Microstructure and Properties of NiCrBSi metal matrix composite coatings by laser processing

An Sun 1,2,3, Yonghui Chen 1,*, Xiaogang Wang 1,3 and Qiang Han 1,2,3

1 School of Automation and Information Engineering, Sichuan University of Science and Engineering, Zigong 643000, China
2 Material Corrosion and Protection Key Laboratory of Sichuan province, Zigong 643000, China
3 Artificial Intelligence Key Laboratory of Sichuan Province, Zigong 643000, China

*Corresponding author e-mail: sunanrenfeng@163.com

Abstract. The NiCrBSi MMC coatings were formed on the surface steel using laser processing to reinforce the wear resistance of steel substrate. The NiCrBSi MMC layer were composed of the coating zone (CZ) and the bonding zone (BZ). The microstructures and properties of the coatings were investigated. The results showed that the NiCrBSi MMC coatings with no micro-cracks, lamella structures, pores and voids mainly consisted of reticulation structure of Fe-Cr solid solution and blocky structure of Fe-Ni solid solution, which were as solid solution strengthening in CZ. A small quantity of Ni3Si phases and carbide dispersed in interdendritic structure. Compared with the steel substrate, the wear properties of the NiCrBSi coatings significantly improved due to the high hardness chrome dendritic phase and contain hard particles. Consequently, the weight loss after wear test for the NiCrBSi coatings is much less than that of steel substrae.

1. Introduction

In two decades, metal matrix composite (MMC) coatings have been extensively studied and applied in the industries due to their great properties [1]. NiCrBSi MMC coatings have high strength and hardness, as well as good corrosion resistance, abrasive resistance and workability at high temperatures owing to solid-solution hardening, carbide strengthening, and precipitation hardening. NiCrBSi coatings have been proven to be a very effective way to protect steel substrate from oxidation and corrosion [2]. This protection is attributed to the reaction of the coating elements with the corrosive environment which results to the formation of an impervious oxide film or to the sacrifice of the coating in several oxidative environments [3]. The practical application of NiCrBSi coatings have proved that the coatings favor improving the surface properties of materials.

Nickel is often used in the coating material technology because of its enhanced corrosion performance and its durability in harsh environments [3]. The addition of boron reduces the melting point due to the presence of a eutectic point at 3.6 wt.%. Silicon is usually added to increase the self-fluxing properties. The role of chromium is to improve the corrosion and wear resistance due to its passivation ability and the formation of hard precipitates such as chromium carbides and chromium
borides. This addition of boron and silicon makes it easier to get hard facing alloys by melting techniques [4].

Such NiCrBSi MMC coatings is fabricated by different methods such as plasma transferred arc welding (PTAW), plasma-sprayed, thermal spray, high velocity oxygen fuel (HOVF), laser clad coating, CVD and PVD methods [5-8]. However, disadvantages of different preparation methods have limited their further extensive application in very high demanding environments. For plasma-sprayed coating, the microstructure is often characterized by a lamellar structure with the existence of various pores, micro-cracks, splat boundaries, and some unmelted particles due to the nature of the deposition process. Furthermore, the bonding strength between the coating and the substrate is relatively low because of the mechanical bond at the interface. In addition, HVOF coatings have a mechanical bond with the substrate, which results in poor bonding strength, which also produces low-quality coatings with some defects such as pores, inclusions and micro-cracks [9, 10].

The laser induction composite coatings with high micro-hardness and metallurgical bonding to substrate are obtained crack-free Ni60A+20 wt.% WC. It is found that increasing the addition of WC weight fraction in the coating for enhancing the wear resistance results in the precipitation of complex carbides and the residual stress which leads to the propagation of cracks during the individual laser cladding without preheating [11]. In this study, the microstructure and properties of NiCrBSi MMC coating prepared by laser process were investigated, which introduced the laser technique to fabricate wear, corrosion and oxidation resistances coatings.

