



# Stress corrosion of pipeline steel under occluded coating disbondment in a red soil environment



Maocheng Yan\*, Cheng Sun, Jin Xu, Tangqing Wu, Shuang Yang, Wei Ke

Environmental Corrosion Center, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

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## ABSTRACT

A crevice cell with a multi-sample loading frame was constructed to study stress corrosion initiation of pipeline steel under an occluded shielding plate simulating coating disbondment under free corrosion condition in a red soil environment. The local potential and pH under the shielding were monitored by microelectrodes. Results show that intensive anodic dissolution and initiation of microcrack were preferential at the open holiday, whereas the corrosion attack was markedly mitigated under the occluded shielding. Species gradient and internal polarization were proposed for the corrosion scenarios of pipeline steel under disbonded coating.

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## 1. Introduction

Steel pipelines buried in soil environments are generally protected from corrosion by combination of insulating coating and cathodic protection (CP). The insulating coating limits the exposed area, while CP, acting as a back-up for coating imperfections, prevents pipeline from corrosion or mitigates corrosion by cathodically polarizing the exposed steel surface as well as modifying the environment at open defects (holiday) of the coating. Generally, the defect area should be less than 1% of the total coating surface to achieve sufficient CP at defects [1]. However, an occluded coating defect forms on pipeline when the CP-impermeable coating loses adherence and disbonds from pipelines or when a gap exists between pipe and coating, as is commonly found close to the toe of weld [2–7]. A thin electrolyte layer local environment forms on pipeline surface inside the occluded disbondment [8–10] after electrolytes penetrate into the disbonded area. Pipeline surface underlying cannot be protected by either coating or CP because of CP shielding by coating disbondment or highly resistive soil. This is especially true for the high insulating coating, such as the high density polyethylene (PE) or the PE tape coating, which tends to remain high insulating after disbonding from pipelines.

The thin electrolyte layer local environment trapped under occluded coating disbondment is found different from the surrounding environment [8,10–15]. Formation and evolution of the thin electrolyte layer local environment are a complex function

of disbondment geometry, coating type, failure mode, soil environment and applied CP. Our previous work [13,16] indicated that the pH of the local electrolyte under disbonded coating may vary significantly from near-neutral to high values, depending on availability of CP current and the CO<sub>2</sub> level. Although the local environment is usually anaerobic, various type of corrosion attacks have been observed on pipelines under disbonded coating, e.g. pitting [17], crevice corrosion, microbiological induced corrosion (MIC) [18,19], stray current corrosion, and especially stress corrosion cracking (SCC), which presents a great uncertainty to pipeline companies in terms of risk management [20,21]. Corrosion under disbonded coating is of most concern also because it cannot be easily detected in the field. The default corrosion rate as high as 0.4 mm/y is suggested in NACE Standard SP 0502-2008 for this case.

SCC under disbonded coating continues to be an important issue for integrity management and operation of high pressure pipelines. Initial microcracks generally originate from corrosion pits associated with non-metallic inclusions or metallurgical discontinuities, and results in colonies of microcracks varying in depth and length on pipeline surface [22]. Based on the field data, two different anaerobic electrolyte environments have been identified under disbonded coating, which corresponds to two forms of SCC [8,20,23–27]: The relative concentrated HCO<sub>3</sub><sup>-</sup>/CO<sub>3</sub><sup>2-</sup> electrolytes with high pH (~9–11) are related to the high pH SCC or classical SCC (IGSCC) which has been extensively studied since the 1960s; while a series of dilute groundwater containing CO<sub>2</sub> with near-neutral pH (NNpH, ~5.5–7.5) has been recognized as the potential environment for near-neutral pH SCC (NNpH SCC, TGSCC).

\* Corresponding author. Tel.: +86 24 2391 3195; fax: +86 24 2389 4149.

E-mail address: [Yanmc@imr.ac.cn](mailto:Yanmc@imr.ac.cn) (M. Yan).

NNpH SCC was first found in Canada in the 1980s, and it is being widely explored in terms of mechanisms and controlling factors for crack initiation and propagation. It has been proposed that NNpH SCC is prompted by the synergistic effects among anodic dissolution, hydrogen ingress and corrosion fatigue, although their individual contributions are still not well identified [28–31]. Most recently, a mechanism referred to as “hydrogen facilitated anodic dissolution” is proposed for NNpH SCC to incorporate contributions of dissolved hydrogen and anodic dissolution [31]. It is generally accepted that fluctuation of load is important or even necessary for crack growth of NNpH SCC [31,32], although initiation of cracks has been observed under some constant load conditions [33,34].

It has been recognized that SCC is a very complicated and specific phenomenon and it is difficult to extract all the mechanistic information from field data alone. A significant amount of research has been performing over the past few decades to reproduce NNpH SCC in laboratory for the purpose of ascertaining the cause or mechanism and identifying the primary controlling factors. Various conditions and factors, involving all aspects of susceptible material, potential environment under disbonded coating and tensile stress, have been studied in the laboratory. Most of these studies were conducted in bulk solution condition maintained the near-neutral pH by purging the CO<sub>2</sub>/N<sub>2</sub> mixture gas [35,36]. However, this methodology neglects the coating disbondment geometry on pipeline surface which has been identified as one of the primary environmental factors related to NNpH SCC.

