Ultrafast laser induced NiCrBSi coatings

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Abstract. NiCrBSi composite coating was fabricated on 1045 steel substrate by ultrafast laser induced process. The composite layer consists of the coating zone (CZ) and the bonding zone (BZ). Microstructure and chemical compositions were investigated. The morphology of transverse section revealed that the microstructure of the substrate mingled with that of the coatings in BZ, it was showed that the substrate-coating interface was excellent metallurgical bonding. Reticulation structure of Fe-Cr solid solution and blocky structure of Fe-Ni solid solution were formed as solid solution strengthening in CZ. A small quantity of Ni3Si phases and carbide dispersed in interdendritic structure. Fine particles of carbide and boride precipitated in Fe-Cr reticulation solid solution. The microcracks and pores were eliminated in the homogeneous composite coating, while the coating efficiency was increased.

1. Introduction

NiCrBSi alloyed coatings are applied extensively in a number of applications. They have high strength and hardness, as well as good corrosion resistance, abrasive resistance and workability at high temperatures due to solid-solution hardening, carbide strengthening, and precipitation hardening. In many types of industrial applications, such as rolling bearings and gears, surface damage is generated because of the rolling contact, and it limits the useful life of the components and hence reduces durability and product reliability. The NiCrBSi alloy has particularly good performance. 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 [1]. Therefore, NiCrBSi coatings are widely employed to improve the quality of components whose surface are subjected to severe tribological conditions such as gear.

Up to now, the deposition of NiCrBSi coatings is investigated using different methods in industrial scale such as laser clad coating [2], plasma-sprayed [3], high velocity oxygen fuel (HOVF) [4], plasma transferred arc welding (PTAW) [5], thermal spray, various CVD and PVD methods and so on. However, there are some drawbacks that limit its application in very high demanding environments such as the microstructure of a plasma-sprayed coating is often characterized by a lamellar structure with the existence of various pores, microcracks, splat boundaries, and some unmelted particles due to the nature
of the deposition process. Moreover, the bonding strength between the coating and the substrate is relatively low because of the mechanical bond at the interface. The existence of these microdefects may limit the use of the plasma-sprayed coatings to low-stress applications in the rolling contact. HVOF produces low-quality coatings that have some defects such as pores, inclusions, microcracks and lamella structure [6]. Flame spray coatings have many drawbacks, such as high porosity, poor adhesion and so on [7]. PTAW process costs expensive, and the damage of the coating initiated near the microdefects where the stress concentration existed. The as-formed coatings by thermal spray (probably with entrained defects [8]), CVD and PVD methods have several disadvantages such as low adherence, high porosity and low hardness [9].

Laser cladding has been developed for its capability of introducing hard particles such as SiC, TiC and WC as reinforcements in the metallic matrix such as Ni-based alloy and Co-based alloy to form the ceramic-metal composite coatings, which have very high hardness and good wear resistance [10]. This paper aims to investigate the microstructure and chemical compositions of NiCrBSi metal-matrix composite coating by ultrafast laser induced, which is the possibility to enhance the surface properties of the substrate, such as wear, corrosion and oxidation resistances, and to take the advantage of a longer service life of the coating.

2. Experimental and methods

2.1. Coatings preparation

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

| Elements concentration | Ni | Cr | B | Si | Fe | C | Particle size (μm) |
|------------------------|----|----|---|----|----|---|-------------------|
| Bal.                   |    | 20 | 3.5 | 4.4 | 4  | 0.9 | 15-50             |

Table 1. Chemical compositions of NiCrBSi powders (in wt. %).

| Elements concentration | Fe | C | Si | Mn | Cr | Ni | Cu |
|------------------------|----|---|----|----|----|----|----|
| Bal.                   | 0.42-0.50 | 0.17-0.37 | 0.50-0.80 | ≤0.25 | ≤0.30 | ≤0.25 |

Table 2. Chemical compositions of 1045 steel substrate (in wt. %).

2.2. Microstructural characterization

The rectangle shaped samples with dimensions 10mm×10mm×10mm were obtained by using wire electrical discharge machining (WEDM), which were taken from the interface and perpendicular to the surface of the NiCrBSi composite layer. The transverse section surface of samples with NiCrBSi composite coating were mechanically grounded by SiC paper from 240 grit to 2000 grit in water suspension, 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).
3. Results and discussion

The transverse section morphology of NiCrBSi coating is shown in Figure 1. It is seen that two regions can be distinguished of the composite layer: the coating zone (CZ) and the bonding zone (BZ). The bonding line is indistinct at the coating-substrate interface, showing that the excellent metallurgical bonding is formed between the composite coating and the substrate [11]. The reason of that is the melting temperature of NiCrBSi powders is approximately $1025^\circ C$ [12], while the temperature of laser beam is much higher than that. The NiCrBSi composite powders and the surface of steel substrate were melted and the alloying elements were penetrated into each other, when the ultrafast laser beam irradiated 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. Results of microstructure are shown that the composite coating is homogeneous with no microcracks and pores.

![Figure 1. SEM micrographs of NiCrBSi coating: cross-section morphology of composite coating, microstructure of coating zone (CZ), bonding zone (BZ) and substrate](image1)

The X-ray diffraction results indicate that the major phases in the composite coating are Fe-Ni and Fe-Cr solid solution, a small quantity of Ni$_3$Si, CrB and M$_7$C$_3$ type carbide with a low intensity, while the phases of in the substrate is Ferrite.

![Figure 2. The SEM morphology of reticulation structure and blocky-like eutectic phase.](image2)
Figure 2 illustrates the magnified SEM images of reticulation structure and blocky-like eutectic phase of composite coating. According to the morphological features of the Fe-Cr phases and Fe-Ni phases, XRD results and EDS analysis, 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 Ni$_3$Si with carbide dispersed in the Ni matrix, the chemical compositions of fine particles phases indicate that Fe-rich, Cr-rich, a small amounts of C and B elements present in the reticulation should be CrB and carbide [13-15]. The previous work notes that B, as a light element, cannot be detected accurately using the EDS analysis [16].

4. Conclusion
The NiCrBSi composite coatings were successfully fabricated on 1045 steel substrate using ultrafast laser induced method, which showed excellent metallurgical bonding between the coating and the steel substrate. Furthermore, the cracks and pores are eliminated in the homogeneous coating. The NiCrBSi composite layer consists of the coating zone (CZ) and the bonding zone (BZ). Microstructure of coatings shows 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. Moreover, fine particles (such as carbide and boride) precipitate in Fe-Cr reticulation solid solution.

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