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Plasma sprayed YSZ coatings deposited at different deposition temperatures, part 2: Tribological performance

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ABSTRACT

In the first part, we reported that the comprehensive desirable properties (high hardness, toughness, cohesive strength and compressive residual stress, etc.) for wear-resistance coatings could be achieved by adjusting the deposition temperatures. In this part, we studied the role of deposition temperature on the tribological performance of YSZ coatings, and the friction mechanisms are analyzed in detail. Results show that changing the deposition temperature enables the coefficient of friction to be reduced to 0.39. Particularly remarkable is the huge boost in wear-resistance of the YSZ coating deposited at 900 °C under high load dry sliding, from 1.05×10^{-3} $mm^3 \cdot N^{-1} m^{-1}$ to 1.64×10^{-7} $mm^3 \cdot N^{-1} m^{-1}$. The excellent tribological performance results from the effective inhibition of generation of cracks and formation of amorphous film, which acts as a shield to protect YSZ coating from further wear. Our work presents a novel concept that utilizes wear debris as raw materials to form a shield with the aid of friction, thereby improving the tribological performance of thermal-sprayed ceramic coatings, which may lead to moving components with much higher security, reliability, and efficiency.

1. Introduction

In engineering application, lowering the coefficient of friction (COF) and enhancing wear-resistance of the components under dry sliding are vital to machines for improving their security, reliability, and efficiency [1–5]. However, most metal components exhibit high COF and poor wear-resistance ability because of the friction-induced plastic deformation [4, 6]. Tremendous efforts were expended in deposition of specific coatings on the components via an appropriate surface engineering technology to reduce friction and protect the machines from severe wear [6–9].

Due to its high melting point, low specific weight, low thermal conductivity, oxygen vacancies, and oxygen-ionic conductivity, yttria-stabilized zirconia (YSZ) has been extensively used in engineering applications, e.g., thermal barrier coatings, solid oxide fuel cells, oxygen sensors, catalyst supports, etc. [10–14]. In addition, owing to the high coefficient of thermal expansion, coupled with high hardness and strength, YSZ or YSZ-based coatings are widely considered as an ideal wear-resistant coating in the systems of aeronautical, astronautical, biomedical and high-class civil fields with high load capacity [15–19].

Various techniques, including chemical vapor deposition, [20] electron beam-physical vapor deposition [21], dip-coating [22], electrodeposition [23], and thermal spraying [24] can be used to fabricate YSZ coatings. Among them, thermal-sprayed YSZ coatings play an important role in the industrial application, because of the scalability, high-deposition rate and economy of thermal spray technology [1, 25]. However, experience shows that thermal-sprayed ceramic coatings do not uniformly live up to their high expectations under extreme conditions [26, 27]. The inherent rather brittle properties of ceramics [28] and higher porosity, lower bonding strength between the splats and high tensile residual stress in thermal-sprayed ceramic coating [8, 29] are believed to be responsible for the poor tribological performance. The brittle properties lead to a high surface roughness of ceramics. Once sliding under high load without any lubrication, the asperities of the ceramic surface would rapidly detach, and fine wear particles are generated, which result in three-body abrasion causing its rapid deterioration. Thermal-sprayed ceramic coatings always suffer more severe condition, since their high porosity leads to decreased hardness, weakening their resistance against abrasion. Meanwhile, splats are apt to be delaminated under frictional force because of low bonding strength in thermal-sprayed ceramic coatings.

Traditionally, extensive research has determined that the poor tribological performance could be improved by introducing lubricants into ceramics matrix [4, 29–32]. Instructed by this concept, we have successfully fabricated self-lubricant ZrO_2/PTFE composite coatings [1], and the composite coating possessed low friction coefficient even

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Table 1
Properties of YSZ coatings deposited at different deposition temperatures.

DP	**P** (%)	**BS** (MPa)	**H** (GPa)	**E** (GPa)	**RS** (MPa)
RT	24.20	30.66	8.10	130.61	65.3
300 °C	19.86	42.21	10.13	140.83	35.9
600 °C	12.38	65.32	18.40	228.27	−33.1
900 °C	5.50	≥75.68	19.07	253.56	−315.0

DP: deposition temperature, **P**: porosity, **BS**: bonding strength, **H**: hardness, **E**: elastic modulus, **RS**: residual stress.
Note: For the values of residual stress, '−' means compressive residual stress.

under ultra-high loads for extremely long lifetime. Furthermore, the composites showed zero-wear property, and caused negligible wear damage to friction pair. However, the improvement was achieved at the cost of other properties, such as serviceability temperature, mechanical properties. Therefore, many researchers focused their attention on the enhancement in the intrinsic properties of ceramic materials, including hardness [9, 26, 27] and toughness [33–35]. However, in the majority of reported literature on the aspect, a slight reduction in COF and wear rates was observed, although their hardness or toughness may be raised many times. The generation of wear particles is responsible for the frustrating results, because they roughen the surface and damage the contact materials, leading to their rapid wear.

