



Parameter optimization for tungsten carbide/Ni-based composite coating deposited by plasma transferred arc hardfacing

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Abstract: Ni-based composite coatings with a high content of tungsten carbides (Stelcar 65 composite coatings) were synthesized by plasma transferred arc (PTA) hardfacing. The welding parameters of Stelcar 65 composite coatings were optimized by orthogonal tests. The PTA welding parameters including welding current, powder feed rate and welding speed have significant influence on the tungsten carbide degradation. The values for the optimum welding current, powder feed rate and welding speed were determined to be 100 A, 25 g/min and 40 mm/min, respectively. The produced WC/Ni-based composite coatings were crack- and degradation-free. The microstructure of deposited layers, as well as the microstructure and microhardness of the optimal coating were further analyzed. **Key words:** plasma transferred arc hardfacing; Ni-based composite; microstructure; welding parameter optimization

1 Introduction

Hardfacing technologies are important methods to enhance the wear resistance of surface materials. These technologies include flame spraying [1,2], laser melt injection [3], laser cladding [4], plasma cladding [5], solution precursor plasma spray (SPPS) [6], plasma transferred arc (PTA) [7], chemical vapor deposition (CVD) [8] and physical vapor deposition (PVD) [9]. Among these technologies, PTA welding deposition is the most utilized method in industries due to its low production cost, low dilution rate and high productivity [10–13]. Moreover, the metallurgical bond between the substrate and the deposited material obtained from the PTA weld welding deposition process ensures a remarkable performance in tribology and wear environments [14]. With regards to materials for coating protection in severe corrosion, wear and tribology environments, Ni-based hardfacing alloys have attracted much attention in mineral, oil and power generation industry [15–17]. Wear and tribology properties of metallic hardfacing materials are usually reinforced by

the hard particles of WC, Cr₃C₂, VC, Al₂O₃, Mo and TiC [18–21]. The tungsten carbide is an excellent candidate to enhance the performances of the deposited coatings used in severe wear environment. The size and type of tungsten carbides have a great influence on the wear resistance of the coatings [22,23]. The coating reinforced with an eutectic mixture of WC and W₂C exhibited better performances in high stress and impact wear tests [23]. Besides, the deposited coatings with higher volume fraction of tungsten carbides would conduct better wear resistances [24]. Recently, Stellite Stelcar alloys have been developed to serve as a hardfacing coating material. In addition, the Stelcar alloys are metal matrix composites (MMCs) that are typically mixed with large amounts of tungsten carbides particles (WC/W₂C) and Ni-based alloys.

However, large amounts of tungsten carbides in Stelcar alloys are vulnerable to carbide degradation during the PTA deposition process. The WC degradation can trigger the formation of brittle phase in the matrix and hard phase, which deteriorates the mechanical properties of MMCs [25,26]. In order to decrease carbide degradation, PTA parameters should be optimized. The

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coatings in the PTA welding process are influenced by many parameters, such as welding current, welding speed, powder feed rate, oscillation width, preheating temperature and working gas flux [16,27]. Given that PTA welding deposition is a process of melting and solidification, the carbide degradation process may be controlled by optimizing the melt superheating [28]. In addition, three welding parameters such as plasma current, powder feed rate and welding speed are related to the heat input. Plasma current plays an important role in the temperature of molten pool, in which the heat input influences the dilution rate and bonding strength between the MMCs coating and the substrate. In addition, an appropriate powder feed rate should be selected to maintain a sufficient energy input for melting the alloy powders. The welding speed is associated with the plasma arc energy per unit time, which implies that a high welding speed may cause particle splash, although heat efficiency decreases at low welding speed. High heat input increases grain size by dominating the elemental diffusion process [29].

In the current study, orthogonal experiment approach was employed to optimize PTA welding parameters to minimize the carbide degradation in Stelcar 65 alloy coatings. The effect of PTA parameters on microstructure was also investigated. Optimal welding parameters with regards to low tungsten carbide degradation were obtained and the mechanism of tungsten carbide degradation was discussed.

