

Article

Optimization of Multi-Track Laser Cladding Process Parameters for Fe-Cr-Ni Wear-Resistant Coatings via RSM-MOPSO

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Abstract

The surface of nodular cast iron is susceptible to wear failure under high-load conditions. In this study, Fe-Cr-Ni wear-resistant coatings were developed on the surface of nodular cast iron using laser cladding technology. The influence of laser power (P), powder feeding rate (F), scanning speed (V), and overlapping rate (ϕ) on the microhardness and dilution rate of the coatings was analyzed by response surface methodology, while the model's accuracy was evaluated through analysis of variance. Subsequently, the multi-objective particle swarm optimization algorithm was utilized to identify the optimal process parameters (P = 1350 W, V = 12.5 mm/s, F = 9 g/min, and ϕ = 45%) based on non-destructive testing results. The predictive model values closely matched the experimental results. The average microhardness of the Fe-Cr-Ni cladding layer was 620.3 HV, which was 2.8 times that of the nodular cast iron substrate. Importantly, the laser cladding layer demonstrated a significant improvement in wear resistance compared to the substrate. The wear mechanisms for the coating predominantly involved mild abrasive wear and adhesive wear, while the substrate primarily experienced severe adhesive wear. This study offers valuable insights for optimizing laser cladding process parameters for nodular cast iron.

Keywords: multi-track laser cladding; wear resistance; process parameter; response surface methodology; multi-objective particle swarm optimization algorithm

1. Introduction

Nodular cast iron is widely utilized in various sectors, including automotive, machinery, pipelines, and mining, due to its low cost and excellent vibration-damping properties [1,2]. However, the presence of spherical graphite phases renders the surface of nodular cast iron susceptible to fatigue cracks, excessive wear, and porosity, ultimately leading to component failure over time [3,4]. The damaged surface of nodular cast iron significantly limits its applicability in industrial components. Consequently, surface repair and remanufacturing strategies for nodular cast iron hold both theoretical and practical significance in extending service life while minimizing production costs.

As an emerging surface modification technique, laser cladding utilizes a high-energy laser beam to rapidly melt and solidify cladding materials onto metallic substrates, facilitating the formation of metallurgically bonded cladding coatings [5,6]. This process



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significantly enhances the wear and corrosion resistance of the substrates. In comparison to conventional surface modification methods such as arc welding [7], electron beam welding [8], and arc spraying [9], laser cladding presents distinct technical advantages, including higher energy density, a narrower heat-affected zone (HAZ), and superior interfacial bonding strength. It has been applied to various materials, including Fe-based [10], Ni-based [11], and Co-based [12] alloys. Su et al. [13] reported that a CuCrZr coating was successfully deposited on nodular cast iron (QT500-7), which exhibited a low friction coefficient ranging from 0.053 to 0.303 and a reduction in wear depth. Ouyang et al. [14] reported that the hardness of a laser-cladded austenitic stainless steel coating on the surface of nodular cast iron reached 40.6 HRC. Additionally, Li et al. [15] performed laser cladding experiments utilizing Ni-Cu alloy powders to facilitate the remanufacturing of nodular cast iron surfaces. However, inappropriate process parameters can lead to the formation of micro-cracks in cladding coatings, primarily due to the mismatch in thermal expansion coefficients between the graphite and the pearlite matrix. Moreover, processing parameters significantly affect the morphologies of the melt pool and the distribution of crack-susceptible phases. Therefore, it is crucial to investigate the impact of laser cladding parameters on coating quality to mitigate the formation of interfacial cracks and brittle secondary phases.

Response surface methodology (RSM) is a robust experimental design and data analysis approach that aims to determine the optimal combination of design variables and response targets through systematic data regression [16,17]. Recent research has extensively utilized RSM to establish correlations between critical processing parameters (such as laser power, scanning speed, and feeding speed) and the macro-quality of cladding layers, including microhardness and dilution ratio. Huang et al. [18] applied RSM to optimize cladding parameters for B₄C-reinforced Ti64 coatings efficiently, achieving a prediction error of less than 8% between predicted and measured values. Furthermore, Yan et al. [19] integrated RSM with experiments to optimize dilution rate and hardness for single-track Fe60 alloy coatings. In recent years, intelligent optimization algorithms have attracted significant attention from academic researchers due to their highly effective global search capabilities in high-dimensional parameter spaces. When integrated with RSM, these algorithms can overcome the limitations of localized process parameter intervals, thereby identifying the optimal combinations of parameters. Luo et al. [20] employed an RSM enhanced by NSGA-II-MOPSO to effectively predict the morphology and performance of coatings. Similarly, Ji et al. [21] utilized RSM in conjunction with NSGA-II to develop a nonlinear model that correlates cladding parameters with cladding performance, achieving the optimal laser cladding parameters of 1253 W power, 15.4 mm/s scanning speed, and 1.8 r/min powder feeding rate. To date, most studies involving RSM and intelligent optimization have concentrated on single-track cladding, while literature addressing the optimization of multi-track laser cladding processes remains scarce.

Due to its low cost, environmental friendliness and broad processing window, Fe-Cr-Ni alloy becomes a promising candidate material for the laser cladding reinforcement of nodular cast iron components. In this study, high-performance Fe-Cr-Ni alloy coatings were successfully fabricated on a nodular cast iron substrate via laser cladding. First, a rRSM was established to systematically investigate the effects of processing parameters (laser power, powder feed rate, scanning speed and overlap rate) on the microhardness and dilution rate of the cladding layers. Subsequently, a multi-objective particle swarm optimization (MOPSO) algorithm was employed to obtain the combination of optimal parameters. Finally, the microhardness distribution was evaluated and the wear mechanisms for the coatings were elucidated through friction and wear tests.

2. Materials and Methods

2.1. Materials Preparation

In this experiment, nodular cast iron QT450 was selected as the substrate material, with the size of 100 mm × 100 mm × 10 mm. According to JMatPro 7.0 software, the thermophysical properties of QT450 are obtained, which is shown in Figure 1. Fe-Cr-Ni alloy powder (JG-8, supplied by Tianjin Zhujin Technology Development Co., Ltd., 6 Xinghe Road, Beichen District, Tianjin, China) was utilized as the coating material. The SEM image of QT450 substrate and Fe-Cr-Ni cladding powder are displayed in Figure 2a,b, respectively. The chemical composition of the Fe-Cr-Ni alloy powder is detailed in Table 1. Prior to the cladding process, the substrate surface was mechanically ground to remove oxide layers and impurities, and was then cleaned with anhydrous ethanol to eliminate grease. The cladding powder was dried in a vacuum oven at 100 °C for 1 h to remove residual moisture.

