

The Microstructure and Wear Properties of Laser-Clad WC-Cr₃C₂ Cermet Coating on Steel Substrate

Qianlin Wu¹ and Wenge Li²

¹*Institute of Marine Materials Science and Engineering, Shanghai Maritime University, Shanghai 201306, P. R. China*

²*College of Materials Engineering, Shanghai University of Engineering Science, Shanghai 201620, P. R. China*

WC-Cr₃C₂ cermet coating on carbon steel was fabricated by laser controlled reactive synthesis and exhibited the metallurgical bonding at the interface between coating and substrate. The microstructure and wear properties of laser-clad WC-Cr₃C₂ Cermet Coating on steel substrate have been investigated by means of scanning electron microscopy (SEM), X-ray diffraction (XRD), microhardness testing and wear testing. Experimental results show that the coating has a very good thermal resistance and high bonding strength due to Ni addition, which decreases stress concentration at the interface and increases the bonding strength due to better wettability. The coating shows superior hardness and wear resistance. In the same wear conditions, the wear resistance of the coating is 4 times than that of steel substrate.

[doi:10.2320/matertrans.M2010410]

(Received December 2, 2010; Accepted December 27, 2010; Published February 9, 2011)

Keywords: WC-Cr₃C₂ cermet, Ni, coating, laser cladding, *in situ*, wear resistance

1. Introduction

Hard ceramic composite coatings, involving such ceramic particles embedded in a metallic matrix can be used to provide high wear resistance to metal substrates. WC and Cr₃C₂ carbides are refractory compounds that combine many favorable properties such as high hardness, certain plasticity and good wettability with the bonding metal. This advantageous combination can make these materials promising candidates as constituents of a protective coating with enhanced resistance against thermal, corrosion and mechanical wear. Thus, these carbides are widely used for producing ceramic-metal composite coatings on the substrate by conventional hardfacing techniques, such as thermal spraying, plasma spraying, electroslag remelting and arc welding, to improve wear resistance.^{1–5} However, the surface coating produced by these technique had some disadvantages, such as the composite coatings with porosities, excessive energy input, the mechanical bonding between the composite coating and the substrate. In recent years, laser cladding technique has been developed and can avoid these disadvantages of the conventional surface techniques mentioned above by choosing optimal parameters.^{6,7}

Conventional production route of ceramic-metal composite coating often involves adding the reinforcing phases into the metal matrix directly, but this often leads to poor wetting behavior between ceramic phase and metal matrix and segregation of reinforcements. In order to overcome these disadvantages, the *in situ* technique has been extensively investigated recently.^{8,9} For the *in situ* technique, reinforcements are synthesized in the metallic matrix by metallurgical reaction between elements or between the elements and compounds during the fabrication process. Compared with the *ex-situ* route, *in situ* process is more economical and has an intrinsic advantage that the surface of the reinforcements is cleaner and hence the bond between the reinforcing phases and the matrix tends to be stronger.¹⁰

The aim of the present work is to develop an *in-situ* WC and Cr₃C₂ carbides ceramic coating on carbon steel substrate by combined combustion synthesis and laser coating of pre-placed powder. Microstructural characteristics, microhardness, wear properties and resistance to thermal shock of the coating were investigated.

2. Experimental Procedures

The surfaces of the carbon steel substrate samples (SAE type 1045 steel; size: 50 mm × 40 mm × 20 mm) were first cleaned with acetone to remove grease. They were then polished with emery paper (300 mesh) and then cleaned in acetone bath in an ultrasonic cleaner. Powders of CrO₃ (~150 μm), WO₃ (~75 μm), Al (~50 μm) and active carbon were weighed out according to the following chemical reaction eqs. (1) & (2) as the reactants and WC powder (~50 μm) was added as diluent for obtain a continuous, smooth and excellent bonding laser coating.¹¹ The chemical reaction equations are exothermic reaction, therefore, a laser controlled reactive synthesis process was developed to achieve the synthesis and cladding of cermet coating on steel substrates at a lower laser density by utilizing the energy of a exothermic reaction. These powders were dry-mixed for 2 h in a ball mill and their mixture was applied on the cleaned surface of substrate with the help of specific quantity of organic binder. Coated specimens were baked in the oven at a temperature of 70°C for 2 h to drive away moisture and other volatile components from the coating. On the average, the thickness of pre-placed powder blends on the substrate was around 1 mm (see Fig. 1). In addition, Ni powder (~50 μm) was placed on the steel substrate with a thickness of 0.5 mm by hot spraying technique for improve the wettability of coating and substrate.