2 Experimental

Stellite Stelcar 65 alloy is a blend of Ni-based alloys with 65% (mass fraction) tungsten carbides. The chemical compositions of Stelcar 65 alloy and the morphology of the alloy powders are listed and shown in Table 1 and Fig. 1, respectively. Sharp-edged fused and crushed tungsten carbide particles with size range of 37–193 μm were found in the alloy. Particle sizes of Ni-based alloy powders were distributed between 25 and 100 μm .

Table 1 Chemical compositions of Stelcar 65 alloy (mass fraction, %)

C	B	Si	Fe	W	Ni
2.50	0.50	1.00	0.50	57.00	Bal.

The Stellite Stelcar 65 alloys were deposited on a 10 mm-thick 45[#] carbon steel by PTA process. The carbon steel plate was preheated to 300 °C before deposition. High purity Ar gas was used as the plasma, carrier and shielding gas. As given in Table 2, PTA welding parameters, such as oscillation width, oscillation speed, nozzle distance to workpiece, and flow rates of

plasma, carrier and shielding gases were constant during the PTA welding, whereas the other three welding parameters including welding current, powder feed rate and welding speed were optimized by orthogonal test (Table 3). A $L_9(3^4)$ orthogonal array was designed to investigate the influence of welding current, powder feed rate and welding speed parameters on the microstructure and carbide degradation of deposition coatings. A series of nine comprehensive experiments were conducted in sequence in this study.

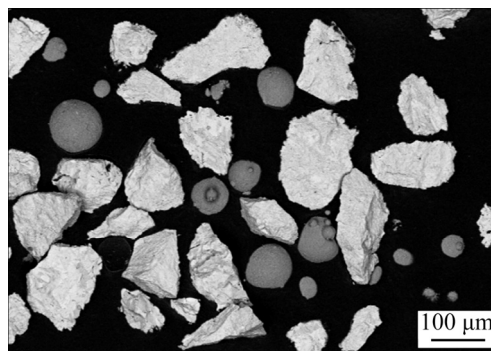


Fig. 1 SEM image of Stelcar 65 powders

Table 2 Constant welding parameters during PTA process

Parameter	Value
Oscillation width/mm	15
Oscillation speed/(mm·min ⁻¹)	90
Plasma gas flow rate/(L·min ⁻¹)	3
Carrier gas flow rate/(L·min ⁻¹)	3
Shielding gas flow rate/(L·min ⁻¹)	18
Nozzle distance to workpiece/mm	30

Table 3 Factors considered during PTA process

No.	Welding current/A	Power feed rate/(g·min ⁻¹)	Welding speed/(mm·min ⁻¹)
1	80	15	40
2	80	20	60
3	80	25	80
4	100	15	60
5	100	20	80
6	100	25	40
7	120	15	80
8	120	20	40
9	120	25	60

After deposition, the PTA samples were cut into the size of 10 mm × 10 mm × 10 mm. The coatings were polished, and then etched using 5% nital (5 mL nitric acid and 95 mL alcohol). The phases of Stelcar 65 alloy powders were examined by an X-ray diffractometer

(XRD, D/max2550VB3+/PC) with Cu K_{α} radiation at a scanning speed of 5 ($^{\circ}$)/min. The microstructure of PTA deposition coatings was observed under scanning electron microscope with energy disperse X-ray analyzer (SEM, Quanta 200 FEG). The microhardness of the deposition was conducted under a Vickers tester (HVS-1000A) using a load of 1.96 N. Image Pro Plus analysis software was applied to measuring the content of tungsten carbides in the PTA deposition coatings.

3 Results and discussion

3.1 Microstructure of as-deposited coating

The XRD patterns of Stelcar 65 alloy powders are presented in Fig. 2(a). The crystalline peaks in the XRD pattern of alloy powders were identified to be γ -Ni (PDF card #70-1849), W_2C (PDF card #79-0743) and WC (PDF card #73-0471) phases. The XRD results indicate that the tungsten carbide in Stelcar 65 alloy powders was a mixture of W_2C and WC phases, which is a typical structure of fused tungsten carbide [25]. Figure 2(b) shows a typical XRD pattern of as-deposit Stelcar 65 alloy coating (welding current, 100 A; powder feed rate, 20 g/min; welding speed, 60 mm/min). Besides the γ -Ni, W_2C and WC phases, Fe_3W_3C (PDF card #89-7205), FeW_3C (PDF card #23-1128) and Ni_2W_4C (PDF card #20-0796) phases were present in the as-deposited coatings. As seen from the XRD pattern for the as-deposited coating, the intensity of W_2C peaks reduces dramatically while the intensity of WC peaks increases.