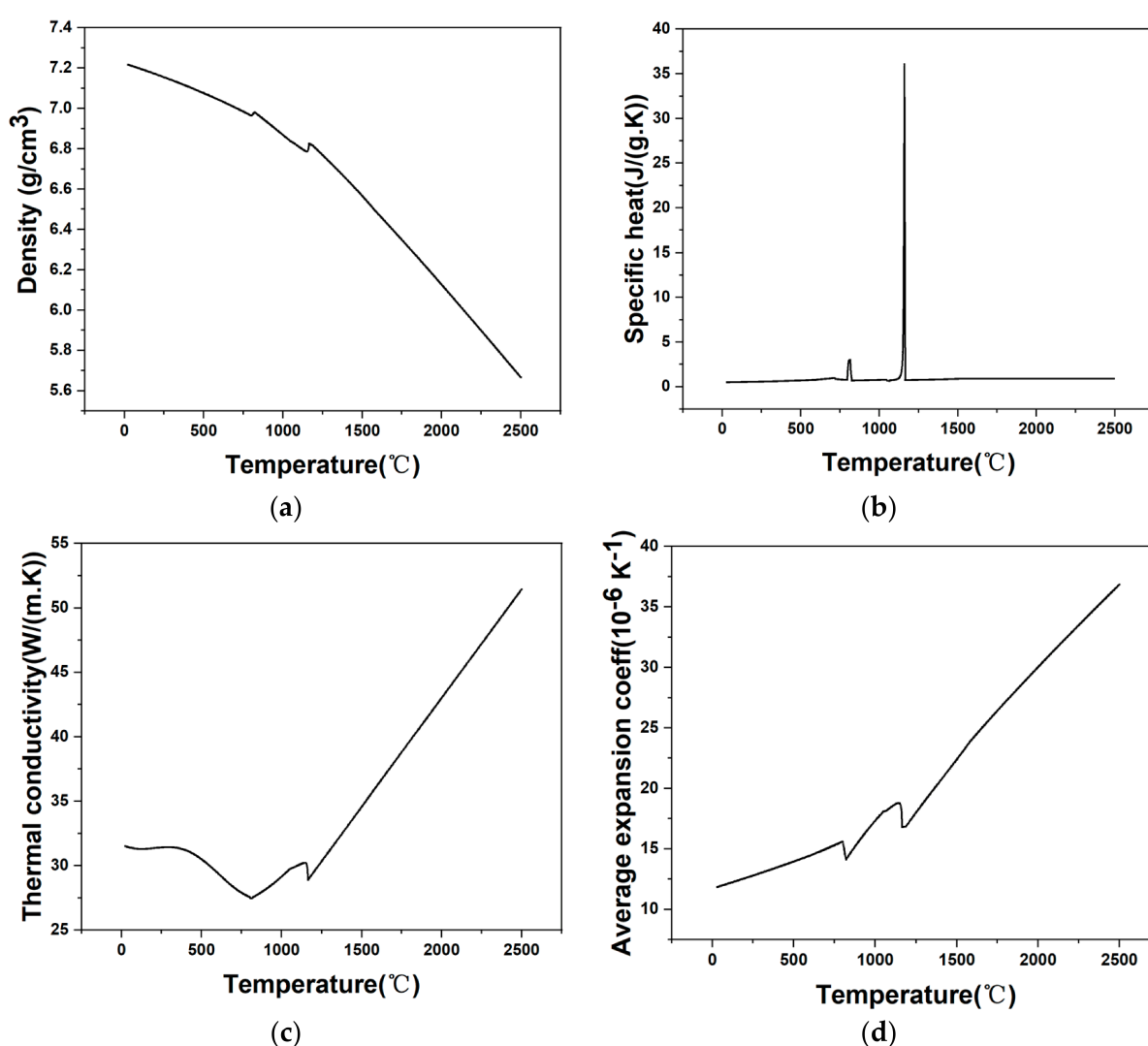


Figure 1. Thermo-physical properties of QT450: (a) density; (b) specific heat capacity; (c) thermal conductivity; (d) thermal expansion coefficient.

Table 1. Chemical composition of Fe-Cr-Ni laser cladding powders.

Fe-Cr-Ni	Element	C	Si	Ni	Cr	Fe
	Content (wt%)	0.15	0.8	2.5	18.5	Bal

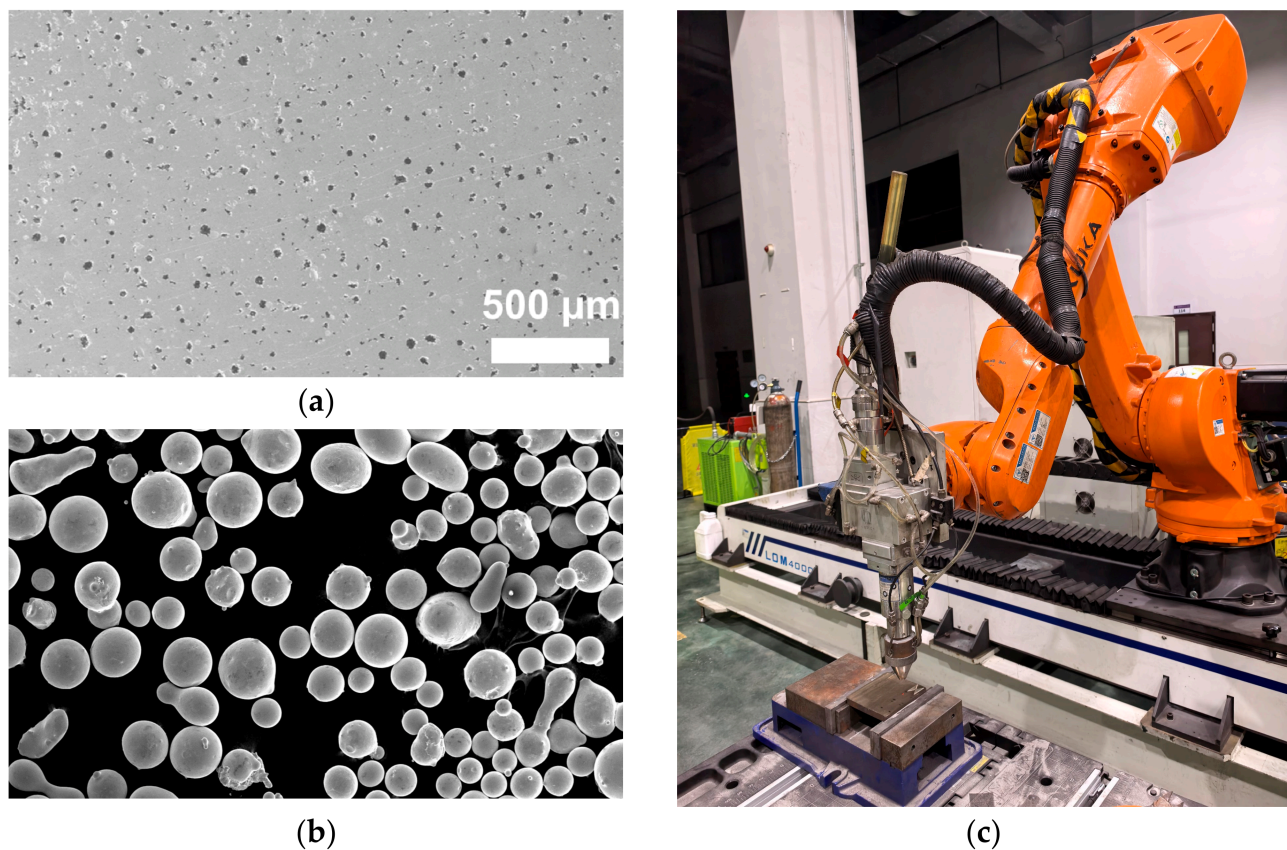


Figure 2. SEM image of (a) nodular cast iron (QT450) substrate and (b) Fe-Cr-Ni cladding powders, (c) laser cladding equipment system.

2.2. Experimental Setup

The multi-track cladding layer of Fe-Cr-Ni on the surface of nodular cast iron (QT450) was fabricated using a coaxial powder-fed laser cladding system (LOM4000, Shandong Leishi Intelligent Manufacturing Co., Ltd., No. 1777, Chunhui Road, High-tech Zone, Jinan, Shandong Province, China), as depicted in Figure 2c. This system features a high-precision KUKA robot and a 6000 W fiber laser head, which together ensure efficient and uniform cladding during the experiment. Argon gas, with a purity of 99.99%, served as the shielding gas for laser cladding, preventing contamination of the molten pool and maintaining a stable environment conducive to high-quality cladding. A laser spot diameter of 3 mm was selected to achieve optimal energy density for an efficient laser cladding process. Following the laser cladding procedure, the specimens were annealed in a vacuum oven at 200 °C for 1 h and subsequently cooled in a furnace to mitigate residual thermal stress.

Laser cladding is a complex process characterized by the coupling of multiple fields, including heat transfer, thermal stress, and melt pool dynamics. The primary process parameters for multitrack laser cladding include laser power (LP), scanning speed (SS), powder feeding rate (PFR), and overlapping rate (OR), as detailed in Table 2. The intricate nonlinear interactions among these parameters significantly affect the quality of the resulting cladding. To clarify the quantitative relationships between these parameters, a four-factor, five-level Central Composite Design (CCD) matrix was developed and analyzed using Response Surface Methodology (RSM) in DesignExpert 12 software, with dilution ratio and microhardness serving as the response variables. The matrix and corresponding results from a total of 30 CCD-based experiments are presented in Table 3.