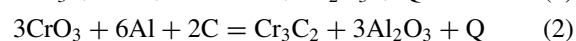
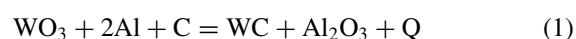


Table 1 Wear conditions used in the present study.

Counter body	Diameter of ball	Normal load	Oscillating frequency	Oscillating amplitude	Sample temperature	Lubrication	Wear time
Si ₃ N ₄	10 mm	90 N	30 Hz	1 mm	Room (25°C)	None	30 min

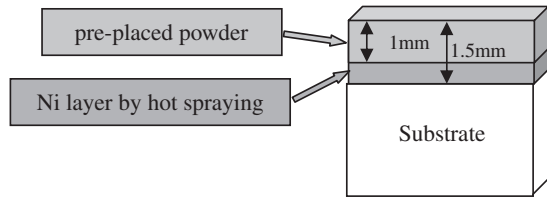


Fig. 1 The schematic diagram of pre-placed powder of the coating.

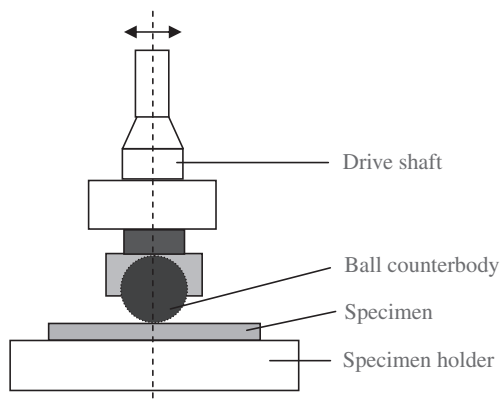


Fig. 2 Schematic view of the wear apparatus.

Laser surface treatment was carried out with an indigenously developed 5 kW continuous wave CO₂ laser system. Laser surface treatment involved scanning the surface of powder-coated substrate with the laser beam of 2 kW power at the rate of 5 mm/s and the round spot with the diameter of 3 mm.

The specimens were cut along cross-section, mechanically grounded, polished in diamond paste and chemically etched in a mixed acid consisting of 75 vol% HCl and 25 vol% HNO₃ to reveal the microstructure which was examined under the scanning electron microscope (SEM), X-ray diffraction (XRD) and electron probe micro-analysis (EMPA). Resistance of thermal shock of coating was tested using thermal cycling consisting of 2 min at a heating temperature of 500°C and 1 min in water for rapid cooling. The hardness profile along the depth of cross-section in the coating was measured using a Vickers hardness tester with a load of 0.2 Kg and a loading time of 15 s.

For wear testing, a ball-on-disk configuration is used for the low-amplitude oscillating dry sliding tests in ambient condition at room temperature. The wear apparatus employed for the tests is shown in Fig. 2. The wear conditions are summarized in Table 1. The section areas of the tracks are measured by a profilometer of Talysurf 5P-120. The wear volume is the product of section area of track multiplied by oscillating amplitude. Accordingly, the wear data of each specimen are presented numerically with the wear volume, and schematically with the wear track profiles.

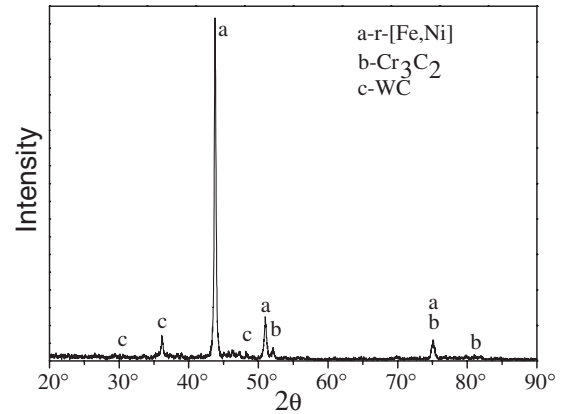


Fig. 3 XRD spectra of the coating.

3. Results and Discussion

3.1 Microstructure

Before the laser beam reached the substrate, it passed through the pre-placed powder which could absorb the laser energy, the residual laser energy triggered combustion synthesis (CS) and subsequent laser alloying of the CS products onto a mild steel substrate. Figure 3 shows the X-ray patterns of the coating. XRD revealed presence of WC, Cr₃C₂, and γ-(Fe, Ni) in the coating. It confirms that WC and Cr₃C₂ reinforcements were *in situ* synthesised by laser scanning.

