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Study on the Effect of CeO₂ on the Performance of WC + Ni60 Laser Cladding Coating

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Abstract: The aim of this investigation was to examine how CeO₂ powder influences the performance of WC + Ni60 composite powder. Various cladding layers of WC + Ni60, incorporating differing mass fractions of CeO₂, were created on the surface of Q235 steel utilizing laser cladding technology. To analyze the microscopic structure of the resulting cladding layer, scanning electron microscopy was employed. Additionally, the abrasion and corrosion resistance properties were assessed through experimentation with a pin-and-disc friction and wear tester and an electrochemical workstation, respectively. The results of the study showed that when the mass fraction of CeO₂ was 1%, the grain on the surface of the coating was refined, the carbide formation was reduced, and the uniformity of the cladding layer was the best. In terms of corrosion resistance, the coating with 1% CeO₂ had a self-corrosion potential of 0.07 V and a self-corrosion current density of $1.82 \times 10^{-5} \text{ A} \cdot \text{cm}^{-2}$, showing the best corrosion resistance, and the coating self-corrosion potential was higher than that of the coating and substrate without CeO₂. In terms of abrasion resistance, coatings with 1% CeO₂ had a lower coefficient of friction (0.47) and a smaller wear rate 0.034 mm^3 , and the wear amount was only 23.5% of that of coatings without CeO₂, resulting in the best wear resistance. In conclusion, coatings containing 1% CeO₂ exhibit the minimal coefficient of friction and the lowest wear rates, while simultaneously providing optimal corrosion resistance.

Keywords: laser cladding; CeO₂; wear; corrosion resistance



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1. Introduction

Bare starling harvesters have been working in seawater and shoal environments for a long time; the working conditions are harsh, and the sand casting device, made of Q235, is prone to wear and is subject to corrosion from seawater, which leads to the failure of the parts and the need for the frequent replacement of parts. This not only reduces the working efficiency, but also increases the cost of use. Therefore, improving the abrasion and corrosion resistance of Q235 steel landing gear and extending its service life has become essential.

Laser cladding technology represents a sophisticated approach to surface modification, employing a high-energy-density laser beam to simultaneously melt both the substrate

and the coating material [1]. This process facilitates rapid solidification, resulting in a surface coating characterized by minimal dilution and a strong metallurgical bond with the underlying material. Such attributes significantly enhance the surface properties of the substrate. By integrating innovative materials and optimizing laser parameters, researchers have continued to expand the applicability of laser cladding across various industries, thereby advancing the field of surface engineering and contributing to the development of more resilient components. Wu, T. et al. [2] used laser cladding technology to prepare two types of coatings on 60Si2Mn spring steel. They examined a cladding configuration that consists of a singular Fe/WC layer, alongside another variant featuring a Ni60 transition layer incorporated with the Fe/WC cladding. The study found that the Ni60 transition layer reduced porosity and cracks, promoting columnar crystal growth. Both coatings consisted of dendritic and eutectic structures, with snowflake-like equiaxed crystals at the top and middle of the Fe/WC coating, and columnar crystals at the bottom. The diffusion of Ni elements decreased microhardness and increased the friction coefficient.

Husen Yang et al. [3] created a composite coating consisting of 60% Ni60 and 60% tungsten carbide (WC) on a base of 316 L stainless steel. They used a technique called laser-directed energy deposition to apply the coating. The aim of their work was to understand how different levels of laser power would change the way the coating's microscopic structure formed and its overall mechanical qualities. They also looked at how the coating's chemical composition, its internal structure, its hardness, and its ability to resist wear and friction were all connected. The research revealed that the amount of energy delivered by the laser, as measured by its power, played a key role in how much energy was absorbed by the material. This energy level determined how much of the Ni60 phase around the WC particles would melt and how well the reinforcing particles would bond with the substrate or the existing coating. As the laser power was increased from 800 W to 1400 W, the coating became more compact, and its surface hardness increased at first before it started to decrease. At the same time, the friction that the coating experienced decreased, with the least wear occurring at a laser power setting of 1200 W. These results emphasize that the laser power is a crucial factor in adjusting the microstructure and enhancing the properties of the coatings produced through laser deposition.

In a study by Xu et al. [4], two nickel-based composite coatings were synthesized on TC4 titanium alloy substrates via laser cladding techniques. These coatings were formulated as Ni60-Ti-Cu-xB4C and Ni60-Ti-Cu-B4C-xCeO₂. Notably, the inclusion of 8 wt.% B4C in the coating composition resulted in a maximum hardness of 1078 HV, which is 3.37 times greater than the hardness of the TC4 base material. Furthermore, the friction coefficient was reduced by 24.7%, and the wear rate was a mere 2.7% of that observed for the TC4 substrate. Similarly, when the CeO₂ content was increased to 3 wt.%, the coating hardness increased to an average of 1105 HV, which is 3.45 times higher than the TC4 substrate's hardness. This enhancement in hardness was accompanied by a further decrease in the friction coefficient of 33.7% and a wear rate that was just 1.8% of the TC4 material's rate. These findings highlight the potential of laser cladding to produce coatings with superior mechanical properties for titanium alloys.

In a collaborative effort led by Xue, K. et al. [5], a Ni25 alloy was utilized to create a transition layer on the compromised surface of H13 tool steel through the application of laser cladding. Following this, an Fe104 alloy was applied to form a reinforcing layer. The researchers conducted a comprehensive analysis to examine how the Ni25 transition layer influenced the phase composition, the internal structure, the hardness at a microscopic level, and the wear characteristics of the Fe104 layer. The results showed that the Ni25 transition layer could improve the comprehensive performance of the Fe104 layer, but could also lead to a decline in some mechanical properties.

In research conducted by Yang et al. [6], the investigators incorporated differing concentrations of ceria dioxide (CeO_2) into the composition of an $\text{AlCoCrFeNi}_{2.1}$ alloy powder. Subsequently, they applied this alloyed powder to fabricate coatings on the H13 steel substrate via the laser cladding method. The investigation revealed that the inclusion of 3% CeO_2 within the alloy yielded multiple advantageous outcomes. Initially, this addition was found to significantly decrease the prevalence of cracks, pores, and inclusions, which are detrimental imperfections capable of compromising the structural integrity of coatings. Furthermore, the presence of CeO_2 stimulated the growth of a finer grain structure within the coatings, a characteristic that contributes to the material's increased strength and robustness. Moreover, the integration of CeO_2 resulted in a more consistent microstructure and a higher hardness for the surface coatings. These enhancements not only augmented the coating's resistance to wear but also substantially improved its resistance to corrosion, thereby rendering the composite coating more resilient and appropriate for environments demanding robustness against both wear and corrosive agents.

