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Study of cracking mechanism and wear resistance in laser cladding coating of Ni-based alloy

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Abstract: Ni-based coatings with the addition of a plastic phase- an austenitic stainless net were prepared using laser cladding technology, and the CeO₂ was added in cladding layers. The cracking mechanism, microhardness, microstructure, phase composition, and wear properties were investigated. The relationship between thermal stress and the elastic and plastic fracture had been developed from the standpoint of fracture mechanics and thermal elastic fracture mechanics. The Fracture criterion of the nickel-based coating was obtained, and the study has shown that the crack sensitivity could be reduced by decreasing the thermal expansion coefficient $\Delta\alpha$. Then a new method was proposed, in which the substrate was prefabricated the stainless steel net. It was found that the number of cracks reduced significantly with the addition of stainless steel net. When the stainless steel net with 14 mesh was added in Ni-based coatings, the average microhardness of nickel composite coating was 565 HV_{0.2}, which was 2.6 times higher than that of the 45 steel substrate. Although the rare earth oxide 4 wt.% CeO₂ and stainless steel net were added in the Ni-based coating reducing the microhardness (the average microhardness is 425 HV_{0.2}), the wear resistance of it improved substantially. The wear volume of Ni-Based composite coating was $0.56 \times 10^{-5} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, which was 85.1% lower than that of 45 steel and 61.9% lower than that of Ni-based coating without CeO₂ and stainless steel net. The experiment results have shown that the Nickel-based composite coating is equipped with low crack sensitivity and high abrasive resistance with austenitic stainless net and the rare earth oxide 4 wt.% CeO₂.

Keywords: laser cladding; wear resistance; crack sensitivity; stainless steel net; rare earth oxide

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1 Introduction

It is well-known that abrasive wear is a severe problem to industrial components and equipment, resulting in energy consumption [1-3]. In order to prolong their service life, these components should be fabricated coatings. Laser cladding is a surface modification technique creating a high-performance coating on the surface of metallic material by a laser beam of high energy densities [4-8]. The technology offers unique superiority in terms of a material with high hardness and high melting point such as ceramic [9], NiTi alloys [10], and nickel-based superalloy [11], etc. Besides, laser cladding is popularly used to manufacture dense metallic parts with high performance, which is applied in aerospace, automotive, and turbines, etc.

The Nickel-based alloy coatings fabricated by laser cladding have outstanding wear resistance and corrosion resistance [7, 12]. In recent years, more and more scholars have made an achievement in fabricating Ni-based alloy coatings and nickel-based composite coatings to further enhance wear resistance. Wang *et al.* [13]. Indicated that wear loss of Ni-based alloy coatings with the addition of Y₂O₃, CeO₂, and La₂O₃ could be reduced remarkably. Simultaneously, the defects, such as porosity, crack, and lack of fusion could be eliminated. In addition, it was worthy to point out that nano-sized particles could exhibit outstanding mechanical properties compared with micron-sized particles [14]. Ning Zhao *et al* [15]. observed nanometer La₂O₃ could refine the microstructure of

interdendritic dramatically. Tang Kangkang *et al.* [16]. reported that Ni60 cladding layers added nano-WC particles displaying high hardness and abrasive wear resistance than the Nickel-based alloy coatings without nano-WC particles. However, Nickel-based alloy coatings have high cracking sensitivity, owing to a large number of hard Cr-rich precipitates and eutectic structures [17, 18].

Although Ni-based alloy coatings fabricated with rare earth, which plays a key role in producing grain refinement effect, might have superior anti-friction properties, coating's cracking susceptibility could not be reduced which attributed to the existence of the eutectics network providing a route for crack growth [19]. Higher hardness and wear resistance could be obtained with the addition of hard ceramic particles, such as WC, TiC, and SiC, but the hard phase is added to a soft matrix could increase the brittleness of coatings at the same time [20, 21]. Some scholars had refocused on the methods to restrict crack formation. Lulu Zhai *et al.* [6]. used alternating electromagnetic force produced by the effects of alternating current to refine grain structure. As a result, by using this approach, approximately 60% of cracks in Nickel-based alloy coatings could be eliminated. Dai Qiulian *et al* [22]. suggested that coating's crack susceptibility could be decreased with the addition of Co element. Lu Yaozhong *et al* [23]. reported that the crack of nickel-based superalloy coating could be healed by laser remelting technology, which reduced grain sizes and quantity of carbonitride due to element segregation in the heat-affected zone and the coatings. The residual thermal stress was considered the driving force of crack to Ni-based alloy coatings, which usually produced stress concentration around the pores. In order to reduce crack susceptibility, a useful method could minimize pore area by optimized process parameters [24-26]. As a common method that, pre-heating had been applied to decrease crack susceptibility [27-29]. These studies had been conducted mostly from rare earth additions, optimizing process parameters, and pre-heating the substrate to reduce the crack. However, the study on improvement of wear resistance and, at the same time, a reduction in crack susceptibility is currently scarcely reported.