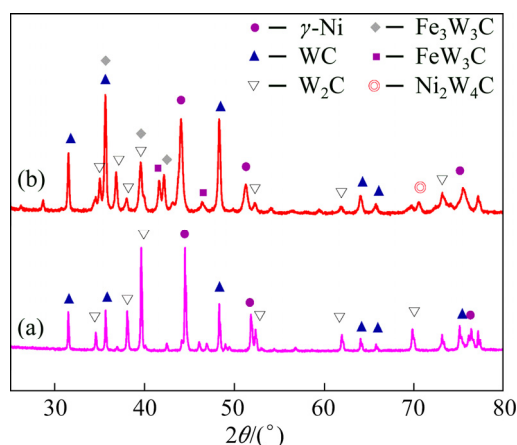


Fig. 2 XRD patterns for powders (a) and typical as-deposited coating (b)

During the PTA welding process, the metal matrix composites (MMCs) powders were gradually dissolved and recrystallized under the thermal effect of high temperature plasma. Ni alloys dissolved initially due to their low melting point (900–1400 $^{\circ}C$) compared with tungsten carbide ((2785 $\pm$ 10) $^{\circ}C$) [30]. At ultrahigh temperature, the tungsten carbides dissolved partially. In

addition, Fe and Ni would gather around the tungsten carbides, causing Fe–W–C and Ni–W–C ternary systems to appear. If the diffusion rate of C is rather higher than that of W [31], the content of C would be lower than W in the ternary system. By combining the ternary diagram [32,33], the η phase formation occurred, which was identified to be Fe_3W_3C , FeW_3C and Ni_2W_4C (Fig. 2(b)), resulting in the decomposition of tungsten carbides. Finally, the thermodynamic equilibrium state would be attained to restrain the η phase grains from growing up. As a result, the W and C were left in the eutectic liquids [34]. In accordance to the W–C phase diagram [35], the solidification transformation in the molten liquids is a series of complex reactions. Primary WC is the prior precipitated phase during the eutectic reaction, followed by W_2C [36]. As a result, the content of W_2C decreased, and recrystallized WC was the main phase of the interface between the Ni matrix and tungsten carbides [37].

Figure 3(a) shows the microstructure of as-deposited coating in transverse cross section. The tungsten carbide particles with bright contrast were homogeneously distributed in the Ni-based alloy matrix. Some pores near the surface were detected. However, the interfaces of tungsten carbide and the alloy matrix varied greatly in different layers in the transverse cross section. On the fusion line layer (Fig. 3(b)), the temperature gradient (G) and the growth rate of grain (R) were at maximum and minimum point, respectively, during the PTA process. As the holding time went to infinity, a state without chemical flux induced the existence of planar crystals [38]. Substantial amounts of Fe were detected by EDS (Spot A) in planar crystals. Moreover, Fe diffused from the steel substrate to the fusion layer due to dilution, which indicated a good metallurgical bonding between the MMCs and the substrate. On the middle layer of as-deposited coating (Fig. 3(c)), the ratio of G/R gradually decreased and the planar crystals transformed to cellular dendrites, rather than columnar dendrites [39]. Combined with the XRD and EDS results, the dendrites were determined to be γ -Ni phase, which was similar to the result referred in the previous work [40]. Moreover, interdendritic eutectics which dissolved C, W, Fe and other elements were also observed. As shown in Fig. 3(d), the fusion zone boundary on the surface layer was perpendicular to the welding orientation. Thus, the R was as large as the welding speed. Moreover, G was very low because of continuous heat power from the plasma arc. As a result, columnar dendrites formed due to the remarkably little ratio of G to R . The tungsten carbides in the surface layer were exposed to intensive thermal radiation by plasma arc, resulting in the existence of some needle-like phases in the alloy matrix. Given the considerably high heat input on the surface layer,

