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Analysing the coupled effects of compressive and diffusion induced stresses on the nucleation and propagation of circular coating blisters in the presence of micro-cracks

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ABSTRACT

This paper presents a study of delamination of coating with micro-cracks under compressive residual stress coupled with diffusion induced stress. Micro-cracks in coating provide a passage for corrosive species towards the coating-substrate interface which in turn produces diffusion induced stress in the coating. Micro-cracks contract gradually with increasing compressive residual stress in coating due to thermal expansion mismatch which blocks the species diffusion towards the interface. This behaviour reduces diffusion induced stress in the coating while compressive residual stress increases. With further increase in compressive residual stress, micro-cracks reach to the point, where they cannot be constricted any further and a high compressive residual stress causes the coating to buckle away from the substrate resulting in delamination and therefore initiating blistering. Blistering causes the contracted micro-cracks to wide open again which increases diffusion induced stress along with high compressive residual stress. The high resultant stress in coating causes the blister to propagate in an axis-symmetric circular pattern. A two-part theoretical approach has been utilised coupling the thermodynamic concepts with the mechanics concepts. Thermodynamic concepts involve corrosive species transportation through micro-cracks under increasing compression, eventually causing blistering, while fracture mechanics concepts are used to treat the blister growth as a circular defect propagation. The influences of moduli ratio, thickness ratio, thermal mismatch ratio, poisson's ratio and interface roughness on blister growth are discussed. Experiment is reported for blistering to allow visualisation of interface and to permit coupled (diffusion and residual) stresses in the coating over a full range of interest. The predictions from model show excellent, quantitative agreement with the experimental results.

1. Introduction

Protective coatings tend to prevent the effects of physical and chemical attack on the substrate. However, in some circumstances this attack is promoted, rather than hindered, and this results in the delamination of coatings [1]. There are several causes of coating delamination such as micro-defects at the coating substrate interface and micro-cracks in coatings [2,3]. Most coating systems suffer deterioration due to the presence of coating micro-cracks. These micro-cracks are produced at the time of fabrication or are very likely to have been caused by the difference in coefficients of thermal expansion of coating and the steel substrate. These micro-cracks may act as pathways for corrosive agents to diffuse through the coating barrier, which may result in the loss

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of adhesion between coating and substrate thus causing delamination [4]. Stress corrosion cracking (SCC), due to micro-cracks opening in a corrosive environment, results when the materials are subjected to tensile residual stress in a corrosive environment [5–8]. Contrary to this, compressive residual stress causes the contraction of micro-cracks resulting in the inhibition of corrosion which proves beneficial for the control of SCC [9–11]. It is implied that micro-cracks behaviour in materials correlate to residual stresses in the materials. Along with the residual stress, the chemical stress (or diffusion induced stress) also influences the micro-cracks behaviour and therefore, affects the stability and reliability of materials [12]. The behaviour of micro-cracks in coatings under the coupling effect of residual stress and diffusion induced stress can result in early failure of coatings due to delamination which is a conventional problem and is currently receiving greater attention from the coatings industry [3].

For residual stress analysis, vast literature has been available since the pioneering work of Stoney [13] on the formulation of stress variations derived from the experimental measurement of system curvature changes. Later on, based on Stoney formula various models have been developed [14–20] to address numerical computations of uniform residual strain in the coating. Recently, a model using computational techniques identified that the corrosion at the interface of coating and substrate is inhibited by compressive residual stress in coating due to the contraction of open corrosion paths in the coatings [21]. However, the model did not address the effects of the compressive residual stress over pre-existing structural micro-cracks in the coating and how compressive residual stress in coating may lead to complete delamination forming blisters. Hence the presented work contributes to significant knowledge creation in this theme.

Meanwhile, for diffusion induced stress various numerical models [22–28] were developed in previous decades after a series of studies on diffusion induced stress in the coating system. Many of these models were based on the pioneering work of Podstrigach [29]. In recent years, models using advanced computational methods involving diffusion induced stress have been developed [2,30–32]. However, it is worth noting that the occurrence of the residual stress in the coating due to mismatch in thermal expansion cannot be neglected. Therefore, both the diffusivity and concentration of corrosive species will be enhanced by the hydrostatic stress [33]. Actually, the existing stress may speed up the diffusivity by opening the micro-cracks under tensile behaviour or hinder the diffusivity by constricting the micro-cracks under compressive behaviour.

When the thermal expansion of coating is greater than the substrate i.e. $\alpha_c > \alpha_s$, the positive temperature diversification ($\Delta T > 0$) from its fabrication temperature will induce compressive residual stress in the coating [10,34–37]. The pre-exiting micro-cracks in coating will gradually contract with increasing compressive residual stress on temperature rise. The increasing compressive residual stress will constrict the pathways for the diffusing corrosive species towards the interface. This will reduce the effect of diffusion induced stress in coating while the compressive residual stress will be high. To this point of rising ΔT, the direction of diffusion induced stress can be treated as opposite to that of the compressive stress gradient. With the further increase in compressive residual stress, the micro-cracks will constrict to the point where they cannot be constricted further and the coating will buckle away from the substrate under high compressive loading. Buckling will cause the tightly closed micro-cracks to wide open again, letting the diffusion of corrosive species. The buckling of coating from the substrate will form circular blister. At this point the direction of diffusion induced stress can be treated as similar to that of the compressive stress gradient. The high resultant stress in coating will cause the blister to propagate in an axis-symmetric circular pattern.

Previous research has analysed [38–48] coating substrate system without the inclusion of micro-cracks. However, this research aims to analyse the coupling effects of residual and diffusion induced stresses on blister growth in the presence of coating micro-cracks. The analysis is performed within the framework of thermodynamics coupled with mechanics. The novelty within this research is the utilisation of two-part theoretical approach for circular blister nucleation and propagation incorporating the effects of coating micro-cracks, which has not been used in previous blistering models [49–55]. The combination of thermodynamics and mechanics approaches provides a novel technique to understand coating failures with micro-cracks. The diffusion concepts are used to model the transport of corrosive species through micro-cracks, under increasing compression, eventually causing blistering, while the fracture mechanics concepts are used to model the blister propagation as circular interfacial defect growth. The theoretical model is based on the experimental study which is conducted to analyse the key role that residual and diffusion induced stresses play in the nucleation and propagation of blisters in the presence of micro-cracks. The experiments validate the predications of theoretical model which are later highlighted in the simulation part. The predications of circular blister growth show excellent quantitative and qualitative agreement with the experiments. This research is significant in terms of wider industrial application both in static and dynamic load applications.

2. Experiment

2.1. Sample preparation and experimental setup

A thin carbon steel (AISI-SAE-1020) substrate with thickness $s = 0.01$ cm was used to prepare seven coated test samples with dimensions 15 cm × 10 cm each. The chemical composition of the carbon steel is 0.18–0.23% C, 0.3–0.6% Mn, and balanced Fe [56]. The purpose of preparing seven test samples was to analyse cross sectional (by using six out of seven samples) and top view (by using remaining one sample) microscopic images during the experimental procedure. The cross sectional analysis is a destructive process and therefore one of six samples at a specific test condition was taken out of the experimental procedure every time for the cross sectional analysis. With such approach, it was possible to attain six distinct cross sectional images (one image for each sample of the six samples) at six different experimental conditions during the experimental procedure. The cross sectional analysis of six samples under the microscope was performed by using a magnification of 10×. The last remaining seventh sample was not required to be taken out of the experimental procedure every time for the top view surface analysis.