

Performance characterization of Ni60-WC coating on steel processed with supersonic laser deposition

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Abstract

Ni60-WC particles are used to improve the wear resistance of hard-facing steel due to their high hardness. An emerging technology that combines laser with cold spraying to deposit the hard-facing coatings is known as supersonic laser deposition. In this study, Ni60-WC is deposited on low-carbon steel using SLD. The microstructure and performance of the coatings are investigated through SEM, optical microscopy, EDS, XRD, microhardness and pin-on-disc wear tests. The experimental results of the coating processed with the optimal parameters are compared to those of the coating deposited using laser cladding.

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Keywords: Ni60-WC; Supersonic laser deposition; Laser cladding; Microstructure; Wear

1. Introduction

Ni60 alloy, in combination with hard tungsten carbide (WC), is widely used to improve the wear resistance of steel as surface coating. Owing to an excellent wear resistance, Ni60-WC has been applied in many fields of industry, such as mining, transport, engineering, manufacturing industries, etc. However, Ni60-WC coatings have been found often to have cracks and pores in them. In recent years, the researchers have attempted to apply various deposition techniques on this type of coating to achieve the crack/flaw-free coatings. The traditional techniques, such as thermal spraying, plasma spraying,

arc welding, and laser cladding (LC), have often been used to produce WC-reinforced Ni60 composite coatings. Wang et al. [1] studied the abrasive resistance of Ni-based coatings with WC hard phase prepared by plasma spraying with laser post-treatment, and tested the abrasive wear resistances of three Ni-WC composite coatings with different contents of WC particles. The results show that the best coating contains the composition of Ni60 + 60%WC (wt%) but it has the pores in it. Although the cold spraying technique offers high deposition efficiency and low oxidation and retains the initial composition and/or phases of coating materials, it cannot be used to deposit the hard particles. In contrast, the arc welding and laser cladding techniques can be used to deposit the hard particles and offer a good metallurgical bonding because a molten pool is formed on the surface of the substrate, but the coating and substrate can be severely deformed due to excessive energy input. In these processes, WC particles are largely dissolved in the melt pool during deposition, which

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reduces the hardness of the final coating. Additionally, the thermal stresses induced during the course of welding or cladding can lead to crack formation in the coating, and the low cladding efficiency increases the processing cost of cladding over large areas [2,3]. Zhou et al. [4–6] observed the cracks in the Ni60 coatings deposited by laser cladding but achieved fully dense and crack-free Ni-based WC composite coatings and Ni60 coatings prepared using laser induction hybrid rapid cladding with an elliptical spot. However, this technique restricts the geometry of substrate to simple shape, such as flat, shaft, etc. It is not suited for preparing the complex products. The key reason why Ni60-WC coatings cannot be applied in many areas is that the carbide particles result in the formation of cracks and pores. Therefore, the content and size of WC grain have an important effect on the characteristics of the coatings [2,7]. Matthew et al. [8,9] successfully combined laser cladding with cold spraying together to prepare high-density coatings consisting of Ti and Ti alloy, and used cold N_2 as a carrier gas to reduce the cost of cold spraying. The supersonic laser deposition (SLD) method offers many advantages by combining laser with cold spraying, in

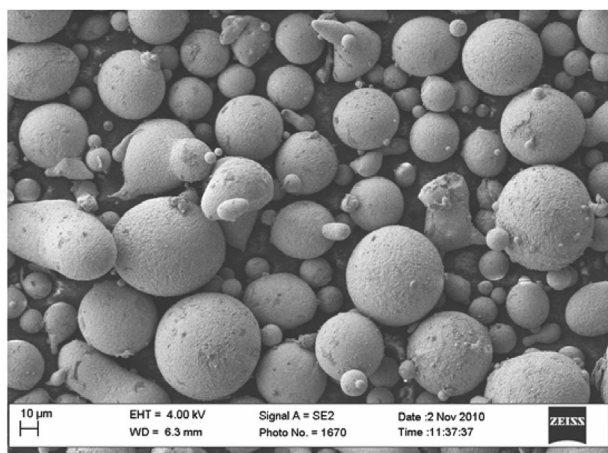
particular, the use of a laser to control the deposition temperature, which allows hard materials, such as Stellite 6 and carbide [10,11], to be deposited while maintains the key advantages offered by solid-state cold spraying and replaces high cost helium with nitrogen. Moreover, the high-speed impact of particles on the substrate produces severe plastic deformation, resulting in a good bonding of the coating and the substrate. Meanwhile, SLD avoids the melting of the coating material and therefore retains the fine microstructure of the coating and prevents WC from degrading.

In the present research, since SLD has many advantages, such as high deposition rate, low dilution, it could be used to deposit hard material on the steel, etc. This paper demonstrates the influence of laser power on the characteristics of Ni60-WC composite coatings deposited using SLD and compares the results of those deposited using LC.

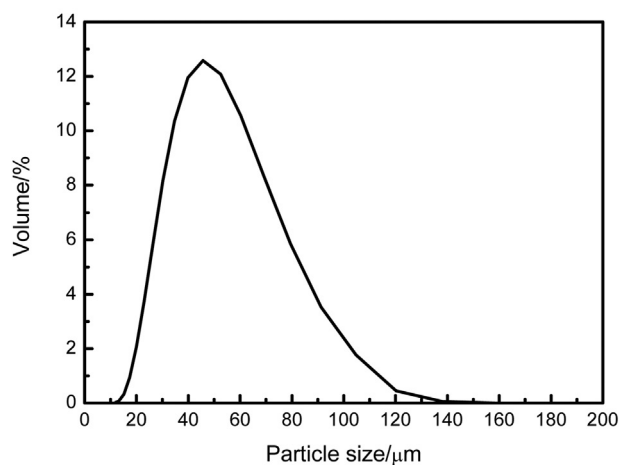
2. Experimental methods

2.1. Powder preparation

The coating material was a mixed powder consisting of Ni60 and 30%WC with different particle sizes. The content

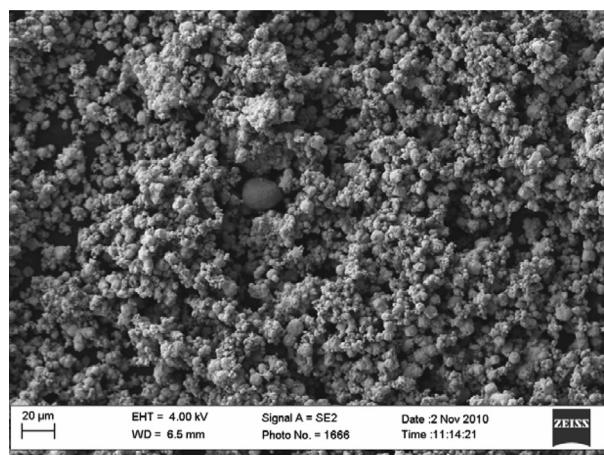


(a) Ni60 particles

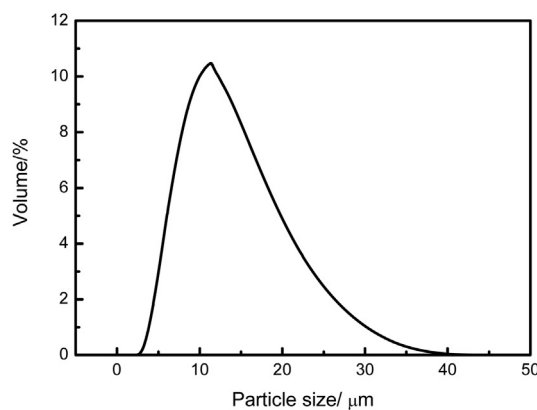


(b) Size distribution

Fig. 1. Ni60 particles and size distribution.



