

FAILURE ANALYSIS: DISBONDED COATING AND CATHODIC PROTECTION SHIELDING FOR PIPELINES AND UTILITY POLES

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A tremendous amount of financial loss is incurred every year as a result of premature failures of paints and coatings. The cost to repair such failures far outweighs the initial cost of painting because excessive rigging may be needed to access the failing areas. Additional liability may also be expected if a facility must stop operation for the necessary repairs to be made. Coating failures can occur for dozens of reasons, although they are typically the result of poor application or surface preparation, a defective coating or an inadequate specification. A determination of the fundamental causes behind coating failures is critical. Not only does this help in assigning financial responsibility, but also knowing how a coating has failed is often the first step in planning how to fix it.

The majority of paint and coating-related

failures can be attributed to seven primary causes. These causes are as follows.

- **Improper surface preparation:** The substrate surface is not adequately prepared for the coating that is to be applied. This may include cleaning, chemical pretreatment or surface profile.
- **Improper coating selection:** Either the coating selected is not suitable for the intended service environment or it is not compatible with the substrate surface.
- **Improper application:** This can be a problem with either shop-applied or field-applied coatings and occurs when the required specifications or parameters for the application are not met.
- **Improper drying, curing and overcoating times:** Again, this problem relates to a lack of conformance to the required specifications or parameters.
- **Lack of protection against water and aqueous systems:** This is a particularly serious

problem with aqueous systems containing corrosive compounds such as chlorides.

- **Mechanical damage:** This results from improper handling of the coated substrate bringing about a breach in the coating.
- **Shielding cathodic protection currents** for underground applications.
- **Stray Current Corrosion:** Discharge of DC current through coating defect.

There are innumerable possible failure modes that can result from these primary causes. The failure modes can be divided into three general categories including formulation-related failures, substrate-related failures and physical-defect-related failures.

The following case studies concern paint and coating failures and the approach adopted for each will provide the principal characteristics of the failure, main identifying features, basic problem-solving techniques and applied aspects of the failures.



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CASE 1: TRANSMISSION AND DISTRIBUTION PIPELINES

A failure analysis investigation was performed on a 12-inch diameter, fusion-bonded epoxy (FBE) coated steel pipe. The pipe carried natural gas for residential service and was under cathodic protection while in service. Figures 1 and 2 (p. 26) show blistering of the FBE coating and Figure 3 (p. 27) shows an example of stray current corrosion in the pipe. A determination of the cause of the blistering was made, as well as presence or absence of corrosion attack under blisters.

Laboratory Analysis

The laboratory analysis for this investigation included cross-section microscopy of the FBE coating at a blistered and non-blistered area of the pipe, coating thickness measurements, chemical analysis of liquid extracted from inside two blisters, chemical analysis of soil taken from near the submitted pipe

and scanning electron microscopy (SEM)/energy dispersive X-ray spectroscopy (EDS) analysis of the underside of the coating from a blister and cross sections of two blisters.

The first work performed was the mapping and photography of five specified coated areas on pipe samples cut from the first area examined, labeled Site 1. Each area was outlined with a dashed line and marked at 15 different spots with a single black dot. The coating thickness was then measured at each of these 15 dots using a coating thickness gage. Each dotted spot was also visually examined and categorized based on the condition of the surrounding coating.

Three coating samples were selected for analysis by EDS. The three samples were cleanly removed from the blistered areas of the coating during the on-site investigation. The presence of chlorine and sodium in all samples was a strong indication of surface contamination.

The back sides of three delaminated coating samples were selected for analysis to determine if contamination was present and if so, to identify specific contaminants. The samples were evaluated at 30-times magnification. Generally, the percentage of contamination (blast material and steel particles) was somewhat higher at the blistered areas (49-to-55 percent) than next to the blistered areas examined earlier (30-to-35 percent). The estimate was recorded as a percentage of the total area.

Cathodic disbondment testing was performed at -1.5V vs. Cu/CuSO₄ for 48 hours on a coated sample cut from the pipe from Site 1. At the end of the test, the coating was chipped off using a utility knife until coating adhesion resisted the levering action. The radius of the dis-bonded area from the holiday edge to the coating was measured to be 5.3 mm. This determination indicates a high FBE delamination rate on areas next to the blisters. The delamination rate was estimated at 5.3 mm/48 hours.

