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Effect of WC content on microstructure, hardness, and wear properties of plasma cladded Fe–Cr–C–WC coating

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Abstract

The Q235 sample was coated with ball-milled Fe–Cr–C–WC powder using plasma cladding technology, and the influence of tungsten carbide (WC) content on the surface microstructure, hardness, and wear properties of the coated steel was evaluated. The single factor test of optimal WC content was carried out on DML–02BD plasma cladding machine, and the material after cladding was analyzed. The microstructure distribution, elemental composition and phase composition of the coating were observed by MIRA3–XMH scanning electron microscopy. The microhardness of cladding layer can indirectly reflect the properties of cladding layer to a certain extent, which is measured by the Vickers microhardness tester. The wear quality, friction coefficient and wear morphology can directly reflect the wear resistance of the test blocks. These are observed by the ring block friction and wear tester and the ultra depth of field microscope, respectively. With an increasing WC content, the microhardness of the cladding layer shows an upward trend. The main hard phases of the cladding layer after adding WC are (Cr, Fe)7C3, (Fe, Ni)23C7, and the other phases are γ–Fe, Fe3W5C, WC and Fe2W. After 6 h friction and wear test, the cladding layer with 30%WC showed the best wear resistance. The total wear amount, wear volume, wear rate and friction coefficient were 0.01 g, 4.22 mm³, 2.344 × 10⁻⁴ mm³/(N·m), and 0.35, which were 1/10, 1/5, 1/5, and 7/10 of those without WC cladding layer, respectively. It can be concluded that different WC contents affect the surface microstructure and properties of Fe–Cr–C alloy coating treated by plasma cladding technology. At a WC content of 30%, the microstructure and properties of the cladding layer reach the best.

1. Introduction

The wear of the critical mechanical parts significantly affects their service life and leads to frequent replacement of the worn part with a new one, which is not so cost-effective. Hence, developing wear-resistant material is of great interest to the research community worldwide [1–4]. The wear resistance of a component can be increased by applying a wear-resistant coating on the surface of the component. Different surface modification techniques are used to improve the wear resistance of different mechanical parts [5–9]. Thermal spray techniques are widely used to develop cost-effective and high-quality coatings with good adherence to the substrate. Xiaoling [10] used the thermal spraying technique to produce a nickel-based coating on the agricultural tools and found a large improvement of the wear resistance of the coated surface than the original tool surface. Plasma cladding technology has found a huge application in the surface treatment of materials, owing to its several advantages like low cost, high precision, etc [11–13]. During plasma cladding of the Fe–Cr–C alloy powder (an iron-based powder) [14–16], a large number of carbide-strengthening phases like (Cr, Fe)7C3, (Fe, Ni)23C7, were produced in the cladding layer, which played an important role in improving the hardness and wear resistance of the material [17]. However, the high content of C and Cr in the hard phases resulted in rough and uneven distribution of the microstructure, which increased the brittleness and eventually decreased toughness [18]. In order to increase the number of defects, ceramic particles with high hardness, chemical stability, and wear resistance were added to

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the metal powders [19–21]. Ceramic particles like tungsten carbide (WC) have reasonably good wettability with Fe–Cr–C and other Fe-based alloy powders [22]. Earlier reports showed that WC could fuse with iron-based powder when sprayed using the high-temperature plasma arc, and produce hard phases by melting, which can improve the performance of the cladded layer remarkably [23].

Azevê studied that the influence of High-Energy Milling and shearing Temperature on Al2O3-WC-Co composite coatings. The results showed that the crystallite sizes of Al2O3 and WC phases decreased with increasing the milling time, attaining 27.47 and 30.55 nm, respectively, after 50 h. When the sintering temperature reaches 1550 °C, the grain sizes reduce to <2 μm. The microstructure and mechanical properties of the composites were observed. The results indicated that the composites reached almost complete densification after sintering, reaching suitable values of apparent porosity (1.15%) and microhardness (26.41 GPa) for industrial applications. The wear rate of the composite was 1.978 × 10−6 mm3/N·m. The composite friction coefficient reached 0.54, and the performance was improved dramatically [24, 25].

