

Article

Study on Microstructure and Properties of Nickel-Based Self-Lubricating Coating by Laser Cladding

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Abstract: Ni35 + 20% SiC + 20% Ni/MoS₂ self-lubricating coatings were fabricated on a grade 45 steel surface by laser cladding to obtain better comprehensive performance of wear resistance and corrosion resistance. The macroscopic morphology, microstructure, microhardness, phase composition, corrosion resistance and wear resistance of the coatings were investigated. The results show that the microstructure of the cladding layer is dense, mainly composed of cellular crystal and equiaxed crystal; The average microhardness of the coating is about 700 HV; The phase composition of the coating mainly includes Ni-Cr-Fe solid solution and metal sulfide, such as MoS₂, NiS, Cr₂S₃, and CrMo₃S₄; Under the simulated seawater environment of 3.5% NaCl, the self-corrosion potential is 0.052 V and the self-corrosion current density is $1.69 \times 10^{-5} \text{ A} \cdot \text{cm}^2$. Compared with grade 45 steel, the corrosion resistance is greatly improved; After 20 min of wear, the weight loss of the cladding layer is about 0.17 times that of the grade 45 steel, the friction coefficient is small, and the wear resistance is significantly improved.

Keywords: laser cladding; self-lubricating; corrosion resistance; wear resistance



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1. Introduction

The failure of marine plunger parts is usually due to the influence of complex working conditions. There are two main types of failure: mechanical wear in reciprocating movement and electrochemical corrosion under the action of chloride and sulfate in seawater [1]. The service life of parts is rapidly reduced due to wear and corrosion. Hence, the surface performance of such parts is improved, which is particularly significant [2]. The grade 45 steel used for plunger parts is one of the most widely used materials in engineering [3]. Improving the wear resistance and corrosion resistance of grade 45 steel has practical reference and significance for the service reliability and life extension of many other key components in hot and humid environments, industrial environments and marine environments [4].

As an emerging green surface modification technology, laser cladding can obtain comprehensive high-performance coatings by controlling the ratio of cladding materials and process parameters [5]. Laser cladding technology has good time and space control. As long as the combination of laser cladding system parameters and cladding materials is well controlled [6], the cladding layer will have high strength, high temperature resistance, oxidation resistance, fatigue resistance, wear resistance, corrosion resistance and other properties better than the base material [7]. Laser cladding technology can form a wear-resistant and corrosion-resistant cladding layer on the surface of the key parts of marine machinery and equipment [8], so as to extend their service life and reduce the operation cost of equipment [9]. Therefore, the study of laser cladding process parameters and material combination has not only theoretical significance, but also practical engineering significance.

Grade 45 steel is a kind of high quality carbon structural steel, with good mechanical properties, good cold and hot processing performance, low price advantages [10], and is widely used in a variety of mechanical equipment, such as ship spindle, crankshaft, gear and connecting rod parts [11]; These parts not only suffer from severe wear during transmission but also from atmospheric corrosion, sea water corrosion and electrical corrosion in the humid ocean environment [12]. In the face of such harsh conditions, the limited wear and corrosion resistance of grade 45 steel has become a major factor limiting its extensive application in the marine field [13]. The rise of laser cladding technology and particle reinforced composites provide a new solution to solve this problem. Its advantage is that the cladding layer has the comprehensive properties of corrosion resistance and wear resistance [14].

Since the 21st century, many kinds of cladding layers have been studied on the surface of grade 45 steel. Some scholars have optimized the laser cladding process parameters [15–17], and others have studied the microstructure hardness and other properties of the cladding layer [18]. Among them, Jiang et al. [19]. prepared the CoFeCrNiSiB alloy cladding layer on the surface of grade 45 steel by orthogonal optimization method, and obtained the high wear resistance cladding layer under the optimal process parameters. Lu et al. [20]. prepared nickel based WC cladding layer with powder ratio of 1:1 on the surface of grade 45 steel, and found that the hardness of cladding layer was 2.7 times higher than that of the matrix. Yang et al. [21]. laser cladding Ni35 powder on the surface of grade 45 steel, using synchronous powder feeding method, to explore the influence of different lap joint methods on cladding layer. The results show that the bonding rate is 35% and the hardness is higher than that of the matrix. Sun et al. [22]. prepared Ni60 and Ni60 + 33.3% Ni/MoS₂ self-lubricating coatings on TC4 plate, and found that all molybdenum disulfide in nickel was decomposed and a new lubricating phase Cr_xS_y was generated. The wear volume and friction coefficient of Ni60 + 33.3% Ni/MoS₂ self-lubricating coating are better than those of Ni60 coating by the interaction of γ -Ni, TiC, CrB and Cr_xS_y. H. Torres et al. [23,24]. coated the 1.4301 steel sheet with different ratios of molybdenum disulfide in nickel cladding and found that Cr₃S₄ was decomposed during the cladding process and that these Cr₃S₄ had an effect on friction reduction during wear. C.C. Qu et al. [25]. prepared nickel based coatings of MoS₂ with different contents on the TC4 plate, and found that when MoS₂ content was higher than 8 wt.%, new TiS₂ phase was synthesized in the original position of the coating, and dense and intact TiS₂ layer was formed on the coating surface during friction, which reduced the wear loss of the coating. These researchers have done some research on the process and tribological properties of self-lubricating composite coatings, but there are few studies on the repair of self-lubricating coatings by laser cladding for marine parts of grade 45 steel base materials.

MoS₂ particles, due to its low friction coefficient, good self-lubrication, can form a stable, heat resistance, weight resistance lubrication protective film, coupled with its good thermal stability, low price, if you can use MoS₂ to play the same effect as h-BN, can greatly reduce the cost of laser cladding remanufacturing high-performance coating. Therefore, in this study, a nickel-based self-lubricating corrosion resistant cladding layer will be prepared on the surface of grade 45 steel by a pre-setting method, which provides theoretical guidance for the wide application of grade 45 steel in the marine environment and extension of service life of equipment parts under complex working conditions.