Laser energy in unit time was simultaneously absorbed by the substrate and the pre-placed powder, and then the molten pool on the surface of the substrate was easily formed. As a result, the melted alloy elements could diffuse each other between the coating and the substrate, which contributed to produce the good metallurgical bonding between the coating and the substrate and the addition of Ni caused the formation of large amount of the γ-(Fe, Ni) in the coating. In addition, because the density of Al₂O₃ particles (3.97 g/cm³) was lower than that of (Fe, Ni) alloy and the violent stirring and convection were driven by thermocapillarity, Al₂O₃ particles as slag easily ascend toward the surface through the molten deposit and remove from the clad coating. This was the main reason that the coating detected were free of Al₂O₃.

Figure 4 shows the SEM micrographs of typical cross-sections of the coating. It can be seen that the microstructure consisted of their eutectic with γ-(Fe, Ni) and plenty of white particles which contained 38.37 mass%Cr, 31.23 mass%W, 13.12 mass% Fe, 5.60 mass% Ni and 10.05 mass%C. The white and fine particles are faceted and exhibit blocky morphology (see insert in Fig. 4(a)) and identified as WC-Cr₃C₂ complex phases by the EDX and XRD results.

From the Fe-Ni binary phase diagram (Fig. 5), Fe and Ni firstly form a γ-(Fe, Ni) solid solution under the liquid line. When the temperature is still reducing, the γ-(Fe, Ni) phase

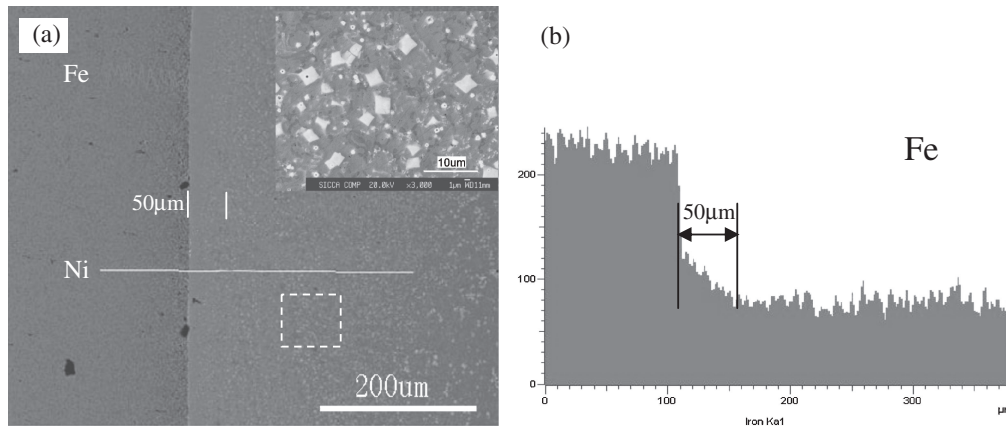


Fig. 4 Microstructures of the Ni-free coating: (a) cross-section of the whole coating; (b) profile of Fe element at interface zone from EPMA.

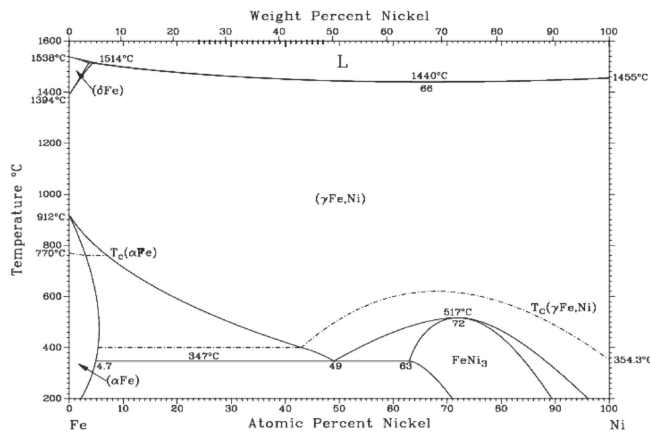


Fig. 5 The Fe-Ni binary phase diagram.