Samples from three blistered and two non-blistered areas of the coated pipe were prepared for cross-sectional optical light microscopic (OLM) examination. Cross-section samples in blistered and non-blistered (good) areas were prepared by sectioning transversely, mounting in epoxy resin and polishing. Both blistered and non-blistered areas displayed an irregular blast profile, surface high-temperature iron oxide, and bubbles and voids in the coating.

Average coating thickness values of the cross-sectioned blistered samples ranged from 9.25 to 10.04 mils and 11.00 to 11.38 mils for the cross-section non-blistered samples. The average values in the blistered areas were not much smaller than those in the non-blistered areas suggesting the coating had not degraded in the blistered area.

Macroscopic thickness measurements were also conducted on the submitted section of pipe in blistered and non-blistered areas.



Fig. 1: Blistering of FBE coating on steel pipe. Figures courtesy of the authors unless otherwise noted.

The thicknesses in the blistered areas were somewhat lower than those in the non-blistered areas, Averaging between 9.99 and 11.91 mils for the blistered sample and 11.48-to-12.55 for the non-blistered samples. Thicknesses below 12 mils are considered very low for underground applications and corrosive moist soil. A minimum of 14-to-20 mils is commonly specified.

As shown in Figure 4 (p. 28), a hypodermic syringe was used to extract liquid from inside two blisters during the on-site investigation for subsequent laboratory analysis. The liquid samples were chemically analyzed to determine if they were harmful to the carbon steel pipe.

The large amounts of nitrates (614 ppm) and sodium (1.16-to-1.62 percent) were significant because they usually do not permeate through the coating readily, which means they were present prior to the application of the coating. Water and oxygen will permeate through the coating and combine with the sodium to create sodium hydroxide.

A sample of soil was collected from an area near the submitted pipe for laboratory analysis. The soil was analyzed to determine its chemical makeup. The resistivity of the soil around the pipe was measured on-site from areas at the bottom of the pipe, top of the pipe and near a blister. Soil resistivity ranged



Fig. 2: Blistering of FBE coating on steel pipe.

from 2,000 ohm-cm near the blister to 7,400 ohm-cm near the pipe top (corrosive to moderately corrosive soil).

Discussion

In order to prevent corrosion of underground structures, moisture must be prevented from reaching the steel surface when there is no disbondment. The penetration of moisture through the coating to the substrate is a controlling factor in the corrosion process. Propelling forces are osmotic and electroendosmotic pressures with transport aided by thermally induced molecular movements and vibrations within the coating that result in diffusion and disbondment. However, all coatings will also possess varied imperfections that will allow



Fig. 3: Stray current corrosion of FBE coated steel pipe. This corrosion-induced failure is not related to blistering or shielding. The accelerated corrosion occurred in short time due to discharge of current at the defect holiday in the FBE coating.

the environment to easily reach the metal surface. For this reason, cathodic protection is used in conjunction with coatings to protect those exposed disbonded areas.

FBE blisters are local defects that form because of the pressure exerted by an accumulation of water or aqueous solution at the coating-substrate interface in conjunction with loss of adhesion and distention of the coating. In general, the mechanism of blistering is attributed to osmotic attack and/or the presence of contamination in the coating interfacial region, in combination with the influence of moisture and cathodic protection.

Chemical analyses of the liquid inside the blisters revealed one of the main factors in the blistering of the FBE coating and back contamination observed on delaminated coatings. As oxygen reduction takes place at the contaminant site under the film, hydroxyl ions build up in the blister solution. The alkaline environment at the cathodic sites weakens or destroys the adhesion of the film while producing osmotically active substances at the coating/metal interface. Sodium was not detected in the coating cross section so it must have been present on the surface of the pipe before the coating was applied. EDS analysis of the back sides of the delaminated FBE coating samples indicated the presence of sodium and chlorine.

The alkaline environment inside the blisters, the presence of negatively charged ions (nitrates) in the blister liquid and the presence of

contaminants (such as sodium and chlorides) are all indications of osmotic (or endosmotic) passage of water from the coating surface to the interface and presence of water-soluble contamination. This resulted in pressures that exceeded the interfacial strength of the film. Eventually, the fracture strength of the film would be affected, causing further delamination of the coating.

