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Force transmission and its effect on structural changes in plasma-sprayed lamellar ceramic coatings

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ABSTRACT

In this study, thermal mismatch strain-induced structural changes in plasma-sprayed lamellar ceramic coatings upon heating were investigated. Experimental results showed that the main structural change is the propagation of inter- and intra-splat cracks along their tips. Correspondingly, significant changes in properties were observed. A lamellar model with connected inter- and intra-splat cracks was developed. The modeling results suggested that shear stress would be primarily concentrated at the interface between two layers, accounting for the propagation of the inter-splat cracks. Subsequently, the stress was transmitted through the residual bonding areas into the upper layer, and thus a tensile effect was generated inside the splat segment. This can be responsible for the propagation of the intra-splat cracks. In addition, dependence of the crack propagation behavior on the structural parameters is discussed. These microscopic structural changes may provide fundamental understanding on the global structural evolution and failure mechanism of coating/substrate systems during service conditions.

1. Introduction

Thermal spraying technology has earned widespread application owing to its fast, flexible, and cost-effective deposition [1]. As a representative application of the thermally sprayed coatings, thermal barrier coatings (TBCs) are utilized in both aircraft engines and land-based gas turbines for their potential in lowering the temperature of the underlying metal substrate. Consequently, the power efficiency is increased significantly by allowing for a higher gas injection temperature [1–5]. The TBC system primarily consists of four layers: a superalloy substrate, a bond coat, a thermally grown oxide (TGO), and a ceramic top coat. Owing to its low thermal conductivity, the ceramic top coat, typically made of yttria-stabilized zirconia (YSZ), offers a high thermal insulation on the superalloy substrate [6,7].

Failure of the air plasma sprayed (APS) TBCs results from the 'link-up' of the microcracks under complex stress during thermal cycling [8]. The stresses may be affected by many factors, such as TGO growth [9–11], mismatch in the coefficients of thermal expansion (CTE) [12], and the YSZ structure [13]. Among these factors, the CTE mismatch stress has a significant effect on the failure of the TBCs, since frequent temperature changes occur during thermal service (e.g., a thermal cyclic test in the laboratory [14]). Therefore, significant efforts have been made to investigate the structural changes induced by extra load in the top-coat of the TBCs. Qian et al. [15] and Chen et al. [16] adopted a tensile method to study the fracture behavior of TBCs. They visualized the failure procedure including cracking initiation, propagation and interfacial decohesion. It is believed that surface cracks can play an important role in the interfacial debonding of TBCs. Zhou et al. [17] analytically predicted the interfacial fracture mechanism of the TBC system with multiple surface cracks. In further studies, Fan et al. [18] and Zhang et al. [19] investigated the interaction between multiple surface and interfacial cracks to estimate the durability of the TBCs. Other groups [20,21] investigated the crack initiation and propagation in TBCs at the interface that result in strain-induced delamination and spallation. The common contribution of the aforementioned research was that a global structural change related to the propagation of multiple cracks was revealed; this might be responsible for failure in the coating. However, much less attention has been paid to the microscopic structural changes under load; it is imperative to analyze these changes since they essentially account for the macroscopic cracking behavior.

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Table 1
The CTEs of different substrates.

Substrate materials	CTE α (K^{-1})	Mismatch strain with YSZ at ΔT of 1373 K Δα·ΔT (‰)
Alumina	~7–8 × 10^{-6}	~ −4.8
YSZ	~11 × 10^{-6}	0
Magnesia	~14 × 10^{-6}	~ +4.1

A thermally-sprayed coating exhibits a typical lamellar structure owing to the successive deposition of molten particles impacting on a substrate followed by lateral flattening, rapid solidification, and cooling [22,23]. The globular voids and the 2D cracks (inter- and intra-splat cracks) are two main defects in the coatings [7]. The intra-splat cracks are generated under a tensile-effect of the quenching stress, and they often run through the thickness of the individual splats [24,25]. Consequently, the disk-shaped splats are divided into several segments [26]. In contrast, the inter-splat cracks often refer to the imperfect bonding regions between the neighboring layers [25,26]. This explains why the apparent bonding ratio between the layers is only approximately 30% [22,27]. In addition, the inter-splat cracks are often oriented nearly parallel to the substrate, whereas the intra-splat cracks are perpendicular to the substrate. To summarize, the thermally sprayed ceramic coatings exhibit a lamellar structure with connected inter-splat cracks and intra-splat cracks. This unique structure with continuous cracks in a continuous material results in three complicated cases: (i) the intra-splat interfaces in an individual layer reduce the force transmission directly from segment to segment in a single layer; (ii) the limited bonding areas between the layers transmit force from layer to layer primarily; and (iii) the inter- and intra-splat cracks may grow along their tips under stress [28]. Based on these considerations, the structural changes in plasma-sprayed ceramic coatings may be very different from the shear-lag model used for brittle coatings [28–30]. The shear-lag model neglects the interfacial debonding between the coating and the substrate. Therefore, it is necessary to investigate the structural changes based on the features of the thermally sprayed ceramic coatings.

