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VISUALIZING DYNAMIC CORROSION AND COATING DISBONDMENT PROCESSES ON SIMULATED PIPELINE CONDITIONS

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SUMMARY: This paper presents an overview of several new methods we developed to overcome major difficulties in monitoring and evaluating buried pipeline corrosion and coating failure under complex environmental conditions. We take advantage of the high temporal and spatial resolution of an electrochemically integrated multi-electrode array for probing localised electrode processes evolving and propagating dynamically on pipeline steel surfaces under the effect of cathodic shielding, anodic transients and coating disbondment. We present cases to illustrate: (i) monitoring localised corrosion under dynamically changing electrochemical environments beneath a simulated pipeline coating, (ii) visualising passivity and its breakdown, and localised pipeline corrosion under the effect of dynamic anodic transients, and (iii) visualising coating disbondment under excessive cathodic protection conditions.

Keywords: Steel pipeline, protective coating, cathodic protection, localised corrosion, stray current corrosion, corrosion monitoring, corrosion sensor.

1. INTRODUCTION

Protective coatings and cathodic protection (CP) are widely applied as the principal means of protecting buried steel pipeline from soil corrosion. Unfortunately under some complex environmental conditions the effectiveness of these methods could not be ensured, and therefore techniques are needed to monitor and evaluate their performance [1,2]. For instance, the potential of a buried steel pipeline could be diverted from the standard ‘safe’ CP level (i.e. -850 mV vs copper/copper sulphate reference electrode) due to various reasons such as stray currents, flawed CP design or faulty CP control, leading to insufficient CP (in cases of anodic potential excursions) and over-protection (in cases of excessive negative potential excursions). Some forms of potential excursions are known to be harmful to buried steel pipelines; however currently the exact effects of potential excursions on CP efficiency and corrosion have not been sufficiently understood primarily due to difficulties in measuring these effects [3,4]. Over-protection is known to cause cathodic disbondment of pipeline coatings [5,6]. However traditional methods of evaluating cathodic disbondment based on visual inspection of pipeline conditions and laboratory testing of cathodic disbondment resistance have some limitations in quantitatively and instantaneously measuring and monitoring disbondment of thick pipeline coatings [6]. There is a need for the development of new methods that are able to perform in-situ and quantitative measurements of stray current corrosion and cathodic disbondment of pipeline coatings.

On the other hand, structural health monitoring and life prediction tools are needed to provide long-term remnant pipeline life prediction and in-situ pipeline condition monitoring. A critical step in pipeline structural health monitoring is the enhancement of technological capabilities that are required for quantifying the effects of key factors influencing buried pipeline corrosion and environmentally assisted materials degradation, and the development of condition monitoring technologies that are able to provide in-situ monitoring and site-specific warning of pipeline damage [1,2]. The concept of in-situ monitoring and site-specific warning of pipeline corrosion is illustrated by a case of monitoring localised corrosion under disbonded coatings using a new corrosion monitoring probe [7-10]. A basic principle that underpins the use of sensors to monitor localised
Corrosion has been presented: Localised corrosion and coating failure are not an accidental occurrence, it occurs as the result of fundamental thermodynamic instability of a metal exposed to a specific environment. Therefore corrosion and coating disbondment occurring on a pipeline will also occur on a sensor made of the same material and exposed to the same environment as a pipeline [2]. Although the exact location of localised corrosion or coating disbondment could be difficult to pinpoint along the length of a buried pipeline, the ‘worst-case scenario’ and high risk pipeline sections and sites are predictable. Sensors can be embedded at these strategic sites to collect data that contain ‘predictor features’ signifying the occurrence of localised corrosion, CP failure, coating disbondment and degradation. Information from these sensors would enable pipeline owners to prioritise site survey and inspection operations, and to develop a maintenance strategy to manage aged pipelines, rather than replace them.

