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Power-law characteristics of damage and failure of ceramic coating systems under three-point bending

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ABSTRACT

Damage and failure of ceramic coatings bonded on alloy substrates was studied by observing crack evolution in the coating systems under in situ three-point bending tests with corresponding load–displacement curves. A damage and catastrophic failure model on the ceramic coatings was proposed based on our experimental results and the Taylor expansion of the controlling variable. The results indicate that the damage increases with increasing stress and obeys the power-law characteristics with the power exponent of 0.5, and the damage is 1 as the stress reaches the critical point corresponding to the failure of the coating systems. The damage rate increases rapidly when the stress is near the failure point and shows a power law singularity of −0.5. The experimental results of thin, thick, nanostructured, and conventional micrometer-scale microstructured coatings are all in agreement with the predictions based on the model.

1. Introduction

Ceramic coatings are widely used in mechanical engineering, chemical engineering, aerospace and marine fields, etc. due to their high melting point and excellent resistance to erosion and wear. For example, ceramic coatings of several hundreds of micrometers are often sprayed or deposited on alloy substrates for thermal protection of blades of aerospace engines [1]. Once the ceramic coatings fracture and spall, the blades exposed high temperature will failure. Therefore, the study on fracture and damage of the ceramic coatings attracts great attention. Zhou et al. studied the fracture characteristics and the crack evolution in the ceramic top coatings for two-layer and multilayer systems under uniaxial tension and four-point bending [2]. They found that the transverse crack (vertical to the interface) density tended saturate as the strain reached a certain value [2]. Qian et al. found similar phenomena in studying the tensile damage behavior of a sandwiched coating system, and proposed a transverse crack evolution mode of the initiation, multiplication and saturation with increasing strain [3]. McGuigan et al. developed an elastic–plastic shear lag model describing cracking under uniaxial tensile strain of a brittle thin film on a deformable substrate and proposed that the (transverse) crack density is a function of applied strain [4]. Thouless et al. studied how the crack modes in films depend on material properties and thickness ratio by numerical analysis related to energy release rate [5–6]. Renusch and Schütze studied the damage kinetics of thermal barrier coatings by acoustic emission analysis of transverse and interface crack evolution, proposed a super-parabolic and accelerating linear dependence of the damage on the thermal cycling oxidation time, respectively, before and during spallation of the coatings, and demonstrated the power law characteristics of the damage with increasing temperature difference [7]. Trunova et al. studies the damage and failure characteristics of thermal barrier coatings by observing interface crack evolution with increasing high temperature oxidation time [8]. Brodin et al. studied fatigue damage of thermal barrier coatings by analyzing interface crack length change with increasing thermal cycling number [9].

It is clear, when ceramic coating/metallic substrate systems are subjected to bending, tension (mechanical load), high temperature oxidation, or thermal shock (thermal load), the microscopic transverse or interface cracks appear in the ceramic coating systems with increasing load or cycling number (for cycling load), i.e., the damage initiates, the number of the transverse cracks saturates and the interface fractures when the load reaches the maximum allowed value or the cycling number reaches the failure critical number [2–4,7–9]. As above indicated, researchers observed the change of the number of cracks or the crack length with strain, time, temperature or cycling number [2–4,7–9]. For thicker coatings or pre-oxidized systems, interface fracture between the coating and the substrate occurs, and the interface crack evolution was studied in particular for the coating systems under mechanical or thermal loading [7–11]. Recently, Zhou et al. studied in detail the damage and fracture of thermal barrier coatings by coupled acoustic emission and digital image correlation techniques [12], and found a similar damage behavior as in the Renusch and Schütze's study [7]. When the controlling variable (time or transverse crack density) reaches a critical value, the damage is 1, after that the damage is even larger than 1 and

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increases sharply, which corresponds to the spallation or delamination of the coatings (i.e., interface fracture), before that the transverse crack evolution corresponds to the damage range from 0 to 1 [7,12]. Although the previous works describe effectively the damage characteristics of ceramic coatings to some degree, the damage larger than 1 is peculiar and a different model on the damage and fracture of the ceramic coatings reflecting physical mechanism is desired. Since ceramics are brittle, the fracture and failure maybe catastrophic, if a scaling law of damage and failure of the ceramic coatings can be developed, it will be significant not only in scientific understanding of coatings fracture but also in prediction of failure.

In this paper, the crack evolution of ZrO_2 ceramic coatings with different thicknesses and microstructures, bonded on the same Ni-based superalloy substrates, under three-point bending were real time observed by in-situ scanning electron microscope. The damage evolution of the ceramic coatings, represented by the transverse or interface crack length, was studied with increasing tensile or shear stress for thin and thick coating systems, respectively, and a power law of the damage was developed based on the experimental results of all kinds of coatings and a unified theoretical analysis resulted from the Taylor's expansion. The scaling law of the damage rate of ceramic coatings, helpful for predicting the catastrophic fracture of coating systems, was revealed.

