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Bending-driven failure mechanism and modelling of double-ceramic-layer thermal barrier coating system

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ABSTRACT

Bending-driven failure test is an effective and efficient method to evaluate the quality and load-bearing capacity of a thermal barrier coating (TBC) system. In this study, the failure mechanism of a double-ceramic-layer TBC (DCL-TBC) system was investigated experimentally and analytically. First, a series of in-situ four-point bending tests were conducted on DCL-TBC system with the two ceramic layers having different thickness ratios. A cracking phenomenon was observed, i.e. vertical cracks (visible on the surface) and interfacial cracks (invisible unless sectioned) simultaneously evolved, from which a concept of critical vertical crack density associated with interfacial crack propagation was proposed to evaluate the bending-driven failure of DCL-TBC system. Second, an analytical model was developed to predict the critical crack density, which was based on a modified shear-lag model and interfacial fracture mechanics. The analytical prediction agreed well with the experimental results. Third, the analytical model was used to establish the failure maps of DCL-TBC system with respect to a series of physical and geometrical parameters in dimensionless form, considering both multiple surface cracking (i.e., vertical cracks) and interfacial cracking. The mechanism-based analytical approach, which has been validated by experimental results, may be used to provide a better evaluation of the damage of DCL-TBC system under bending.

1. Introduction

Thermal barrier coating (TBC) system is widely used in gas turbines for aircraft engines and electricity generators to achieve both insulation from operating temperature and resistance to oxidation (Chang et al., 1987; Evans et al., 2001; Miller, 1987; Padture et al., 2002). A typical TBC system consists of a superalloy substrate, metallic bond coat (BC) layer and ceramic top coat (TC) layer. Conventionally, 7–8 wt.% Y_2O_3-stabilised ZrO_2 (YSZ) is used for the ceramic layer because of its excellent thermal insulation properties and high durability. However, YSZ's use is limited to temperatures under 1473 K because sintering and phase transformation can occur at higher temperatures (Levi, 2004; Vaßen et al., 2010; Vaßen et al., 2004). The state-of-the-art double-ceramic-layer TBC (DCL-TBC) system is regarded as one of the most promising thermal protection systems to achieve a higher working temperature for the next generation of gas turbines (Stöver et al., 2004; Vassen et al., 2009). In a DCL-TBC system, two ceramic layers are deposited on the BC layer above the substrate. The top ceramic layer, which could comprise materials such as $La_2Zr_2O_7$ (LZ) and $La_2Ce_2O_7$ (LC), has a low thermal conductivity and high phase stability, thus acting as a thermal insulator to protect the second ceramic layer, i.e. the inner YSZ coat. As reported by Dai et al. (2006), DCL-TBC system has excellent thermal cycling performance and performs better than traditional single-ceramic-layer TBC (SCL-TBC) system.

Cracks in DCL-TBC system usually initiate in ceramic layers and then gradually propagate and deflect across or propagate along the interfaces between different coating layers due to inevitable thermal stresses in service (Evans et al., 2001; Fan et al., 2012a,b; Xu et al., 2016; Zhang et al., 2011; Zhou et al., 2002), similar to the cracking process observed in SCL-TBC system. Such cracks eventually lead to the delamination of DCL-TBC system. Geometric and physical factors have significant effects on the failure mechanism (Fan et al., 2014; Fang et al., 2015; Li et al., 2014; Xu et al., 2014a,b; Zhu et al., 2014). Dai et al. (2006) experimentally revealed that the thermal cycling life of DCL-TBC system decreased dramatically with the increase in thickness ratio of the top and second ceramic layers. Mack et al. (2006) developed a type of TBC system based on metal–glass composite. This provided the possibility of easily adjusting the modulus and thermal expansion coefficient by changing the metal to glass ratio of the composite, which presents differ-

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ent degradation behaviour and thermal cycling lifetime. Bending-driven failure tests are usually used to evaluate the production quality and load-bearing capacity of TBC system before service and for understanding the fracture process (Yamazaki et al., 2006; Zhou et al., 2002). Despite the wide practical use, the bending-based evaluation method lacks a solid theoretical basis, and the results are often interpreted with specific experience. Moreover, for DCL-TBC system, a bending-driven failure evaluation criterion based on key material parameters is still not available at present.