(a) WC particles



(b) Size distribution

Fig. 2. WC particles and size distribution.

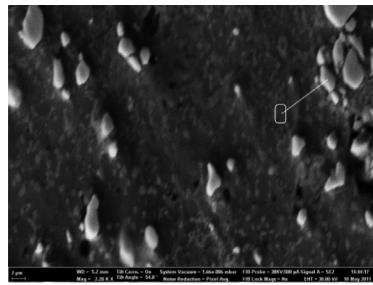
Table 1
Chemical composition of Ni60 powder.

Element	B	Cr	C	Si	Fe	Ni
Wt%	2.5–4.5	14–17	0.6–1.0	3–4.5	<15	Bal

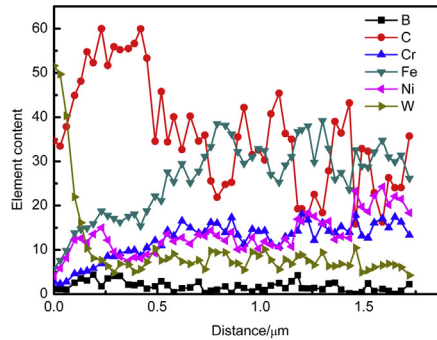
Table 2
Process parameters for a single track of SLD.

Specimen number	N ₂ pressure/bar	N ₂ temperature/°C	Laser power/kW	Traverse rate/(mm·s ⁻¹)
1	30	450	2.0	10
2	30	450	2.5	10
3	30	450	3.0	10
4	30	450	3.5	10
5	30	450	4.0	10

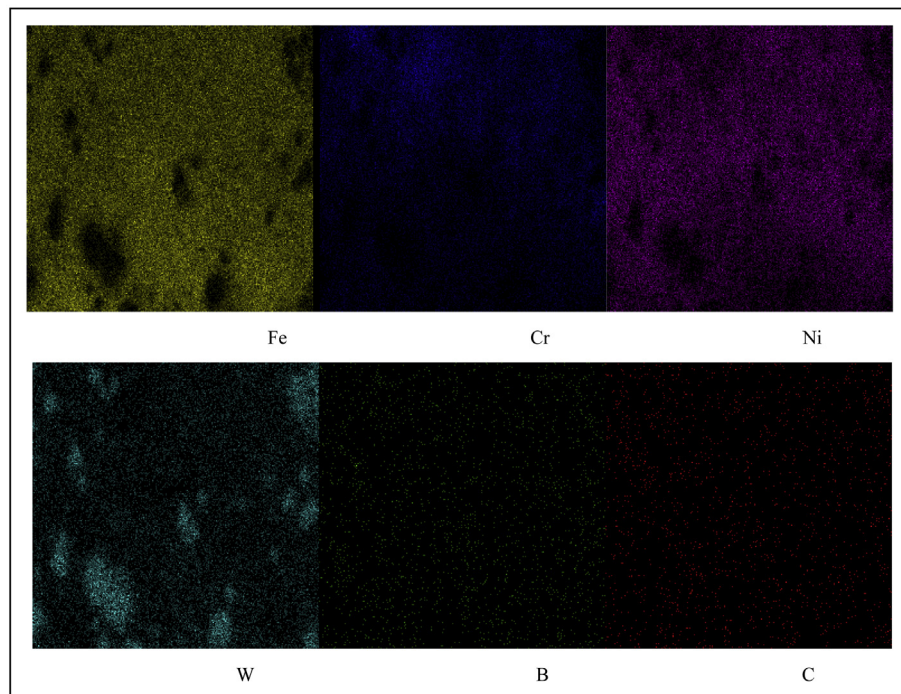
proportion of Ni60 to WC was optimized from many experiments of laser cladding, spray remelting and AC-HVAF spray [1,15]. The size of particle in the feed stock powder was analyzed by laser dispersion. The diameter of powder particle was selected based on Refs. [12–17], and the product of the Ni60 spray powder is commercially available. The diameters of most particles in Ni-based self-fluxing alloy are in the range from 30 μm to 50 μm , as shown in Fig. 1, and the diameters of most particles in WC powder are approximately 10 μm , as shown in Fig. 2. It can be observed that the clusters of WC particles are stuck together and the individual WC particles are hardly found. The chemical composition of Ni60 and the weight percentage of each element are given in Table 1. The mixed 70%Ni60 and 30%WC powder was deposited on carbon steel substrate using a SLD system [8,9,18], and the process parameters for a single track are listed in Table 2.



(a) Structure of coating



(b) Line scan



(c) Element mapping

Fig. 3. Characteristics of coating specimen 1.