This study focused on the mechanistic studies of cracking in the Ni-based coatings and presenting a fracture criterion for coatings from the viewpoint of fracture mechanics. Experiments, prefabricating metal nets on the substrate, were conducted to confirm the criterion of fracture by laser cladding. The influence rules of crack susceptibility on the variation of the mesh of metal nets were analyzed. Simultaneity, wear resistance of coatings by the addition of CeO₂ were investigated on the corresponding mechanical properties, frictional coefficient, and wear volume. The present results will offer an efficient solution to produce components with low crack susceptibility and high wear-resistance coatings fabricated by laser cladding.

2 Methodology on crack suppression

2.1 Crack formation mechanism

During laser processing, the mismatch of expansion and shrinkage between the coating and the substrate is generally related to the difference in elastic modulus and thermal expansion coefficients. Based on thermal thermoelasticity theory, the thermal stress σ generated after solidification of the molten pool can be calculated by Eq (1) [30]:

$$\sigma_{x\max} = -f(x, L)E\Delta\alpha\Delta T \quad (1)$$

Where $f(x, L)$ is a function of the analysis location and the initial length of the specimen, E is the modulus of elasticity, $\Delta\alpha$ is the thermal expansion coefficient of deposited material, ΔT is the temperature difference between the analysis position and the restricted area. In addition, a large temperature gradient along the deposition direction is generated in the molten pool, during which the temperature of the substrate is lower than that of the coatings owing to the good thermal conductivity of the substrate. Therefore, the cladding layer's shrinkage will be restrained by the substrate when the molten pool cools and solidifies, and the tensile stress is generated in the coating, which might bring a great tendency of cracking [30].

2.2 Elastic and plastic fracture in Ni-based alloy coating

By observing the cracks, the tensile stress leading to the fracture of the cladding layer is perpendicular to the direction of crack cracking, which belongs to the crack opening type. According to the COD criterion of elastic-plastic fracture mechanics, the critical opening displacement obtained by the D-M model is taken as the physical

parameters of the crack-tip field.

The AB segment of the crack surface is extended forward and intersects with the vertical line of the tip D at point E. The Crack opening displacement δ is measured by 2ED. The crack tip opening displacement is illustrated in Fig 1(a).

It is assumed that there are infinite microcracks of equal length in the direction perpendicular to the scanning direction, The crack length is $2a$, The interval between adjacent cracks is $2h$, the uniform tensile stress in the scanning direction is σ , the length of microcrack and its simplified plastic zone is $2c=2a+2R$, a schematic illustration of the microcracks of the coating as shown in Fig 1(b). Cracking occurs when the crack opening displacement reaches the critical value δ_c . At this time, the critical tensile stress can be calculated by Eq (2).

$$\sigma_{sc} = \frac{\delta_c \pi E}{8 \sin \int_0^{\pi/2} \frac{\cos X}{\sqrt{1 - \sin^2 \alpha \sin^2 X}} \ln \left[\frac{\sin(X + \theta)}{\sin(X - \theta)} \right] dX} \quad (2)$$

Fig 1 Cracking mechanism of Ni-based coating: (a) critical opening displacement (b) microcracks of coating

2.3 Fracture criterion of nickel-based coating

Thermal stress of coating is expressed in two forms, $\Delta\alpha < 0$ when the thermal expansion coefficient of the substrate is less than that of the cladding layer, and the coating is subjected to tensile stress. On the contrary, $\Delta\alpha > 0$ when the thermal expansion coefficient of the substrate is high than that of the cladding layer and the coating is subjected to compressive stress. In order to protect Ni-based coating from cracking, it should be ensured that the maximum tensile stress σ_{xmax} in the nickel-based coating is less than the critical tensile stress σ_{sc} when there exist crack tendency in cladding layers. According to Eqs. (1) and (2), the micro-crack propagating condition can be described as follows:

$$-f(x, L) E \Delta \alpha \Delta T < \frac{8 \delta_c \sin \theta}{\pi} \int_0^{\pi/2} \frac{\cos X}{\sqrt{1 - \sin^2 \alpha \sin^2 X}} \ln \left[\frac{\sin(X + \theta)}{\sin(X - \theta)} \right] \quad (3)$$

