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An experimental and simulation study of interface crack on zinc coating/304 stainless steel

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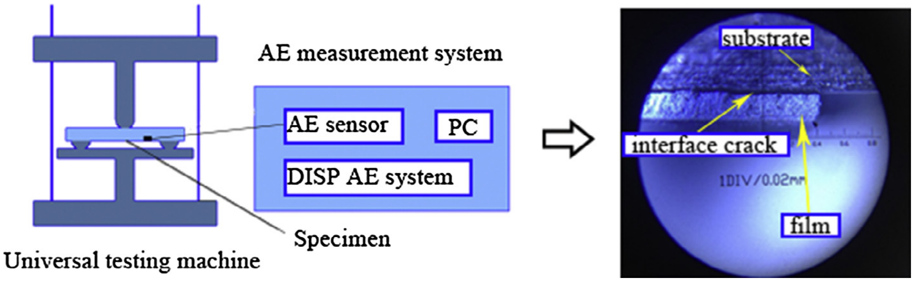
HIGHLIGHTS

- An acoustic emission technique was taken to obtain crack-initiation threshold.
- Interface fracture toughness of zinc coating/304 stainless steel was obtained.
- A FEM was employed to verify the accuracy of acoustic emission method.
- The relationship between crack spacing and the film thickness was obtained.
- Effects of different parameters on the interface bonding strength were analyzed.

GRAPHICAL ABSTRACT



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ABSTRACT

The three-point bending tests were carried out on zinc coating/304 stainless steel with different film thicknesses by means of a universal testing device equipped with an acoustic emission technique to obtain crack-initiation threshold and interface fracture toughness. Tensile test was used to obtain the relationship between crack spacing and the film thickness. Then, the critical fracture toughness and the interface shear stress were studied and utilized to evaluate the mechanical properties of interface layer. At last, a finite element method (FEM) was employed to verify the accuracy of acoustic emission method by the comparison of results between experiment and FEM analysis. Both interface crack propagation length and stress phase angle were analyzed. The results illustrate that the propagation length of interface crack increases with increasing film thickness and external load. However, it decreases with the increase of the interface fracture toughness and the elastic modulus of the film. The stress phase angle at the crack tip declines as the elastic modulus of the film increases. With uniform condition, the interface crack length and stress phase angle change little when the Poisson's ratio increases.

1. Introduction

Film/substrate systems not only works well in the fields of medical and electronic industry, but were highly developed in large bridge engineering, especially in the application of layered composite material where film can serve as anti-corrosion coating [1,2]. According to the theory of fracture mechanism for the film, which is widely applied to analyze the failure of film attached on elastic or plastic substrates, when the film cracks or interface debonding occurs between film and substrate, the structure is assumed to be invalid. Thus, the interface bonding strength

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between film and substrates is an important parameter to evaluate the reliability of the cable system [3].

Surface crack and interface crack may occur under the influence of residual stress or thermal change inside film substrate system [4]. The generation of crack is one of energy-releasing patterns resulting from mismatch of elastic modulus between tensile stress and brittle coating material when the thermal changing or external load occurs [5,6]. Scholars often refer interface fracture toughness to evaluate interface bonding strength. It has been studied that tensile testing can be used to effectively evaluate interface bonding strength between film and substrate [7]. The brittle film bonded to a substrate may fail and an array of uniformly distributed cracks might occur under the action of tensile stress. And with the increase of tensile stress on the substrate, additional cracks will be developed until the saturated crack spacing is fully achieved [8,9]. As the tensile stress rises continuously, the surface crack tip will extend to the interface and the crack may quickly spread along the direction of interface [10]. Later on, the crack spacing will not increase along the external loading, but the coating may peel from the substrate [11]. Some researchers who discovered the equation between interface shear stress and crack density with consideration of interface de-bonding and plastic deformation also pointed out that the interface fracture toughness has little effect on the crack spacing [12]. Some scholars established a simple shear lag model by conducting in-situ observation of coating crack behavior, in which the condition of TiN-coated specimens under tensile stress are monitored by scanning electron microscope and they gave a reasonable prediction for the maximum shear stress at the interface between coating and substrate [13]. Some others analyzed the interface shear stress and strain distribution in the whole film by conducting finite element simulation for cracking and implied the interface shear stress development can be approximated by a quarter segment of an elliptical function instead of sine function. Besides, they asserted that the maximum shear stress appears at the end of the middle crack spacing [14]. Some other researchers implemented a series of tests by applying Acoustic emission (AE) monitoring system to monitor the fatigue of steel bridge component and crack propagation from a stable stage to an unstable one in steel bridge material [15]. Besides, employing AE monitoring system and indentation method, P. Dyjak characterized the initiation and propagation of cracks in brittle materials [16]. However, few scholars used acoustic emission technique and finite element simulation to study the interface fracture toughness of film and the influence of various parameters on the interface bonding strength of film.