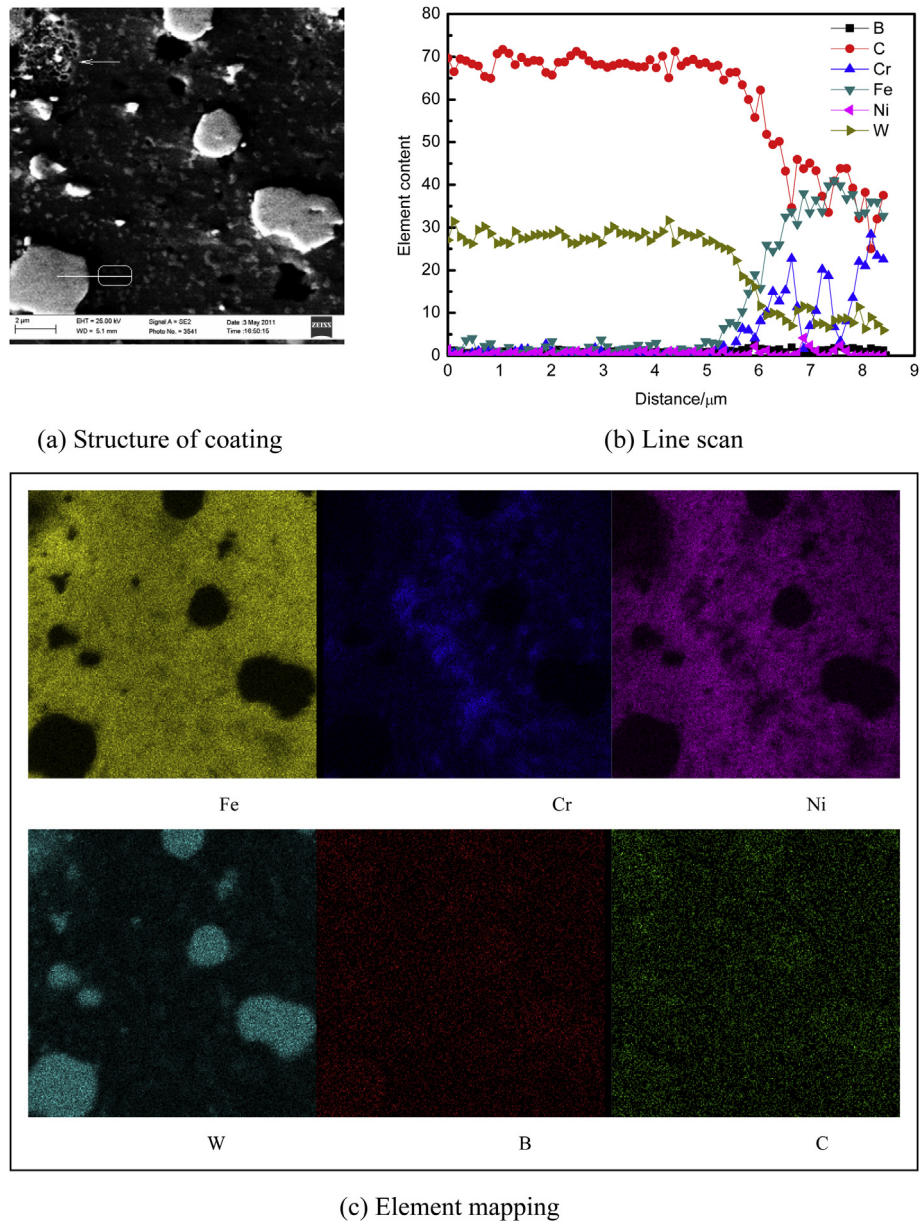


Fig. 4. Characteristics of coating specimen 3.

Initially, the single track was sprayed over a range of operating conditions to identify the laser power ranges required for deposition. To quickly identify the optimal laser power, the operating pressure was kept at 30 bar to give a gas velocity of approximately 1000 m s^{-1} and a traverse rate of 10 mm s^{-1} for SLD. Low-carbon steel plates with dimensions of $160 \times 55 \times 2 \text{ mm}$ were used as substrates.

2.2. Microstructure analysis

The obtained SLD coating structures were examined under an optical microscope, in combination with A4i image analysis software. The cross-sections of the coating specimens were polished and then etched with the chemical solution which consists of 5 g FeCl_3 , 2 ml HCl and 99 ml ethanol.

A scanning electron microscope was used to analyze the surface topography and microstructure of coating specimen. The chemical compositions of the coatings were evaluated using an energy dispersive spectroscopy (EDS), and the phases in the microstructures were identified using an X-ray diffractometer and the X'Pert Pro analysis software.

3. Results and discussion

3.1. Single track for SLD

3.1.1. Coating structure

The coating specimens 1, 3 and 5, as numbered in Table 2, were selected for analysis. The structures of these specimens are shown in Figs. 3–5(a), respectively. A large amount of

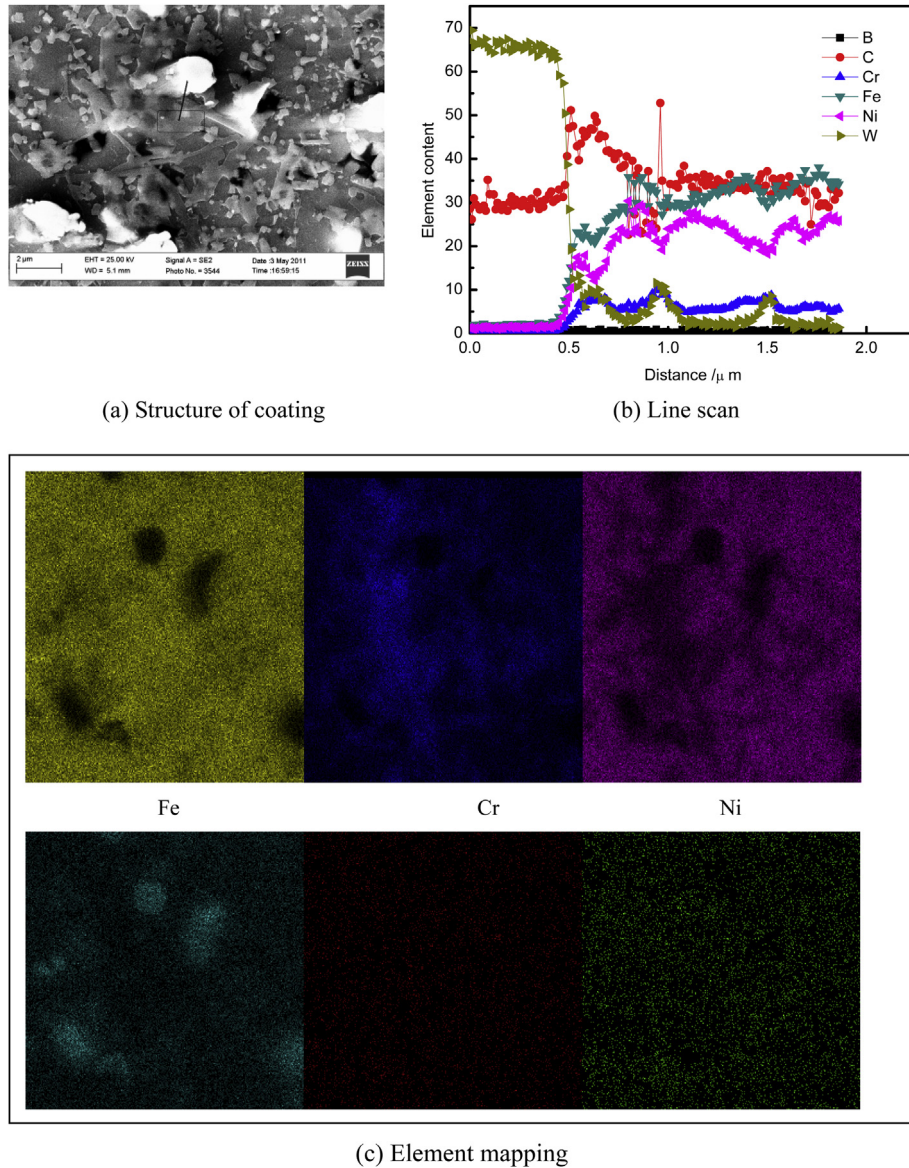


Fig. 5. Characteristics of coating specimen 5.

small, bright and white particles, which sizes of the range from 1 μm to 3 μm are observed from Fig. 3(a); the small pits and pores are distributed in the matrix. The element distributions are illustrated in Fig. 3(b), showing peaks and valleys, where the former of the curve (white particle) indicates the peaks: high tungsten and carbon contents, the later (rectangle) indicate the valleys: low tungsten content, and high chromium and iron contents. Fig. 3(c) shows the scanning graph of elements of coating specimen 1. The bright and white object should be WC, the thin and white dendritic crystals in the matrix are likely to be chromium carbide. These results confirm that the bright and white object is WC particles, which are distributed in the matrix with FeNi and chromium carbides. Fig. 4(a) shows that the larger bright objects are distributed in the matrix with larger pits and pores. Fig. 4(b,c) show that the larger polygonal and bright object are WC particles, the small white crystals probably are Cr_7C_3 and Cr_{23}C_6 , and the matrix may be with FeNi.

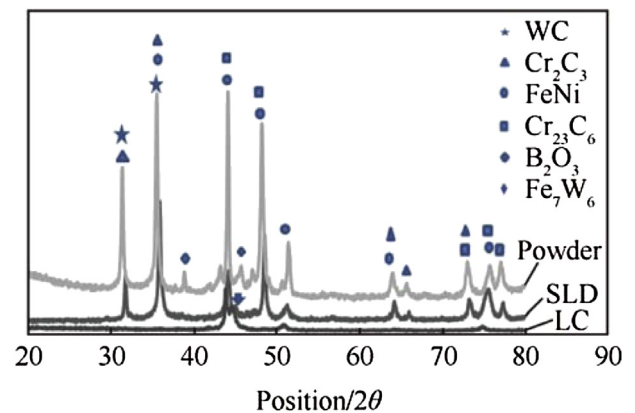


Fig. 6. XRD spectra of Ni60-WC powder and Ni60-WC coatings.

