Low-Stress Abrasion Behaviors of Fe-Cr-C (1.4~5.6 wt-%) Hardsurface Coatings

By increasing the carbon content, the coating hardness increased and the mass loss from low-stress abrasion decreased

BY S. LIU, Y. F. ZHOU, X. L. XING, J. B. WANG, Y. K. GAO, Y. L. YANG, AND Q. X. YANG

ABSTRACT

Fe-Cr-C (1.4~5.6 wt-%) hardfacing coatings were prepared for this investigation. Their microstructures and phase structures were observed and determined. Their hardness and low-stress abrasion behaviors were also tested and investigated. The results show that, with increasing C content, the microstructures of the coatings were changed from hypoeutectic to near eutectic, then to hypereutectic structures. The primary phase of Fe-Cr-C (1.4 wt-%) coating is cellular austenite, while those of Fe-Cr-C (3.5 wt-%) and Fe-Cr-C (5.6 wt-%) coatings are M7C3 carbide. The hardness of the coatings was increased, while the mass loss of the coatings is decreased. The low-stress abrasion mechanism of Fe-Cr-C hardfacing coatings was plastic deformation (PD).

KEYWORDS

• Welding • Coating • Abrasion • Low-Stress Sliding

Introduction

With excellent wear resistance, the Fe-Cr-C alloy has been commonly used to clad workpiece surfaces to prolong their service life (Refs. 1–6). However, after a period of time, the hardfaced surface may fail because of severe working conditions (Ref. 7).

The most common failure form of the hardfaced workpiece during service is abrasion, which is the phenomenon where abrasion particles are not broken.

According to C content, the microstructure of the Fe-Cr-C coating can be defined as hypoeutectic, eutectic, and hypereutectic structures (Ref. 13). The primary phases of the hypoeutectic and the hypereutectic Fe-Cr-C coating are austenite and M7C3 carbide, respectively (Ref. 14). The primary M7C3 carbides are revealed to be polygonal rods (Ref. 15). In recent years, researchers have put great efforts on investigating the microstructure and wear resistance of Fe-Cr-C coatings. D. J. Kotecki et al. (Ref. 16) proved that the carbon content is the most important factor to determine the wear resistance of a Fe-Cr-C coating. Y. F. Liu et al. (Ref. 17) found that the primary M7C3 carbide in hypereutectic Fe-Cr-C coatings can act as the wear-resistant phase. X. H. Tang et al. (Refs. 7, 18–21) demonstrated that with increasing C content, the volume fraction of the M7C3 carbide in the Fe-Cr-C alloys are increased, so that the wear-resistance is promoted.

S. D. Borle et al. (Ref. 22) revealed that decreasing the alternating current balance can lead to an increase in size and volume fraction of the primary M7C3 carbide. C. M. Lin et al. (Refs. 23–25) proved the number, size, and orientation of the polygonal-rod M7C3 carbide affect the wear resistance of the Fe-Cr-C alloy. It showed the wear resistance along its perpendicular direction is higher than that along the parallel direction.

The wear resistance of Fe-Cr-C coatings was widely investigated. However, little research on the low-stress abrasion mechanism was reported. Even if the low-stress abrasion was studied, it was always investigated by comparing the mass losses or by analysis of the abrasion morphology. In this research, a CSM Revetest Xpress scratch tester was creatively used on Fe-Cr-C hardfacing coatings to simulate the single trace of the abrasive particle in the low-stress abrasion process, which can provide some novel details of the low-stress abrasion. The mass loss of Fe-Cr-C coating.
hardfacing coatings was measured by self-made abrasive-belt abrasion tester. Then the abrasion mechanisms of the hypoeutectic, eutectic, and hypereutectic Fe-Cr-C hardfacing coatings were discussed, which can provide a wide basis for the application of Fe-Cr-C hardfacing coatings.

