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Preparation of plasma sprayed mullite coating on stainless steel substrate and investigation of its environmental dependence of friction and wear behavior

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ABSTRACT

Spray-dried mullite powder was plasma sprayed onto steel substrates to form mullite coating. The microstructure of mullite coating and its tribological properties coupled with Si_3N_4 ball under dry sliding as well as water and hydrochloric acid solution were investigated. Results indicate that mullite coating exhibits high porosity and retains an amorphous phase. The mullite coating-Si_3N_4 exhibits greatly reduced coefficient of friction under HCl solution, due to the boundary lubrication of the hydrated silica layer and the hydrodynamic lubrication of the acid solution. Moreover, since the wedging action of water, the mullite coating has the highest specific wear rate under water environment.

1. Introduction

Because of its high temperature and low pressure formation conditions, mullite occurs only rarely in nature. Regardless of its rare occurrence in nature, mullite is definitely one of the most important ceramics either as conventional ceramics or as advanced structural and functional ceramics [1]. With outstanding physical and chemical properties, such as low thermal expansion, low thermal conductivity, high temperature and creep resistance and excellent stability under harsh chemical environment, mullite and mullite-based ceramics have been highly focused on recently [2–4].

Previous work about mullite-based ceramics mainly concentrates on their applications as high temperature thermal insulation materials [3,5,6]. Meanwhile, thanks to its excellent mechanical properties and chemical stability under harsh environment, mullite exhibits promising potential as a candidate wear-resistant material. However, few literatures are currently available about the tribological behavior of mullite coatings subjected to wear damage and corrosion attack which result in reduced service life time. Actually, as a joint result of wear and corrosion attack, not only the physical chemistry of friction material but also its surface topography can affect the friction and wear behavior. Gao et al. [7] illustrated that the pitted wear track caused in the combined effect of wear and corrosion is conducive to forming hydrodynamic film thereby exerting improved lubrication performance. Lebeck et al. [8] stated that the surface roughness and waviness would be contributive to causing a hydrodynamic lubrication. Scaraggi et al. [9] reported that a regular array of micro-holes is favorable for the reduction of friction while parallel micro-grooves cause an increase of friction.

Bearing the above perspective in mind, in the present research we pay special attention to the fabrication of mullite coatings on 316 L stainless steel substrate by atmospheric plasma spray (denoted as APS) as well as the structural characterization and tribological behavior evaluation of the coatings. APS is now adopted, because the plasma core temperature (up to 15000 K) significantly exceeds the melting point of any known materials; consequently, wide varieties of materials can be used to produce coatings [10–12]. Moreover, APS is a cost-effective technique for the fabrication of thick coatings on many materials. This paper reports the preparation of mullite coatings by plasma spraying of spray-dried mullite powder and the characterization of microstructure of the as-prepared mullite coatings. Particularly, the friction and wear behavior of mullite coatings sliding against Si_3N_4 balls under water environment and acid solution is highlighted with the hope to

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provide guidance to the application of mullite coatings as wear-resistant material in harsh environments.

2. Experimental

2.1. Preparation of mullite coating

Mullite coatings were deposited on 316 L stainless steel substrates (Φ24 mm × 7.8 mm) with an APS-2000 A system (Institute of Aeronautical Manufacturing Technology, Beijing, China). The chemical composition of 316 L stainless steel is shown in Table 1. The mullite feedstock powder was prepared by spray-drying under optimized parameters reported elsewhere [13]. Before spraying, the stainless steel substrate was sand-blasted with silica powder and cleaned with acetone in an ultrasonic bath to roughen the surface and ensure good adhesion between the coating and substrate. No air cooling of the substrate was adopted during plasma spraying, and a thin Ni–22Cr–10Al–1.0Y bond coating (about 80 μm) was fabricated on the steel substrate before the deposition of mullite coating in order to reduce the residual thermal stress between substrate and ceramic coating [13]. The APS parameters selected in the present work are shown in Table 2.

Table 1
Chemical composition of stainless steel 316 L in wt%.

Element	C	Si	Mn	Cu	Cr	Mo	Ni	Fe
Wt%	0.03	0.44	1.24	0.86	18.48	1.75	11.96	Balance

Table 2
Atmospheric plasma spraying parameters.