Conclusion and Recommendations

Based on testing and analysis, it was determined that the root cause of blistering of the FBE-coated steel pipe was due to surface contamination of the pipe prior to, or during the coating application. This determination was based on the following items.

- The presence of chlorine in the sample, nitrate ions in the blister solution and

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Fig. 4: Solution extraction for laboratory analysis; high alkalinity solution was present in the blister.

- sodium in all three samples, was a strong indication of surface contamination.
- The presence of nitrates, sodium and chlorine (on the back side of the delaminated coating) in the blisters confirms the proposed failure mechanism.
- Cathodic disbondment testing indicates a high FBE delamination rate on areas next to the blisters.
- SEM/EDS analysis of the coating showed there was no sodium in the coating, which confirms it was not permeating through the coating but rather already present on the pipe surface as a contaminant.
- The blister liquid analysis indicates the contamination was present prior to the application of the coating.
- FBE coatings do not shield cathodic protection and as such, no corrosion was observed under blisters, indicating a fail-safe coating for pipelines.

To ensure public safety and avoid liability claims, it is very important that the blister growth, FBE delamination, adhesion loss and cathodic protection effectiveness on this pipe be monitored. The pipe should be recoated in areas where extensive delamination of the coating is observed to avoid localized corrosion of the pipe in the event there is lack of protection, inadequate cathodic protection or shielding effects. Blister formation and FBE delamination can be controlled through appropriate application of the FBE coating by being extremely careful in cleaning the substrate of all contaminants and implementing a quality-control program to ensure there are no



Fig. 5: A weathering steel transmission pole.

contaminants present on the substrate prior to the coating application.

This case history clearly shows when cathodic protection is used in conjunction with coated pipeline, the end users must consider a non-shielding coating. This case indicates that FBE coating is compatible with cathodic protection and the pipe will be protected even though disbondment occurs.

CASE 2: WEATHERING STEEL TRANSMISSION POLES

The client in this case had expressed concern regarding the integrity of the coating over weathering steel (WS) pole structures on the newly constructed 115 kV transmission line in upstate New York. Weathering steel is not typically coated, the exceptions being for color or appearance or when accelerated corrosion is exhibited. One such structure is shown in Figure 5. Both foundation support and direct embedment methods of pole erection were being used and the concern was with regard to the above-grade portions of the 273 structures on this new line.

A site visit was conducted to assess coating issues and to obtain paint samples for further laboratory analysis. During this period, 50 structures were inspected. Seven of these were base-plate structures and the remainder were direct-embedded structures. Of the 50 structures inspected, the following was determined.

- The primer thickness was low on eight structures.



Fig. 6: Photograph showing mechanical damage to paint.



Fig. 7: Rust in area of paint delamination.

- The topcoat thickness was low on five structures and high on five structures.
- Mechanical damage to the coating was observed on all structures (Fig. 6).
- Weld splatter defects were observed on 44 structures.
- Corrosion products of weathering steel (rust) was observed on 46 structures (Fig. 7).
- Coating defects were observed on 34 structures.
- Coating repairs were observed on 3 structures.

coating specifications for the primer or base coat and the topcoat was conducted. Important information follows.

Primer or base coat: A low-VOC organic zinc-rich epoxy primer for steel substrates. Recommended dry-film thickness is 3.0-to-5.0 mils per coat. Dry-film thickness in excess of 10 mils per coat is not recommended. A 1.0-to-3.0 mil surface profile of the substrate prior to coating application is specified.

Topcoat: An aliphatic acrylic-polyester polyurethane. Recommended dry-film thickness is 3.0-to-5.0 mils per coat. Dry-film thickness in excess of 7 mils per coat is not recommended.

Laboratory Analysis of Collected Samples

Paint chip samples from five poles were collected during the field inspection and analyzed in the laboratory. The following analyses were conducted on each of the five samples.

- Light microscopy of primer or base-coat surface.
- Cross-section light microscopy to determine coating layer thickness.
- Fourier transform infrared spectroscopy (FTIR) of the topcoat layer to ascertain consistency of coating chemistry.