Meanwhile, a significant amount of studies have been carried out on electrochemical condition on the surface of pipeline steels under disbonded coating, through either laboratory simulation or modeling. But, unfortunately, most of the previous research focused on crevice corrosion [37–39] under aerobic conditions or on microbiologically influenced corrosion (MIC) [18,19,40,41] under anaerobic conditions. It is clear that these results cannot be borrowed since environmental conditions used in those studies are not related to the potential environment of SCC of pipeline steel. Although some attempts have been conducted in the context of SCC of pipeline [8,10,13,29,30,36,42–44], systematic and well controlled experimental study is still needed for fundamental insight into SCC initiation on pipeline under disbonded coating. Improved in measurement techniques and more realistic test conditions would be helpful to further understand the initiation mechanism, and to identify the primary controlling factors of NNpH SCC.

Furthermore, three-layer polyethylene (3LPE) coating, combining advantages of fusion bonded epoxy (FBE) coating and PE coating, has been being widely used on long-distance high pressure transmission pipelines. Because of high insulation, 3LPE coating lacks failure security: It tends to shield CP current after disbonding [45,46]. External corrosion (e.g. SCC, stray current corrosion) under disbonded coating appears to be a potential problem for the high pressure pipeline with 3LPE coating [11]. Disbonding failures of the coating and corrosion risk of pipeline under coating disbondment have caused serious concern to pipeline companies.

In this context, a new research program has been initiated on this subject. The overall goal is to systematically investigate corrosion scenarios and mechanochemical interaction of high grade pipeline steels under disbonded coating in different soil environments, particularly to further mechanistic understanding the initiation of NNpH SCC on pipelines under disbonded coating. We also desire to complement the methodology of pipeline corrosion under shielding disbondment by characterizing corrosion with various electrochemical techniques and by providing a mechanistic basis for corrosion and NNpH SCC of pipeline steel under coating disbondment. The present paper highlights the corrosion scenarios of API X80 pipeline steel with or without tensile stress under an occluded shielding plate with 1 mm gap simulating coating

disbondment in a red soil environment. The concentration gradients of various species (e.g. CO<sub>2</sub>, HCO<sub>3</sub><sup>-</sup>, Fe<sup>2+</sup>) and the induced internal polarization were identified as factors that appear to exert a significant influence on corrosion inside the occluded coating disbondment. This work will improve our understanding on corrosion scenarios and initiation of SCC of pipelines under disbonded coating.

## 2. Experimental

### 2.1. Construction of simulated coating disbondment system with multi-sample loading frame

An integrated test system was constructed combining an occluded crevice cell and a multi-sample loading frame, as schematically shown in Fig. 1. A 25 × 6 cm<sup>2</sup> shielding crevice region was formed by bolting polytetrafluoroethylene (PTFE) gasket between a shielding plate and a serial of stand-alone specimens attached on a base plate. Both the shielding plate and the base plate were made from PMMA material. The PMMA material does not permit CP current and CO<sub>2</sub> to penetrate through, and the electrochemical condition formed under PMMA is reported to be similar to that under the PE coating disbondments [42]. In this work, the shielding gap was controlled at 1 mm by the thickness of the PTFE gasket. The electrolyte inside the shielding simulates the local environment trapped under coating disbondment. A bulk solution container (9.5 cm × 6.0 cm and 11 cm in height) was fixed at one end of the shielding plate to simulate the bulk soil environment surrounding pipelines in the field. At the bottom of the container, a 1 × 5 cm<sup>2</sup> rectangular open mouth was opened through the shielding plate to serve as the open defect (holiday) of coating disbondment. The local electrolyte under the shielding was connected to the bulk soil environment only through the opening. The area ratio between the surface in the shielding and that exposed to the opening was 25.0. Holes for measurement ports were drilled through the shielding plate above the center of each specimen couple. The bulk solution container was carefully sealed but containing a gas inlet extended to the bottom of the container and a gas outlet at the top for maintaining the atmospheric condition.

The crevice cell was assembled to a multi-sample loading frame to supply tensile stress for the steel specimens. Four stand-alone samples can be loaded simultaneously in parallel along the shielding crevice. The schematic of the loading frame and configuration of the specimens are shown in Fig. 1b. The constant tensile load was applied for the specimens by fastening the screws and the value of the load was monitored by a force transducer. A trial test indicated that the load can keep quasi-constant in a three month experiment, owing to the good creep resistance of the steel.

Eight (in 4 couples) stand-alone specimens were glued to the PMMA base plate along the shielding crevice. The stand-alone specimens were 5 mm wide along the shielding crevice. To closely simulate the real pipeline surface condition under a disbonded coating, the rest spaces between the specimens on the PMMA base plate were patched by 5 auxiliary plates made with the same steel. The adjacent specimens were insulated electrically each other by a 1 mm thickness gap filled with silicone rubber. Only the upside of the specimen was exposed, giving a work surface of 0.5 × 6 cm<sup>2</sup>. The specimens exposed to the opening simulated the part of pipeline at the holiday. The arrangement of steel specimens in the crevice is presented in Fig. 1c. All the steel specimens and plates were electrically connected through the parallel wire, which made them work as one single body of pipeline steel under the shielding. For convenience, the specimen couple at the opening

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