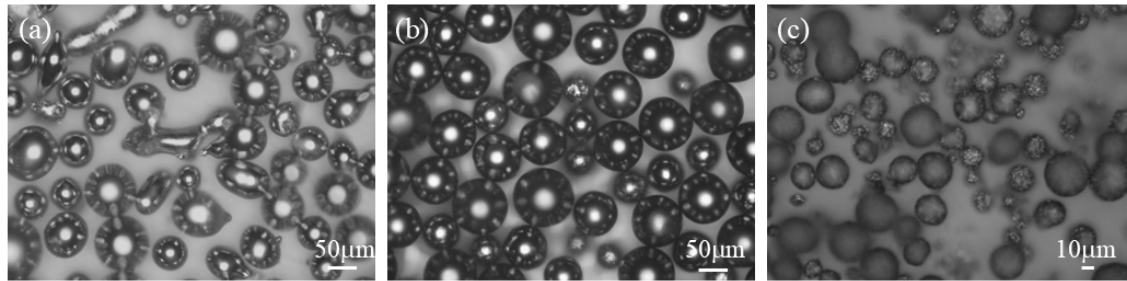


Figure 1. Powder morphologies (a) FeNiCrMo powder, (b) WC powder, (c) WC-17Co powder.

Table 1. Elemental composition of the test powders and of the Q235 steel substrate (wt.%).

Material	C	Si	Fe	B	Mo	W	Cr	Ni	Co	Ct	Cf
FeNiCrMo	0.21	0.91	Bal.	0.91	1.01	-	18.42	2.35	-	-	-
WC	3.95	-	0.2	-	-	95.85	-	-	-	-	-
WC-17Co	-	-	0.015	-	-	Bal.	-	-	17.06	5.04	0.03
Q235	≤0.20	≤0.35	Bal.	-	-	-	-	-	-	-	-

2.2. Laser Cladding Process

The schematic diagram of the LC process is shown in Figure 2. To ensure the formation of a strong metallurgical bond between the coating material and the Q235 steel substrate during the LC process, the substrate surface must be carefully controlled and properly treated. Before the LC process, the metal substrates were cleaned using laser cleaning equipment [21]. Laser cleaning technology employs a high-energy laser beam that acts instantaneously on the material surface, effectively removing adhered oxide scale, oil, and other microscopic impurities, thereby significantly reducing the potential interference of impurities on molten pool formation and microstructural uniformity. The pretreatment process not only reduces the generation of porosity and inclusions during the deposition process, but also effectively inhibits the separation between the coating and the substrate caused by interfacial contamination, thereby ensuring the stability of the melt pool in subsequent deposition.

FeNiCrMo powder, FeNiCrMo/WC powder, and FeNiCrMo/WC-17Co powder were preheated at 80 °C for 2 h in vacuum to reduce the moisture content in the powders. Then, the laser power was set to 1200 W, the scanning speed was set to 480 mm/min, and the hatch spacing was set to 1.6 mm, resulting in a deposition thickness of approximately 0.5 mm. The coating thickness was measured on polished cross-sections of the deposited samples by optical microscopy and further confirmed by SEM observations. For each coating, at least five positions evenly distributed along the deposition direction were measured, and an average thickness of approximately 0.5 mm was obtained for all three coatings.

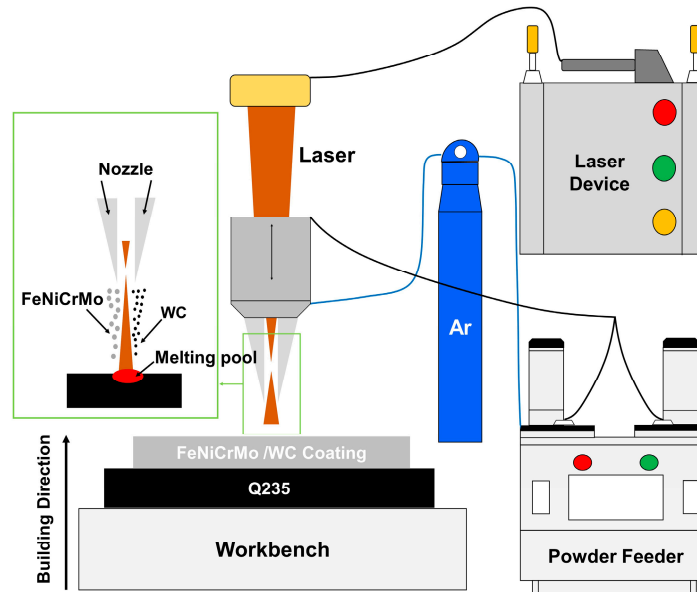


Figure 2. Schematic diagram of laser cladding process.

2.3. XRD Analysis and Microstructural Characterization

The sample was gradually polished on sandpapers with a particle size range from 80 to 2000 mesh until no obvious deep scratches remained on the surface. Subsequently, mechanical polishing was carried out until the surface exhibited uniform brightness. The arithmetic mean surface roughness (R_a) of the polished surfaces of the three coatings, measured by white-light interferometry, was approximately $0.05\ \mu\text{m}$; this polished surface state was used as the starting condition for all subsequent wear and corrosion tests.

The X-ray diffraction (XRD) method was used to analyze the phases of the FeNiCrMo alloy. Cu $K\alpha$ radiation was used at 40 kV and 40 mA. The diffraction patterns were recorded from 10° to 100° in 2θ at a scanning speed of $5^\circ/\text{min}$. The cards for the η -carbides $\text{Co}_3\text{W}_3\text{C}$ (PDF #27-1125) and $\text{Co}_6\text{W}_6\text{C}$ (PDF #23-0939) were also consulted, but no reflection attributable to these phases could be resolved in the present patterns, and they are therefore discussed in Section 3.1 as expected minor phases rather than as indexed ones.

The samples were etched using Kalling's solution (5 g CuCl_2 + 100 mL HCl + 100 mL ethanol) for approximately 20 s. Subsequently, the microstructures were observed by JSM-IT700HR scanning electron microscopy (SEM) (JEOL Ltd., Akishima, Tokyo, Japan).

2.4. Vickers Hardness

A MVH-1000 Vickers hardness tester (MEGA Instruments Co., Ltd., Chengdu, China) was used to perform microhardness tests on the cross-section of the specimen. During the testing process, a load of 200 gf was applied for a holding time of 10 s. Along the deposition direction, starting from the Q235 substrate through the interface to the composite coating area, a data point was measured every $100\ \mu\text{m}$. Hardness values are reported as the mean $\pm$ standard deviation of three measurements. The error bars indicate the standard deviation at each measurement position.