Materials and Methods

Materials

Fe-Cr-C (1.4–5.6 wt-%) hardfacing coatings were prepared by cladding self-made flux cored wires on low-carbon steel substrate. The self-made flux cored wires contained atomized magnesium aluminum powders (Mg:Al = 40:60), which can act as self-protecting components. Therefore, the open arc hardfacing welding method was used. The chemical composition of the low-carbon steel substrate is listed in Table 1.

The open arc hardfacing process (schematically shown in Fig. 1) was conducted manually with a ZXG3-300-1 DC welding machine, and the process parameters are listed in Table 2.

Methods

A CS-8800 infrared carbon-sulfur analyzer and Advant/p-381 x-ray fluorescence spectrometer were used to determine the compositions of the Fe-Cr-C hardfacing coatings, which are listed in Table 3. From Table 3, the C contents of Nos. 1, 2, and 3 coatings are 1.4, 3.5, and 5.6 wt-%, respectively. Then the mass fraction curves of all phases during cooling were calculated with Thermal-Calc software.

The phase structures of the coatings were determined by D/max-2500/PC x-ray diffraction (XRD). The microstructures were observed by Axiocert 200 MAT optical microscope (OM). Their hardness was tested with a HR-150A Rockwell hardness tester. A low-stress unidirectional-scratching experiment was conducted on Fe-Cr-C hardfacing coatings by a CSM Revetest Xpress scratches tester, whose diamond indenter can simulate hard particles under abrasion conditions (schematically shown in Fig. 2). The load for the low-stress unidirectional-scratching experiment is 1N. Then the worn morphologies were observed by Hitachi S4800 field emission scanning electron microscopy (FESEM).

An abrasion experiment under the same load (1N) was conducted by a self-made abrasive-belt abrasion tester. The abrasive-belt abrasion tester is schematically shown in Fig. 3. The cuboid coating samples were set above the abrasive belt, which con-

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>S</th>
<th>P</th>
</tr>
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<tr>
<td>Contents (wt-%)</td>
<td>≤0.16</td>
<td>0.3–0.5</td>
<td>≤0.03</td>
<td>≤0.2</td>
<td>≤0.3</td>
<td>≤0.03</td>
<td>≤0.03</td>
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<table>
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<tr>
<th>Wire Diameter (mm)</th>
<th>Welding Voltage (V)</th>
<th>Welding Current (A)</th>
<th>Welding Speed (mm•min⁻¹)</th>
<th>Cladding Thickness (mm)</th>
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<td>3.2</td>
<td>24–26</td>
<td>200–224</td>
<td>300</td>
<td>4.6–5.0</td>
</tr>
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</table>

Fig. 1 — Schematic of the hardfacing process.

Fig. 2 — Schematic of the CSM Revetest Xpress indenter.

Fig. 3 — Schematic of the abrasive-belt abrasion tester.
tained much silica sand. Each group of six samples was tested simultaneously, and the average mass loss was measured every 2 h. Each group was weighed 10 times.

Results

Microstructures of Fe-Cr-C Hardfacing Coatings

Mass Fraction of All Phases

The mass fraction curves of all phases in Fe-Cr-C hardfacing coatings during cooling are shown in Fig. 4.

From Fig. 4A, a large amount of \( \delta \)-Fe precipitated at 1344°C. When the temperature was 1282°C, the eutectic reaction occurred, namely a large amount of eutectic \( \gamma \)-Fe and \( M_7C_3 \) carbide formed. With temperature continually decreasing, \( \gamma \)-Fe gradually transformed into \( \delta \)-Fe. From Fig. 4B, a few primary \( M_7C_3 \) carbides precipitated at 1306°C. When the temperature was 1285°C, the eutectic reaction occurred, where a large amount of eutectic \( \gamma \)-Fe and \( M_7C_3 \) carbide formed. When the temperature decreased to 801°C, the majority of \( \gamma \)-Fe transformed into \( \delta \)-Fe, while a little transformed into \( M_7C_3 \) carbide. From Fig. 4C, a large amount of primary \( M_7C_3 \) carbides precipitated when the temperature decreased to 1382°C. When the temperature was 1241°C, the eutectic reaction occurred, where \( \gamma \)-Fe and \( M_7C_3 \) carbide formed. When the temperature decreased to 752°C, the majority of \( \gamma \)-Fe transformed into \( \delta \)-Fe, while a little transformed into \( M_7C_3 \) carbide.

