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Mechanical properties of zinc-aluminum film on steel cable substrate in corrosion environment

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ABSTRACT

This paper presents an experimental program aimed at finding out the effect of salt spray corrosion on the mechanical properties of the film in the zinc-aluminum film/304 stainless steel substrate system. At first, the salt spray tests were carried out on the film/substrate specimens to observe the corrosion phenomenon and obtain the porosity of the zinc-aluminum film. Then, the three-point bending tests were carried out on the specimens with different film thicknesses and different corrosion time by a universal testing device equipped with an acoustic emission system (AE) to obtain the effective elastic modulus of the corroded film. After that, the crack-initiation threshold of the film was accurately detected to further obtain the fracture toughness of the corroded film by AE system. Also, tensile tests were used to obtain the critical film thicknesses and the relationship between crack spacing and the film thickness of the corroded film under different strains. The test results illustrated that the effective elastic modulus and fracture toughness of zinc-aluminum film decrease with the increase of corrosion time; the porosity of the film decreases with the increase of the film thickness; the decline rate of the effective elastic modulus and fracture toughness of the corroded film can be decreased by slightly increasing the film thickness; the critical thickness of the film decreases with the increase of tensile strain and the corroded film is easier to crack than the non-corroded film due to the decrease of critical cracking strain.

1. Introduction

As the main load-bearing and force-transmitting components of cable structure, the cable is usually corroded under natural environmental conditions, resulting in the service life of the cable being less than 30 years and causing significant economic losses [1]. In practical engineering, the surface of the cable is usually coated with a metal film to protect the cable from corrosion, so it forms a typical film/substrate system. Likewise, the mechanical properties of the film on the cable surface will also be altered under the corrosive environment during the service process of the cable structure. Therefore, the study of the effect of corrosion on the mechanical properties of the film bonded to metal substrate can provide significant theoretical guidance for protection of the cable structure.

Under atmospheric conditions, pitting, intergranular corrosion, denudation, stress corrosion and corrosion fatigue usually occurs on the surface of the film bonded to substrate in cable structure, among which the pitting is the most common form of corrosion damage [2]. Pitting is a form of concealed and dangerous local corrosion that leads to the creation of small holes of which the depth is larger than the diameter on the surface of the film. The mechanism of autocatalysis inside the pit is generally recognized as the mechanism of development of pitting corrosion [3]. Furthermore, Landes J D and Wei R P illustrated the autocatalytic corrosion battery working mechanism by taking the zinc-aluminum film as the sample [4,5]. Observed from a large number of corrosion tests and engineering accidents, nucleation of stress corrosion cracks and corrosion fatigue cracks are generally formed by corrosion pitting [6,7]. Turnbull divided the process of cracking into four stages: pitting pit formation stage, pitting pit development stage, crack formation stage and crack propagation stage [8]. The nucleation and propagation of cracks caused by pitting are the most common factors contributing to decreasing the mechanical properties of the film. The crack mechanism of the film/substrate system is closely related to the elastic mismatch between the two materials of the film and the substrate, so Dundurs proposed two elastic mismatch parameters (α and β) to describe the elastic mismatch between the film and the substrate [9]. Therefore, it is of great significance to obtain the elastic modulus of film for the study of the crack mechanism of film/substrate system. Likewise, the difficulty of film cracking is characterized by the fracture toughness which is also an essential property of the film. Hutchinson and Suo studied the fracture mechanical property of film/substrate system and multilayer film system [10]. The two parameters proposed by Zhang S and Huang R used to characterize fracture toughness are the stress intensity factor and the energy release rate [11,12]. Moreover, Beuth J L et al. pointed that when the length of crack is more than twice as much as

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the film thickness, the steady state energy release rate of the film crack can be obtained [13–15]. Meanwhile, H.M. Yin and G.H. Paulino et al. studied the elastic solution of brittle film with periodic crack on elastic substrate, and obtained steady-state energy release rate at the front edge of the film crack [16]. However, the current research cannot give a reasonable solution for the effect of corrosion damage on the mechanical properties of the cable film.

For now, scholars mainly study the corrosion of metal substrate in film/substrate system, but the research on the effect of corrosion on the film bonded to metal substrate in cable structure is not enough. In particular, the mechanism of film corrosion damage in film/substrate system has not been fully recognized and concluded. Moreover, the mechanical properties of the film on the cable surface will be altered under corrosive environmental conditions during the service life of cable structure. Therefore, the study of the effect of corrosion damage on the mechanical properties of cable film can provide theoretical guidance for extending the service life of cable structures.

