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To cite this article: D. Kuang & Y. F. Cheng (2015) Effect of alternating current interference on coating disbondment and cathodic protection shielding on pipelines, Corrosion Engineering, Science and Technology, 50:3, 211-217

To link to this article: http://dx.doi.org/10.1179/1743278214Y.0000000246

Published online: 08 Jan 2015.

Article views: 58

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Effect of alternating current interference on coating disbondment and cathodic protection shielding on pipelines

D. Kuang and Y. F. Cheng*

In this work, the effects of alternating current (AC) interference on coating disbondment on X65 pipeline steel and the cathodic protection (CP) permeation into the disbonding crevice were investigated. Cathodic disbondment tests showed that the AC is able to promote disbonding of coating from the steel, which is attributed to the solution alkalisation by the enhanced cathodic reduction reaction and generation of hydroxyl ions. In the absence and presence of AC, CP can be shielded by the geometry of coating disbondment. At small AC current densities, such as 100 A m\(^{-2}\), the AC results in an enhancement of permeation of CP current into the crevice. However, with the increase in AC current density, corrosion product generates and deposits in the solution, blocking the ionic diffusion and CP permeation. When the AC current density is up to 500 A m\(^{-2}\), the CP is blocked completely to reach the disbonding crevice.

Keywords: Coating disbondment, Pipelines, Alternating current, Cathodic protection shielding

This paper is part of a special issue on ‘Pipeline corrosion’

Introduction

Pipeline coatings usually contain various defects such as pinholes, holidays or flaws, which can be generated during coating manufacturing, transportation and pipeline construction. Ground water, corrosive gases and chemical species may penetrate through the defects and reach the pipe steel surface, causing coating disbonding and pipeline corrosion at the defect and under the disbondment. All buried pipelines are under cathodic protection (CP), which should provide protection to the steel from corrosion attack. However, due to the geometrical limitation of the defects and the shielding effect of disbonded coating, frequently, CP is shielded, at least partially, from reaching the corroded steel for corrosion protection.\(^1,2\) Furthermore, when the CP current is access to the steel, the solution pH would be elevated due to CP driven reduction in water, promoting the cathodic disbondment of the coating.\(^3\)

External corrosion of pipelines under disbonded coatings has been studied extensively. Parametric effects, such as the geometry of disbondment, solution resistivity, temperature, CP potential, exposure time, oxygen partial pressure, etc., have been investigated, and important conclusions have been demonstrated.\(^4-10\) At the same time, the presence of alternating current (AC) interference from the adjacent high voltage power transmission lines would enhance external corrosion of buried pipelines and shift the CP potential from the design value.\(^11-16\) However, there has been limited work to study the effect of AC on coating disbondment and, further, to investigate the CP permeation into the disbonding crevice under the AC interference.

In this work, the effect of AC on disbonding of a fusion bonded epoxy (FBE) coating from X65 steel was investigated by cathodic disbondment (CD) testing under different AC current densities. Electrochemical measurements and pH monitoring were conducted to study the role of AC in CP permeation into the disbonding crevice. The parametric effects, such as AC current density, CP potential and disbonding thickness, were determined.

Experimental

Electrode and solution

Fusion bonded epoxy coated X65 steel coupons were supplied by Bredero Shaw. The thickness of the coating was 180 \(\mu\)m. The chemical composition of the steel is C 0.04 wt-%, Si 0.2 wt-%, Mn 1.5 wt-%, P 0.011 wt-%, S 0.003 wt-%, Mo 0.02 wt-% and Fe balance.

For CD testing, a 3 wt-%NaCl solution was used. For CP permeation testing, a near neutral pH bicarbonate solution simulating the trapped electrolyte under the disbonds coating was used. The solution contained 0.01M NaHCO\(_3\). The solution was purged with 5% CO\(_2\)/N\(_2\) for 48 h before and throughout testing. The solution pH was 7.5. All solutions were made from analytic grade reagent and ultra pure water.
Cathodic disbondment testing under AC interference

To investigate the CD resistance of FBE under AC interference, an experimental set-up shown in Fig. 1 was used according to the standard CSA Z245-20-02. The coated steel specimen with 20 mm x 20 mm was used as the working electrode and connected to a direct current (DC) power supply to the negative pole, and a platinum sheet was connected to the positive pole. The DC voltage 235 V [saturated calomel electrode (SCE)] was applied on the working electrode for 48 h. A carbon rod was connected to AC signal source through a slide rheostat, and the AC current density was varied from 0 to 500 A m\(^{-2}\) by adjusting the AC voltage on the rheostat. A capacitor was used to block DC signal to flow in the AC circuit.

A 3-2 mm diameter holiday was created at the centre of the specimen through the coating to expose steel substrate in 3 wt-%NaCl solution. The test cell was placed in a water bath maintained at 65°C. After testing, the cell was disassembled, and the coated steel specimen was cooled in air to ambient temperature. A utility knife was used to make eight radial cuts starting at the holiday through coating to the steel substrate at a 45° angle between cuts. The coating was then peeled off manually until a resistance was met. The peel off distances of eight directions were measured, and the average distance was defined as the CD radius.

