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Coating Life Assessment: The Use of Adhesion Strength in Parametric Development in Coating Degradation Evaluation

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Abstract. Most of the steel structures used in industrial and non-industrial applications are exposed to outdoors weathering conditions. Organic coating typically protects them from corrosion. The maintenance actions can be done efficiently only if there is sufficient information of the condition. Therefore, the deterioration of the coating system and its lifetime has to be assessed accurately. This paper focuses on the development of parameters based on adhesion strength useful for that purpose. Three parameters are proposed, namely stress intensity factor, strain energy density, and J-integral.

Introduction

Significant amount of financial loss is incurred every year as a result of premature failures of paints and coatings. The cost to repair such failures can easily overshadow the initial cost of painting. Additional liability may also be expected if a facility must stop operation for the necessary repairs to be made. This is the rationale of the coating life assessment and failure analysis. It was proposed that in general, coating deterioration and degradation could be modeled in three ways [1]:

- •As a black-box statistical time to failure (such as lifetime distribution);
- •As a grey-box stress-strength model based on a measurable quantity indicating time-dependent deterioration and failure;
- •As a white-box model through simulation of the physics of measurable deterioration and failure.

In this research, we focus on both the third method with some manipulation similar to that of life assessment methodology for metal structures [2–4]. A number of papers have been published on the degradation of systems exposed to outdoor weathering conditions. For example, Chan and Meeker [5] relate degradation to environmental factors, such as the weather. These factors are transformed into a degradation rate. A time series modeling approach was proposed to predict daily degradation. Heutink et al. [6] describe how the maintenance methodology used in the Netherlands was applied to protective paint systems. The lifetime-extending maintenance model, in which deterioration is modeled by a gamma process with expected deterioration non-linear in time, is applied successfully to optimize maintenance of the coating of the Haringvliet storm–surge barrier. Among other deterioration parameters, this paper emphasize on the adhesive strength taking the advantage of the blister formation and development as a symptom of the coating deterioration.

Blistering in Coating

Blisters are local defects due to the pressure exerted by an accumulation of substrate at the coating-substrate interface in conjunction with loss of adhesion and distention of the coating. At these local regions, corrosion of the substrate may occur. Typically the loss of coating adhesion is related to the development of a cathodic area under the coating adjacent to the defect. Oxygen also permeates the coating while ionic materials are leached from the substrate or from the coating and these all concentrate to make an electrochemical corrosion cell beneath the blister. Therefore blisters are an early sign of corrosion but are often neglected. Conversely, the elimination, reduction, or delay in blister formation will delay the onset of corrosion of the steel substrate.

Several different forms and mechanisms for blister formation are postulated the most likely possibilities are identified here. In general, the mechanism of blistering is attributed to osmotic attack or the presence of defects in the coating interfacial region, in combination with the influence of moisture. The following sequence of events leading to blistering is general to most types [7,8]:

- The film absorbs water from solution, possibly containing dissolved salts. Or water and/or corrosive substance enter through some coating damage such as defect/cut at the coating.
- Once sufficient chloride ions pass through to the underlying metal, primary corrosion is initiated at sites along the interface, particularly at existing defective areas or areas of substrate contamination.
- As corrosion proceeds at the anodic sites under the film, ions build up at cathodic sites.
- The alkaline environment at the cathodic sites weakens or destroys the adhesion of the film while producing osmotically active substances at the coating/metal interface.
- The presence of these active substances at the interface causes osmotic (or endosmotic) passage of water from the coating surface to the interface resulting in pressures that exceed the interfacial strength of the film and eventually the fracture strength of the film causing further deadhesion or coating rupture.

Several mechanisms are generally proposed to explain blister formation: volume expansion due to swelling, gas inclusion or gas formation, electroendosmotic blistering, osmotic blistering, and cathodic blistering.

The idea of coating degradation is similar to that of the delamination [9] that metallurgical failure analysts are familiar with. Figure 1 shows how typical delamination is found in the field.

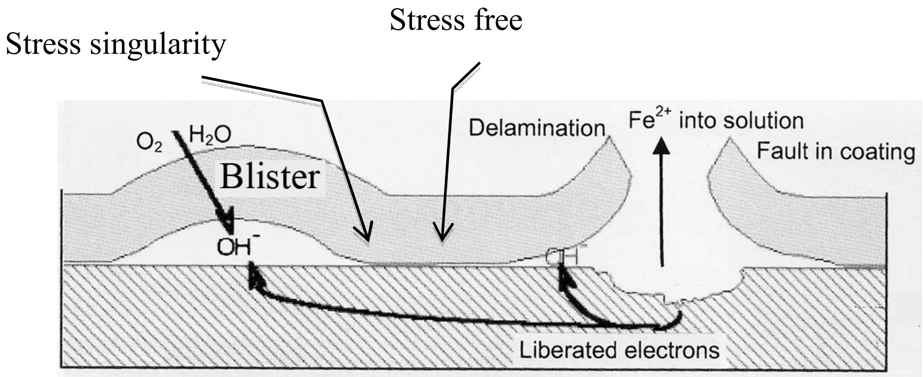


Figure 1. Corrosion delamination mechanism [10].

In the metal/composite society, the delamination is often approached by using the fracture mechanics concepts. In this research, mimicking those approaches, fracture mechanics approach is used.

