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Enhanced and weakened strength in brittle film-substrate structure

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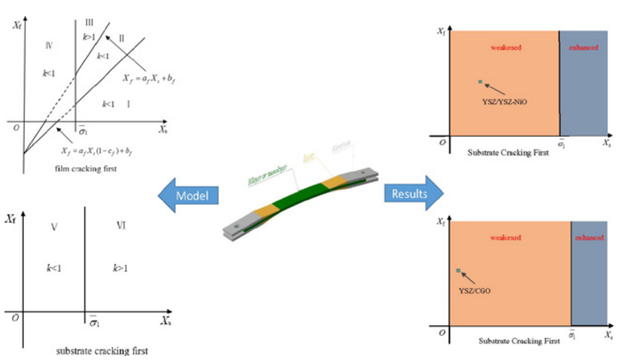
HIGHLIGHT

- Experimental results show that fracture stress of laminated half-cell is lower than that of corresponding anode substrate.
- A model is proposed to predict whether or not the laminated membranes have improved the mechanical behavior of single substrates.
- The weakening behavior of bilayer yttria-stabilized zirconia/gadolinia-doped ceria under uniaxial tensile obtained by present model is opposite to biaxial flexure.

GRAPHICAL ABSTRACT



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ABSTRACT

The mechanical properties of multi-use multilayers including the apparent tensile strength are important for estimating the multilayer's reliability. Yet in biaxial flexure, there exist enhanced or weakened performances when measuring apparent strength of laminates, resembling those found in uniaxial tensile load. In this paper, a model is proposed to predict the effect of thin film on apparent strength in terms of the applied tensile load. Six cases are discussed to characterize the enhanced or weakened performances of laminated membranes by introducing Apparent Strength Enhancement Factor (ASEF). It is notable that the ASEF is independent from thermal residual stresses in the case where substrate can continue to sustain the entire external load solely when film cracks first. Experimental results show clearly that fracture stress of laminated half-cell is lower than that of corresponding anode substrate. The prediction capability of the proposed model has been validated by the experimental results, though additional experiments are still required in order to critically assess the model's predictions over a range of bilayer laminates. In addition, comparison of the reverse mechanical performances between different types of loading reveals that the present analysis is significative for design and discussion of the mechanical integrity for multi-use multilayers.

1. Introduction

Multilayer laminated systems have promising applications in microelectronic, optical, and structural components, electrochemical devices [1–3]. In general, ceramic multilayers are designed primarily from a functional point of view. A certain mechanical strength, however, is essential for maintaining the durability and reliability of multilayered systems during handling or use [4–6]. When multilayered structures are cooled to room temperature from its fabrication temperature or subjected to temperature change during its applications, the differential thermal expansion coefficients (CTEs) of the components will inevitably

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induce residual stresses [7]. Influence of these residual stresses on the mechanical properties of laminated structures has been widely reported by many researchers [6,8–11], and it has commonly been shown that the residual stresses could effectively strengthen the layers under compressive residual stresses and weaken the layers under tensile residual stresses. For example, one strategy of developing tough and strong ceramics consisting of multilayers is to induce compressive residual stresses in the outer layers of multilayers [12].

A. Atkinson and his co-workers have investigated the difference of fracture behavior between bilayer membranes with asymmetrical structure, trilayer membranes with symmetrical structure, and monolithic membranes in biaxial flexure [13–15]. The experiment data show that gadolinia-doped ceria (CGO) laminated with a thin layer of yttria-stabilized zirconia (YSZ) has higher apparent strength than single-layered CGO. The strength of symmetric NiO-YSZ/YSZ/NiO-YSZ laminates is almost equal to that of the un-laminated YSZ plates, while the symmetric LSM/YSZ/LSM laminates show a large and detrimental effect on the strength of YSZ itself. These results manifest that film-substrate systems can enhance or weaken the strength of pure substrate. The various strengths mainly come from two contributions [13,16]. One is due to residual stresses, the other is due to quality of bonding which decides the crack deflection. Nonetheless, causes of the significantly weakening behavior of trilayer membranes still cannot be understood clearly due to the complexity of biaxial flexure [14]. This particular problem reviewed here is to propose straight-sided tensile test which indeed provide an insight to understand the various strengths of laminates for apparent strength measurement. Thus, quality of bonding contributes little to the various strengths of laminates.

Up to now, though several analytical models have been developed to describe the mechanical behavior of multilayers due to both residual stressed and external load [3,6,17–19], the purpose of these previous works is for bending test. In particular, the closed-form solution which relates the strength to the fracture load for thin multilayered disks subjected to biaxial flexural load have been derived [2,20]. Thus, in the presence of residual stresses, one can obtain resultant stresses in the multilayered disks by superposing the thermal stresses [21] on the stresses caused by biaxial flexure tests. Unfortunately, the curvature of asymmetrical structure is excluded from the calculation [20], and the uncertain apparent strength [13] depending on which the side of the laminate is in tension, can still be found in bending test for spherically curved layered specimen. Intuitively, tensile test can avoid the drawback of bending test for spherically curved layered specimen. Furthermore, the non-linear deformation behavior leading to difficulties in bending test and analysis arises due to the large deflection [22]. In principle non-linear behavior can also be avoided in pure tensile tests.