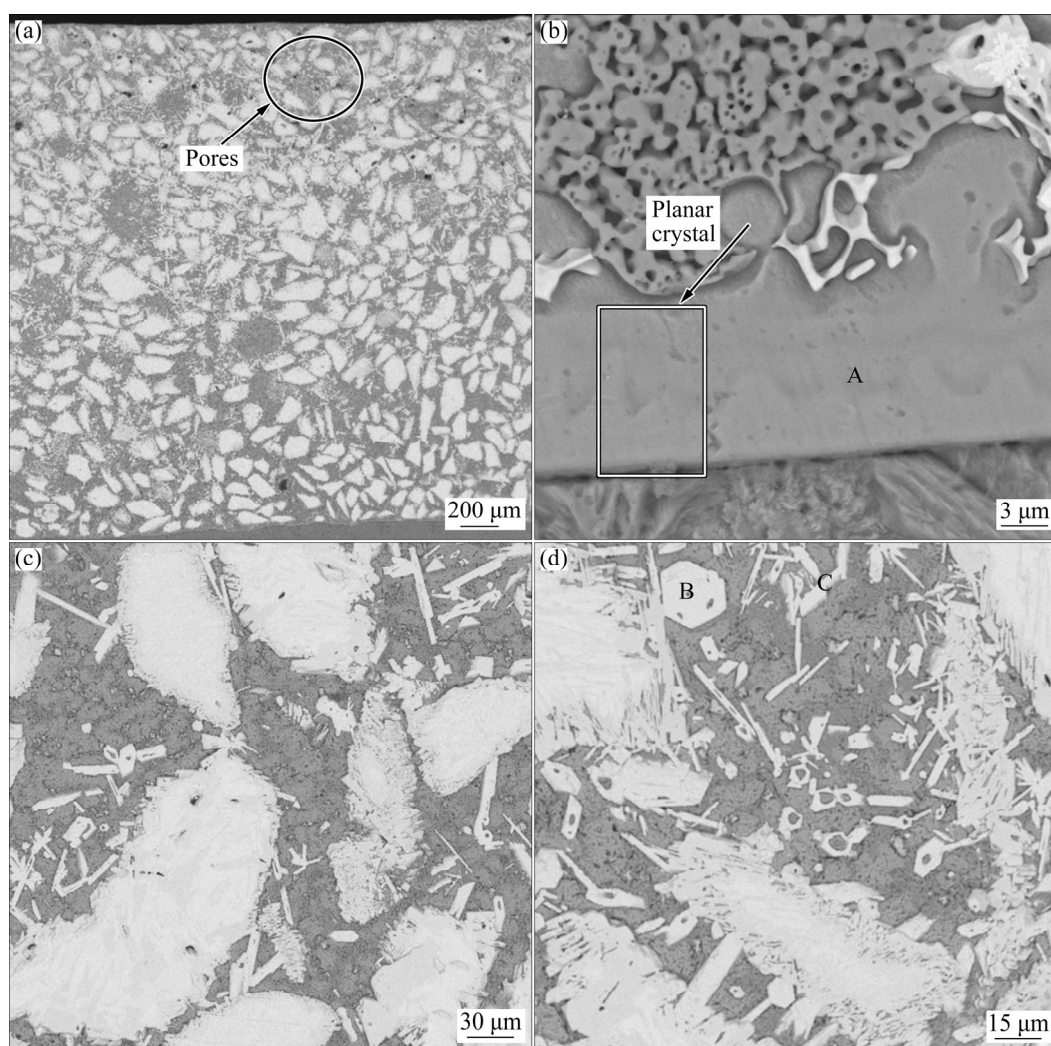


Fig. 3 SEM images of typical as-deposited Stelcar alloy coating in transverse cross section (a) and details at positions of fusion layer (b), middle layer (c) and top layer (d)

tungsten carbides were easy to dissolve. The EDS results (Spots B and C, given in Table 4) illustrated that the content of W in needle-like phases was around 70%, and some Ni and Fe elements were also detected. The needle-like phase may be M_6C (Fe_3W_3C or Ni_2W_4C) [34,41].