Based on existing research findings, various aspects have been explored regarding the combination of Fe/WC overlay layers and Ni60 transition layers, Ni60/60% WC composite coatings, and nickel-based composite coatings containing B4C and CeO_2 . Among these, WC has the effect of improving hardness [7], while Ni60 can impact the bonding performance between the coating and substrate [8–10]. CeO_2 has also been shown to have a significant influence on the coating hardness and friction coefficient in previous studies. However, there is relatively limited research on the simultaneous combination of CeO_2 , WC, and Ni60 in overlay layers. Conducting research on CeO_2 + WC + Ni60 overlay layers, by combining these three components, holds the promise of enhancing the coating's mechanical attributes, including its hardness and resistance to frictional wear, thus augmenting its performance in engineering contexts.

2. Experimental Materials, Methods, and Equipment

2.1. Materials

This experiment chooses Q235 steel as the base material, which has a general hardness between HB 100 and 150; at a relatively low hardness, it is easy to carry out a variety of mechanical processing techniques. The wear resistance is general; in some cases that require high wear resistance, it may be necessary to take measures such as surface treatment to improve its wear resistance. Due to its good mechanical properties and economy, it is widely used in construction and manufacturing industries. To improve the wear and corrosion resistance of Q235 steel, a surface coating consisting of Ni60, WC, and CeO_2 is employed, as detailed in Table 1. The Ni60 alloy, known for its superior properties, serves as the primary coating material, thereby significantly enhancing the material's overall performance and extending its service life.

Table 1. The proportions of Ni60, WC and CeO_2 (mass fraction, %).

Ni60	WC	CeO_2
75	25	0
74	25	1
73	25	2

According to the SEM results, the quality fraction of the elements in Ni60 is shown in Table 2, and their microscopic morphology is mostly spherical, as shown in Figure 1a. This morphology helps the coating to form a uniform coating layer on the substrate surface, thus enhancing the adhesion and wear resistance of the coating. The size distribution of powder also has important effects on the formation of the coating and its properties. The Ni60

(Tsuengyue Metal Materials Co., Santai, Sichuan, China) powder is shown in Figure 1b; the maximum particle size is 133.43 μm , the minimum particle size is 45.89 μm , the average particle size is 85.14 μm , and the powder size meets the normal distribution. This property indicates that the particle size distribution of the chosen powder is appropriate for the coating procedure. Such a distribution enhances both the mobility and filling capabilities, ultimately facilitating the more cohesive and uniform application of the coating.

Table 2. Ni60 powder and Q235 chemical composition (mass fraction, %).

Element	C	Cr	B	Mn	Si	Fe	P	S	Ni
Ni60	0.8–1.2	14–16	3–3.5	-	3.5–4.0	14–15	0.02	0.02	Bal
Q235	0.22	-	-	0.3–0.7	0.35	Bal	0.045	0.05	-

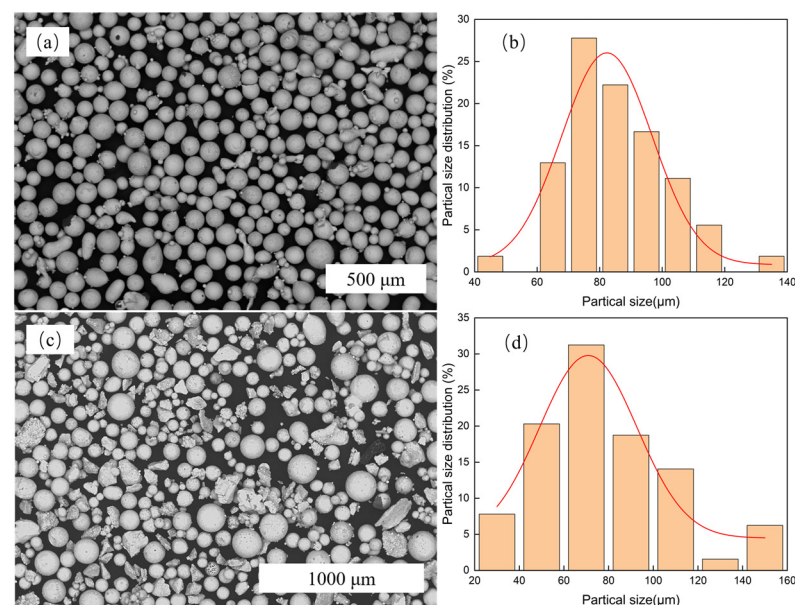


Figure 1. Morphology and particle size distribution of mixed powder. (a) Ni60 material morphology, (b) Ni60 material size, (c) WC material morphology, (d) WC material size.

The coating contains WC (Tsuengyue Metal Materials Co., Santai, Sichuan, China), as shown in Figure 1c, which is a hard material that significantly improves the hardness and wear resistance of the coating. The particle size coincidence analysis of WC is shown in Figure 1d; the standard deviation is 15.65, the maximum particle size is 156.96 μm , the minimum particle size is 24.16 μm , the average particle size is 77.86 μm , and the powder size conforms to the normal distribution. This particle size characteristic makes it possible to strengthen the coating, and the strength and toughness of the coating can be effectively enhanced through reasonable particle size selection.

2.2. Equipment and Methods

Laser cladding: In this experimental process, the laser cladding test was carried out by using the XL-F2000T laser (Guangzhou Xingrhenium Laser Technology Co., Ltd., Guangzhou, China) as the experimental facility, with the power parameter set at 1200 W, the scanning rate set at 800 mm/min, and the defocusing amount constant set at 3 mm. CeO_2 , WC, and Ni60 powders were selected for the experiments and mixed according to specific ratios, and then pre-packed onto the Q235 steel plate substrate, with the thickness of the powder precisely controlled to 1 mm; then, the multi-pass cladding process was implemented.

Scanning electron microscopy: Following the polishing and treatment of the experimental specimens, their surface morphology was analyzed and recorded using a Czech MIRA3 scanning electron microscope (SEM) (Brno, Czech Republic). This investigation focused on understanding the interactions between the matrix and the reinforcing phases while also characterizing the microstructural attributes of the coating. Additionally, the elemental distribution within the coating was assessed using an energy-dispersive spectrometer (EDS), allowing for both qualitative and quantitative evaluations.

The phase composition of the coatings was assessed through the use of a Shimadzu XRD-6100 X-ray diffractometer (Shimadzu, Tokyo, Japan). This analysis involved a diffraction scanning range that spanned from 10 to 90 degrees, with a meticulous scanning step of 0.04 degrees and a scanning speed of 6° per minute. By employing this method, we ensured a comprehensive examination of the coatings' structural characteristics, thereby facilitating a clearer understanding of their properties and potential applications.