When focusing on the brittle film-substrate system subject to tension, it also can see similar enhanced or weakened performances in biaxial flexure. Since there are few studies focusing on enhanced or weakened performances of laminates under applied tensile stress to date. Hence, it is essential to develop a model to characterize such performances. In this paper, we are intended to establish a model that can predict the enhanced or weakened performances as well as the apparent tensile strength after thin film deposits on substrate with compressive residual stresses in film. To achieve this, the apparent strength of bilayer is calculated depend upon the comparison between the strength and stress distribution of the individual layers. Then, specific results are examined to validate the proposed model. Finally, the model is employed to predict enhanced or weakened performance of bilayer YSZ/CGO reported by A. Atkinson [13] in terms of tensile load.

2. Analytical model

2.1. Tensile model with the presence of residual stresses

As a unit-wide asymmetric-stresses-crooked bilayer strip is stretched, it will deform into a critical state of straight strip which is foundational to subsequential steps of analysis. Hence, this case is studied first. Inspired by Hsueh [18,21,23], during the straightening process, the apparent strain, $\overline{\varepsilon}_a$, which is measured by strain gages pasted onto the center of the free surface of film or substrate, can be also decomposed into an apparent uniform strain component, namely $\overline{\varepsilon}$, induced by external tensile force, and a reduced bending strain component, $\varepsilon_{\overline{M}}$, which is relative to the bending strain component, ε_M, as analyzed in Hsueh's previous study [21]. The decomposition can be expressed in the following equation

$$\overline{\varepsilon}_a = \overline{\varepsilon} + \varepsilon_{\overline{M}} \tag{1}$$

It is worth noting that the reduced bending strain component at the center of the top of film is opposite to that at the center of the bottom of substrate. Besides, the absolute value of reduced bending strain component at the center of the top of film is also not equal to that at the center of the bottom of substrate due to the discrepancy between the position of bending axis and that of centroidal axis in bilayer system.

When bending strain component vanishes, a simple analytic model is shown schematically in Fig. 1 based on strain compatibility theory. According to equilibrium relationship of axial force, external resultant force is given by

$$F = F_f + F_s \tag{2}$$

in which

$$F_f = E_f\overline{\varepsilon}h_f + \sigma_{T,f}h_f \tag{3a}$$

$$F_s = E_s\overline{\varepsilon}h_s + \sigma_{T,s}h_s \tag{3b}$$

where F_i, $i = f$, and s, represent resultant forces in film and substrate, respectively. E is Young's modulus, for convenience, in our model, E_f is assumed to be bigger than E_s. While $\sigma_{T,i} = E_i(c\text{-}\alpha_i\Delta T)$, denotes thermal mismatch stresses, in which $c = \Delta T(E_f\alpha_f h_f + E_s\alpha_s h_s)/(E_f h_f + E_s h_s)$ was solved by Hsueh [21]. Substituting Eqs. (3a) and (3b) into Eq. (2) yields

$$\overline{\varepsilon} = \overline{\sigma}/\overline{E} \tag{4}$$

in which

$$\overline{\sigma} = F/(h_f + h_s)$$
$$\overline{E} = (E_f h_f + E_s h_s)/(h_f + h_s)$$

where F is applied resultant force, $\overline{E}$ is defined as the macroscopic effective elastic moduli in double-phase composites, and $\overline{\sigma}$ is apparent uniform stress corresponding to apparent uniform strain, $\overline{\varepsilon}$ (See Fig. 1.).

When apparent uniform stress equals $\overline{\sigma}_0$, the critical condition where bending strain component exactly disappears is satisfied. For zero bending moment, the balance equation of bilayer with respect to

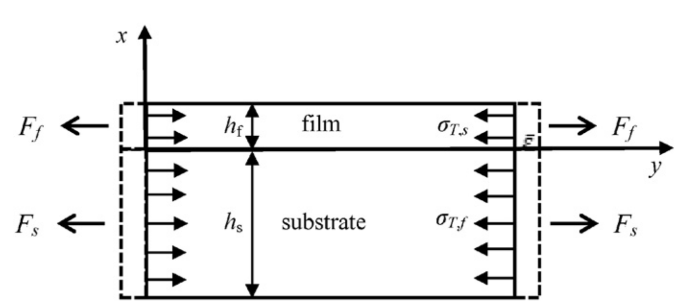

Fig. 1. Sketch of force analysis of film and substrate with the presence of thermal mismatch stresses and external force on the basis of strain compatibility when bending strain component vanishes.