

Article

The Microstructure and Properties of Laser-Cladded Ni-Based and Co-Based Alloys on 316L Stainless Steel

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Abstract: To extend the service life of 316L stainless steel components in harsh environments, this study utilized laser cladding technology to enhance the hardness, wear resistance, and corrosion resistance of the 316L stainless steel surface. Nickel-based and cobalt-based cladding layers were prepared on the surface of the 316L stainless steel, and the microstructure and phases of the layers were analyzed using scanning electron microscopy, energy dispersive spectroscopy, X-ray diffraction, and X-ray photoelectron spectroscopy. In addition, the hardness of the substrate and the cladding layers was tested with a microhardness tester, the frictional wear performance was tested with a pin on disc wear tester, and the corrosion resistance was tested with an electrochemical workstation. The experimental results indicate that the nickel-based cladding layer primarily comprises the γ -(Fe, Ni), Cr_7C_3 , and Ni_3Si phases, with equiaxed and dendritic grains being the predominant morphologies. By contrast, the cobalt-based cladding layer mainly comprises the γ -Co, Cr_7C_3 , and Co_7W_6 phases, with columnar and dendritic grains being the predominant morphologies. Both cladding layers displayed a significantly better microhardness, wear resistance, and corrosion resistance than the substrate. Between the two cladding layers, the nickel-based cladding layer demonstrated a superior microhardness, whereas the cobalt-based cladding layer slightly outperformed in wear resistance and corrosion resistance. The findings from our results are important for understanding the performance of laser-cladding layers and laying a scientific basis for the promotion and optimization of laser cladding technology in industrial applications. Moreover, our results showed that laser cladding technology is increasingly important in extending the service life of components and improving the material performance.

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

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1. Introduction

316L stainless steel has been extensively employed in the industrial area owing to its outstanding mechanical strength, excellent processing properties, and cost-effectiveness [1–3]. It is essential in various fields such as aerospace, automotive manufacturing, chemical processing, marine exploration, and medical devices. However, with the rapid advancements in science and technology, 316L stainless steel must adapt to increasingly stringent operating conditions. For instance, in the aerospace sector, 316L stainless steel needs to withstand extreme pressure changes and intense mechanical vibration, and minor damage to any component in aerospace equipment will lead to extremely serious consequences [4]. The automotive industry requires long-term stable operation under the harsh conditions of high-speed rotation and friction. In the marine sector, the outside surface of 316L stainless steel material may still be damaged due to difficulty in withstanding the wear and corrosion caused by complex marine environments [5,6]. In the medical field, it is extensively used in the manufacture of bioimplants and surgical instruments. Some of the properties

desired to be present in bioimplant applications include a high strength and toughness, good fatigue, good wear resistance, good corrosion resistance, and non-toxicity in physiological environment [7]. Therefore, enhancing the surface modification technology of 316L stainless steel becomes particularly important. Through surface modification techniques, significant improvements can be made in the microhardness, corrosion resistance, wear resistance, and biocompatibility with human tissues. For example, techniques such as laser cladding, ion implantation, physical vapor deposition (PVD), Chemical Vapor Deposition (CVD), electric arc surfacing, and electric spark alloying can effectively establish a barrier against environmental corrosion, prolong material service life, and reduce maintenance costs [8–12].

Laser cladding involves melting the surface of the substrate and pre-placed powder with a high-energy laser beam, which solidifies after cooling to form a metallurgical bonded cladding layer, thereby enhancing the surface hardness, wear resistance, and corrosion resistance of the substrate [13,14]. Yuqiang Feng et al. [15] observed that separately cladding 55NiTi alloy powder and a mixture powder consisting of 55NiTi alloy and 5% pure Ni onto the surface of 316L stainless steel results in significant differences in the properties of the cladding layers. Zhang Song et al. [16] used a high-power semiconductor laser system to prepare a cobalt-based alloy cladding layer on the surface of 316L stainless steel. The crystal structure of the cladding layer was characterized using primarily fine dendritic grains. The microhardness of the cladding layer was approximately 720 HV, which is three times that of the substrate. Linlin Zhang et al. [17] found that adding different amounts of cobalt-based alloy powder to the nickel-based alloy can promote the formation of hard compounds, refine the austenite grain, change the phase-type of the eutectic structure, and significantly improve the wear resistance of the cladding layer. Changchun Zhang et al. [18] prepared Co47+5%w(WC) and Ni60+5%w(WC) alloy powder cladding layers. The results show that the cobalt-based cladding layer has a higher thickness and hardness than the nickel-based cladding layer. The two cladding layers displayed similar microstructures consisting of dense amorphous crystals on the surface, large columnar grains in the transition zone, and both flat and dendritic grains in the bottom layer. The wear resistances of both cladding layers were approximately three times that of the substrate. Andrea Angelastro et al. [19] prepared a nickel-based tungsten carbide/cobalt/chromium composite cladding layer using multilayer laser cladding. After optimizing the process parameters, the cladding layer achieved a porosity rate of 0.24% and crack-free surfaces with excellent adhesion. Rui Liu et al. [20] investigated the deposition of a cobalt-based alloy coating on H13 steel using a pulsed Nd:YAG laser to enhance the steel's resistance to corrosion in molten aluminum and to understand the underlying corrosion mechanisms. Among them, nickel-based alloy powder is widely used owing to its good wear resistance and comprehensive performance [21]. Cobalt-based alloy powder is known for its excellent strength, toughness, wear resistance, and corrosion resistance [22]. Although studies on the laser cladding technology of nickel-based and cobalt-based alloys have been extensively conducted, comparative analysis between them and comprehensive studies on their microhardness, wear resistance, and corrosion resistance are relatively rare. Moreover, studies on the effects of their microstructure and solidification structure on their properties are lacking.

In this study, nickel-based and cobalt-based cladding layers were prepared using laser cladding technology, and the microstructure and phases of the two cladding layers were extensively investigated. A comparison of the microhardness, wear resistance, and corrosion resistance of a substrate and the surfaces of the two cladding layers was conducted. We discussed the strengthening effect of the cladding layers and explored the potential mechanisms for their corrosion resistance. Through comparative analysis, significant improvements were observed in the hardness, wear resistance, and corrosion resistance of the cladding layers, compared with the substrate.