Table 2. Center composite design experimental program.

Factor	Level				
	−2	−1	0	1	2
P (W)	1200	1350	1500	1650	1800
V (mm/s)	5	7.5	10	12.5	15
F (g/min)	6	9	12	15	18
φ (%)	35	45	55	65	75

Table 3. Experimental results from the CCD experimental program.

Experimental Number	Experimental Factors				Response Objectives	
	P (W)	V (mm/s)	F (g/min)	φ (%)	η (%)	HV
E1	1350	7.5	9	45	27.5	575.78
E2	1650	7.5	9	45	40.7	632.18
E3	1350	12.5	9	45	22.3	615.48
E4	1650	12.5	9	45	18.7	659.93
E5	1350	7.5	15	45	20.7	577.52
E6	1650	7.5	15	45	38.1	630.36
E7	1350	12.5	15	45	21.2	531.54
E8	1650	12.5	15	45	18.1	568.85
E9	1350	7.5	9	65	27.6	511.15
E10	1650	7.5	9	65	43.6	519.98
E11	1350	12.5	9	65	23.6	600.12
E12	1650	12.5	9	65	23.5	599.41
E13	1350	7.5	15	65	21.9	638.82
E14	1650	7.5	15	65	42.9	647.75
E15	1350	12.5	15	65	18.6	602.38
E16	1650	12.5	15	65	24.4	621.62
E17	1200	10	12	55	23.1	585.61
E18	1800	10	12	55	35.3	656.46
E19	1500	5	12	55	32.2	609.94
E20	1500	15	12	55	13.1	631.24
E21	1500	10	6	55	20.8	566.24
E22	1500	10	18	55	20.9	575.65
E23	1500	10	12	35	34.1	618.76
E24	1500	10	12	75	34.2	583.22
E25	1500	10	12	55	33.4	657.82
E26	1500	10	12	55	33.2	656.52
E27	1500	10	12	55	32.1	640.75
E28	1500	10	12	55	32.6	642.06
E29	1500	10	12	55	35.2	640.95
E30	1500	10	12	55	32.7	641.08

2.3. Characterization

Dye penetrant inspection (DPI) was utilized for the non-destructive evaluation of microcracks on the surface of laser cladding, followed by the measurement and statistical analysis of their lengths. Specimens were wire-cut in the transverse direction of the cladding layer using an electrical discharge machine to obtain various samples for subsequent testing. The cross-sections of the samples intended for metallographic observation were sequentially ground with 800, 1000, 1500, and 2000# SiC abrasive papers and polished with an automatic polisher to achieve a mirror finish. The cross-sections were rinsed with anhydrous ethanol and subsequently etched with aqua regia (HNO_3 : HCl = 1:3 by volume) for 10–15 s. The cross-sectional areas of the cladding layer A_c and the remelted substrate

A_m were measured using ImageJ 1.x software to calculate dilution ratio η of cladding layer according to Equation (1):

$$\eta = \frac{A_m}{A_m + A_c} \quad (1)$$

The cross-section microhardness was measured at five evenly distributed points using a Vickers microhardness tester (Model: HV-1000), with a test load of 100 g and a dwell time of 10 s. The average value was calculated to represent the microhardness.

Prior to the friction and wear tests, the surface of the cladding layer was mechanically ground to reduce the running-in period. The tribological performance was assessed using a wear test machine (reciprocating friction test, UMT-3) under dry sliding conditions at room temperature. Reciprocating friction pairs consisted of a Si^3N^4 ceramic ball with a 3 mm diameter. The tests were carried out with a 20 N normal load, a 5 mm reciprocating stroke, and a 5 Hz frequency over 30 min. The worn cladding surface was examined using an ultra-depth three-dimensional microscope (KS-X5000A, KathMatic, Nanjing, China) and a scanning electron microscope (TESCAN MIRA LMS, Brno, Czechia) with an energy-dispersive spectrometer (BRUKER Quanta $\times 400$, Karlsruhe, Germany).

3. Results

3.1. Establishment of Polynomial Response Surface Model

The regression coefficients for dilution rate and microhardness in the prediction models were derived from the experimental results (Table 3) using Design-Expert 13 software. The mathematical expressions for the established response surface models are provided in Equations (2) and (3):

$$f_\eta = -213.93 + 0.1955P + 22.1V + 3.617F - 1.46\varphi - 0.0114PV + 0.002167PF + 0.000783P\varphi + 0.083333VF + 0.002V\varphi + 0.00125F\varphi - 0.000042P^2 - 0.412V^2 - 0.336F^2 + 0.003\varphi^2 \quad (2)$$

$$f_{HV} = -1265.96 + 1.5P + 53.82V + 35.22F + 8.06\varphi - 0.004452PV + 0.001299PF - 0.006446P\varphi - 3.383VF + 0.365V\varphi + 0.9479F\varphi - 0.000339P^2 - 1.24V^2 - 2.24F^2 - 0.1265\varphi^2 \quad (3)$$

Based on the experimental data, an analysis of variance (ANOVA) was conducted to assess the goodness-of-fit of the response surface methodology (RSM) models, as presented in Table 4. In the ANOVA, the F-value indicates the relative influence of the experimental factors on the response objective. For dilution rate, the significance order of the parameters is $V > P > F > \varphi$, while for microhardness, the order is $P > F > \varphi > V$. Moreover, an R^2 value approaching 1 signifies a strong correlation with the regression model. The R^2 values for the two RSM models are 0.9766 and 0.9728, respectively, underscoring the robust fitting and predictive capabilities of the models. Additionally, the adequate precision (signal-to-noise ratio) for both models exceeds 4, demonstrating the accuracy and effectiveness of the established models.

Figure 3a,b compare the predicted and experimental values for the response targets, specifically dilution rate and microhardness. The data points are uniformly distributed along the ideal fitting line ($Y = X$), with no significant deviations noted. This observation indicates that the established RSM demonstrates excellent goodness-of-fit and high predictive accuracy, effectively capturing the relationship between response targets and process parameters. Additionally, the normal probability plots of residuals for η and HV are shown in Figure 3c,d. The residuals closely align with the red theoretical line, and no evident systematic deviations or outliers are identified, suggesting minimal fitting errors characterized by a high degree of randomness. The approximately normal distribution of the residuals satisfies the fundamental assumptions of regression analysis, thereby affirming

the reliability and effectiveness of the developed models. In summary, the established RSM models accurately elucidate the non-linear response relationships between the experimental factors and the response targets.

Table 4. Variance analysis of multiple regression prediction model.

Project	η		HV	
	F-Value	p-Value	F-Value	p-Value
Model	44.73	<0.0001	38.18	<0.0001
P	117.35	<0.0001	63.16	<0.0001
V	242.46	<0.0001	5.45	0.0339
F	6.49	0.0223	7.09	0.0177
φ	5.12	0.039	6.85	0.0194
PV	100.04	<0.0001	0.4965	0.4919
PF	5.17	0.0381	0.0608	0.8085
P φ	7.51	0.0152	16.66	0.0010
VF	2.13	0.1655	114.65	<0.0001
V φ	0.0136	0.9087	14.81	0.0016
F φ	0.0077	0.9314	144.07	<0.0001
P ²	8.2	0.0118	17.82	0.0007
V ²	61.86	<0.0001	18.34	0.0007
F ²	85.37	<0.0001	124.12	<0.0001
φ^2	0.8396	0.374	48.86	<0.0001
Lack of fit	3.26	0.1019	1.47	0.3506
R ²		0.9766		0.9727
Adjusted R ²		0.9548		0.9472
Predictive R ²		0.8787		0.8727
Adeq Precision		25.4955		23.3315

The influence of laser cladding process parameters on the dilution rate of the coatings is illustrated in Figure 4a–c. According to Table 4, laser power and scanning speed are the two most significant parameters affecting the dilution rate. Overall, the dilution rate exhibits a positive correlation with laser power and a negative correlation with scanning speed. Specifically, an increase in laser power enhances the energy absorption of the Fe–Cr–Ni powder and the nodular cast iron substrate, resulting in deeper and wider molten pools that elevate the dilution rate of the cladding coatings. In contrast, a higher scanning speed reduces the specific heat input, leading to a lower dilution rate. Figure 4d–f depicts the relationship between the process parameters and microhardness. The general trend indicates that microhardness is positively correlated with laser power and negatively correlated with feeding speed beyond the central point. Elevated laser power provides sufficient heat to ensure complete melting of the powder, significantly reducing internal porosity and enhancing the microhardness of the coating [22]. Meanwhile, an increased powder feed rate after the central point can result in the accumulation of unmelted cladding powder, introducing defects into the coatings and consequently decreasing microhardness [23].

