Study on microstructure and mechanical properties of Ni60 + WC/Ni35/AISI1040 functional surface gradient structure of remanufacturing chute plate for the mining scraper by a low cost high power CO2 laser cladding technique

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Abstract

CO2 laser cladding is a type of green remanufacturing technology, which is of many technical advantages in repairing and remanufacturing industry, especially for some large-scale key mining equipment or parts due to its characteristics of high quality, high efficiency and environmental protection (e.g. energy and material saving). In this paper, the chute plate of coal mining scraper is fixed and remanufactured by CO2 laser cladding technique. Ni60, WC, Ni35, IG55 and other composite powders are selected to design and build the gradient functional structure for chute plate in order to improve the reproduced lifetime. A lot of high power low cost CO2 laser cladding tests are carried out on the matrix material (AISI 1040 steel plate) of old attrite chute plate. The optical microscope, SEM, XRD, microhardness test and wear experiment are adopted to analyze the relationships among the laser cladding process, the overlaying composite material, gradient functional structure and mechanical properties of the remanufacturing scraper’s chute plate. The research results show that laser power and scanning speed are the dominant cladding process parameters, which have a significant influence on the geometric dimension (including width and height), dilution rate and hardness of the deposited layer. These composite powders (especially including the rare earth metals) are the key factor to form the gradient functional structure. The laser cladding Ni60 + WC/Ni35/AISI1040 composite gradient functional structure has a reasonable toughness and strength of the transition layer structure, and a high hardness and wear-resistant surface functional layer, so the fixed and remanufactured product has formed good ductile plasticity and wear resistance properties as a result of the gradient functional structure. The unique Ni60 + WC/Ni35/AISI1040 gradient functional structure makes sure that the chute plate of mining scraper has excellent comprehensive performance, which is satisfied with the service requirements of mechanical parts or equipment in the harsh working environment of the mining industry. This research work provides technological guidance for the fix and remanufacturing chute plate, and achieves the goal of low cost, high efficiency and long life reproduced chute plate of mining scraper.

1. Introduction

Laser cladding technology is surface modification, maintenance and remanufacturing technique for old attrite parts or used equipment. The principle of laser cladding is to obtain the metallurgical bonding coating or deposited layer on the surface of a matrix using high energy laser beam melting alloy powders and some base...
Recent nickel-based alloy powder has been widely used as laser cladding material due to its excellent comprehensive properties, such as corrosion resistance, oxidation resistance, heat resistance, low-stress abrasive-wear resistance, good impact toughness, self-lubricity and strong wetting ability to a variety of matrix and WC particles [7, 8]. Many researchers have done a lot of researches on the improvement of the hardness of nickel-based cladding layer, refinement of microstructure, improvement of corrosion resistance, wear resistance and other properties. Ma [7] found that adding titanium powder to Ni60 + WC composite powder can promote the dissolution of WC particles, inhibit the coarse bulk ceramic particles in the original cladding layer, generate more finer TiC particles and improve the hardness of cladding layer. Afanas [8] studied the microstructure and the wear resistance of Ni-Cr-Si-B coating on an AISI 1030 steel substrate, they found a linear relationship between wear resistance and the distance between second-order dendrite arms. Wang [9] obtained the Ni60 cladding layer with a hardness up to 1400 HV by adding rare-earth oxide to the nickel-based alloy powder. Yang [10] compared the cladding structure and wear resistance of high-hardness Ni60 coating and low-hardness Ni25/WC-12Co composite coating on W1813N non-magnetic stainless steel substrate. The results show that although the friction coefficients of the two coatings are similar, the wear volume of the composite coating is only 10% of the Ni60 coating. Yao [11] induced the ultrasonic effect to laser cladding process. The results showed that compared with traditional laser cladding, the cladding layer with finer structure and higher microhardness was obtained through the ultrasonic laser cladding process.

Laser cladding process parameters have an important influence on the cladding layer microstructure, performance and morphology. Huang [12] studied the influence of process parameters on the performance of the Ni35 laser cladding layer on AISI 1045 steel substrate. The study showed that with the increase of scanning speed, the dendrite structure of the cladding layer was refined and the hardness of the cladding layer was improved. Shu [13] studied the effect of laser power on the microhardness and wear resistance of the cladding layer. The results show that the performance of the cladding layer is poor when the laser power is too high or too low. Luo [14] studied 304 stainless steel CO2 laser welded joints. They found that when the laser power is low, the highest hardness is at the center of the weld and decreases to both sides of the cladding layer. As power increases, the hardness of the weld center decreases significantly, and the hardness distribution trend is reversed. At the same time, they [15] also found that the higher laser power and the lower cooling rate will cause thermal cracks in the center of the weld, and larger cooling rate and temperature gradient will cause holes in the weld. Mondal [16] adopted the gray correlation analysis method to investigate the relationship between process parameters and the geometry size of the cladding layer and obtained the optimal combination of process parameters, which greatly simplified the optimization process by transforming the multi-objective optimization problem into a single-objective optimization problem. Luo [17] simulated the laser cladding process based on the Gaussian heat source model. The results show that as the laser power increases, the heat affected area increases. Hofman [18] established a finite element model of laser cladding to study the relationship between the width of the cladding layer and the dilution rate. The results show that the dilution rate is lower when the width of the cladding layer is less than 90% of the laser beam diameter.