translates into Fe, Ni or Fe_3Ni phases according to the phase diagram. However, the phase transformation does not or partly occur due to the rapid heating and rapid cooling rate by laser cladding technique, correspondingly, plenty of γ -(Fe, Ni) was remained and detected by XRD. Consequently, during the melting and solidified process, substrate Fe and pre-placed Ni by hot spraying can form γ -(Ni, Fe) solid solution by mutual diffusion of atoms at the interface, which acts as a diffusion layer and the content of nickel and iron adjacent to the interface varies gradually with the distance from the interface, as is shown in Fig. 4. Mutual diffusion of Fe and Ni atoms at the interface forms a wide metallurgical bond between the coating and substrate. In addition, the presence of a diffusion gradient at the interface can decrease solid-liquid interface energy, leading to significant improve the wettability of coating and substrate^{12,13)}

3.2 Resistance to thermal shock

The occurrence of crack and stripping in local sites, in particular at the interface between coating and substrate, was observed after many thermal cycles due to the difference of the expansion coefficient and elastic modulus between coating and substrate. Therefore, the bonding strength of the coating can indirectly be evaluate using thermal shock test. In this investigation, the coating did not crack or flake off

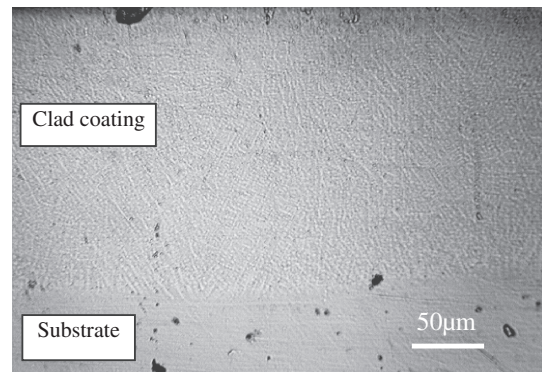


Fig. 6 SEM image of the bonding interface after thermal shock.

after 50 thermal cycles (see Fig. 6), which indicates that the coating has a very good thermal resistance and high bonding strength. This is accounted for by increasing mutual diffusion zone of the bonding interface due to Ni addition, which decreases stress concentration at the interface and increases the bonding strength due to better wettability. The encouraging result in the present study is that no crack and stripping of Ni-modified coating was observed in the ferrous matrix surface composite and is of great importance for a practical engineering material used at elevated temperatures.¹⁴⁾

3.3 Microhardness

The microhardness profile of the specimen is shown in Fig. 7. The profile can be divided into three regions: clad layer, heat affected zone (HAZ) and substrate. It can be seen that microhardness values of the clad coating has a significant improvement than the steel substrate. There is a maximum value of about 430 HV near the surface region of the coating, and average microhardness of coating is about 380 HV. This improvement of hardness can be attributed to the fine and uniformly dispersed WC-Cr₃C₂ complex phase particles.

3.4 Wear resistance of clad coating

The wear volume of the clad coating and substrate are illustrated in Fig. 8. The wear track profiles of the coating and substrate are shown in Fig. 9. The track depth of the clad coating is about 30 μm; however, the track depth of substrate

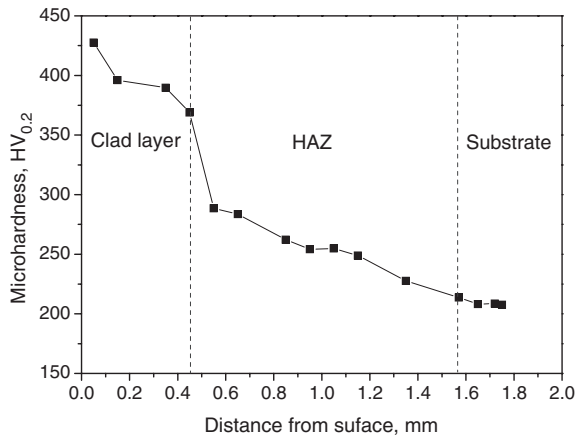


Fig. 7 Microhardness distribution along the depth in cross-section of laser clad coating.

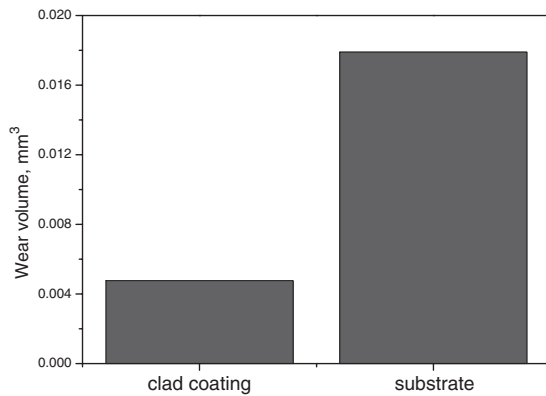


Fig. 8 Wear volume loss of the clad coating and substrate.

is as large as 80 μm . According to the wear volume after the same process, it can be concluded that the wear resistance property of the coating is about 4 times as good as that of substrate. The superior wear resistance property of the clad coating is attributed to the peculiar microstructure of the coating, containing very fine and faceted WC-Cr₃C₂ complex phase particles.