Table 4 Chemical composition of typical as-deposited Stelcar alloy coating in transverse cross section (mass fraction, %)

Spot	C	Cr	Fe	Si	Ni	W
A	10.57	0.38	41.53	0.41	38.23	8.88
B	15.53	0.43	6.16	0.25	7.57	70.06
C	10.99	0.30	0.59	0.30	11.87	76.21

3.2 Welding parameter optimization

To minimize the degree of tungsten carbide degradation, three welding parameters including welding current, powder feed rate and welding speed were optimized by orthogonal test. Samples 1–9 were

deposited by PTA with parameters listed in Table 3. Figure 4 shows the SEM images of PTA deposit coating samples 1–9 in the transverse cross section. As shown in Fig. 4, three welding parameters play an important role in the microstructure and tungsten carbide degradation.

Three welding current values (80, 100 and 120 A) were used in orthogonal test. When the welding current was at a low level (80 A) (Figs. 4(a–c)), the alloy powder particles may not be completely melted, resulting in the increase of surface roughness. As the current was increased to 100 A (Figs. 4(d–f)), the surface quality of the coatings was improved. When the coatings were processed with higher deposition current (120 A), the powder particles were overheated, and the degradation of tungsten carbides became very serious (Fig. 4(g)), which was corresponded with the previous work [42]. The welding current is a direct reflection of heat energy input, and the welding current has a great influence on dilution rate and element penetration degree [43]. On coatings processed with lower deposition current (80 A), the