However, laser cladding also has many problems. When the thermophysical properties of cladding layer material and base material are significantly different, stress concentration is likely to occur at the cladding layer/substrate interface, resulting in cladding layer cracking [19]. Sun [20] studied the temperature and stress field of the single-layer multi-channel laser cladding process. The results show that after cladding, the cladding layer is under tensile stress, and the longitudinal stress along the scanning direction is much greater than the transverse stress. Therefore, the control method for cracks reduction is necessary for the laser cladding process. Zarini [21] found that cracks can be avoided in the Ni40 or Ni60 cladding layer with a correct setting of the pre-heating temperature. Yang [22] found that when the Cr content is 15% in Ni60A alloy powder, the cladding layer has high mechanical performance and low crack rate. Luo [23–25] proposed a gradient cladding layer structure composed by matrix/transition layer/wear resistant layer. Material with better toughness and plasticity is used in the transition layer, while the wear resistant layer composed of high hardness, high wear resistance materials. The experiment results showed that the gradient cladding structure significantly improves the wear resistance of the cladding layer surface, while effectively preventing the cladding layer from cracking. Jiang [26] found that the gradient cladding structure relieved the stress concentration of the cladding layer, which is helpful to reduce...
cracks. Chen [27] introduced a Nickel-based alloy transition layer between Cu alloy substrate and Co-based alloy layer, the result showed that the transition layer provided sufficient bonding strength and reduced the crack susceptibility at the same time.

AISI 1040 steel is widely used in engineering due to high strength and good machinability. It is often used in moving parts such as shafts and connecting rods, as well as steel plates and steel belts. This paper aims at the problem of high maintenance cost due to wear failure of the chute plate of coal mine scraper made of AISI 1040 steel. The laser cladding method is used to deposit a layer of high wear resistance alloy so that the chute plate substrate can be used repeatedly, which greatly reduces the cost of use.

2. Material and methods

2.1. Material

In this paper, AISI 1040 steel, which is the same as the chute plate, is selected as the base material in the cladding experiment. Its chemical composition is shown in table 1. For a certain matrix material, choosing the appropriate cladding material is the key to obtain the cladding layer with high quality and performance. To obtain high quality cladding structure, the melting point of the cladding material and base material should be close and the wettability of the cladding material to hard particles such as WC particles should also be good. In this experiment, Ni60 + WC composite alloy powder was used as a cladding material, and the melting temperature of Ni60 was 950 °C–1050 °C, adding WC particles to Ni60 could improve the hardness and wear resistance of the cladding layer. In this paper, the size of the powder of Ni60, Ni35 and WC powder are 50–100 μm, and the size of the IG55 powder is 50–200 μm.

The morphology of the Ni60 powder is shown in figure 1, and the chemical composition of Ni60 is shown in table 2. In addition, in the process of laser cladding, the cladding layer with higher hardness and more hard phase particles such as WC has a certain cracking tendency, which is because the crack will initiate around these particles under tensile stress [28, 29]. Therefore, adding a certain thickness of alloy powder with lower hardness between the substrate and cladding layer as the transition layer is conducive to reducing the cracking tendency of the cladding layer. In this paper, Ni35 alloy powder is used as the transition layer material, and its chemical composition is shown in table 2. IG55 alloy powder, which is often used in the remanufacturing of the chute plate with high cost rare earth (RE), is also used in this paper to compare its performance with the performance of Ni60 + WC composite coating proposed in this paper.
2.2. Experiment

The laser cladding equipment used in this paper is shown in figure 2, which is mainly composed of an optical system, powder feeding system and CNC control system. The CNC control system is used to control the movement of the working table and the powder feeding amount. The optical system uses a CO₂ laser for laser cladding of the parts. The powder feeding system is used to transport the cladding powder from the hopper to the molten pool continuously and evenly. The methods of powder feeding for laser cladding mainly include coaxial powder feeding method and side blowing powder feeding method [30]. In this paper, IGS-3L side blowing powder feeder with a hopper capacity of 5 kg and a powder feeding amount of 10–80 g min⁻¹ was adopted. The powder feeder can adapt to 150 ∼ 320 mesh Fe-based, Ni-based, Co-based and Cu-based alloy powder. The side blowing powder feeding nozzle is shown in figure 3. The powder feeding nozzle is placed in front of the laser beam and has a certain inclination angle. During the cladding process, the laser and the powder feeding nozzle keep stationary, the scanning movement is generated by the moving of the working table in the opposite direction.

