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Effect of critical plasma spraying parameter on microstructure and wear behavior of mullite coatings

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ABSTRACT

Mullite coatings were fabricated by atmosphere plasma spraying (APS) at varying primary gas flow rates. The flattening behavior of deposited particles as well as microstructure, mechanical properties of mullite coatings were studied in relation to the critical plasma spraying parameter (CPSP). Moreover, the dry sliding friction and wear behavior of mullite coatings was also evaluated. Results show that at a primary gas flow rate of 40 L/min (referring to a CPSP of 562.5), the spraying powders exhibit high melting degree, spreading degree and deposition efficiency. More importantly, the resultant mullite coating has the best mechanical and tribological properties.

1. Introduction

Ceramics are of significance in a variety of applications, because they usually possess excellent wear/corrosion/thermal resistance [1–5], and their performance and application fields can be further enhanced and expanded with the assistance of an advanced new processing technique [6]. For example, mullite ($3Al_2O_3 \cdot 2SiO_2$) ceramic with excellent thermostability and chemical inertness has been widely used as candidate of thermal/environmental barrier coatings (TBC/EBCs) to prevent the hot parts in gas turbine engines from hot corrosion and high temperature oxidation, with the rapid development of surface engineering technology such as plasma spraying (PS) and electron beam physical vapor deposition (EB-PVD) [7–11]. Of various processing techniques for preparing mullite coatings, atmospheric plasma spraying (APS) technology is very attractive and powerful, because its low economic cost, high deposition efficiency and good adaptability to workpiece dimension [12–14]. More importantly, the special lamellar structure of APS ceramic coatings with some pores can effectively decrease the thermal conductivity [15–17]. Previous studies indicate that, under certain carrier gas flow rate, powder feed rate, spraying distance, and traverse speed of plasma gun, the structure and performance of plasma-sprayed ceramic coatings are mainly determined by the critical plasma spray parameter (abridged as CPSP), namely the input power (in W) divided by the primary gas flow rate (in L/min) [18–21].

Due to the particulate nature of the exhaust, especially when gas turbine engines serves in the dusty environment like desert region [22–24], these TBC/EBCs often experience severe wear. Therefore, high mechanical strength, load-bearing capacity and wear resistance should be provided for these protective coatings, following thermostability, chemical stability and low thermal conductivity [25,26]. Unfortunately, few publications are currently available about the wear behavior of mullite coatings. Moreover, although it has been found that the performance of APS ceramic coatings is strongly dependent on flattening behavior of the deposited particles [27–29], which are closely related to spraying parameters, the relationship between flattening behavior of mullite particles and microstructure of mullite coatings is not well understood, not to mention that less insight is currently available about the correlation between the critical plasma spray parameter and tribological properties of mullite coatings.

Our previous study showed that the input power mainly influenced the glass phase content in APS mullite coating, and the coating deposited at a spraying power of 22.5 kW had a highest content of crystalline mullite and no obvious cracks, which was considered to have high thermostability and be hopeful to be applied in high temperature protection [30]. On this basis, in the present research a series of mullite coatings are prepared at various primary gas flow rates under fixed input power of 22.5 kW. The influence of CPSP on the flattening behavior of spraying mullite powders as well as the microhardness, the origin of porosity, adhesion strength, microstructure and wear resistance of as-sprayed mullite coatings are studied in detail. The wear mechanism of the mullite coatings is also discussed in relation to its microstructure, mechanical properties and worn-surface.

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2. Experimental procedures

2.1. Feedstock powder

Mullite ceramic and 1Cr18Ni9Ti stainless steel substrate have much different coefficient of thermal expansion ($5.6\times10^{-6}\,K^{-1}$ and $20\times10^{-6}\,K^{-1}$) [31,32], which means that there should exist a large thermal stress at the mullite coating-steel substrate interface thereby reducing the adhesion strength of the as-sprayed mullite coating to the steel substrate. To overcome this drawback, in the present study we introduce a bond coating of NiCrAlY (its coefficient of thermal expansion is about $13.3\times10^{-6}\,K^{-1}$ [33]; and as-received NiCrAlY powder (trademark of AMDRY 9625, Sulzer Metco), has a particle size range of 40–75 μm) deposited on the steel substrate by APS before the mullite coating is prepared. This bond coating, with the ability to accommodate the thermal dissimilarity between the mullite coating and the steel substrate, is capable of improving the microstructure of the ceramic coating. The thickness of the NiCrAlY bond coating was controlled to be about 50 μm. The mullite feedstock for plasma spraying is a kind of agglomerated powder with an average size of 18 μm and size distribution range of 1–70 μm, whose preparation processing is available in reference [30]. The SEM micrographs of the NiCrAlY powders and mullite feedstock powders are shown in Fig. 1, from which the two kinds of powders are seen to exhibit good sphericity.