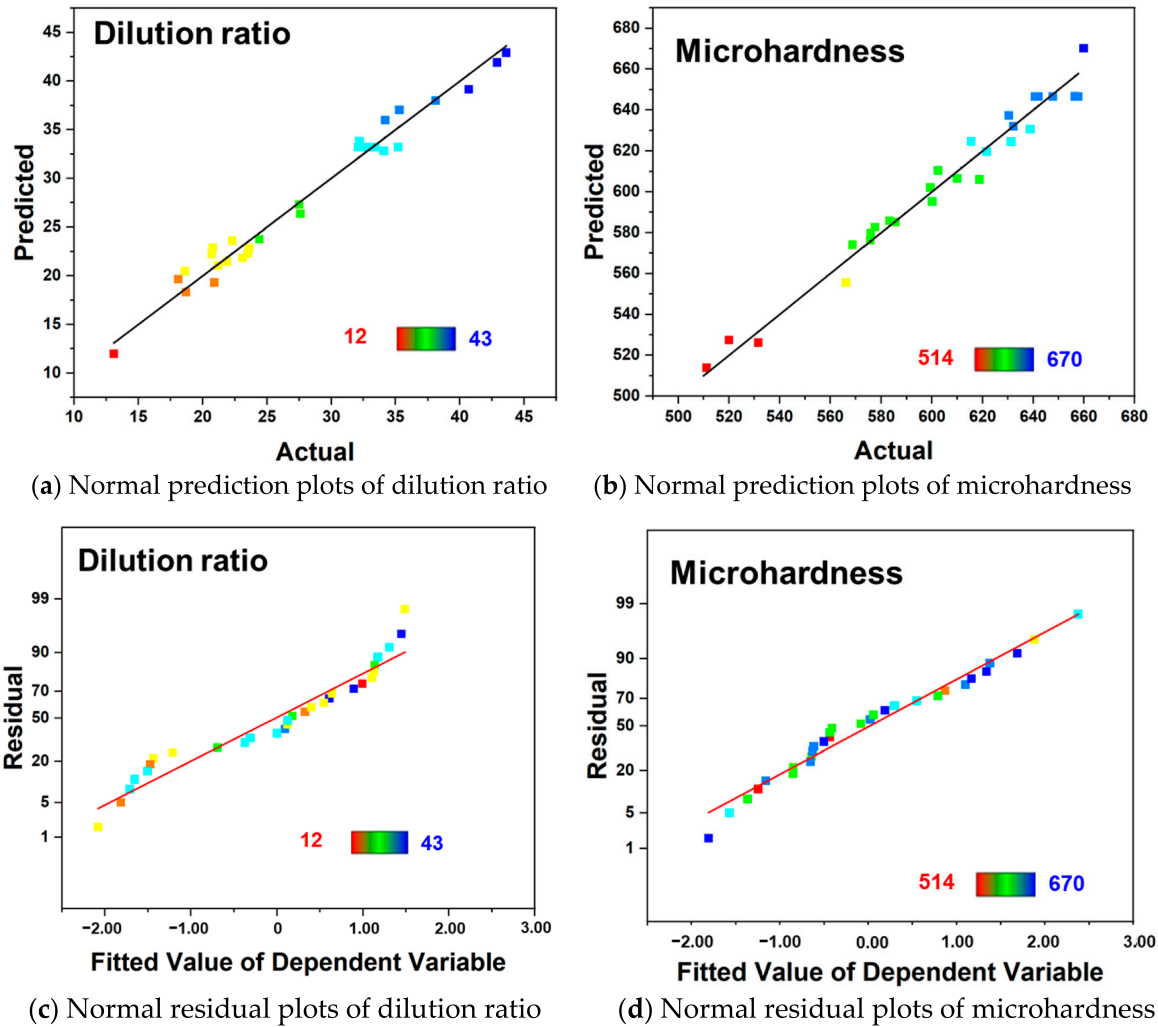


Figure 3. Reliability analysis plots of various parameters.

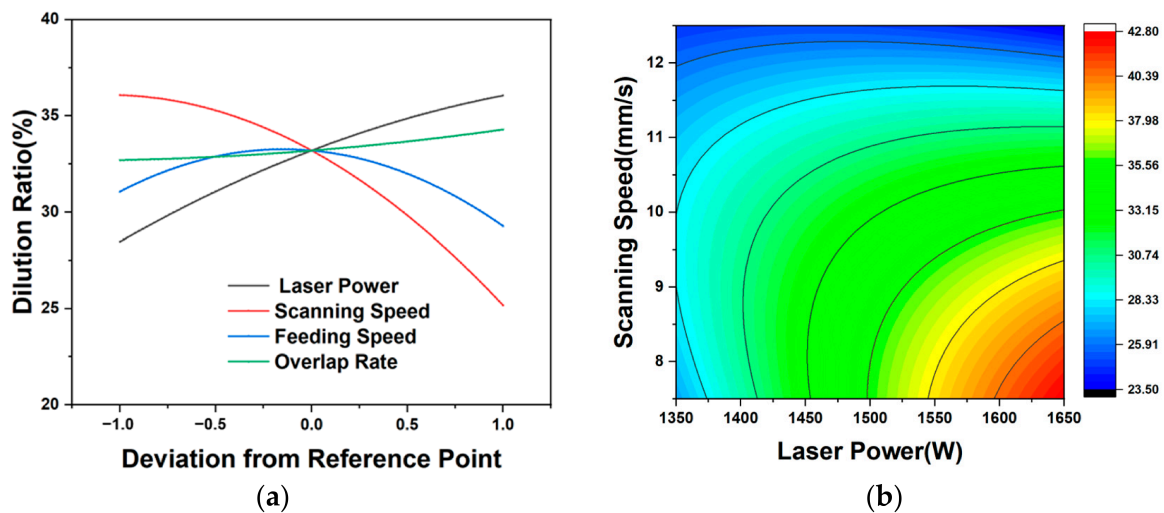


Figure 4. Cont.