2. Experimental Methods and Procedures

A 316L stainless steel plate with a thickness of 12 mm was selected as the substrate material. Its chemical composition is presented in Table 1. Nickel-based and cobalt-based alloy powders were prepared in-house. Their chemical compositions are presented in Tables 2 and 3, respectively. High-power laser processing equipment was employed. The processing parameters were set as follows: a laser power of 2.50 kW, a laser beam spot area of 15 mm × 3 mm, a scanning speed of 2.0 mm/s, and a powder feed rotating disk speed of 6.67 r/s.

Table 1. Chemical composition of 316L stainless steel (wt.%).

Element	C	Si	Cr	Fe	Ni
Content	≤0.08	≤1.00	16.0–18.0	10.0–14.0	Bal

Table 2. Chemical composition of nickel-based cladding layer (wt.%).

Element	C	Si	Cr	Fe	Ni
Content	3.85	1.84	25.66	18.84	49.81

Table 3. Chemical composition of cobalt-based cladding layer (wt.%).

Element	C	W	Cr	Fe	Co	Ni
Content	2.08	3.43	28.4	16.8	45.96	3.33

Following the laser cladding tests, the substrates and clad samples were machined into cylinders with diameters of 18 mm and cubes measuring 10 mm × 10 mm using a wire-cut electrical discharge machine (WENJIE Co., Taizhou, China). The surfaces were subsequently treated to eliminate any oxidation layers using a grinder (FUXINCHENG Co., Beijing, China). The cylindrical samples were ground, polished, etched, and then prepared into metallographic samples. The microstructures and elemental distribution of both the substrate and the cladding layers were tested with an S-3400N scanning electron microscope (SEM) (HITACHI Co., Tokyo, Japan) equipped with an energy-dispersive spectrometer (EDX). In addition, the phase structure of the cladding layer was tested with a D8-ADVANCE X-ray diffractometer (XRD) (BRUKER Co., Leipzig, Germany) with a scanning range of 20–80°. Furthermore, the chemical states of the cladding layer surface were tested with a 250Xi X-ray photoelectron spectrometer (XPS) (THERMOFISHER Co., Waltham, MA, USA). Electrochemical corrosion testing was conducted with a CHI660E electrochemical workstation (CHENHUA Co., Shanghai, China), with both 3.5 wt.% NaCl and 0.5 mol/L H₂SO₄ solutions employed as the corrosive medium. The sample electrode was set as the working electrode, a saturated calomel electrode as the reference electrode, and a platinum sheet electrode as the auxiliary electrode. The corrosion area was set as a circular surface with a diameter of 12 mm, and the test temperature was set to 25° ± 5°. Tafel polarization tests were conducted with a scanning rate of 0.01 V/s, starting from 1.5 V and ending at 1.5 V, and Nyquist impedance tests were conducted with a frequency range of 0.01 Hz to 10 kHz. Square samples were also ground. The microhardnesses of the substrate, interface, and cladding layer were measured on the cross sections of the nickel-based and cobalt-based laser-clad samples using an HVST-1000Z digital microhardness tester (ZHONGYAN Co., Shanghai, China). The frictional wear performances of the substrate and the two cladding layers were tested using an MMW-1A wear tester (HENGXU Co., Jinan, China) with the process parameters set as follows: a rotational speed of 5 r/s, a load of 30 N, and a lubricating medium of 500SN. The wear surface morphology was obtained with an OLS5000 three-dimensional confocal laser measuring microscope (OLYMPUS Co., Tokyo, Japan).

3. Experimental Results and Analysis

3.1. Microstructure, Phases, and Microhardness Analysis

Figure 1 shows the SEM images of the nickel-based and cobalt-based cladding layer cross sections. All the cladding layer cross sections consisted of a cladding layer and a substrate, in which the cladding layer cross sections had no cracks or pores. The average thicknesses of the nickel-based and cobalt-based cladding layers were 680 and 620 μm , respectively.

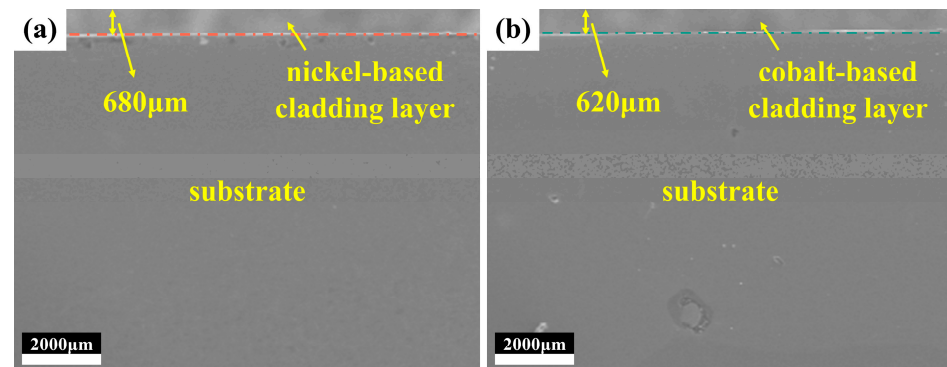


Figure 1. SEM images of cross sections: (a) nickel-based cladding layer; (b) cobalt-based cladding layer.

Figure 2a shows that the surface of the cladding layer primarily consisted of equiaxed and dendritic grains. Figure 2b–f revealed that the equiaxed grains were rich in Si, Cr, Fe, and Ni elements. Among them, Si, Cr, and Fe were predominantly distributed at the grain boundaries and Ni was concentrated within the grain cells. The dendritic grains contained high concentrations of Cr, Fe, and Ni. Further analysis with the XRD indicated the presence of multiple phases in the cladding layer, possibly including γ -(Fe, Ni), Cr_7C_3 , Cr_2Ni_3 , and Ni_3Si [1,23].

Figure 2g shows that, in the nickel-based cladding layer, the coexistence of Ni and γ -Fe, both possessing face-centered cubic structures and being mutually soluble in unlimited proportions, results in the continuous nucleation of crystalline cores that steadily grow by absorbing Ni atoms, ultimately forming a network-like γ -(Fe, Ni) austenitic phase enriched with Ni. From the perspective of the solidification theory, the nickel-based cladding layer exhibited a smaller temperature gradient on its surface than in its other regions. Consequently, it underwent the fastest solidification process, resulting in insufficient grain growth and the formation of relatively uniform equiaxed grains. In addition, convective stirring during the cladding led to irregular crystal growth directions, promoting secondary dendritic growth [24].