2.5. Friction Behavior and Wear Performance

The wear resistance tests of the coatings are carried out using the ring-on-block sliding wear test method, in which a stationary block is loaded against a rotating ring, in a constant-temperature environment (10°C to 35°C , humidity 45% to 65% RH). GCr15 bearing steel is selected as the counter-body material. Dry friction tests are conducted at a

rotational speed of 200 r/min for 60 min under loads of 90 N, 120 N, and 150 N, respectively, and the friction coefficient curve is recorded in real time; the linear sliding speed of the present tests was not measured directly, so the rotational speed is reported as the controlled kinematic parameter and the comparison with the literature is made in terms of the applied load and the rotational speed rather than of the sliding velocity. For the analysis of the wear morphology, a Keyence VHX-3000 ultra-depth-of-field optical microscope (Keyence Corporation, Osaka, Japan) and a Bruker white light interferometer (with a vertical resolution of 0.1 nm) (Bruker Corporation, Billerica, MA, USA) are used to measure the track profile. The wear mechanism and material transfer phenomena are analyzed using SEM. The wear volume discussed in Section 3.2 is derived from the measured mass loss.

2.6. Corrosion Measurements

The samples were electrically connected from the back and mounted in epoxy resin, exposing only one side to the 3.5 wt% NaCl electrolyte. Potentiodynamic polarization, chronoamperometry (i-t), Mott-Schottky (M-S), electrochemical impedance spectroscopy (EIS), and open-circuit potential (OCP) measurements were performed using an electrochemical workstation, Corrosion Test CS2350 (Wuhan Corrtest Instruments Co., Ltd., Wuhan, China). EIS and Mott-Schottky measurements were conducted at OCP, and all electrode potentials were referenced to the Ag/AgCl reference electrode.

A three-electrode cell configuration was employed with the sample as the working electrode, Ag/AgCl (saturated KCl) as the reference electrode, and platinum as the counter electrode. The exposed test area was 0.3 cm². Prior to electrochemical testing, samples were immersed in the electrolyte for 3000 s until the OCP reached a steady state. The potentiodynamic polarization curve was recorded with initial potential −0.65 V, termination potential 0.85 V, and potential interval 0.5 mV at a scan rate of 2 mV/s. EIS measurements were conducted at the OCP over a frequency range of 100,000 Hz to 0.01 Hz with a 5 mV sinusoidal perturbation and ten points per decade. The Mott-Schottky measurement frequency was 1000 Hz, AC amplitude 10 mV, initial potential −1 V, termination potential 1.5 V, and potential increment 0.01 V. Chronoamperometry was set with initial potential 0.5 V, high potential 1 V, low potential −0.8 V, pulse width 800 s, and sampling frequency 100 Hz. All measurements were repeated at least three times to ensure reproducibility, and EIS spectra were fitted using Zview software 3.0a.

3. Results and Discussion

3.1. Phase Composition and Microstructure

Figure 3 presents the XRD patterns of the three composite coatings. The XRD patterns of FeNiCrMo coating fabricated by the LC process mainly show the γ -Fe phase with a face-centered cubic structure, which reflects good phase stability and solid solution strengthening characteristics. After the addition of micron-sized WC powder with a particle size range of 45–106 μm , in addition to maintaining the γ -Fe matrix phase, the XRD results reveal the formation of hard carbide phases such as W_2C . After adding WC-17Co powder with a particle size range of 15–45 μm , only a small amount of WC could be detected in the sample through XRD patterns, indicating that most of the WC-17Co particles had dissolved into the FeNiCrMo matrix.

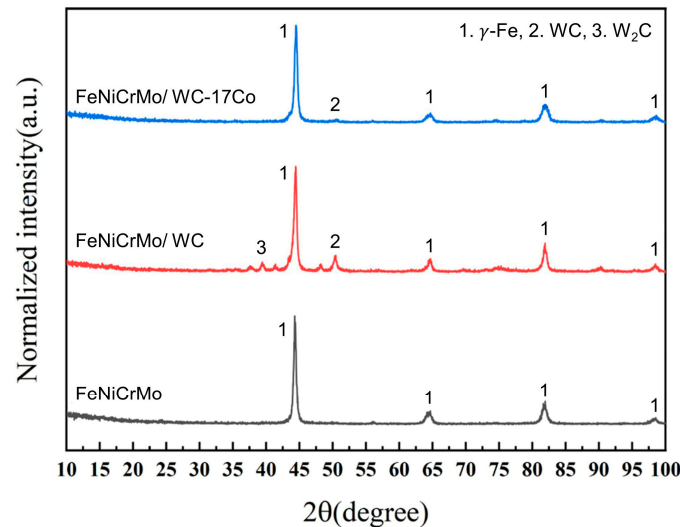


Figure 3. XRD patterns of the three coatings over the 2θ range of $10\text{--}100^\circ$. Peaks labelled 1, 2 and 3 correspond to γ -Fe (PDF #33-0397), WC (PDF #25-1047) and W_2C (PDF #35-0776), respectively.

The microstructures of the three composite coatings are presented in Figure 4. As shown in Figure 4(a1,a2), the FeNiCrMo coating primarily consists of uniformly distributed cellular crystals. In addition, columnar crystals are observed, arranged directionally in elongated strip-like morphologies. The presence of cellular crystals suggests that during solidification, crystal growth follows a “cellular $\rightarrow$ columnar” sequence, indicating a distinct directional solidification behavior in the microstructure.

As can be seen from Figure 4(b1,b2), micron-sized WC particles can be observed in the FeNiCrMo/WC coating [22]. These WC particles have regular morphologies and clear boundaries. In addition to cellular crystals in the matrix, equiaxed crystals also appear, indicating that the introduction of WC particles has changed the crystal growth mode. Columnar crystals are still present, but the microstructure becomes more fragmented due to the presence of WC particles, and the directionality of crystal growth is weakened. Elemental diffusion occurs in the interface region between the WC particles and the matrix. Decarburization of WC occurs at the interface, resulting in the formation of W_2C , which further affects the uniformity of the microstructure.

As can be seen from Figure 4(c1,c2), the microstructure of the FeNiCrMo/WC-17Co coating is mainly composed of cellular crystals and equiaxed crystals, with a relatively uniform distribution. Due to the bonding effect of Co in WC-17Co, the dispersibility of the reinforcing phase is improved, and no obvious large particle agglomeration occurs. The cellular crystal characteristics are distinct, and the equiaxed crystals are further refined. The uniformity and densification of the microstructure are superior to those of the first two coatings. Since the particle size of WC-17Co is significantly smaller than that of conventional WC particles, the WC-17Co particles are almost completely incorporated into the FeNiCrMo matrix, thereby refining the grains and resulting in a more uniform microstructure. These features can be interpreted using the columnar-to-equiaxed transition (CET) criterion. Growth remains columnar while the undercooled zone ahead of the solidification front is too narrow for new grains to nucleate and survive, and becomes equiaxed once the equiaxed volume fraction increases. The CET limit is governed by the nucleation-site density N_0 and the temperature gradient G : a higher N_0 or a lower G favours equiaxed growth, whereas $G \cdot R$ sets the scale of the microstructure rather than its morphology [23–25]. In the WC-17Co coating, the finer particles and their more complete

dissolution increase N_0 and reduce G , consistent with the refined and uniform cellular/equiaxed microstructure in Figure 4(c1,c2).