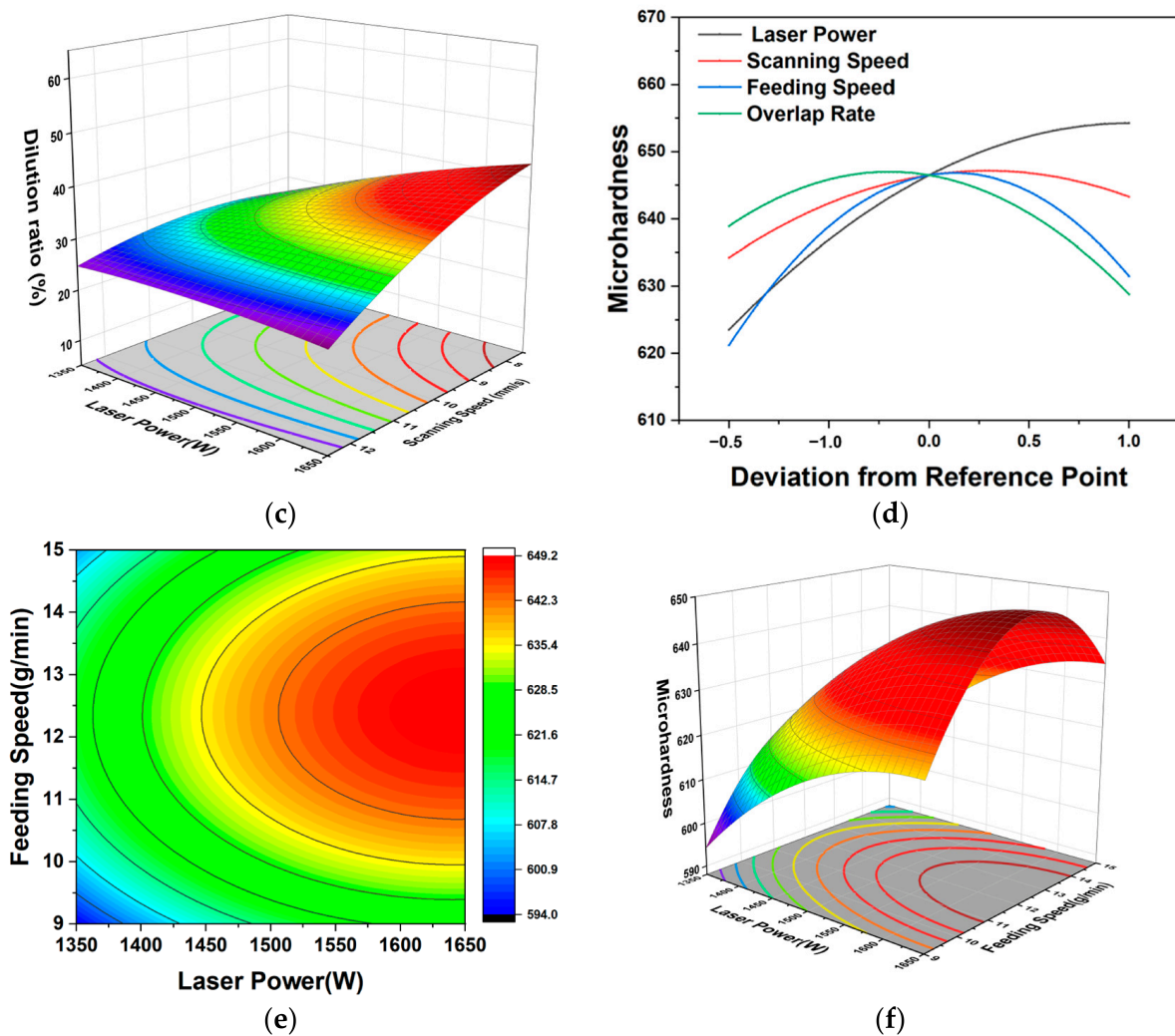


Figure 4. Relationship between the process parameters and dilution ratio: (a) perturbation; (b) contour diagram; (c) response surface diagram; relationship between the process parameters and microhardness; (d) perturbation; (e) contour diagram; (f) response surface diagram.

3.2. Multi-Objective Optimization of the Process Parameters Using MOPSO

The multi-objective particle swarm optimization (MOPSO) algorithm, derived from the classical particle swarm optimization (PSO) paradigm, aims to identify the optimal trade-offs among multiple conflicting objectives [24]. This algorithm is inspired by systematic observations of the foraging behavior of birds in nature. During their random search for food, individuals dynamically adjust their flight paths based on personal experiences and the perceived positions of their peers, ultimately converging in areas with the most abundant food resources. Drawing from this intelligent biological behavior, researchers conceptualize individual birds as “particles” and associate target food positions with optimal solutions to specific problems, thereby establishing a swarm-intelligence-based framework grounded in group collaboration. In the MOPSO algorithm, each particle represents a candidate solution that iteratively explores a D-dimensional search space. The position and velocity updates of the particles are influenced by both their historical optimal position (pbest) and the global optimal position (gbest). Through the sharing of information among individuals and group co-evolution, the algorithm progressively approaches and

converges to the global optimal solution of the optimization problem. Velocity and position update formulation are expressed as Equations (4) and (5):

$$v_i(t+1) = \omega v_i(t) + c_1 r_1 [pb_i(t) - x_i(t)] + c_2 r_2 [gb_i(t) - x_i(t)] \quad (4)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (5)$$

which t is the number of iterations, w_t is the inertia factor at the t th iteration, $x_i(t)$ denotes the position of the particle at the t th iteration, $v_i(t)$ represents the velocity of the particle at the t th iteration, $pb_i(t)$ is the best position of individual particles at the t th iteration, $gb_i(t)$ is the best position of all particles at the t th iteration, c_1 and c_2 are accelerating factors and r_1 are r_2 random number between 0 and 1.

The specific implementation process of the MOPSO algorithm is depicted in Figure 5 and is detailed as follows. The key parameters, including population size, maximum number of iterations, Pareto archive capacity, learning factor, and inertia weight, are initialized. Subsequently, an external archive structure is established to store non-dominated solutions. The fitness of each particle is then calculated based on the objective functions and constraint conditions. A particle is randomly selected from the external archive to serve as the gbest guide. The velocity and position of each particle are updated according to Equations (4) and (5), respectively. The fitness values are subsequently re-evaluated to update the individual pbest positions and the external archive. Ultimately, the solution set for the Pareto front is derived based on dominance relations and crowding distance, reflecting the distribution of optimal solutions for the multi-objective optimization problem.

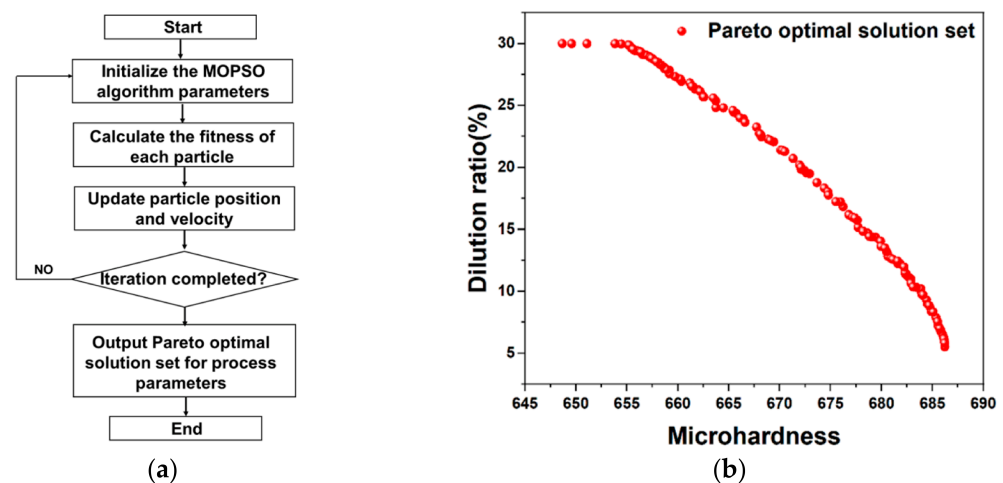


Figure 5. (a) MOPSO algorithm operation process; (b) Pareto optimal solution set for laser cladding process.

The results presented in Figure 5 demonstrate that the response surface methodology (RSM) reveals conflicting effects of laser cladding process parameters on both the dilution rate (η) and microhardness (HV). Consequently, it is imperative to utilize the multi-objective particle swarm optimization (MOPSO) algorithm to determine the Pareto front for η and HV. Previous studies have indicated that the dilution rate is a critical metric for assessing the quality of the cladding layer [25]. An inadequate dilution rate hampers the formation of a robust metallurgical bond between the coating and the substrate, leading to diminished interfacial strength. In contrast, an excessively high dilution rate can result in substantial migration of alloying elements into the substrate material, thereby increasing the susceptibility of the cladding coating to cracking. Based on the RSM analysis, a dilution rate of 30% is identified as optimal [26]. Microhardness (HV) is a primary indicator for evaluating the wear resistance of the coating, as an increase in microhardness generally enhances wear

resistance. Therefore, improving microhardness is essential for ensuring the durability of the cladding layer. The objective functions and constraints for optimization, as derived from the RSM analysis in the present study, are formulated as shown in Equations (6) and (7), respectively.

$$\begin{cases} \min |f\eta(P, V, F, \varphi) - 30\%| \\ \max |fHV(P, V, F, \varphi)| \end{cases} \quad (6)$$

$$s.t. \begin{cases} 1200 \text{ W} \leq P \leq 1800 \text{ W} \\ 5 \text{ mm/s} \leq V \leq 15 \text{ mm/s} \\ 6 \text{ g/min} \leq F \leq 12 \text{ g/min} \\ 35\% \leq \varphi \leq 75\% \end{cases} \quad (7)$$

The Pareto-optimal front, derived from the MOPSO algorithm, is illustrated in Figure 4b. To further refine the optimal process parameters, dye penetrant testing was utilized to assess the microcracks within the cladding layers, as shown in Figure 6. Notably, no significant microcracks were detected on the surfaces of specimens from groups 1, 3, 6, 8, 15, 20, 21, 25, and 27. The top-ranked optimized process parameters are as follows: $P = 1350 \text{ W}$, $V = 12.5 \text{ mm/s}$, $F = 9 \text{ g/min}$, and $\varphi = 45\%$. The relative errors between the actual and predicted values of dilution rate and microhardness are 1.7% and 2%, respectively, which confirms the predictive capacity and reliability of the RSM model.