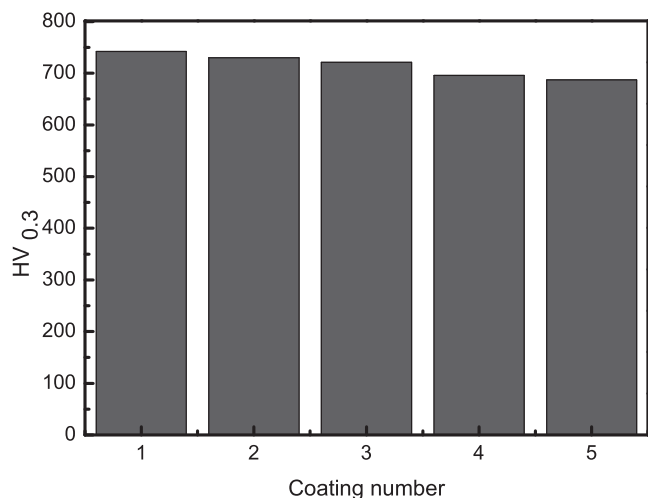


Fig. 7. Microhardnesses of cross-sections of 5 coating specimens.

From Fig. 4(a) it can be seen that, for coating specimen 3 which was prepared with higher laser power, the sizes of the white particles and the small white crystals increase with the increase in laser power; the sizes of some WC particles are over 2 μm , and they exhibit partially dendritic crystals, as indicated by arrow at top left corner. With the increase in laser power, the large WC particles (light) of coating specimen 5 in Fig. 5 are distributed in the dendritic crystals of Cr_7C_3 , Cr_{23}C_6 and FeNi matrix.

It can be seen from Figs. 3–5(a) that the crystals of chromium carbides grew from thin dendritic crystals to coarse dendritic crystals with the increase in laser power; so did the WC particles. Hard phases, such as Cr_7C_3 , Cr_{23}C_6 and WC particle, are the key factors of improving the hardness and anti-wearing properties of the coatings.

X-ray diffraction (XRD) analysis was conducted on the coating specimens to confirm the phases formed during deposition. The XRD spectra are shown in Fig. 6. The phases of the coatings deposited by SLD are Cr_7C_3 , Cr_{23}C_6 , FeNi, and WC. This is quite different from the normal laser cladding of

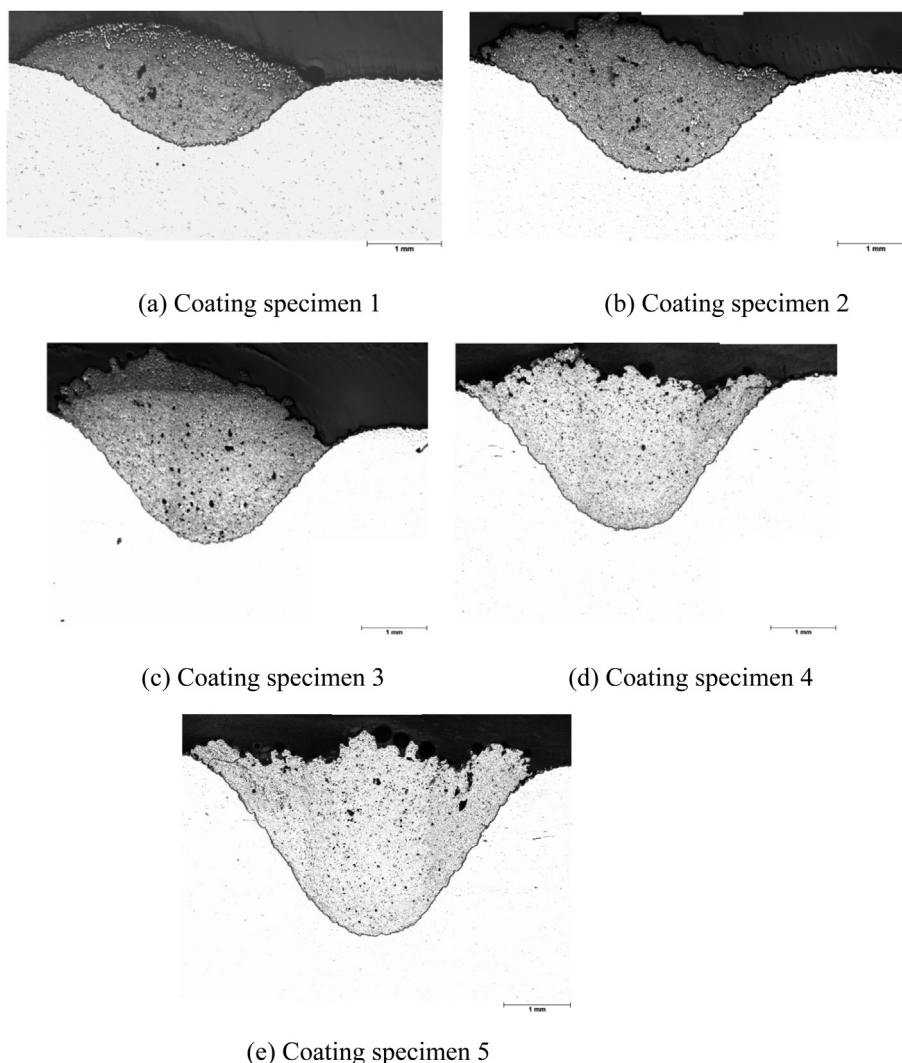


Fig. 8. Topographies of coating cross-sections.

WC-Ni, where WC in the coating hardly dissolves and is diffused into laser cladding and form compound.

3.1.2. Microhardness of cross-sections

Since the change in the amount of WC results in a large variation in hardness data, the microhardness of coating is

measured along horizontal direction and vertical direction from the interface to the coating surface at constant intervals of 0.4 mm using a digital micro-hardometer. The average hardnesses of five coatings are shown in Fig. 7. It can be seen from Fig. 7 that the microhardness of coating 1, $HV_{0.3}$ 742, is the highest, and the microhardness of coating 5, $HV_{0.3}$ 687, is the lowest. These results show that the differences among the microhardnesses are small. It may infer that the hardness is dependent on the structure of carbide. Consider this again from Figs. 3–7, there is also a correlation among laser power, coating structure and coating hardness.

3.1.3. Cross-section topography

Fig. 8 shows the topographies of the coating specimens in Table 2. Coating specimen 1 in Fig. 8(a) shows the highest density among the coatings. At the top of coating layer appear many bright and fine WC particles, which is consistent with the hardness test result.

Many pores and small WC are observed in coating specimen 2 in Fig. 8(b). These carbides particles are uniformly distributed in the coating, but their amount is very little.

The pits or pores in the coating are increased with the increase in laser power. This is because the coating material starts to melt partially in this case. The sizes of Ni60 and carbide particles were found to be increased with the increase in laser power. Oxygen in air can possibly react with some chemical elements of the coating, such as carbon, to produce gases, resulting in the formation of pores. Fig. 8(c–e) show the pits in the coatings. However, most pits may not be pores, as shown in Fig. 9; they are the holes left when WC particles are spalled off during polishing.