Cathodic protection permeation measurements in presence of AC interference

Figure 2 shows the cell to simulate the crevice under a disbonded coating and the installation of probes for potential and pH measurements. The cell contained an X65 steel substrate 200 mm x 25 mm x 20 mm in dimension. To prepare an artificial disbondment, an FBE membrane with a thickness of 200 µm was applied on the steel surface using a TESA double sided self-adhesive tape. A hole (10 mm in diameter) was created on the coating to simulate the coating holiday. Six smaller holes with diameter of 3-16 mm were created, with 30, 60, 90, 120, 150 and 180 mm respectively, from the originally opened, bigger hole. The CP and AC were applied at the bigger holiday with the same circuit connection shown in Fig. 1.

At each smaller hole, a combination of measurement kit including a SCE reference electrode and a pH meter was installed to monitor local potential and solution pH. The potential measurement was performed through the AC/DC real time data acquisition system developed in the authors’ group. The local solution pH was measured using an Oaklon Acorn pH meter. The testing was performed at room temperature of ~23°C.

The effect of AC current density on CP permeation in the crevice was studied. The gap between coating and the steel was in a thickness of 120 µm to simulate the coating disbondment. In order to prepare the simulated disbondment, two layers of tape with a known thickness were adhered to the surface of the steel. The FBE membrane was adhered to form an artificial disbondment on the steel surface. The disbonding thickness was determined by the total thickness of the tape layers and was measured by a coating thickness gauge. The boundaries of tape/steel/coating were sealed with epoxy resin.

The corrosion potential of the steel in the near neutral pH bicarbonate solution was −0.755 V (SCE). Cathodic potentials of −0.875 V (SCE) and −0.975 V (SCE) were applied to protect steel from corrosion in the absence of AC interference. In the presence of AC, the AC current densities were ranged from 0 to 500 A m\(^{-2}\).
Results

Effect of AC current density on coating disbondment

Figure 3 shows the surface morphologies of coated steel specimen after CD testing under various AC current densities. It is seen that, generally, the coating disbonding area increases with the increasing AC current density after CD test.

Figure 4 shows the disbonding radius from the centre of the holiday as a function of AC current density. It is seen that the CD radius of FBE coating is 3.37 mm in the absence of AC, which is similar to that obtained previously. Upon AC application, the CD radius increases obviously. At the AC current density of 500 Am^{-2}, the radius is up to 7.98 mm, more than twice of the one measured without AC. Thus, AC is able to promote coating disbondment.

Effect of AC current density on CP permeation into disbonding crevice

Figure 5 shows the potential distribution under the coating disbondment (disbonding thickness of 120 μm) at CP potential of −0.875 V (SCE) under various AC current densities. It is seen that, even in the absence of AC, CP would be shielded to reach the disbonding crevice along the depth direction. At the open holiday, i.e. distance to the holiday of 0 mm, the measured potential is at the applied CP potential of −0.875 V (SCE) up to 48 h of testing. However, at the distance of 30 mm from the open holiday, the potential is shifted less negatively to about −0.8 V (SCE). With the increase in distance from the holiday, the potential becomes less negative. When the distance is up to 60 mm, the
potential would not change with the increase in the distance to the holiday. It is thus seen that the geometry and coating disbondment shield the CP permeation, decreasing the CP performance at the crevice depth. The critical depth in the absence of AC is 60 mm, above which CP would not be able to reach, and the steel is at free corrosion potential of \(-0.755\) V (SCE).

Upon AC application, the DC potential of the steel electrode is shifted negatively. Moreover, as the AC current density increases, the potential shift is more negative, as seen from the potential measurements on the holiday (distance of 0 mm) in Fig. 5b–f. Moreover, along the direction towards the disbonding depth, the potential is shifted less negatively. Obviously, the CP shielding due to the crevice geometry also applies under the AC interference. It is also interesting to find that, as small AC current densities, such as 100 A m\(^{-2}\), the critical crevice depth where CP cannot reach is
150 mm from the open holiday. With the increasing AC current density, the critical crevice depth decreases. When AC current density is up to 200, 300 and 400 A m$^{-2}$, the critical depths are 120, 90 and 30 mm respectively. When the AC current density is 500 A m$^{-2}$, there is no CP that can permeate into the potential monitoring regions. Thus, at small AC current densities, the AC results in more negative potentials at individual disbonding depth compared to those measured in the absence of AC. However, the trend is diminished with increasing AC current density. When comparing the potential profiles measured in the absence of AC (Fig. 5a) and at AC current density of 400 A m$^{-2}$, there is a high similarity under the disbonding crevice, except...
the latter has a more negative potential at open holiday. At large AC current density such as 500 A m\(^{-2}\), CP is completely shielded from reaching the disbonding crevice.