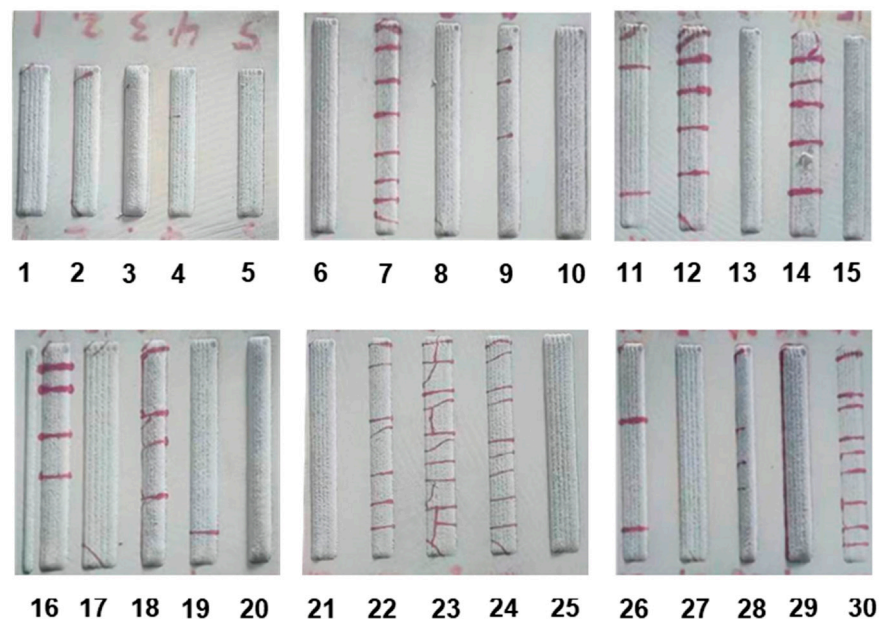


Figure 6. Dye penetrant inspection results (E1–E30) of surface micro-cracks in laser cladding.

3.3. Microstructure

Figure 7 presents SEM images of the cladding coating produced using optimal process parameters (laser power: 1350 W, scanning speed: 12.5 mm/s, powder feeding speed: 9 g/min, overlap rate: 45%) along the thickness direction. The results indicate that no significant defects, such as pores, inclusions, or microcracks, are present. Notably, the cladding coating demonstrate a robust metallurgical bond with the substrate, affirming the high overall quality of the coatings prepared under the optimized conditions. Furthermore, the microstructure of the cladding coating reveals a distinct gradient distribution. In the upper region, the microstructure predominantly consists of fine equiaxed crystals. The rapid solidification results in a high cooling rate of the molten pool, which promotes grain refinement. The middle region exhibits a mixed zone of columnar and equiaxed crystals. In contrast, the microstructure at the bottom of the coating features a typical dendritic

structure aligned with the heat flow direction, driven by the significant thermal gradient during the cladding process [27].

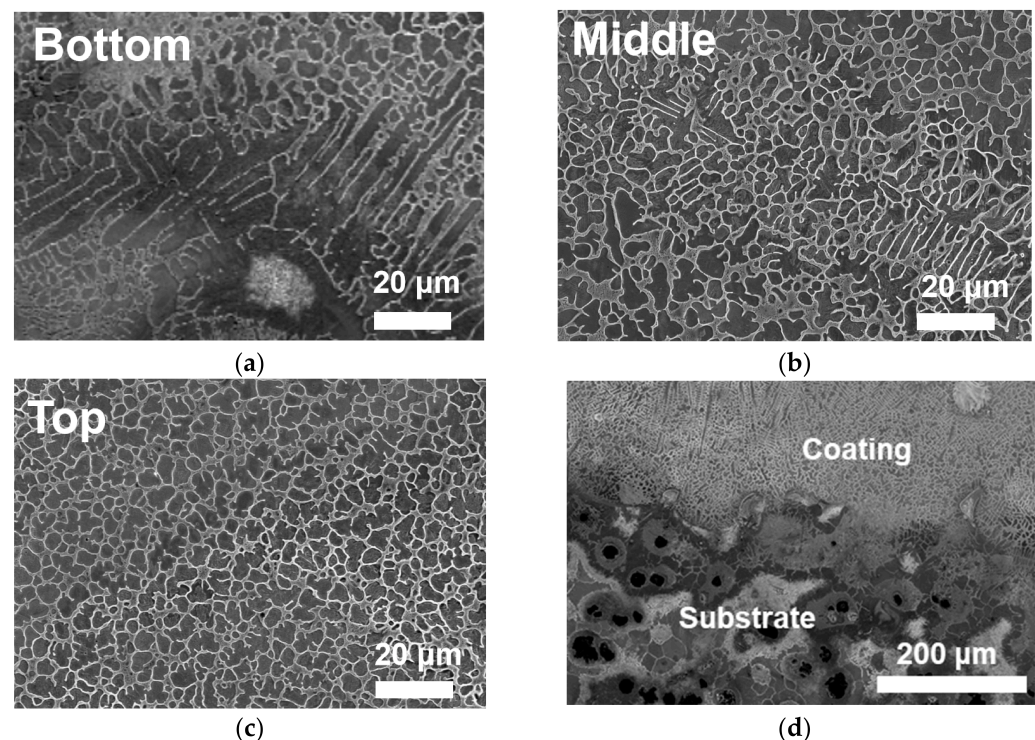


Figure 7. SEM results of laser cladding layers with optimal process parameter: (a) bottom; (b) middle; (c) upper; (d) substrate/coating interface.

3.4. Microhardness and Wear Resistance of Fe-Cr-Ni Cladding Coatings

Microhardness serves as a crucial indicator for characterizing tribological performance according to the Archard model. The longitudinal microhardness distribution of the multi-track Fe-Cr-Ni cladding coating is illustrated in Figure 8a. A gradual decrease in microhardness is evident from the cladding layer to the substrate, with a pronounced transition at the interface between the coating and the heat-affected zone (HAZ). The average microhardness of the cladding layer measures 620.3 HV, approximately 2.8 times that of the nodular cast iron substrate. During the laser cladding process, both the powder and substrate experience rapid melting and non-equilibrium solidification due to high-energy beam irradiation, leading to significant grain refinement within the cladding layer. Furthermore, the rapid heating and cooling associated with the Fe-Cr-Ni cladding coating process contribute to solution strengthening, thereby improving the microhardness gradient.

The tribological properties of the Fe-Cr-Ni coating and the nodular cast iron substrate were evaluated through wear testing. The variations in the coefficient of friction (COF) for both the substrate and coating under dry conditions are illustrated in Figure 8b. Notably, the COFs of both the substrate and coating exhibit a rapid increase during the initial running-in period, attributed to the elevated shear force required to fracture the welded junctions. During the wear stages, the COF curve for the Fe-Cr-Ni coating reaches a relatively steady state with an average value of approximately 0.5. In contrast, the COF curve for the nodular cast iron substrate displays significant fluctuations before ultimately reaching equilibrium with an average value of approximately 0.6. The lower COF observed in the Fe-Cr-Ni/Si₃N₄ friction system can be attributed to the higher hardness of the Fe-Cr-Ni coating compared to the nodular cast iron, which results in reduced debris generation during the wear test. This finding indicates that the Fe-Cr-Ni cladding coating possesses superior friction properties relative to the nodular cast iron substrate. Furthermore, as

shown in Figure 8c, the Fe-Cr-Ni cladding coating demonstrates a reduced wear rate compared to the nodular cast iron substrate under dry friction conditions, indicating a significant enhancement in wear resistance.

