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Visualizing the impact of mechanical strain and the environment on pipeline coatings from a three dimensional perspective

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ABSTRACT

The effects of organic coating's structural characteristics such as the void structure on pipeline coating degradation under combined mechanical and environmental effects have been studied using the data-constrained modelling (DCM) technique with multi-energy X-ray computed tomography (X-ray CT), in conjunction with three dimensions (3D) finite element analysis (FEA) modelling that provides a qualitative interpretation of the DCM microstructure data in terms of the concentration of stress at heterogeneous interfaces within coatings. It has been found using the DCM technique that unstrained coating films are heterogeneous in nature, showing characteristic features similar to the D-type and I-type coating regions espoused in the historical literature. For strained coating films, the interfaces of heterogeneities were seen to provide preferential sites to form voids by mechanical straining. Moreover, the void network was also found at the interfaces of the inorganic fillers and the organic polymers. These have been corroborated by simulation carried out using the FEA modelling, with a 3D model indicating the role of fillers in the formation of a tortuous void network in a heterogeneous coating subjected to both mechanical straining and corrosive environment.

1. Introduction

The durability and degradation of organic coatings, which are widely used for mitigating corrosion of buried high pressure oil, gas and water pipelines, are known to be affected by complex factors including mechanical stress and the corrosive environment. For instance, pipeline coatings are exposed to the influence of various forms of mechanical stresses during the pipeline installation and operation, as a result of horizontal directional drilling, hydrostatic testing, the internal fluid pressure, the soil stress and other forms of mechanical effects [1]. These stresses could work concomitantly with the corrosive components in soil such as moisture and ions. The ingress of electrolytes, containing corrosives, plays an important role in facilitating the degradation of coatings [2,3]. The propagation of electrolyte into the coating occurs through a number of pathways in the coating that may be categorised into three major types of internal void spaces in the coating – free volume [4–6], microcapillaries [4,7], and larger voids. For a coating with a soluble component, it was recently shown that a fourth transport pathway for electrolyte can be created through networks formed by dissolved particles [8–10]. With respect to free volume in the polymer component of the coating, Rudnick et al. [6], has described it as the free space between the individual polymer molecules in the coating. A network of interconnected free volume and small void spaces form microcapillaries, also referred to as microporosity by Budd et al. [4]. Electrolyte ingress through this free volume was modelled in two dimensions by Putta et al. [5]. Gebäck et al. [11] attempted to visualize these microcapillaries by imaging the epoxy moulding compound using confocal laser scanning microscopy. The images obtained were treated in software such as FIJI and MATLAB to obtain 3D images of the observed epoxy polymer. This revealed the presence of the fluid flux lines which were proposed to be the electrolyte paths, and may correlate with the microcapillaries described above.

While these studies provide some important insights into void formation in coatings, the characterisation of these voids is still difficult and is in its infancy. Moreover there are many applications where the coatings have a number of inorganic components which add complexity to the generation of transport paths through coatings. For example, in coatings containing soluble inhibitors, it has recently been proposed, on

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the basis of computed tomography (CT) and positron annihilation spectroscopic studies, that the only transport path for an inhibitor is through microvoid pathways created by the dissolution of the inhibitor. These void networks are fractal in nature and transport through them does not exhibit Fickian behaviour [10]. Additionally, when in service, most coatings are subjected to mechanical strain usually in cycles. Previous work by Ranade et al. [12] carried out using a novel laboratory scale setup [13] where a coated substrate was subjected to a corrosive environment while under low plastic strains showed that an increase in the mechanical strain level led to an acceleration of electrolyte ingress, suggesting the development of new void networks associated with the application of mechanical strain. Preliminary results presented in that work indicated that these void networks that were developed under strain were created at the interface between inorganic fillers and the organic components.

The purpose of this paper is to explore in more detail the nature of the void networks that develop in high solids coatings through a new approach of characterizing coatings under complex mechanical and environmental effects. The internal structure of the coating was characterized using the data-constrained modelling (DCM) technique with multi-energy X-ray computed tomography (X-ray CT) in order to investigate the epoxy coated substrates subjected to mechanical strain and environment effects [14]. DCM is known to offer an avenue to measure substructures within the inorganic/polymer composite on the micrometre to hundreds of micrometres scale [15–18]. This approach therefore allows the determination of the spatial distribution of void, polymeric and inorganic components within the coating. These studies have been supplemented in a qualitative fashion using finite elements analysis (FEA) modelling that has been extended to three dimensions (3D) as distinct to the 2D studies of the previous paper in order to facilitate the correlation with the features observed using the DCM technique. This provides a qualitative interpretation of the DCM microstructure data in terms of the concentration of stress at heterogeneous interfaces within coatings.