Before experiment, in order to prevent the powder particles from agglomerating and make the composition of the cladding layer uniform during laser cladding, taking 1 kg of 90% Ni60 + 10% WC composite alloy powder and baking it at 120°C for 30 min to dry the powder, and then reduce the moisture and other adsorbed gases from the powder [31]. After filtering with a 40–60 mesh screen, put the powder into the hopper of powder feeder. An AISI 1040 steel workpiece with a size of 320 mm × 150 mm × 10 mm which has a flatness less than 0.20 mm and a surface roughness of 6.4−12.5 μm is used. The workpiece is derusted mechanically before cladding, and the surface of the workpiece is cleaned with ethanol or acetone. After the workpiece being clamped reliably on the working table, the surface of the workpiece is preheated by laser scanning.

### Table 2.

| Name  | C    | Si   | B     | Cr   | Fe   | Ni      | Re |
|-------|------|------|-------|------|------|---------|----|
| Ni60  | 0.5  | 3.5  | 3.0   | 15   | 30   | balance | —  |
| Ni35  | 0.3  | 3.0  | 2.0   | 10   | 15   | balance | —  |
| IG55  | 4.0  | 1.0  | 1.5   | 43   | 47   | balance | 2  |

2.2. Experiment
Experiments in this paper are divided into two groups of experiments for determination of the optimal process parameters and the optimal design parameters of gradient structure, respectively. The experiment arrangements of process parameters is shown in table 3, which is divided into three groups of experiments. Experiment 1 changes the laser power and scanning speed to study the effect of process parameters on the cladding layer geometry size. Experiment 2 and 3 change the laser powder and scanning velocity (cladding or deposited speed) respectively to study the effect of process parameters on the surface hardness of the cladding layer.

The experiment arrangements of the design parameters of gradient structure is shown in table 4. Experiment 4, 5 and 6 change the thickness of the Ni35 layer, the content of WC particle of the cladding layer and alloy powder type of the cladding layer to study their effects on the hardness or wear resistance of the cladding layer. Experiment 7 is compared with Experiment 6 used different alloy powders on the same conditions.

### Table 3. Experiment arrangements of laser cladding process parameters.

| No. | 1# | 2# | 3# |
|-----|----|----|----|
| Laser power (KW) | 2.6–3.4 | 2.6–3.4 | 3.2 |
| Scanning velocity (mm min$^{-1}$) | 260–340 | 300 | 260–340 |
| Defocus amount (mm) | 0 | 0 | 0 |
| Feeding amount (g mm$^{-1}$) | 8 | 8 | 8 |

### Table 4. Experiment arrangements of design parameters of the gradient structure.

| No. | 4# | 5# | 6# | 7# |
|-----|----|----|----|----|
| Ni35 layer thickness (mm) | 0.2–1 | 0.6 | 0.6 | 0.6 |
| WC content (%) | 10 | 0–45 | 35 | 35 |
| Alloy powder type | Ni60 | Ni60 | Ni60 | IG55 |

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#### 2.3. Characterization

After the laser cladding experiment, the sample is cut into small strips, and the cross section of sample is sanded to bright, as shown in figure 4. The height, width and penetration of the cladding layer are measured by low power microscope. Aqua regia, which is a mixture of 25% hydrochloric acid and 75% nitric acid, is used to etch the laser cladding samples. The microstructure is observed by JSM-6830 SEM. The phase of the sample is analyzed by XPERT-PRO x-Ray Diffractometer (XRD). The hardness of the cladding layer is measured by MH-3 Victorinox microhardness testing machine. According to the microhardness test standard of GB/T4340.1-2009, the load is 9.8 N, and the loading time is 15s.

In the wear test, MMU-5G wear test machine is used. The pin-disk friction mode is selected. The cladding sample is made into a disk, and the pin is made of GCR15 bearing steel [32]. In the wear test, the rotation speed of
the disk is 400–1200 rpm, the load is 100 N and the wear time is 30 min. The samples are taken from the wear test machine every 10 min to observe the wear morphology of the cladding layer and measure the weight loss.

3. Results and discussion

3.1. Effect of process parameters

Figure 5 shows the schematic of the geometry size of the cladding layer. In this case, the effects of process parameters (including laser power and scanning velocity) on the cladding layer height ($H$), width ($W$) and dilution rate ($\eta$) are discussed. The dilution rate ($\eta$) is defined as the ratio of molten matrix area ($A_{m}$) to the area of cladding layer and molten matrix ($A_{c} + A_{m}$). For the calculation convenience, the dilution rate can be simplified to equation (1) which also has high accuracy [33].

\[
\eta = \frac{A_{m}}{A_{m} + A_{c}} \approx \frac{h}{h + H}
\] (1)

3.1.1. The geometry size of the laser cladding layers

Figure 6 shows the relationship between the width of the cladding layer and process parameters on a laser power of 2.6 KW, 2.8 KW, 3.0 KW, 3.2 KW, 3.4 KW and a scanning speed of 260 mm min$^{-1}$, 280 mm min$^{-1}$, 300 mm min$^{-1}$, 320 mm min$^{-1}$, 340 mm min$^{-1}$ respectively.

