External Polymeric Pipeline Coating Failure Modes

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Pipeline coating is a major defense against corrosion. Cathodic protection provides protection at coating holidays. Any change in the chemical, physical, or electrochemical properties of an external pipeline coating can be considered as a failure. Some failures are catastrophic, whereas others have little or no effect on the coating performance. The eight most common failure modes of external polymeric pipeline coatings are assessed in this article.

As long as pipeline coatings are intact and completely isolate the pipeline from the environment, corrosion should not occur. But over the years, coatings undergo changes that affect their ability to isolate the pipeline from the environment. Generally, any changes in the properties of a coating are considered as a coating failure. The degree of influence of the changes on pipeline integrity varies, depending on the extent and the nature of changes. The predominant failure modes are discussed in this article.

Mode of Failure

AIR PERMEATION

Polymeric pipeline coatings are permeable because of the presence of pores at the molecular level. Gas can permeate through the pores. When gases permeate a coating that is well bonded to steel, the pressure within the coating increases. At high levels of permeation, the build-up of pressure may be reduced by the liberation of gases, causing disbondment of the coating. At low levels of permeation, the state of equilibrium is reached without any chemical or physical changes to the coating.[1]

WATER PERMEATION

In addition to gases, water and salts can also penetrate the coating. Permeation is further facilitated by osmosis and electro-osmosis. When a semipermeable membrane (e.g., pipeline coating) separates a solution of different concentrations, the water permeates from the concentrated solution side to the dilute solution side so that the concentrations at both sides of the membrane become the same. This process is called osmosis. The presence of salts on the contaminated steel surface results in the development of the osmosis process. If osmosis is facilitated by the electrical current flow caused by the application of cathodic protection (CP), it is called electro-osmosis.[2-4]

LOSS OF ADHESION

Adhesion is a measure of the degree of attachment between the coating and the pipeline steel with which it is in contact. The adhesion is a force that keeps the coating on the steel surface.[5] Adhesion may be caused by chemical, physical, and mechanical interactions. When these interactions are diminished, the coating loses its adhesion.

LOSS OF COHESION

The cohesive strength is the bonding within the coating itself that holds the coating together as an entity. A coating with great cohesion will break the adhesive bond with the surface and then peel from the surface to form a free-standing coating (Figure 1). On the other hand, if the cohesive strength is less than the adhesive strength, the coating will break within itself, leaving part of the coating on the surface and part of it off the surface (Figure 2).[6] Because the pipe surface is protected by the remainder

of the coating, the damage is not as severe as that caused by adhesion failure.

BLISTERING

The swelling of coatings from water absorption causes a lateral distortion of the film with respect to the steel. Stresses at the coating/steel interface arising from the distortion produce a loss of adhesion, causing a blister. If CP completely penetrates through the blistered coating, then the pH of the solution will be in the alkaline range (>7). Under blistered coatings, a pH as high as 12 has been observed.[7-8]

DISBONDMENT AND PASSAGE OF CATHODIC PROTECTION CURRENT

Degradation of adhesion by CP is known as cathodic disbondment.[9] Factors including pH, cathodic potential, the stability of the interfacial oxide, the substrate surface roughness, defect geometry, coating formulations, cyclic wetting and drying, and water uptake contribute to cathodic disbondment. As in the case of a blistered coating, if CP completely penetrates the disbonded coating, the pH of the solution below the disbonded coating will be in the alkaline range.[10] The increase in pH comes from the consumption of hydrogen ions and the generation of hydroxyl ions. Maintaining a high pH environment helps to protect the steel beneath a disbonded coating by passivating the pipeline steel. The interruption or removal of the CP system may cause a decrease in pH and cause the potentials to shift to more positive values. At more positive potentials, corrosion may occur.[11]

