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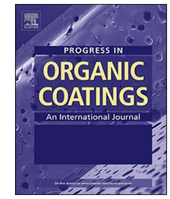

The initiation and propagation of coating morphological and structural defects under mechanical strain and their effects on the electrochemical behaviour of pipeline coatings

S. Ranade, M. Forsyth, M.Y.J. Tan*

Institute for Frontier Materials and School of Engineering, Deakin University, Waurn Ponds, Geelong, Victoria, Australia

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A B S T R A C T

Polymeric coatings on buried high pressure steel pipelines are subjected to multiple complex influences of mechanical stresses, the underground soil corrosion environment and cathodic protection (CP). It is known that an applied mechanical strain can cause the formation of morphological and structural defects in coatings; however the impact of such mechanically induced defects on the coating's corrosion resistance has not been examined sufficiently. This paper reports an investigation of the influence of such coating defects on a typical high build epoxy pipeline coating by assessing the coating's electrochemical properties using electrochemical impedance spectroscopy (EIS) and a new tensile–electrochemical testing setup. In situ and ex situ scanning electron microscopy was employed to trace and characterise coating defects from the very early stages of micro shear bands initiation to the formation of full coating cracks. Finite element analysis has been employed to understand the influence of strain on the initiation and propagation of coating defects by modelling stress distributions. A correlation has been found between the applied strain levels and the corresponding coating resistance and capacitance values. The strain distribution and shear stress distribution patterns obtained using the finite element analysis were used to explain typical features observable in EIS data based on the formation of electrolytic pathways through unstrained and strained coatings. This approach has been consolidated into a two dimensional model proposed to explain the electrolyte movement in a coating impacted by applied mechanical strain and environmental exposure.

1. Introduction

Energy pipelines buried underground are protected from external corrosion by means of organic coatings and cathodic protection (CP). Coatings are considered to be the first line of defence against corrosion of steel pipelines that are exposed to complex soil environmental conditions [1]. Commonly applied pipeline coatings are polymers including coal tar epoxy, polyethylene, high build epoxy, polyurethane, and polyolefin [2]. Such coated pipelines are not only exposed to corrosive soil environments, but they may also concomitantly be under the influence of mechanical stresses in the form of internal pressure exerted during the hydrostatic testing and flow of internal fluids, or external pressure such as those imposed during the field bending of pipes [3]. This mechanical influence may lead to accelerated degradation of the coating's mechanical, electrochemical and barrier properties, leading to premature failures. Therefore, it is critical to study the impact of mechanical stresses on coatings in order to gain a better understanding of the nature and the extent of organic coating degradation under complex pipeline scenarios.

Currently high build epoxy coating is one of the most widely used coating types in the pipeline industry and therefore it is selected as a typical coating to study in this work. Although there has been work done on the mechanical properties of the epoxy polymer in the past [4–9], little has been done to understand their role when it is utilized as a coating on a metallic substrate subjected to mechanical stresses. Morgan et al. [10] carried out an investigation where microscopic changes occurring under mechanical stresses were examined in the case of a thin unpigmented epoxy polymer, in the form of coatings as well as free films. The epoxy polymer was coated on brass substrates (0.1 mm thickness) and was elongated to a high strain of about 10%. The subsequent bright field transmission electron microscopy (TEM) investigation, performed using the carbon-platinum replicas of the epoxy surface, revealed the presence of crazes and shear bands. Voids appeared to have formed at the tips of the crazes as a result of the applied stress. It was hypothesised that the voids coalesced to form bigger voids and lead to fracture. The crazing and shear bands have also

* Corresponding author.
E-mail address: mike.tan@deakin.edu.au (M.Y.J. Tan).

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(a)
(b)
(c)

