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Investigation of competing failure mechanism and life of plasma sprayed Fe-based alloy coating under rolling–sliding contact condition

Shu-ying Chen [a], Guo-zheng Ma [a], Hai-dou Wang [a,*], Jia-jie Kang [b], Bin-shi Xu [a], Hai-jun Wang [a], Ming Liu [a]

[a] National Key Lab for Remanufacturing, Academy of Armored Forces Engineering, Beijing 100072, China
[b] School of Engineering and Technology, China University of Geosciences, Beijing 100083, China

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ABSTRACT

The paper aims at the investigation of the effect of slip ratio on the rolling contact fatigue (RCF) performance of Fe-based alloy coatings. A double-roll test machine is employed to perform the experiment. The result shows that slip ratio has a significant influence on the RCF performance of Fe-based coating. With the increment of the slip ratio, the RCF failure life keeps decreasing but the shape parameter β of Weibull mode decreases first, then increases. The failure mechanism under pure rolling contact condition is the accumulation of micro-pits and the propagation of fatigue cracks within the coating. However, under nonzero slip ratio condition, failure is controlled by the coupling of the cyclic loading action and of the friction force.

1. Introduction

Thermal spraying technology as an important approach for surface modification of materials, which was rapidly developed in the last few decades, has now been successfully applied to many industrial fields [1–3]. Various kinds of coating systems enable the use of this technology to improve the performance of components to resist corrosion, wear, high temperature etc. according to different needs. In addition, the technology is often employed to repair parts suffering from surface damage, such as abrasion, due to its characteristics of convenience and high-efficiency. Rolling contact fatigue (RCF), which is often recognized as a cause for the initiation and propagation of cracks within the material, is an extremely common failure mode of rotating components such as gears, shafts, rollers, etc. [4,5]. In order to enlarge the application of thermal spray coatings to repair damaged parts, it is of great significance to obtain a detailed understanding of RCF failure mechanism of thermal spraying coatings.

In general, the factors which affect the RCF property of coatings can be divided into two classes: first, the internal causes decided by the structure integrity of the coating, including material properties, micro-defects, adhesion strength, micro-hardness, surface roughness, etc.; secondly, the external causes, which are also defined as service conditions, such as lubrication state, contact stress, rotating speed, contact form (point contact/line contact), and so on [6]. The former focuses on the selection of the material and optimization of the coating, while the latter aims at evaluating the performance of the coating under different working conditions. Many remarkable laws of RCF failure performance have been obtained by different researchers in the last few decades [7–12].

Fe-based alloy coatings are widely used categories of thermal spray coatings due to their high hardness, good wear resistance, and low cost. Piao et al. have conducted different experiments to comprehensively study the effects of underlying bond coatings, of surface nitriding and of surface roughness to the RCF property of Fe-based alloy coatings [13–15]. As is known, except the external factors mentioned above, rotating components may experience acceleration, deceleration, braking, etc. during rolling contact service process, leading to a rolling/sliding contact state, which has great impacts on the RCF performance of coatings [16]. Nevertheless, few researches about the detailed mechanism influencing the RCF life of Fe-based alloy coatings can be seen in the published literature. In the paper, the RCF failure mechanism and lives of Fe-based alloy coatings under different slip ratios were investigated at length.

2. Experimental procedures

2.1. Preparation of coatings

The chemical composition of the spraying particles prepared by the water atomization method was Cr-13.6, B-1.6, Si-1.1, C-0.16 and Fe-balance (wt%). The function of element chromium was to enhance the wear resistance and corrosion resistance, while the

* Corresponding author. Tel.: +86 10 66718475; fax: +86 10 66717144.
E-mail address: wanghaidou@aliyun.com.cn (H.-d. Wang).

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role of silicon and boron was to protect the powders from oxidation. The Ni/Al alloy coating was selected as the bonding coating to reinforce the adhesion strength of Fe-based coating to its substrate. The particle size distribution of the Fe-based alloy powder and Ni/Al powder is 40–65 μm and 25–45 μm, respectively. Both of the powders are provided by Tian Zhujing Technology Develop Corporation (China).

The highly efficient supersonic plasma spray equipment invented by national key laboratory for remanufacturing (HEPJet-II, China) was employed to fabricate the coating. The detailed information and schematic of the novel SPS gun can be found in the published literature [17,18]. The spray parameters are shown in Table 1. A Ni/Al alloy coating was prepared as bond coating. Ar was used as the primary gas, which was easy to ionize and played the role of keeping stability of the plasma arc. H_2 and N_2 were selected as the secondary gases for the Fe-based alloy powder and the Ni/Al alloy powder respectively. Compared with N_2 gas, the ionization energy of H_2 was higher, which means it could provide more heat. Nevertheless, N_2 was cheaper and safer than H_2. Therefore, N_2 could be used as secondary gas when high temperature was not demanded to spray the particles. The reaction between Al and Ni during the spraying process could keep releasing heat which ensured diffusion at the interface and the formation of a metallurgical bonding between the Ni/Al layer and the substrate. Besides, the reduction of the residual stress caused by the sudden cooling of the melted particles when impacting onto the substrate and the solidified coating, the decrease of the mismatch between the elastic modulus of the substrate and that of the Fe-based layer, the better wettability of the Ni/Al particles was also among the reasons for the enhancement of the adhesion strength of the coating system [19]. Prior to spraying, acetone solution was utilized to clean the surface of the substrate, which was then blasted to an average surface roughness of R_a=4.6 μm. After that, the substrate was preheated to about 120 °C by the plasma spray flow.