On the condition of a certain laser power, the width of the cladding layer decreases with the increase of the scanning speed. When the scanning speed is constant, the width of the cladding layer decreases with the decrease of the laser power, which can attribute to less laser energy absorbed by the alloy powder per unit time with the increase of scanning speed or decrease of laser power, resulting in the decrease of temperature of the molten pool and the melting amount of the powder. When the scanning speed is too fast or the laser power is too small, the alloy powder cannot be fully melted and the bonding strength between cladding layer and substrate is low. Considering the effect of scanning speed on production efficiency, the laser power should be increased to ensure the high scanning speed and meeting the requirements of bonding strength and geometry sizes at the same time.

Figure 7 shows the relationship between the cladding layer height and process parameters on a scanning speed of 260 mm min$^{-1}$, 280 mm min$^{-1}$, 300 mm min$^{-1}$, 320 mm min$^{-1}$, 340 mm min$^{-1}$ and a laser power of 2.6 KW, 2.8 KW, 3.0 KW, 3.2 KW, 3.4 KW respectively.

On the condition of a certain laser power, as the scanning speed increases, the height of the cladding layer decreases, which is due to the laser energy absorbed by the alloy powder per unit time decreases so that the melting amount of the powder decreases. Compared with the molten alloy powder, the unmelted alloy powder is more widely distributed under the same amount, resulting in a decrease in the height of the cladding layer. On a certain scanning speed, as laser power increases, the height of the cladding layer gradually decreases. However, the effect of laser power on the height of the cladding layer is different according to the laser power, which can be explained from two aspects. Firstly, as the laser power increases, the area of the molten pool increases so that more powder will enter the molten pool, increasing the height of the cladding layer. On the other hand, with the continual expansion of the molten pool as the laser power increases, the metal in the molten pool will flow out to both sides of the cladding layer, making the molten pool become wider and lower when the surface tension of the liquid metal in the molten pool cannot balance with its gravity. Therefore, the ultimate height of the layer is determined by the combined effect of these two aspects. The relationship of the width and height of the cladding layer and process parameters obtained in this paper are consistent with Xi’s work [34].
3.1.2. The dilution rate of the laser cladding

The dilution of the CO2 laser cladding refers to the change of the composition of the cladding alloy due to the molten substrate permeates into the molten pool in the laser cladding. The dilution rate reflects the degree of alloy composition changing in the cladding layer. Hemmati [35] studied the dilution effect on the mechanical properties of the laser cladding structure, they found that as the dilution rate increases, the Fe content of the cladding layer increases, which reduced the size and content of Cr borides and diminished the amount of Ni–Si–B eutectic phases, leading to a reduction on the hardness of Ni–Cr–B–Si–C cladding layer. However, a too low dilution rate may cause low bonding strength between cladding layer and substrate, making the cladding easily fall off when loaded [36]. A dilution rate of 5%–10% was thought to be a reasonable value in Nickel-based cladding layer [35–37]. Figure 8 shows the relationship between the dilution rate and the process parameters on a laser power of 2.6 KW, 2.8 KW, 3.0 KW, 3.2 KW, 3.4 KW and a scanning speed of 260 mm min$^{-1}$, 280 mm min$^{-1}$, 300 mm min$^{-1}$, 320 mm min$^{-1}$, 340 mm min$^{-1}$ respectively.

In the figure 8, when the laser power is constant, the dilution rate $\eta$ gradually decreases with the increase of scanning speed, which is because with the increase of scanning speed, the absorbed energy of matrix is reduced, resulting in the reduction of the melting amount of the matrix and the reduction of the dilution rate. When the scanning speed is constant, the dilution rate $\eta$ increases gradually with the increase of laser power, which is due
to the increase of the energy absorbed by the matrix, resulting in the increase of the melting amount of the matrix and the dilution rate. In addition, when the laser power is 2.6 kw, the dilution rate is only 2%, which is too low for achieving sufficient bonding strength according similar works [35, 36]. Furthermore, it can be found that the dilution rate hardly changes with the change of scanning velocity. The reason for the low dilution rate (2%) and its change trend can be explained from two aspects. On the one hand, according to figure 7, when the laser power is 2.6 kw, the height of cladding layer is the highest and changes the most smoothly with the change of scanning velocity. On the other hand, the penetration of matrix is the lowest when the laser power is 2.6 kw. According to equation (1), the dilution rate is defined as penetration divided the sum of height and penetration. Therefore, under the combined effect of penetration and height, the dilution rate is low and hardly changes with the change of scanning velocity.

3.1.3. The microhardness of the single laser cladding layer

Figure 9 shows the relationship between process parameters and the surface microhardness of the CO2 laser cladding layer with a laser power of 3.2 KW or a scanning speed of 300 mm min$^{-1}$ respectively. The blue line represents the effect of the scanning speed on the microhardness at a laser power of 3.2 KW, and the black line represents the effect of the laser power on the microhardness at a scanning speed of 300 mm min$^{-1}$.

