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Effect of substrate preheating treatment on the microstructure and ultrasonic cavitation erosion behavior of plasma-sprayed YSZ coatings

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ABSTRACT

Inconel 718 was used as the substrate and preheated at different temperatures to deposit yttrium stabilized zirconia (denoted as YSZ) coatings by atmospheric plasma spraying. The microstructure of the as-deposited YSZ coatings and those after cavitation-erosion tests were characterized by field emission scanning electron microscopy, Raman spectroscopy, and their hardness and toughness as well as cavitation-erosion resistance were evaluated in relation to the effect of substrate preheating temperature. Results indicate that the as-deposited YSZ coatings exhibit typical layered structure and consist of columnar crystals. With the increase of the substrate preheating temperature, the compactness and cohesion strength of coatings are obviously enhanced, which result in the increases in the hardness, elastic modulus and toughness as well as cavitation-erosion resistance of the ceramic coatings therewith. Particularly, the YSZ coating deposited at a substrate preheating temperature of 800 °C exhibits the highest hardness and toughness as well as the strongest lamellar interfacial bonding and cavitation-erosion resistance (its cavitation-erosion life is as much as 8 times than that of deposited at room temperature).

1. Introduction

Cavitation erosion, a kind of surface damage caused by the relative motion of solid surface and liquid, usually occurs on the surface of pump parts, turbine blades and ship propellers [1–3]; and it often corresponds to water-hammer effect associated with the formation, development and collapse of bubbles at a high frequency of 100,000–200,000 times per second. As bubbles collapse adjacent to the specimen surface in water, a shock wave produced by the implosion of bubbles is up to about 1500 MPa [4]. Such a high pressure often results in an instantaneous high temperature and a great impact force to the surface of materials [5,6]. For example, honeycombed or even spongy holes are formed on the surfaces of mechanical parts under the repeated action of shock waves or micro-jets, which leads to serious influences on the operation safety of the mechanical parts in association with a sharp decline in the strength and expected service life of materials [7–9]. Therefore, it is imperative to get rid of the cavitation erosion of hydraulic machinery in order to extend the service life.

Ultrasonic cavitation damage mainly occurs on the surface of materials, which could make it feasible to improve the cavitation erosion resistance of materials by applying suitable surface-protection techniques. In this sense, plasma spraying technique, with the advantages such as unlimited substrate dimension, extensively selectable feedstock and controllable coating thickness, could be of special significance in extending the service life of mechanical components [10–12]. Nevertheless, previous researches on anti-cavitation erosion coatings primarily focus on metal coatings which are less competitive under corrosive medium and high temperature in association with breakage of bubbles [13–15]. To deal with this issue, some researchers pay special attention to ceramic coatings like yttrium stabilized zirconia (denoted as YSZ) coatings [16,17]. In fact, plasma sprayed YSZ coatings exhibit excellent performances, such as high temperature resistance and corrosion resistance as well as good chemical stability, and they have promising applications in preventing metal substrates from corrosion under high temperature and strong corrosion environment [18–20]. However, because of the inherent characteristics of atmospheric plasma spraying technology, as-sprayed YSZ coatings often inevitably contain pores and micro-cracks. Moreover, as-sprayed YSZ coatings usually exhibit weak inter-splat and splat/substrate combination, which facilitates the generation, growth and collapse of cavitation bubbles as well as large spalling in association with the expansion and inter-connection of cracks at the defect positions [21,22]. Furthermore, fluid medium, upon penetrating through the pores and cracks in the as-sprayed YSZ coatings, can also cause the exfoliation of coating, thereby greatly

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decreasing the cavitation-erosion resistance of the ceramic coating and leading to direct corrosion to metal substrates [23,24]. Therefore, it is necessary to reduce the micro-defects and improve the strength of lamellar interfacial bonding of the as-sprayed YSZ coatings in order to increase their cavitation-erosion resistance and extend their service life in harsh environment. For this purpose, some researchers make use of laser cladding, surface sealing and substrate preheating to enhance the densification of ceramic coatings [17,25,26]. The substrate preheating temperature directly affects the state of molten droplets deposited on substrate, the degree of particles flattening and grain size, thereby further influencing the structure and quality of the coating (such as hardness, toughness, bonding strength and porosity). Hou et al. [27,28] and Valette et al. [29] separately prepared Al_2O_3 coating by substrate preheating. They found that the increase of preheating temperature promotes the epitaxial growth of γ-Al_2O_3 grains in Al_2O_3 coating, which is favorable for increasing the densification of coating and increasing the hardness and wear resistance. Yang et al. [30] and Xing et al. [31] found that strong chemical bonding would form among splats when the preheating temperature exceeds a critical one (above 600 °C), thereby greatly improving the bonding strength and compactness of ZrO_2 coating.

In the present research, we adopt Inconel 718, a kind of superalloy with high strength, good toughness, anti-oxidation as well as machinability, as the substrate to prepare YSZ coating (mass fraction of yttrium: 8%; the resultant YSZ coating is denoted as 8YSZ) by atmospheric plasma spraying (abridged as APS). This paper reports the effect of the preheating temperature of the substrate on the microstructure and mechanical properties as well as cavitation erosion behavior of the as-deposited 8YSZ coatings.