Where, $\alpha = \frac{\pi c}{2h}$, $\sin \theta = \frac{\sin(\pi a/2h)}{\sin \alpha}$, $\sin X = \frac{\sin(\pi x/2h)}{\sin \alpha}$. Eq (3) presents the factors that influence the Microscopic cracks, including material thermophysical parameters (E , $\Delta\alpha$, ΔT), specimen length, the critical crack opening displacement when cracking occurs. In terms of crack susceptibility, the majority of these researches have mainly focus on temperature gradient ΔT [31] [32]. The authors conclude that reduce the temperature gradient by preheating significantly decreased the residual stress after laser cladding. However, there is little information about the thermal expansion coefficient on cracks sensibility. Hence, this paper focuses mainly on the thermophysical parameters $\Delta\alpha$ [33]. Cracks could be suppressed by reducing the absolute difference of thermal expansion coefficient between the Ni-based coating and the substrate.

3. Experiments procedures

3.1 Initial materials

A medium carbon steel plate (0.45 wt.% C) was selected as the substrate material, and its dimension was 55 mm × 37 mm × 10 mm. 304 stainless steel net with eight different mesh (8 mesh, 10 mesh, 12 mesh, 14 mesh, 16 mesh, 20 mesh, 24 mesh, and 30 mesh, respectively) were selected for an experiment. The chemical composition of the 45 steel and the 304 stainless steel net was shown in Table 1. Ni60 powders with a particle size of 40-80μm were used as the raw powder. The chemical composition of the powder is listed in Table 2. The CeO₂ particles with the contents of 4% were adsorbed on the Ni60 powders by mechanical ball grinding, and the morphology of two kinds of powders was showed in Fig 2.

Table 1 Chemical composition of 45 steel and 304 stainless steel net (wt%)

Elements	C	Si	Mn	P	S	Cr	Ni	Fe
45 steel	0.42~0.5	0.17~0.37	0.5~0.8	≤0.035	≤0.035	≤0.25	≤0.28	Balance
304 stainless steel net	0.15	0.8	0.2		≤0.03	17.5~18.5	8~12	Balance

Table 2 Chemical composition of Ni60 powders (wt%)

Elements	C	Cr	Si	W	Fe	B	Ni
Content %	0.80	15.50	4.00	3.00	15.00	3.50	Balance

Fig 2 SEM micrographs. (a) Ni60 powders, (b) Ni60 powders with the addition of 4% CeO₂

3.2 Experiment apparatus and process parameters

Ni-based composite coatings were performed on the LDM-800 laser additive manufacturing system built by Shenyang aerospace university, as schematically shown in Fig 3. It consists of a 6 kw IPG fiber laser, a three-axis motion execution system, a three-bin coaxial powder feeder (RC-PGF-D3), a coaxial powder feeding system with a Precitec laser cladding head (YC52), and an oxygen analyzer and control system. Pure argon with 99.99% purity was used to deliver the powders and shield the molten pool from oxidation, which ensured the oxygen level below 50 ppm. The reciprocating scanning strategy was adopted, and the single-track cladding layer length was 35 mm. The process parameters of laser cladding were shown in Table 3. Before the experiment, the powder was dried in a vacuum oven at 80 °C for 8 h in order to increase fluidity. The substrate was ground and polished with sandpaper to remove the oxide layers, then was cleaned with ethanol. The 304 stainless steel net was washed with acetone to remove oil and then placed on the substrate.

Table 3 Parameters of experiments

Laser power	Scanning speed	Powder feeding rate	Defocusing	Overlap rate
LP / (W)	SS / (mm/s ⁻¹)	PFR / (g/min ⁻¹)	D/ (mm)	η / (%)
2100	8	6.6	14	50

3.3 Characterization of the coating

After the experiments, cross-sections of all coatings were obtained by using the wire cutting machine, then The specimens were polished with 400 # to 1500 # grit sandpapers, and the microstructure was observed by an etchant (H₂O and HNO₃ and HF with a ratio of 7: 3: 1). The microstructure of coatings was studied and analyzed by metallographic microscope (MR5000). Zeiss sigma500 scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS) was employed to further confirm the microstructure and identify the and chemical compositions of the coatings. The phase constitution of the cladding layer was performed using D/max-2500/PC X-ray diffraction (XRD) with a copper target, and the range of diffraction angle (2θ) was selected as 10°-90°; X-ray tube high voltage: 40KV, X-ray light tube current: 100mA. The XRD was implemented with a voltage of 40 kV, a current of 30 mA, a continuous scanning speed of 8°/min, and scanning from 10° to 90°. The microhardness of cladding layers from the surface to the bottom was tested using an HVS-1000 Vickers microhardness tester with a loading force of about 0.98N for 10 s. One point was measured vertically every 0.1 mm at the cladding layer, each point was measured three times, and the final microhardness was the average value of measurements. The friction and wear tests were carried out on the MS-G5000 wear experimental machine, and the Si₃N₄ balls were employed as friction pairs with a diameter of 5mm. The tests were conducted with a rotation speed of 200 rpm/min and a radius of 5.5 mm, and 45 min friction tests with a 3 N normal load. The wear tracks after the 310 m sliding test were observed with a Keyence Digital Microscope VHX-500F. The wear volumes were assessed by Alpha-Step D-100 profilometer.