In the figure 9, when the scanning speed is fixed to 300 mm min$^{-1}$, as the laser power increases from 2.6 KW to 3.2 KW, the hardness of the cladding surface increases and reaches the maximum value (about 800 HV) at 3.2 KW. With the increase of the laser power, the molten Ni60 + WC powder increases so that more carbide hard phases such as WC will form in the cladding layer, increasing the surface hardness of the cladding layer. However, when the laser power is higher than 3.2 KW, the hardness decreases sharply as the laser power increases. The reason for the sharp reduction when the laser power is 3.4 KW can be explained through the combined effect of the amount of hard phase and dilution rate. On the one hand, according to figure 8, when the scanning velocity is 300 mm min$^{-1}$, as the laser power changes from 2.6 kw to 3.4 kw, the dilution rate changes from 2% to 12%, which is adverse for the improvement of the hardness of cladding layer [35]. On the other hand, as the laser power increase, more WC particles dissolve, resulting in more hard phases precipitating in the cladding layer, which is advantageous to improve the cladding layer hardness [38]. When the laser power is higher than 3.2 kw, the negative effect of dilution on hardness overweight the positive effect of hard phase, therefore, resulting in the softening of the cladding structure and reduction of the hardness under a laser power of 3.4 kw. The change of the microhardness with the change of laser power shows good agreement with previous research [39].

Figure 9 also shows that the effect of scanning velocity and laser power on the microhardness of the cladding layer is similar. When the laser power is constant (3.2 KW), as the scanning velocity decreases from 340 to 260 mm min$^{-1}$, the surface microhardness of the cladding layer increases and reaches the maximum value (about 800 HV) at 300 mm min$^{-1}$. With the increase of the scanning speed, the cooling rate of the cladding layer increases, resulting in the refinement of the grains and improvement of the surface hardness. At the same time, when the heat input is sufficient, as the scanning speed increases, the amount of heat input per unit time in the deposited area gradually decreases, which also effectively reduce the softening of the material structure in the
deposited area, which also contributes to the improvement of microhardness. However, when the scanning velocity is higher than 300 mm min$^{-1}$, the surface microhardness of cladding layer begins to decrease drastically and reaches the minimum value (about 500 HV) at 340 mm min$^{-1}$, which is mainly because of the insufficient heat input when the scanning velocity is too high, resulting in the inadaptable melting amount of alloy powder and low bonding strength, which is also in accordance with previous research [39].

Based on the results and discussion in section 3.1, the optimized process parameters are a laser power of 3.2 KW and a scanning speed of 320 mm min$^{-1}$, the CO2 laser cladding layer with low dilution rate, high hardness, high efficiency and reasonable geometry sizes can be obtained in this case.

3.2. The microstructure of gradient structure

Figure 10 shows the SEM images of the interface of the Ni35 transition layer/AISI 1040 matrix. The metallurgical bond formed at the Ni35/AISI 1040 interface directly determines the bonding strength between the cladding layer and the substrate. The component analysis of Position A, B and C on the interface are shown in table 4.

As shown in figure 10, the interface of the laser cladding layer is white and composed by planar crystals. According to the composition analysis of point A at the interface, the Fe element there is higher than that at point C in the cladding layer, and the structure is a solid solution formed between Fe, Ni and Cr. In figure 10(b), about 3 μm on the left side of the interface, the matrix absorbs the laser energy and melts. A small amount of Ni and Cr
elements diffuse into the matrix, as shown in point B, forming an alloying zone. The mutual permeation of metals on both sides of the interface indicates that there is metallurgical bonding between the cladding layer and the matrix, indicating a high bonding strength and a low dilution rate, which ensures that the properties of cladding layer materials are not affected by the substrate and at the same time, the high bond strength between cladding layer and substrate.

There is the heat affected zone (HAZ) between the substrate and cladding layer, about 5 μm on the right side of the interface shown in the figure 10(b). The HAZ belongs to part of the base metal. But there is a significant difference between the matrix and the HAZ. The microstructure, formation and grain size of the HAZ are mainly related to the alloy elements diffusion, heating transferring and cooling rates in the laser cladding process. The HAZ has a relatively large size’s microstructure, most of which are irregular shape. The phase components of the HAZ are mainly the residual austenite and the martensite.

According to EDS test results, the distribution of Cr, Ni and Fe elements in the HAZ along the direction from the substrate to the cladding layer is as follows: the content of Cr and Ni elements near the interface of the cladding layer is relatively low, while the content of Fe is relatively high, indicating that there is dilution phenomenon near the interface between the HAZ and the cladding layer (shown in the table 5). This is the result of local segregation of interfacial alloying elements without uniform diffusion during laser cladding. The microstructure, phase components and grain size of HAZ will affect mechanical properties (such as the bonding strength and wear resistance) of the cladding layer. The microstructure of HAZ is complex. It is because of the interdiffusion, phase transition and solid solution of alloying elements in the HAZ that a good metallurgical bond is formed between the matrix and the cladding layer. In the laser cladding process, the temperature gradient near the interface is very large [40]. Therefore, the matrix metal near the interface is quickly heated to austenite transformation temperature and then rapidly cooled down owing to heat dissipation of the cold substrate, which make the matrix material undergo a heat treatment process and form the coarse martensite and remnant residual austenite as shown in red circle of figure 10(b). The microhardness value in the HAZ is not evenly distributed. The microhardness near the cladding layer is greater than that near the base metal, and the microhardness in the whole HAZ is less than that of the base metal. In the process of cladding, the HAZ absorbs a lot of heat and then cools, which the formation of residual austenite phase. Therefore, the microhardness value of HAZ is less than that of the substrate. The microhardness value of the cladding layer does not fluctuate much, which indicates that the microstructure of the cladding layer is more uniform and of good quality in the laser cladding process.