2. Experimental procedures

2.1. Preparation of YSZ coatings

Commercial zirconia powder stabilized with 8 wt% yttria (8YSZ, Sulzer Metco, USA; particle size: 11–125 μm) was employed as the feedstock. An APS-2000A system (Institute of Aeronautical Manufacturing Technology; Beijing, China) connected to a six-axis robot (IRB 2400, ASEA Brown Boveri Ltd.; Switzerland) was performed to deposit 8YSZ coatings on Inconel 718 substrate (Φ30 mm × 8 mm). Prior to spraying, the work surface of each substrate was sand-blast with silica powders (grit size: 80–120 μm) to roughen the surface in order to increase the mechanical anchoring between the coating and substrate. The as-roughened substrates were cleaned with acetone in an ultrasonic bath. A NiCrAlY bonding layer (Ni-22Cr-10Al-1.0Y (wt%); Sulzer Metco, USA) was deposited on the substrates to reduce the residual stress between the substrates and ceramic coatings. The substrates with the bonding layer were heated with a high power inductive stove to 200 °C, 400 °C, 600 °C and 800 °C, respectively (the temperature was detected with a thermocouple in contact with the sample surface). The 8YSZ coatings with a thickness of ∼300 μm were deposited on the substrates preheated at different temperatures. For convenience, the coatings deposited on untreated substrate (room temperature) and those preheated at 200 °C, 400 °C, 600 °C and 800 °C are designated as S1, S2, S3, S4 and S5, respectively. The plasma spray parameters used in this study are listed in Table 1.

In order to better explore the influence of substrate preheating temperature on the flattening behavior of ceramic droplets on the bonding coating surface as well as the microstructure of corresponding coatings, we polished the specimen with the bonding coating to mirror-like so that the ceramic droplets can well spread. The powder feed rate was kept at a low value of 2 g/min and the gun speed was kept at a high value of 1 m/s so as to obtain single ceramic splats.

Table 1
Atmospheric plasma spraying parameters.

Items	NiCrAlY bonding coating	8YSZ coating
Voltage (V)	70	75
Arc current (A)	600	550
Argon gas flow rate (L/min)	50	35
Powder gas flow rate (L/min)	5	10
Spray distance (mm)	100	90
Spray angle (°)	90	90
Gun speed (m/s)	0.6	0.2

2.2. Structure characterization

The surface and fractured morphologies of the as-prepared 8YSZ coatings and the coatings after cavitation erosion tests were analyzed with an ultra-high resolution field emission scanning electron microscope (FESEM; SU8020, Hitachi, Japan). The cross-sections and collected cavitation debris of coatings was observed with a scanning electron microscope (SEM; JSM-5601LV, Japan). An OLYCIA m3 image microscope was used to measure the porosity of as-sprayed coatings. The hardness and elastic modulus of 8YSZ coatings deposited on the substrates preheated at different temperatures were measured by nano-indentation (CSM, Switzerland; diamond indenter). The maximum load of nano-indentation test is 20 mN. Five indentations were performed at different regions of the polished coating surface. The microhardness distribution on the cross-section of as-sprayed 8YSZ coatings was measured using a MH-5-VM micro-hardness tester at a load of 3 N and a dwelling time of 5 s. The roughness of the polished coating surfaces and those after cavitation erosion tests was detected with a Micro-XAM-3D non-contact surface profiler (ADE Corporation, Massachusetts, USA). The water contact angle was measured according to the sessile drop technique with an OCA 15 contact angle goniometer (Dataphysics Co. Germany). The chemical constituents of the mirror-polished bonding coating were analyzed with a confocal Raman microprobe (LabRAM HR Evolution, HORIBA Jobin Yvon S.A.S., France) operating with an argon-ion laser source.

2.3. Cavitation erosion test

The ultrasonic cavitation erosion behavior of the as-sprayed 8YSZ coatings was evaluated by vibration induced cavitation according to ASTM standard G-32 [32]. The schematic diagram of the cavitation test rig is shown in Fig. 1, where the stainless steel serves as the upper specimen and the 8YSZ coating serves as the lower specimen. Both the

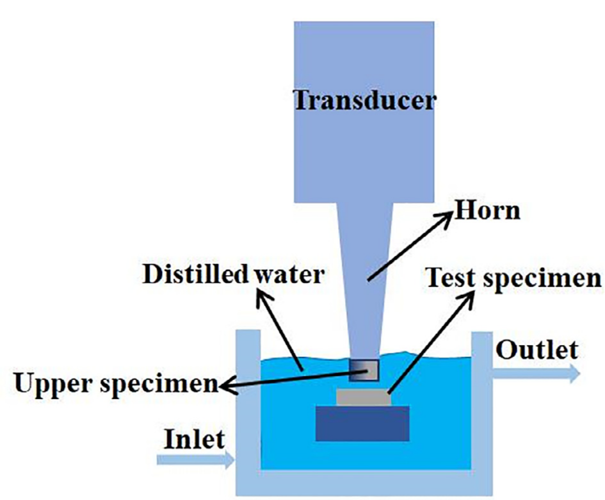

Fig. 1. Schematic diagram of cavitation test rig.