Figure 2h shows that the microhardness of the cladding layer was roughly 2.8 times that of the substrate. This increase in hardness is attributed to the lattice distortion caused by the Ni and Cr elements. This distortion significantly enhances the hardness of the cladding layer through solution strengthening. Furthermore, phases such as Cr_7C_3 , Cr_2Ni_3 , and Ni_3Si act as nucleation sites within equiaxed and dendritic grains, refining the network-like eutectic structure of the cladding layer, resulting in fine grain strengthening. These hard phases also serve as dispersion-strengthening agents, hindering the dislocation movement and, thereby, further enhancing the microhardness of the cladding layer.

Figure 3a shows that the surface of the cladding layer was primarily characterized by columnar and dendritic grains, displaying a relatively disordered growth pattern. This is also attributed to convective stirring during the cladding process causing varied crystal growth directions. Figure 3b–g shows that the columnar grains contained high amounts of Cr, Fe, and Co and minor amounts of W and Ni elements. Meanwhile, the dendritic grains had significant differences in their composition between the grain cells and grain boundaries. The concentrations of C, W, and Cr were relatively high at the grain boundaries.

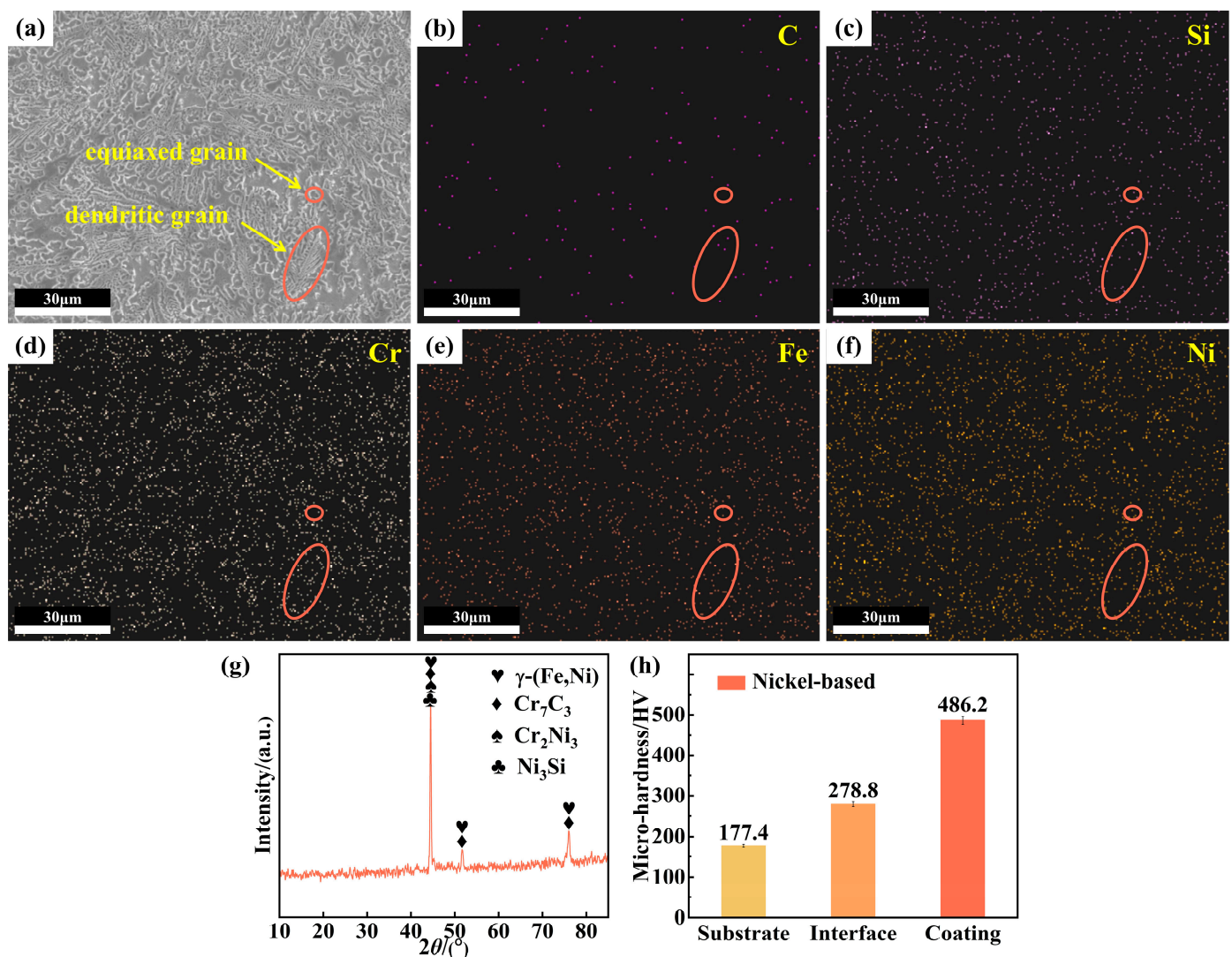


Figure 2. (a) EDX images; (b–f) elemental distribution maps; (g) XRD images; (h) microhardness at feature points on the nickel-based cladding layer surface.

The isomorphous transition characteristics of cobalt indicate that, above 417° , cobalt adopted a face-centered cubic (fcc) structure ($\gamma\text{-Co}$), and, below this temperature, it transformed into a hexagonal close-packed (hcp) structure ($\varepsilon\text{-Co}$). However, laser cladding is a rapid non-equilibrium cooling solidification process. As a result, lattice-stabilizing elements such as Ni in cobalt-based powders maintained the spatial lattice in an fcc structure, inhibiting the $\gamma\text{-Co}$ to $\varepsilon\text{-Co}$ transformation. Consequently, the cobalt-based cladding layer remained in the form of a $\gamma\text{-Co}$ solid solution at room temperature. Combined with Figure 3h, phases such as $\gamma\text{-Co}$, Cr_7C_3 , Cr_2Ni_3 , and Co_7W_6 were possibly included within the cladding layer [16,25].