Fig. 9 presents the analysis of red areas in percentage of pits in the coatings. The dark areas may represent the pores formed in the SLD process, and the holes due to spallation of WC particles during polishing. It can be seen from Fig. 9 that the percentage of dark areas in coating specimen 1 (2 kW laser power) is the least.

Higher laser energy can result in stronger adhesion between the WC particles and Ni60 matrix, but it can also reduce the WC content. When the laser power was increased from 2 kW to 4 kW, the amount of WC particles decreased, as show in Fig. 9. However, the laser power was not sufficiently high to melt the alloy completely; the deposited particles were not completely melted. Some areas show the good adhesion between the WC particles and Ni-based matrix, with the spallation of WC particles pull-out being avoided during polishing. However, not only the adhesion between the Ni-based coating and WC is affected by the input energy, but it is also affected

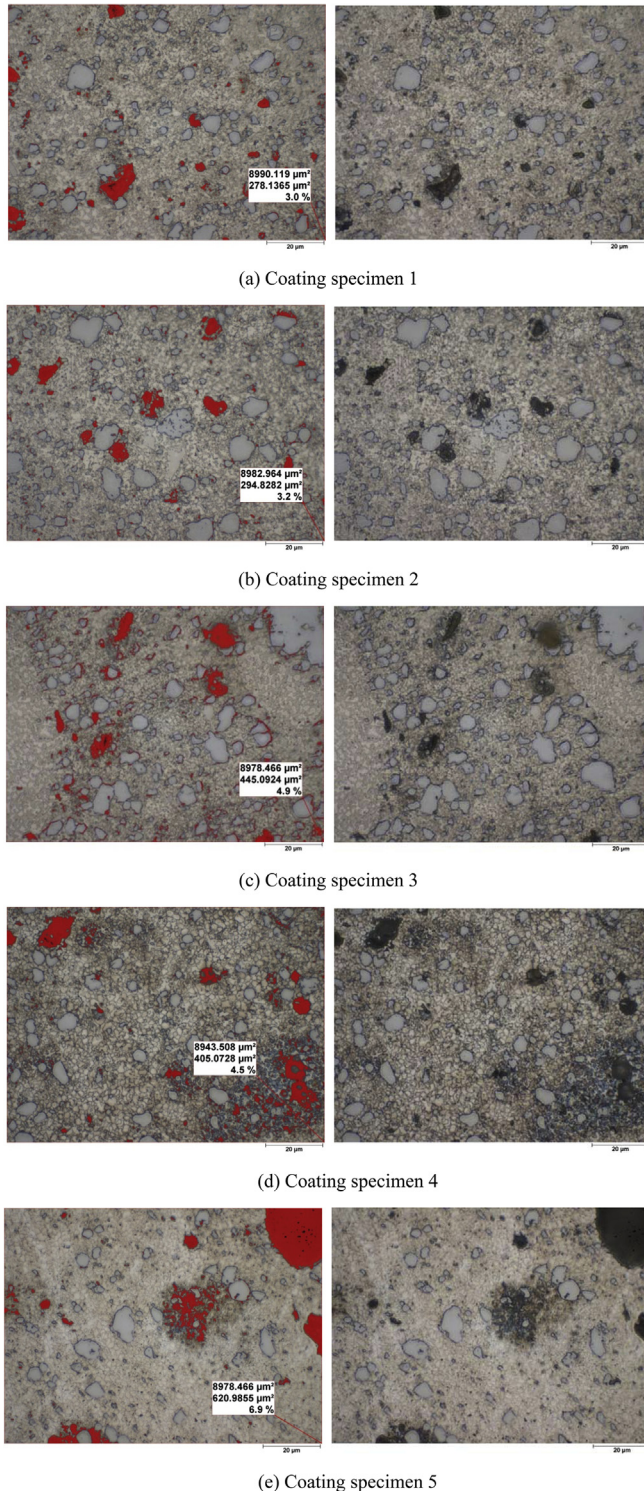


Fig. 9. Porosity analysis of the coatings.

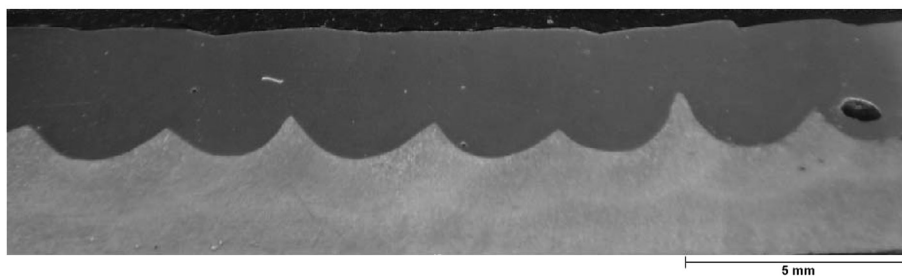
Table 3

Process parameters for single tracks and multi-tracks of LC.

Parameter	1	2	3	4	5 (multi-tracks)
Laser power/kW	1.8	2	1.8	2	2
Traverse rate/(mm·s ⁻¹)	10	10	4	4	10
Beam size/mm	4	4	4	4	4



(a) Dye penetrant inspection of LC coatings



(b) Cross- section of multi-tracks

Fig. 10. Multi-track LC coatings.

Table 4
Optimal process parameters for multi-tracks.

Specimen	N ₂ pressure/bar	N ₂ temperature/°C	Laser power/kW	Traverse rate/(mm·s ⁻¹)	Beam size/mm
SLD specimen	30	450	2	10	4
LC specimen			2	10	4

by the coefficients of thermal expansion of Ni60 and WC. If their coefficients of thermal expansion are the same, the growth rates of these particles are the same, the amount of pits or pores would be reduced due to good matching with each

other, the adhesion between the Ni-based coating and WC would be better at the same laser power.

The above analysis indicates that coating specimen 1, deposited under a N₂ atmosphere at a pressure of 30 bar, a temperature of 450 °C and a deposition power of 2 kW, is the best among the coating specimens under study. Single track coatings prepared with these parameters were further investigated in dilution rate.

3.2. Comparison of SLD coating with LC coating

Ni60-WC powder was deposited on low-carbon steel by LC with laser power of 1.8–2.0 kW and scanning velocity of 3–10 mm s⁻¹, as detailed in Table 3. Only one coating (No.2

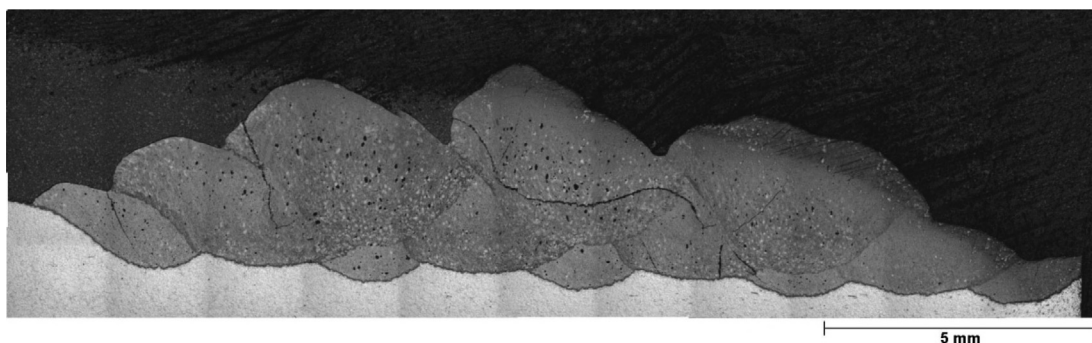


Fig. 11. Cross-section of SLD coating.