In this study, the porosity, decline rate of elastic modulus and fracture toughness were used to evaluate the effect of corrosion on the mechanical properties of the film. At first, the salt spray tests were carried out on the zinc-aluminum film/304 stainless steel substrate system specimens to observe the corrosion phenomenon and obtain the porosity of the film. Then, the three-point bending tests were carried out on the specimens with different film thicknesses and different corrosion time by a universal testing device equipped with an acoustic emission system(AE)to obtain the effective elastic modulus and fracture toughness of the corroded film. Finally, tensile tests were used to obtain the critical film thicknesses and the relationship between crack spacing and the film thickness of the corroded film under different strains.

2. Theoretical analysis

2.1. Porosity method

In order to study the effect of corrosion pitting evolution on the mechanical properties of the film, the parameter of porosity ξ should be introduced according to the damage mechanics and the equation is shown as [17]:

$$\xi = \frac{\nu}{d \cdot \rho} \tag{1}$$

where ξ is the porosity, ν is the weight loss rate of corroded film, d is the film thickness, and ρ is density of film.

The damage degree of zinc-aluminum film was evaluated by weight loss rate. The calculation formula of corrosion weight loss rate is:

$$\nu = \frac{m_0 - m_1}{S} \tag{2}$$

where m_0 is the initial weight of the film before corrosion, m_1 is the weight of the corroded film after removing the corrosion product, and S is the film surface area.

2.2. Measurement of elastic modulus using three-point bending test

During the three-point bending test, the equation used to obtain the mid-span deflection (ω_0) of substrate specimen without film was [18]:

$$\omega_0 = \frac{\rho L^3}{48 E_{sub} I_0} \tag{3}$$

where P is the concentrated force, L is span length, I_0 is inertia moment of substrate specimen, and E_{sub} is the elastic modulus of substrate.

The inertia moment (I_0) of substrate specimen can be written as:

$$I_0 = BH^3/12 \tag{4}$$

where H is the thickness of substrate, B is the width of substrate.

The Eq. (3) can be rewritten as:

$$\omega_0 = \frac{\rho L^3}{4BH^3 E_{sub}} \tag{5}$$

The film / substrate specimen can be considered as a composite beam composed of two layers of different materials. During the three-point bending test, the equation used to obtain the mid-span deflection (ω) of the film / substrate specimen was:

$$\omega = \frac{\rho L^3}{4B(H+h)^3 BE_{comb}} \tag{6}$$

where I is the inertia moment of the film/substrate specimen, h is the thickness of film, and E_{comb} is the elastic modulus of composite material, which is determined by the elastic modulus of film and substrate.

The inertia moment of the film/substrate specimen (I) was:

$$I = \frac{BH^3}{12} + \frac{\alpha Bh^3}{12} + BH\left[\frac{\alpha h(\mathrm{H}+h)}{2(\alpha h+H)}\right]^2 + \alpha Bh\left[\frac{H^2+Hh}{2(\alpha h+H)}\right]^2 \tag{7}$$

where α is the elastic modulus ratio of the film to substrate.

$$\alpha = E_{coat}/E_{sub} \tag{8}$$

$$I - I_0 = \frac{BH^3}{12}\left(\frac{\omega_0}{\omega} - 1\right) = \alpha\left[\frac{Bh^3}{12} + 025BHh\frac{(H+h)^2}{(\alpha h+H)}\right] \tag{9}$$

$$F = \frac{\omega_0}{\omega} = 1 + \alpha\left[R^3 + 3R\frac{(1+R)^2}{(1+\alpha R)}\right] \tag{10}$$

where F is the ratio of mid-span deflection of the coated specimen to that of uncoated specimen, and R is the ratio of the film thickness (h) to the substrate thickness (H), $R = h / H$. F can be rewritten as:

$$F = (1+R)^3 \frac{E_{comb}}{E_{sub}} \tag{11}$$

The Eq. (10) can be simplified to the following form:

$$a\alpha^2 + b\alpha + c = 0 \tag{12}$$

where $a = R^4$, $b = R^3 + 3R(1+R)^2 + R(1+F)$, $c = 1 - F$.

The α can be obtained as:

$$\alpha = \frac{-A + \sqrt{A^2 + \mathrm{C}}}{2R^3} \tag{13}$$

Therefore, the elastic modulus of the film can be expressed as:

$$E_{coat} = \alpha E_{sub} = \frac{-A + \sqrt{A^2 + \mathrm{C}}}{2R^3} E_{sub} \tag{14}$$

where $A = 4R^2 + 6R + 4 - F$, $C = 4R^2(F-1)$.

2.3. Theoretical calculation of effective elastic modulus

Under the corrosive environmental conditions, the micro-cracks and micro-pores continuously form, develop and penetrate on the surface of the brittle film. Due to the existence of micro-cracks and micro-pores, the mechanical properties of film will change significantly. The effective