As shown in the microhardness graph of Figure 3i, the microhardness of the cobalt-based cladding layer was approximately 2.4 times that of the substrate, indicating a significant increase in hardness. A combined analysis of the EDX and XRD images shows that this enhancement was primarily attributed to the high content of columnar grains in the cladding layer and the dispersion-strengthening effect of hard phases such as those of Cr_7C_3 and Co_7W_6 .

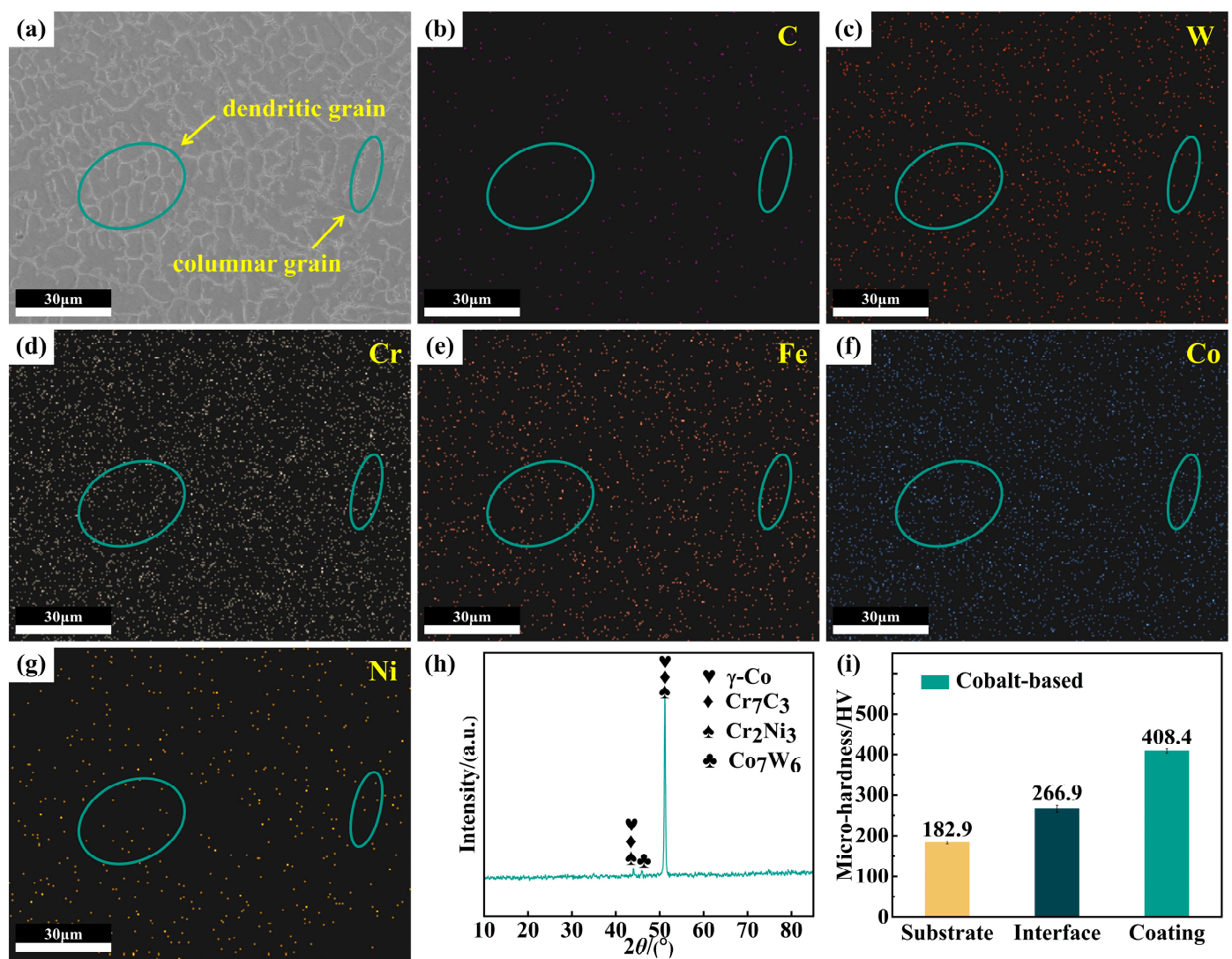


Figure 3. (a) EDX images; (b–g) elemental distribution maps; (h) XRD images; (i) microhardness at feature points on the cobalt-based cladding layer surface.

A comprehensive analysis of the microstructural characteristics of the two cladding layers revealed similar surface morphologies, consisting of fine equiaxed or columnar grains. This imparted excellent hardness properties to the cladding layers. Nonetheless, the network structure on the surface of the nickel-based cladding layer comprised relatively uniformly distributed fine equiaxed and dendritic grains, whereas the cobalt-based cladding layer comprised coarser columnar and dendritic grains. Therefore, the microstructure of the nickel-based cladding layer was relatively more uniform and finer than that of the cobalt-based layer, resulting in a more significant enhancement in the hardness on the 316L substrate.

3.2. Frictional Wear Performance Analysis

Figure 4 shows the three-dimensional morphology of the wear on the surfaces of the 316L stainless steel substrate and the nickel-based and cobalt-based cladding layers. The substrate surface experienced significant wear, displaying deep and irregular furrows along with a detachment of blocky materials. These signs indicated the presence of abrasive and adhesive wear. By contrast, the cladding layers showed minor signs of wear. The surfaces were relatively smooth, only featuring a small amount of shallow furrows. No significant blocky detachment was observed.