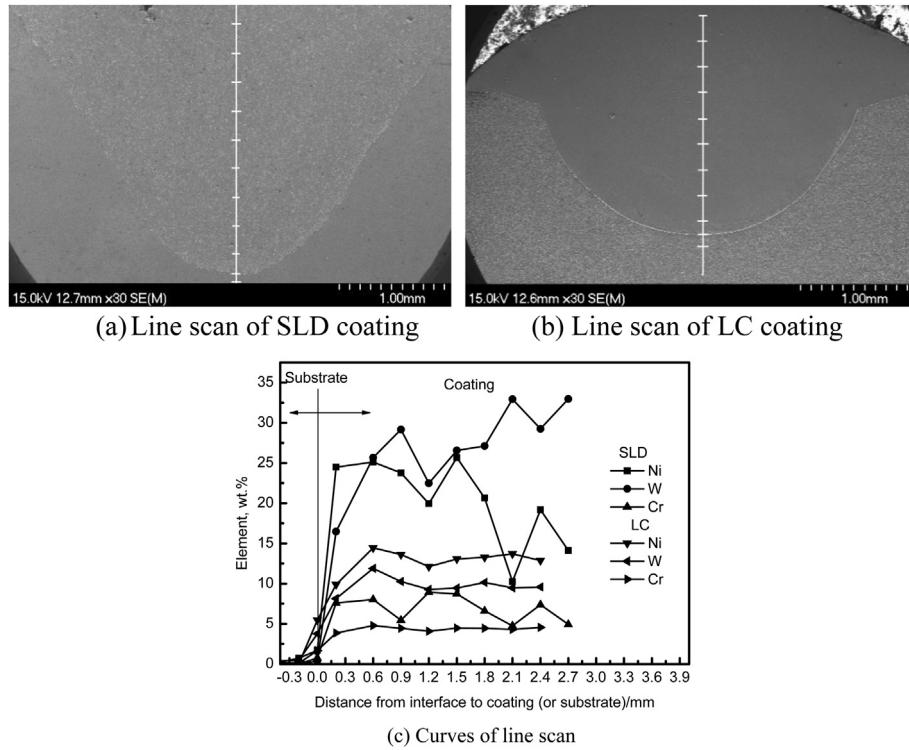


Fig. 12. Element line scan of SLD and LC coatings.

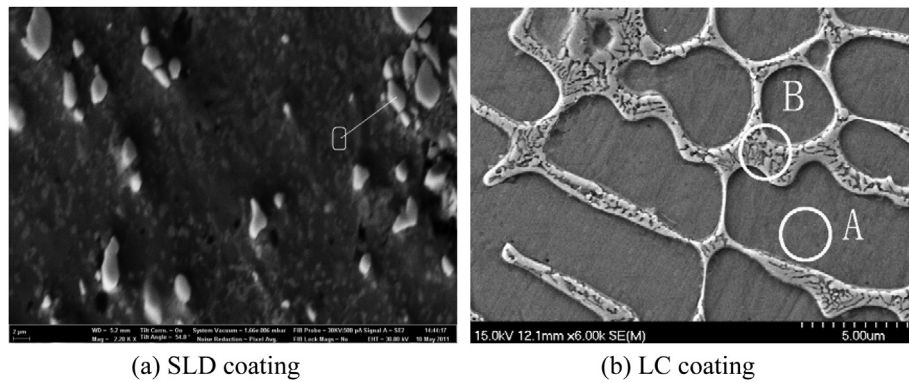


Fig. 13. Structures of Ni60-WC coatings.

in Fig. 10(a)) deposited at laser power of 2 kW and scanning velocity of 10 mm s^{-1} was crack-free.

Multi-tracks with a deposition width of 4 mm and overlap of 2 mm were made to investigate the performances of the coatings under the deposition conditions with laser power of 2 kW and traverse rate of 10 mm s^{-1} . The cracks were also found in these coatings. The cross-sections of LC coatings are shown in Fig. 10(b), which were compared with the SLD

coating having a deposition width of 4 mm and three layers under the conditions of optimal process (N_2 atmosphere, pressure of 30 bar, temperature of 450°C , deposition power of 2 kW and traverse velocity of 10 mm s^{-1}). The optimal process parameters of multi-track coating are listed in Table 4.

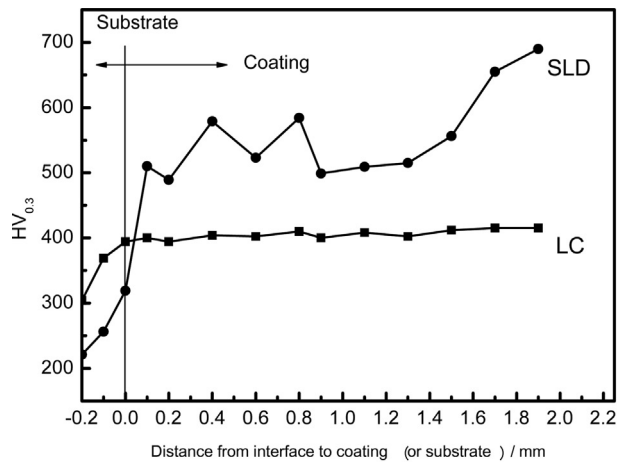
Cracks are hardly found in the first and second layers of the multi-track SLD coating, but they are observed in the third layer, as shown in Fig. 11. The cracking may be due to the phase transition of the material at different temperatures, resulting in the change of volume or stress.

3.2.1. Analysis of element dilution

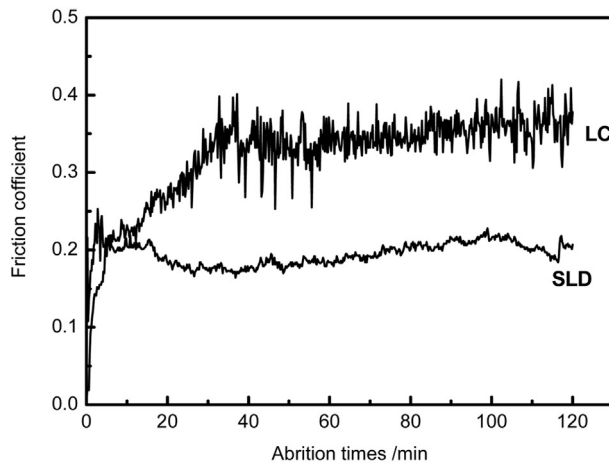
During the LC process, a high pressure gas supply was split and delivered to a nozzle directly via a high pressure

Table 5
Element compositions of LC coating.

	Element	W	Cr	C	Fe	Ni	B
Area A	Wt.%	4.97	5.67	6.28	65.1	17.85	0.13
Area B	Wt.%	26.72	6.19	11.07	38.69	6.5	10.83



(a) Microhardness curves



(b) Friction coefficient curves

Fig. 14. Distribution curves of microhardness and friction coefficients for the Ni60-WC coatings.

powder feeder where the metal powder particles are entrained. The temperature in a deposition zone was monitored by a high-speed IR pyrometer (Kleiber). The consistent deposition site conditions were maintained by using the pyrometer to control the laser power via a PID loop built in to the control software.