In this work, we take advantage of the high temporal and spatial resolution of an electrochemically integrated multi-electrode array, often referred to as the Wire Beam Electrode (WBE) method, for probing localised electrode processes evolving dynamically and propagating freely on a steel electrode surface under the effect of cathodic protection and anodic transients. This paper provides an overview of our new approaches aimed at developing new sensors for monitoring, categorising and quantifying the level and nature of external pipeline and coating damages under the combined effects of various inter-related variables and processes such as cathodic shielding, stray current corrosion, coating disbondment and localised corrosion [11-13].

2. EXPERIMENTAL DETAILS

Figure 1 illustrates a typical experimental configuration using an electrochemically integrated multi-electrode array based sensor to facilitate the in-situ monitoring and visualisation of electrochemical processes occurring on buried steel surfaces under CP and anodic transient conditions [12]. The WBE sensor used in this work consists of 100 closely packed but isolated square shaped carbon steel electrodes (e.g. 2.44 mm x 2.44 mm) embedded in epoxy resin. The gaps between neighbouring electrodes were kept small (e.g. 0.10 ± 0.05 mm). After grinding using SiC grit paper, the sensor was installed in a specifically designed sandy soil box cell [4,12] that facilitates the effective simulation and control of CP testing conditions. Washed fine sand with a typical resistivity of 1000 Ohm.cm was used in the sand box cell, and the resistivity was adjusted using a 3% NaCl solution. The sand box cell was sealed to prevent evaporation. A potentiostat (Bio-Logic Science Instrument) was used to apply CP and anodic transient signals on the sensor surface under potentiostatic control. Similar electrochemical cells and experimental setup were used in experiments for studying various inter-related processes such as cathodic shielding and localised corrosion [11], coating damage and disbondment [13]. More details on the experimental and data analysis methods can be found elsewhere [11-13].
3. RESULTS AND DISCUSSION

3.1 Case 1: The monitoring of localised corrosion processes under simulated disbonded coatings

The monitoring of localised corrosion processes under a dynamically changing electrochemical environment under disbonded coatings is a technical challenge. Cathodic disbondment is a major form of electrochemically induced coating failure that frequently takes place at the metal/coating interface on cathodically protected steel infrastructure such as pipelines. Disbonded coatings are believed to shield CP current, and therefore localised corrosion frequently occurs under disbonded coatings. Currently there is no technique that can be used to perform in-situ monitoring of its occurrence in the field. Electrochemical techniques such as conventional electrochemical impedance spectroscopy (EIS), localised electrochemical impedance spectroscopy (LEIS), scanning kelvin probe and scanning vibrating electrode techniques (SVET) have been employed to measure coating disbondment in the laboratory; however, there are significant obstacles for these techniques being practically used to monitor in-situ cathodic disbondment of thick pipeline coatings (e.g. 1000 μm in thickness) [7-9]. Currently detecting corrosion under disbonded coatings, especially at pipeline joints, relies heavily on periodic time based routine inspections using pipeline condition assessment methods including in-line inspection tools (intelligent pigs) and historical excavations. These methods are useful for detecting and locating big defects on the pipeline and for assessing the operation of CP systems, however they are often expensive and therefore are performed only on a periodic basis (usually every 5-15 years for intelligent pigs). Another approach that should be useful for pipeline corrosion management is the use of corrosion monitoring and warning sensors. Currently the most widely adopted corrosion monitoring sensors in the pipeline industry are steel coupons and electrical resistance probes (ER probes). Steel coupons buried next to the pipe and electrically connected to it are used to assess the operation of CP systems; however conventional weight-loss measurement can be difficult for buried structures because of practical difficulties in coupon installation and excavation. ER probes, often referred to as ‘intelligent’ weight-loss coupons, are used to detect corrosion by monitoring the electrical resistance between the ends of an elongated coupon of constant cross-section subjected to the corrosive environment. The ER coupon can be electrically connected to the pipeline to simulate the bare metal surface.
exposed in a coating defect for detecting corrosion data under CP. A major limitation of ER probes is in the
detection of localised corrosion such as corrosion under disbonded coatings, because an ER probe may not be
able to simulate corrosion under disbonded coatings, and also because localised damages may not lead to any
significant change in electrical resistance detectable by an ER probe. Although corrosion monitoring has been
widely applied to many industrial structures such as chemical plants, practical application of existing corrosion
monitoring techniques to buried structures such as a steel pipeline has been limited probably due to
unavailability of suitable sensors [2].