2. Experiment

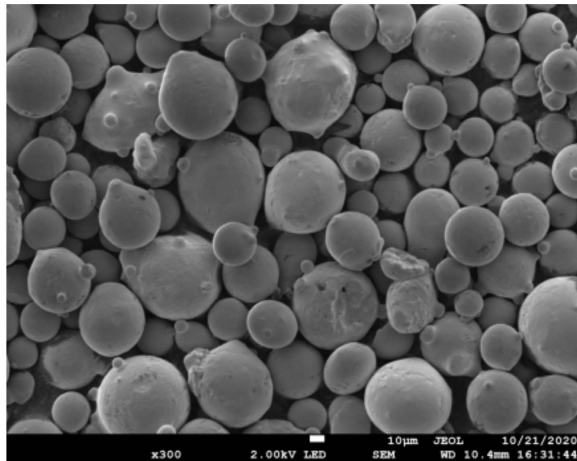
2.1. Materials

Grade 45 steel with the dimension of 150 mm × 60 mm × 8 mm was used as the substrate in this experiment. Ni35 autolysis alloy powder (power size: 75–98 μ m), SiC (power size: 75–98 μ m) and Ni/MoS₂ powder (power size: 75–98 μ m) provided by Qinghe County Chuangying Metal Materials limited company, Xingtai, China were used as cladding materials. Table 1 shows the chemical composition of grade 45 steel and Ni35 powder. Figure 1 shows the morphology of Ni35 powder, Ni35 + 20% SiC powder, SiC powder and Ni/MoS₂

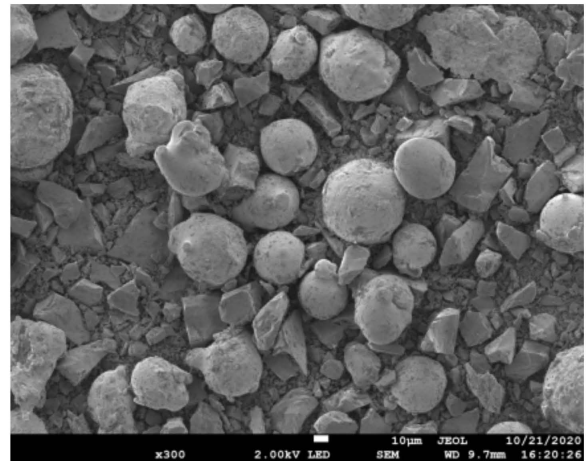
powder. In this paper, the powder ratio of the cladding layer is Ni35 + 20% SiC + 20% Ni/MoS₂.

Table 1. Chemical composition of grade 45 steel substrate and Ni35 (wt.%).

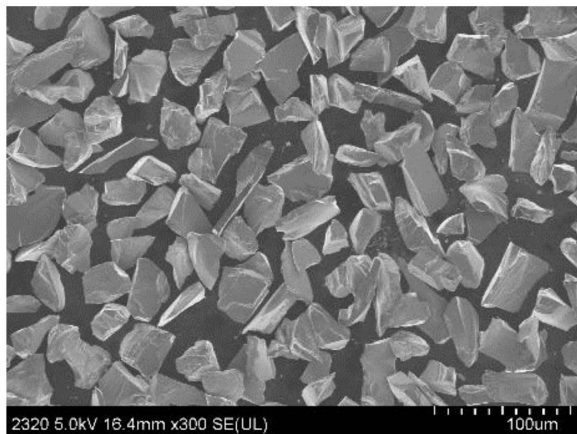
Element	C	Si	Mn	Cr	Ni	B	Fe
grade 45 steel	0.45	0.21	0.67	0.15	0.16	-	Bal.
Ni35	0.5	3	1	12	Bal.	2	10



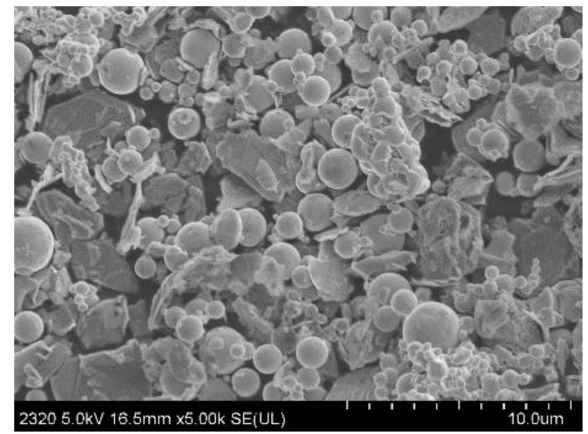
(a)



(b)



(c)



(d)

Figure 1. Micromorphology of the powder. (a) Ni35; (b) Ni35 + 20% SiC; (c) SiC; (d) Ni/MoS₂.

2.2. Experimental Procedure

In this experiment, a Germany YSL-2000-IPG fiber laser (American Praxair limited, Danbury, CT, USA), a KUKA-KR30HA mechanical arm (Shanghai Sifeng Trading Co., Düsseldorf, Germany), a Siasun double bin negative pressure powder feeder (Siasun Robot & Automation Co., Ltd., Shanghai, China), laser wavelength 1070 nm, spot diameter 2 mm. Before the experiment, the oxide layer on the substrate surface was removed with 200 mesh abrasive paper, cleaned with anhydrous ethanol for 30 min, and then placed in a drying oven for later use. The powder was weighed according to the mass ratio and placed in a drying oven (Xuji Electric Shanghai Co., Ltd, Shanghai, China) and dried at 120 °C for 2 h.

After drying, the KQM planetary ball mill was used to grind the powder for 4 h to ensure the uniformity of mixing. The parameters were set as follows: the speed was 400 rad/min and the direction was changed for 0.5 h. At the same time, 97 mL water was added to 3 mL polyvinyl alcohol, heated and stirred until it was completely dissolved, and 3% polyvinyl alcohol aqueous solution was made as a binder. After finishing the mixing, the powder was poured into a clean beaker and an appropriate amount of 3% polyvinyl alcohol solution was poured into the beaker. After mixing the powder and 3% polyvinyl alcohol solution evenly, an 0.8 mm thickness on the surface of grade 45 steel was preset and the powder and solution were put into a drying oven for drying. The dried preset plate was fixed to the experimental platform for test. After the optimization experiment of laser cladding process in the early stage, the experimental process parameters were selected, as shown in Table 2. Argon was used as the protective gas with a flow rate of 10 L/min. After the coating was finished, the metallographic and wear samples with sizes of 8 mm × 8 mm × 8 mm and 31 mm × 7 mm × 8 mm were cut by wire.