Friction and wear: To investigate the abrasion resistance of the coatings, the cross-sectional abrasion resistance of the coated samples was assessed utilizing the SFT-2M friction and wear testing apparatus manufactured by CKH Technology Development Co. (Zhongkehua Science and Technology Development Co., Ltd., Lanzhou, China). The dimensions of the friction and wear test specimen were 15 mm by 15 mm, with GCr15 steel serving as the material for the friction vice. The parameters for the wear test included a loading force of 60 N, a duration of 30 min, an operational speed of 200 revolutions per minute, a rotational radius of 2.5 mm, and a scanning length of 3 mm.

The characterization of electrochemical workstations: In this study, the CS Studio electrochemical workstation was employed to evaluate the corrosion resistance properties of the tested samples. Given that seawater predominantly consists of a high concentration of sodium chloride (NaCl), along with trace amounts of other salts, the corrosive medium was configured as an aqueous solution of NaCl with a mass fraction of 0.035 to mimic the corrosive seawater environment. This was done to prevent the inclusion of additional contaminants that could introduce variability into the assessment of corrosion factors. The experimental setup included a pre-test electrode system, which utilized a three-electrode electrochemical cell. The coated sample served as the working electrode, while the platinum sheet and the saturated calomel electrode (SCE) were designated as the auxiliary and reference electrodes, respectively. The scanning rate was adjusted to 0.5 mV per second, and the sampling frequency was set at 1 hertz. Polarization curves were derived from the analysis of the experimental data, and the corrosion potentials and currents for each sample were determined from these curves, thereby enabling an evaluation of the materials' corrosion resistance.

3. Results and Analysis

3.1. Coating Morphology

Figure 2 clearly indicates that there are no significant pores or cracks present. This feature is crucial for the performance of the coating, as the presence of pores and cracks often greatly weakens the mechanical properties, corrosion resistance, and other key performance indicators of coatings.

In the fusion-coated coating without CeO₂ addition, a high number of WC particles can be clearly recognized. As shown in Figure 2a, there are 15 white particles. These WC particles are responsible for enhancing the hardness and wear resistance of the coating system [11,12], and contribute to the strengthening of the overall performance of the coating. After the introduction of CeO₂, the microstructure of the coatings underwent a significant evolution. Specifically, the CeO₂-added coating exhibits a clearly recognizable white bright band in the area of the fusion mark. At the same time, the number of WC

particles decreases compared to the coating without CeO_2 . The number of white particles decreases to 11 in Figure 2b, and further decreases to 9 in Figure 2c. This phenomenon is most likely attributed to the substantial interference and remodeling of the solidification process and the microstructure formation mechanism of the coatings with CeO_2 . During the solidification process, CeO_2 may affect the temperature distribution, elemental diffusion behavior and crystal growth kinetics of the molten pool, which may alter the dissolution of WC particles and ultimately lead to a reduction in the number of WC particles [13], which is a special microstructural feature; this microstructural transformation may be further associated with a change in the macroscopic properties of the coating [14], which is worthy of in-depth investigation and analysis.

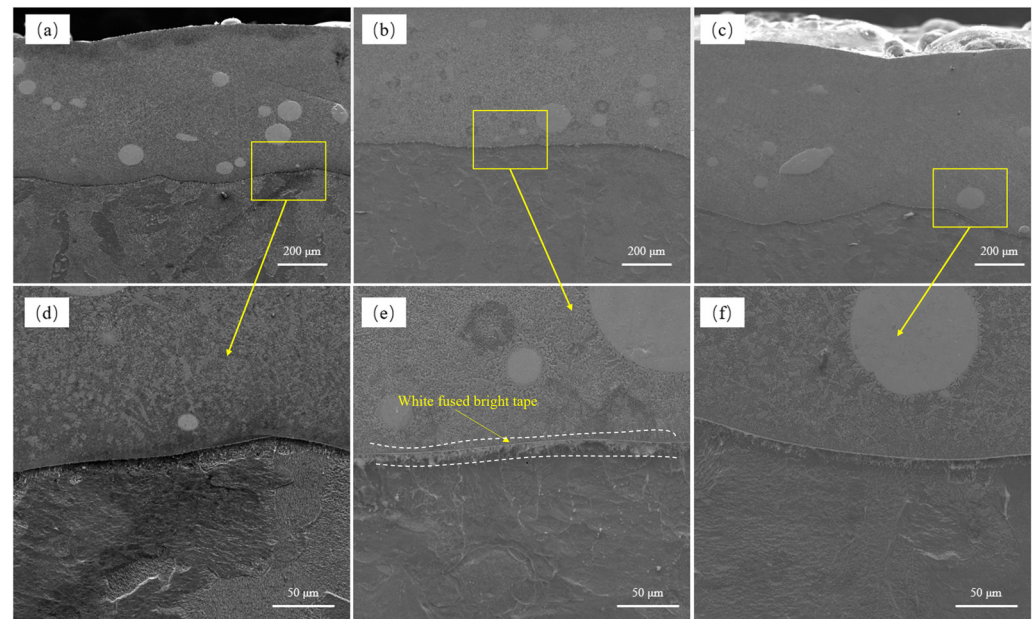


Figure 2. Interface morphology with different amounts of CeO_2 . (a) Topography of the cross-section without CeO_2 and (b) 1% CeO_2 . (c) Cross-sectional morphology of 2% CeO_2 . (d) Enlarged view at the weld line without CeO_2 addition. (e) Enlarged view at the 1% CeO_2 weld line. (f) Enlarged view at the 2% CeO_2 weld line.

When CeO_2 is added, the width of the white bright band at the fusion mark increases, in which case the diffusion and fusion between the cladding material and the substrate are more significant, which positively affects the bond strength. During this process, Ce elements may react with Fe, Cr, Ni and other elements in Ni60 alloys and form intermetallic compounds. The formation and distribution of these intermetallic compounds at the fusion marks can effectively strengthen the bonding strength between the cladding layer and the substrate [11]. At the same time, the introduction of CeO_2 may lead to the formation of more rare-earth compound phases. These rare-earth compound phases are enriched or diffusely distributed at the fusion marks, and their presence has a significant impact on the diffusion and fusion mechanism between the cladding material and the substrate [12], thus changing the bonding characteristics and overall performance of the cladding layer and the substrate at the microstructural level.

Figure 2b,e correspond to a coating with 1% CeO_2 . In both images, the bright white band at the weld mark is the widest and most distinct. This indicates that the microstructure of the coating has undergone a special microstructural change during the welding process with the addition of CeO_2 . This variation may be related to the effects of CeO_2 on the solidification kinetics, crystallization behavior, and elemental diffusion of the coating.