2. Experimental

2.1. Specimen preparation

The thermal barrier coating samples used in this study consist of YSZ (8 wt.% Y_2O_3 stabilized ZrO_2) top coatings prepared by the standard atmospheric plasma spraying method [13–14], NiCrAlY (25.42wt%Cr-5.1wt%Al-0.48wt%Y) bond coatings prepared by the high velocity oxygen fuel method, and Ni-based superalloy substrates [14]. The detailed preparation process and the microstructure of the coatings were described in Ref. [14]. We prepared thick coating samples with a coating thickness of 350–490 μm, and thin coating ones with a coating thickness of 150–200 μm. The coating thickness actually includes the thickness of the ceramic top coating and the thickness of the bond coating of about tens of micrometer to a hundred micrometer. For both the thin and thick coating samples, two kinds of ceramic coatings were prepared by the use of different raw powders. One kind of coating with grains of about 40–100 nm diameter prepared from nanostructured YSZ powder [14], is represented by Nx with x being the sample number. The other kind is a conventional coating with micrometer scale splat grains of 200 μm diameter and 2 μm thickness prepared from conventional YSZ powder [1,14] and is represented by Mx. A single number x denotes the thin coating samples, such as N0, M3…, and a double number x represents the thick coating samples, such as M00, N30, etc. The samples had a fabricated length, width and thickness of about 15 mm, 3 mm and 1.5 mm, respectively.

2.2. In-situ three-point bending test

The samples were grinded and polished, then were placed in the sample room of the FEI Sirion 400 NC scanning electron microscope (SEM) and were sandwiched in the designed jig for in-situ observation of crack initiation and propagation on the side face of the samples under loading by using the mechanical testing apparatus - Gatan Microtest 2000, as shown in Fig. 1 in Ref. [11]. The three-point bending measurements were carried out by a slight movement of the jig controlled by the mechanical testing apparatus and the load–displacement curves were obtained. The load was applied on the alloy substrate face, and two fulcrums contact the ceramic coating face, as shown on Fig. 1. The span was 10 mm. The loading rate was 0.1 mm/min. The evolution of cracks on the side face with increasing load was observed and recorded by use of the SEM. At some loading points corresponding to the crack initiation and propagation, the loads were stopped temporarily to take pictures for obtaining the crack maps. After taking pictures at a displacement point, the load was resumed and applied continuously again. The crack length was calculated by image analyzing based on the side face micrographs of the coatings.

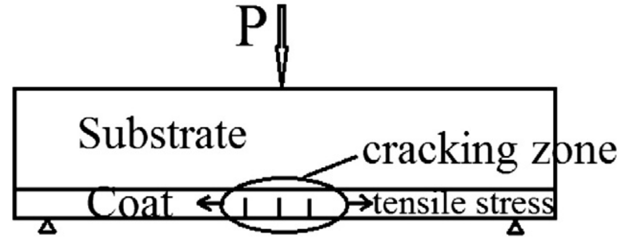

Fig. 1. Schematic of the coating/substrate systems under the three-point bending, the transverse cracks occur with loading for elastic brittle coatings.

3. Experimental results and damage model

3.1. Experimental results

The load–displacement curve of each sample with a series of corresponding crack evolution maps can be obtained as shown in Ref. [11]; here two examples are shown in Figs. 2-3. Fig. 2(a) shows the load–displacement curve of the nanostructured thin coating sample N0, from which it can be seen that the load increases with enhancing displacement up to the peak value. The process corresponds to the initiation, propagation and saturation of the transverse cracks in the coating, as shown in Fig. 2(b). After that the load drops with enhancing displacement, corresponding to the rupture of coating and cracks in the substrate. Note that the approximate plateau in the curve corresponds to plastic deformation of the substrate, and the cracks propagated through the interface and into the substrate, as shown in Fig. 2(c), which is not our focus. The crack maps before the peak load and close after the peak were paid attention. The elastic segment in the load–displacement curve was almost kept before the peak load. The tiny jumps in the curve correspond to the points of stopping the loading and taking pictures, during the process the load dropped slightly without change of displacement. The crack maps corresponding to some points in the load–displacement curve, such as the numbers 1–9 in Fig. 2(a) and the numbers 1–6 in Fig. 3(a), were real time obtained. For example, the crack maps corresponding to the numbers 2, 6, and 9 in Fig. 2(a) are shown in Fig. 2(b), which shows the initiation, multiplication and saturation of the cracks in the same position and is similar to the previous reports [3,11]. Note that Figs. 2(b), (c) and 3(b) only shows a part of all maps of the whole sample due to limited field of view. In fact, many pictures with different fields of views, corresponding to each point in the curve were taken.

It can be found from the experimental observation that the transverse crack, vertical to the interface between the coating and the substrate, initiates at some defect in the coating with loading, and multiple transverse cracks in the thin coatings emerge instantaneously and saturate soon when the load is close to a critical peak value corresponding to a tensile stress level of coating strength. For the thin coating systems, tensile failure dominates and the multiple transverse cracks emergence are the main fracture mode as analyzed in Ref. [11]; thus the length of the transverse cracks was measured when the damage was evaluated.

For the thick coating systems, interface shear failure dominates and interface fracture between the coatings and the substrates is the main fracture mode [11], as shown in Fig. 3(b), and thus the length of interface crack was calculated for describing damage. The load–displacement curves of the thick coatings show obvious load drop after the peak values compared to those of the thin coatings, as shown in Fig. 4 in