Fig 3 A schematic illustration of the laser cladding process

4 Results and discussion

4.1 The effect of the stainless steel net on cracks and wear resistance of nickel-based composite coatings

4.1.1 Macroscopic morphology analysis of nickel-based composite coating

When the cladding layers was detected by dye penetrant test, there are transverse and longitudinal cracks in the Ni-based coating without net, as illustrated in Fig 4. This is attributed to the thermal stresses that develop during solidification acting on grain boundaries, which is the main cause for cracking tendency. It is believed that cracks are occurred when the stress exceed the yield limit of materials. It is well known that Austenitic stainless steel offers a comprehensive property of lower yield strength, better antioxidant properties, strong toughness, and weldability. The stainless steel net are prefabricated on the substrate before the laser cladding experiment to obtain the coating Ni-based composite coating which was achieved after solidification. Experimental results showed that the 304 stainless steel net ($7 \times 10^{-6} \sim 21 \times 10^{-6}/K$) on the substrate with different mesh leading to the cracks in the cladding layer decreased. This is because the thermal expansion coefficient of 304 stainless steel net is higher than that of the 45 steel ($11.9 \times 10^{-6} \sim 13.1 \times 10^{-6}/K$). The stainless steel net which was prefabricated on the surface of 45 steel substrate can be regarded as a part of the substrate. At this time, the overall thermal expansion coefficient $\alpha_o = (\alpha_{45} + \alpha_{304})$ is greater than 45 steel. The absolute difference between the thermal expansion coefficient of the substrate after pre-fabricated the 304 stainless steel net and the Ni-based coating ($13.9 \times 10^{-6} \sim 20 \times 10^{-6}/K$) decrease. From the above Eq (2), the thermal stress of cladding layer decreased, which led to reduce the crack sensitivity. However, there still existed cracks in Ni-based composite coating with the addition of stainless steel nets of 16 mesh and 24 mesh. It demonstrated that the mesh number of the net is not the larger the better, nor the smaller the better, there exist a critical range to inhibit both the initiation and growth of crack.

Fig 4 crack observation by dye penetrant test. (a)Ni60, (b)Ni60 coating+ mesh, (c) Ni60 coating+ 10 mesh, (d) Ni60 coating+ mesh, (e) Ni60 coating+ 14 mesh, (f) Ni60 coating+ 20 mesh, (g) Ni60 coating+ 24 mesh, (h) Ni60 coating+ 30 mesh

4.1.2 Analysis of cross-section morphology of nickel-based composite coating

From Fig 5, some large pores exist in Ni-based composite coating with 8 mesh stainless steel net prefabricated on the substrate. Because there is a gap between the stainless steel net and the substrate, when the melting pool rapidly solidified, the gas in the gap can not be eliminated in time, forming pores. Compared with the cross-section morphology of Ni-based coating without net, there was incomplete melting stainless steel wire in the Ni-based composite coating which the substrate was prefabricated stainless steel net with 10 mesh, and the presence of microcracks in the Ni-based composite coating which the stainless steel net with 12 mesh was prefabricated on the substrate. However, there was no obvious cracks or pores appeared in the composite coating which the stainless steel net with 14 mesh was prefabricated on the substrate. It was found that there were small cellular pores in nickel-based composite coating which the stainless steel net with 24 mesh and 30 mesh were prefabricated on the substrate through an optical microscope. When the specimen subject to external forces, the existence of porosity has a positive effect on crack propagation, improving the crack sensitivity and decreasing the mechanical property of specimens. The above studies suggested that the precipitating gas hole existed in nickel-based composite coating, and the gas content in a molten solute increased during the solidification of molten metal, and the gas that precipitated near the bottom of grain boundaries. Similarly, it has large driving force to precipitate gas. The solute of lower solubility are enriched at the intergranular phase, which provide geometric stabilization for bubble

miconuclei. Shrinkage cavity which is associated with solidification shrinkage, and it is in a vacuum state at the initial stage, which creates favorable conditions for bubble precipitation.

