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Study on erosion–wear behavior and mechanism of plasma-sprayed alumina-based coatings by a novel slurry injection method

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ABSTRACT

In this paper, Al_2O_3–Cr_2O_3 composite coating was fabricated by plasma spraying. It has better mechanical performances than Al_2O_3 coating. Erosion–wear resistance of the coatings was evaluated by a new type of solid particle impact test (slurry jet). Slurry was mixed with compressed air in the nozzle and eventually injected on coating surface at high velocity. Injected slurry on coating surface resulted in a wear progression (wear rate) proportionately to the erosion strength of the coating material. Al_2O_3–Cr_2O_3 composite coating possesses better erosion–wear resistance than pure Al_2O_3 coating.

1. Introduction

Oxide ceramics exhibit high strength, high hardness and anti-wear performance, as well as high temperature and good oxidation resistances [1–3]. The corresponding coatings manifest excellent potential to be employed for special surface protection of metal components operating at severe working conditions [4,5]. Atmospheric plasma spraying is the most flexible or versatile thermal spray technique, which enables deposition of many ceramic materials such as alumina, chromia, titania, zirconia and related mixture [6]. As their quintessential representative, alumina coatings are good candidates for anti-wear and anti-corrosion applications, due to their high hardness, chemical inertness and high melting point, as well as to their great resistance to abrasion and erosion [7,8]. Al_2O_3 coatings are able to retain up to 90% of their strength at 1100 °C [9]. With respect to oxide ceramics, low toughness restricts their practical applications [10]. It is difficult to combine conventional toughening methods with plasma spraying technology. These traditional toughness improvement means contain particle toughening [11], fiber toughening [12], transformation toughening [13] and gradient structure toughening [14]. Strengthening and toughening from grain refinement or solid solution are beneficial to the enhancement of the strength and toughness of the ceramic coatings. The addition of TiO_2 (3, 13 and 40 wt%) allows to increase coating toughness and resistance to wear and erosion [15,16]. However, the corresponding coatings are accompanied by the decrease of hardness and high-temperature stability, which are essential for tribological and high temperature erosion applications. Al_2O_3–ZrO_2 composite coatings possess good fracture toughness and poor thermal conductivity [17]. Cr_2O_3 and α-Al_2O_3 enjoy the same crystalline structure. Cr^{3+} and Al^{3+} have the approximate ionic radiuses. Accordingly, Al_2O_3–Cr_2O_3 solid solutions are easily formed. In our previous studies [18–20], Al_2O_3–Cr_2O_3 composite coatings were fabricated by plasma spraying. The phase compositions, microstructures, mechanical and thermal properties of the coatings were investigated. The sliding wear performances of the coatings were also evaluated under the severe condition. The obtained results suggest that Al_2O_3–Cr_2O_3 composite coatings have better mechanical, thermal and anti-wear properties than Al_2O_3 coating.

It can be observed that the tribological behavior of the coatings in sliding wear situation is dominated by the formation of a surface tribofilm and by its progressive change, which would have significant effects on the accumulation of wear debris [21]. However, the failure mode of erosive wear is exceedingly different from that of sliding wear. Erosion wear of materials occurs by the removal of target material from the impact zone, owing to repeated impacts of the erodent, by a micromechanical deformation/fracture process. Several related wear mechanisms are largely controlled by the particle material, the particle size, the impact velocity, the impact frequency per unit area, and the angle of impingement [22]. The

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properties (material and size) of the eroding particle are regarded as relevant parameters for this type of wear process. Higher angle of impingement causes greater impact. The speed of the particle brings an extremely strong effect on the erosive wear. Solid particles are transported by compressed air or high speed liquid. Additionally, there are differences between erosive wear behaviors of bulk materials and coatings. Hard coatings have been considered to be especially useful in applications standing up to erosive and abrasive wear. Ceramic or cermet coatings are suitable for the application of water turbine blade and sluice gate roller, which requires excellent anti-erosion performance of the workpiece surface. With respect to atmospheric plasma spraying, the coatings are made up of flattened particles, known as splats. The splats constitute layers in the coating and these layers in turn create the lamellar structure of the deposit. Simultaneously, the coating structure always contains unmelted particle, porosity, oxidized particle and microcrack. The erosive wear behaviors of coating are not fully understood.

The current study investigated the erosion wear behavior of plasma sprayed alumina-based coatings by a new type of solid particle impact test (slurry jet). Combined with the phase composition, microstructure and mechanical performance of the coatings, the erosive wear mechanisms were elucidated.