Coating disbondment leads to the formation of crevices. Sizes of disbondments depend on the coating, the species in the environment, the morphology of the disbondment, and the level of CP. Where access to the inside of a crevice is restricted, a significantly different chemistry may be present compared to the chemistry in the groundwater.
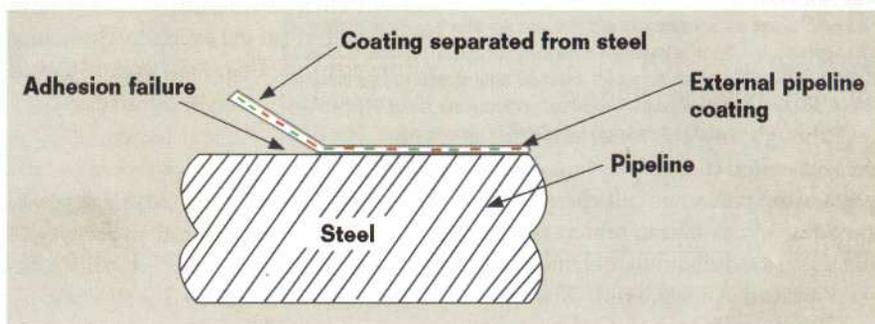
Where the solution is trapped and there is little or no exchange with fresh

FIGURE 1
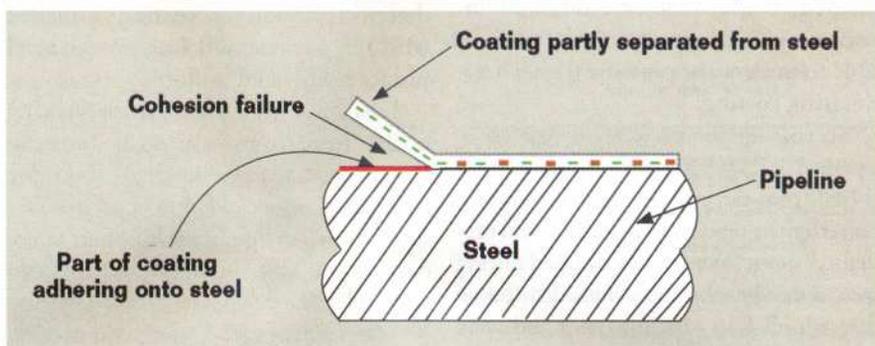
Sketch showing adhesion failure of a coating.

FIGURE 2

Sketch showing cohesive coating failure.

solution, the corrosion rate of steel will decrease rapidly and remain at low values. Where an exchange of solution (the flow of water between the coating and the pipe) can occur, a frequent or continual generation of alkalinity by external polarization is required to control corrosion.[12]

In high-conductivity solutions, CP can be effective within a crevice. Clean crevices with large openings are easier to polarize than those containing mill scale or corrosion products. The pH of the solution inside the crevice is alkaline,[8-12] whereas the bulk solution just outside the crevice remains neutral.

DISBONDMENT AND PREVENTION OF THE PASSAGE OF CATHODIC PROTECTION

Generally, if the solution resistance is high, there is a large ohmic drop and essentially no flow of current into the disbonded region.[13] If CP does not penetrate, then corrosion occurs at the disbonded

region even when the pipe-to-soil potential at the ground surface meets the −0.85 V or other criterion.

INCREASE IN CATHODIC PROTECTION CURRENT

Even on a microscopic level, polymeric coatings exhibit pores or holidays. The origin of holidays can be traced to the mode of crystal formation/growth.[14] During construction, crews are careful not to damage the protective coating. In spite of these precautions, sometimes coatings are removed and/or damaged. These areas act as potential locations where disbondments may initiate. External coatings and CP work synergistically to mitigate the corrosion of pipelines. It is difficult to cathodically protect a bare pipeline because the magnitude of the current required for protection is high. A good-quality coating can decrease the current required by a factor of 1,000 or more. As the coating deteriorates and/or more and more holidays are

formed, the CP current demand increases, until it is economically not feasible to protect the pipeline with a deteriorating coating.

Six coating systems were evaluated over a period of 25 years: fusion-bonded epoxy (FBE), coal-tar enamel, asphalt enamel, polyethylene tape, asphalt mastic, and urethane.[15] Several locations exhibited pitting corrosion. These locations were distributed through all four coating types and were generally located in areas where the coating conditions were poor. Many of the defects were in areas where the CP was initially considered to be adequate, indicating that, where coatings were in poor condition, CP was not completely effective.

Ranking of Coating Failure Modes

Although any chemical, physical, or electrochemical changes may be considered as a coating failure, not all changes affect the ability of coatings to protect the pipeline. In an ideal situation, polymeric coating protects the pipeline and, when it fails, the CP acts as the backup. Only after both defense mechanisms fail would the pipeline become susceptible to corrosion.