Fracture Mechanics Approach in Blistering Development/ Propagation

Regardless of the types of the blistering, it is evident that blistering can be used as a parameter to detect the lifetime of the coating. This is very convenient since it is strongly related to adhesion strength. However, to use the adhesion strength directly would be impossible, since its value is too dependent on so many factors. Therefore, three approaches based on fracture mechanics are postulated. Fracture mechanics deals with the study of the propagation of cracks in materials. Its applications on areas other than mechanics are enormous, especially in materials science area [10]. In principle, our selection of the parameter must be able to describe and accommodate the stress singularity at the crack tip as shown in Figure 1. Near the tip where the blister is propagating is defined as stress singularity area. The pressure difference between the atmospheric pressure and internal pressure of the blister is the driving force for the crack propagation, which in this case is blister propagation.

Using Stress Intensity Factor (SIF): SIF is typically used to govern crack propagation on a brittle metal. In here, the SIF due to the pressure difference *p* can be converted to SIF analytically or computationally. The use of the weight function is one of the easiest ways to derive the SIF. The detailed discussion on the method is available elsewhere [10]. In here the SIF of modes I and II respectively become:

$$K_I = \alpha \cdot p_y E \sqrt{y_c} \Big/ (1-v^2) \tag{1a}$$

$$K_{II} = \alpha \cdot p_x E \sqrt{y_c} \Big/ (1-v^2) \tag{1b}$$

where K_I and K_{II} are the mode I and mode II of stress intensity factors, p is the pressure difference (adhesion strength), E is the Poisson's ratio and α is the blister shape function and y_c is the blister height. Alternatively, the SIF can also be obtained by numerical method, see Figure 2.
Typical shape function of the blister can be obtained by cross sectioning the blister and approach it using the displacement polynomial function, such as:

$$u(x,r) = y_c \cdot \sum_{i=0}^{n} \left(\frac{x}{r}\right)^i \tag{2}$$

which the value of α can be computed from

$$\alpha = \int_0^r \frac{\partial u(x,r)}{\partial r} dx \tag{3}$$

where r is the blister radius.
Using Strain Energy Density (SED)*:* Based on SED a mixed mode analysis can be done easier. We published the result of the parameter using SED elsewhere [11]. Our proposed parameter using SED is as follows:

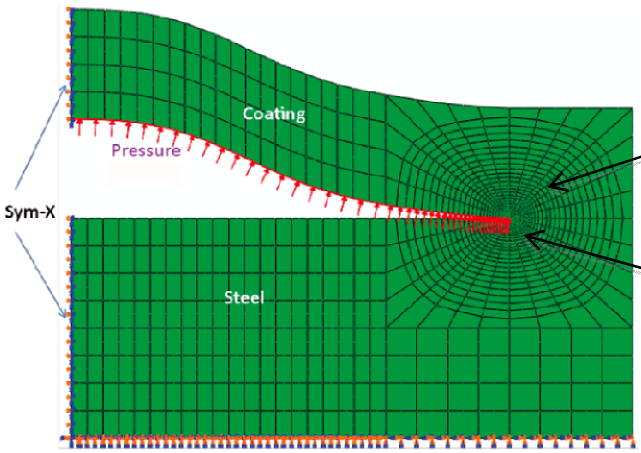
$$SED = \frac{\alpha \cdot E\sqrt{y_c}}{(1-v^2)} (a_{11} \cdot p_x + 2a_{12} \cdot p_x \cdot p_y + a_{22} \cdot p_y) \tag{4}$$

where *SED* is the strain energy density factor, p is the pressure difference (adhesion strength), E is the Poisson's ratio and α is the blister shape function.

Using J-Integral (J-int): J-int is extension of SIF in term of the stress linearity coverage. While the SIF is popular in governing the crack propagation in brittle material, J-int is also widely accepted in non-linear elastic material. The drawback of this method is its difficulty in the usage analytically outside the area of linear elastic. Within the area of linear elastic, its value is strongly related to SIF. However, outside the linear elastic area, practically it relies upon computational approach alone. Figure 2 shows the computational approach of J-int calculation.

How the Parameter Useful for Coating Life Assessment

In here, similar to the metal delamination problem, the parameters, SIF, SED, or J-int, can be used as a parameter for coating life assessment. The time starts with t_0, where the coating is applied, and the parameter has the highest value. It ends at t_{end}, where the coating has chemically deteriorated, where the value of the parameter become negligible. Time t_C is the time where coating is no longer usable, which is several percentage before t_{end}. A graph to relate the time versus the parameter can be made and used for life assessment. The advantage of this approach is that any accelerated test module can be used, since the time is similar to that of normalized time. The detailed usage of the parameters is the same with the previously published method using the SED approach [12]. Therefore, the readers are advised to refer to it directly.



J-int can be obtained by contour spider-web in FEA.

SIF can also be obtained numerically using the same method or different methods.

Figure 2. Modeling of the coating blistering using FEA to obtain stress singularity parameters, such as SIF, SED, or J-int.

Summary and Conclusions

Fracture mechanics methods are used to explore new parameters for coating (degradation) life assessment. Three candidates are selected in here; stress intensity factor, strain energy density, and J-integral. From the practical point of view, among the three, the stress intensity factor is the easiest to use. This also carries the drawback of being least reliable. J-integral, on the other hand, is the most accurate method. However, it is rather not practical since it is involved computation utilizing finite element analysis. It is worth noting that this paper is written at the early stage of the research and therefore supporting experimental data is not available yet.

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