Fig 5 Cross-section morphology of nickel-based composite coating with the addition of stainless steel net. (a) Ni60 coating+ 8mesh, (b) Ni60 coating+ 10mesh, (c) Ni60 coating+ 12mesh, (d) Ni60 coating+ 14mesh, (e) Ni60 coating+ 24mesh, (f) Ni60 coating+ 30 mesh.

4.1.3 Analysis of microhardness of nickel-based composite coating

The microhardness profile along the depth direction of Ni60A coating are showed in Fig 6. When the stainless steel net was prefabricated on the substrate, the microhardness of the composite coating decreased. Due to the stainless steel net was melted at high temperatures, the Fe content increased. As a result, the precipitation of the hard phase was suppressed in the melt pool, which caused a reduction in the microhardness [34]. However, it was found that the microhardness of the coating was improved as the number of meshes of stainless steel net increases. When the stainless steel net with 14 mesh was prefabricated on the substrate, the highest average microhardness of the cladding layer reaches 565HV_{0.2}, which was approximately 2.6 times higher than that of the substrate. This is due to the fact that as the number of mesh of the stainless steel net increase, the diameter of wire become increasingly slender. Besides, the content of Fe element decrease with the reduction of the mass of stainless steel net per unit area prefabricating on the substrate, which contribute to the precipitation of the hard phase increases. When 4wt.% CeO₂ was added in Ni-based composite coating which the stainless steel net with 14 mesh was prefabricated on the substrate, the average hardness of the Ni-based composite coating was found to be 425 HV_{0.2} which showed a 31% reduction compared Ni-based composite coating without rare earth oxides, but it was still about 2 times as much as that of the 45 steel substrate. Due to the addition of CeO₂, the laser energy absorbed by molten pool increases, increasing the convection and inducing a large number of Fe element from the substrate come into the molten pool [35].

Fig 6 Microhardness of nickel-based compositions coatings

4.1.4 Analysis of friction coefficient of nickel-based composite coating

Fig 7 presents how the friction coefficient of the surface of the 45steel and cladding layer varies with time at 3 N load. When the surface has undergone a relatively short running-in stage, the contact area between the surface and Si₃N₄ ball is smaller and had large contact stress. The microconvex bodies on the surfaces were abraded vigorously and improving the friction coefficient. When the friction coefficient leveled off, it was demonstrated that the wear process gradually enters a stable stage. It can be seen in Figure 6 that the 45 steel shows highest friction coefficient, and the average friction coefficient is 0.76. This is because the difference between the hardness of 45 steel and Si₃N₄ ball is more significant, which the steel surface is highly susceptible to damage. In the process of friction and wear, the production of wear debris increased frictional resistance, the friction coefficient increased. As it can be seen, the Ni60 coating exhibited an average friction coefficient of 0.50. This is due to the precipitation of borides and carbides can significantly improving the hardness of the cladding coating, offering the advantage of resistance to abrasive wear. When the substrate was prefabricated stainless steel net with 8 mesh, 10 mesh, 12 mesh, and 14mesh respectively, the friction coefficient increased as the mesh number decreased. The average friction coefficient of Ni-based composite coating with different stainless steel net was 0.64, 0.59, 0.57and 0.46, respectively. The friction coefficient of Ni-based composite coating which the stainless steel net with 14 mesh was prefabricated on the substrate decreased by about 70% than that of the 45 steel and decreased by about 8% than that of the Ni60 coating. It was demonstrated that the Ni-based composite coating which the stainless steel net with 14 mesh was prefabricated on the substrate had good antiwear and friction-reduction behaviour. The relative investigations reveal that the pores and cracks of the Ni-based Alloy Coating with addition of 4 wt.% CeO₂ is increased comparing with that of the coating without CeO₂ [36]. Therefore, the average coefficient of friction of Ni-based composite coating in Ni-based composite coating that the stainless steel net with 14 mesh was prefabricated on the substrate was 0.49, after the 4 wt.% CeO₂ was added to it. The Ni-based composite coating increased by 6.5% compared to coating without rare earth oxides and decreased by 36% compared to 45 steel.