2. Experimental procedures

2.1. Coatings preparation

The 1045 steel was chosen as the substrate, and its chemical compositions are shown in Table 1. The compositions of the NiCrBSi powders were provided in Table 2. The coatings powders were mixed with reduced iron powder 10wt.% using a dry milling technique with no large agglomerations occurring, which the reduced iron powder is used for additive. The composite powders were uniform for coatings by mechanical stirring. The steel substrate was thoroughly cleaned and rinsed. Subsequently, the paste coating powders were subsequently pre-placed on the surface of steel substrate and dried in air. The laser processing was performed with Nd: YAG laser system.

| Elements concentration | Fe | C   | Si  | Mn | S   | P   | Cu |
|------------------------|----|-----|-----|----|-----|-----|----|
| Bal.                   |    | 0.42-0.50 | 0.17-0.37 | 0.50-0.80 | ≤0.03 | ≤0.03 | ≤0.25 |

| Elements concentration | Ni | Cr | B | Si | Fe | C | Particle size (μm) |
|------------------------|----|----|---|----|----|---|-------------------|
| Bal.                   |    | 15.7 | 3.0 | 4.5 | 4.0 | 0.9 | 20-50             |

2.2. Microstructural characterization

The NiCrBSi MMC coating samples with dimensions 10×10mm×10 mm³ were obtained by using wire electrical discharge machining (WEDM), which were taken from the interface and perpendicular to the surface of the NiCrBSi MMC layer. The transverse section surface of samples with NiCrBSi MMC coating were mechanically grounded by SiC paper from 800 grit to 2000 grit, and polished in the 5 μm diamond paste according to standard metallographic techniques. The microstructure of the cross-section was revealed after etching with a solution of nital 4%. The interface view of the NiCrBSi layer was examined by Zeiss-Evo18 scanning electron microscope (SEM) and chemical composition was...
measured by energy dispersive X-ray spectroscopy (EDS). Phase compositions present in the composite coating were identified by D/max-RC X-Ray diffraction (XRD).

2.3. Dry sliding wear test
A wheel grinder was used for dry sliding wear test of NiCrBSi coatings with abrasive paper 240, 600 and 1000 grit under the load of 15 N. The wear resistance of NiCrBSi coatings was evaluated based on their weight loss.

3. Results and discussion
Figure 1 shows the cross-section morphology of NiCrBSi MMC coatings. It can be found that the coating zone (CZ) and the bonding zone (BZ) are distinguished in the SEM image of the composite layer. However, the bonding line is indistinct at the coating-substrate interface, which indicated that the excellent metallurgical bond was formed between the composite coating and the substrate [12]. The NiCrBSi powders and the surface of steel substrate were melted and the alloying elements were penetrated into each other during the laser beam irradiating the coating with high temperature. Figure 1 illustrates the microstructure of alloy phases and the matrix phase, in which the dark phases are alloy phases and the bright phases are matrix phase. It can be seen obviously that the morphology of alloy phase present at the upper of the substrate.

The microstructure of the composite coating is homogeneous and completely free from micro-cracks, lamella structures, pores and voids.

From the X-ray diffraction results, it is shown that the major phases in the composite coating are Fe-Ni and Fe-Cr solid solution, a small quantity of Ni₃Si, CrB and M₇C₃ type carbide with a low intensity, while the phases of in the substrate is Ferrite. According to the morphological features of the Fe-Cr phases and Fe-Ni phases, the reticulation eutectic phase structure should be the Fe-Cr solid solution, and the blocky-like phase should be the Ni-Fe solid solution. The interdendritic phase was formed eutectic structure of Ni and Ni₃Si with carbide dispersed in the Ni matrix, the chemical compositions of fine particles phases indicate that Fe-rich, Cr-rich, a small amount of C and B elements present in the reticulation should be CrB and carbide [13, 14]. The previous work notes that B, as a light element, cannot be detected accurately using the EDS analysis [15].

The wear loss of NiCrBSi MMC coating and substrate samples is shown in Figure 2, which is indicated the mass loss of steel substrate sample increases more rapidly than that of the NiCrBSi coating sample under 15 N loading. The reason is mainly attributed to NiCrBSi MMC coatings have higher hardness chrome dendritic phase and contain hard particles such as chromium borides and carbides in the coating zone, which work as ploughing stoppers as can be clearly seen in Figure 3(a) and it is well
known that chromium borides and carbides with excellent wear resistance. This result confirmed that the chromium borides and carbides as the strengthen phase can improve the wear resistance of NiCrBSi coatings and prevent failure.