Table 5. Component analysis of the Ni35/AISI 1040 interface (wt%).

| Test element | Si  | Cr  | Fe  | Ni  | Total |
|--------------|-----|-----|-----|-----|-------|
| Test location|     |     |     |     |       |
| A            | 2.85| 12.07| 52.93| 32.15| 100   |
| B            |     | 1.08 | 97.61| 1.31 | 100   |
| C            | 2.31| 29.07| 35.52| 33.10| 100   |

Figure 11 shows the SEM image of Ni60 + WC functional surface cladding layer. Figure 12 shows the XRD analysis results of Ni60 + WC functional surface cladding layer, which shows that these phases in Ni60 + WC functional surface cladding layer.

In figures 11 and 12, the Cr$_7$C$_3$, $\gamma$-(Ni,Fe), WC, CW3 and other phases are found in the Ni60 + WC functional surface cladding structure, which is due to the rapid cooling condition and high temperature gradient during the laser cladding process, making the molten metal far from the equilibrium state, resulting in the formation of a large number of over-saturated solid solutions, semi-stable phases and even new phases in the solidification structure. In the figure 11(a), the cladding layer is composed of a uniform dendrite, cellular crystal and irregular blocky structures. During the laser cladding process, crystallization initially begins as a flat crystal in the alloying zone at the interface (such as functional surface/transition layer interface or transition layer/matrix interface or functional surface/matrix interface). Due to the low temperature of the matrix, the temperature gradient of the adjacent liquid phase is large, and the crystallization rate is small at the initial stage of crystallization, that is, the degree of supercooling is small, and the crystal is produced in a planar form. As the crystallization moves into the molten pool, the solid-liquid temperature gradient decreases, the crystallization speed increases, and the crystal transform into dendrite. Some crystals transform into cellular and columnar crystals due to the increase of matrix temperature and the absorption of heat released in the crystallization process, reducing the crystallization speed. Due to the presence of more Cr, Si and other impurity elements in the cladding layer, crystal nucleus are easy to form at the positions of these impurity elements in the crystallization process. In addition, due to the large degree of undercooling, equiaxed crystals with fine grains are formed outside the cell grain boundary surface. As shown in red circle of figure 11(b), the dense agglomerated
structure outside the dendrite is a composite carbide formed by the combination of WC and Ni60 alloy powder. These WC particles have undergone re-melting, and the grain size is significantly smaller than that of the powder particles. Some of the un-melted WC in the cladding layer will be in the form of particles. Some of the un-melted WC in the cladding layer will be in the form of particles.

3.3. Mechanical properties of the gradient structure

3.3.1. Microhardness of the gradient structure

Figure 13 shows the microhardness distribution from the substrate to the surface cladding layer. The microhardness test value at the interface is at the coordinate origin, the negative direction of the X-axis is the substrate, and the positive direction of the X-axis is the cladding layer. According to the test results, the microhardness at the AISI 1040 matrix is 260 HV, which is significantly lower than that of the Ni35 cladding layer, and slightly higher than that of the transition zone near AISI 1040 matrix. The microhardness of the transition zone near AISI 1040 matrix is lower than that of AISI 1040 base metal due to the coarsened grain in this region. The transition area near Ni35 deposited layer is in the range of 0 to 0.2 mm. The microhardness of the transition zone near Ni35 layer is lower than that of the Ni35 cladding layer, which is due to the fact that the interfacial structure is a planar crystal formed under high temperature gradient and low solidification rate [41], and it does not contain the hard phases in the Ni60 + WC cladding layer. The Ni35 deposited layer is in the range of 0.2 to 0.7 mm. The microhardness of this area is about 500 HV. With the increase of distance, the microhardness gradually increases from 500 HV of the Ni35 transition layer (so called middle layer) to 800 HV of the Ni60 + WC functional surface cladding layer (shown in figure 14). Furthermore, the microhardness of
Ni35 transition layer and Ni60 + WC layer are consistent with the microhardness of single Ni35 layer [15] and single Ni60 + WC layer [42] in others’ researches, respectively, indicating that Ni35 transition layer and Ni60 + WC layer are bonded with low dilution rate. The gradient distribution of microhardness ensures the wear resistance of the Ni60 + WC functional surface cladding layer while avoiding the cracking tendency caused by the large microhardness difference between the AISI 1040 substrate and the Ni60 + WC functional surface cladding layer.

3.3.2. Effect of Ni35 transition layer on the microhardness

Figure 14 shows the relationship between the thickness of the Ni35 transition layer (middle layer) and the surface microhardness of the Ni60 + WC functional surface cladding layer.