Fig 7 Friction coefficient of nickel-based composite coatings

4.1.5 Analysis of wear scar morphology and wear amount of nickel-based composite coating

The surface morphologies of the wear scars can be revealed by Fig 8, the depth and width of the wear scar of the modified nickel-based composite coating were less than 45 steel, and it was demonstrated that the modified coatings are apparently much excellent wear resistant than 45 steel. Under cyclic contact stresses, the surface of 45 steel was presented severe wear, and the contact-welding was generated in a local high temperature environment. Adhesion occurred due to the bonding of the two contact surfaces atoms. The adhesive spots were sheared off and spalled during the subsequent sliding friction. Because of the lower hardness of 45 steel, the microcracks is generated and propagated freely. Then A large number fatigue spalling pits were found on the worn surface. The bulk of wear debris exhibited large plastic deformation after repeated rolling. As the time progresses, part of the undischarged wear debris adhered to the worn surface and wear continued. According to the above analysis, the wear mechanisms of the 45 steel were fatigue wear and adhesive wear. When stainless steel net was prefabricated on the the substrate, as the mesh number increased, the width of the wear scars narrower. It was demonstrated that the antifriction properties of Ni-based composite coating improves as the mesh number increased. It can be consistent with variation of the friction coefficient of Ni based alloy composite coating. The Ni-based Alloy Coating that the stainless steel net with 10 mesh was prefabricated on the substrate after the addition of the rare earth oxide 4 wt.% CeO₂, the width of the wear scars slightly increased, and the fatigue spalling pits were not found, which indicated that There are no large pieces of wear debris on the worn surface. In summary, when the content of CeO₂ was 4 wt.%, the nickel-based composite coating which the stainless steel net with 14 mesh was prefabricated on the substrate shows better wear resistance.

Fig 8 The surface morphologies of the wear scars of Nickel-based composite coatings. (a)45 steel, (b) Ni60 coatings, (c) Ni60 coating+8mesh, (d) Ni60 coating+ 10mesh, (e) Ni60 coating+ 12mesh, (e) Ni60 coating+ 14mesh, (e) Ni60 coating+ 14mesh+ 4%CeO₂

To further investigate the wear properties of nickel-based composite coating by laser cladding, the Wear volumes of the specimens were quantified separately using a surface profiler, as observed in Fig 9. In fact, in a radial section profile of erosion trace, which the outside edges are significantly higher than that of the inner ones. Due to the plastic deformation of the wear debris produced by the surface spalling after repeated rolling. Through comparative analysis, it can be found that the 45steel had the widest section profile of erosion trace, and the maximum depth was 7 μ m, and the wear volume of that was $3.75 \times 10^{-5} \text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$. The width of the erosion trace of Ni60 coating decreased significantly, and the wear volume of that was $1.47 \times 10^{-5} \text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, which was 60.8% lower than that of 45 steel. The width of the erosion trace of the Ni-based composite coating that the stainless steel net with 14 mesh was prefabricated on the substrate decreased significantly, and the wear volume of that was $2.89 \times 10^{-5} \text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, which is 22.9% lower than that of 45 steel. When the rare earth oxide 4 wt.% CeO₂ was added to it, the depth of the erosion trace of Ni-based composite coating decreased significantly, and the wear volume of that was $0.56 \times 10^{-5} \text{mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, which was 80.6% lower than that of Ni-based coating without rare earth oxide, and 85.1% lower than that of 45 steel substrate. Although the rare earth oxide 4 wt.% CeO₂ added in the Ni-based composite coating which the stainless steel net with 14 mesh was prefabricated on the substrate reducing the microhardness, the abrasion wear resistance of it improved substantially. This is consistent with previous studies [37, 38] indicating that there is no correlation between wear resistance and hardness in multiphase materials. Hardness describes only the hard body's penetration resistance, but it does not include mechanisms of formation and propagation of cracks which finally lead to the separation of the material [39]. The wear resistance of multiphase materials is controlled not only by the hard phase of materials, but also the strength and toughness of the matrix phase.

Fig 9 Radial wear scar profile. (a)45 steel, (b) Ni60 coatings, (c) Ni60 coating+14mesh, (d) Ni60 coating+ 14mesh+ 4%CeO₂

4.2 Microstructure and phase analysis of CeO₂ to nickel-based composite coating

4.2.1 XRD phase analysis of nickel-based composite coating

To further investigate the mechanism of reduction of hardness and increase of wear resistance of Ni-based composited coating with the addition of 4 wt. % CeO₂, Fig 10 exhibits the phase composition of materials using the XRD technique. Ni60 coating is mainly composed of the matrix γ -(Ni, Fe) solid solution and the reinforcement phases such as M₂₃C₆, M₇C₃ and hard phase CrB, CeCr₂B. Due to the high contents of Fe, Ni and Cr of 304 stainless steel, peaks of nickel-based composite coating that the stainless steel net with 14 mesh was prefabricated on the substrate intensified at $2\theta = 44.1^\circ$. But there is no difference in phase composition compared to Ni60 coating. The appearance of peak broadening at the diffraction angle of about 51.0° and 75.3° was obtained through the addition of the rare earth oxide 4 wt.% CeO₂ into Ni-based composite coating, and there are mainly hard phase CrB and eutectic phase M₂₃C₇, at the same time, a new phase of CeCr₂B appeared.