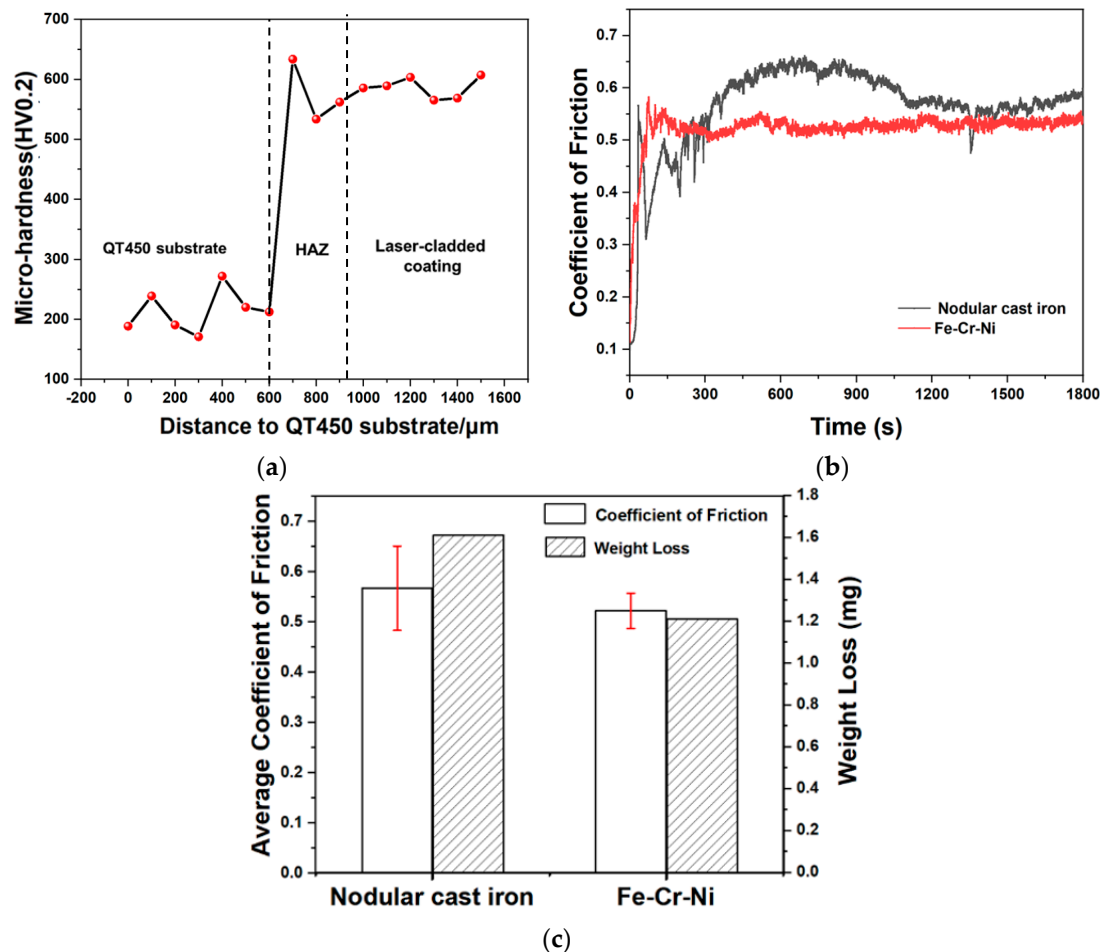


Figure 8. (a) Hardness distribution of the laser cladding coating; (b) friction coefficients curves of nodular cast iron substrate and Fe-Cr-Ni coating; (c) average friction coefficient and weight loss of nodular cast iron and Fe-Cr-Ni during friction wear tests.

The three-dimensional wear scar and corresponding worn surfaces of the nodular cast iron substrate and the Fe-Cr-Ni cladding coating are presented in Figure 9 and Figure 10, respectively. Notably, the nodular cast iron substrate and the Fe-Cr-Ni cladding coating exhibit marked differences in their wear scar morphologies, as shown in Figure 9a,b. The wear scar depth of the nodular cast iron substrate measures 50 μm, which is greater than that of the Fe-Cr-Ni cladding coating, as presented in Figure 9c. As shown in Figure 10a, the worn surface of the substrate displays extensive ploughing grooves and delamination, accompanied by significant spalling, indicating pronounced plastic deformation during the wear test. The lower hardness of the nodular cast iron, attributed to the uneven distribution of graphite particles, contributes to this plastic deformation under the influence of frictional shear forces. The detachment of a substantial amount of debris results in grooves that align parallel to the wear direction. Thus, the predominant wear mechanism for the nodular cast iron is adhesive wear. In contrast, as illustrated in Figure 10b, only a few abrasive particles, resulting from mild ploughing wear, are present on the worn surface of the coating. The formation of a dense chromium oxide film and grain refinement reduces plastic deformation and brittle spalling, leading to a significant decrease in adhesive wear. The shear stresses induced by friction cause the adhesive bonds at surface irregularities to rupture, leading to

the progressive removal of the superficial material and the exposure of metal surfaces. These newly exposed surfaces display chemical reactivity, promptly engaging with atmospheric oxygen to form oxide layers [28–30]. Furthermore, as reported in ref. [31], during dry sliding or reciprocating friction, the contact zone undergoes significant shear and contact stresses, leading to severe plastic deformation in the surface of the Fe-Cr-Ni coating. This results in the formation of a high density of dislocations that nucleate, glide, and interact within the surface layer, giving rise to dislocation walls and tangles. With continued strain accumulation, these dislocation walls transform into low-angle grain boundaries and then into high-angle grain boundaries, dividing the initial coarse grains into smaller equiaxed grains. Consequently, the primary wear mechanism for the Fe-Cr-Ni cladding coating is mild abrasive wear and adhesive wear.

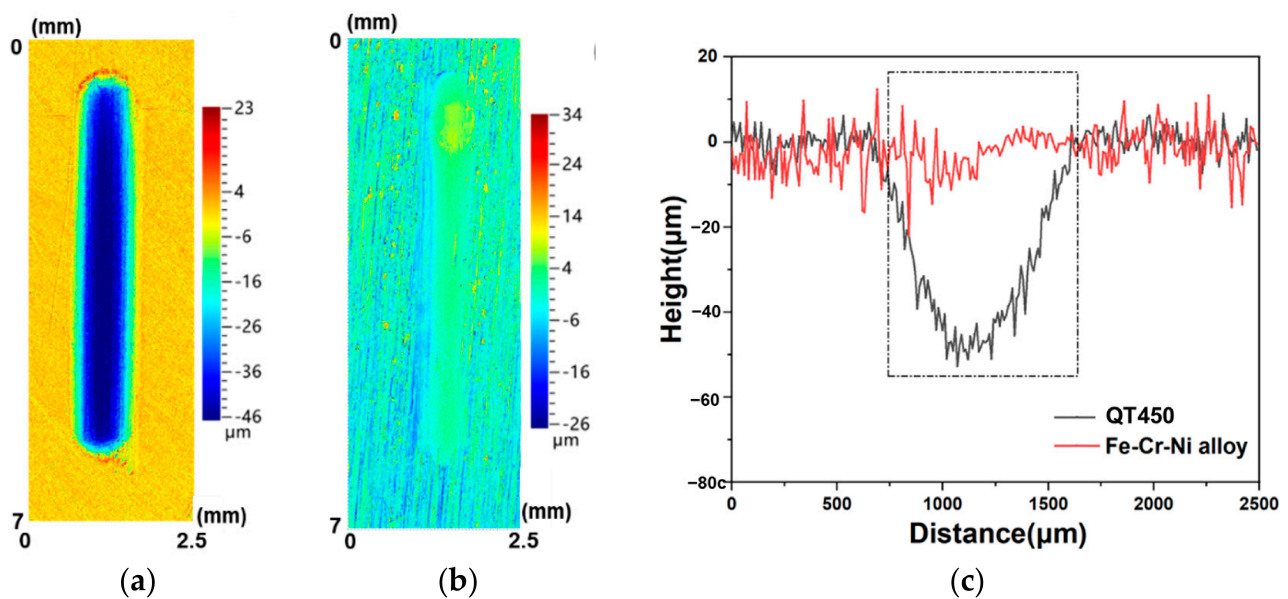


Figure 9. Reciprocating friction wear scars: (a) nodular cast iron; (b) Fe-Cr-Ni cladding layer; (c) depth of wear scars.