2. Experimental

2.1. Materials

Steel samples of grade C450 were used as metal substrates, the nominal composition of which is given in Table 1 [19]. For samples to be subjected to mechanical straining, tensile dog bone samples were prepared out of the steel plate. The C450 steel plate was obtained in the form of a 1.6 mm thick rectangular hollow section. The four sides of the section were separated by cutting along its edges using a vertical band saw. The individual plates obtained were then cut into rectangular strips of about 2.5 cm width which were then subjected to further cutting on a milling machine to prepare tensile dog bone shaped samples, according to the ASTM E8 standard. All the steel samples were then painted with a coat of a high build epoxy coating.

Table 1
Chemical composition of steel as C450 given by AS/NZS 3678. [10].

Element	%	
Carbon (C)		0.22
Silicon (Si)	Minimum	–
	Maximum	0.55
Manganese (Mn)		1.80
Phosphorus (P)		0.040
Sulphur (S)		0.030
Chromium (Cr) (Max)	Minimum	–
	Maximum	0.25
Nickel (Ni)		0.50
Copper (Cu)	Minimum	–
	Maximum	0.60
Molybdenum (Mo)		0.35
Aluminium (Al)		0.100
Titanium (Ti)		0.040
Micro-alloying elements: Vanadium		0.10% maximum.
Micro-alloying elements: Niobium		0.06% maximum
Micro-alloying elements: Niobium plus vanadium plus titanium		0.15% maximum
Carbon equivalent (CE)		0.48

Table 2
Composition of high build epoxy coating used in this work [11].

Resin		Hardener	
Ingredients	%	Ingredients	%
Epoxy Resin	15–40	N-Aminoethylpiperazine	40–70
Calcium Carbonate	15–40	Epoxy Novolac Resin	15–40
Talc	15–40	Nonyl Phenol	10–30
Bisphenol F Epoxy	10–30	Amino Silane	3–7
Aliphatic Glycidyl Ether	3–7	Bisphenol “A”	3–7
Orqanophillic Clay	1–5	Polyfunctional Aziridine	3–7
Titanium Dioxide	1–5		
Phenyl Carbinol	1–5		
Fumed Silica	0.5–1.5		
Orqanophilic Clay	0.5–1.5		
Propylene Carbonate	0.5–1.5		

The coating chosen for this work is a two-part high build epoxy used in the pipeline industry. It is an amine-cured epoxy comprising major fillers of calcium carbonate ($CaCO_3$) and talc. According to its materials safety data sheet [20] as shown in Table 2, it also consists of other fillers in small amounts such as organophilic clay, silicon dioxide, and titanium oxide, among other components. The coating is usually employed as a field joint coating for girth welds, boring application welds, fittings, as well as for directional drilling and road bore pipelines, among others [21]. The resin and the hardener of the coating were mixed together in the ratio 3–1 by volume. It was then applied on the steel plates using a sheen drawdown applicator. The average dry film thickness selected for all the experiments was 230 μm. The coating was allowed to cure for at least one week under ambient conditions, before being used for experiments.

2.2. Mechanical straining

The new laboratory scale tensile testing setup described in references [12,13] was employed to enable the tensile elongation of coated steel samples. The testing setup consists of a rectangular frame with a lower stationary clamp and an upper moveable clamp. Tensile samples were fitted between these clamps by means of screws. A strain gauge was used to monitor the strain. More details about the experimental setup can be found in references [12,13]. In this work, the tensile samples were loaded to a mechanical strain of 2.5%. Under the test condition, the mechanical behavior of the coating was significantly influenced by the presence of the steel substrate and the mechanical behavior of the coated steel is dominated by the steel substrate. The strain of 2.5% lies in the low plastic region of the stress strain curve for the C450 steel, as shown in Fig. 1. The low plastic region is the focus of this work, as this strain has been observed to lead to structural modifications in the coating without leading to the baring of metal substrate underneath. This strain has been seen to lead to a degradation of the electrochemical properties of the coating in a previous work by the authors [12,13].

2.3. X-ray computed tomography

The coating has been studied using X-ray CT under three conditions (i) as prepared, (ii) sample strained at 2.5% in air, and (iii) sample strained at 2.5% and exposed to electrolyte for 27 days. For each piece of coating sample, two sets of X-ray absorption projection images were acquired in Shanghai Synchrotron Radiation Facility (SSRF) at the