The worst-case scenario of coating failure is the one in which the coating no longer protects the pipeline, and, in addition, the coating prevents the CP from protecting the pipeline. This type of failure mode is primary in terms of the impact of the failure on the protection of the pipe.

The presence of holidays is the second most common cause of failure because the CP current increases as the holiday size and number increase. The alkaline pH created by the CP can easily become diffused, and hence, the CP should be applied continuously.

The formation of disbondment behind a coating that passes CP presents the third ranking. In this case the coating has failed, but CP can act as the backup. Because of the diffusion limitation of the hydroxide (OH⁻) ions, the amount of CP required is smaller.

The formation of blisters is the fourth-ranked cause of coating failure. This failure is associated with the penetration of water, so that CP can prevent corrosion at this location. This case is better than

that with disbonded coating protected with CP because CP reaches the steel surface readily and uniformly.

Loss of adhesion makes the coating unable to perform its primary function (i.e., to cover the steel surface). This is the fifth-ranked mode of failure. Loss of cohesion is the sixth because at least part of the coating still covers (and hence protects) the steel surface.

Water permeation through the coating is the seventh-ranked failure mode. This mode of failure establishes electrochemical cells, facilitating conditions for corrosion to occur.

The permeation of gases may break certain chemical bonds, but may have limited effect on the overall performance of the coating. This is the eighth-ranked failure mode.

Summary

- Any change in the chemical, physical, or electrochemical properties of the external polymeric pipeline coatings can be considered as a failure.
- Some failures are catastrophic, whereas others have little or no effect on the coating performance.
- The eight most common failure modes of external polymeric pipeline coatings are ranked in the order of the impact of the failure on the protection of the pipe.

Acknowledgments

References

1. D.F. Siddal, "Permeability and Corrosion in Protective Coatings," Corrosion 2, 6 (1946): p. 78.

2. F. Bellucci, L. Nicodemo, "Water Transport in Organic Coatings," Corrosion 49, 3 (1993): p. 235.

3. NACE Task Group T-6B-B, "Amine-Cured Epoxy Resin Coatings for Resistance to Atmospheric Corrosion," MP 9, 5 (1970): p. 37.

4. D. Gervasio, I. Song, B. Trautman, J.H. Payer, "Fundamental Research on Disbonding of Pipeline Coatings," Gas Research Institute Report GRI-93/0265/GTI2110, 1993.

5. "Line Pipe Coating Analysis Volume 2: Topical Report on Adhesion," American Gas Association, November 1979, p. 38.

6. C.G. Munger, "Surfaces, Adhesion, Coatings," MP 5, 7 (1983): p. 33.

7. W. Schneider, "Ambient Temperature Curing Waterborne Epoxy Systems," MP 30, 1 (1991): p. 28.

8. G.R. Ruschau, J.A. Beavers, "Performance of Blistered FBE-Coated Pipe," PR-186-9810, December 2000.

9. J.H. Payer, B. Trautman, D. Gervasio, "Chemical and Electrochemical Processes of Cathodic Disbonding of Pipeline Coatings," CORROSION/93, paper no. 579 (Houston, TX: NACE International, 1993).

10. R.N. Parkins, A.J. Markworth, J.H. Holbrook, R.R. Fessler, Corrosion 41, 7 (1985): p. 389.

11. B.W. Cherry, A.N. Gould, MP 6, 8 (1990): p. 22.

12. K. Fink, J.H. Payer, R. Savinell, "Mitigation of Corrosion by Modification of the Environment Beneath Disbonded Coatings on Pipelines," CORROSION/93, paper no. 578 (Houston, TX: NACE, 1993).

13. J.J. Perdomo, I. Song, "Chemical and Electrochemical Conditions on Steel under Disbonded Coatings: The Effect of Applied Potential, Solution Resistivity, Crevice Thickness, and Holiday Size," Corros. Sci. 42 (2000): p. 1,389.

14. S. Papavinasam, "Permeability and Electrocatalytic Properties of Film Prepared by Electropolymerisation of m-Aminophenol," Synthetic Metals 58 (1993): p. 173.

15. J.L. Banach, "Pipeline Coatings—Evaluation, Repair, and Impact on Corrosion Protection Design and Cost," CORROSION/87, paper no. 29 (Houston, TX: NACE, 1987).

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