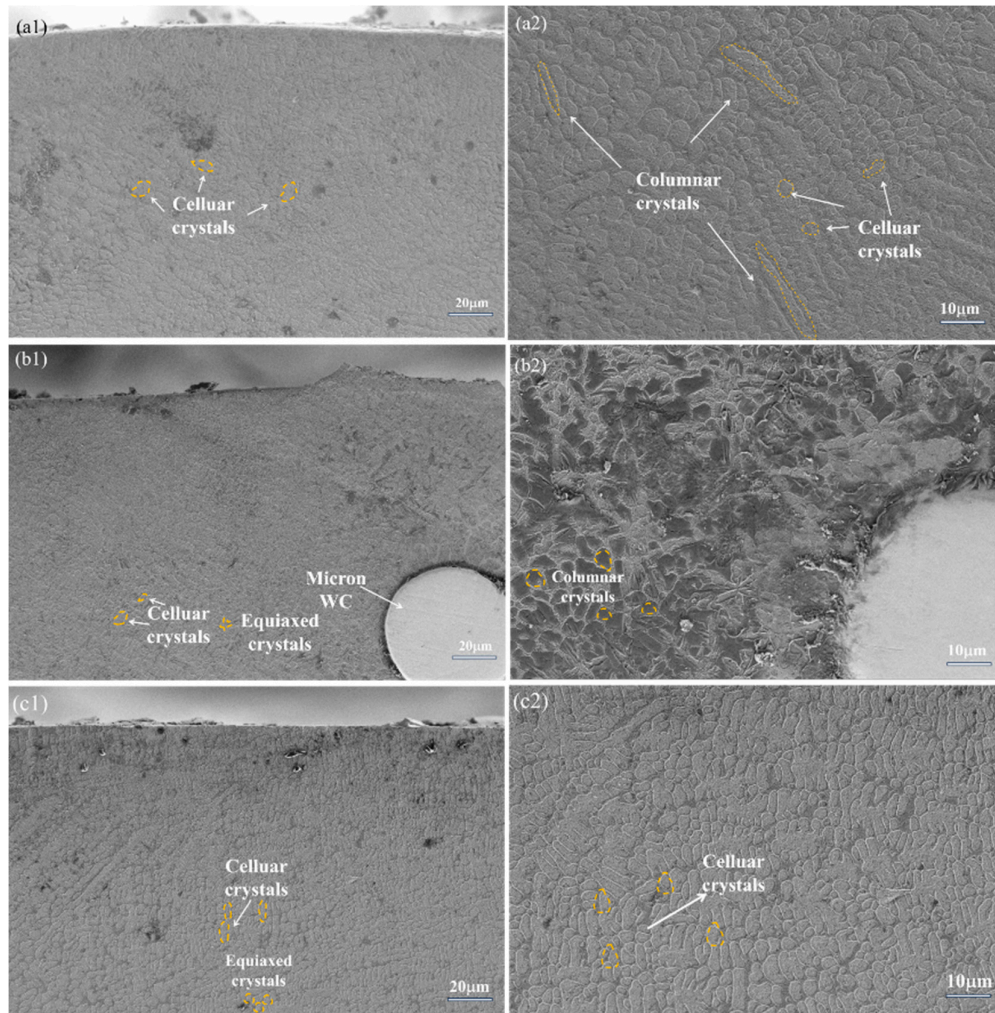


Figure 4. Microstructure morphologies of the three composite coatings. (a1–a2) FeNiCrMo; (b1–b2) FeNiCrMo/WC; (c1–c2) FeNiCrMo/WC-17Co.

Figure 5 presents the elemental distribution of various coatings as determined by EDS analysis. In the FeNiCrMo coating (Figure 5a), Fe, Ni, and Cr are uniformly distributed in the substrate without obvious aggregation. The signals of W and C are weak and dispersed, indicating that this coating consists of a pure alloy substrate with uniform elemental mixing. In the FeNiCrMo/WC coating, W and C elements are highly concentrated in the granular regions, corresponding to the WC particles in the microstructure; Fe, Ni, and Cr are uniformly distributed in the matrix region, with no obvious diffusion around the WC particles. This indicates that the interfacial bonding between WC and the FeNiCrMo matrix is primarily mechanical mixing, with minimal elemental diffusion. In the FeNiCrMo/WC-17Co coating, W and C accumulate in the granular regions, corresponding to WC particles; Co is uniformly distributed within the WC particle regions, while Fe, Ni, and Cr are uniformly distributed in the matrix. In the FeNiCrMo/WC-17Co coating, by contrast, the boundary between the WC particles and the matrix is markedly less distinct than in the FeNiCrMo/WC coating, and the Co $K\alpha$ signal is not confined to the WC particles but extends continuously across the boundary into the surrounding matrix. Since no comparable diffusion is resolved at the WC/FeNiCrMo interface, this

difference is attributable to the Co-rich binder of the WC-17Co powder. This binder melts at a temperature well below that of the carbide itself; it is therefore preferentially liquefied in the melt pool and spreads along the carbide/matrix boundary, so that Co bridges the WC particle and the surrounding FeNiCrMo matrix, and the interface acquires a partly metallurgical character instead of being purely mechanical.