Fig. 1 shows the schematic of the preparation process of Fe-based alloy coating. A specialized fixture was used to fix the test rollers to the turntable assembled in the permanent seat. Dried air with high velocity is utilized to control the temperature of the coatings. During the spraying process, the turntable rotated with a rotational speed of ω rad/s, while the spraying gun did a reciprocating motion at the velocity of v m/s. In order to obtain coatings with homogeneous thickness and prevent the substrate from being overheated, which could decrease the adhesion strength of the coating system, the rotational speed (ω) and moving velocity (v) should submit to the experimental formulation:

$$4\pi/\omega=(L+2r)/v \quad (1)$$

where L was the width of material bead deposited by a single torch pass, and r the radius of the plasma spray jet footprint at the substrate location. The actual values of v, ω, L and r were 0.84 m/min, 140 rpm, 5 mm and 0.35 mm, respectively.

Table 1
Supersonic plasma spraying parameter.

Parameter	FeCrBSi	Ni/Al
Flow of Ar gas/(m^3/h)	3.5	3.0
Flow of H_2 gas/(m^3/h)	0.4	–
Flow of N_2 gas/(m^3/h)	–	0.9
Powder feed rate/(g/min)	40	40
Standoff distance/mm	100	130
Spraying current/A	380	360
Spraying voltage/V	165	150

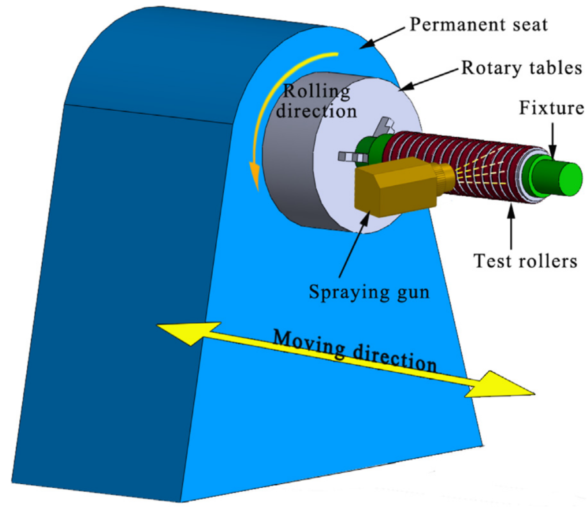

Fig. 1. Preparation process of Fe-based alloy coating.

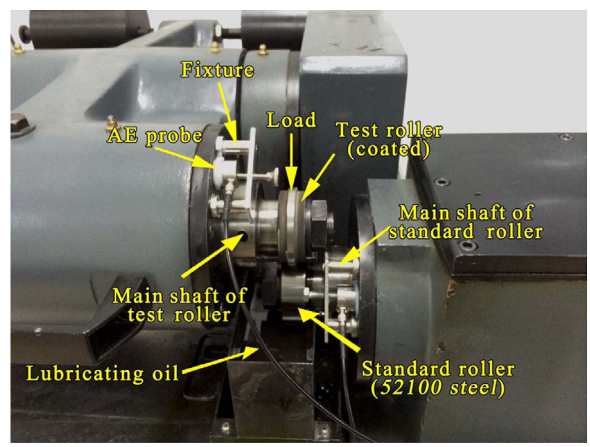

Fig. 2. Schema of two-roller test machine.

2.2. The RCF test system

A double roller test machine (shown in Fig. 2) was employed to perform the experiment. The test roller and the standard roller were fixed on the main shaft controlled by two independent servo motors, so that the rotating speed could be commanded accurately. The slip ratio is defined as the ratio of the rotational speed difference between standard roller and test roller to the rotational speed of the standard roller. The loading behavior was realized by a hydraulic control system. The friction coefficient and oil temperature were monitored by a torque sensor and a temperature sensor respectively. The lubricant is simply dragged by the standard roller dipping into an oil tank and is changed after each test. The whole failure process of Fe-based coating was monitored by an acoustic emission (AE) probe because of its sensitivity to brittle fracture and plastic deformation of metals. The test machine would ceased automatically when the AE count was higher than 350. The detailed information of the machine can be seen in published literature [18]. During the experiment, the normal load was 1146 N. The rotational speed of the counter-body was kept at a constant value of 600 rpm, while the rotational speed of the coated disk was 600, 450, 300 and 150 rpm when the slip ratios were 0, 25%, 50% and 75%, respectively.

Fig. 3 shows the configuration of test roller and standard roller, which were made of tempered AISI 1045 steel and AISI 52100