The substrate was held stationary while the nozzle, laser head and pyrometer can be moved using a CNC X–Y stage, allowing the samples to be up to 1600 mm in diameter.

Fig. 12(a,b) show the line scan of Ni, Cr and W from the interface to the coating (or substrate) along the cross-sections of SLD and LC coatings, the testing distance is 2.7 mm and 2.4 mm, respectively. Since the substrate material of SLD does not contain Ni, Cr and W, these results exhibit a low dilution rate from the coating to the substrate for SLD.

As illustrated in Fig. 12(c), the contents of Ni, Cr and W in the coatings are higher, and the contents of Ni, Cr and W in the substrates are lower. The contents of Ni, W and Cr in SLD coating are higher than those in LC coating. This shows that the W or Cr reacted with C-forming carbides in the LC coating, and Ni reacted with Fe-forming FeNi, which resulted in the decrease of the elements in the LC coating, that is, higher element dilution.

3.2.2. Microstructural analysis

As shown in Fig. 13(a), the small polygonal and bright WC particles are embedded in Ni60 matrix. The pits in black may be the holes due to the spallation of WC particles during polishing or the pores formed due to the impact among the particles.

Fig. 13(b) shows the clear formation of dendritic crystals. The white eutectics were distributed along the crystal boundary, and the circular areas of the LC coating were measured and analyzed using an energy dispersive X-ray (EDX) detector. The results are presented in Table 5. It can be seen that the iron and nickel contents in area A are higher than those in area B, and the tungsten and carbon contents in area B are higher than those in area A. These results, together with X-ray diffraction (XRD) analysis results in Fig. 6, were used to identify the eutectics formed during the LC deposition. The phases of the coating deposited using LC are Cr_7C_3 , Cr_{23}C_6 , FeNi, and Fe_7W_6 ; the LC coating has no WC because Fe reacts with W-forming Fe_7W_6 . This may be attributed to the fact that the input energy of LC was much higher than that of SLD, which led to the formation of Fe_7W_6 . If the process parameters in Table 4 are used, the energy density of SLD is the same as the optimized energy density of LC, but the laser melts the powder in LC, while the laser heats the deposition area in

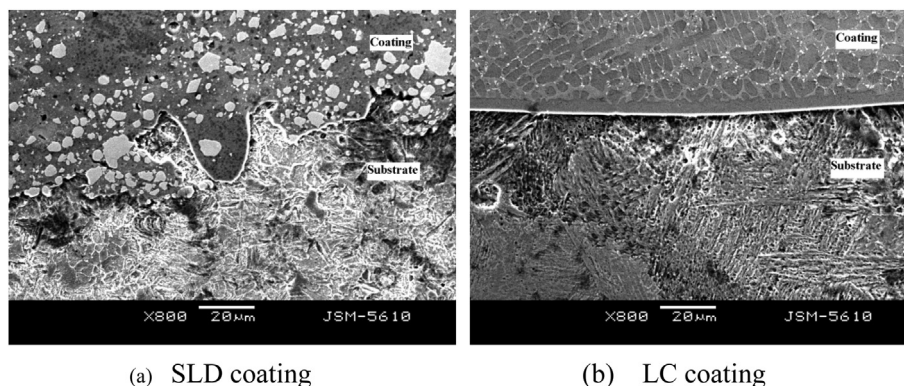


Fig. 15. Structures of coating cross-sections.

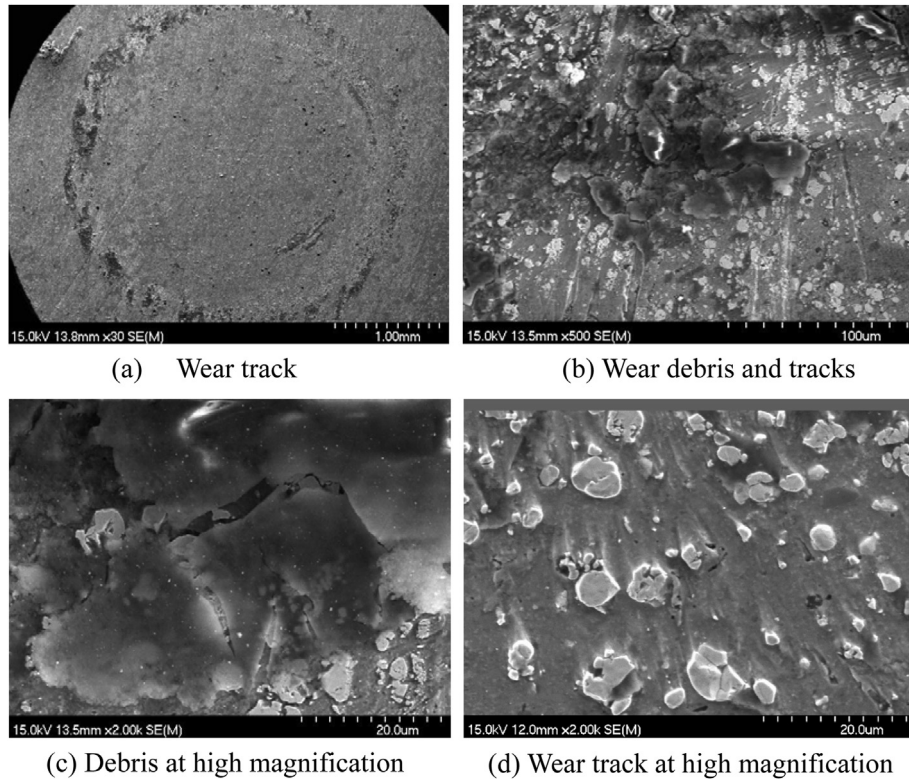


Fig. 16. Worn surface of Ni60-WC coating prepared using SLD.

SLD. Therefore, for LC, the main phase in area A is FeNi, and the main phases in area B are Cr_7C_3 , Cr_{23}C_6 and Fe_7W_6 .

A comparison of the phases among Ni60-WC powder, LC coating and SLD coating shows that B_2O_3 is not present in SLD and LC coatings. The reason for this may be that the area B is oxidized when it was exposed in air during the powder preparation. B_2O_3 would be vaporized at over 1500 °C.

3.3. Microhardness and wear resistance

The frictional and wear forces to which machinery components are subjected result in great loss of energy and material. Hardness is a key property that accounts for the anti-wearing ability of materials. Thermal spraying, laser cladding and other surface techniques can be used to deposit the hard particles on the substrates to improve their hardness and wear properties against the frictional and wear forces that act on the surfaces of components [15,19–24].