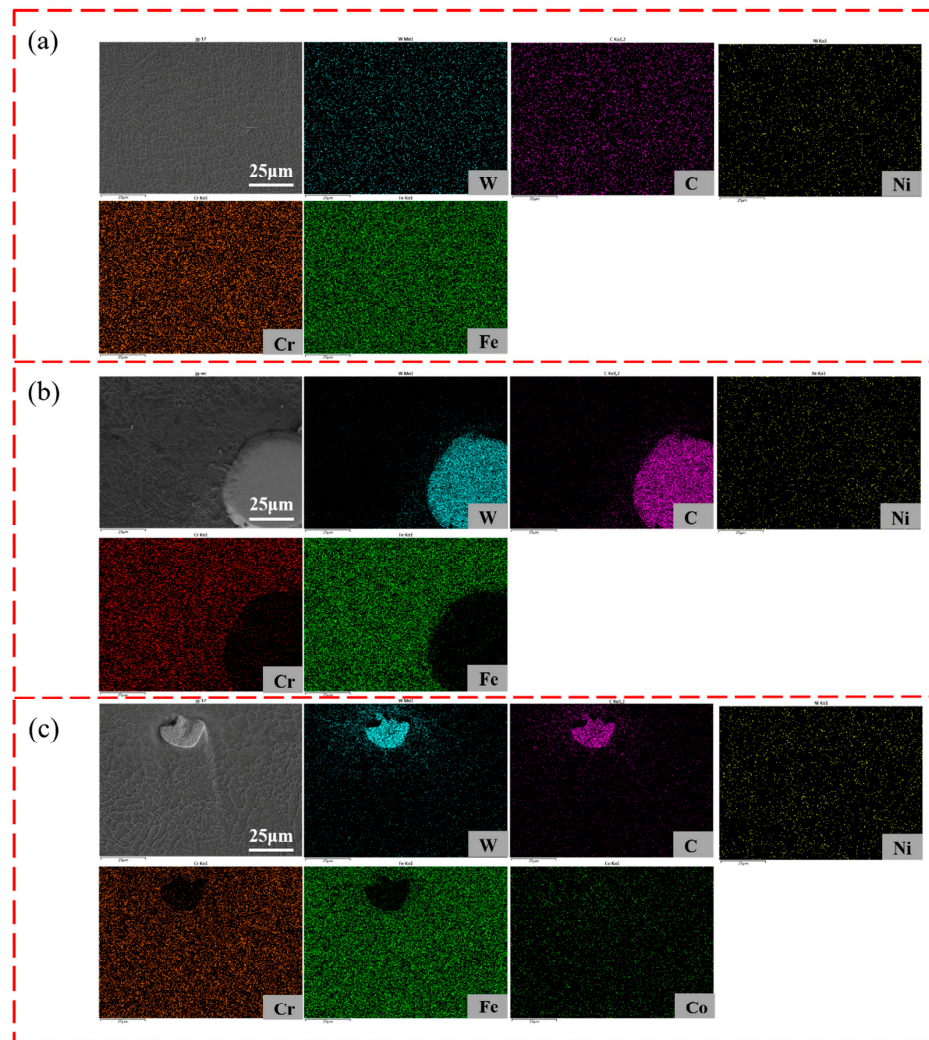


Figure 5. Elemental distribution of different coatings. (a) FeNiCrMo; (b) FeNiCrMo/WC; (c) FeNiCrMo/WC-17Co.

The microstructure changes significantly after the addition of micron-sized WC particles to the matrix [22]. As can be seen from Figures 4(b1,b2) and 5b, WC is partially dissolved in the high-temperature melt pool and reacts in situ with elements such as Fe, Cr, and Mo to generate finely dispersed carbide particles, which are mainly enriched in the regions between grain boundaries and dendrites. Moreover, the original austenite matrix grain size is further refined, the number of columnar grains is reduced, and a more uniform equiaxed grain structure is formed. This microstructure feature helps to improve the hardness and crack resistance of the deposited layer [26]. After the introduction of micron WC-17Co composite particles, in addition to a large number of diffusely distributed carbide particles observed in the microstructure, some Co-enriched regions are also seen forming a fine blocky or network-like phase structure. During molten-pool solidification, partial decarburisation of WC drives the formation of fine Co- and W-bearing carbides at

grain boundaries. In the feedstock, Co binds the carbide particles; once the particles enter the melt the binder is released and retained in the matrix and in the Co-enriched intergranular regions resolved by EDS (Figure 5c). The XRD patterns show clear W_2C reflections in FeNiCrMo/WC but only weak ones in FeNiCrMo/WC-17Co (Figure 3), indicating that decarburisation proceeds to a lesser extent in the latter. In the W–C–Co system the relevant ternary carbides are the η -carbides M_6C and $M_{12}C$, which share one structural family and differ in metal-to-carbon ratio [27,28]. They form even below the stoichiometric bulk carbon content, because partial dissolution of WC locally raises carbon activity and enriches the melt in W, making Co-enriched intergranular regions approaching the η stoichiometry thermodynamically favourable; formation is therefore confined to these regions rather than to a bulk phase. Comparable carbides have been reported in laser-clad WC-reinforced coatings, namely rod-like and blocky W_2C with η_1 - M_6C in a WCp/Ni–Cr–B–Si–C coating [28], Co_3W_3C together with WC_{1-x} in a Co-based layer containing nano-WC [29], and herringbone Fe_3W_3C in Ni–WC coatings [30]. Their formation depends strongly on local heat input and dilution, M_6C appearing only from 1200 J/mm upwards and being absent at 800 and 1000 J/mm [30]. The η -type carbides observed here are accordingly inferred from the combined XRD, EDS and hardness evidence rather than directly identified, and a definitive identification would require TEM/SAED together with a thermodynamic calculation. The resulting microstructural densification and improved interfacial bonding are nevertheless evident. Compared with the FeNiCrMo coating, the addition of the reinforcing phase (WC or WC-17Co) not only transforms the microstructure from coarse columnar grains to fine equiaxed grains [23], but also forms a variety of diffusely distributed reinforced phases, which significantly improves the microstructure homogeneity and the distribution of reinforcing phases.

3.2. Microhardness and Wear Resistance Properties

Figure 6 demonstrates the Vickers microhardness distribution along the depth direction for three different coatings: FeNiCrMo, FeNiCrMo/WC, and FeNiCrMo/WC-17Co. The hardness of the pure FeNiCrMo specimen varies little throughout the test depth range, with an average hardness of about 473 $HV_{0.2}$, showing a more stable austenitic microstructure. After the addition of micron-sized WC powder with a particle size of 45–106 μm , the overall hardness of the deposited layer slightly increased, with an average hardness of approximately 475 $HV_{0.2}$. In contrast, the deposited samples after the addition of the WC-17Co composite reinforcing phase showed higher hardness levels throughout the deposition zone, with an average hardness of 550–600 $HV_{0.2}$, indicating a more significant composite strengthening effect. This strengthening effect is attributed mainly to the Co- and W-enriched intergranular regions resolved by EDS (Figure 5c), within which η -type M_6C / $M_{12}C$ carbides are expected to form as set out in Section 3.1, together with the partial decarburisation of WC, whose product W_2C is identified by XRD (Figure 3). Direct XRD identification of discrete Co_3W_3C or Co_6W_6C reflections was, however, not achieved in the present scan, so the contribution of these phases is treated as a possible rather than a demonstrated strengthening path. In addition, the hardness curve exhibits a slight increase near the substrate, suggesting the presence of a transitional zone within the alloyed region; however, the overall bonding remains satisfactory. The error bars in Figure 6a span the standard deviation of the three indentations at each measurement position, and at every position this scatter remained within $\pm 3\%$ of the corresponding mean hardness.

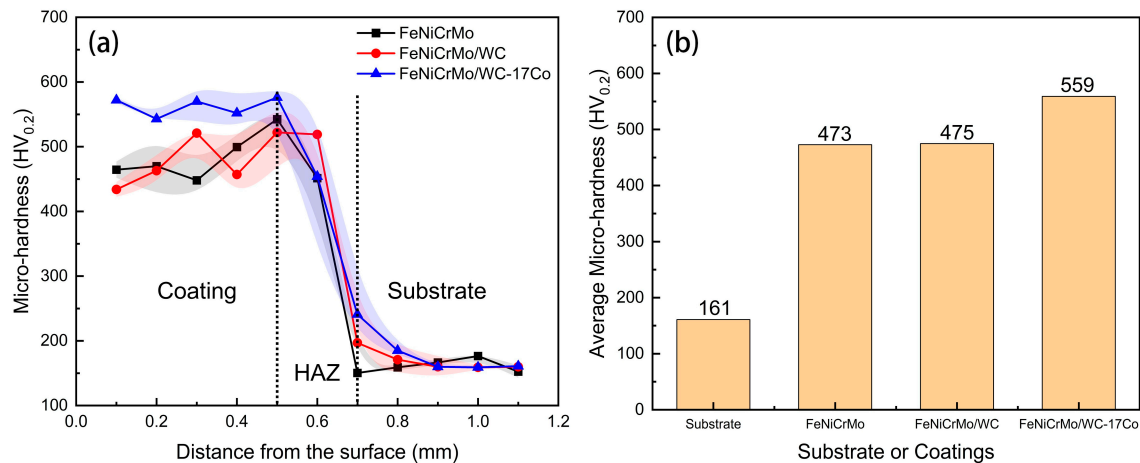


Figure 6. Hardness profiles of the three composite coatings measured from the coating surface to the substrate interface. (a) Hardness profiles; (b) Average hardness of the coatings.