The evaluation criteria for brittle films under mechanical loading have been studied extensively. The multiple surface cracking and interfacial cracking have been considered in previous studies, but these two types of fracture mode are normally treated separately. For multiple surface cracking behaviour, through-thickness vertical cracks were emphasised and a perfectly bonded interface was usually assumed. For instance, Wojciechowski and Mendolia (1989) studied the multiple fractures of brittle and low-elongation thin films adhering to high-elongation plastic substrates and developed an empirical model to describe the evolution of crack density. Yanaka et al. (1998) proposed a modified shear lag model for the multiple cracking of thin films, which was applied to analyse the tensile test results of transparent gas barrier films and to estimate the critical fracture stress in SiO_X films. Hsueh (2001) presented an energy model for multi-cracking behaviours of brittle films, assuming that the change in elastic strain energy of a film–substrate system after the occurrence of vertical cracks is equal to the fracture energy of the brittle film. McGuigan et al. (2003) established a phenomenological model describing the cracking of a brittle thin film under uniaxial tensile strain on a deformable substrate with an elastic–plastic interface layer. Fu et al. (2013) developed an analytical model to derive the closed-form solutions for the stress distribution and redistribution due to the edge effects in the film segments. Guo et al. (2015, 2016) conducted brittle-film cracking experiments on a ductile substrate to study the effects of external applied stress and film elastic properties. Alam et al. (2011) and Parlikar et al. (2015) investigated the effects of BC properties and oxidation exposure on the substrate behaviour during the multiple cracking process. However, the interfacial damage and delamination of a brittle film–substrate system were studied using a different approach. The interfacial failure is usually divided into three stages: the initiation of micro-cracks at the interface, steady-state crack propagation and delamination. The steady-state propagation of interfacial cracks in brittle materials is often an indication of delamination. Williams (1988) and Suo and Hutchinson (1990) and Charalambides et al. (1989) established energy-based steady-state propagation criteria of interfacial cracks in film/substrate systems, which have been widely used in interfacial fracture problems (Chen et al., 2011; Hai et al., 2013; Volinsky et al., 2002; Xia and Hutchinson, 2000; Yang et al., 2013; Zhao et al., 2012).

The fracture problem becomes complicated when multiple surface cracking and interfacial cracking occur simultaneously during the fracture process of brittle films such as the ones in the TBC system. In fact, the evolution of multiple surface cracks can be affected, and even interrupted, by interfacial damage. Despite this significant implication, the interaction between multiple surface cracking and interfacial cracking has not been considered in previous studies. From a practical point of view, it is well known that the non-destructive detection of interface cracks in TBC system is difficult, while the detection of surface cracks is much easier (Ellingson et al., 2002; Fukuchi et al., 2016), indicative of the benefit of understanding the relationship between the two types of cracking.

In this study, the bending-driven failure mechanism of DCL-TBC system is investigated, and a failure criterion is proposed, considering both multiple surface cracking and interfacial cracking. This paper is organised as follows. In Section 2, the sample preparation of DCL-TBC system and the experimental setup of an in situ four-point bending test are described. In Section 3, the detailed fracture process of DCL-TBC system during bending is presented, and the simultaneous evolution of vertical and interfacial cracks is characterised. A new concept of critical vertical crack density, which is associated with the steady-state propagation of interfacial cracks, is proposed to evaluate the failure of DCL-TBC system under bending. In Section 4, an analytical model is established to obtain the closed-form solution of critical crack density, using a modified shear-lag model and the interfacial fracture mechanics. In Section 5, experimental and analytical results of critical crack density with different ceramic thickness ratios are compared for validation of the analytical approach. Then, failure maps relating to a series of physical and geometric parameters in non-dimensional forms are given using the validated analytical approach. Finally, concluding remarks are drawn.

Table 1
Detailed thermal spray parameters of DCL-TBC system.

Parameters	Bond coat	LC (TC1)	YSZ (TC2)
Gun	Praxair JP-8000	METCO F4	METCO F4
Spraying method	HVOF	APS	APS
Power (kW)	–	31.5	41.8
Distance (mm)	380	100	120
Ar/H_2 (SLPM)	–	40/6.5	35/10
Feed rate (g/min)	60	35	40
Gun velocity (mm/s)	700	400	500

2. Experimental procedure

2.1. Preparation of DCL-TBC system samples

DCL-TBC system samples were prepared and nickel-based superalloy Hastelloy X was used as the substrate (40 mm × 7 mm × 1.5 mm). Commercial NiCoCrAlY powders (45–75 µm, Ni 32 wt.%, Co 38.5 wt.%, Cr 21 wt.%, Al 8 wt.%, Y 0.5 wt.%, Sulze-Metco) were chosen for spraying BC. Commercial LC and YSZ powders (45–100 μm, purity 99.99%, Institute of Process Engineering, Chinese Academy of Science) were used for spraying the top and second ceramic layers, i.e. TC1 and TC2, respectively. High-velocity oxygen fuel spraying was used to deposit a 100 μm NiCoCrAlY BC onto the superalloy substrate. The LC/YSZ DCL coatings were prepared with different thickness ratios by the air plasma spraying (APS) method. The ratios of the LC layer's thickness to the YSZ layer's thickness, R_h, are selected as 50/250, 100/200, 150/150 and 200/100, respectively. The total thickness of the two ceramic layers was controlled to be approximately 300 µm. Detailed parameters used in the thermal spraying are listed in Table 1.

2.2. In situ four-point bending test

A four-point bending device (DEBEN, MICROTEST 2000) integrated into a scanning electron microscope (SEM, FEI QUANTA 400) was used to perform the in situ bending test and record the cracking process of the TBC sample. The outer rollers were fixed, while the inner rollers were moved upward to apply the bending load. The spans of the inner and outer rollers were 10 and 30 mm, respectively. The velocity of the inner roller was maintained at 1.6 μm/s. See Fig. 1 for details of the experimental setup.

During the four-point bending test, a uniform moment was generated in the sample between the inner rollers, leading to the deformation and cracking of DCL-TBC system, which were imaged by the SEM. The number of vertical cracks originating from TC surface and the length of interfacial crack were then measured