Table 2. Laser cladding process parameters.

Parameters	Values
Laser power/W	1000
Scanning speed/(mm/s)	8
Spot diameter/mm	2
Focus-deviating/mm	10
Overlap rate/%	50%

2.3. Performance Test

The macroscopic morphology of the cladding layer surface and section was photographed by an industrial electron measuring microscope (Shanghai Weihai Photoelectric Technology Co., Ltd, Shanghai, China). After wire cutting, the sample was ground with 200, 400, 600, 800, and 1000 mesh metallographic sandpaper and polished with a diamond polishing machine (Weiyi metallographic manufacturers, Guangzhou, China). The cross sections of the sample were corroded with aqua ($V(HCl):V(HNO_3) = 3:1$), and the microstructure, wear scar morphology and corrosion morphology of the coating were observed with an LED-1430 VP scanning electron microscope (Zeiss, Jena, Germany), and a D&Advance X-ray diffractometer (Bruker AXS GmbH, Karlsruhe, Germany) was used to detect the phase composition of the cladding layer. An HXD-1000 tb microhardness tester (Shanghai CAI Kang Optical Instrument Factory, Shanghai, China) was used to test the hardness of the cladding layer, the heat-affected area and the matrix. The indenter load was 200 g and the loading time was 15 s. A CHI660E electrochemical workstation (Gamry, Warminster, PA, USA) was used to test the electrochemical corrosion performance of the cladding layer. Calomel saturated electrode was used as the reference electrode, and a platinum electrode was used as the auxiliary electrode, with the cladding layer sample used as the working electrode, and a 3.5% NaCl solution was used as the corrosion solution. The test parameters were as follows: potential range $-2-2$ V, scanning speed 2 mV/s, frequency range $10^{-2}-10^4$ Hz, sampling frequency 5 Hz. The wear performance of the cladding layer was tested by an M-2000 ring block friction and wear testing machine at room temperature. The grinding pair of hardened grade 45 steel with a radius of 20 mm was mainly used to simulate the plunger in the introduction. In addition, the friction and wear test parameters of several groups of common marine plungers were tested. The rotation speed was 180 rad/min, the load pressure was 45 N, the grinding time was 20 min, the direction was unidirectional, and the linear speed was 22.608 m/min. The wear surface of the sample after wear was analyzed by scanning electron microscope, the wear quantity was calculated by the weight loss method, and the friction coefficients were compared. The diagram of wear test is shown in Figure 2.

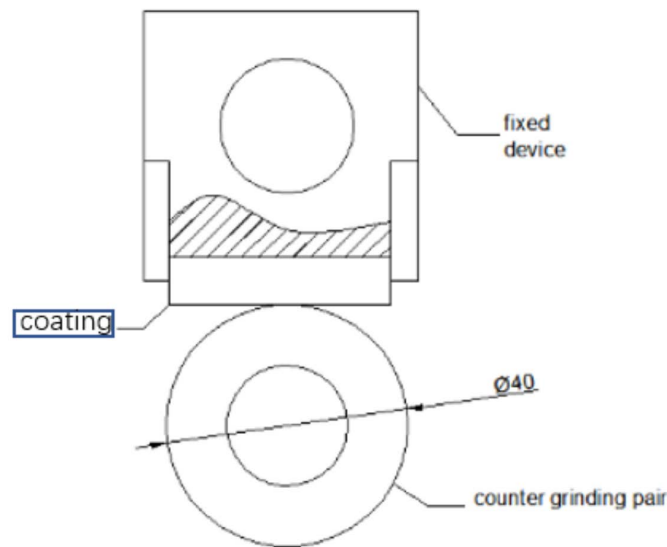


Figure 2. Schematic diagram of wear experiment.

3. Results and Discussion

3.1. Macro Morphology

The macro morphology of the cladding layer is one of the indexes to evaluate whether the laser cladding process parameters are reasonable [26]. The macro morphology of the cladding layer is presented in Figure 3. The surface of the cladding layer is compact and has no defects such as porosity or cracking (Figure 3a). There are clusters of ripples on the surface of the overlapping of the cladding layer caused by the combined action of the movement of high-energy laser beam and the rapid cooling of the molten pool (Figure 3c). Figure 3b shows the characteristics of the elliptical laser cladding layer. Simultaneously, the width of the cladding layer is 2.2 mm, the height is 0.34 mm, and the dilution rate ((Equation (1)) is about 21%. The microstructure from the top of the cladding layer to the bonding area has no obvious porosity cracks and other defects, and the overall shape is good.

$$\eta = \frac{h}{H + h} \quad (1)$$

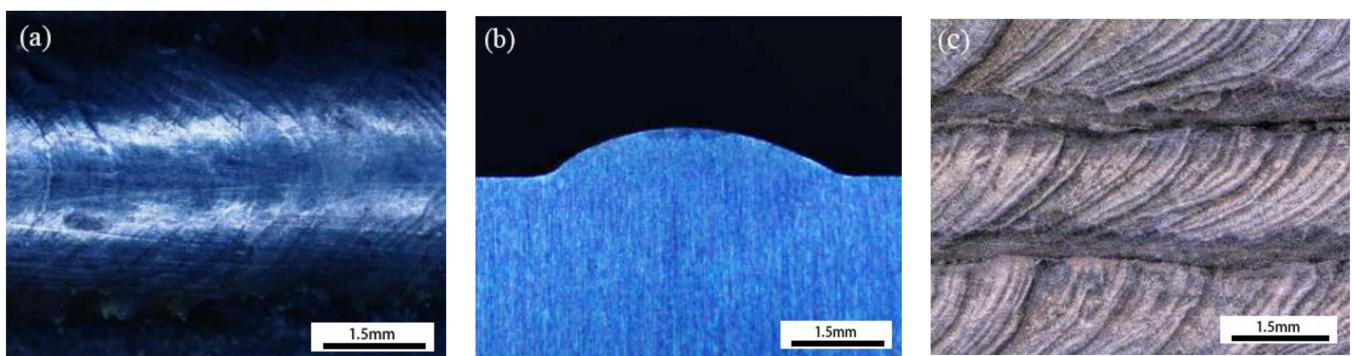


Figure 3. Macro morphology of cladding layer. (a) Single-channel surface, (b) Single-channel cross section, (c) Overlapping surface.