Figure 7a shows the friction coefficient of the FeNiCrMo coating and its two composites (FeNiCrMo/WC and FeNiCrMo/WC-17Co) under loads of 90, 120 and 150 N. The steady-state friction coefficients of all three coatings fall within 0.21–0.34. The un-reinforced FeNiCrMo coating remains at the upper end of this range at every load (0.31–0.34) and has the least reproducible friction signal, which agrees with the extensive plastic deformation, material transfer and adhesive tearing on its worn surface. The addition of micron-sized WC particles has its clearest effect at 150 N, where the steady-state friction coefficient of FeNiCrMo/WC drops to about 0.21. At 90 and 120 N, it stays comparable to that of the un-reinforced coating. FeNiCrMo/WC-17Co, containing micron-sized WC-17Co composite particles, gives friction coefficients slightly below those of the un-reinforced coating (0.26–0.32), though not as low as FeNiCrMo/WC at 150 N. It also shows the smallest fluctuations over the entire load range, and the standard deviation of the last 30% of the sliding record remains below 0.004 at every load.

As can be seen from Figure 7b, the pure FeNiCrMo coating exhibited the highest wear amounts at all loads—0.026 g at 90 N, 0.036 g at 120 N, and 0.045 g at 150 N—indicating that the material's ability to resist wear during friction is weak. After the incorporation of micron-sized WC particles, the wear mass loss of the FeNiCrMo/WC composite deposited layer was significantly reduced to 0.001 g, 0.010 g, and 0.013 g under applied loads of 90 N, 120 N, and 150 N, respectively, demonstrating that the reinforcing phase effectively enhances the wear resistance of the deposited layer. This improvement is mainly attributed to the high hardness and excellent wear resistance of the WC particles, which can effectively inhibit plastic deformation and furrow formation in the material matrix during the friction process, thereby reducing the wear rate. When micron-sized WC-17Co composite particles were further added, the wear mass loss of the FeNiCrMo/WC-17Co deposited layer was lower than that of the pure FeNiCrMo coating but higher than that of the FeNiCrMo/WC coating at every applied load (0.005 g at 90 N, 0.018 g at 120 N and 0.024 g at 150 N). At a given load, the wear mass loss of the deposited layers follows the order FeNiCrMo > FeNiCrMo/WC-17Co > FeNiCrMo/WC. This indicates that adding the reinforcing phase, especially micron-sized WC particles, significantly improves the wear resistance of the deposited layers. The improvement arises from the load-bearing support of the hard phase, reduced ploughing caused by local hardening of the matrix around the particles, and the mechanically mixed surface layer that lowers the energy dissipated in the contact.

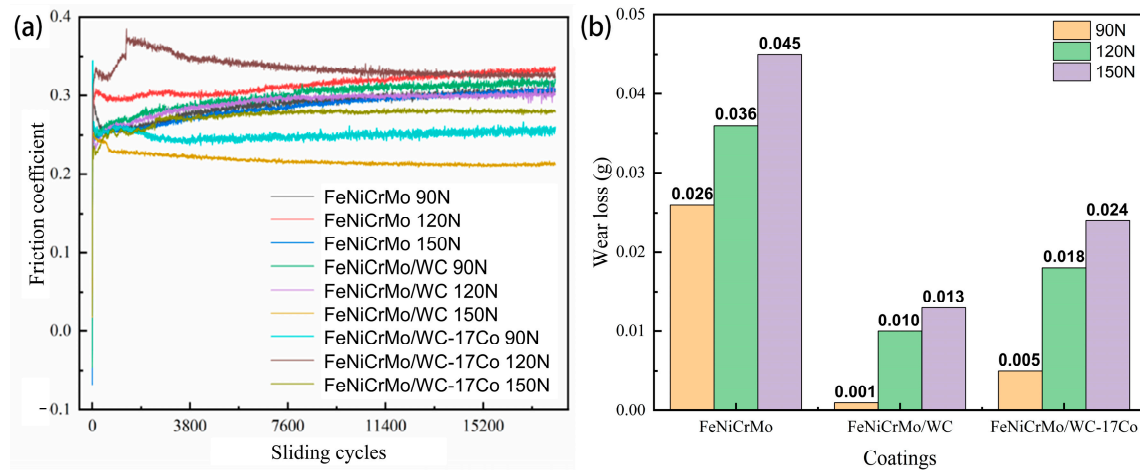


Figure 7. (a) Friction coefficient graph; (b) wear mass loss graph.

Figure 8 demonstrates the wear surface morphology characteristics of the three coatings under 90 N, 120 N, and 150 N loads. A large number of obvious plow grooves, deep tensile streaks, and surface tearing features can be observed in the wear track area of the pure FeNiCrMo coating, indicating that material removal is dominated by a combination of severe abrasive ploughing and adhesive/plastic deformation, the two being superimposed rather than mutually exclusive [31]. The edges of the wear tracks are accompanied by obvious material accumulation and peeling phenomena, and the surface damage is further aggravated with increasing load, with microcracks and spalling pits appearing in localized areas, leading to higher friction coefficients and wear rates.

After the addition of micron-sized WC particles into the FeNiCrMo, SEM observation revealed more uniformly distributed shallow furrows on the surface of the wear tracks, accompanied by fine abrasive grain exfoliation features, indicating that abrasive ploughing remains the principal material-removal mechanism but operates at a much reduced severity; the grooves become progressively shallower and narrower and the exfoliated debris becomes finer. However, under high loading conditions, phenomena such as grain exfoliation and interfacial fracture still occurred in localized areas, resulting in reduced wear resistance, which is consistent with the trend observed in the wear volume curve.