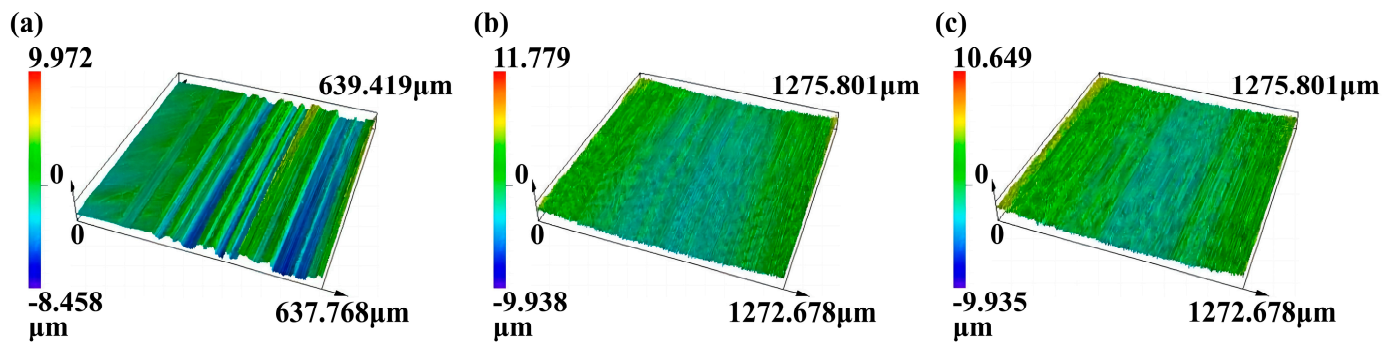


Figure 4. Three-dimensional morphology of wear on the surfaces: (a) 316L stainless steel substrate; (b) nickel-based cladding layer; (c) cobalt-based cladding layer.

Figure 5a shows that the wear of the substrate was 5 mg, and the wear of the nickel-based and cobalt-based cladding layers was 2 mg (40% of the substrate) and 1 mg (20% of the substrate), respectively. Figure 5b shows that the friction coefficient of the substrate fluctuated significantly, and the friction coefficient of the cobalt-based cladding layer fluctuated significantly at the beginning stage but quickly became stable, which was probably caused by frictional coupling. In contrast, the nickel-based cladding layer was relatively stable. The average friction coefficients of the substrate and the nickel-based and cobalt-based cladding layers were 0.178, 0.134, and 0.139, respectively. Notably, the friction coefficient of the substrate increased over time, particularly intensifying after 1200 s. This was primarily because of ineffective debris clearance in the wear region, increasing the friction coefficient.

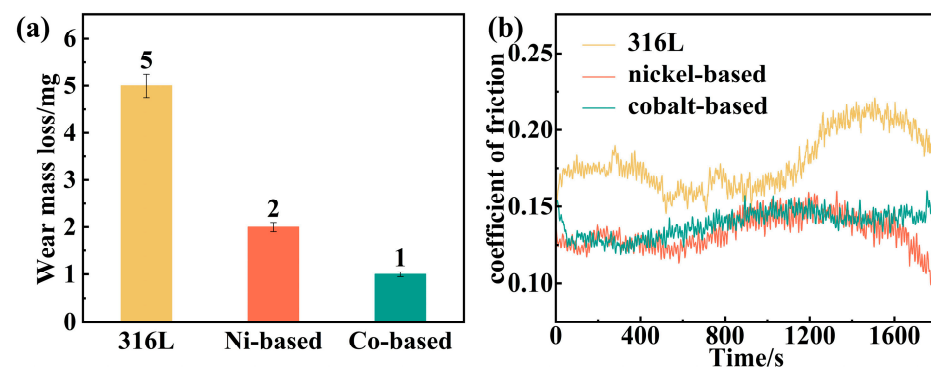


Figure 5. (a) Mass loss; (b) friction coefficient charts of wear after 1800 s of wear on the surfaces of the 316L substrate and the nickel-based and cobalt-based cladding layers.

During the initial running-in period, minimal contact was observed between the surface asperities because of the surface roughness of the substrate and its friction pair. This caused high-stress concentrations at the contact points. The wear resistance was insufficient to withstand this stress, leading to blocky detachment or significant furrows. In addition, the surface asperities of the substrate and its friction pair may undergo plastic deformation or shear. The shear-induced hard particles were in a free form, inducing abrasive wear during the subsequent wear process, causing the formation of new furrows. As the running-in period ended, new stable asperities were formed. However, furrowing phenomena persisted during the wear test, and the high temperatures generated during wear may also lead to the occurrence of adhesive wear. For the cladding layers, the hard strengthening phases such as Cr_7C_3 and Cr_2Ni_3 in the nickel-based cladding layer and Cr_7C_3 and Co_7W_6 in the cobalt-based cladding layer effectively inhibited the movement of dislocations during friction, thereby enhancing the wear resistance of the cladding layers [26,27]. The comparative analysis revealed that the wear of the nickel-based cladding layer was twice that of the cobalt-based cladding layer. We deduced that the cobalt-

based cladding layer had a slightly superior wear resistance than that of the nickel-based cladding layer.

3.3. Electrochemical Corrosion Performance Analysis

Figure 6 shows the Tafel plots of the 316L stainless steel substrate and the nickel-based and cobalt-based cladding layers in both 3.5 wt.% NaCl and 0.5 mol/L H₂SO₄ solutions, indicating that all three samples experienced varying degrees of passivation after a brief period of active dissolution in the two solutions. This indicates that, after the potential reached a certain level, a dense and protective passive film formed on the surface, effectively slowing down the corrosion process. The passive film consisted mainly of chromium oxide, which is essential in enhancing the stability of the passive film. The EDX results also confirmed that all three samples contained a high proportion of Cr.

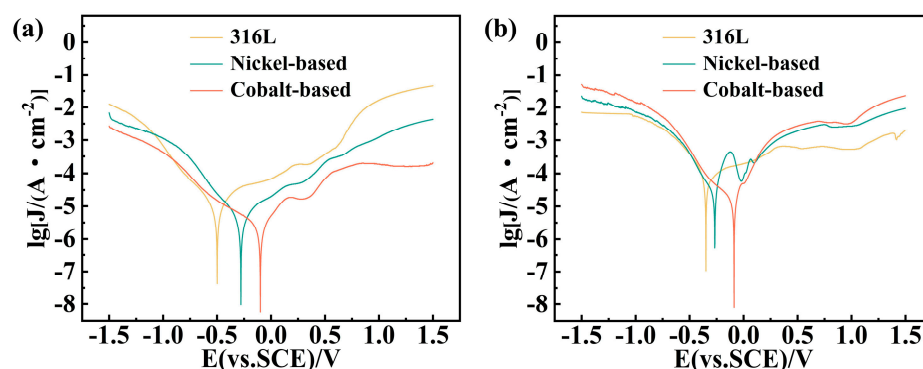


Figure 6. Tafel plots in (a) 3.5 wt.% NaCl solution; (b) 0.5 mol/L H₂SO₄ solution.

