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A multilayer structure shear lag model applied in the tensile fracture characteristics of supersonic plasma sprayed thermal barrier coating systems based on digital image correlation

W.G. Mao[a], Y.Y. Chen[a], Y.J. Wang[a], M. Zhou[a], H.Y. Yang[a], Z. Wang[a], C.Y. Dai[a,*], X. Chen[b,*], D.N. Fang[c]

[a] *School of Materials Science and Engineering, Xiangtan University, Hunan 411105, China*
[b] *Department of Earth and Environmental Engineering, Columbia University, New York 10027, USA*
[c] *Institute of Advanced Structure Technology, Beijing Institute of Technology, Beijing 100081, China*

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ABSTRACT

We developed a multilayer structure shear lag model used in analyzing tensile fracture behavior of supersonic plasma sprayed 8 wt% yttria-stabilized zirconia thermal barrier coatings (TBCs). The closed-form solutions of plane and shear stresses were deduced by using the shear lag model. Dynamic strain fields, cracking nucleation and propagation features of TBCs during tensions were in-situ monitored by non-contact digital image correlation (DIC) measurement system. The evolutions of plane and shear stresses in TBCs were estimated by the above closed-form solutions. Using in-situ measurement results of DIC, we further obtained the fracture strengths, interface shear strengths, fracture energy and fracture toughness of TBCs, and summarized the whole tensile fracture mechanisms of TBCs. This shear lag model with the aid of DIC is useful for measuring the mechanical properties of other novel multiple-layer structure brittle coating/ductile substrate systems.

1. Introduction

It is known that many different kinds of brittle functional coating/films deposited on ductile substrates have been widely applied in surface engineering areas, improvements of the surface characteristics of those important components [1, 2]. Most of these coating materials display heat insulation or wear resistance, or corrosion preventive functions. For example, thermal barrier coatings (TBCs) are typical multiple-layer structure brittle coating/ductile substrate systems, which have been widely applied in aero engines and space vehicle fields. It is important to understand how to effectively measure and appraise the mechanical properties of brittle coating/ductile substrate systems including interfacial adhesion strength, coating fracture strength, interfacial shear strength, fracture toughness and residual stress under different temperatures, scales and thermal cycling. The reliable properties would play a crucial role in predicting the service life and disabilities of brittle coating/ductile substrate systems.

Therefore, there are numerous studies investigating the mechanical properties and failure mechanisms of brittle layers on substrates [3–5]. In previous works, different experimental methods such as scratch, bending, indentation, pull-off test, laser-acoustics and tension have been developed to evaluate the adhesion characteristics of brittle coating/ductile substrate [6–8]. A lot of researchers found that well-controlled tensile test with the aid of shear lag model can effectively appraise the coating fracture strength and interfacial shear strength by using micro-observation tools [6, 9–15]. In addition, relatively simple analysis and inexpensive experimental instruments are also outstanding advantages [12]. In past several decades, many researchers paid more attention to developing the shear lag models and got a lot of outstanding achievements. Hu et al. discussed a self-consistent analysis of the film edge-induced stress in substrates by allowing a distributed force in the film [9]. Subsequently, they studied the critical stress for the steady-state cracking of adherent thin Cr films on a Al or stainless steel ductile substrate [10]. Agrawal et al. proposed a kind of shear lag model to describe tensile fracture process of silica film/pure copper system, and obtained the film tensile fracture strength and interface ultimate shear strength [6]. In their models, they assumed that the interface shear stress between film and substrate is sinusoidal and antisymmetric. But this stress distribution form was suggested to be revised as a quarter segment of an elliptical function proposed by Chen et al. [7]. The influence of residual stress was neglected in their work. Subsequently, Jeong et al. studied the failure behavior of diamond film/

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[*] Corresponding authors.
E-mail addresses: daicuiying@xtu.edu.cn (C.Y. Dai), xichen@columbia.edu (X. Chen).