A new sensor [9-11] has been designed to measure the distribution of electrochemical currents over an electrode
array surface partially covered by a crevice that simulates a disbonded coating. The sensor has been evaluated
using immersion tests at open circuit potential (OCP) and under CP conditions. A typical series of results are
shown in Figure 2. Under both OCP and CP conditions, anodic as well as cathodic current densities were
detected within the crevice. Corrosion patterns were estimated based on the current density distributions from
two different methods [9-11]. The acceptable level of correlation with the corrosion damage observed at the
array surface at the end of the tests suggests that the sensor surface has the potential to monitor localised
corrosion under disbonded coatings. Using sensors to simulate and detect early stages of corrosion or to measure
corrosion susceptibility under disbonded coatings could provide a valuable and inexpensive means of obtaining
in situ monitoring information on the health of a structure.

3.2 Case 2: The monitoring of the effects of various forms of stray currents
Significant efforts have been made to systematically categorise and quantify the level and nature of damage to a
pipeline as a result of CP excursions, however there are still major difficulties in drawing decisive conclusions
because of the complexity of the electrochemical corrosion processes occurring at the complicated soil/buried
steel interface. Technological difficulties in measuring buried steel corrosion under CP are believed to be the
prime reason responsible for the lack of conclusions on the exact effects of CP excursions on pipeline corrosion.
Currently potential recording is the most commonly used method for inspecting stray current activities in the
pipeline industry; however potential recording does not provide sufficient information about corrosion rates and
patterns. Weight-loss coupons have been used to determine corrosion rates of steel buried in soil, however
weight-loss coupons are unable to provide in situ corrosion rate data required for quantifying the effects of
relatively short duration CP potential excursions.

A major difficulty in stray current corrosion research is the lack of reliable and reproducible experimental
methodologies that are able to systematically categorise and quantify the level and nature of damage as a result
of various modes of CP excursions. In this work, the WBE method has been applied for the first time as a new
sensor for detecting localised corrosion initiation under various dynamic anodic transient influences.
Experiments have been carried out for measuring the effect of an anodic transient on the corrosion of a steel
WBE sensor in a soil corrosion cell [12]. A typical series of results are shown in Figure 3. A common
phenomenon that was observed from these tests is that shortly after an anodic transient was applied to a CP
protected steel surface, anodic current and corrosion activity dropped dramatically from an initial anodic current
peak value. This has been explained by the passivity of steel under CP induced high pH condition. Another
phenomenon observed by inspecting the occurrence of local anodic currents in WBE maps was that localised
corrosion initiation occurred after a critical duration. This critical duration could be explained by the breakdown
of passivity under the effects of anodic transient induced pH and surface chemistry changes. This work suggests
that the WBE sensor could be used as an effective tool for studying localised corrosion initiation under the
effect of complex factors, as well as for the in-situ monitoring of stray current corrosion of buried steel
structures.

3.3 Case 3: The monitoring of cathodic disbondment of coatings
Cathodic disbondment is a major form of electrochemically induced coating failure that frequently takes place at
the metal/coating interface on cathodically protected steel infrastructure such as pipelines. Extensive research
over the past decades has developed a good understanding of the phenomenon, however currently there is no
technique that can be used to perform in-situ monitoring of its occurrence in the field. Traditional methods of
evaluating cathodic disbondment of pipeline coatings are based on ex-situ visual inspection of excavated pipes.
Electrochemical techniques such as conventional electrochemical impedance spectroscopy, localised
4. CONCLUSIONS

Sensors designed using an electrochemically integrated multi-electrode array have been successfully employed for (i) monitoring localised corrosion under the dynamically changing electrochemical environment under a simulated coating disbondment; (ii) visualising passivity and its breakdown and localised corrosion under the effect of dynamic anodic transients; and (iv) detecting coating disbondment under excessive cathodic protection conditions by measuring local electrochemical impedance.