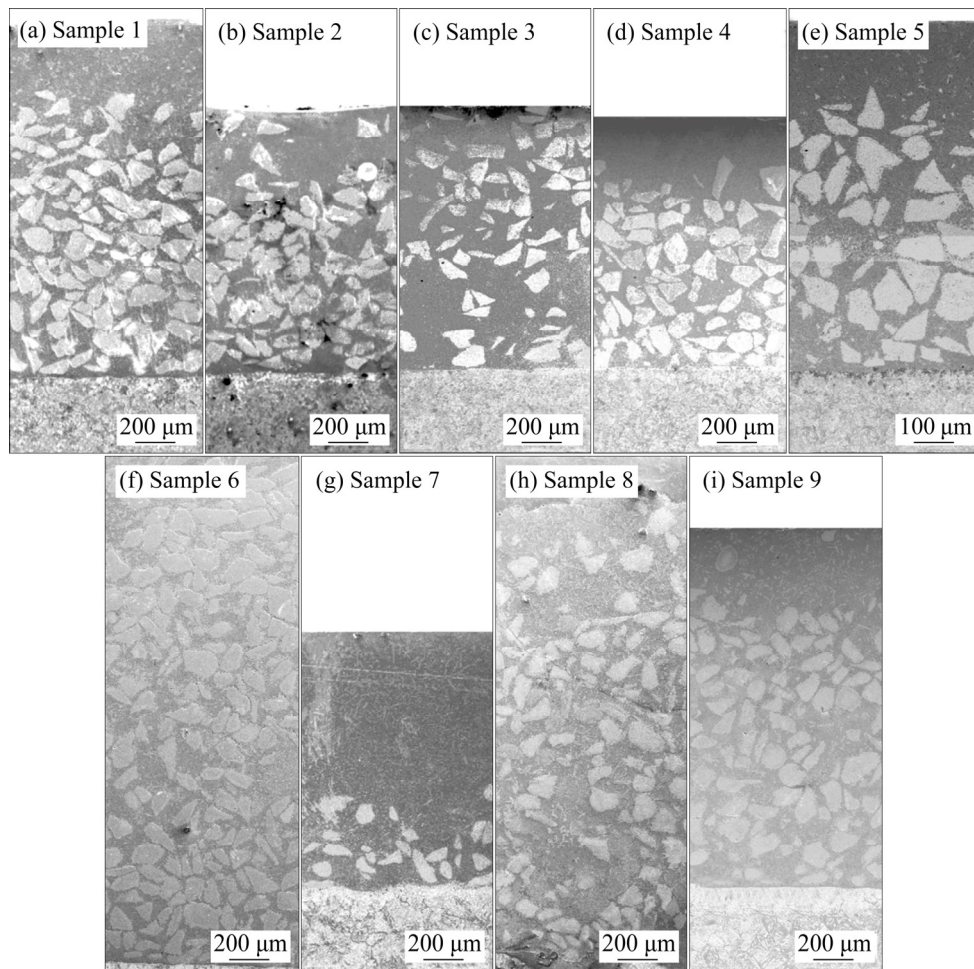


Fig. 4 SEM images of Stelcar alloy coating samples with different processing parameters

fusion lines were straight, which implied a lower dilution rate. Curved fusion lines (Figs. 4(d–f)) were observed at high deposition current (120 A), indicating the unexpected increase in dilution rate.

The powder feed rate also has a great influence on the microstructure of as-deposited coatings. Three powder feed rates (15, 20 and 25 g/min) were used. Settlement of tungsten carbide particles was observed at a powder feed rate of 15 g/min (Figs. 4(a, d, g)). The thickness of as-deposit coatings increased at a high powder feed rate (25 g/min) (Figs. 4(c, f, i)). Increasing the powder feed rate was also beneficial to the homogeneous distribution of the WC [44].

Finally, the thickness of the as-deposited coatings was mainly affected by the welding speed. A thick coating could be obtained at a low welding speed (Figs. 4(f, h)). When the welding speed was increased to 80 mm/min, the thickness of coating was reduced to 1000 μm (Figs. 4(c, e, g)). The thin coating can be illustrated in two aspects: the high welding speed reduced the heat energy input per unit length [45], and

the volume of alloy powders deposited on per unit time was lower due to the high welding speed [46].

As for the contrast differences between tungsten carbide particles and Ni-based matrix alloy, tungsten carbides remaining in the coatings were evaluated by calculating the volume fraction of tungsten carbide using the transverse cross section of SEM images. The statistical results are given in Table 5. The volume fraction and distribution of tungsten carbide particles within the matrix varied considerably with the PTA welding parameters. The volume fraction of tungsten carbide particles was in the range of 17.2%–52.9%.

Proper welding parameters are the key to suppress the degradation of tungsten carbides. Further analysis of the factors and the mean variance revealed that the reliabilities on the influence of the welding current, powder feed rate and welding speed were 0.95, 0.9 and 0.9, respectively. Moreover, the best parameters of welding current, powder feed rate and welding speed were determined to be 100 A, 25 g/min and 40 mm/min, respectively.

Table 5 Thickness of as-deposited coatings and volume fractions of tungsten carbides

Sample No.	Thickness/ μm	Volume fraction of tungsten carbides/%
1	1230	38.1
2	1333	36.7
3	1353	33.6
4	1290	40.2
5	1088	38.4
6	2620	52.9
7	1226	17.2
8	2489	33.1
9	1845	38.1

3.3 Microstructure of as-deposited coating with optimum parameters

The SEM images of coating deposited using the optimal parameters are shown in Fig. 5. A Stelcar alloy

coating with high volume fraction of tungsten carbide (52.85%) was obtained. Most tungsten carbide particles retain their original irregular sharp-edged morphology (Fig. 5(a)). It should be noted that no needle-like phase was observed across the transverse cross section compared with previous samples, indicating a lower tungsten carbide degradation degree and outstanding mechanical properties [47]. The distribution of tungsten carbide particles was more homogenous in different layers than in other samples. In the fusion layer (Fig. 5(b)), straight fusion line was observed in the interface of Stelcar alloy coating and carbon steel substrate, which indicated a low dilution rate. In the middle layer (Fig. 5(c)), the tungsten carbide particles homogeneously arranged. Abundant tungsten carbide particles were preserved in the top layer (Fig. 5(d)), which was favorable to the improvement of surface mechanical properties. The XRD pattern of high quality Stelcar alloy coating is presented in Fig. 6, where the intensity of tungsten carbide in this coating was very