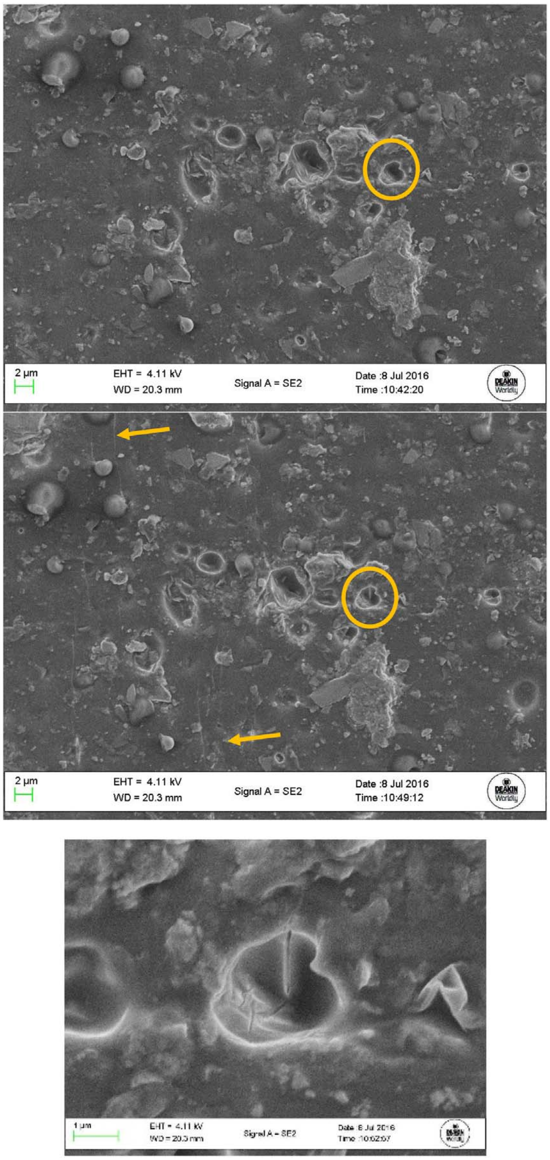

Fig. 1. Morphology of coating at – (a) elastic load; and (b) plastic load. Arrows denote shear bands, circles denote formation of defects at the pre-existing pores in the coating. Image (c) shows the magnified circled pore, showing a crack of an approximate width of 150 nm.

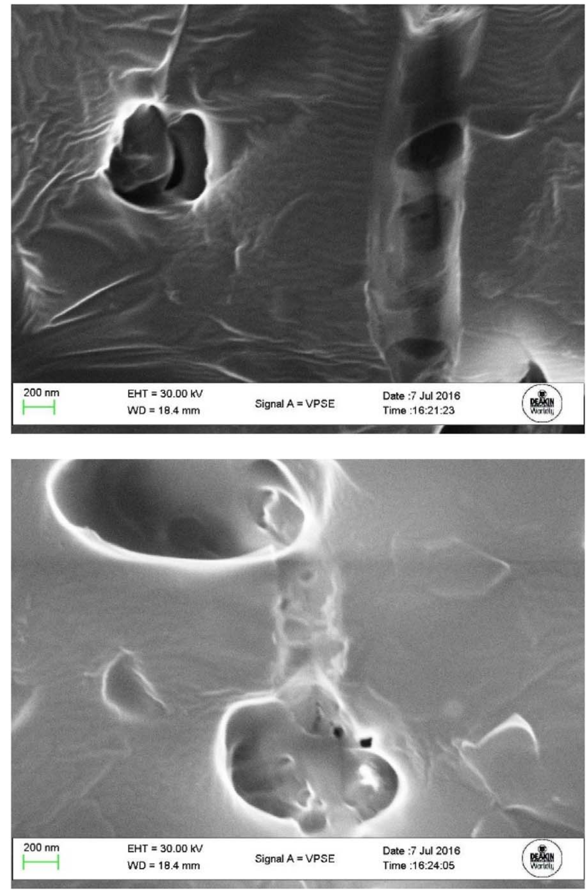

Fig. 2. Formation of nano shear bands as depressions in the coating, depicted by arrows.

been observed in subsequent research by various groups during the fracture studies of epoxy [5,6,11].

Such morphological changes may alter the electrical and electrochemical properties of the polymer that could impact the coating's ability to protect against a corrosive environment. One way of measuring these changes in coating properties is by utilizing electrochemical impedance spectroscopy (EIS), which has previously been attempted by a few researchers [12–24]. While some reports [13,16–18,21,22] have selected the stresses in the elastic region of the coating polymers for the purpose of EIS analysis, others have chosen to employ stresses in the plastic region up to strain levels as high as 25% [12,19,20,23,24]. A typical example of the use of plastic stresses is given in the work performed by Lavaert et al. [20]. Lavaert et al. made use of a silicon coated galvanised steel plate, with a zinc layer (25 µm thickness), a primer, and a top coat of a silicon polyester coating (25 µm thickness). The coated plates were subjected to uniaxial tensile elongation. The surfaces of the coatings showed the presence of Lüder bands at a strain of 1%, while higher strains of 5% showed the occurrence of cracks. The cross-section for the coated substrate at 1% strain showed presence of microcracks, and decohesion. These features were similar to those observed for the fractured epoxy polymer described in the literature previously [5,6,10,11]. The strained samples were exposed to ASTM D 1147 seawater, and were examined using the EIS technique. The samples with a higher deformation level showed lower impedance values, and also showed lower coating resistance values. This trend continued at longer exposure times as well, with the rate of the reduction of the impedance being higher for the higher deformation. The coating capacitance showed a higher value for the larger value of deformation. While the strain levels of 1–4% have also been included, the focus of the study was broadly on the electrochemical impedance variations between intact coatings, and coatings which had cracks large enough to expose bare metal and engage the metal substrate in the corrosion process.

A major weakness in all these tests reported in the literature is that they have been conducted ex situ, leaving an uncertainty in the reliability of results because ex situ measurements may be affected by the occurrence of a relaxation in the applied strain, especially in the lower strain values. Another knowledge gap is that some of the past research on thermosetting polymers such as epoxy coatings has primarily been in the elastic region, therefore the behaviour of their cracking under the applied mechanical load in the plastic region have not been understood, although thermoplastic polymers such as polyester and polyethylene have been studied under enough strain to induce cracking defects. Moreover, some of the studies do not take into account the role of the fillers in the mechanical behaviour of a coating.

Hence, in this study, high build epoxy coating has been investigated