4. Conclusions

- (1) The WC-Cr₃C₂ cermet coating on steel substrate was *in situ* produced by laser controlled reaction synthesis route.
- (2) The coating has a very good thermal resistance and high bonding strength due to Ni addition, which decreases stress concentration at the interface and increases the bonding strength due to better wettability.
- (3) The laser cladding achieved a high hardness, of the order of 400 HV, and presented excellent dry sliding wear behaviour.

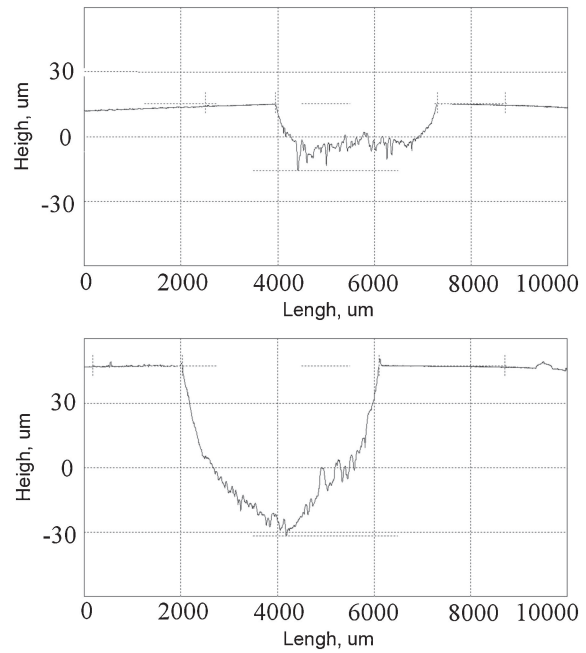


Fig. 9 Wear track profiles of the clad coating and substrate.

Acknowledgements

This research was supported by National Natural Science Foundation of China (no. 50772066) Shanghai Maritime University Foundation (no. 20100071).

REFERENCES

- 1) M. Komaki, T. Mimura, Y. Kusumoto, R. Kuraasi, M. Kouzaki and T. Yamasaki: *Mater. Trans.* **51** (2010) 1581–1585.
- 2) S. F. Zhou, Y. J. Huang and X. Y. Zeng: *Appl. Surf. Sci.* **254** (2008) 3110–3119.
- 3) J. H. Chen, P. N. Chen, P. H. Hua, M. C. Chen, Y. Y. Chang and W. Wu: *Mater. Trans.* **50** (2009) 689–694.
- 4) Q. L. Wu, Y. S. Sun and G. Q. Li: *J. Univ. Sci. Technol Beijing* **15** (2008) 769–774.
- 5) K. H. Baik: *Mater. Trans.* **47** (2006) 2815–2820.
- 6) Y. X. Li, P. K. Bai and Y. M. Wang: *Mater. Design.* **30** (2009) 1409–1412.
- 7) T. M. Yue, H. O. Yang, T. Li and K. J. Huang: *Mater. Trans.* **50** (2009) 219–221.
- 8) A. Anal, T. K. Bandyopadhyay and K. Das: *J. Mater. Process. Technol.* **172** (2006) 70–76.
- 9) B. S. Du, Z. D. Zou and X. H. Wang: *Mater. Lett.* **62** (2008) 689–691.
- 10) A. Singh and N. B. Dahotre: *J. Mater. Sci.* **39** (2003) 4553–4560.
- 11) W. G. Li, G. J. Zhang and J. Li: *Key Eng. Mater.* **368–372** (2008) 1872–1875.
- 12) T. H. Wu and W. G. Li: *J. Mater. Sci. Eng.* **27** (2009) 924–927.
- 13) J. R. Tinklepaugh and W. B. Crandall: *Cermets*, (Reinhold Publishing Corp, New York, 1960) pp. 34–39.
- 14) Q. L. Wu, J. Q. Zhang and Y. S. Sun: *Corros. Sci.* **52** (2010) 1003–1010.