In the formula: H is the height of the cladding layer, and h is the penetration depth of the substrate.

3.2. Coatings Microstructure

The microstructure of SiC ceramic reinforced Ni-based composite coatings is mainly affected by the temperature at the crystallization interface in the molten pool [27,28], and its shape control factor is the ratio of the temperature gradient G in the crystallization direction to the solidification speed R G/R . When the composition of the cladding layer is constant, the value of G/R controls the crystal morphology of the solidification structure [29]. Figure 4 shows the metallographic microstructure of the coating and EDS is performed to detect the element distribution as shown in Table 3. It has been observed that the microstructure of the cladding layer is mainly equiaxed grains and cellular grains. During the solidification process, the molten pool cools slowly, the heat dissipation is even, so the value of G/R is small, which facilitates the growth of cellular and equiaxed crystals in a uniform distribution. The temperature gradient (G) is high and the solidification rate (R) is very low at the bottom of the molten pool, so the value of G/R is large and the solidification structure grows as columnar grains and cellular grains along the heat dissipation direction. Continuous planar grains are formed at the joint between the substrate and the cladding layer, which demonstrates that a good metallurgical bonding is formed between the substrate and coating [30]. The microstructure of the cladding layer shows a trend of gradually refining dendrite and decreasing dendrite spacing from bottom to top.

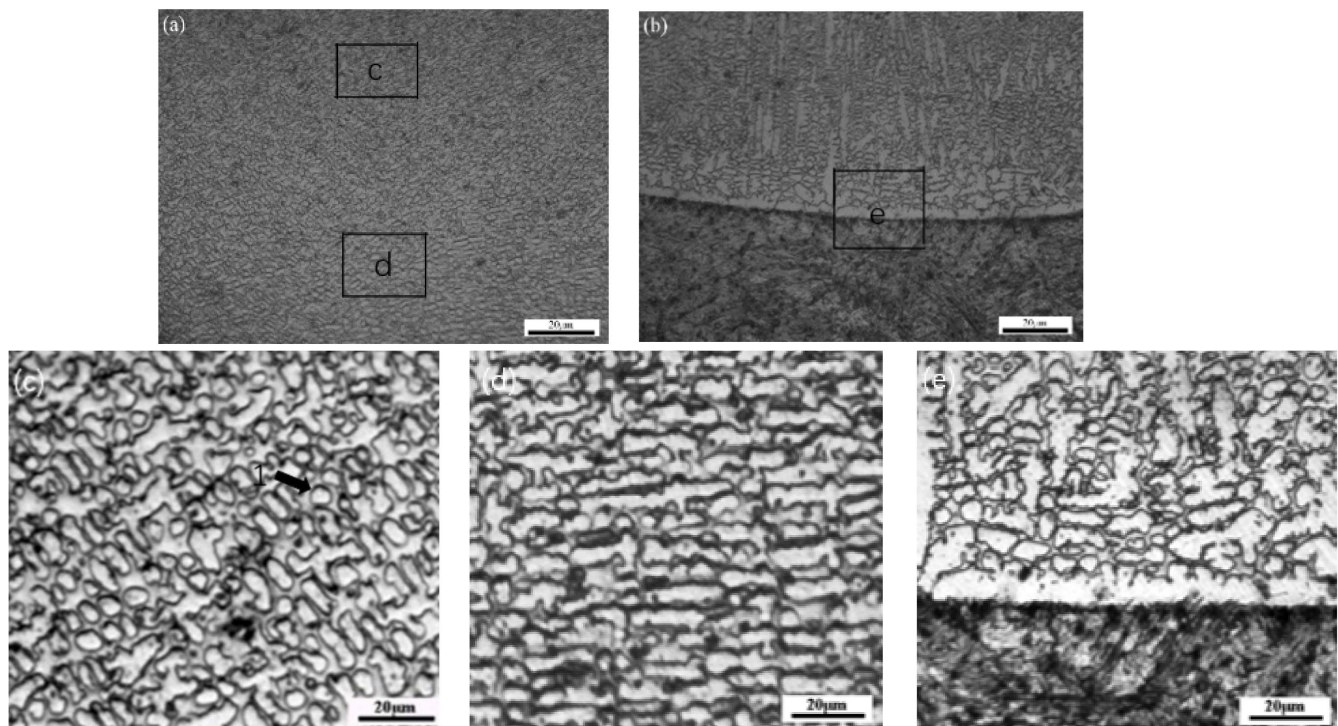


Figure 4. Metallographic microstructure of the coating. (a) Cladding surface, (b) Bonding zone, (c) Top of cladding, (d) Middle of cladding, (e) Bottom of cladding.

Table 3. EDS composition analysis of test point in coating (atom fraction/%).

Position	Cr	S	Mo	Fe	Ni
1	46.67	40.15	7.02	3.42	2.52

3.3. Phase Structure Analysis of Cladding Layer

The characteristic spectral line analysis shown in Figure 5 shows that the phases in the cladding layer fall mainly into two categories: solid solution and metal sulfide. There are two sources of Fe element forming solid solution; one is Ni35 alloy powder, and the other is the diffusion of Fe in the grade 45 steel matrix, because in the laser cladding process,

after the cladding material is melted by laser, the residual energy melts the matrix so that the cladding layer forms a good metallurgical combination with the matrix. During the bonding process, a small amount of Fe elements in the matrix enter the cladding layer by thermal diffusion [31]. The presence of the Si element indicates that SiC decomposes during the laser cladding process. It can be seen from Figure 4 that there are some lath martensite structures in the cladding layer, and Si is often dissolved in martensite structures, which also explains the existence of the $(\text{Ni,Fe})_{22}\text{Si}_7$ solid solution in the XRD pattern [32]. According to the original design intention of the cladding layer, it is hoped to add molybdenum disulfide coated by nickel to prevent the decomposition of molybdenum disulfide in the forming process so that it may act as a self-lubricant, reducing friction and increasing wear resistance. The sole source of S element in the cladding layer is Ni/MoS₂. The diffraction peak shows that the coating consists of MoS₂, NiS, Cr₂S₃ and CrMo₃S₄, which demonstrates that Ni/MoS₂ is partially decomposed during laser cladding. Subsequently, the S element reacts with other metals to form metal sulfides. The MoS₂ in the cladding layer is due to the rapid heating and rapid cooling of the molten pool, which leads to the fusion of the Ni on the surface of the Ni/MoS₂ as soon as the molten pool is solidified and the Ni/MoS₂ has not been decomposed in time. Therefore, the Ni/MoS₂ has a protective effect on MoS₂ decomposition in the molten pool. Metal sulfides are mostly soft phases with layered structure and have a self-lubricating effect [33]. The variety of lubricating phases increases and the anti-friction is good [34], and the specific anti-friction effect is presented in the subsequent wear experiment.