In the first part, we reported that the comprehensive desirable properties (high hardness, toughness, cohesive strength and compressive residual stress, etc.) for wear-resistance coatings could be achieved by adjusting the deposition temperatures. The data of the properties of YSZ coatings deposited at different temperatures are summarized in Table 1. With the expectation of alleviation of sliding-induced wear particles and cracks generation via the improvement in the comprehensive properties, coupled with avoiding repeated damage to contact materials by the collection of wear debris in its inherent pores, the present work aims to significantly improve the tribological performance of thermal-sprayed YSZ coatings by adjusting the deposition temperatures. Furthermore, the friction mechanisms are investigated in detail.

2. Experiment procedures

2.1. Preparation of coatings

The YSZ coatings are fabricated under the same methods with the first part reported. Briefly, before deposition of YSZ coating, the substrates (316L stainless steel discs) were sandblasted followed by fabrication of bond coating via high velocity oxy-fuel spraying device (Diamond Jet 2700, Sulzer Metco). The substrates were preheated to different temperatures (room temperature, 300, 600, 900 °C) to deposit YSZ coatings by an APS 2000 plasma spraying system (Institute of Aeronautical Manufacturing Technology, Beijing, China). The parameters and detailed information of the fabrication process are given in the first part. For easier reading, the coatings are designated as C1–C4, depending on the deposition temperatures.

2.2. Characterizations

The thin foils of worn surface used for transmission electron microscopy (TEM, FEI tecnai G2 TF20, USA) observation were produced through focused ion beam (FIB, Helios nanolab 600, FEI Corporation, USA). The worn surface of YSZ coatings were observed with a scanning electron microscope (SEM, JSM-5600LV, Japan) equipped with an energy dispersive spectrometer (EDS). The morphologies and diameters of wear scar on the pairing Al_2O_3 ceramic balls were observed by an Olympus microscope.

2.3. Tribological test

Friction and wear behaviors were evaluated with a universal tribometer (CSM, Switzerland) under ball-on-disc mode. All the friction tests were conducted at room temperature with a relative humidity of 40 ± 5%. The sliding velocity, amplitude and applied load were set as 100 mm/s, 2.5 mm, and 10 N (corresponding to the maximum Hertzian contact pressure of 2064 MPa) respectively. Al_2O_3 ceramic balls (Φ 5 mm, Ra ≤ 0.2 μm) were used as counterparts. The volume loss of polished coating was detected by Micro-XAM-3D non-contact surface profiler (ADE Corporation, Massachusetts, USA). The wear rate (W, $mm^3 \cdot N^{-1} m^{-1}$) was calculated by the following equation:

$$W = V/PL$$

where V is the wear volume loss of coating in mm^3, P is the applied load in N and L is the sliding distance in m.

At the end of each test, the diameter of wear scar on the Al_2O_3 ball was measured by an Olympus microscope with an accuracy of 0.01 mm. The wear volume (V_b) of the ball is approximated from the relationship: [36]

$$v_b = \frac{\pi \rho^4}{4r} \quad (1)$$

where ρ is the radius of the wear scar in mm, r is the radius of the ball in mm.

Then the specific wear rate (W_b) of the ball was calculated as below:

$$Wb = \frac{v_b}{PL} \quad (2)$$

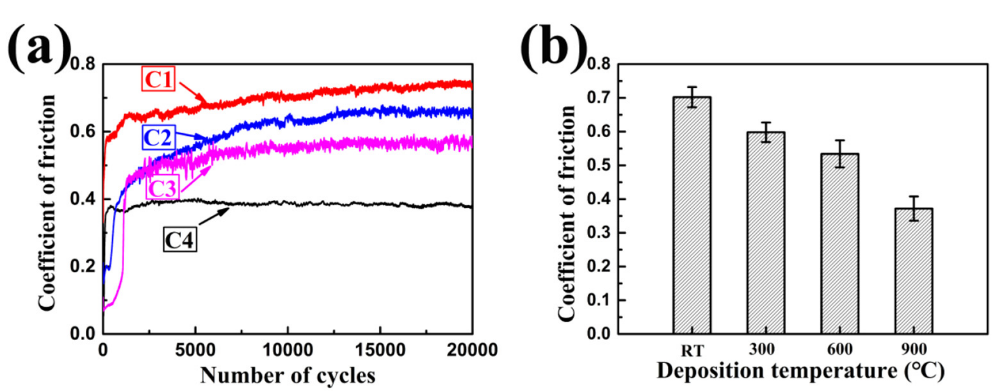

Fig. 1. Coefficient of friction curves as a function of sliding cycles (a), and average values for YSZ coatings deposited at different deposition temperatures.