In this work, the Fe–Cr–C alloy powder is mixed with WC powder in a certain mass fraction by ball milling and applied on the surface of Q235 steel by plasma cladding. The microstructural distribution along with the elemental composition of the coating is analyzed by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS). The phase composition of the coating is evaluated using the X-ray diffraction technique (XRD). The hardness of the cladding layer is measured by the Vickers microhardness tester. The wear quality, friction coefficient, and wear mark morphology directly reflect the wear resistance of the material, so the wear performance of the coated sample is evaluated by the ring-block type friction and wear tester, and the wear scars are analyzed using the ultra-depth of field microscope. The cladding experiment was carried out on the surface of Q235 steel; it provides a reference for improving the surface wear resistance of steel matrix components.

| Table 1. Chemical composition of the Q235 steel (wt.%). |
| --- |
| Element | Mn | Si | C | S | P | Fe |
| Content | 0.40–0.65 | 0.12–0.30 | 0.14–0.22 | <0.03 | <0.035 | Bal |

| Table 2. Chemical composition of WC alloy powder (wt.%). |
| --- |
| Element | Cr | Ct | Cf | O | Fe | Ti | V | Si | W |
| Content | 0.018 | 4.08 | 0.02 | 0.004 | 0.19 | 0.003 | 0.001 | 0.02 | Bal |

| Table 3. Chemical composition of Fe–Cr–C alloy powder (wt.%). |
| --- |
| Element | Cr | Ni | Mo | Si | Nb | N | C | Fe |
| Content | 15.7 | 7.1 | 1.0 | 0.9 | 0.31 | 0.22 | 0.07 | Bal |

Figure 1. Microstructure of WC powder.
2. Material and method

2.1. Experimental materials

Q235 steel plate (120 mm × 120 mm × 12 mm) is widely used in several parts, so it is chosen as the base plate in this test. The contents of each element are shown in table 1. The cladding material is made of Fe–Cr–C Fe-based alloy powder mixed with WC powder in a ball mill for 8 h. The content of WC powder is 0%, 10%, 20%, 30%, 40%; the number of WC powder and Fe–Cr–C Fe-based alloy powder are 140–270 and 80–270 respectively. The chemical compositions of WC and Fe-Cr-C alloy powder are shown in tables 2 and 3. The SEM analysis was carried out at Shenyang Institute of Automation, CAS, and the micrographs are shown in figures 1 and 2. Before the test, the rust and oxide layer on the surface of the substrate is removed by an angle grinder, then the surface of the substrate is cleaned by acetone and ethanol, and then dried [26]. Before the milling, both the powders were placed in the furnace for 2 h at 110 °C to remove the moisture, then the powders were weighed by electronic balance according to the mass fraction, and finally the powders were mixed and stored.

2.2. Experimental setup

The Fe–Cr–C–WC coating was prepared using the DML-02BD plasma cladding machine. The process parameters used are as follows: current 105A, scanning speed 100 mm min\(^{-1}\), powder feeding speed 12r min\(^{-1}\), powder feeding flow 3 l h\(^{-1}\), lap rate 35%.

After coating the steel surface with Fe–Cr–C–WC powder by plasma cladding, the samples were cut into several pieces of 18 mm × 12 mm × 10 mm dimension. Various grids of sandpapers (240 Mesh, 400 Mesh, 600 Mesh, 800 Mesh, 1000 Mesh, 1500 Mesh) were used for polishing the samples.