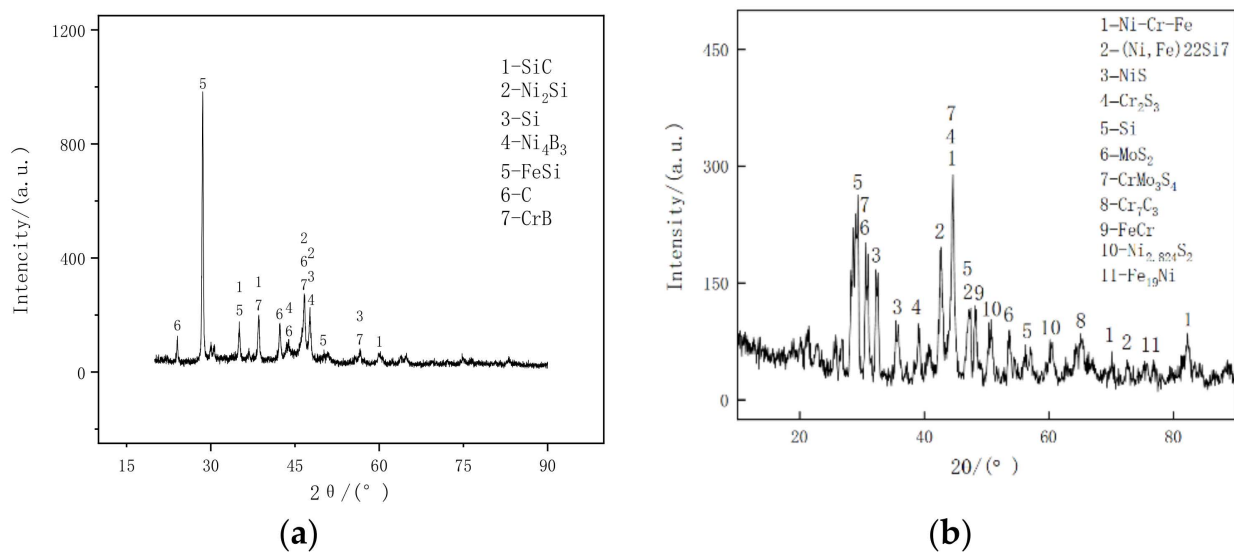


Figure 5. XRD pattern of (a) Ni35 + 20% SiC, (b) Ni35 + 20% SiC + 20% Ni/MoS₂ coating.

3.4. Microhardness

The microhardness of coating determines the ability of material to resist deformation or destruction [35], which is the external performance of material microstructure and an important parameter to measure material performance [36]. Figure 6 presents the microhardness of the cladding layer. It can be clearly seen that the average hardness of the coating is about 700 HV. On the one hand, due to the existence of Ni/MoS₂, some MoS₂ is retained in the cladding layer and NiS, Cr₂S₃, CrMo₃S₄ and other layered metal sulfides are generated. During the cladding process, Fe in the matrix diffuses into the molten pool, in which Fe reacts with Ni, Cr to form Ni-Cr-Fe solid solution in the cladding layer. Si reacts with Fe, Ni to form $(\text{Ni, Fe})_{22}\text{Si}_7$ solid solution. The composite structure with uniform distribution of soft and hard phases in the cladding layer makes the cladding layer have relatively high hardness [37]. On the other hand, the rapid cooling and rapid heating characteristics of the molten pool lead to grain refinement, which makes the cladding layer dense and a less interdendritic structure [38,39]. The combined effect of two aspects makes

the microhardness of the cladding layer 700 HV. The high hardness of the heat-affected zone is mainly due to the martensite structure formed by the quenching of the matrix during the laser cladding process.

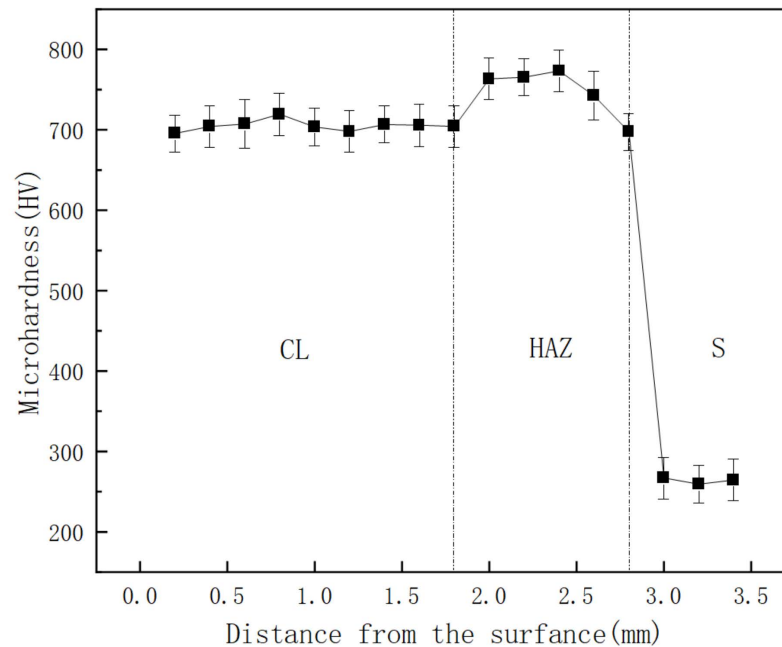


Figure 6. Hardness distribution of Ni35 + 20% SiC + 20% Ni/MoS₂ cladding layer.