Fig 10 XRD phase diagram of nickel-based composite coating

4.2.2 Microstructure analysis of nickel-based composite coating

Fig 11 and Table 4 reveal the micro-morphologies and the constituent phases of the nickel-based composite coatings. Fig 11(a) shows that nickel-based composite coating mainly consists of bulk phase with irregular shape (A), interdendritic eutectics with the rod-shape structure (B), cellular dendrite phase (C). Due to B and C belong to low atomic number elements, can not be determined by EDS analysis. the estimation of the constituent phases can be done as follows. Through XRD analysis and reference to the relevant literature, the following can be inferred. The bulk eutectic contains a high concentration of Ni, Cr, and Fe, slight amount of C elements, and B poor. It could be inferred that this phase is probably borides CrB. The interdendritic eutectics with the rod-shape structure are identified as γ -(Fe,Ni) + M₇C₃ (M=Fe, Ni, Cr) with fewer quantities of C. As can be seen from Table 3, the relatively high content of Ni is overwhelmingly in cellular dendrite phase in which relatively low contents of C and Cr are dissolved. It can be confirmed that the cellular dendrite is the primary γ -(Fe,Ni) solid solution.

Fig 11(b) shows that nickel-based composite coating with the addition of 4 wt.% CeO₂ mainly consists of blocky phase (D), flake-like eutectic phase (E), cellular dendrite phase (F). Compared to coating without rare earth oxide, the Fe element content increased and the Cr element content decreased. On the one hand, the laser energy absorbed by the molten pool increases due to the addition of CeO₂, increasing the convection and inducing the excessive melting of the substrate[35]. It contributes to an amount of Fe coming into the molten pool. On the other hand, Fe and Cr belong to the elements of the third period, and the radius of the Fe atom is close to that of Cr atom. When the Fe concentration is higher, the Cr atoms are replaced with Fe to form solid solution phase. A new phase CeCr₂B is formed after the addition of CeO₂, due to the addition of CeO₂ are comparatively less in quantity and the finite dimensions of the probe, the element of Ce fails to detect. Combined with XRD analysis and relevant references, the blocky phase (marked with D in Fig 11(b)) may be identified as CrB with significant quantities of Fe. The flake-like eutectic phase (marked with E in Fig 10(b)) may be identified as γ -(Fe,Ni) + M₂₃C₇ (M=Fe, Ni, Cr) eutectics with small quantities of Si. The cellular dendrite phase may be identified as γ -(Fe,Ni) solid solution with small quantities of C, Cr and Si.

Fig 11 (a) Nickel-based composite coating+ 14 mesh, (b) Nickel-based composite coating+ 14 mesh + 4% CeO₂

Table 4 EDS composition analysis of Nickel-based composite coating+ 14 mesh and Nickel-based composite coating+ 14 mesh + 4% CeO₂ (mass fraction/%)

Location	B	C	Cr	Fe	Ni	W	Si
A	10.45	6.08	31.26	39.06	9.79	1.14	
B		9.7	15.93	33.62	34.36		2.24
C		7.83	4.23	34.64	47.19		3.42
D	7.16	9.13	9.67	66.11	7.37	0.29	0.27
E		10.35	5.01	68.58	14.79		1.27
F		8.64	5.06	71.42	13.79		1.09

Through comparative analysis, when 4wt.% CeO₂ is added in Ni-based composite coating which the stainless steel net with 14 mesh was prefabricated on the substrate, the size of the cellular dendrons increase and the resistance of the crystal boundary reduce. When an external force is applied, the plasticity distortion is very easy to go through the crystal boundary from one crystal grain to another [40]. Besides, hardness describes only the hard body's resistance to penetration [39]. The hardness of coating reduced. When the cladding layer is subjected to thermal stress, part of the internal stress will be removed by plastic deformation, which would reduce the cracking tendency. It can be seen from Fig 11(b) that the size of the bulk phase decrease. When the melt pool temperatures higher than 2050 °C, CeO₂ could be decomposed to Ce ion. In addition, Ce enriches as inner adsorption element mainly at grain boundary, which decreases the interfacial energy and Gibbs free energy of cladding layer, and reduces the driving force for crystal growth, thereby hindering the growth of crystals [41]. From this, hard phases (CeCr₂B) are distributed at grain boundaries of bulk phases. The ductile phase γ -(Fe,Ni) is precipitated after the primary hard phase during laser cladding, and the ductile phase is prone to inhibition, so the amount of the hard phase decrease contributing to the number of ductile phases increased. When the surface layer is subjected to external force, it can reduce the probability of damage to the surface layer in an elastic deformation manner within a certain range. The softer matrix phase is worn, and the hard phase which plays a certain supporting and bearing role is not easy to be peeled off due to the small size of it, thus, reducing the viscous force. In addition, the softer matrix phase act as inlaying wear debris and hard particle, therefore the wear resistance is improved greatly.