In figure 14, when the thickness of Ni35 transition layer is thin, the surface microhardness of the Ni60 + WC functional surface cladding layer is almost not affected by the transition layer. When the thickness of Ni35 transition layer exceeds a certain thickness (>0.6 mm), the surface microhardness of Ni60 + WC functional surface cladding layer begins to decrease, which is because the Ni60 + WC wear resistant functional layer is significantly diluted by the Ni35 transitional layer, resulting in less hard phases in the Ni60 + WC functional surface deposited layer and the reduction on the surface hardness. According to Amado’s research [43] a crack free NiCrBSi + WC cladding structure was obtained under a low WC content in transition layer (15% WC in transition layer and 60% WC in outer layer and the thickness ratio of two layers is about 1:1).
However, in our case, the WC content in outer layer is relatively lower (35%) and the WC content in transition layer is 0%, which allows the transition layer can keep the WC content at a low level (<15%) under a thin transition layer after the transition layer subjected to the dilution effect of outer layer. Therefore, combined with figure 14 and above discussion, the thickness of Ni35 transition layer should be selected as 0.6 mm, which is the maximal thickness in the premise that the Ni35 transition layer has little influence on the microhardness of the Ni60 + WC functional surface cladding layer.

3.3.3. The wear resistance of the gradient structure

Figure 15 shows the weight loss of the CO2 laser cladding Ni60 + WC/Ni35/AISI 1040 gradient structure under different contents of WC after 10 min, 20 min and 30 min wear test respectively.

In figure 15, with the increase of the WC content from 0% to 45%, the wear loss firstly decreases and then drastically increases. When WC content is 35%, the wear loss is the least and the weight loss is about 58% of the CO2 laser cladding Ni60 + WC/Ni35/AISI 1040 gradient structure, indicating the best wear resistance. When the WC content increases to 45%, there is sharp reduction on the wear resistance of the Ni60 + WC/Ni35/AISI 1040 gradient structure and the wear loss reaches the maximum value after 30 min wear test. This change is because when the WC content is low, the microstructure of the gradient structure does not change significantly and is similar with Ni60 surface’s microstructure, and with the increase of the WC content, more WC particles dissolves and form more hard carbides, making the surface hardness and the wear resistance of the gradient structure increased. When WC content reaches 45%, there are a large number of hard phases in surface cladding layer, resulting in a decrease in the toughness phase around the hard phase, which makes the hard phases easier to fall off when loaded, resulting in a sharp decrease on wear resistance of the gradient structure, which is consistent with the experimental result of Wang’s work [43]. In one word, the excessive WC changes the ductile microstructure of the Ni60 + WC/Ni35/AISI1040 gradient structure resulted in a decrease in wear resistance.

Figure 16 shows the macrostructure of the friction surface of the CO2 laser cladding Ni60 + WC/Ni35/AISI 1040 gradient structure with different WC contents after wear experiment.

In figure 16(a), there is no WC content, the wear surface of the gradient structure has typical abrasive wear (shown in the point A) and adhesive wear characteristics (shown the black area pointed by B which is the thin oxide formed after the wear test according to Garcia’s work [44]). When WC hard particles are added in Ni60 powder, the adhesive wear characteristics almost disappear, as shown in figures 16(b)–(f), which can mainly attribute to the abrasive action of broken WC particles which prevents the adhesive action between workpiece and counterpart [44]. As the content of WC hard particles in Ni60 powder increases, the surface wear and scratch of the Ni60 + WC/Ni35/AISI1040 gradient structure decrease. Because the hard phase WC particles can effectively block the micro-cutting effects of the wear wheel [45]. But with the increase of friction between wear wheel and gradient structure surface, the relatively softer dendrites around the hard phase will be firstly removed, gradually reducing the bonding strength between the hard phase and cladding layer, eventually leading to the removal of the hard phase by the wear wheel, and even leaving small pits on the surface [45], as shown in the point C in figure 16(c). It is noted that when the WC content increase from 35% to 45%, a lot of pits appears at the cladding layer as shown in figure 16(f), which is consistence with the sharp increase of the wear loss.
according to figure 15. In conclusion, the optimal WC content in Ni60 layer is 35% according to the weight loss and wear morphology.

3.4. Effect of different alloy powder types
Table 6 shows the comparison results of the CO2 laser cladding microstructure and performance between the AISI1040/Ni35/Ni60 + WC gradient structure and the AISI1040/Ni35/IG55 gradient structure. The results show that the hardness and wear resistance of the cladding Ni60 + WC gradient structure are superior to that of
the IG55 gradient structure on the condition of the same process parameters. In addition to IG55 powder, the surface hardness of some cladding structures with hard phase \cite{46} or rare earth oxides \cite{47, 48} reported in recent years are also tabulated in Table 6. Compared with these cladding structure, AISI1040/Ni35/Ni60 + WC gradient structure shows great advantages in cost saving and hardness improvement.