Figure 6 shows the solution pH profile under the coating disbondment (disbondment thickness of 120 \(\mu\)m) at CP potential of \(-0.875\) V (SCE) under various AC current densities. It is seen that, in the absence of AC, the CP application enhances the solution pH at the open holiday to \(\sim 8\) (the original solution pH is 7.5). Under the disbonding crevice, there is a lower solution pH compared to that at the holiday. With the increase in disbonding depth, the pH is decreased. Upon AC application, the solution pH at open holiday is elevated obviously, but the solution pH inside the disbonding crevice is lower. As the distance to the open holiday increases towards the disbondment bottom, the pH further drops. Moreover, with the increase in AC current density, the solution pH under the disbonding crevice decreases.

Discussion

The present work shows that AC could enhance disbonding of coating from the steel substrate, as shown in Figs. 3 and 4. To understand mechanistically this phenomenon, the effect of AC current density on local pH inside the disbonding crevice, e.g. at 180 mm from the open holiday, is plotted in Fig. 7. It is clear that the solution pH at the crevice bottom is elevated by increasing AC current density.

Upon application of AC, anodic oxidation and cathodic reduction reactions occur during the positive and negative half cycles respectively. During corrosion of X65 pipeline steel in near neutral pH bicarbonate solution under disbonded coating, the anodic and cathodic reactions at the AC positive and negative half cycles are the iron oxidation and reduction in water (in the absence of oxygen in the environment) respectively: \(^{19}\)

\[
\text{Fe} \rightarrow \text{Fe}^{2+} + 2e^{-} \quad (1)
\]

\[
2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + 2\text{OH}^- \quad (2)
\]

The electrochemical reactions generate OH\(^-\) ions as product to elevate pH of solution trapped under disbonded coating. Moreover, as the AC current density increases, the water reduction is enhanced at more negative potential in AC negative cycles. Thus, the solution becomes more alkaline, as shown in Figs. 6 and 7. Obviously, solution alkalisation is the primary reason to result in coating disbondment during AC application. The generated hydrogen bubbles due to cathodic reaction (2) can also contribute to coating disbonding by weakening the bonding of the coating to steel.

Furthermore, it is demonstrated from this work that the potential of steel at the open holiday is shifted negatively upon AC application, as seen in Fig. 5. This result is consistent with the authors' previous study.\(^{15,16}\) This is attributed to accelerated diffusion of cation ions that are generated during corrosion of steel under AC enhanced electric field. As a consequence, the number of positive charges in the double charge layer decreases, resulting in a negative shift of the potential. It is noted that AC induced negative shift of the potential is due to
enhanced corrosion, rather than cathodic polarisation of the steel.

In the absence and presence of AC, CP can be shielded by the geometry of coating disbondment, as shown in Fig. 5, where the local potentials inside the disbonding crevice are less negative than the potential at the open holiday. In order to show clearly the effect of AC current density on CP permeation into the disbonding crevice, the local potentials at the disbonding sites of 30 and 180 mm from the holiday are plotted as a function of AC current density, as shown in Fig. 8. It is seen that, at small AC current densities such as 100 and 200 A m⁻², the local potential at both sites is shifted negatively by AC. As discussed, this shift is associated with the enhanced corrosion of steel under AC interference. When the AC current densities increase from 300 to 500 A m⁻², the potentials are shifted in the positive direction. At high AC current densities, the iron dissolution and water reduction are further enhanced in the positive and negative cycles of AC. There are more ferrous and hydroxyl ions generated during anodic and cathodic reactions. Owing to limited space under the disbonding crevice, the corrosion product is not able to diffuse outwards freely. The positive shift of the steel potential is associated with deposit of corrosion product, such as Fe(OH)₃, on the steel.

Furthermore, at small AC current densities, the AC enhanced steel corrosion generates ferrous and hydroxyl ions, improving the conductivity of solution trapped under disbonded coating. This results in enhancement of permeation of CP current into the crevice. As shown in Fig. 5, at AC current densities of 100, 200 and 300 A m⁻², the critical disbonding depths are 120, 90 and 60 mm respectively, while that in the absence of AC is 30 mm only. The reason that the critical disbonding depth decreases with increasing AC current density is associated with the blocking effect of corrosion product under coating. As discussed, corrosion product generates and deposits at high AC current densities, blocking the ionic diffusion and CP current and decreasing the CP permeation. When the AC current density is increased to 500 A m⁻², the CP is blocked completely to reach the disbonding crevice. Thus, it is important to note that, under high AC current densities, the applied CP can be shielded completely from reaching the coating disbondment.

Conclusions

The AC is able to enhance coating disbonding from the steel substrate, which is attributed to the solution alkalisation by the enhanced cathodic reduction reaction, resulting in generation of hydroxyl ions.

In the absence and presence of AC, CP can be shielded by the geometry of coating disbondment. At small AC current densities, such as 100 A m⁻², the AC enhanced corrosion generates ferrous and hydroxyl ions, improving the conductivity of solution trapped under disbonded coating. This results in enhancement of permeation of CP current into the crevice. However, with the increase in AC current density, corrosion product generates and deposits in the solution, blocking the ionic diffusion and CP permeation. When the AC current density is up to 500 A m⁻², the CP is blocked completely to reach the disbonding crevice. Thus, it is important to note that, under high AC current densities, the applied CP can be shielded completely from reaching the coating disbondment.

Acknowledgement

This work was supported by Canada Research Chairs Program.

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