3.5. Corrosion Resistance

When the metal comes into contact with the electrolyte solution, the galvanic cell reaction will occur; The corrosion of steel in a marine environment is the most prominent example of electrochemical corrosion [40]. In this work, the electrochemical corrosion performance of the cladding layer will be reflected by the polarization curve.

Figure 7 shows the polarization curve of grade 45 steel and an Ni35 + 20% SiC + 20% Ni/MoS₂ cladding layer in 3.5% NaCl solution. In the process of electrochemical corrosion, when the corrosion of metal is relatively stable, the potential at this time is self-corrosion potential [41]. The value of self-corrosion potential represents the difficulty of the corrosion of materials [42]; The higher the self-corrosion potential is, the smaller the corrosion tendency of the material is, and the lower the self-corrosion potential is, the greater the corrosion tendency of the material is; The corrosion current corresponding to the self-corrosion potential is the self-corrosion current, which reflects the speed of corrosion of materials; The greater the self-corrosion current, the greater the corrosion rate of the material, and the smaller the self-corrosion current, the smaller the corrosion rate of the material. Generally, a higher self-corrosion potential and a lower self-corrosion current indicate that the material has better corrosion resistance [43]. It can be seen from Figure 7 that at the initial stage of corrosion, the self-corrosion potential of grade 45 steel is -0.964 V, the self-corrosion current density is 2.30×10^{-5} A·cm², and the polarization curve has an inflection point with the positive shift of potential, indicating that passivation occurs in the process of electrochemical corrosion. This is due to the formation of passive film on the substrate surface during electrochemical corrosion, which delays the progress of corrosion. When the polarization potential exceeds the self-corrosion potential, the current density increases rapidly with the positive shift of the potential, indicating that the oxide film produced in the early stage of corrosion is destroyed due to anodic polarization. The self-corrosion potential of Ni35 + 20% SiC + 20% Ni/MoS₂ cladding layer is 0.052 V, and the self-corrosion current density is 1.69×10^{-5} A·cm². Passivation also occurs in the corrosion process of the cladding layer. This is because the cladding layer contains a large number of corrosion-resistant substances such as NiS, Cr₂S₃, MoS₂ and CrMo₃S₄, which makes the

self-corrosion potential of the cladding layer higher, reduces the thermodynamic trend of the electrochemical corrosion reaction and reduces the trend of further corrosion [44].

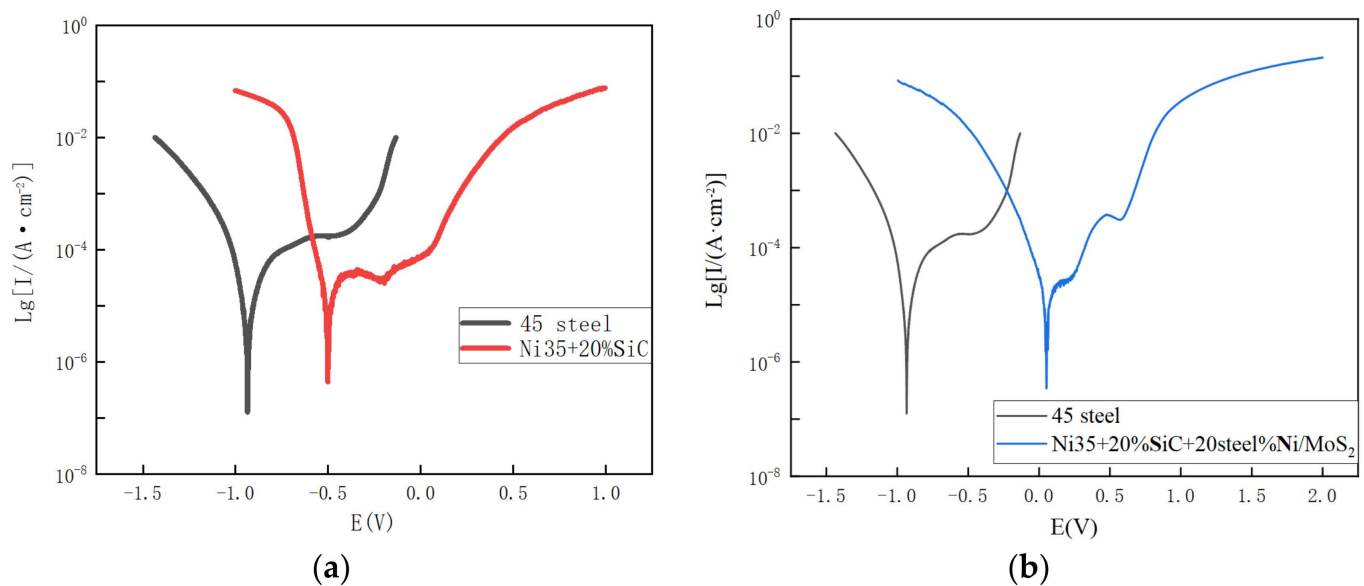


Figure 7. Polarization curve of grade 45 steel and coating in 3.5% NaCl solution. (a) Ni35 + 20% SiC, (b) Ni35 + 20% SiC + 20% Ni/MoS₂ coating.

Figure 8 and Table 4 are equivalent circuit diagrams and equivalent circuit fitting data tables of grade 45 steel and Ni35 + 20% SiC + 20% Ni/MoS₂ cladding in 3.5% NaCl solution, respectively. The sample forms a closed loop in the electrolytic cell, R₁ represents the resistance in the solution, Q₁ represents the constant phase Angle element of the oxide film surface/medium interface, n₁ dispersion effect index for Q₁, R₂ is the solution resistance in the etched hole, The long phase Angle element at the anode metal/medium interface in Q₂ etching hole, n₂ is the dispersion effect index of Q₂, R₃ is the reaction resistance in the etching hole. It is found that the charge transfer resistance R₃ (2000.5 Ω·cm²) of Ni35 + 20% SiC + 20% Ni/MoS₂ coating is about 3.25 times of R₃ (615 Ω·cm²) of grade 45 steel. The results show that Ni35 + 20% SiC + 20% Ni/MoS₂ cladding coating has great corrosion resistance and corrosion resistance. Some studies suggest that the dispersion effect is related to electrode surface roughness [45]. With the sample surface corrosion, further corrosion hole enlargement and the rise in the numbers and corrosion products of the sedimentary roughness increases, which results in an increased dispersion index n₁ and n₂. However, under the same corrosion process, the dispersion index of the cladding layer is greater than that of grade 45 steel, indicating that a denser passive film is formed during the corrosion process of the cladding layer, which hinders the further corrosion of the corrosive solution into the cladding layer and reduces the average rate of further corrosion. In conclusion, the corrosion resistance of Ni35 + 20% SiC + 20% Ni/MoS₂ coating in 3.5%NaCl solution is better than that of grade 45 steel.