In a 3.5 wt.% NaCl solution environment, Figure 6a shows that both nickel-based and cobalt-based cladding layers have a passive range, showing a better corrosion resistance than the substrate material. To compare the dynamic corrosion performance of the three samples, the Tafel extrapolation method was used to fit the polarization curves to obtain the free corrosion potential (E_{corr}) and free corrosion current density (I_{corr}), as presented in Table 4. Compared with the nickel-based cladding layer, the cobalt-based cladding layer has a higher E_{corr} and a lower I_{corr} , which indicates that the cobalt-based cladding layers have a slower corrosion rate and stronger corrosion resistance [28]. In a 0.5 mol/L H₂SO₄ solution environment, Figure 6b shows that all three specimens show an obviously different corrosion behavior due to the weak oxidizing property of the testing solution. Considering the wide active–passive range and high current character, the 316L stainless steel substrate shows rather worse corrosion resistance than the nickel-based and cobalt-based cladding layers [29]. As for both cladding layers, the nickel-based exhibits a higher E_{corr} and a lower I_{corr} in Table 4 compared with the cobalt-based, which means that the cobalt-based cladding layer was less susceptible to corrosion than the nickel-based.

Table 4. Tafel electrochemical parameters.

Materials		316L	Nickel-Based	Cobalt-Based
NaCl	E_{corr}/V	−0.503	−0.279	−0.101
	$I_{\text{corr}}/\mu\text{A}\cdot\text{cm}^{-2}$	4.477	2.075	1.409
H ₂ SO ₄	E_{corr}/V	−0.332	−0.282	−0.097
	$I_{\text{corr}}/\mu\text{A}\cdot\text{cm}^{-2}$	50.351	26.731	13.213

For a deeper understanding of the corrosion performance of the substrate and the cladding layers, equivalent circuit models were employed, as shown in Figure 7, and Nyquist plots were obtained by fitting the data using ZView 3.1 software in both 3.5 wt.% NaCl and 0.5 mol/L H₂SO₄ solutions.

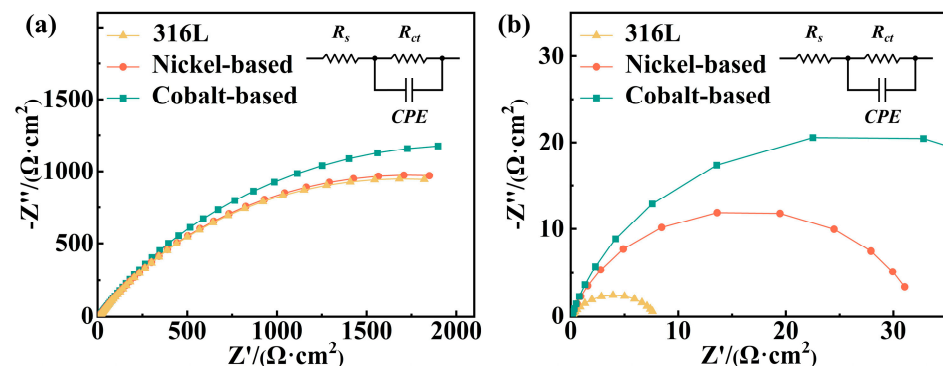


Figure 7. Nyquist plots in (a) 3.5 wt.% NaCl solution; (b) 0.5 mol/L H_2SO_4 solution.

In an equivalent circuit model, CPE represents a constant phase angle difference element instead of an ideal capacitor, R_s represents solution resistance, and R_{ct} represents the charge transfer resistance of the electrode [30]. The test results are presented in Table 5. The R_{ct} value reflects the corrosion resistance of the cladding layers, with lower values indicating more active charge exchange processes and faster corrosion rates. In the 3.5 wt.% NaCl solution environment, the cobalt-based cladding layer had the highest value, followed by the nickel-based and the substrate. Figure 7a shows that all three samples exhibited a single capacitive arc, indicating the presence of a single time constant during the electrochemical corrosion reaction. This stemmed from the homogeneity of the samples and the reaction primarily occurring at the sample-solution interface. Regarding the capacitive arc radius, the cobalt-based cladding layer had the largest, followed by the nickel-based cladding layer and the substrate. The capacitive arc radius reflected the electrochemical impedance of the material surface. A larger radius indicated a higher surface impedance and a better ability to form a passive film, thus a better corrosion resistance [31]. In the 3.5 wt.% NaCl solution environment, Figure 7b shows that all three samples also exhibited a single capacitor arc. Compared with the substrate, the cladding layers showed a larger capacitive arc radius. Table 5 shows that the R_{ct} value of the cladding layers were significantly greater than that of the substrate. Therefore, the experimental results demonstrated that both cladding layers had a superior corrosion resistance compared with the substrate, and the cobalt-based cladding layer slightly outperformed the nickel-based cladding layer. This finding corroborated the results from the Tafel curves.

Table 5. Nyquist electrochemical parameters.

Materials		316L	Nickel-Based	Cobalt-Based
NaCl	$R_s/\Omega \cdot \text{cm}^2$	7.598	7.698	8.527
	$R_{ct}/\Omega \cdot \text{cm}^2$	3382	3466	4093
H_2SO_4	$R_s/\Omega \cdot \text{cm}^2$	0.881	1.966	2.179
	$R_{ct}/\Omega \cdot \text{cm}^2$	7.875	32.43	54.54

3.4. XPS Analysis of Cladding Layers

To further analyze the chemical composition of the cladding layer surfaces, XPS tests were conducted on both the nickel-based and cobalt-based samples. As shown in Figure 8a, the surface of the nickel-based cladding layer primarily consisted of characteristic spectral lines such as C 1s, Fe 2p, Cr 2p, Ni 2p, and Si 2p. Figure 8b–f shows that the cladding layer surface mainly contained different valence state oxides and hydroxides comprising Fe, Cr, Ni, and Si elements. Based on the band theory, the Fe 2p orbitals comprised peaks corresponding to Fe_2O_3 (708.92 eV), Fe_3O_4 (713.66 eV), Fe^0 (721.83 eV), and FeO (711.36 eV). Similarly, the Cr 2p orbitals had peaks corresponding to Cr_2O_3 (575.84 eV), CrO_3 (578.76 eV), $\text{Cr}(\text{OH})_3$ (585.08 eV), and Cr^0 (576.75 eV), primarily existing in the forms of Cr^{3+} and Cr^{6+} . The Ni 2p orbitals contained NiO and its satellite peaks, with binding

energies of 854.60 and 871.62 eV, respectively. They also involved Ni(OH)₂ (860.79 eV) and Ni⁰ (855.93 eV). Meanwhile, the Si 2p orbitals comprised peaks corresponding to SiO₂ (101.13 eV), SiO (101.72 eV), SiC (101.39 eV), and Si⁰ (105.28 eV).