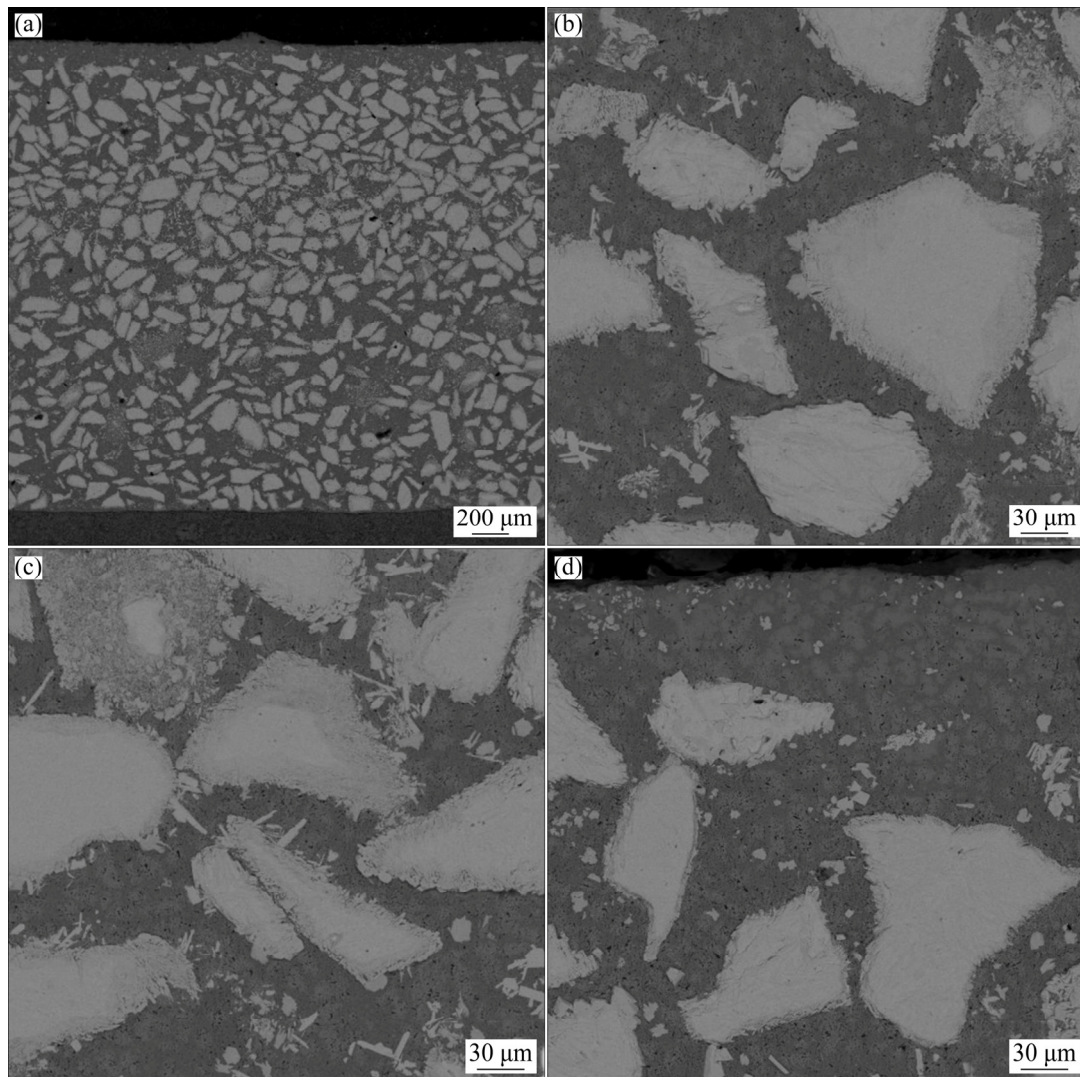


Fig. 5 SEM images of Stelcar alloy coating deposited using optimal parameters on transverse cross section (a) and details at different regions of fusion layer (b), middle layer (c) and top layer (d)

strong. The high strong intensity indicated the large amount of tungsten carbides and the diminutive distance between them, which was undoubtedly beneficial to the mechanical performances [26].