Items	Mullite coating	NiCrAlY coating
Arc current (A)	450	550
Voltage (V)	50	50
Argon gas flow rate (L/min)	40	40
Hydrogen gas flow rate (L/min)	10	15
Powder gas flow rate (L/min)	8	10
Spray distance (mm)	90	120
Spray angle (°)	90	90
Gun speed (m/s)	0.2	0.3

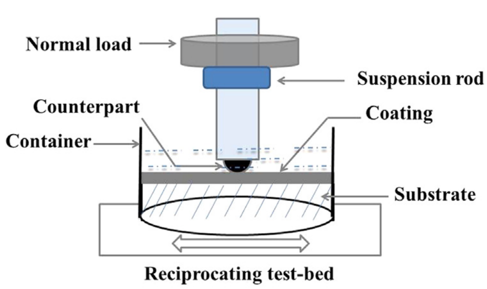

Fig. 1. Schematic diagram of the reciprocating ball-on-disc tester.

2.2. Characterization of feedstock powder and as-prepared mullite coating

Particle size distribution of the spray-dried powders was determined by using a Malvern 3000 laser diffraction analyzer (Malvern, UK). X-ray diffraction (XRD; Philips, Netherlands, Cu Kα radiation) analysis was conducted to determine the phase composition of mullite feedstock and coatings. The morphologies of the powders as well as the microstructure of the as-prepared mullite coatings and their worn surface morphology were analyzed with a scanning electron microscope (SEM; JEOL Corporation, Japan, equipped with an energy dispersive spectrometer (EDS)). The porosity of the mullite coatings was calculated by processing their cross-sectional SEM images with OLYCIA m3 image analysis software (Reco, China). An X-ray photoelectron spectroscope (XPS; PHI-5702, Al Kα X-ray source) was performed to detect the chemical composition of the worn surfaces of Si_3N_4 balls (the binding energy of carbon contaminant (C1s = 284.6 eV) was used as the reference for calibration).

An MH-5-VM micro-hardness tester was performed to measure the micro-hardness of the polished cross-sections of as-prepared mullite coatings (load 3 N, dwelling time 15 s; 10 indentations). The specific surface area and pore volume of the mullite feedstock powders were measured with an automated surface area analyzer (JW-BK122W, China), with which the specific surface area was determined based on the Langmuir theory. A contact angle meter (JC2000D1, China) was used to evaluate the wettability of distilled water and HCl solution on the polished surface of mullite coatings, with which the goniometry method was adopted.

2.3. Friction and wear test

Friction and wear tests were carried out with a reciprocating ball-on-disc tribometer (CSM, Switzerland). Fig. 1 shows the schematic diagram of the reciprocating ball-on-disc tester. Si_3N_4 ceramic balls (Φ6 mm, 1700 HV, Ra ≤ 0.2 μm, Shenzhen HTB Fine Ceramics

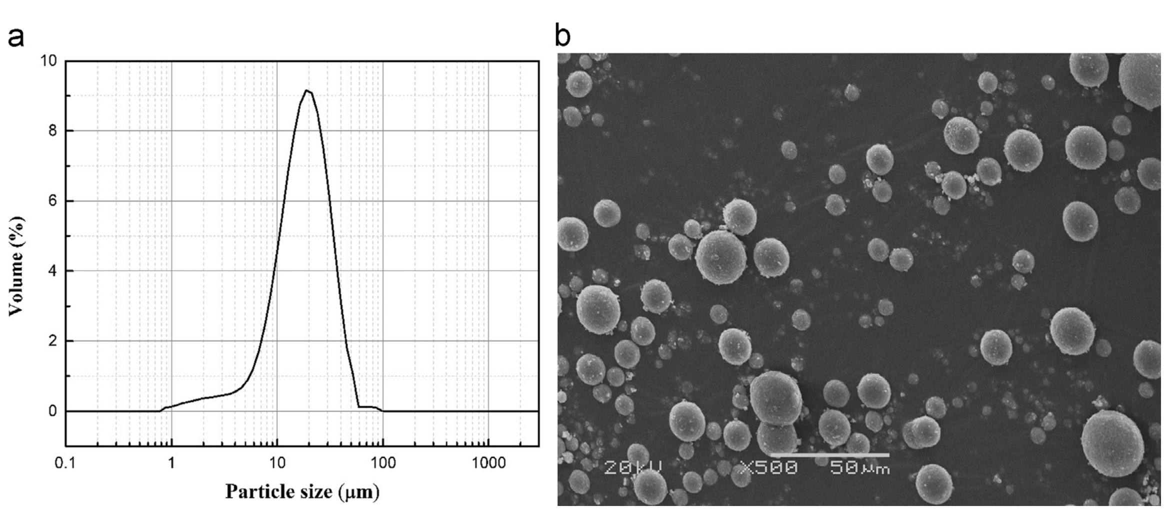

Fig. 2. Particle size distribution for mullite feedstock (a) and SEM micrographs of mullite feedstock.