The figure 17 shows the Ni60 + WC/Ni35/AISI1040 functional surface gradient structure of chute plate for the mining scraper is remanufactured and manufactured successfully by a low cost high power CO2 laser cladding technique, which is of a good wear resistance, high quality and long lifetime. The hardness of chute plate with the Ni60 + WC/Ni35/AISI1040 gradient structure is obviously higher than that of AISI1040 chute plate, and the wear resistance of remanufactured chute plate with the gradient structure is increased more than 2 times higher than the new AISI1040 chute plate. On the other hand, the remanufactured chute plate with the Ni60 + WC/Ni35/AISI1040 functional surface gradient structure is of the low cost and high performance compared with one new manufactured AISI1040 chute plate.

4. Conclusions

In this paper, the CO2 laser cladding Ni60 + WC/Ni35/AISI1040 functional surface gradient structure is designed for solving the problem of high maintenance cost of the chute plate of coal mining scraper. The process parameters of the CO2 laser cladding process parameters, geometry size of cladding layer, dilution rate, hardness of cladding layer, thickness of transition layer, microstructure and wear resistance of the gradient structure are studied and discussed. The optimal process parameters are 3.2 KW laser power, 300 mm min\(^{-1}\) scanning speed, 0 mm defocusing distance, 80 g min\(^{-1}\) powder feeding amount, 0.6 mm thickness of the Ni35 transition layer, 35% WC content. The design of gradient cladding layer is Ni60 + WC/Ni35/AISI1040 functional surface gradient structure with a high performance. The research results are issued as follows.

(1) Laser power and scanning speed are the main factors affecting the geometry size and dilution rate of the cladding layer. As the laser power increases or the scanning speed decreases, the width, height or dilution rate of the cladding layer increase. The surface hardness of the cladding layer increases firstly and then decreases as the laser power or scanning speed increases continuously. The highest microhardness of the gradient structure is obtained on the condition of a laser power of 3.2 KW and a scanning velocity of 300 mm min\(^{-1}\).

(2) The interface of the AISI 1040 substrate/Ni35 transition layer is bright white. Alloy elements on both sides merge with each other, forming a good metallurgical bond. The Ni35 transition layer and Ni60 + WC

| Cladding structure                        | Surface hardness (HRC) | Weight loss rate (%) | Surface quality | Cracks | References |
|-------------------------------------------|------------------------|----------------------|-----------------|--------|------------|
| AISI1040/Ni35/Ni60 + WC                   | 58–62(700–800 HV)      | 2.3                  | Smooth          | No     | —          |
| AISI1040/Ni35/IG55(FeCrSiB + RE)          | 53–58                  | 2.7                  | Squamous        | No     | —          |
| AISI1045/Fe50 + TiC                        | 60                     | —                    | —               | —      | \cite{46}  |
| H13/CoFeCrNiSiB + CeO2                   | (600–750 HV)           | —                    | —               | —      | \cite{47}  |
| 42CrMo/3540Fe+CeO2                        | (700–800 HV)           | —                    | —               | —      | \cite{48}  |
cladding layer are mainly composed of Cr2C3, γ-(Ni, Fe), Fe3Ni2, CrB and other phases, and the microstructure is mainly a dendrite, cell crystal, and a lumpy structure formed by combining WC and Ni60 alloy powder. A part of the WC particles are not melted and exist in the tissue in the form of solid particles.

(3) The CO2 laser cladding AISI1040/Ni35/Ni60 + WC gradient structure is of a smooth gradient transition about microhardness. The microhardness of the AISI 1040 matrix is 280 HV, the hardness near the Ni35 transition layer is 500 HV, and the surface hardness of the Ni60 + WC layer is 800 HV. Through inducing a Ni35 transition layer between AISI1040 substrate and Ni60 + WC wear-resistance functional surface layer, the difference of microhardness near the both interfaces is reduced, which reduces the cracking tendency of the cladding layer and prevents the Ni60 + WC cladding layer from being over diluted by the substrate, ensuring high hardness and high wear resistance of the cladding layer surface.

(4) The design of the gradient cladding structure has a significant influence on the hardness and wear resistance of the cladding layer. When the thickness of the Ni35 transition layer is greater than 0.6 mm, the Ni35 transition layer has a significant dilution effect on Ni60 + WC surface layer, resulting in a decrease in surface hardness. As the content of WC in the Ni60 cladding layer increases, the wear resistance of the CO2 laser cladding Ni60 + WC/Ni35/AISI1040 functional surface gradient structure increases firstly and then reduce, and the best wear resistance of the Ni60 + WC/Ni35/AISI1040 gradient structure is obtained when the WC content is 35% of Ni60 + WC powders. The hardness and wear resistance of the gradient structure obtained by the Ni60 + WC is higher than that of the IG55 as the cladding functional surface material.

(5) The chute plate with the Ni60 + WC/Ni35/AISI1040 functional surface gradient structure for the mining scraper is remanufactured and manufactured successfully by a low cost high power CO2 laser cladding technique, which is of a good wear resistance, high quality and long lifetime.

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