Figure 2c,f show the topography of the 2% CeO₂ coating and an enlarged view near the weld scar. As is evident, the weld line appears as white and wavy. This unique morphology may be due to a combination of specific thermal stresses, hydrodynamic effects, and chemical reactions during the welding process at this CeO₂ addition. Further study of the formation mechanism of this wavy weld line is of great significance for understanding the effect of CeO₂ on coating properties and for optimizing the preparation process of coatings.

3.2. Phase Analysis

Through the analysis of XRD patterns (Figure 3), it was found that the effect of CeO₂ additives in the laser cladding Ni60 + WC powder system was determined by precise X-ray diffraction (XRD) analysis, which performed a detailed phase characterization of the coatings without and with different proportions of CeO₂. The experiment showed that the presence of r-(Fe, Ni) solid solution, carbide M₂₃C₆, and FeNi₃ phases was mainly detected in the reference coating without CeO₂ [13]. However, when CeO₂ was introduced into the cladding system as an additive, it not only maintained the basal phase mentioned above, but also significantly induced the formation of a new phase, CeNi, which directly confirmed the chemical activity of CeO₂ during the cladding process and its effect on the phase composition [14].

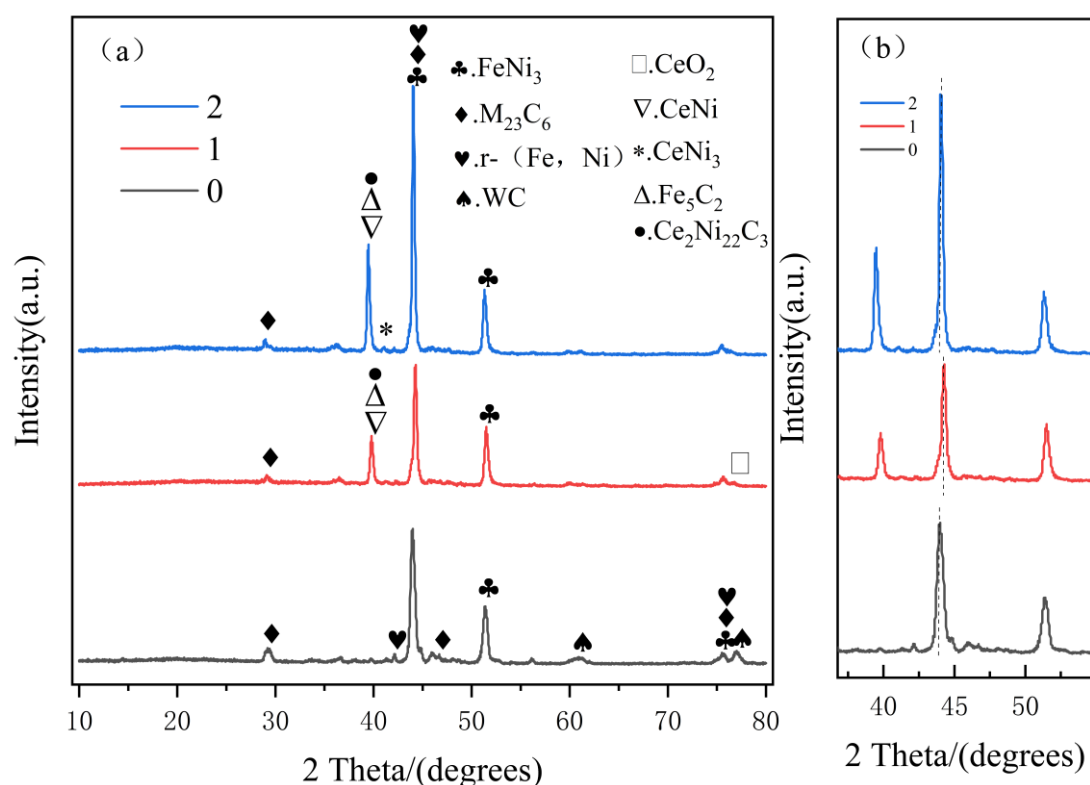


Figure 3. XRD diffraction spectrum analysis. (a) Diffraction patterns of fused cladding layers with different contents of CeO₂. (b) The main diffraction peak magnification shows a different amount of CeO₂.

By further analyzing the XRD pattern, it can be observed that in Figure 3b, with the addition of CeO₂, there is a subtle but identifiable shift in the position of specific diffraction peaks. This is typically attributed to changes in lattice parameters, possibly due to the formation of new phases or the influence of CeO₂ on the existing phase structure. The intensity of the 1% CeO₂ diffraction peak decreased, indicating that the grain in the coating was refined [15]. The intensity of the diffraction peak at 2% CeO₂ is significantly enhanced compared to the coating without CeO₂, with a significant increase in the carbide

concentration. CeO_2 , as a rare-earth oxide with excellent catalytic performance, may promote the chemical reaction between WC powder and the Ni60 matrix through multiple paths, including, but not limited to, reducing the activation energy of the chemical reaction, so as to overcome the energy barrier, so that the reaction that does not occur easily at high temperatures can be carried out smoothly, thereby promoting the formation and accumulation of carbide phases. The addition of CeO_2 also significantly improves the fluidity and nucleation dynamics of the melt pool [16]. Its unique physical properties, such as reducing the surface tension and critical nucleation resistance of liquid metal, effectively promote the uniform mixing and full reaction of various chemical components in the molten pool, and create more favorable conditions for the formation of carbides. At the same time, CeO_2 may also act as a nucleating agent [17], promoting grain refinement and increasing the number of grain boundaries and phase boundaries; these interfaces serve as preferred sites for carbide nucleation and growth, further improving the efficiency and quantity of carbide formation.

As the CeO_2 content increased to 2%, the chemical reaction path and equilibrium state in the molten pool changed, resulting in more WC powder participating in the carbide formation reaction. In addition, CeO_2 may undergo complex chemical reactions with other molten pool elements to form new compounds or interphases, which further promote the stabilization and growth of the carbide phase, which is manifested as a significant increase in the intensity of the corresponding diffraction peaks [18].

3.3. Coated SEM and Energy Spectrum Analysis

In the laser cladding Ni60 + WC composite powder system, the effect of CeO_2 on the microstructure and chemical composition of the cladding layer was systematically studied by introducing CeO_2 as an additive and increasing its content from 1% to 2%; the following detailed observation and analysis results were obtained.

Figure 4a demonstrates the results of the energy spectral analysis of Spectrum A in the microscopic region (Table 3), at the middle position of the fused cladding layer without added CeO_2 , where the mass percentage of W element is as high as 26.43%, and the atomic ratio of carbon (C) is 10.88%. These data combinations show the aggregation of WC phases, possibly due to the lack of an efficient refinement or dispersion mechanism. The analysis of Ni in Spectrum B revealed a mass percentage of 58.59%, indicating that Ni is the main component in this region.