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Al substrate system under tension with a modified shear lag model. Effect of residual stress on the fracture process and stress distribution in the substrate was considered. A closed-form solution was deduced for appraising film fracture strength and interfacial shear strength [11]. Harry et al. studied the adhesion of the tungsten and tungsten-carbon coatings on steel substrate by using micro tensile experiments with a scanning electron microscope, and obtained the fracture toughness of the coatings with a shear lag model proposed by Hu et al. [16]. Hsueh et al. deduced more rigorous closed-form solution to analyze the edge effects on residual stress in film strip/substrate systems. The stress variation through the film thickness was ignored and it was considered along the substrate thickness in their work [14]. Then they also presented a three-dimensional analytical model to analyze multiple film cracking in SiO_x film on polyethylene terephthalate substrate using both the strength and the energy criteria [15]. McGuigan et al. presented a phenomenological model describing cracking SiO_x film on PET substrate under uniaxial tensile, and proposed a modified shear lag model to predict average crack density and average crack opening as a function of applied strain and material parameters [17]. Tong et al. analyzed the tensile fracture of Al_2O_3/Al-5%Mg system with shear lag model and finite element method, and suggested that the direct strain measurements in the coating are desirable to clarify carefully the cracking opening features and fracture modes as the substrate is loaded in tension [12]. Based on Hsueh's [15] and Frank's works [18], Ahmed et al. considered the effect of plastic deformation of the substrate in as-received samples on the stress-strain behavior and stress distribution in the cracked coating, and discussed the cracking of a brittle diamond coating on a titanium substrate under tensile tests by micro-Raman spectroscopy and modified shear lag model [13]. Fan et al. proposed an effective and efficient lag model to evaluate the quality and load-bearing capacity, failure mechanism of a double-ceramic-layer TBCs system by bending tests with the aid of in-situ SEM observations [19]. Generally, different kinds of shear lag models have been developed to analyze the parallel cracking of coating/film in the transverse direction during unidirectional tensile tests. The crack density increases and the crack spacing decreases as the strain increases, until the crack spacing saturates and no further cracks form. Delamination between the coating and substrate will occur when the interfacial shear stress reaches a critical value due to substrate strain. Major factors including residual stress, bond coat, and substrate plastic deformation would influence the accuracy and validity of shear lag model. For the analysis of residual stress calculation of a coating system, Timoshenko et al. used the classical bending theory to derive the analytical solution model for the elastic thermal stress of the two layer material system [20]. However, both layers were assumed to have the same curvature in his work, and there were three unknowns to be solved for the bilayer cases. Based on the physical method of the experimental procedure, Chu et al. [21] and Chuang et al. [22] re-examined the problem and presented the general solution of the residual stress in the two layer system. Klein et al. proposed a correct formula for estimating the residual stress based on the Stoney equation and the correction factor [23]. Zhang et al. derived an analytical calculation model for evaluating the residual stress of a three layer structure based on the force and moment balances and classical beam bending theory [24]. We established a multiple-layer model for analyzing the residual stress variation of each layer during cycling [25]. Especially, how to consider the effect of multiple intermediate layers on the stress transfer to the coating/film should be resolved [13]. However, most efforts have been concentrated primarily on discussing the closed-form analytical solution of the two layers (coating/substrate) in the previous shear lag models. Little systematic study has been carried out to clarify the stress distribution among the intermediate layers. Only a few studies provide dynamic in-situ strain and cracking evolution during tensions. Eberl et al. observed the cracking evolutions of thermal barrier coating under bending loads through digital image correlation (DIC) technique [26]. Bumgardner et al. combined DIC and finite element method to study the cracking behaviors of TBCs during thermal cycling, revealing the relationship between coating microstructure, deformation, and failure [27]. Therefore, it is necessary to further reveal the tensile failure mechanisms of multiple-layer structure brittle coating/ductile substrate systems by developing shear lag model and using those advanced direct strain measurement tools.

To tackle the above challenges, a major goal of our study is to develop a closed-form general analytical solution of multiple-layer structure shear lag model, which can be used to predict the evolution of stress fields of TBCs during tensions. In the second section, a two-dimensional finite element model was established to estimate the influence of residual stress in the as-prepared coating on the substrate, which further proves the reasonability and feasibility of tensile failure mechanisms of TBCs. As an example, the strain fields and cracking behavior of 8 wt% yttria-stabilized zirconia (8YSZ) TBCs (typical brittle coating/ductile substrate) were in-situ monitored during tensions with the help of non-destructive and non-contact DIC technique. Using the closed-form stress solutions, FEM analysis and critical experimental data, we evaluated the fracture strength, interfacial shear strength, fracture energy and fracture toughness of TBCs. These results are useful for further elucidating the tensile fracture mechanisms of TBCs.

2. Closed-form stress solutions of multiple-layer shear lag model

As an example, we first consider a tri-layer brittle coating/ductile substrate system under external uniaxial tensile load, F, only applied on the substrate. The method can be easier to be extended to three or more multiple-layers. Here the Cartesian coordinates x, y and z are set as shown in Fig. 1. In the coordinate system, the x axis represents the width direction of the coating, the y axis denotes the length direction of the coating, and the z axis is the thickness direction of the coating. As we know, the interface shear stress would induce the deformation of the bond coat and the coating when the substrate is loaded by tensions. When tensile stress in the top coating (TC) reaches its fracture strength, a number of perpendicular cracks occur quickly and propagate toward the TC/bond coat (BC) interface. As the shear stress exceeds the

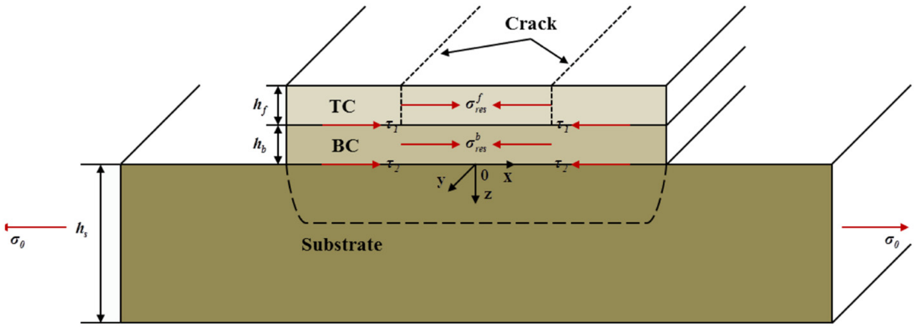

Fig. 1. Schematic diagram of tensile failure of tri-layers structure coating system.