![Figure 2](image)

**Figure 2.** Mass loss of the NiCrBSi coating and steel substrate under 15 N.

The morphologies of worn surface for the NiCrBSi coating and the steel substrate are shown in Figure 3(a) and (b), respectively. Both of the worn surfaces show parallel and continuous grooves. Shallow ploughing and brittle fracture can be found in some areas. However, an obvious feature of ploughed furrows appears on the worn surface of the steel substrate samples (seen in Figure 3b), and the furrows are deeper and wider. The wear properties mentioned above shows that the NiCrBSi coating exhibits excellent wear resistance as dry sliding abrasion condition.

![Figure 3](image)

**Figure 3.** SEM micrographs of the wear surfaces of (a) NiCrBSi coating and (b) steel substrate.

4. Conclusion

The metallurgical bonding between the NiCrBSi MMC coatings and steel substrate was fabricated using laser process. The NiCrBSi composite layer consists of the coating zone (CZ) and the bonding zone (BZ). The microstructure of the composite coating is homogeneous and completely free from micro-cracks, lamella structures, pores and voids. The Microstructures of NiCrBSi coatings exhibit that the surface morphology of coating is composed of reticulation structure of Fe-Cr solid solution and blocky-like of Ni-Fe solid solution, and a small amount of Ni$_3$Si phases and carbide dispersed in the
interdendritic phase. In addition, fine particles (such as carbide and boride) precipitate in Fe-Cr reticulation solid solution. The wear properties show that the NiCrBSi coatings have good wear resistance as dry sliding abrasion condition. Such wear resistance are resulted from the high hardness chrome dendritic phase and contain hard particles, such as chromium borides and carbides, of the NiCrBSi MMC coatings.

Acknowledgments

This work was financially supported by Nature Science Foundation of Sichuan University of Science & Engineering (No.2016RCL30, 2017RCL12), the Opening Project of Material Corrosion and Protection Key Laboratory of Sichuan province (Grant No. 2018CL01, 2016CL12), Foundation of Artificial Intelligence Key Laboratory of Sichuan Province (No. 2017RZJ02), Sichuan Science and Technology Program of China (Grant No.2018JY0197) and Foundation of Sichuan Educational Committee of China (Grant No. 14ZA0205, 18ZA0357).

References

[1] B. Yin, H. D. Zhou, J. M. Chen and F. Y. Yan, Surf. Eng. 27 (2011) 458-463.
[2] S. L. Liu, X. P. Zheng and G. Q. Geng, Mater. Des. 31 (2010) 913-917.
[3] D. Chaliampalias, G. Vourlias, E. Pavlidou, S. Skolianos, K. ChriSSafis, and G. Stergioudis, Appl. Surf. Sci. 255 (2009) 3605-3612.
[4] D. Filgueroso, R. Vijande, J.M. Cuetos, R. Tucho, A. Hernández, Wear 264 (2008) 257-263.
[5] J.M. Miguel, J.M. Guilemany, and S. Vizcaíno, Tribol. Int. 36 (2003) 181-187.
[6] C. Guo, J.M. Chen, J.S. Zhou, J.R. Zhao, L.Q. Wang, Y.J. Yu, H.D. Zhou, Surf. Coat. Technol. 206 (2012) 2064-2071.
[7] X.C. Zhang, B.S. Xu, F.Z. Xuan, Z.D. Wang, S.T. Tu, Surf. Coat. Technol. 205 (2011) 3119-3127.
[8] J.M. Guilemany, M. Torrell, and J.R. Miguel, J Therm. Spray Technol. 17 (2) (2008) 254-262.
[9] W.M. Zhao, Y. Wang, L.X. Dong, K.Y. Wu, and J. Xue, Surf. Coat. Technol. 190 (2005) 293-298.
[10] S.L. Liu, X.P. Zheng, and G.Q. Geng, Mater. Design 31 (2010) 913-17.
[11] S.F. Zhou and X.Q. Dai, Appl. Surf. Sci. 256 (2010) 4708-4714.
[12] D.Y. Lan, Q. Wang, and Z.Z. Xuan, Mater. Sci. Eng. A 473 (2008) 312-316.
[13] T. Yu, Q.L. Deng, G. Dong, and J.G. Yang, Appl. Surf. Sci. 257 (2011) 5098-5103.
[14] O. Knotek, and E. Lugscheider, Welding Research Supplement (1976) 314-318.
[15] P. Niranatlumpong, and H. Koiprasert, Surf. Coat. Technol. 206 (2011) 440-445.