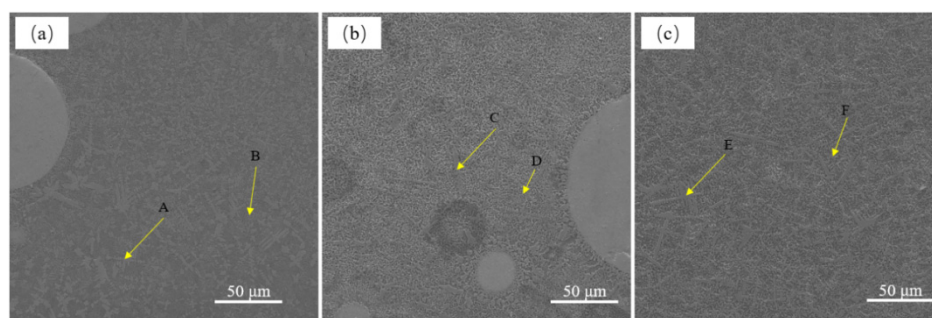


Figure 4. Coating EDS scan points with different CeO_2 contents. (a) EDS scanning points without added CeO_2 . (b) EDS scanning points with 1% CeO_2 content. (c) EDS scanning points with 2% CeO_2 content.

Table 3. Distribution of the main elements of EDS scan points.

Element		B	C	Si	Ce	Cr	Fe	Ni	W
Spectrum A	Weight %	0.54	2.12	0.41	-	10.78	18.07	41.11	26.43
	Atomic %	3.09	10.88	0.89	-	12.8	19.98	43.24	8.88
Spectrum B	Weight %	1.74	1.11	0.77	0.74	5.29	24.93	58.59	6.83
	Atomic %	8.61	4.94	1.46	0.28	5.45	23.88	53.39	1.99
Spectrum C	Weight %	1.33	3.27	0.64	0.55	14.22	15.79	34.12	30.09
	Atomic %	7.16	15.78	1.32	0.23	15.87	16.41	33.73	9.5
Spectrum D	Weight %	3.05	1.82	0.25	0.47	11.63	21.4	47	14.37
	Atomic %	14.62	7.84	0.46	0.17	11.57	19.84	41.44	4.05
Spectrum E	Weight %	0.39	2.26	0.4	0.55	14.12	11.41	30.5	40.37
	Atomic %	2.45	12.94	0.98	0.27	18.63	14.02	35.64	15.07
Spectrum F	Weight %	0.87	1.56	0.44	0.49	11.85	19.78	43.76	21.26
	Atomic %	4.8	7.75	0.93	0.21	13.64	21.18	44.58	6.91

Figure 4b and Table 3 shows that the atomic ratios of Cr, Fe, and Ni are 15.87%, 16.41%, and 33.73%, respectively, while the atomic ratios of carbon (C) increase to 15.78%, respectively. Notably, the atomic ratios of these elements are close to the stoichiometric ratios (23:6) of the $M_{23}C_6$ (M stands for Ni, Fe, Cr) complex carbides, thus strongly supporting the conclusion that dendritic tissues are identified as $M_{23}C_6$ complex carbides [19]. The mass percentage of Ni and the mass percentage of Fe in Spectrum D are 47%, and the mass percentage of Fe is 21.4%; the supersaturated solid solution with C, W, Cr and other elements is solidly dissolved [20,21].

In addition, the discovery of boron (B) in Spectrum D with a mass percentage of 3.05% and an atomic ratio of 14.62% confirms the presence of borides, which may be due to impurities in the original powder or the formation of by-products during the reaction.

The changes in the microstructure when the CeO_2 content is increased to 2% are shown in Figure 4c. The energy spectrum analysis of Spectrum E showed that the mass ratio of W increased significantly to 40.37%, while the atomic ratio reached 15.07% and the atomic ratio of carbon (C) was 12.94%. At this time, the atomic ratio of W to C approached 1:1, and the aggregation of the WC phase appeared, which may be related to the effect of CeO_2 on the growth kinetics of the WC phase at a high concentration. The analysis of Spectrum F for Ni showed that its mass percentage was 43.76%, and when adding 2% CeO_2 , r-(Ni) supersaturated solid solution became the dominant phase state in this region, which may be related to the stabilizing effect of CeO_2 on the Ni matrix phase and its ability to promote the formation of solid solutions.

Figure 5a shows a scanning electron microscope (SEM) image of the cladding layer without CeO_2 , and after a careful microstructural analysis, small holes in the cladding layer can be observed. The formation of these holes is most likely due to the failure of the internally generated CO_2 gas to escape in time during the rapid cooling of the melt pool, leaving these defects in the solidified coating [22]. Further observation shows that the coating is mainly composed of irregularly shaped blocks and secondary dendrites, and these structural characteristics indicate that the distribution of the strengthening phase in the coating is uneven, which may adversely affect the overall performance of the coating.

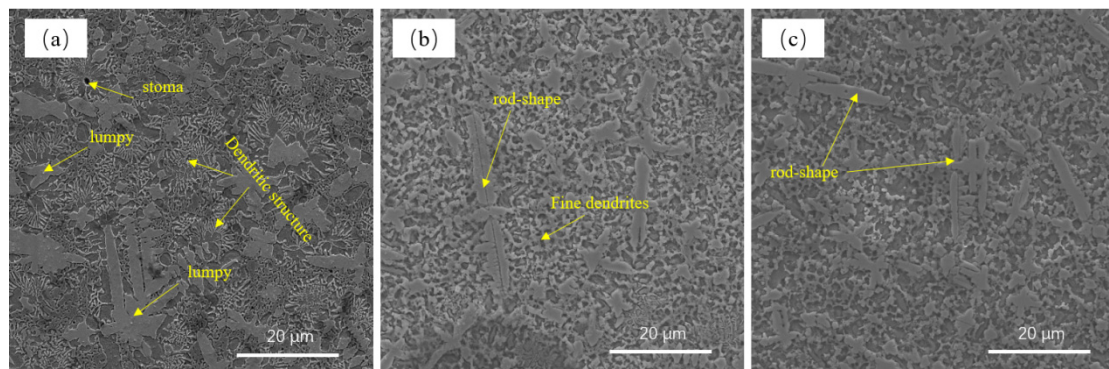


Figure 5. Microstructure with different CeO_2 contents. (a) 2000-fold microstructure without added CeO_2 . (b) 2000-fold microstructure containing 1% CeO_2 . (c) 2000-fold microstructure containing 2% CeO_2 .