2. Experimental procedure

2.1. Coating preparation

The Multicoat atmospheric plasma spraying system equipped with a F4-MB plasma gun (Sulzer Metco AG, Switzerland) was applied to produce coatings. Commercially fused and crushed Al_2O_3 and Cr_2O_3 powders were used as feedstock. The median particle sizes are 17.5 μm and 16.7 μm. The corresponding particle size distributions can be obtained in Ref. [18]. According to a certain mass ratio, the starting Al_2O_3 and Cr_2O_3 powders were directly mixed in the roller with its rotation speed of 150 rpm. Mechanical mixing time was 120 h. Prior to spraying, the stainless steel substrates were degreased ultrasonically in acetone and then grit blasted with corundum to the roughness (Ra) of 6–8 μm. Moreover, NiCr powder was applied to fabricate bond coating prior to spraying ceramic coatings. According to our previous investigations [18], AC_{70} composite ceramic coating possesses better comprehensive mechanical properties. The addition of Cr_2O_3 is beneficial to the stabilization of α-Al_2O_3. With increasing the content of Cr_2O_3 in the original composite powders, the resulting composite coatings possess lower porosity, higher hardness, larger bending strength and better thermal conduction performance. Simultaneously, AC_{70} composite coating possesses the maximum of the bending strength. Consequently, the Cr_2O_3 weight fraction in mechanically mixed composite powder used in this study was 70 wt%. The plasma spraying parameters for NiCr bond coating and top ceramic coating are displayed in Table 1. In order to obtain great coating performance, spray parameters need good matching relationships. Namely, these parameters possess mutual restrictions. Therefore, each parameter has a certain range of variations in the value. Due to mechanically mixed method and feedstock particle size, solid solution only exists in the contact surfaces of molten Al_2O_3 and Cr_2O_3 droplets. This would strengthen phase interface and decrease porosity in the coatings. Additionally, Al_2O_3 and Cr_2O_3 droplets could not be totally mixed in plasma spraying procedure. Mechanical mixing takes 120 h, which ensures distribution homogeneity of the composite powder. Heterogeneous nucleation and partial solid solution are obtained in the composite structure [19].

Table 1
The plasma spraying parameters for NiCr bond coating and top ceramic coating.

Parameters	NiCr bond coating	Top ceramic coating
Arc current (A)	590–610	640–650
Primary plasma gas (Ar) (slpm)	55–60	40–50
Secondary plasma gas (H_2) (slpm)	6–8	6–8
Carrier gas (Ar) (slpm)	3.0–4.0	3.0–4.0
Powder feed rate (g min^{-1})	15–20	30–40
Spray distance (mm)	110–120	100–110

2.2. Coating characterization

The phase compositions of as-sprayed coatings were identified by X-ray diffraction (XRD) using a Rigaku D/Max2550 Diffractometer with nickel-filtered Cu Kα radiation (λ=0.15406 nm). The XRD measurements were executed in the 2θ range from 20° to 80° at a scanning speed of 4° min^{-1} (the corresponding peak integral intensity calculation was corrected accounting for structure factors, peak multiplicities, and unit cell volumes). The cross-sectional morphologies of the coatings were observed by a Hitachi TM3000 scanning electron microscope. Vickers microhardness measurements were carried out on the polished cross-sections of the coatings using an Instron Wilson-Wolpert Tukon 2100B Hardness Tester under the load of 200 gf with a dwell time of 10 s. The coating microhardness represented the average of 10 indentations. The fracture toughness and bending strength of the coatings were measured with a universal testing machine (Model Instron-5566, Canton, USA) at room temperature and averaged over the values for five specimens. The detailed thick coating preparation and mechanical property test methods could be obtained in Ref. [18].

2.3. Erosion–wear testing

The erosion wear performances of the coatings were evaluated by a new type of slurry jet test. Slurry (water and solid particle mixture) was mixed with compress air in the nozzle and eventually injected on coating surface at high velocity. Injected slurry on the coating surface resulted in a wear progression (wear rate) proportionately to the erosion strength of the coating. It is a new type of solid particle impact test (slurry jet) to swiftly estimate wear properties of the hard coatings. The slurry jet tester (MSE TESTER S201, Palmeso Company, Japan) was used to perform the erosion wear tests, which possess four notable features (shown in Fig. 1). These characteristics are: ① about 1 μm in diameter and hold 10–50 nm of wear depth per solid particle; ② accurate control of slurry injection pressure and flow rate; ③ wear progression by solid particle collusion with up to 100 m/s in velocity using compress air; ④ high velocity wear progression by some hundred million of solid particle impact per second. Compared to other erosive wear systems, the originalities of the test study are: (a) nanoparticles are used to effectively increase impact frequency and injection energy concentration degree; (b) the impact velocity is higher; (c) slurry injection pressure and feed rate could be accurately controlled; (d) the dimension of predefined wear scar is about 1 mm × 1 mm, which indicates better erosion area controllability than other erosive wear systems. Therefore, the obtained performance evaluation results of the coatings would be more reliable. The dimension of test specimen (stainless steel substrate) was Φ28 mm × 6 mm. In this study, stainless steel substrates were used for better comparison test (in our previous investigations, stainless steel substrates were applied [20]). The test conditions are presented in Table 2. The measurement steps were as following aspects: firstly, slurry was injected on predefined coating specimen surface; secondly, shape measurement was conducted along the center of wear scar of A–A′