The primer or base coat surfaces of each of the five paint chip samples were examined using a stereo microscope. The samples were observed and photographed at magnifications

Review of Coating Specifications

Before undertaking the laboratory analysis, a review of the client-supplied



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of 7 times and 45 times. At the highest magnification of 45 times, the surfaces appeared to be relatively smooth. This calls into question whether the substrate surfaces had the proper surface profile prior to primer application. The specified surface profile is 2.0-to-3.0 mils. Rust spots were apparent at selected areas of the primer/base coat surface as shown in Figure 8 (p. 33). It cannot be concluded whether this rust was present prior to coating application or appeared as a result of a breach or separation of the coating from the substrate.

Sections of each of the five paint chip samples were cut, mounted in cross section, ground and polished in accordance with standard metallographic procedures. Cross-sectional microscopic observations were undertaken in the as-polished condition using a stereo microscope. The samples were observed and photographed at a magnification of 45 times. When comparing coating-thickness measurements to the specifications, it was noted that the topcoat thickness on three of five samples exceeded the stated specification requirement that dry-film thicknesses in excess of 7 mils per coat are not recommended.

The base and topcoated sides of the five paint chip samples were subjected to FTIR analysis using a spectrometer in attenuated reflectance (ATR) mode. FTIR analysis of the base coated sides of the paint chips did not provide sufficiently distinct absorption bands for analysis. This is presumably due to the high metallic zinc loading of the base or primer coat. FTIR spectra are consistent in showing characteristic IR absorption bands attributable to aliphatic acrylic-polyester polyurethane. Figure 9 (p. 33) presents a representative FTIR spectrum of the top coating. Also, the topcoat on all five paint chip samples appeared to be of the same coating chemistry.

Conclusions and Recommendations

Field observations suggest many structures fail to meet the manufacturer's minimum recommended coating thickness for the specified coating system. They also suggest poor coating application and surface preparation at recessed welds, mounting holes and grounding-plate-weld areas. Poor ground sleeve weld geometry



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also results in sharp and recessed edges, which are difficult to effectively coat.

Field and laboratory evaluations indicate the aliphatic polyurethane topcoat thickness was greater than the recommended maximum of 7 mils on some structures. Coating thicknesses too great can assert excessive surface-tension stresses on the underlying primer and result in delamination from the

substrate, particularly if the surface roughness is inadequate.

Transportation and handling damage was evident and was manifested at locations of inadequate coating thickness. Mechanical damage from the installation process was also evident and was manifested at bolted connections due to contact by assembly tools, attachment to structure connections caused

by impact and backfill aggregate impacting the structure during the backfill process.

The client should make the pole manufacturer aware of welding and coating deficiencies found on the structures and should work to minimize transportation- and handling-induced coating damage. The client should also make the installation contractor aware of the coating damage found on the structures caused during installation and work to minimize handling- and installation-induced coating damage.

CASE 3: GALVANIZED TRANSMISSION UTILITY POLES

The client in this case developed a problem with in-service poles exhibiting corrosion near the ground-line. During a field study of galvanized transmission utility poles, it was observed that some of the poles exhibited corrosion near the ground-line. One pole in particular exhibited extensive red rust (discoloration) formation on one side of the underground- and ground-line sections of the pole. At the time of the investigation, the pole had been in service for approximately three years when red rust from the coated surface was observed. Under normal conditions, aboveground vertical pole conditions do not produce red rust in three years.

On-Site Inspection

Visual inspection of the aboveground section of the pole revealed red rust and minor mechanical damage that consisted of a slight depression around it. The aboveground galvanized thickness range was 4.2-to-5 mils; polyurethane plus galvanizing was 17-to 25-mils. Visual inspection of the below-ground section of the pole also revealed red rust under soil deposits and mechanical damage that consisted of several small spots on the corner and a larger triangle area to one side. The coating in this area was disbanded and easily peeled away to reveal red and white rust under soil deposits. The below-ground polyurethane plus galvanized coating thickness was measured at 15-to-22 mils. Uniform corrosion attack and thickness loss around the circumference of the pole was not observed, indicating the corrosion attack was localized in nature due to