When 1% CeO_2 is added to the feedstock, the microstructure of the cladding layer changes significantly, as shown in Figure 5b. At this time, the cladding layer is mainly composed of reticulated and needle-like structures, the grain size is significantly reduced, which can make the microstructure size more uniform, and the refinement effect is significant; the grain size can be determined by the XRD diagram shown in Figure 3a [23]. The reason for this change is that trace amounts of active Ce ions play a key role in the melt pool. They are easily adsorbed onto the surface of the crystal nucleus, forming a barrier layer, which effectively hinders the further growth of the grain and allows the tissue to be refined [24]. At the same time, the addition of Ce ions also reduces the supercooling phenomenon of the components in the solidification process, reduces the degree of segregation between the components, and weakens the directionality of dendrite growth, which makes the structure of the cladding layer more uniform.

Figure 5c shows the SEM image of the coating when 2% CeO_2 is added to the composite feedstock. At this time, the cladding layer is mainly composed of equiaxed crystals and rods, and the number of small blocks increases. This phenomenon indicates that with the increase in the amount of CeO_2 added, the ability of rare earth elements to promote the fluidity of liquid metals gradually emerges. The addition of rare-earth elements can reduce the melting point and surface tension of liquid metal, thereby improving the fluidity of liquid metal. This increased fluidity facilitates the chemical reaction, which facilitates the generation of more compounds [25]. However, it is also important to note that excess REEs may lead to more lumps in the coating, which may have an impact on the mechanical properties and corrosion resistance of the coating. Therefore, when preparing the cladding layer, it is necessary to reasonably control the addition of rare-earth elements to obtain the best coating performance.

3.4. Friction and Wear Analysis

Figure 6a–c show the data for the coefficient of friction of the coating. Figure 6a shows that the coefficient of friction of the cladding coating surface fluctuates within the range of 0.50 to 0.53 without the addition of CeO_2 .

When 1% CeO_2 is added, the coefficient of friction stabilizes at around 0.47. With the addition of 2% CeO_2 , the coefficient of friction fluctuates between 0.52 and 0.67. Through a comparative analysis of the coefficient of friction under different addition ratios, it can be clearly seen that the coefficient of friction of the cladding surface with 1% CeO_2 is the smallest. Figure 6b shows the friction and wear topography. A closer comparison shows that the mixed-powder coating with 1% CeO_2 performs best in terms of wear and wears the least. Figure 6c shows a wear of 0.146 mm^3 on the cladding coating surface without the

addition of CeO_2 . When 1% CeO_2 is added, the amount of wear is significantly reduced to 0.034 mm^3 , which is 0.112 mm^3 less than the amount of coating wear without CeO_2 . With the addition of 2% CeO_2 , the amount of wear is 0.039 mm^3 . It can be seen that adding the right amount of CeO_2 can effectively reduce the amount of wear on the cladding coating surface, and that the best results are achieved at a 1% addition ratio. This phenomenon may be due to the addition of CeO_2 , which alters the microstructure and mechanical properties of the coating [26], thereby improving the wear and friction resistance of the coating. Further research could explore the mechanism of the influence of CeO_2 on coating performance and the mechanism of coating performance change under different addition ratios, so as to provide a theoretical basis and technical support for optimizing the coating design and improving the coating performance.

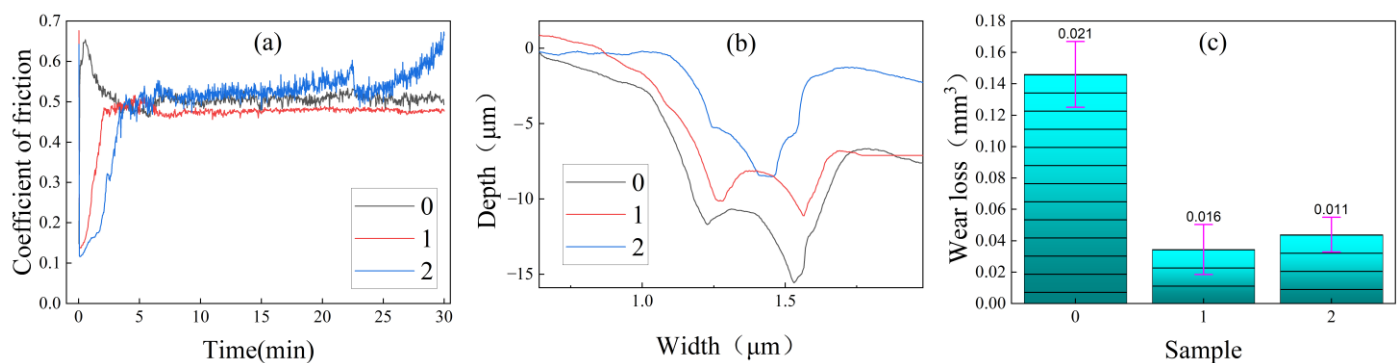


Figure 6. Friction and wear. (a) Coefficient of friction of each coating surface. (b) Wear profile. (c) Amount of wear.

Without the addition of CeO_2 , as shown in Figure 7a, a furrow topography with a width of $760 \mu\text{m}$ is presented. This furrow topography is one of the typical features of abrasive wear. Abrasive wear is usually caused by hard particles or hard protrusions cutting and scratching the surface of the material during friction. In this case, it is the detached particles produced by the friction pair itself during the friction process that act as an abrasive. From a microscopic point of view, these abrasives are constantly cutting the surface of the material under the action of relative motion, resulting in a pronounced furrow. At the same time, the electron microscope image with a local magnification of 2000 times, as shown in Figure 7d, shows the presence of friction debris, which further confirms that it is mainly abrasive wear. These chips may be formed by the continuous shedding of the material under the cutting action of the abrasive. The degree of abrasive wear is usually closely related to factors such as the hardness, shape, and size of the abrasive, as well as the relative movement speed of the friction pair.

The abrasion topography for when 1% CeO_2 is added is shown in Figure 7b. The width of the abrasion mark is approximately $620 \mu\text{m}$, which is reduced compared to that without the addition of CeO_2 . Very little debris can be seen at this point, and there are obvious sticking marks and strains on the worn surface, indicating that it may be mainly adhesive wear. Adhesive wear is caused by the instantaneous high temperature generated at the contact point under the action of high pressure and the temperature generated when the two contact surfaces move relative to each other, which softens or melts the surface of the material, resulting in the adhesion of the material on the contact surface. In the subsequent relative motion, the adhesive point is sheared, resulting in adhesive wear. This is because fine grains can increase the strength and hardness of the material, but they can also change the surface properties of the material. After grain refinement, the surface of the material is more uniform and the contact area increases, which makes it easier to form adhesive points during friction. Reducing the coefficient of surface friction in CeO_2 also has

an effect on the adhesive wear. A decrease in the coefficient of surface friction means that during relative motion, the frictional force decreases. A lower coefficient of friction may result in a smoother relative motion between the contact surfaces, increasing the likelihood of adhesion [27]. When there is less friction between two surfaces, they are more likely to come into close contact, forming sticking points.