In contrast, the surface of the FeNiCrMo/WC-17Co samples with the addition of micron-sized WC-17Co composite particles exhibited the flattest abrasion marks, with a significant reduction in the width and depth of the furrows and a continuous, compact tribo-film of oxidised and mechanically mixed wear debris observed on the surface. No EDS or XPS analysis of the wear tracks was carried out here, so this interpretation rests on the worn-surface morphology (Figure 8) rather than on a direct chemical identification. Moreover, although this layer is the most compact and continuous of the three coatings, the wear volume of the FeNiCrMo/WC-17Co coating remains slightly higher than that of the FeNiCrMo/WC coating, which is fully consistent with the wear-mass data in Figure 7b [32]. The introduction of the reinforcing phases therefore does not replace one wear mechanism by another but suppresses the severity of the dominant one: the abrasive ploughing inherited from the un-reinforced coating becomes progressively shallower and narrower, and the increasing coverage of the surface by a compact tribo-oxide/mechanically mixed layer lowers its severity further, so that the abrasive mechanism remains the dominant one but acts more mildly, with a progressively larger share of the load carried by the compact surface layer. The wear rate ω can be expressed by the following equation:

$$\omega = \frac{m}{\pi \cdot d \cdot n} \quad (1)$$

In the equation, m represents the mass loss of the deposited sample before and after the wear test, d is the diameter of the counterface ring, and n is the number of revolutions of the ring. According to Figure 7b and the wear rate formula, the wear rate of the FeNiCrMo material was 1.38×10^{-8} g/mm under a load of 90 N, 1.90×10^{-8} g/mm under 120 N, and 2.39×10^{-8} g/mm under 150 N. For the FeNiCrMo/WC material, the wear rate was 5.3×10^{-10} g/mm at 90 N, 5.31×10^{-9} g/mm at 120 N, and 6.89×10^{-9} g/mm at 150 N. The FeNiCrMo/WC-17Co material exhibited wear rates of 2.65×10^{-9} g/mm at 90 N, 9.55×10^{-9} g/mm at 120 N, and 1.27×10^{-8} g/mm at 150 N.

To allow a more quantitative comparison, the specific wear rate k was calculated using the Archard relation $k = \Delta V / (F \cdot L) = \Delta m / (\rho \cdot F \cdot L)$, where ΔV is the wear volume, Δm the mass loss, ρ the density of the coating (7.9, 8.1 and 8.1 g·cm⁻³ for FeNiCrMo, FeNiCrMo/WC and FeNiCrMo/WC-17Co, respectively), F the normal load and L the sliding distance (1884 m, calculated from a counter-face diameter of 50 mm and 12,000 revolutions). The wear rates and the specific wear rates are summarised in Table 2 and confirm that FeNiCrMo/WC exhibits the lowest specific wear rate at all three applied loads, in agreement with the trend observed in Figure 7b.

Table 2. Wear rate ω and specific wear rate k of the three coatings under different applied loads.

Coating	Load (N)	ω ($\times 10^{-9}$ g·mm ⁻¹)	k ($\times 10^{-6}$ mm ³ ·N ⁻¹ ·m ⁻¹)
FeNiCrMo	90	13.8	19.41
FeNiCrMo	120	19.0	20.16
FeNiCrMo	150	23.9	20.16
FeNiCrMo/WC	90	0.53	0.73
FeNiCrMo/WC	120	5.31	5.46
FeNiCrMo/WC	150	6.89	5.68
FeNiCrMo/WC-17Co	90	2.65	3.64
FeNiCrMo/WC-17Co	120	9.55	9.83
FeNiCrMo/WC-17Co	150	12.7	10.48

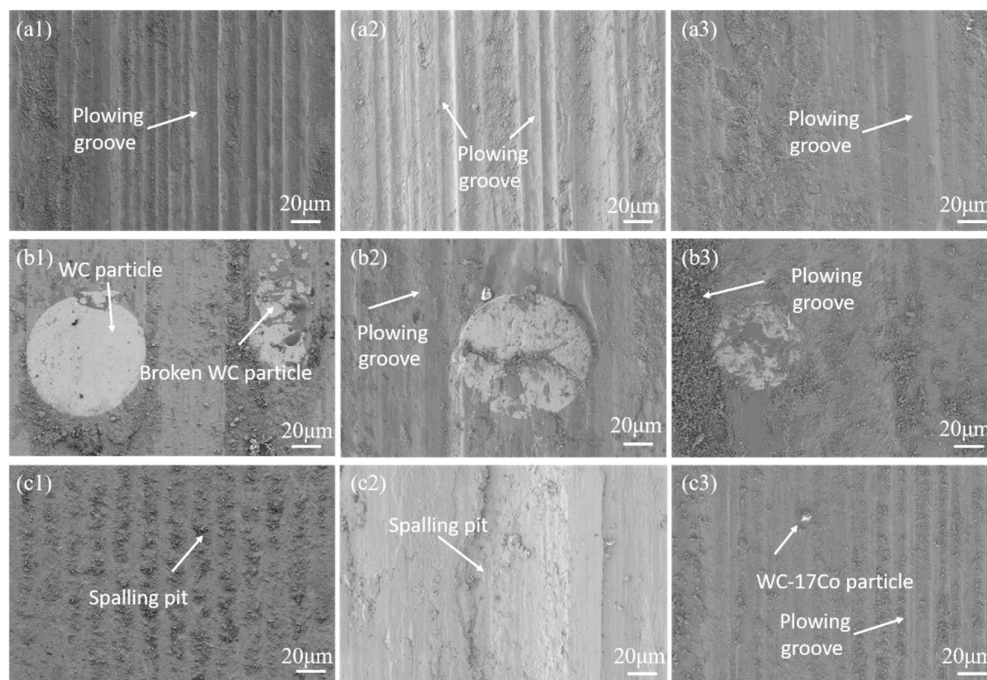


Figure 8. Abrasion mark diagrams of composite coatings. (a1) FeNiCrMo at 90 N; (a2) FeNiCrMo at 120 N; (a3) FeNiCrMo at 150 N; (b1) FeNiCrMo/WC at 90 N; (b2) FeNiCrMo/WC at 120 N; (b3)

FeNiCrMo/WC at 150 N; (c1) FeNiCrMo/WC-17Co at 90 N; (c2) FeNiCrMo/WC-17Co at 120 N; (c3) FeNiCrMo/WC-17Co at 150 N.

Figure 9 shows the friction wear mechanism diagrams of the FeNiCrMo/WC and FeNiCrMo/WC-17Co composite coatings, respectively. The overall microhardness of both composite coatings is significantly increased, which effectively enhances the resistance of the deposited layer to plastic deformation under applied load, thereby reducing the friction coefficient and wear volume to a certain extent. Especially in the FeNiCrMo/WC coating, although its microhardness is slightly lower than that of FeNiCrMo/WC-17Co, its wear volume is smaller and its wear resistance is superior, even though its friction coefficient over the load range investigated is comparable to that of FeNiCrMo/WC-17Co (Figure 7a). This performance advantage is mainly attributed to the uniform distribution and good retention of a large number of high-hardness micron-sized WC particles in the FeNiCrMo/WC composite coating. During the wear process, these particles not only form a strong supporting structure on the material surface and effectively bear part of the external load, but also disperse stress concentrations at the contact interface and significantly inhibit plowing and cutting wear caused by abrasive particles on the substrate. In addition, the presence of WC particles helps reduce thermal softening and plastic flow on the surface of the coating, thereby further enhancing its wear resistance.

In contrast, the FeNiCrMo/WC-17Co deposited layer is weakened by the introduction of the Co element, which may trigger partial melting or interfacial reactions of WC particles, reducing its strengthening effect. Moreover, the decrease in particle bonding strength and distribution uniformity may also lead to an increase in the frequency of their detachment during the wear process, resulting in three-body wear and further aggravating material surface damage. In summary, although both composite deposited layers achieved hardness enhancement and improved friction and wear performance, the FeNiCrMo/WC layer exhibited better performance in terms of particle stability, load-bearing capacity, and wear resistance, demonstrating superior application potential.