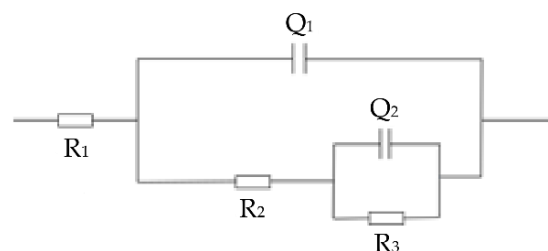


Figure 8. Equivalent circuit diagram of grade 45 steel Ni35 + 20% SiC and Ni35 + 20% SiC + 20% Ni/MoS₂ cladding in 3.5%NaCl solution.

Table 4. Equivalent circuit diagram fitting data table.

Material	R_1 / $\Omega \cdot \text{cm}^2$	Q_1 / $\Omega \cdot \text{cm}^2 \cdot \text{sn}$	n_1	R_2 / $\Omega \cdot \text{cm}^2$	Q_2 / $\Omega \cdot \text{cm}^2 \cdot \text{sn}$	n_2	R_3 / $\Omega \cdot \text{cm}^2$
Grade 45 steel	6.757	0.00504	0.5988	1.268	0.0132	0.6539	615
Ni35 + 20% SiC	4.196	0.00123	0.6362	26.97	0.00129	0.6189	221.0
Ni35 + 20% SiC + 20% Ni/MoS ₂	4.61	0.007866	0.662	2.134	0.001972	1	2000.5

3.6. Wear Resistance

Wear is the process of material consumption and loss on the surface of two components due to the relative motion of two components [46]. Table 5 and Figure 9 show the wear test results of substrate grade 45 steel and a Ni35 + 20% SiC + 20% Ni/MoS₂ cladding layer. It can be seen that the wear of the cladding layer is significantly less than that of the substrate, and the weight loss of the cladding layer is 3.2 mg, 19.1 mg and 0.17 times of that of grade 45 steel when worn for 20 min. The excellent wear resistance is due to the fact that the cladding layer contains hard phases with high hardness and wear resistance and friction reduction. These hard phases on the one hand improve the hardness of the cladding layer and on the other hand reduce the adhesion between the friction pair and the cladding layer during the friction process. The reason why the cladding layer has lower wear is that the hard particles such as Ni-Cr-Fe contact directly with the surface of the wear pair, and the hard particles break, which has an anti-wear effect on the cladding layer. The surface adhesion of two wear parts is reduced, the consumption of two wear parts in the wear process is reduced, so the weight loss of the wear parts is reduced.

Table 5. Wear weight loss measurements of class grade 45 steel and coating.

Sample Mass Loss	First/mg	Second/mg	Third/mg	Average/mg
substrate	19.15	19.12	19.03	19.10
Ni35 + 20% SiC	4.88	4.92	4.90	4.90
Ni35 + 20% SiC + 20% Ni/MoS ₂	3.19	3.18	3.23	3.20

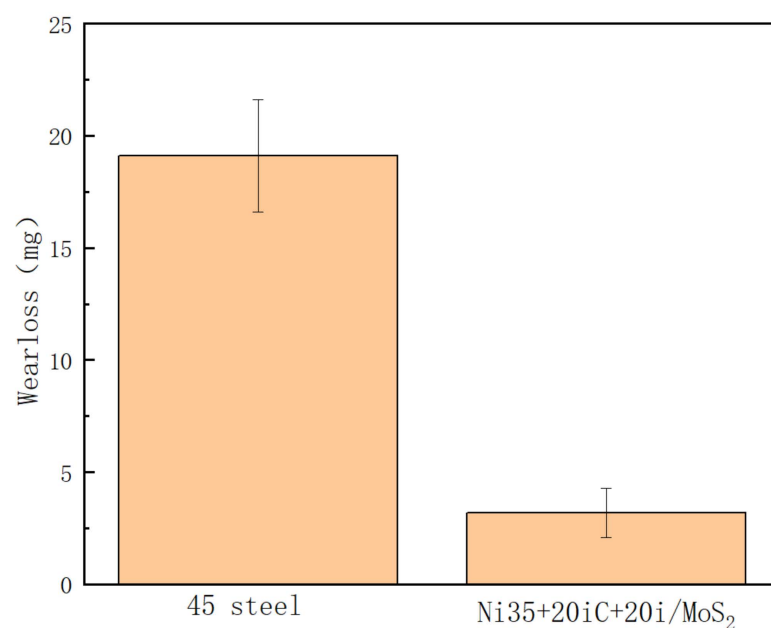
**Figure 9.** Mass loss of grade 45 steel and coating.

Figure 10 shows the variation of friction coefficient of grade 45 steel and Ni35 + 20% SiC + 20% Ni/MoS₂ cladding with time. The friction state of the sample can be divided into two stages: the initial running and wear stage and the stable wear stage. The friction coefficient of Ni35 + 20% SiC + 20% Ni/MoS₂ cladding increases rapidly from 0.71 to 0.77, then decreases rapidly, and finally fluctuates at about 0.62. The reason for the rapid increase and decrease of the friction coefficient is that in the running and wear stages, the hardness and rough surface of the two pairs of grinding materials are relatively high, the number of contact points is small, but the contact area of each contact point is large. At this time, friction occurs sharply, so the friction coefficient changes greatly. With the end of the running and wear stages, the top of the micro peaks on the surface of the material is ground off, the roughness decreases, the actual contact area increases, the number of contact points increases, and the friction becomes stable [47], so the friction coefficient is stable at about 0.62. Compared with the friction coefficient of grade 45 steel, the friction coefficient of 20% Ni/MoS₂ cladding is smaller in both running and wear stages and stable wear stages, which is due to the formation of NiS, Cr₂S₃, MoS₂ and CrMo₃S₄ metal sulfides in the cladding layer caused by the addition of nickel coated MoS₂. Most of them are soft phase with a layered structure and have certain self-lubrication effects. These metal sulfides are extruded to form lubrication film between the friction pair in the friction process [48], and the wear between two wear parts is changed into the wear between two lubrication films, which reduces the friction coefficient.

