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# Influence of loading levels on RCF life and failure mode of Ni-based alloy and WC–Ni ceramic composite coatings

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This paper studied influence of loading levels on rolling contact fatigue (RCF) performance of NiCrBSi/WC–Ni composite coating. The results showed that abrasion, spalling, delamination, and rolling cracking were four kinds of main failure modes related with contact stress. Under relatively high contact stress, intense deformation of NiCrBSi particles resulted in rolling cracking failure. Furthermore, RCF life can be predicted by established lognormal distribution and $\sigma_{max} - N$ model. The study also found that RCF life was closer to expectation $E(N)$, higher failure probability of the coating. And RCF life became more discrete and more difficult to predict as contact stress increased.



## 1. Introduction

Rolling contact fatigue (RCF) can be defined as an accumulative damage process on the material surface and sub-surface bearing long-term and alternating contact stress [1–4]. The RCF can reduce the service life and reliability of some key parts in the transmission system, such as gears, rolling bearings, and camshafts [5–7]. Furthermore, the RCF failure usually can cause disastrous accidents due to its suddenness and unpredictability. Therefore, it is urgently needed to improve the RCF resistance and reliability of the surface materials. Furthermore, the surface modification by depositing high quality materials on the surface of the component is an effective technology, which can improve the RCF resistance and prevent the RCF failure or reduce the damage degree [8–10].

With excellent economic efficiency and good manufacturability, plasma spraying is an effective thermal spaying technology that has been successfully and widely applied in various industrial fields [11–14]. Previous studies have showed that self-fluxing NiCrBSi alloys exhibit a low melting point, good deoxidizing and slagging properties, great wettability, relatively high strength, good toughness, and excellent corrosion resistance. Based on their excellent properties, they have been extensively used in many applications, such as the thermal spraying, flame spraying, laser cladding, and surfacing [15,16]. However, under the relatively high loading conditions, the low hardness and poor wear resistance of the NiCrBSi alloys restrict their extensive application. Lots of studies showed that addition of hard ceramic particles, such as tungsten carbide (WC), in the Ni-based alloys could increase the coating hardness, wear resistance and contact fatigue resistance [17–20]. Furthermore, compared to other carbides, WC particles with favorable properties, such as high hardness, certain plasticity and a good wettability by molten metals, have been widely used as hard phase for manufacturing metal composites [21,22]. Moreover, it is very profitless that WC can decarburize to soft $W_2C$ during the thermal spraying [23–26]. However, WC-coated Ni can prevent and reduce the decarburization during the plasma spraying process.

Some studies have been performed on the microstructure, wear behaviors at room-temperature and high-temperature of the NiCrBSi/WC composite coatings [17–22]. Interestingly, influence of loading conditions on RCF performance of the plasma sprayed NiCrBSi/WC–Ni composite coating has not been systematically studied yet. Therefore, in this work, we focused on investigating evolution regulation of the RCF life and failure mode of the NiCrBSi/WC composite coatings under different contact stress levels. The failure modes and mechanisms of the NiCrBSi/WC–Ni coatings were analyzed under different contact stresses. Furthermore, the RCF lives were evaluated using the lognormal distribution method and $\sigma_{max} - N$ model. This study had a certain significance to evaluate the RCF life and failure mode of the NiCrBSi/WC composite coating in the industrial application.

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## 2. Experimental procedures

### 2.1. Preparation of coatings

A kind of NiCrBSi/WC–Ni composite powders with 15 wt.% WC–Ni were used as sprayed material. The composition of the NiCrBSi powders is Cr 16, B 7.5, Si 4.7, C 0.9, Fe $\leqslant$ 4.5, Ni-balance (wt.%), with smooth particles of 40–80 μm size and globular shape, as indicated by the arrow in Fig. 1(a). The composition of WC–Ni is Ni 5, WC balance (wt%), with relatively rough particles of 40–100 μm size and irregular shape, as indicated by the arrow in Fig. 1(a). A NiAl alloy powder with a composition of Ni 80, Al 20 (wt.%) and particle size of 50–100 μm was used as the undercoating material, as shown in Fig. 1(b). The tempering 1045 steel was used as a substrate. Fig. 2(a) shows the size of both the sprayed specimen and the RCF-tested specimen. The length of the line contact in the RCF test is 6 mm. The red surface area shown in Fig. 2(a) is planed to prepare for the coating.