2.2. Coating deposition

The 1Cr18Ni9Ti stainless steel substrates with dimensions of ϕ 24 mm × 7.7 mm and ϕ 25 mm × 40 mm were used for mullite coating depositions, and the mullite coatings deposited on the steel substrate with the dimension of ϕ 25 mm × 40 mm were used for the measurement of adhesion strength. Prior to the coating deposition, the steel substrates were sand blasted by silica with a grit size of 80–120 μm to increase its surface roughness ($Ra=2.00\pm0.26$ μm), followed by ultrasonically cleaning with acetone and drying in ambient air.

An APS-2000 plasma spraying system (Institute of Aeronautical Manufacturing Technology, Beijing, China) was performed to prepare the mullite coatings. Ar and H_2 gas were used as the primary and secondary plasma gases, respectively. Considering that the primary gas flow rate directly determines the enthalpy and velocity of the sprayed powders thereby greatly influencing the structure and properties of the as-sprayed coatings, we prepared mullite coatings at pre-set primary gas (Ar) flow rates of 35 L/min, 40 L/min and 45 L/min under fixed input power of 22.5 kW; and relevant mullite coatings are denoted as coating 1, coating 2, and coating 3. The spraying parameters for preparing the NiCrAlY bond coating is determined based on comprehensive consideration of the melting degree of the feedstock powders (many partially molten powders can result in large porosity and low bonding strength), oxidized degree of the feedstock powders and magnitude of thermal stress in the coating (seriously oxidized degree and large thermal stress can induce low bonding strength). In addition to the melting degree of feedstock powders and thermal stress in the coating, amount of amorphous phase that can compromise the toughness and thermostability of coating is a more important factor for selecting spraying parameters for mullite coatings [30]. The optimum spraying parameters for preparing the NiCrAlY bond coating and the spraying parameters for preparing mullite coatings are listed in Table 1. The surface roughness of bond coating, coating 1, coating 2 and coating 3 is 9.73 ± 1.41 μm, 9.60 ± 1.14 μm, 8.49 ± 0.80 μm and 9.29 ± 1.35 μm, respectively. Moreover, the mullite splats are collected on the polished surface of 1Cr18Ni9Ti stainless steel substrate at the three primary gas flow rates to better understand the influence of different spraying parameters on the flattening behavior of spraying powders as well as the microstructure and properties of relevant coatings.

2.3. Friction and wear test of mullite coatings

As-sprayed mullite coatings were successively ground on silicon carbide abrasive papers with meshes of 320, 600, 800, 1000, 1200, 1500, and 2000, followed by polishing with diamond paste and ultrasonically cleaning with acetone. Sliding wear tests of the plasma sprayed mullite coatings were conducted with a friction and wear test (CSM, Switzerland) in a ball-on-disk contact configuration at room temperature (about 25 °C). The polished coatings were fixed as specimens, while Si_3N_4 balls with a diameter of 6 mm were selected as the upper counterparts. Sliding wear tests were conducted at an amplitude of 2.5 mm, a frequency of 7 Hz, a normal load of 5 N, and a sliding distance of 200 m. The friction coefficients of the sliding pairs were recorded by the attached computer. After the sliding friction and wear tests were

Table 1
Plasma spraying parameters.

Items	Values			
	Coating 1	Coating 2	Coating 3	Bond coating
Primary gas (Ar) flow rate (L/min)	35	40	45	40
Secondary gas (H_2) flow rate (L/min)	0.5	0.2	0.1	0.8
Current (A)	450			600
Voltage (V)	50			60
Powder gas flow rate (L/min)	8			10
Powder feed rate (rpm)	30			30
Spray distance (mm)	100			120
Injector angle (deg)	90			90
Gun speed (m/s)	0.6			0.8

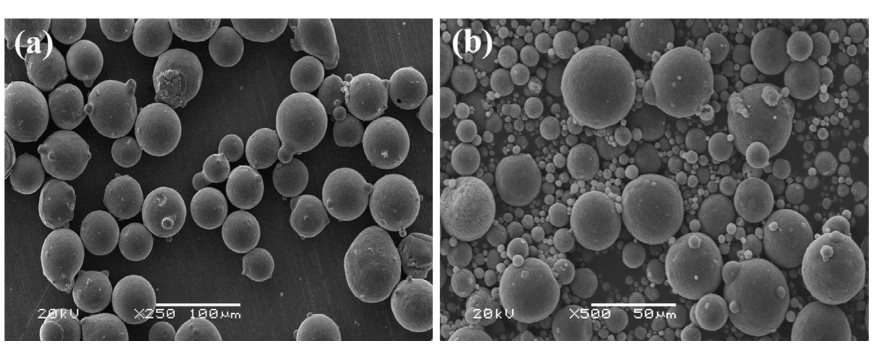

Fig. 1. SEM micrographs of feedstock powders: (a) NiCrAlY powder and (b) mullite powder.