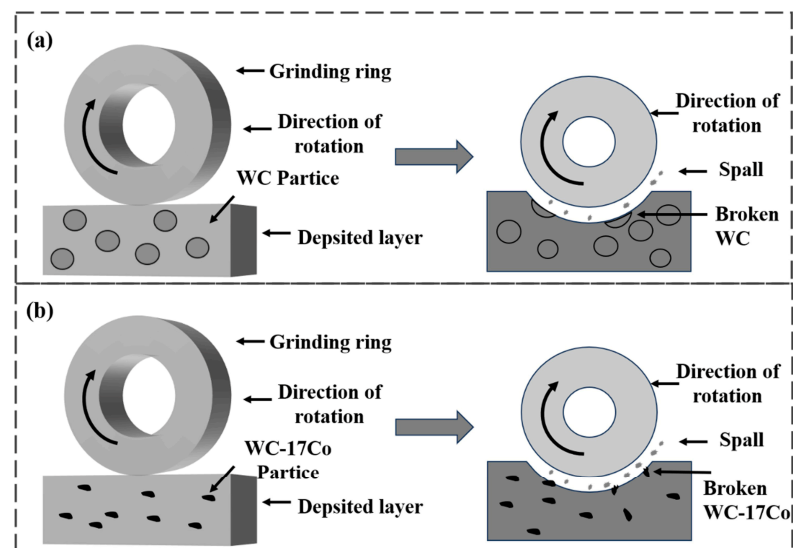


Figure 9. Friction and wear mechanisms of composite coatings: (a) FeNiCrMo/WC; (b) FeNiCrMo/WC-17Co.

3.3. Corrosion Resistance

Figure 10a–c shows the potentiodynamic polarization curves used to analyze the corrosion current density (I_{corr}) and corrosion potential (E_{corr}) of materials, reflecting their

corrosion resistance. The more positive the E_{corr} and the smaller the I_{corr} , the better the corrosion resistance performance. Figure 10d presents the electrochemical impedance spectroscopy (EIS) results, where the corrosion resistance of materials is evaluated using the impedance modulus ($|Z|$, Ω/cm^2) and charge transfer resistance (R_t). Specifically, the larger the impedance modulus in the low-frequency region (which reflects the comprehensive resistance of the corrosion system) and the wider the semicircle diameter in the Nyquist plot (corresponding to higher R_t , when the system conforms to a single-time-constant equivalent circuit), the greater the resistance of the passivation film or interface formed during corrosion.

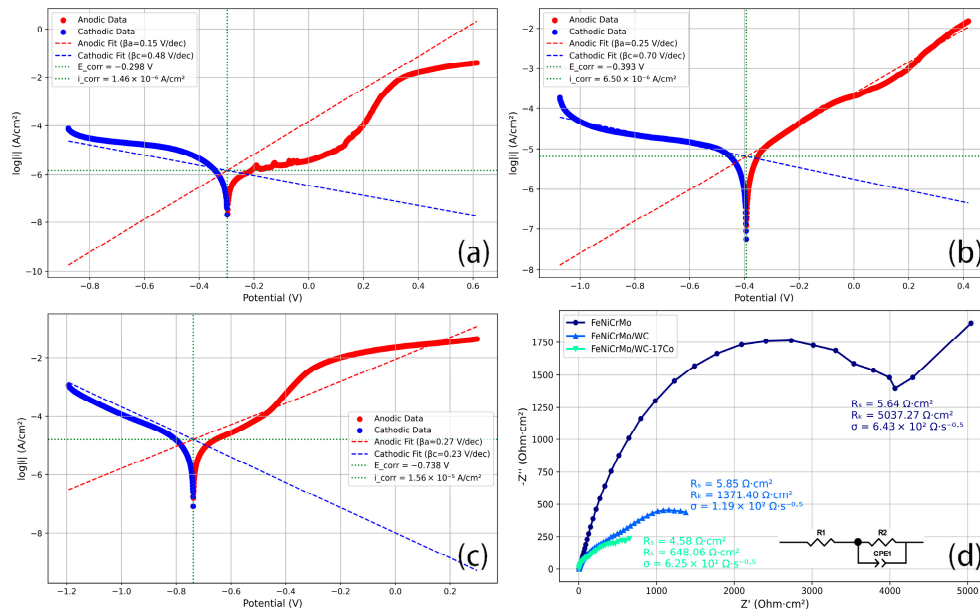


Figure 10. The voltammetric polarization curves and electrochemical impedance spectra of the three coatings: (a) FeNiCrMo; (b) FeNiCrMo/WC; (c) FeNiCrMo/WC-17Co; and (d) their corresponding electrochemical impedance spectra.

As can be seen from Figure 10a–c, there are significant differences in the E_{corr} and I_{corr} values among the three curves, corresponding to the different corrosion behaviors of the three coatings. The corrosion potential E_{corr} (−0.298 V) of the FeNiCrMo coating's polarization curve is the most positive. The slope of the anodic polarization region is relatively steep, indicating a strong ability to form a passive film, and the corrosion current density I_{corr} ($1.46 \times 10^{-6} \text{ A}/\text{cm}^2$) is the smallest. This suggests that a continuous and dense passive film can easily form on the surface of the pure alloy matrix, where Cr and Mo elements are key components, forming stable oxide films such as Cr_2O_3 and MoO_3 , which effectively block the penetration of corrosive media and inhibit both anodic dissolution and cathodic reduction reactions.

The E_{corr} (−0.393 V) of the polarization curve of the FeNiCrMo/WC coating shifts negatively compared to that of the pure FeNiCrMo coating, and the I_{corr} ($6.5 \times 10^{-6} \text{ A}/\text{cm}^2$) increases. The main reason is that the interfacial bonding between the WC particles and the FeNiCrMo matrix is poor. The EDS maps of Figure 5b show that the WC/FeNiCrMo interface is established mainly by mechanical mixing with only limited elemental diffusion, so that tiny pores, cracks or interfacial gaps can remain there and act as pathways for corrosive media. Moreover, WC particles lack passivation ability and cannot form a protective oxide film. Corrosion preferentially occurs at the interface (interface corrosion effect), leading to an increase in the overall corrosion rate. Figure 10d shows that the

FeNiCrMo/WC coating exhibits a smaller impedance modulus ($|Z|$) in the low-frequency region and a narrower semicircle diameter in the mid-low frequency range compared to the FeNiCrMo coating. This indicates that the introduction of WC leads to interface defects, which disrupt the continuity of the passive film and reduce the R_t . As a result, corrosive media can more easily penetrate the matrix, leading to weaker corrosion resistance of the FeNiCrMo/WC coating relative to the pure FeNiCrMo coating.