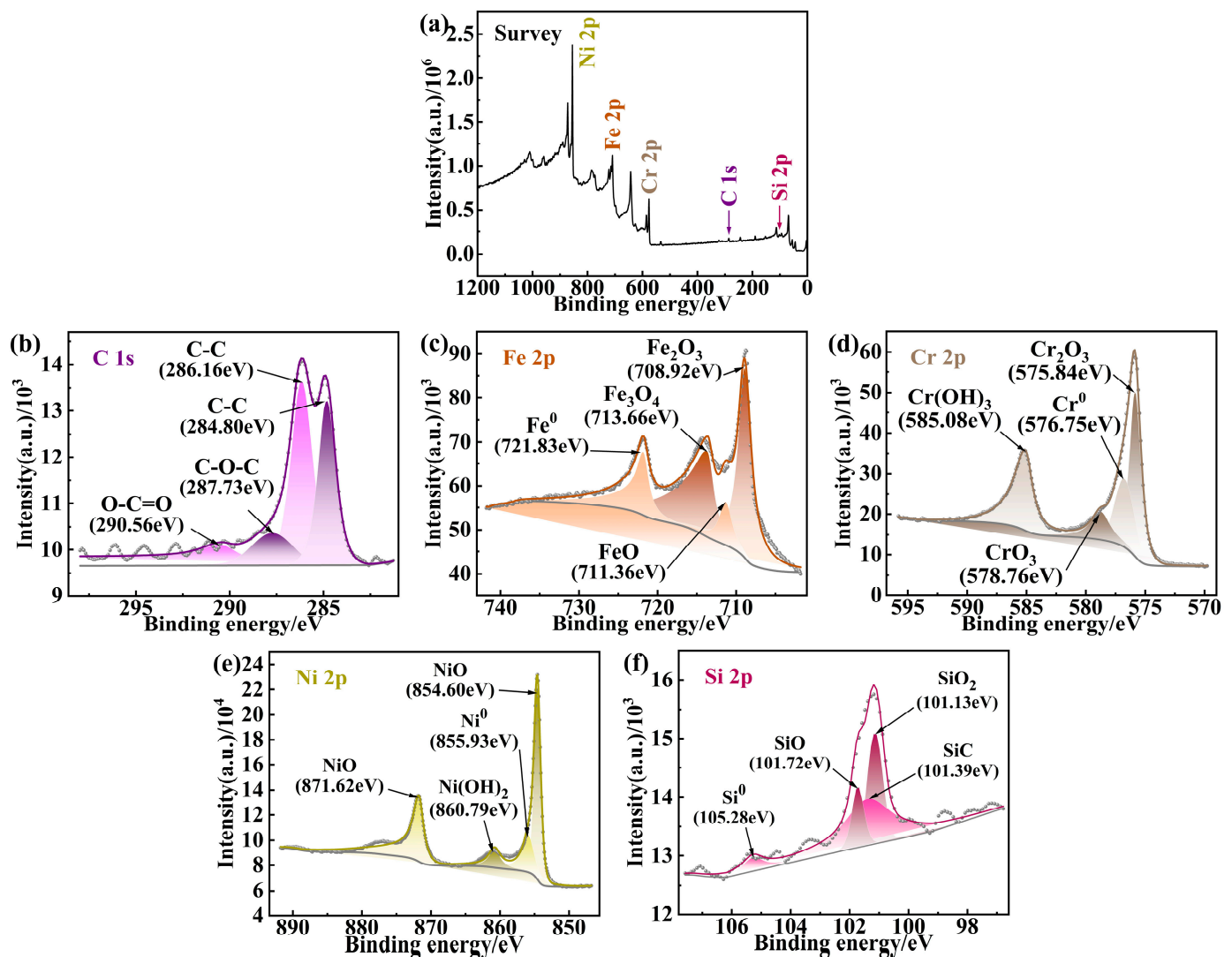


Figure 8. XPS results for the surface of the nickel-based cladding layer: (a) Survey; (b) C 1s; (c) Fe 2p; (d) Cr 2p; (e) Ni 2p; (f) Si 2p.

Figure 9a shows that the surface of the cobalt-based cladding layer primarily contained characteristic spectral lines such as C 1s, Fe 2p, Cr 2p, Ni 2p, W 4f, and Co 2p. Figure 9b–g shows that the cladding layer surface primarily contained different valence state oxides and hydroxides comprising Fe, Cr, Ni, W, and Co elements. Among them, the 2p orbitals of Fe, Cr, and Ni had peaks similar to those in the nickel-based cladding layer. The W 2p orbitals included peaks corresponding to WO₃, W⁰, and its satellite peaks, with binding energies of 33.04, 35.21, 43.88, and 45.28 eV, respectively. Meanwhile, the 2p orbitals of Co consisted of peaks corresponding to Co₃O₄ (780.05 eV), CoO (780.73 eV), Co(OH)₂ (784.51 eV), and Co⁰ (795.05 eV).

Related studies have indicated that oxides such as Fe₂O₃, Cr₂O₃, NiO, and SiO₂ in the nickel-based cladding layer and Fe₂O₃, Cr₂O₃, NiO, WO₃, and Co₃O₄ in the cobalt-based cladding layer can form wear-resistant oxide layers [26,29]. These oxide layers effectively reduce friction and enhance wear resistance. Similarly, the passive films formed by the oxides and hydroxides of elements such as Cr, Ni, and Co in the cladding layers can effectively capture dissolved metal ions and resist environmental attack and penetration,

thus slowing down the corrosion rate and improving the corrosion resistance of the cladding layers. These analytical conclusions align with the experimental results of wear resistance and corrosion resistance performance.