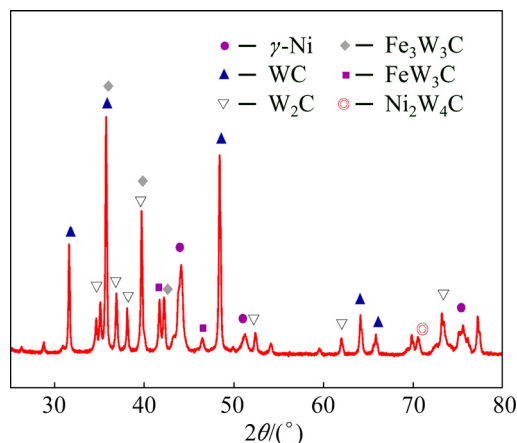


Fig. 6 XRD pattern of Stelcar alloy coating deposited using optimal parameters

Figure 7 shows the microhardness of the transverse cross section in the Stelcar alloy coating. The substrate hardness was measured randomly and the mean microhardness was around $HV_{0.2}$ 130. To measure the hardness of the matrix, the transverse cross section was divided into several layers, beginning from the fusion line with an interval of 0.5 mm. The mean microhardness of the nickel matrix was about $HV_{0.2}$ 540. Thus, the mean microhardness of Ni-based matrix is much higher than that of carbon steel substrate due to the formation of brittle secondary carbides [48]. Because of the fine cellular grains of dendrites forming in the middle section, the microhardness of that section was clearly higher than in other regions, resulting in a peak value. On the surface layer, the grains grew into columnar dendrites, equiaxed dendrites and steering dendrites, decreasing the microhardness [46].

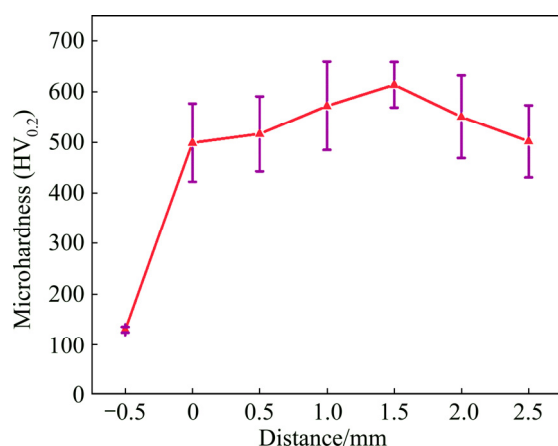


Fig. 7 Microhardness of Stelcar alloy coating deposited using optimal parameters

4 Conclusions

1) Stelcar 65 alloy coating was vulnerable to carbide degradation due to the inappropriate parameters. Fe_3W_3C , FeW_3C and Ni_2W_4C phases were presented after the tungsten carbide degradation.

2) High current conditions (120 A) lead to overheat effects, and the degradation of tungsten carbides became serious.

3) Powder feed rate and welding speed have a great influence on the thickness of the as-deposited coating. The coating thickness increased at a high powder feed rate and a low welding speed.

4) The optimum welding current, powder feed rate and welding speed were determined to be 100 A, 25 g/min and 40 mm/min, respectively.

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等离子转移弧堆焊碳化钨/Ni 基 复合材料堆焊层的参数优化

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摘 要: 采用等离子转移弧堆焊技术制备高碳化钨含量的镍基复合材料(Stelcar 65 合金), 并通过正交试验优化 Stelcar 65 合金的堆焊参数。堆焊电流、送粉率和堆焊速度等参数均对碳化钨的分解有显著影响。正交试验优化后的最佳堆焊电流、最佳送粉率和最佳堆焊速度分别为 100 A、25 g/min 和 40 mm/min, 堆焊层无裂纹、无分解。并对优化后的堆焊层显微组织和显微硬度进行分析。

关键词: 等离子转移弧堆焊; 镍基复合材料; 显微组织; 堆焊参数优化

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