The microstructural distribution and the elemental composition of the coating were observed by scanning electron microscopy (SEM, MIRA3-XMH) and energy dispersive spectroscopy (EDS). The phase composition of the coating was observed by an X-ray diffractogram (XRD, MIRA3-XMH). The HXD-1000TMC/LCD Vickers microhardness tester (load 4.903N, dwell time 10 s) was used to measure the micro-hardness of the substrate and the cladded layer. The average of multiple measurements was chosen as the microhardness value. The wear and friction coefficient of the specimens were measured by ring-type friction and wear tester (MRH-3). The process parameters of the friction and wear test are as follows, hardness of the GCr15 ring was 770 HV, the load applied during the wear test was 200 N, the friction force was 300 N, the spindle speed was 200 r min\(^{-1}\), the number of main shaft gears was 36, the test duration was 360 min. After the test, the samples were weighed. The wear pattern, volume, and wear surface area are the main test factors, which can directly reflect the wear resistance of the test sample. Hence, the volumetric wear rates of the samples were measured by the ring-block type friction and wear tester using equation (1), and the wear scars were analyzed using the VHX-5000 ultra-depth of field microscope [27].

$$W_r = \frac{V}{F \times D}$$  \hspace{1cm} (1)

where \(W_r\) is the sample’s volumetric wear rate (mm\(^3\)/(N·m)), \(V\) is the wear volume (mm\(^3\)) of the sample, \(F\) is the load (N), and \(D\) is the sliding distance (m).
3. Results and discussion

3.1. Phase analysis of the cladding layer

X-ray diffractograms of the cladding layer with different amounts of WC are shown in figure 3. Figure 3(a) shows that the Fe–Cr–C cladding layer (without WC) is mainly composed of (Fe, Cr) solid solution and the presence of different phases like Cr7C3, (Cr, Fe)7C3, (Fe, Ni)23C6, Fe2Nb, Fe3Mo, etc, confirms this observation. Figure 3(b) displays the phase composition of the Fe–Cr–C cladding layer with different content of WC. Because of the high melting point of WC, the plasma arc could not completely melt the WC particles, so some partially melted WC particles are seen in the cladding layer. In some cases, the WC particles were melted entirely during the coating process and reacted with other elements in the molten pool, and the phases like Fe3W3C and Fe2W were formed, which are observed from the figure. These phases can enhance the hardness of the cladding layer.

3.2. Microstructural analysis of the cladding layer

The SEM micrograph of the cladding layer with 30% WC content is shown in figure 4, which shows a trapezoidal distribution of hard phases in the cladding layer from top to bottom, with a maximum amount of clustering in the mid zone. This could be caused by the pure powder present in the middle part of the cladding. However, in the lower part, the cladding powder settles at the bottom of the molten pool after melting. The matrix material is doped after fusion with the molten matrix, leading to a slight decrease in hardness.

SEM micrographs of the cladding layer with various WC contents (0%, 10%, 20%, 40%) are shown in figure 5. In most cases, the microstructure of the cladding layer looks more compact, and the amount of hard phase increases significantly with the increase in WC content. The combined EDS results with the XRD results are shown in figure 6 and table 4. A large amount of grey area A of the cladding layer is the γ-Fe phase, and B is the W element (mainly from the partially melted WC particles). The bright white phase C is rich in Fe, W, etc. The reaction between the molten WC and Fe led to Fe3W3C phase formation. The hard phases like (Cr, Fe)7C3 and (Fe, Ni)23C7 of the cladding layer comprise the dark gray phase D, which is rich in Fe, Cr, Ni, etc.
3.3. Microhardness

The hardness of the Q235 steel substrate was found to be 148.5 HV, which was obtained from the average value of 15 indents (measured below 0.2 mm of the cladding layer). After cladding, the average microhardness of the cladding layer was increased to 325.28 Hv, with 0% of WC. Figure 7 shows that the hardness of each group of

![Figure 5. SEM microstructures of the cladding layer with various WC contents (a) 0%, (b) 10%, (c) 20%, and (d) 40%.](image)

![Figure 6. High magnification SEM micrograph of the middle part of the cladding layer with 30% WC content.](image)