5. Conclusion

- (1) The fracture criterion of nickel-based coating was presented basing on thermoelasticity theory and fracture mechanics. Factors that influence the Microscopic cracks included material thermophysical parameters(E , $\Delta\alpha$, ΔT), specimen length and critical crack opening displacement when cracking occurs.
- (2) The difference in thermal expansion coefficient $\Delta\alpha$ was reduced by prefabricating an austenitic stainless steel net

on the surface of the substrate, and a significant number of the transverse and longitudinal cracks were disappeared in the Ni-based coating. However, a few macroscopic cracks were found in Ni-based coating with the addition of stainless steel nets of 16 mesh and 24 mesh.

- (3) As the number of meshes of stainless steel net increased, the average microhardness of the nickel-based composite coating improved and the friction coefficient decreased. When the stainless steel net with 14 mesh was prefabricated on the substrate, the highest average microhardness of nickel composite coating is 565HV which is 2.6 times higher than that of the substrate and the average friction coefficient is 0.46 which is decreased by about 70% than that of the 45 steel substrate and decreased by about 8% than that of the Ni-based coating without nets.
- (4) After the 4 wt.% CeO₂ was added to Ni-based composite coating that the substrate was prefabricated stainless steel net with 14 mesh, the average friction coefficient is 0.49, and the average hardness was found to be 386 HV. Comparing with coating without rare earth oxides, the average hardness showed a 36% reduction and the average coefficient of friction increased by 6.5%. But the wear resistance of coating with the addition of 4 wt.% CeO₂ and stainless steel net with 14 mesh improved substantially. The wear volume of that was $0.56 \times 10^{-5} \text{ mm}^3 \cdot \text{N}^{-1} \cdot \text{m}^{-1}$, which was 80.6% lower than that of Ni-based coating without rare earth oxide, and 85.1% lower than that of 45 steel substrate.

Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author's contributions are as follows: Zhenglei Yu, Lunxiang Li, Deqiang Zhang was in charge of the whole trial; Lunxiang Li wrote the manuscript; Guangfeng Shi, Guang Yang, Zezhou Xu, Zhihui Zhang assisted with sampling and laboratory analyses.

Competing interests

The authors declare no competing financial interests.

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Figures

Figure 1

Cracking mechanism of Ni-based coating: (a) critical opening displacement (b) microcracks of coating

Figure 2

SEM micrographs. (a) Ni60 powders, (b) Ni60 powders with the addition of 4% CeO₂

Figure 3

A schematic illustration of the laser cladding process

Figure 4

crack observation by dye penetrant test. (a) Ni60, (b) Ni60 coating+ mesh, (c) Ni60 coating+ 10 mesh, (d) Ni60 coating+ mesh, (e) Ni60 coating+ 14 mesh, (f) Ni60 coating+ 20 mesh, (g) Ni60 coating+ 24 mesh, (h) Ni60 coating+ 30 mesh

Figure 5

Cross-section morphology of nickel-based composite coating with the addition of stainless steel net. (a) Ni60 coating+ 8mesh, (b) Ni60 coating+ 10mesh, (c) Ni60 coating+ 12mesh, (d) Ni60 coating+ 14mesh, (be) Ni60 coating+ 24mesh, (f) Ni60 coating+ 30 mesh.

Figure 6

Microhardness of nickel-based compositions coatings

Figure 7

Friction coefficient of nickel-based composite coatings

Figure 8

The surface morphologies of the wear scars of Nickel-based composite coatings. (a) 45 steel, (b) Ni60 coatings, (c) Ni60 coating+8mesh, (d) Ni60 coating+ 10mesh, (e) Ni60 coating+ 12mesh, (e) Ni60 coating+ 14mesh, (e) Ni60 coating+ 14mesh+ 4%CeO₂

Figure 9

Radial wear scar profile. (a) 45 steel, (b) Ni60 coatings, (c) Ni60 coating+14mesh, (d) Ni60 coating+ 14mesh+ 4%CeO₂

Figure 10

XRD phase diagram of nickel-based composite coating

Figure 11

(a) Nickel-based composite coating+ 14 mesh, (b) Nickel-based composite coating+ 14 mesh + 4% CeO₂