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. For the NiAl alloy powders, the flow rates of argon, hydrogen and nitrogen were controlled at 30 L/h, 140 L/h, and 5 L/h, respectively. The spraying voltage and current were, respectively, 56 V and 500 A. Furthermore, for the NiCrBSi/WC–Ni composite powders, the flow rates of argon, hydrogen and nitrogen were, respectively, 30 L/h, 130 L/h, and 6 L/h. The spraying voltage and current were, respectively, 60 V and 500 A. Prior to the spraying process, in order to reduce contaminations and form a rough surface for enhancing the bond strength, the substrate surface was cleaned in acetone solution and sandblasted using the corundum powders. And the substrates were preheated to 100–200 °C in order to reduce the heat stress. The substrate specimens were first assembled on a rotation axis, and then were fixed in a rotating platform by a clamping fixture, and setting rotating speed of 4 rpm. The plasma spraying gun was assembled to an automatic control device, and perpendicular to the rotation axis. The automatic control device was controlled and reciprocated at a moving speed of constant 12 mm/s by setting the program. The substrate specimens were cooled by cooling gas during the plasma spraying.

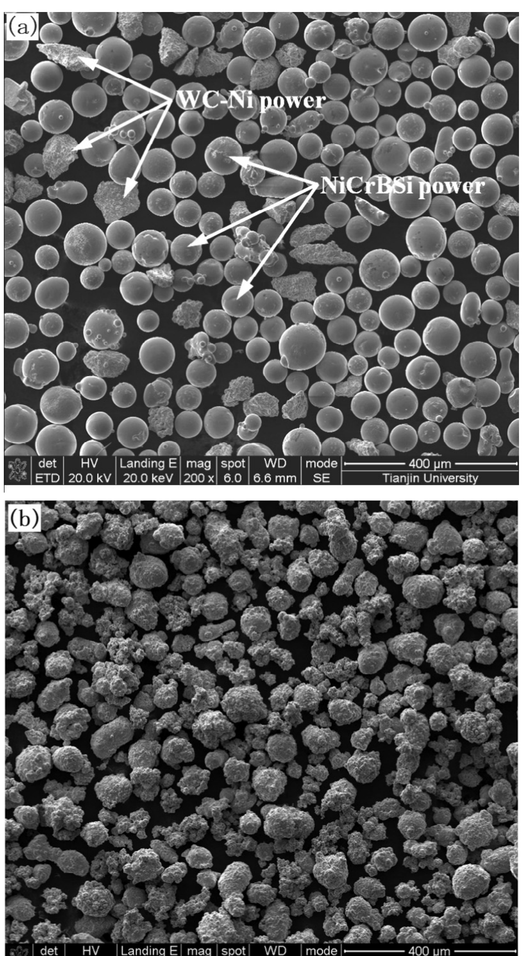


**Fig. 1.** Morphology of spraying powders: (a) NiCrBSi/WC–Ni composite powders; and (b) NiAl alloy powders.

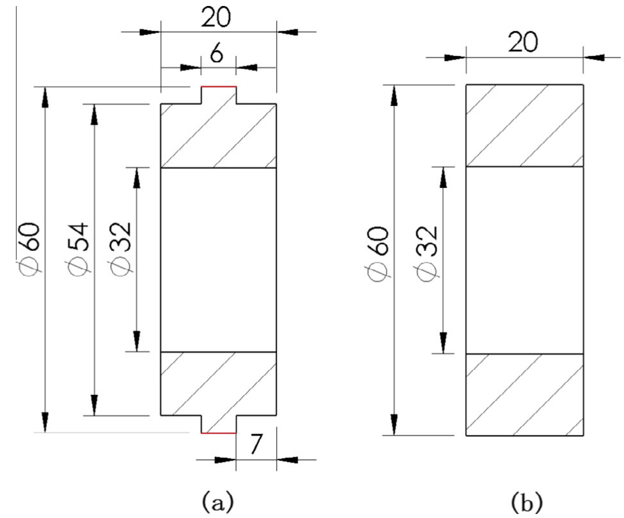


**Fig. 2.** The geometry sizes of the RCF specimens: (a) the tested roller with coating; and (b) the paired contact roller.

### 2.2. Characterization of the coatings

The microhardness of the NiCrBSi/WC–Ni composite coating was measured using a HV-1000A Vickers microhardness tester, at 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 microstructure and the RCF failure morphology of the coating were observed by scanning electron microscopy (SEM, Philips Quant 200). 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 were randomly collected by SEM, and an average value was calculated from the ten different porosity test results.

### 2.3. The RCF test

The RCF performance of the NiCrBSi/WC–Ni composite coatings was evaluated using a double-roller test-rig [27]. A tested roller with the coating and a paired contact roller were fixed on the rotation axis by a clamp, and were driven by two servo motors, respectively. The type of rolling contact is a line contact. The paired contact roller was machined by AISI 52100 steel with a surface roughness of 0.012 μm and a Rockwell hardness of 62-65 HRC. In addition, the thickness, external diameter, and internal diameter of the paired contact roller were kept to 20 mm, 60 mm, and 32 mm, respectively, as illustrated in Fig. 2(b). The rotation speed