From Fig. 4, the primary phase of No. 1 coating is \( \delta \)-Fe, while Nos. 2 and 3 are \( M_7C_3 \) carbide. The mass of primary \( M_7C_3 \) carbide in No. 2 coating is extremely low.

XRD

XRD patterns of Fe-Cr-C hardfacing coatings are shown in Fig. 5, which indicates that the coatings are mainly composed of \( \alpha \)-Fe (\( \delta \)-Fe), \( \gamma \)-Fe, and \( (Fe, Cr)_7C_3 \) carbide. With increasing C content, the single peaks of \( (Fe, Cr)_7C_3 \) carbide were increasingly obvious. The XRD pattern of the No. 1 coating even showed no single peak of \( (Fe, Cr)_7C_3 \) carbide, which indicated that the fraction of \( (Fe, Cr)_7C_3 \) carbide in the No. 1 coating was very low. It should be noticed that the content of \( \gamma \)-Fe was much higher than that of \( \delta \)-Fe in the No. 1 coating, which was due to the high cooling rate during hardfacing.

Microstructure

The microstructures of Fe-Cr-C hardfacing coatings are shown in Fig. 6. From Fig. 6A, the microstructure of the No. 1 coating was hypoeutectic, in which the white areas are cellular primary \( \gamma \)-Fe (austenite), while the dark areas are eutectic structures (austenite and carbide). Figure 6B shows that the

<table>
<thead>
<tr>
<th>Elements and Contents (wt-%)</th>
<th>C</th>
<th>Cr</th>
<th>Si</th>
<th>Mn</th>
<th>B</th>
<th>V</th>
<th>Ti</th>
<th>Fe</th>
</tr>
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<tr>
<td>No. 1</td>
<td>1.4</td>
<td>27.2</td>
<td>1.2</td>
<td>1.0</td>
<td>0.25</td>
<td>0.07</td>
<td>0.03</td>
<td>Bal</td>
</tr>
<tr>
<td>No. 2</td>
<td>3.5</td>
<td>26.8</td>
<td>1.0</td>
<td>1.1</td>
<td>0.24</td>
<td>0.07</td>
<td>0.02</td>
<td>Bal</td>
</tr>
<tr>
<td>No. 3</td>
<td>5.6</td>
<td>26.9</td>
<td>1.2</td>
<td>1.1</td>
<td>0.26</td>
<td>0.06</td>
<td>0.03</td>
<td>Bal</td>
</tr>
</tbody>
</table>
microstructure of the No. 2 coating was near eutectic, which mainly consists of eutectic structures with a few primary carbides in a hexagon shape. The microstructure of No. 3 coating contained more hexagon-shaped primary carbides — Fig. 6C. Figure 6 agrees well with Figs. 4 and 5.

Figure 7 shows the cross-sectional metallographs of the Nos. 1, 2, and 3 coatings. The left sides were the low-carbon steel substrates, and the right sides were the hardfacing coatings, respectively. It can be seen that metallurgical bonding was formed between the hardfacing coatings and the substrates. There was no apparent inclusion or hole in the graphs, which indicated that the bonding between the coatings and the substrates was good.

**Abrasion Behavior of Fe-Cr-C Hardfacing Coatings**

**Rockwell Hardness**

The Rockwell hardness of the Fe-Cr-C hardfacing coatings are shown in Fig. 8. With increasing C content, the hardnesses of Nos. 1, 2, and 3 coatings were HRC 43.0, 57.5, and 60.6, respectively. The difference in hardness was mainly due to the primary phases. The primary phase of the No. 1 coating was austenite, which is soft, so the hardness of the No. 1 was the lowest. The primary phases of Nos. 2 and 3 coatings were both (Fe, Cr)₇C₃ carbide, so their hardness was similar. Because the amount of primary carbides in the No. 3 coating was larger than that in No. 2, the hardness of the No. 3 was higher than that of No. 2.