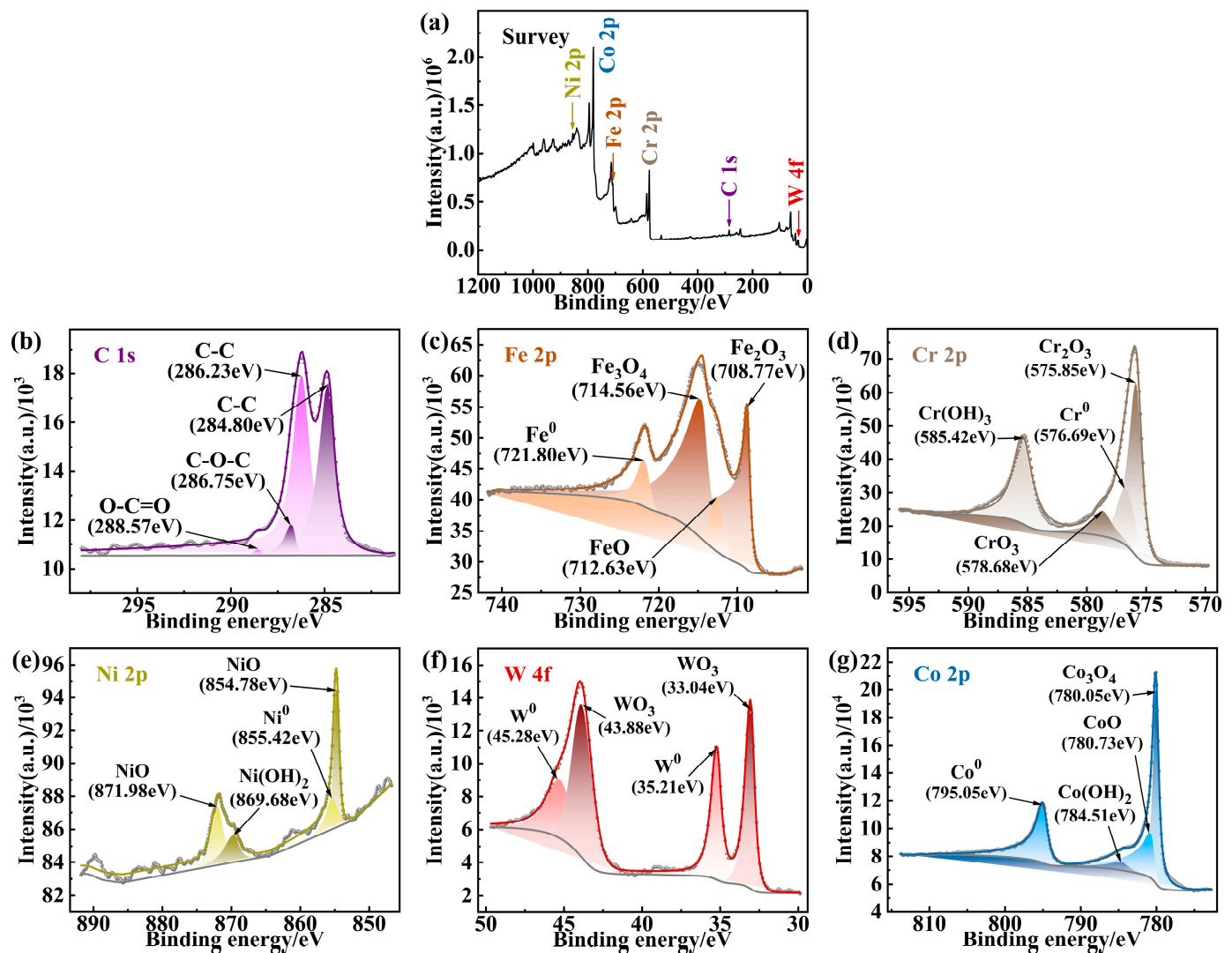


Figure 9. XPS results for the surface of the cobalt-based cladding layer: (a) Survey; (b) C 1s; (c) Fe 2p; (d) Cr 2p; (e) Ni 2p; (f) W 4f; (g) Co 2p.

4. Conclusions

This study prepared nickel-based and cobalt-based cladding layers using laser cladding technology to enhance the surface properties of 316L stainless steel. A comparative analysis of the chemical composition, microstructure, and phase composition of the substrate and cladding layers was conducted, along with tests for microhardness, wear resistance, and corrosion resistance. The research findings are as follows:

- (1) The surface of the nickel-based cladding layer primarily consisted of equiaxed and dendritic grains. The phases primarily included a γ -(Fe, Ni) solid solution and Cr_7C_3 and Ni_3Si compounds, and the oxide layer mainly comprised Fe_2O_3 , Cr_2O_3 , NiO , and SiO_2 . By contrast, the cobalt-based cladding layer primarily comprised columnar and dendritic grains. The dominant phases were γ -Co, Cr_7C_3 , and Co_7W_6 , and the oxide layer primarily comprised Fe_2O_3 , Cr_2O_3 , NiO , WO_3 , and Co_3O_4 .

- (2) The hardness test results showed that the microhardness of the Ni-based cladding layer was about 2.8 times that of the matrix. The microhardness of the cobalt-based cladding layer was about 2.4 times that of the substrate.
- (3) Regarding wear resistance, the wear rates of the nickel-based and cobalt-based cladding layers were 2 and 1 mg, respectively, accounting for 40% and 20% of the substrate. The average friction coefficients of the substrate and the nickel-based and cobalt-based cladding layers were 0.178, 0.134, and 0.139, respectively.
- (4) In 3.5 wt.% NaCl and 0.5 mol/L H₂SO₄ solutions, the free corrosion current densities of the cladding layers were less than those of the substrate, while their charge transfer resistances were higher than those of the substrate.

Our findings are important for understanding the performance of laser-cladding layers and laying a scientific basis for the promotion and optimization of laser cladding technology in industrial applications.

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