For the polarization curve of the FeNiCrMo/WC-17Co coating, the E_{corr} (-0.738 V) is the most negative, the I_{corr} (1.56×10^{-5} A/cm²) is the largest, and there is no obvious passivation plateau in the anodic polarization region. For the EIS curve, the impedance modulus ($|Z|$) is the smallest, the high-frequency semicircle diameter is the narrowest, and there may even be a rapid decrease in impedance in the low-frequency region. This indicates that the R_t is the lowest, with the high-frequency semicircular arc reflecting a reduced interfacial double-layer resistance and the low-frequency linear region showing a decreased ion diffusion resistance. Consequently, the corrosive medium has rapidly penetrated the coating, initiating substrate dissolution and resulting in the poorest corrosion resistance of the material.

The FeNiCrMo coating is mainly subject to mild general corrosion, and local corrosion is not obvious. As shown in Figure 11(a1–a3), the surface corrosion products are sparse and relatively evenly distributed. There are no obvious deep corrosion pits or localized perforations, and the original morphology of the substrate is well preserved. Only mild surface layer corrosion has occurred. The corrosion product layer is thin and uniformly distributed, providing a certain barrier effect on the substrate and slowing down the penetration of the corrosive medium into the interior of the substrate, thus exhibiting better corrosion resistance performance.

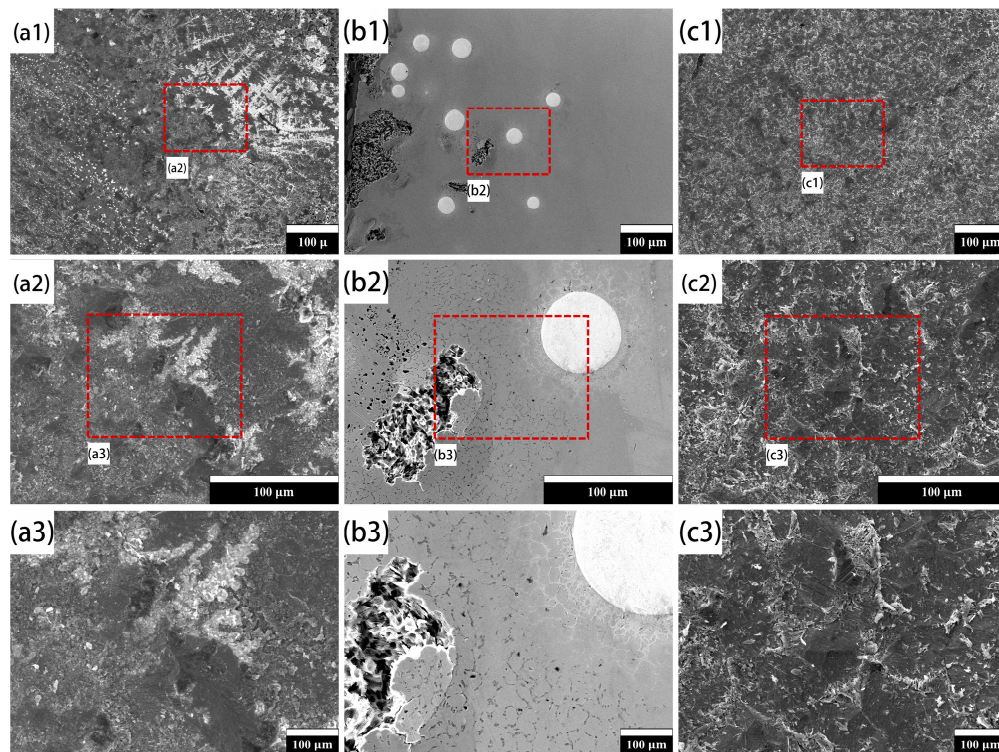


Figure 11. Electrochemical corrosion morphologies of the coatings: (a1–a3) FeNiCrMo; (b1–b3) FeNiCrMo/WC; and (c1–c3) FeNiCrMo/WC-17Co.

The FeNiCrMo/WC coating is mainly subjected to severe local corrosion. In Figure 11(b1), a large number of circular corrosion pits or corrosion areas around WC particles

can be observed. From Figure 11(b2,b3), it can be seen that obvious corrosion pits and accumulated corrosion products occur in the matrix surrounding the WC particles, indicating that corrosion preferentially occurs at the interface between WC and the matrix. This is because the electrochemical compatibility between WC and the matrix is poor, leading to the formation of a microcell. The interface becomes the anodic region, resulting in accelerated local corrosion.

The FeNiCrMo/WC-17Co coating is mainly subject to general corrosion, accompanied by localized deep-pit corrosion. From the enlarged details in Figure 11(c1–c3), it can be seen that the surface is almost entirely covered by continuous corrosion products, which exhibit a reticular accumulation pattern, indicating uniform corrosion over a large area. Moreover, there are obvious deep corrosion pits in certain local areas. The matrix has been penetrated to a significant depth, and its integrity is severely compromised. The corrosion product layer is thick and densely distributed. However, such a loosely structured layer cannot effectively protect the substrate, resulting in relatively poor corrosion resistance.

4. Conclusions

This study focuses on metal matrix composites, aiming to enhance the performance of FeNiCrMo coatings in high-load environments by using laser cladding to prepare FeNiCrMo, FeNiCrMo/WC, and FeNiCrMo/WC-17Co composite coatings. The main points are summarized as follows:

- (1) The phase composition of the laser-directed energy-deposited layer of FeNiCrMo coating has been significantly changed from a single γ -Fe phase to a multiphase composite structure in which a variety of hard carbides (e.g., W_2C) and Co-rich solid solutions coexist. The generation of reinforced phases not only enhances the microstructural stability and solid solution strengthening effect of the deposited layer, but also effectively improves its mechanical properties, providing important support for the optimization of the layer's properties.
- (2) The addition of micron-sized WC and WC-17Co enhanced phases significantly improved the microhardness of the FeNiCrMo coating, in which the WC-17Co system achieved the optimal composite strengthening effect through hard phase precipitation, grain refinement, and the synergistic effects of alloying elements.
- (3) Through the addition of micron-sized WC and WC-17Co composite particles, the friction coefficient and wear rate of the FeNiCrMo austenitic stainless steel deposited layer were greatly reduced. In particular, the FeNiCrMo/WC coating exhibited the lowest wear mass loss at all applied loads. The ploughing grooves that dominate the worn surface of the unreinforced coating are still present in both composite coatings but are markedly shallower and narrower, and a compact tribo-oxide/mechanically mixed layer forms on the worn surfaces, so that the abrasive contribution is reduced in severity rather than eliminated, and the abrasive mechanism remains dominant but is moderated by the compact surface layer.
- (4) The FeNiCrMo coating exhibits superior corrosion resistance due to the formation of a dense passivation layer, while the FeNiCrMo/WC composite suffers from interfacial microgalvanic corrosion, and the FeNiCrMo/WC-17Co coating exhibits severe general corrosion with minimal passivation capability.

Overall, compared with the FeNiCrMo coating, the incorporation of micron-sized WC particles significantly reduces both the friction coefficient and the wear rate, thereby effectively enhancing its wear resistance while only marginally degrading its corrosion resistance. However, the addition of WC compromises the coating's corrosion resistance to some extent. In comparison with fine-sized WC-17Co powder, larger WC particles not

only provide superior wear resistance but also better preserve the inherent corrosion resistance of the coating.

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