In this work, plasma-sprayed yttria-stabilized zirconia (YSZ) was chosen to analyze the microscale structural changes under load. To begin with, the properties of the plasma-sprayed YSZ coatings were determined after heating. Subsequently, the microstructural changes were examined from the perspective of individual splats, since the individual splat is the fundamental unit of the whole ceramic coating. A general lamellar finite element model (FEM) with connected inter- and intra-splat crack network was developed. Subsequently, dependence of the cracking behavior on the stress distribution as well as the structural parameters was systematically discussed. This would benefit in structurally tailoring of the TBCs for the desired application.

2. Materials and methods

2.1. Preparation of samples

The experimental part includes two stages. In the first stage, property changes induced in the plasma-sprayed YSZ coatings by thermal treatment are investigated. A commercially available 8 wt% fused-crushed YSZ powder (FC, 5~22 μm, Fujimi, Aichi, Japan) was used as the feedstock. Several bulk ceramic materials with different CTEs were used as the substrates. Detailed information on the various substrates can be found in Table 1. YSZ coatings with a thickness of approximately 500 μm were obtained by plasma spraying at room temperature. Before the coating deposition, the substrate was grit-blasted to ensure effective adhesion between the coating and the substrate. For comparison, YSZ coatings were also deposited on stainless steel to obtain free-standing coatings through post-spray dissolution of the substrate by hydrochloric acid. The plasma spraying equipment used is a commercial system (GP-80, 80 kW class, Jiujiang, China). The spraying parameters are shown in Table 2.

Table 2
The spraying parameters of APS.

Parameters	APS
Plasma arc voltage (V)	70
Plasma arc current (A)	600
Flow rate of primary gas (Ar) (L·min^{-1})	50
Flow rate of secondary gas (H_2) (L·min^{-1})	7
Flow rate of powder feeding gas (N_2) (L·min^{-1})	7
Spray distance (mm)	80
Torch traverse speed (mm·s^{-1})	800

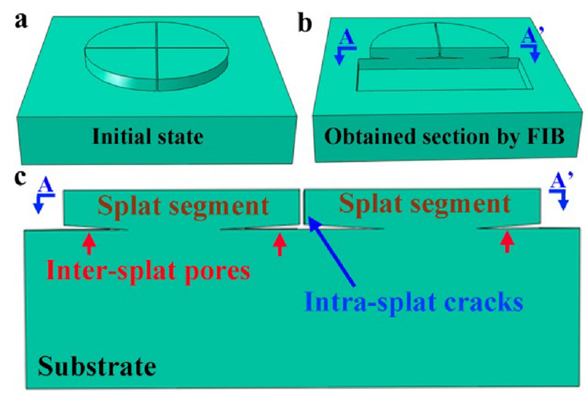

Fig. 1. Schematic for the FIB preparation of the cross-section of an individual splat bonded to the substrate: (a) initial state, (b) obtained cross-section, and (c) cross-section of A-A' corresponding to (b).

The second stage of the investigation was conducted on individual splats to reveal the microscopic structural changes related to the unique structure of the plasma-sprayed ceramic coatings. In spite of a rough interface near the substrate, the plasma-sprayed ceramic coatings primarily exhibit a lamellar structure, and most splats lie nearly parallel to the substrate [26,31]. This implies that the inter-splat cracks would be perpendicular to the deposition direction, whereas the intra-splat cracks may be parallel to the deposition direction. This is quite similar to individual splats on a flat substrate. Based on this consideration, it is reasonable to investigate the microstructural changes induced by a CTE mismatch stress in the plasma-sprayed ceramic coatings from the individual splat perspective. The feedstock was the same as the one used for coating deposition. During deposition, the polished substrates were preheated to 160 °C and 600 °C. The latter deposition temperature leads to a better bonding condition, and is used for comparison. Consequently, individual YSZ splats with different morphologies and bonding areas could be obtained. The spraying parameters can be found in Table 2.

2.2. Structural characterization and thermal treatment

The cross-section of a splat bonded to its underlying substrate was prepared using a focused ion beam (FIB) system (Helios NanoLab600i, FEI, USA) to avoid damage on the initial bonding state. The schematic for the FIB preparation of the samples are shown in Fig. 1. Quasi in situ morphological observations were made using a scanning electron microscope (SEM, TESCAN MIRA 3, Czech Republic). In addition, an atomic force microscope (AFM, Innova, Veeco, USA) was used to characterize the surface topography of individual splats. The apparent porosity of the samples