**Scratch Morphologies**

Figures 9, 10, and 11 are the scratching worn morphologies of the Fe-Cr-C hardfacing coatings, which include the overall scratch, edge, tip, and bottom of the scratches.

Figures 9A, 10A, and 11A show the overall scratches of Fe-Cr-C hardfacing coatings. Figures 9B, 10B, and 11B show the edge of the scratches. Because the primary phases of the Nos. 1 and 2 coatings were different, the scratch widths were sharply reduced from 40 to 25 µm — Figs. 9B and 10B. Even though the primary phases of the Nos. 2 and 3 coatings were both carbide, the primary carbide amount of the No. 3 coating was larger than that of the No. 2 coating. Therefore, the scratch width of Nos. 2 and 3 coatings are 25 and 20 µm, respectively — Figs. 10B and 11B.

Figures 9C, 10C, and 11C show the tips of the scratches on the Nos. 1, 2, and 3 coatings, respectively. Because the plasticity of the hypoeutectic coating was larger than that of hypereutectic coating, the tip shapes were changed from sharp-angled to circular.

Figures 9D, 10D, and 11D show the bottoms of the scratches. It can be seen that grain boundaries at the bottoms are clear, in which the austenite in the No. 1 coating and the carbide in the Nos. 2 and 3 coatings can be observed. There are two main abrasion mechanisms (Ref. 26): 1) mass loss caused by plastic deformation (PD), and 2) mass loss caused by fracture. During the abrasion process, both plastic deformation and fracture may occur, regardless if the material is plastic or brittle. However, because of the difference in wear conditions and material properties, either mechanism may be dominant.

As shown in Figs. 9 to 11, no cracks
can be found in the scratching worn morphologies, so the dominant low-stress abrasion mechanism of the Fe-Cr-C hardfacing coatings is plastic deformation (PD).

**Mass Loss Curves**

Figure 12 shows the mass loss curves of the Fe-Cr-C hardfacing coatings from the abrasion experiment. The mass loss curves of the coatings all increased with time, with the mass loss of coating No. 1 being the most, while that of the No. 3 coating being the least. After 18 h, the mass loss of the No. 1 coating was about $2.0 \times 10^{-2} \text{g/mm}^2$, while those of the Nos. 2 and 3 coatings were $0.6 \times 10^{-2} \text{g/mm}^2$ and $0.3 \times 10^{-2} \text{g/mm}^2$ similarly. The mass losses of Nos. 2 and 3 coatings were extremely less than that of No. 1 coating, which indicated the wear-resistance was highly promoted with increasing C content.

In the PD mechanism, the Fe-Cr-C hardfacing coatings were squeezed by abrasive particles (silica sand), so protrusions were formed beside the scratch. In this process, material was not directly removed. After multiple plastic deformations, the deformed area was hardened, which caused debris to peel off and mass losses from the coatings.

From Fig. 8, the deformation of the coating with higher hardness is smaller, so its mass loss was less.

**Conclusions**

With increasing C content, the microstructures of Fe-Cr-C (1.4-5.6 wt-%) hardfacing coatings changed from hypoeutectic to near eutectic, then to hypereutectic structures. The primary phase of the Fe-Cr-C (1.4 wt-%) hardfacing coating was cellular austenite, while those of the Fe-Cr-C (3.5 wt-%) and the Fe-Cr-C (5.6 wt-%) coatings were hexagon-shaped $M_7C_3$ carbide.

With increasing C content, the mass losses of Fe-Cr-C (1.4-5.6 wt-%) hardfacing coatings abraded for 18 h decreased from $2.0 \times 10^{-2}$ to $0.3 \times 10^{-2}$ g/mm², which indicates that the wear-resistance improved. The low-stress abrasion mechanisms of the Fe-Cr-C hardfacing coatings were plastic deformation.

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References