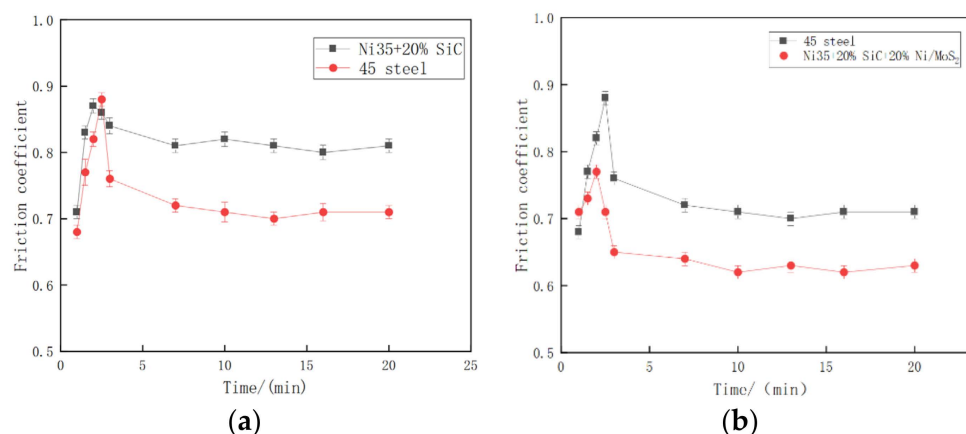


Figure 10. The variations in friction coefficient of grade 45 steel and coating with the wear time. (a) Ni35 + 20% SiC, (b) Ni35 + 20% SiC + 20% Ni/MoS₂ coating.

Figure 11 shows the wear morphology of grade 45 steel and Ni35 + 20% SiC + 20% Ni/MoS₂ cladding. The surface roughness of grade 45 steel is large, the adhesion wear is serious, and the obvious fish scale peeling and lamination peeling can be observed. This is because in the process of wear test, the grinding pair and cladding layer surface under the action of the testing machine loading force and molecular binding force, the two surfaces have a certain degree of combination, as the friction process continues to tear the binding point, the cladding layer surface formed adhesive wear. The surface of Ni-coated molybdenum disulfide cladding layer is smooth, and there are obvious abrasive grains and furrows, which are typical characteristics of abrasive wear. The furrows and abrasive particles on the friction surface are caused by the micro-cutting action of the hard relative coating during the wear process. The friction surface is fine and smooth because the layered metal sulfide in the cladding layer is extruded to form a lubrication film during the wear process, and the lubrication film is extruded to the furrow with the wear [49]. The wear mechanism of 45 steel is adhesive wear, while that of Ni35 + 20% SiC + 20% Ni/MoS₂ coating wear mechanism is abrasive wear. According to the results of the wear and friction coefficient, it is not difficult to see that the anti-friction and friction reduction effect of the cladding layer with molybdenum disulfide coated nickel is obvious.

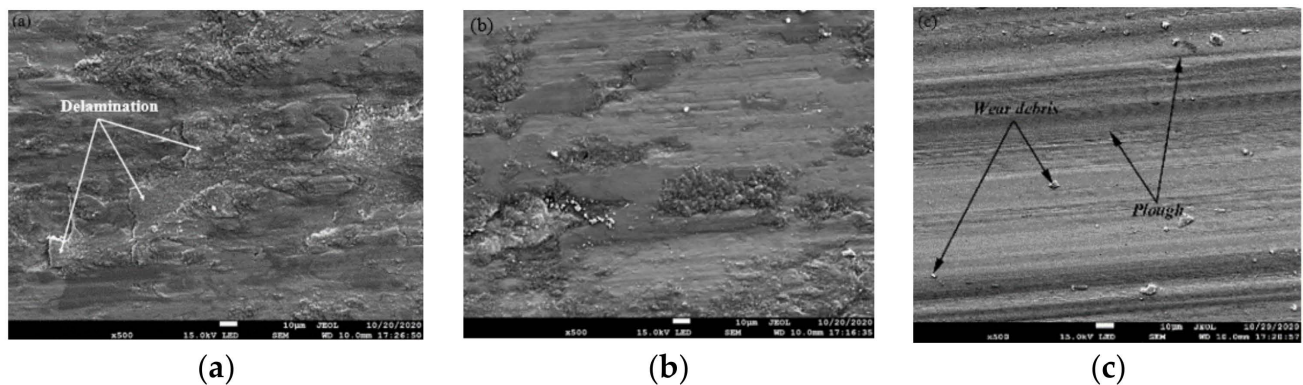


Figure 11. SEM micrographs of the worn surfaces. (a) grade 45 steel, (b) Ni35 + 20% SiC, (c) Ni35 + 20% SiC + 20% Ni/MoS₂.

4. Conclusions

- (1) The microstructure of Ni35 + 20% SiC + 20% Ni/MoS₂ cladding layer fabricated at 1000 W laser power and 8 mm/s scanning speed is dense and flawless, and the microstructure is mainly cellular grains and equiaxed grains.
- (2) During the laser cladding process, SiC are completely decomposed and Ni/MoS₂ is partially dissolved. The melting layers mainly include solid-soluble Ni-Cr-Fe, (Ni, Fe)₂₂Si₇ and metal sulfide MoS₂, NiS, Cr₂S₃, CrMo₃S₄. The complex phase components have a solid-soluble strengthening and diffuse enhancement effect, so that the coating obtains higher hardness and a lower wear rate. The microhardness of the coating is about 700 HV, the wear rate is about 0.17 times that of the grade 45 steel, and the wear resistance is significantly improved.
- (3) The self-corrosion potential and corrosion current density of the cladding layer in the electrochemical test were 0.052 V and $1.69 \times 10^{-5} \text{ A} \cdot \text{cm}^{-2}$, respectively. The comparison of the substrate shows that the cladding layer has good corrosion resistance, which indicates that the corrosion resistance of the cladding layer is obviously enhanced.

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