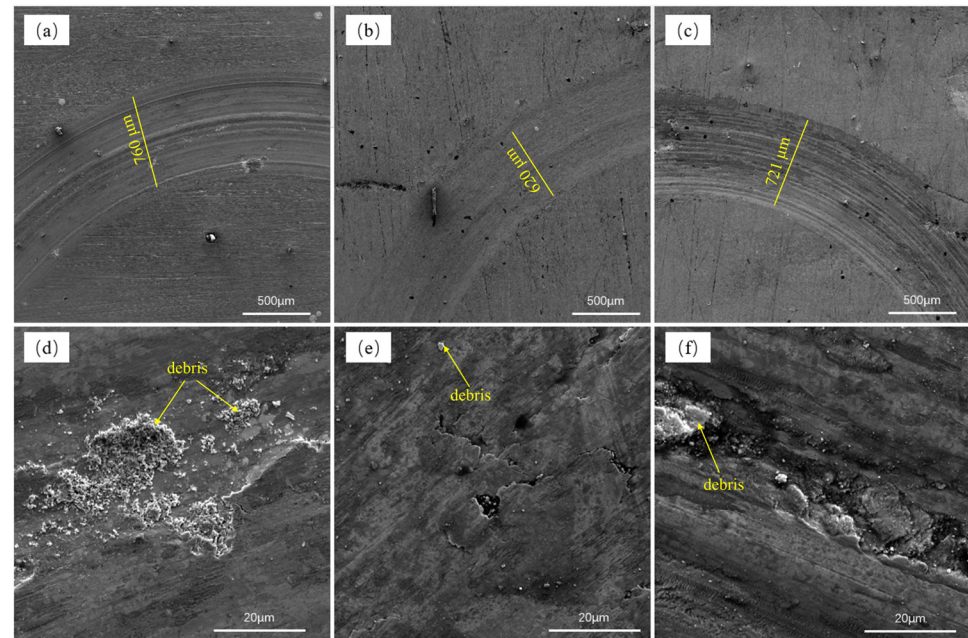


Figure 7. Scanning electron microscope (SEM) image after wear. (a) Post-wear morphology of fused cladding layer with CeO₂ mass fraction 0. (b) Post-wear morphology of fused cladding layer with CeO₂ mass fraction 1. (c) Fused cladding layer with CeO₂ mass fraction of 2 after abrasion. (d) Localized magnification of the furrows after abrasion of the fused cladding layer with a CeO₂ mass fraction of 0 by a factor of 2000. (e) Localized magnification of the furrows after the abrasion of the fused cladding layer with a CeO₂ mass fraction of 1 by a factor of 2000. (f) Localized magnification of the furrows after the abrasion of the fused cladding layer with a CeO₂ mass fraction of 2 by a factor of 2000.

The topography after wear for when 2% CeO₂ is added is shown in Figure 7c, with a width of about 721 μm in the wear scar groove. A partial enlargement of Figure 7f shows streamlined marks, the appearance of debris, and strain on the wear surface, suggesting possible mixed wear. There are multiple wear mechanisms operating at the same time during friction. In this case, it may be a combination of abrasive wear, adhesive wear, and other wear mechanisms [28–30]. The appearance of chips can be a sign of abrasive wear, while the phenomenon of strain is related to adhesive wear. The case of mixed wear is complex and requires a combination of factors.

3.5. Corrosion Resistance Analysis

The polarization curves in Figure 8 show that the corrosion resistance of the cladding layer is better than that of the base material (Q235). Combined with the values in Table 4, it is clear that the self-corrosion potential of the substrate is −0.78 V, the self-corrosion current density is $5.81 \times 10^{-4} \text{ A}\cdot\text{cm}^{-2}$, the self-corrosion potential of the mixed-powder cladding coating without CeO₂ is −0.67 V, and the self-corrosion current density is $2.87 \times 10^{-5} \text{ A}\cdot\text{cm}^{-2}$; the current density is significantly lower because the high temperature causes the WC and Ni60 powders to melt and mix rapidly. This is followed by rapid cooling and solidification during the laser cladding process. This rapid thermal cycling process contributes to the formation of a dense coating structure, reducing defects

such as porosity and cracks [31,32]. Porosity and cracks are often channels for the intrusion of corrosive media, and reducing them can effectively prevent the penetration of corrosive media, thereby improving the corrosion resistance of coatings [33]. The dense structure also improves the physical barrier of the coating, making it more difficult for corrosive media to reach the base material, further enhancing the corrosion resistance. Ni60 is a nickel-based alloy powder containing a high content of nickel, chromium and other elements. Nickel and chromium are able to form dense oxide films, such as nickel–chromium oxides, which have good stability and corrosion resistance.