**Table 4. EDS analysis of cladding layer with 30% WC content (wt.%).**

| Areas | C   | Si  | Nb  | Mo  | Cr  | Fe  | Ni  | W   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| A     | 1.17| 1.92| 0.24| 0.44| 8.41| 58.37| 8.39| 21.06|
| B     | 1.43| 7.12| 0.00| 0.09| 0   | 0.19 | 0   | 91.16|
| C     | 1.48| 3.66| 0.2 | 0.84| 10.47| 34.01| 3.19| 46.16|
| D     | 2.00| 3.99| 0.42| 1.06| 11.97| 29.11| 1.35| 50.11|

![Figure 7. SEM microstructure showing the hardness distribution of the cladding layer with various WC contents.](image)
samples (with different content of 10%, 20%, 30%, and 40% WC) increases with the increase in the percentage of WC powder. According to the 20 measured indentation data for a group of samples, it is seen that the hardness of the upper and middle layer of the cladded coating is comparatively higher than the bottom layer, which is close to the matrix. Although not apparent, the trend is there. The main reason for this phenomenon is that the hard phase is distributed more uniformly and compactly in the mid-zone of the cladding layer, and the hardness of the bottom zone of the cladding layer is reduced due to the dilution of the molten matrix. With 40% of WC addition, the average microhardness of the cladding layer reaches the maximum value of 662.05 Hv, which is about 2.04 times of the cladding layer without WC.

3.4. Wear performance of the cladding layer
After the friction coefficient reaches the steady-state, the coefficient of friction is obtained from figure 8. The friction coefficient curve initially increases sharply, then decreases, and finally reaches a steady state, which is related to the distribution and content of the hard phase in the cladding layer. At the beginning of the wear test, under the gradual application of load with time, the friction ring and the sample asperities come in close contact with each other during the relative motion. In this process, wear debris is produced, which exists between the sample and the friction ring and acts like abrasive particles. Thus, it leads to abrasive wear apart from the sliding wear. During the friction and wear test, the partially melted WC particles move relative to the samples, and due to the high hardness, these particles resist the wear of the sliding pairs. The friction coefficient of the cladding
layer with 0% WC is the maximum, and the friction coefficient of the cladding layer with 30% WC is found to be minimum, which is attributed to the uniform and compact layer hard phase in the cladded coating.

Figure 9 shows the wear scar morphology (obtained after 6 h of wear) of the cladded samples with 0%—40% WC content. The results show deeper surface wear marks of the cladding layer without WC powder than their counterparts under the same experimental conditions. Comparing the data as mentioned in table 5, the performance of the coating without WC is found to be different from the coating with WC. According to the data shown in table 5, the wear volume, wear rate, and friction coefficient of the cladding layer first decreases and then increases with the increase in WC content. However, with 30% of WC, these values are the lowest, suggesting the optimum wear resistance of the cladded material with 30% of WC.

4. Conclusion

The Fe–Cr–C alloy coating with different percentages of WC was produced by the plasma cladding technique on the Q235 steel, and the effect of WC percentage on the microstructure, hardness, and wear performance of the coating was evaluated, and the following conclusions were obtained.

(1) The formed hard phases of the Fe–Cr–C–WC cladded coating were mainly (Cr, Fe)23C7 and (Fe, Ni)33C7, and the rest were Fe, Fe5W5C, WC, Fe2W, etc. Due to the high melting point, some partially melted WC particles were seen in the microstructure.

(2) With 30% of WC. The average hardness of the cladding layer was 560.7 HV, which is about 3.8 times higher than that of the substrate.

(3) The total amount of wear of the cladded sample with 30% WC was about 7–8 times lesser than the coated sample without WC. The wear volume and wear rate of the cladded sample (with 30% WC) was 1/5 of the sample without WC. Hence it can be ascertained that WC plays a vital role in improving the wear performance of the Fe–Cr–C alloy coated Q235 steel.
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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