In the study of cracking mechanism of the film, interface fracture toughness and stress phase angle at crack tip were widely applied to evaluate the interface bonding strength between brittle film and substrate. In this study, interface crack and bonding strength between film and substrate were analyzed from experiment and interface fracture toughness and crack-initiation threshold were obtained by applying the combination of three-point bending test and acoustic emission technique. In tensile test, critical fracture toughness and critical film thickness were estimated at different strains. At last, different parameters such as interface fracture toughness, elastic modulus and Poisson's ratio that affect the interface bonding strength were analyzed by the comparison of finite element analysis with experiment results.

2. Theoretical analysis

2.1. A modified shear-lag model

Series of periodic cracks on the surface of film result from uniaxial tensile stress. Distance between cracks is an important mechanical property to assess the performance of a thin/substrate system. However, due to the irregularity of cracking space, it is difficult to analyze the relation between crack spacing and film crack. To deal with this problem, the saturated crack spacing and maximum shear stress were always utilized to simulate the film cracking behavior when the uniaxial tensile stress was loaded on the surface of the film. The film/substrate systems will display elastic mismatches and finally suffer from failure marked by de-bonding of film from substrate when experienced with various loads.

Here, we assume that the interface layer is elastic-plastic and the stress distribution is presented in Fig. 1. The tensile strain along the film thickness direction is assumed to be uniform. Furthermore, we suppose that the load will be transferred from substrate to coating when the crack initiates and the displacement distribution of the inter-layers is linear along the thickness direction.

As shown in Fig. 1, d_1 is the thickness of film, d_2 and d_3 are the thickness of interface layer and substrate respectively. The crack spacing of coating is assumed to be λ. The cracked coating segments are distributed on the substrate with spacing of 2a. The distributions of normal stress $\sigma(x)$ and interface shear stress $\tau(x)$ can also be referred in Fig. 1.

After the coating cracks, the relation between normal stress inside coating and interface shear stress can be illustrated in the equilibrium equation as:

$$d_1 \frac{d\sigma(x)}{dx} = -\tau(x) \tag{1}$$

Based on the assumption that the thickness of coating is uniform, the relation between normal stress $\sigma_{\max}$ and interface shear stress $\tau(x)$ should satisfy such conditions as:

$$\sigma_{\max} = \frac{1}{d_1}\int_0^a \tau(x)dx \tag{2}$$

$$\tau(x) = \frac{G[\varepsilon x - u(x)]}{d_2} \quad x \le a_c \tag{3}$$

$$\tau(x) = G\gamma_b = \tau_b \quad x \ge a_c \tag{4}$$

where E and G are the elastic modulus and interface shear modulus respectively, $u(x)$ is the displacement of the coating, ε is the applied strain and γ_b is the plastic shear strain of the interface layer at which the shear stress reaches the critical value τ_b at $x = x_b$. At tensile strain, the equation of displacement can be written as:

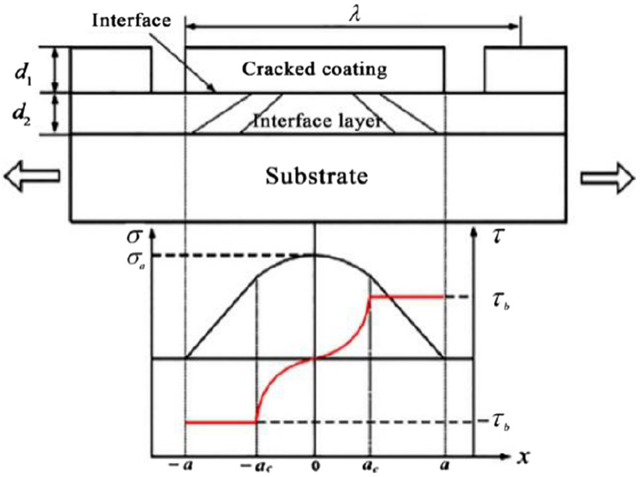

Fig. 1. Illustration of the tensile stress distribution in coating and shear stress distribution in interface layer of a cracked segment coating when substrate is subjected to plastic deformation.