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Characterization of microstructure and rolling contact fatigue performance of NiCrBSi/WC–Ni composite coatings prepared by plasma spraying

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ABSTRACT

In this paper, the properties of NiCrBSi/WC–Ni composite coatings deposited by plasma spraying were analyzed, including their microstructure, element distribution, phase composition, porosity, and microhardness. The rolling contact fatigue (RCF) life and failure modes were also investigated. The results showed that the NiCrBSi/WC–Ni composite coating exhibited a typical lamellar structure. Furthermore, evenly distributed W_2C/WC phases were well wetted by other phases. In addition to WC and W_2C phases, the NiCrBSi/WC–Ni composite coating consisted mainly of γ-Ni, Cr_7C_3, $Cr_{23}C_6$, $FeNi_3$, Ni_3Si, CrB, and NiC. The study also found that the NiCrBSi/WC–Ni composite coating (porosity of 1.84%) had a slightly lower density than the NiCrBSi coating (porosity of 1.62%). The microhardness of the NiCrBSi/WC–Ni composite coating was significantly enhanced by the addition of hard WC–Ni. Furthermore, the results indicated that the NiCrBSi/WC–Ni composite coating had a higher dispersion degree of the RCF life and a longer life than the NiCrBSi coating under 0.881 GPa. Therefore, under this stress level, the RCF performance of the NiCrBSi/WC–Ni composite coating was superior to that of the NiCrBSi coating.

1. Introduction

Plasma spraying is an effective surface engineering technology that has been widely applied in various industrial fields [1–5]. Plasma spraying coating can improve the contact fatigue resistance, wear resistance, and corrosion resistance in metal components such as rollers in paper manufacturing, shafts and screws in petrochemical processes, and transmission shafts in construction machinery and cars. In addition, the plasma spraying technology can be applied to a wide range of materials, such as ceramics, pure metals or alloys, and polymeric materials [6–8]. Previous studies have showed that self-fluxing NiCrBSi alloys exhibit a low melting point, good deoxidizing and slagging properties, and great wettability. Based on their excellent processing properties, they are also particularly suited for the plasma spraying technology [9–11]. Theoretically, B is included in the NiCrBSi alloy to shift the alloy closer to the Ni–Ni_3B eutectic composition and reduce the melting temperature of the alloy. In addition, B can form hard phases with Ni, such as Ni_3B, thus improving the hardness of the coating. The addition of Si enhances the self-fluxing properties of the NiCrBSi alloy. Unless a large amount is added, Si will remain in solid solution with Ni. Si also slightly increases the hardness of the alloy. Furthermore, Cr can be added to the alloy to improve its corrosion and wear resistance. The amount of Cr determines the structure of the alloy. If the content of Cr and C is sufficient, hard carbides such as Cr_3C_2, Cr_7C_3, and $Cr_{23}C_6$ can be formed. As the coating formation relies on the rapid solidification of the materials during the plasma spraying process, phase transformations are undoubtedly hindered to some degree, resulting in a unique microstructure. The addition of hard ceramic particles, such as tungsten carbide (WC), in a self-fluxing Ni-based alloy may increase the coating hardness, abrasive wear resistance, and contact fatigue resistance. Compared to other carbides, WC combines favorable properties such as high hardness, plasticity, and a good wettability by molten metals [9]. Therefore, WC is widely used as the hard phase in manufacturing metal composites. Moreover, previous studies have showed that WC can decarburize to W_2C and result in a relatively soft W phase. However, WC-coated Ni can prevent and reduce the decarburization during the plasma spraying process [12–16].

Some studies have been performed on the effects of the addition of WC on the performance of the NiCrBSi alloys. The microstructure of a NiCrBSi/WC composite coating prepared by electric arc spraying technology consisted of NiCr, NiCrW, and WC/W_2C as major phases [9]. In addition, NiCrBSi coatings and NiCrBSi/WC–Ni composite coatings were prepared on stainless steel by laser cladding technology. The results showed that the NiCrBSi/WC–Ni composite coating had a higher wear resistance at high temperature than the NiCrBSi coating, and the difference was attributed to the formation of a hard WC phase after laser cladding [17]. Several types of mixtures of self-fluxing NiCrBSi

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alloy powder and WC–Ni powder (10 wt.% Ni and balance WC) were laser cladded on stainless steel substrates. The study found that most of the clad layer properties, such as its porosity and microhardness, were affected by the percentage of the WC particles present in the mixture. Dense and pore-free layers could be obtained as long as the WC content in the mixture was kept below 50 wt.% [18].

However, the properties of the plasma-sprayed NiCrBSi/WC–Ni composite coatings, such as the microstructure, element distribution, phase composition, porosity, and microhardness, have not been systematically studied yet. Moreover, since the rolling contact fatigue (RCF) failure of the majority of the components originates from the surface or subsurface [19,20], plasma spraying can play an important role in repairing the surfaces of failed parts, thus prolonging their lives [21–23]. Interestingly, the RCF resistance of the NiCrBSi/WC–Ni composite coatings has not been investigated yet. The RCF can be defined as a damage process on the contact surface of the rotating components bearing alternating stress [24]. In this work, we focus on the preparation of a protective NiCrBSi/WC–Ni composite coating on tempered 1045 steel by plasma spraying. The properties of the NiCrBSi/WC–Ni composite coating, including the microstructure, element distribution, phase composition, porosity, and microhardness were analyzed. In addition, the RCF life performance and failure mode were also examined. A NiCrBSi coating was prepared to provide a comparison with the NiCrBSi/WC–Ni composite coating.