5. ACKNOWLEDGMENTS

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6. REFERENCES


12. Ying Huo, Mike Yongjun Tan, Maria Forsyth, Visualising dynamic passivation and localised corrosion processes occurring on buried steel surfaces under the effect of anodic transients, Electrochemistry Communications, 66: 21–24 (2016)


Figure 2. Current density maps taken from a steel WBE immersed in 0.1M NaCl solution with CP. CP potential: -730mV against Ag/AgCl/Sat. KCl reference electrode [11].
Figure 3. Monitoring of currents and WBE maps over a steel WBE buried in a soil cell under three different CP and anodic transient conditions [12].
Figure 4. Typical maps of impedance amplitude ($|Z|$ at 300 mHz) and direct currents measured over a coated sensor after various periods of exposure and under different CP potential.

7. AUTHOR DETAILS

Mike Yongjun Tan is a Professor in Applied Electrochemistry and Corrosion Technologies at Deakin University in Australia. He is also a Research Program Leader of the Energy Pipelines Cooperative Research Centre. Dr Tan’s principal teaching and research interests are in corrosion science and engineering and their applications for enhancing the reliability and durability of civil and industrial infrastructures. He contributed to electrochemical methods for corrosion testing, monitoring and prediction and corrosion inhibitor and anti-corrosion coating research. He is the author of some 150 publications and a book entitled ‘Heterogeneous Electrode Processes and Localised Corrosion’ (2012 John Wiley & Sons).

Facundo Varela, also known as Bob, is a Research Fellow in the Institute for Frontier Materials at Deakin University, working on an Energy Pipeline CRC sponsored project. He completed his PhD studies on corrosion sensors at Deakin University in 2016. His PhD project was on the development of new corrosion monitoring technologies to measure corrosion rates under disbonded coatings in underground structures. His completed materials engineering studies with honours in the Instituto de Tecnología Jorge A. Sábat in 2009. As bachelor final year project, he joined Professor María Forsyth’s Group at Monash University where he worked on the Inhibition of Stress Corrosion Cracking in aluminium 7075.

Ying Huo is currently a PhD student at Deakin University in Australia. He graduated from Ji Lin University in China, with a Bachelor degree in Construction Management. In 2012 he attained a Master of Professional Water Engineering from Deakin University. Ying’s final year experiment was entitled ‘Effects of high salt concentration and residue on copper and aluminium corrosion’ and the results were published as a journal article. Ying’s PhD work examines the effects of electrical interference signals and the environment on the effectiveness of cathodic protection (CP). The aim of this project is to conduct a fundamental study of stray current and environmental influences on CP efficiency. The results of this study is expected to help improving the Australian pipeline industry CP standard.

Fariba Mahdavi graduated from the University of Karshan in Iran and worked on anti-corrosion coatings for 6 years before studying for a Master degree at the University Putra Malaysia. She is currently a PhD student at Deakin University in Australia. Fari’s PhD research is on electrochemical research on the disbondment of protective organic coatings to avoid limitations in traditional methods of evaluating cathodic disbondment of pipeline coatings by means of advanced electrochemical methods.

Professor Maria Forsyth completed her PhD in January 1990 at Monash University and moved to Northwestern University to take up a Fulbright Fellowship in the area of solid electrolytes for lithium batteries. On her return to Melbourne she worked at DSTO for a year before joining the Department of Materials Engineering as a Lecturer in 1993. In 2001 she was awarded an ARC Professorial Fellowship and is currently the Chair in Electromaterials and Corrosion Sciences at Deakin University, within the Institute for Technology Research and Innovation (ITRI). She is co-author of over 280 refereed journal papers, has delivered over twenty invited talks in the last 5 years and has over 7000 citations at present.
Professor Bruce Hinton is Honorary Professor at Institute for Frontier Materials, Deakin University, Australia. Prof Hinton has provided extremely valuable and pertinent technical leadership to DSTO for more than 35 years. He is recipient of many national and international awards including Frank Newman Speller Award. His main interests lie in the areas of corrosion inhibition, metal finishing, stress corrosion cracking, corrosion fatigue and hydrogen embrittlement.