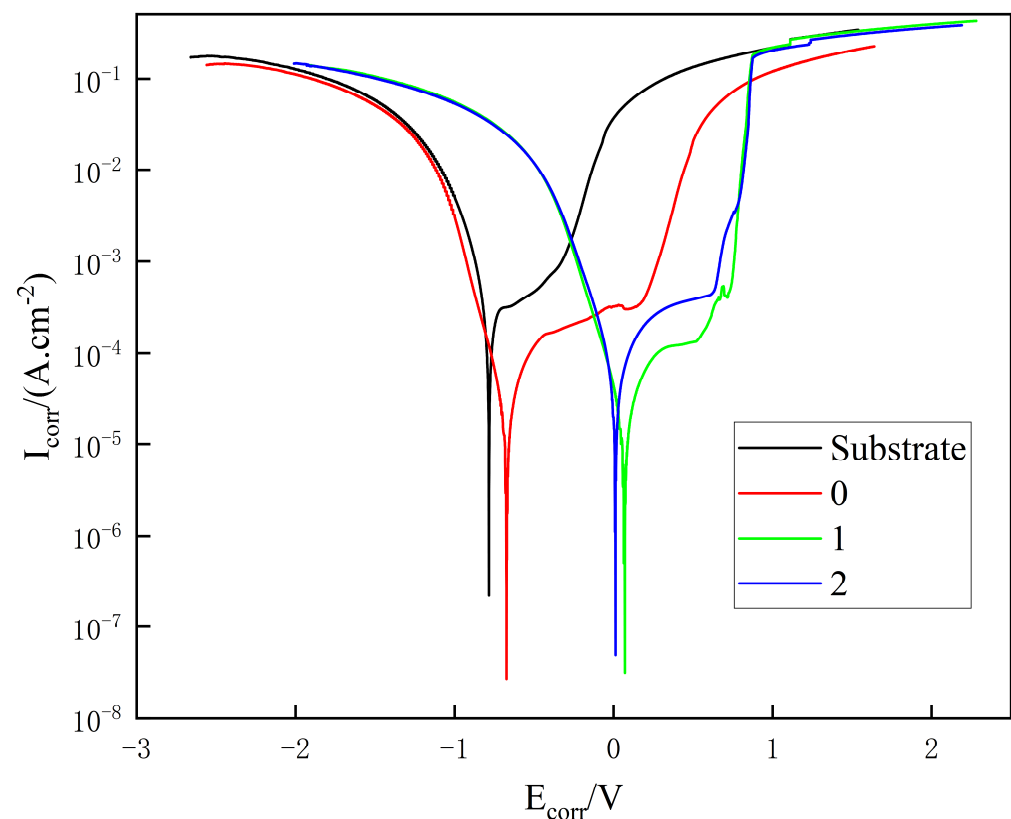


Figure 8. Polarization curves of cladding layers with different mass fractions of CeO₂.

Table 4. Corrosion test results of samples in 3.5% NaCl solution.

Sample	Base Metal	0	1	2
E_{corr}/V	−0.78	−0.67	0.07	0.01
$I_{\text{corr}}/(\text{A}\cdot\text{cm}^{-2})$	5.81×10^{-4}	2.87×10^{-5}	1.82×10^{-5}	8.01×10^{-5}

The coating with 1% CeO₂ + WC + Ni60 mixed-powder laser fusion has a self-corrosion potential of 0.07 V and a self-corrosion current density of $1.82 \times 10^{-5} \text{ A}\cdot\text{cm}^{-2}$, which is greater than the coating without added CeO₂; the current density is less than that of the coating without added CeO₂, which refines the grains, and the grain refinement makes the size of each grain become smaller, which reduces the microcells. The electrode potential difference reduces the corrosion current and improves the corrosion resistance of the material [34]. CeO₂ promotes the alloying elements in Ni60 in the molten pool to improve the strength and hardness of the coating through mechanisms such as solid solution strengthening and precipitation strengthening, and enhances the corrosion resistance of the coating. Chromium improves the oxidation and pitting resistance of the coating, and nickel improves the reduction and stress corrosion resistance of the coating [35]. The generation of a high percentage of solid solution improves the corrosion resistance.

The self-corrosion potential of the coating with 1% CeO₂ + WC + Ni60 mixed-powder laser cladding is 0.07 V, the self-corrosion current density is $1.82 \times 10^{-5} \text{ A}\cdot\text{cm}^{-2}$, the self-corrosion potential is greater than that of the coating without CeO₂, and the current density is less than that of the coating without CeO₂, which refines the grains; the number of grain boundaries can be increased by the refined grains. Grain boundaries are often high in energy and chemical activity, which can hinder the propagation of corrosion [34]. When corrosion occurs at grain boundaries, the path of corrosion becomes more tortuous due to the increase in the number of grain boundaries, which prolongs the time needed for the corrosive medium to reach the substrate and improves the corrosion resistance of the coating. CeO₂ promotes the alloying elements in Ni60 in the molten pool to improve the strength and hardness of the coating through mechanisms such as solution strengthening [12] and precipitation strengthening, and enhances the corrosion resistance of the coating. Chromium can improve the oxidation and pitting resistance of coatings, and nickel can improve the reducing and stress corrosion resistance of coatings [35]. A large proportion of solid solution is generated, which improves the corrosion resistance.

The self-corrosion potential of the coating with 2% CeO₂ mixed-powder laser fusion is 0.01 V, and the self-corrosion current density is $8.01 \times 10^{-5} \text{ A}\cdot\text{cm}^{-2}$ greater than that of the 1% CeO₂ fusion coating layer, whose self-corrosion density is $1.82 \times 10^{-5} \text{ A}\cdot\text{cm}^{-2}$. It can be seen in Figure 5 that the overall number of carbides in the 1% CeO₂ fusion layer is less than that in the 2% CeO₂ fusion coating layer, which is due to the greater number of carbides generated; the large number of carbides generated increases the possibility of intergranular corrosion [36] and carbide generation, which increases the possibility of intergranular corrosion [36]. The intergranular region tends to have high chemical activity due to its different chemical composition and intragranular structure. When carbides are present in large quantities at grain boundaries, the chemical stability at grain boundaries decreases and they are more susceptible to attack by corrosive media. Corrosive media preferentially erode at grain boundaries, leading to the occurrence of intergranular corrosion, which reduces the overall corrosion resistance of the coating. Elements such as nickel and chromium in Ni60 often form a dense oxide film, such as nickel–chromium oxide, which plays a vital role in improving the corrosion resistance of the coating. However, when chromium is combined with carbon, it can lead to the uneven distribution of chromium, which in turn adversely affects the corrosion resistance of the coating. On the one hand, chromium plays a key role in the formation of oxide films. The dense oxide film can effectively block the intrusion of corrosive media and provide good protection for the coating [37]. When chromium is evenly distributed, the oxide film is formed more stably and continuously, and its protective effect can be better exerted.

On the other hand, when chromium is combined with carbon, carbides are formed [38]. The presence of these carbides may disrupt the microstructure of the coating, resulting in a decrease in the density of the coating [12]. At the same time, due to the formation of carbides, part of the chromium is consumed, so that the distribution of chromium in the coating becomes uneven. At the same time, due to the formation of carbides, part of the chromium is consumed, so that the distribution of chromium in the coating becomes uneven. In areas with a low chromium content, the formation of an oxide film is inhibited, which reduces the corrosion resistance of the coating [39].

4. Conclusions

1. The coating with 1% CeO₂ has a lower coefficient of friction (0.47) and a lower amount of wear (0.034), which is 0.112 mm³ less than the coating without CeO₂, showing the best wear resistance. A decrease in the coefficient of friction means that during the friction process, the friction between the coating surfaces decreases.

2. The coating with 1% CeO₂ has a self-corrosion potential of 0.07 V and a self-corrosion current density of $1.82 \times 10^{-5} \text{ A} \cdot \text{cm}^{-2}$, showing the best corrosion resistance. The self-corrosion current density is significantly reduced, indicating that the corrosion resistance of the coating has been enhanced. In summary, coatings with 1% CeO₂ exhibit significant advantages in terms of grain refinement, abrasion resistance, and corrosion resistance. This provides an important reference for the development of high-performance coating materials.

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