2. Experimental procedures

2.1. Preparation of the coatings

A GP-80 plasma spraying system manufactured by Taixing Spraying Corporation of China was used to prepare the NiCrBSi/WC–Ni composite coating and NiAl undercoating. Hydrogen, argon, and nitrogen were used as working gas, protective gas, and feeding gas, respectively. Commercial tempered 1045 steel was used as a substrate. Fig. 1 shows two-dimensional and three-dimensional diagrams of both the coated and RCF-tested specimens. The size of the specimens is shown in Fig. 1(a). The length of the line contact in the RCF test is 6 mm. The red surface area shown in Fig. 1(b) is planed to prepare for the coating. Fig. 2 shows NiCrBSi/WC–Ni composite powders with 15 wt.% WC–Ni as sprayed material. The composition of the NiCrBSi alloy powder is Cr 16, B 7.5, Si 4.7, C 0.9, Fe ≤ 4.5, Ni balance (wt.%), with particles of 40–80 μm size and globular shape, as indicated by the arrow in Fig. 2. The composition of WC–Ni is Ni 5, WC balance (wt.%), with particles of 40–100 μm size and irregular shape, as indicated by the arrow in Fig. 2. A NiAl alloy powder with a composition of Ni 80, Al 20 (wt.%) and particle size of

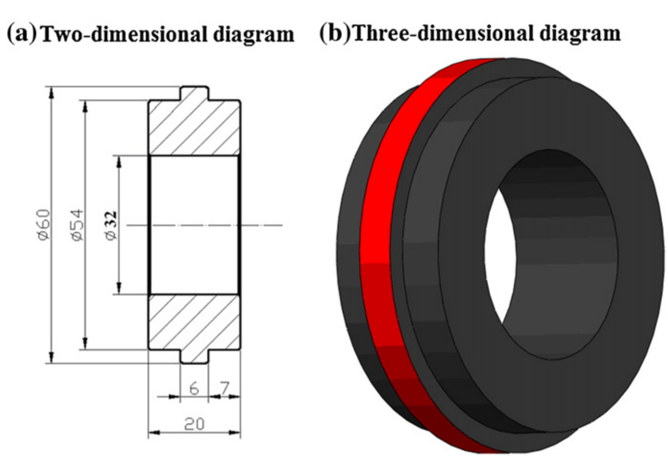

Fig. 1. Diagram of the coated and RCF tested specimens.

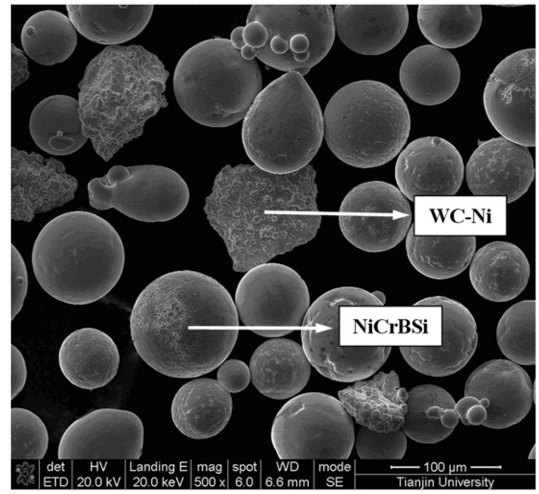

Fig. 2. Morphology of the NiCrBSi/WC–Ni composite powders.

50–100 μm was used as the undercoating material. The bond strength between the coating and the substrate can be significantly increased as a result of the heat generated by the reaction between the melting nickel and aluminum arriving on the substrate. The optimized plasma spraying parameters are listed in Table 1. Fig. 3 illustrates the preparation process of plasma spraying coating. The thicknesses of the NiCrBSi/WC–Ni composite coating and NiAl undercoating were adjusted in the range of 500–600 μm and 200–250 μm, respectively. In addition, a NiCrBSi coating was also prepared to provide a comparison with the NiCrBSi/WC–Ni composite coating. The composition of the NiCrBSi powder was identical to that of NiCrBSi in the NiCrBSi/WC–Ni composite powder. The spraying parameters and the thickness were the same as those of the NiCrBSi/WC–Ni composite.

2.2. Characterization of the coatings

The microstructure and RCF failure morphology were observed by scanning electron microscopy (SEM, Philips Quant 200), while the composition and distribution of the elements were analyzed by energy dispersive spectroscopy (EDS, Philips Quant 200). The phase composition was identified using a D8 X-ray diffractometer (40 kV, 30 mA, Cu Kα radiation, $\lambda_{K\alpha} = 0.154$ nm, 2θ scanning step of 0.03°, scanning in the range of $30° < 2\theta < 100°$). The microhardness distribution along the depth direction of the coating was determined using a HV-1000A Vickers microhardness tester with a load of 0.98 N and dwell time of 5 s. For each hardness profile along the depth direction of the coating, three tests were performed (the spacing of each press mark was less than 50 μm) and the averaged results of the three repeated tests were used in this article. The porosity of the coating was measured by image processing software based on the gray analysis method. Ten cross-sectional micrographs of the coating at 500× magnification

Table 1
Plasma spraying parameters.

Processing parameters	NiCrBSi/WC–Ni	NiAl
Spraying voltage (V)	60	56
Spraying current (A)	500	500
Argon gas flow (L/h)	30	30
Hydrogen gas flow (L/h)	130	140
Nitrogen gas flow (L/min)	6	5
Spraying distance (mm)	90–110	90–110
Coating thickness (μm)	500–600	200–250