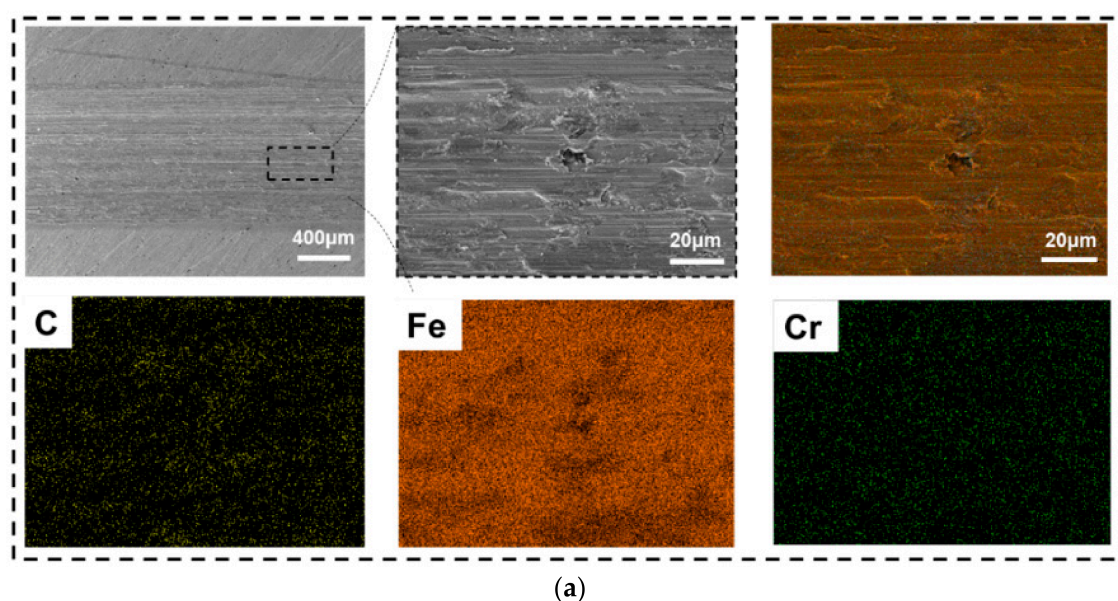


Figure 10. Cont.

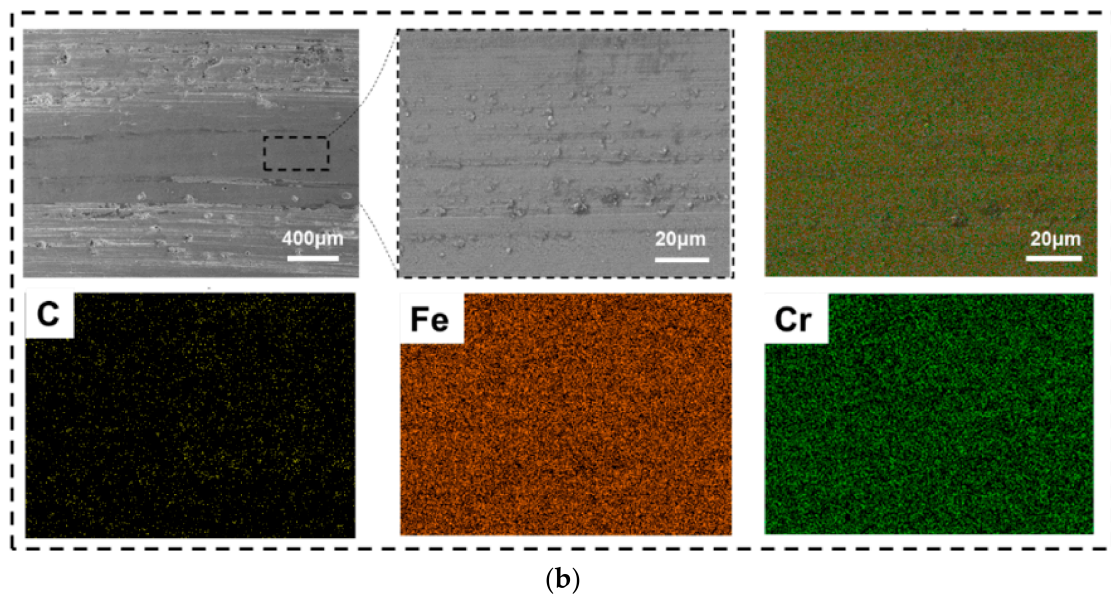


Figure 10. SEM image of worn surface morphologies: (a) nodular cast iron; (b) Fe-Cr-Ni cladding layer.

During this process, the extremely high cooling rates, typically ranging from 10^3 to 10^6 K/s, induce highly non-equilibrium solidification conditions [32]. As a result, the coating primarily solidifies as an austenitic matrix, while competitive precipitation of martensite/ferrite and retained austenite occurs simultaneously. The rapid cooling rate hinders diffusional phase transformations, facilitating the formation of metastable phases, which enhances the hardness and wear resistance of the cladding coating [33]. During the laser cladding process, carbon element is dissolved from the graphite and accumulates between dendrites. Chromium reacts with diffused carbon to generate carbides like Cr_{23}C_6 and Cr_7C_3 , which then precipitate along the grain boundaries, contributing to the improvement of the hardness and wear resistance of the cladding coating [34].

4. Conclusions

In this study, Fe-Cr-Ni coatings were successfully fabricated on nodular cast iron substrates via laser cladding. A central composite design (CCD) was employed to establish quantitative correlations between the cladding process parameters and the response variables. The optimal process parameters were determined using a multi-objective particle swarm optimization (MOPSO) algorithm. Additionally, the microstructure, microhardness distribution, and wear resistance of the multi-track coatings were systematically characterized, offering valuable insights into the wear mechanisms of the Fe-Cr-Ni coating system. The conclusions are presented as follows:

1. Based on the results of the central composite design (CCD), response surface models were effectively developed to correlate process parameters—namely, laser power, powder feed rate, scanning speed, and overlap rate—with coating performance indices, including dilution ratio and microhardness. Statistical analysis of variance (ANOVA) and residual analysis indicated that the models exhibited high reliability, as evidenced by significant model terms ($p < 0.05$) and non-significant lack-of-fit ($p > 0.05$). This confirms the strong predictive accuracy of the established models.
2. The optimal laser cladding parameters for Fe-Cr-Ni alloy were determined using the multi-objective particle swarm optimization algorithm as follows: a laser powder of 1350 W, a scanning speed of 12.5 mm/s, a power feed rate of 9 g/min, and an overlap rate of 45%. Experimental validation demonstrated relative errors of only 1.7% for

the dilution ratio and 2% for microhardness when comparing the experimental and predicted values, thus affirming the reliability of the optimization outcomes.

3. The Fe-Cr-Ni coating exhibited enhanced tribological performance compared to the nodular cast iron substrate. This improvement is mainly ascribed to grain refinement resulting from the rapid solidification process in laser cladding, leading to reduced friction coefficient and wear rate. Additionally, the wear mechanism transitioned from severe adhesive wear in the nodular cast iron to a blend of mild abrasive wear and adhesive wear in the Fe-Cr-Ni coating.

This research primarily focuses on the optimization of cladding process parameters, while research on the influence of working conditions on the friction and wear properties of the cladding layer remains relatively limited. To further expand the application of Fe-Cr-Ni alloy reinforced coatings in the automotive and mining industries, future work will investigate the friction and wear performance of Fe-Cr-Ni cladding layers subjected to heavy loads.

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