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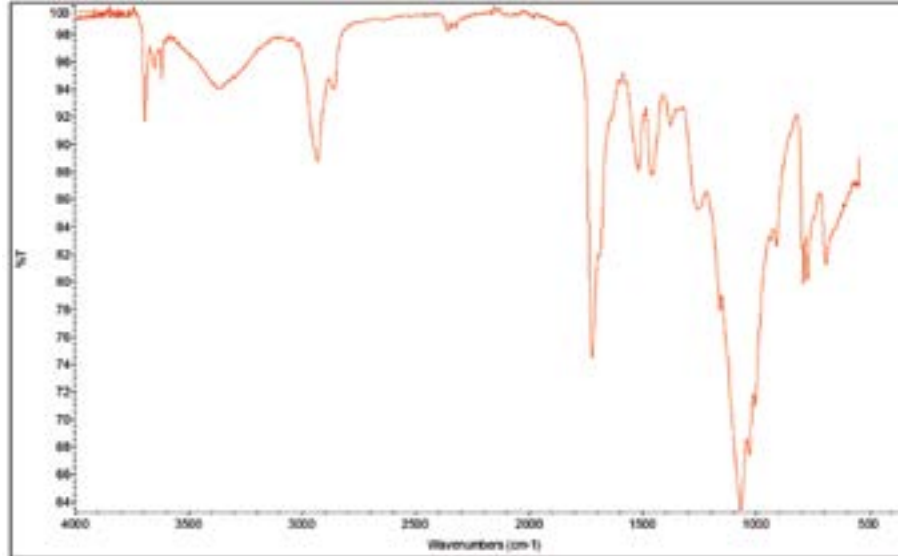
Fig. 8: Photomicrograph of rust on underside of primer at 7-times magnification.

Fig. 9: (Right) Representative FTIR spectrum of topcoat.

shielding of cathodic protection current. The soil corrosivity measured by soil resistivity and linear polarization resistance (LPR) method and found to be mildly corrosive.

Conclusions and Recommendations

The corrosion observed on this pole was uncharacteristic of what would have been expected under these circumstances. It



was evident that corrosion had been accelerated by disbondment and accumulation of corrosive ions. Further studies revealed the corrosion on this pole had initiated in storage prior to installation due to coating disbondment. The corrosion initiates with an

accumulation and permeation of moisture and corrosive compounds at the galvanized coating interface. Disbonded coating acts as a barrier to cathodic protection current from galvanic-anode protection underground. Once moisture is present and

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cathodic protection current is unreachable to the substrate under disbonded coating, the accelerated corrosion can take place. Coatings that do not shield cathodic protection currents should be selected for this type of underground corrosive applications.

This case clearly shows that when cathodic protection is used in conjunction with coated transmission and distribution structures, the end users must use a non-shielding coating. This case also indicates that thick, barrier coating is not compatible with cathodic protection and the underground portion of the pole will not be protected by cathodic protection when disbondment occurs due to shielding of cathodic protection currents.

CONCLUSION

This article emphasizes the basic problems and applied aspects of failures encountered at three separate structures and details the factors and mechanisms affecting the failures. It should be noted that in underground

structures protected by cathodic protection, coatings should be selected that do not shield cathodic currents. Coatings that shield cathodic protection have resulted in localized corrosion, perforation and in some instances, explosions in gas pipelines. This is true for both oil and gas and transmission and distribution utility structures. Electrochemical impedance spectroscopy and disbondment tests can be utilized to test coatings for cathodic protection shielding.

ABOUT THE AUTHORS



Dr. Mehrooz Zamanzadeh ("Dr. Zee") is a materials and corrosion engineer specializing in root cause failure analysis of paints and protective coatings, corrosion risk

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Zamanzadeh is a NACE-certified Corrosion/Cathodic Protection/Coating Specialist. His degrees include a Bachelor of Science and a Masters of Science in materials science and engineering, as well as a Ph.D. in materials science from Pennsylvania State University. He holds four certifications from NACE International and has received a number of awards including the 2010 Colonel George C. Cox Award; NACE Fellow Award (2007); ASM Fellow Award (2006); NACE Outstanding Service Award (1996) and the ASM Entrepreneur of the Year Award (2004). Zamanzadeh holds over 40 registered patents and has authored over 60 technical publications on a wide array of topics.



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