Fig. 14(a) provides the average microhardnesses measured for 3 or 5 indentations at constant longitudinal interval of 0.3 mm from the interface to the coating surface (or substrate) using a digital micro-hardometer. The friction coefficients were measured using a pin-on-disc machine with a Si_3N_4 ceramic ball having 5 mm in diameter. The rotational radius was 2.5 mm, the normal load was 200 g, the rotational speed was 800 r min^{-1} , and the test duration time was 2 h. As shown in Fig. 14, the highest hardness value is $\text{HV}_{0.3}$ 690 that is for the SLD coating. This is due to the fact that the amount of carbides in the coating as hard phases is greater than that in the

LC coating. The lowest hardness value is $\text{HV}_{0.3}$ 394 that is for the LC coating. This is because of the higher energy density induced by decomposing a mass of carbides as hard phases to form Fe_7W_6 . Moreover, Fig. 14(a) shows that the microhardness of the interface close to the substrate is higher than that of substrate, which is due to the fact that the input energy resulted in a phase change to lath martensite. Fig. 14(b) shows that the friction coefficient of LC coating is almost twice that of SLD coating. The friction coefficients of LC and SLD coatings show the fluctuations between 0.10–0.40 and 0.13–0.23, respectively. Furthermore, in Fig. 15(a), the martensite is present in thinner dendritic crystal due to lower energy density of SLD in comparison with that of LD in Fig. 15(b). Chen et al. [25] proved that the micron scale WC particles can play a very effective role in resisting wearing.

The worn surface of Ni60-WC coating processed using SLD is shown in Fig. 16. Fig. 16(a) shows the wear track, and Fig. 16(b) shows the wear debris. The scars were caused by the abrasion of Si_3N_4 ball, and the scratches are likely due to the cracking of carbide. Fig. 16(c) shows the debris at high magnification; it can be deduced that some relatively larger bulks with irregular shapes are possibly WC particles broken due to wearing or coating with WC. The debris was examined

Table 6
Element compositions of debris on SLD coating.

Element	Cr	C	W	Fe	Ni
Wt.%	5.19	34.7	28.42	16.21	15.48

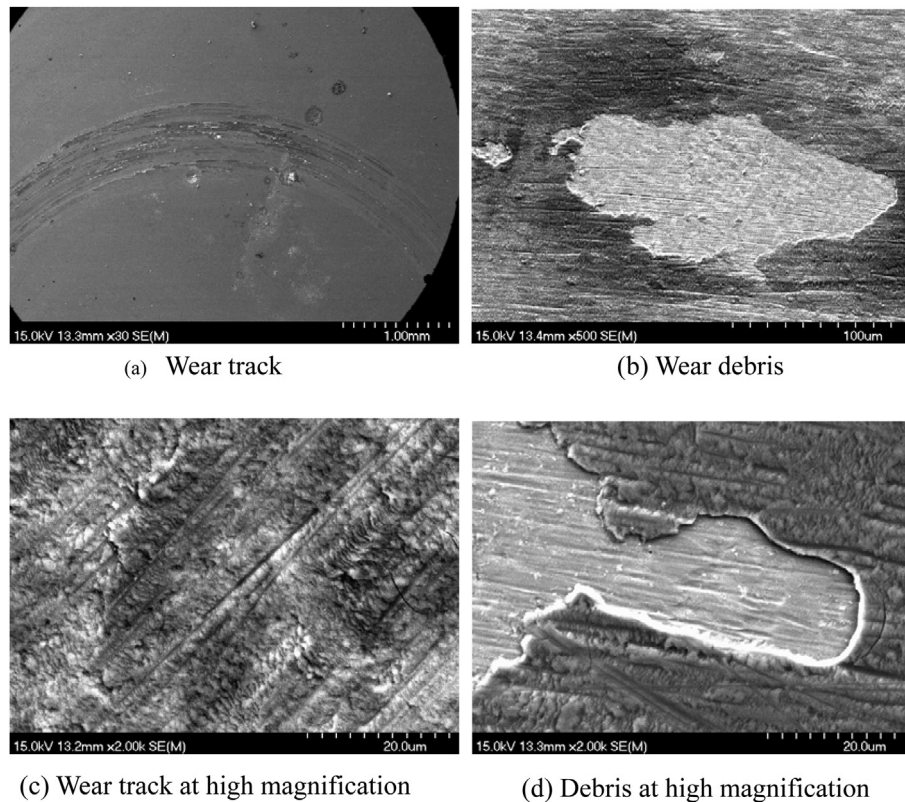


Fig. 17. Worn surfaces of Ni60-WC deposited using LC.

using EDX, and the results are presented in Table 6, which shows that the debris consists mainly of WC and FeNi.

Fig. 16(d) shows the wear track at high magnification, where it can be seen that a mass of WC is embedded in the Ni alloy matrix. The matrix with the scars left on the worn surface was abraded. High-hard WC on the coating during wearing can protect the coating from wearing. As a result, the wear resistance is improved, and the coating base can support the hard particles, avoiding WC fracture and abscission, retaining the high hardness of WC and losing less mass. During the later stages of wearing, the supporting base is continually abraded, and the supporting effect of the base is gradually reduced. As a result, part of the WC phase begins to crack and fall off. The worn surface transforms into a new layer, and the process is continually repeated.

The worn surface of the Ni60-WC coating prepared using LC is shown in Fig. 17. As seen in Fig. 17(a), the wear track is quite different from that in Fig. 16(a). Fig. 17(b) shows the wear debris. Fig. 17(c) shows the obvious, deep and broad wear scars. The debris is grind to form a laminate on the worn surface. Fig. 17(d) shows that a part of the debris moves away due to the brittle debris pulling out during wearing, and reveals the topography of the wearing surface. Table 7 shows the

element compositions of the debris for LC coating. It can be seen from Table 7 that the contents of C and W are lower than those in SLD coating, and the content of Fe is higher than that of SLD coating. It can be seen from the dilution analysis that the elements of LC coating diffused into the substrate or the elements of the substrate diffused into the coating. It can be seen from Fig. 6 and Fig. 13(b) that the phases of Ni60-WC coating deposited by laser cladding exclude WC phase, and the tungsten and iron form the compound Fe_7W_6 . The lost weights, friction coefficients and average hardnesses of SLD and LC are shown in Table 8, respectively, which show that the lost weight and the friction coefficient of SLD coating are lower than those of LC coating, and the microhardness of SLD is higher than that of LC. These data prove that SLD results in improved tribological properties of Ni60-WC coating in comparison to that produced using LC.

4. Conclusions

- 1) The characteristics of the Ni60-WC composite coating deposited on low-carbon steel using SLD with the various

Table 7
Element compositions of debris on LC coating.

Element	Cr	C	W	Fe	Ni
Wt.%	3.27	16.14	8.51	64.6	7.48

Table 8
Properties of Ni60-WC coatings.

	SLD coating	LC coating
Average $\text{HV}_{0.3}$	555	406
Weight loss/mg	0.065	0.073
Average friction coefficient	0.18	0.32

process parameters were studied. The optimal deposition conditions are N_2 atmosphere, pressure of 30 bar, temperature of 450 °C, traverse rate of 10 mm s⁻¹ and laser power of 2 kW with respect to the microhardness and wear properties of the coating.

- 2) The coating deposited using SLD contains Cr_7C_3 , $Cr_{23}C_6$, FeNi, and WC particles while the coating deposited using LC contains Cr_7C_3 , $Cr_{23}C_6$, FeNi, and Fe_7W_6 . Both of the coatings do not have B_2O_3 . The interface between the coating and the substrate bonds strongly. WC particles are embedded in the alloy matrix in the SLD coating, while the carbide is distributed along the grain boundaries for the LC coating. A diluted layer is hardly found in the coating deposited using SLD.
- 3) The microhardness and wear properties of Ni60-WC coatings deposited using SLD and LC were examined. Compared with the LC coating, the hardness of the SLD coating is higher, and its friction coefficient and the weight loss are lower.

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