ABSTRACT

In this paper failure analysis methodology will be applied to the principal mechanisms by which paints and coatings fail during service; with specific application to case studies involving T&D pipelines and utility structures. The case studies apply standard failure analysis techniques to determine the primary causes and modes of failures.

INTRODUCTION

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, since 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, 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 knowing how a coating has failed is often the first step in planning how to fix it.

FAILURE ANALYSIS

A more in-depth discussion of the techniques for failure analysis of paints and coatings is given in a previous paper (1). The stages of analysis performed when conducting paint or
coating failure analysis investigation should begin with the collection of background data and sample removal. This step includes site inspection, information regarding the current history of the failure, all relevant record keeping, and records on past failures if applicable.

A preliminary examination of the failed coating and the substrate, as well as a non-destructive examination of the failure, with extensive photographic documentation, precedes any destructive laboratory evaluation and analysis. The preliminary examination does not change or damage the failed coating or substrate in any way.

At this point in the investigation, the specimens should be selected and identified for further laboratory testing and analysis. Management should be notified of any specimens collected from paint and coating failure, as the specimens, including the underlying substrate, are often damaged and of little use after testing.

A macroscopic examination of the surface of the selected specimen begins this stage of analysis, followed by a microscopic examination. A close examination of failed paint and coating chips using a stereo microscope at magnification of 50x or less may reveal that one of the layers is brittle and full of cracks, or perhaps that an entire layer of paint is missing. An examination of failed and non-failed samples may reveal that all of the failed samples are of improper thickness. A microscope at magnifications ranging from 50x to 1000x can be used to examine the cross section of failed paint and coating samples for voids or inclusion, as well as observation of underlying corrosion products on substrates.

A chemical analysis of the paint or coating, as well as the substrate and corrosion products is usually the next step. Chemical analysis techniques typically used in the laboratory for paint and coating failure analysis are Fourier transform infrared spectroscopy (FTIR) for organic functional group analysis, scanning electron microscopy (SEM) with associated energy dispersive x-ray spectroscopy (EDS) for elemental analysis, and x-ray photoelectron spectroscopy (XPS) for surface elemental analysis.

Accelerated environmental exposure tests, such as salt spray (fog) tests, humidity tests, and ultraviolet light (QUV) exposure tests can help to confirm the proposed failure mechanism of a painted or coated substrate sample. Accelerated exposure testing can be complemented with electrochemical impedance spectroscopy (EIS). In the EIS technique, capacitance and electrical properties of the coating are measured as a function of time. If the impedance ratio does not change as a function of time, then one can, with high degree of confidence, conclude that the coating is not altered and performs very well under actual service conditions.

Analysis of the evidence; and a review of the existing data and documentation are the final stages of failure investigation. All information is gathered and analyzed to form a determination on the mode and probable cause of the failure. Identification of the mode and cause of failure provide the source for recommendations for corrective action. A final report including all relevant data, analyses, and recommendations are compiled and presented to the client. In litigation investigations, the client may not be interested in the recommendations section of the report.
PAINT AND COATING FAILURES

The majority of paint and coating-related failures can be attributed to six 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 roughening.
- Improper coating selection – either the paint or 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 over-coating 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 – which results from improper handling of the painted or coated substrate, resulting in a breach in the paint or coating.

There are innumerable possible failure modes which 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.

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

T&D 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 show blistering of the FBE coating and Figure 3 shows an example of stray current corrosion in the pipe. A determination of the cause of the blistering was made; as well as a determination of detrimental effects to the pipe wall.

Laboratory Analysis

The laboratory analysis for this investigation included cross-section microscopy of the FBE coating in a blistered and non-blarsted area of the abandoned pipe; coating thickness measurements, chemical analysis of liquid extracted from inside two blisters; chemical analysis of soil taken from near the submitted pipe and SEM/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 sample cut from 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 energy dispersive x-ray spectrometer (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 backsides of three delaminated coating samples were selected for a contamination analysis. The samples were evaluated at 30x magnification. Generally, the percent contamination was somewhat higher at the blistered areas (49-55%) than next to the blistered areas (30-35%). The estimate was recorded at percentage of 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. 0.01 M NaOH was used as the electrolyte. At the end of the test, using a utility knife, the coating was chipped off until coating adhesion resisted the levering action. The radius of the disbanded 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 abandoned 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/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. 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 is considered very low for underground applications and corrosive moist soil. A minimum of 14-20 mils is commonly specified.

As shown in Figure 4, 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 analyzed to reveal their chemical analysis and determine if they were harmful to the carbon steel pipe.

The large amounts of nitrates (614 ppm to 0.16%) and sodium (1.16 to 1.62%) 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 make-up. 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 from 2000 ohm-cm near the blister to 7400 ohm-cm near the pipe top.

**Discussion**

In order to prevent corrosion of underground structures, moisture must be prevented from reaching the steel surface. 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. But, all coatings will also possess varied imperfections that will allow the environment to easily reach the metal surface. For this reason, cathodic protection is used in conjunction with coatings to protect those exposed 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.

One of the main factors in the blistering of the FBE coating was the chemical analysis of the liquid inside the blisters 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 backside of the delaminated FBE coating samples indicated the presence of sodium and chlorine. SEM/EDS analysis of the coating shows there is 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 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. 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 fusion bonded epoxy (FBE) coated steel pipe was due to surface contamination of the pipe prior to or during the coating application. This determination is based on the following items:

- The presence of chlorine in Sample, nitrate ions in the blister solution and sodium in all three samples, is a strong indication of surface contamination.
• The presence of nitrates, sodium and chlorine (on the backside 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.
• Sodium was not detected in the cross section analysis; therefore, it must have been present on the surface of the pipe.
• SEM/EDS analysis of the coating shows there is 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.

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 general delamination of the coating is observed. This is to avoid localized corrosion of the pipe in the event there is lack of protection, inadequate cathodic protection, or shielding effects due to areas where the epoxy coating has a much higher thickness than 12 mils. Blister formation and FBE delamination can be controlled through appropriate application of the FBE coating by (a.) being extremely careful in cleaning the substrate of all contaminants, and (b.) implementing a quality control program to ensure there are no contaminants present on the substrate prior to the coating application.

**UTILITY STRUCTURES**

The client has expressed concern regarding the integrity of paint coatings over weathering steel (WS) pole structures on the newly constructed 115 kV transmission line in upstate New York. One structure is shown in Figure 5. Both foundation support and direct embedment methods of pole erection are being used, and concern is with regard to the above-grade portions of the 273 structures on this new line.

A site visit was conducted from February 21 thru March 3, 2014 to assess coating issues and to obtain paint samples for further laboratory analyses. During this period, 50 structures were inspected. Seven of the structures were base plated structures, and the rest were direct embedded structures. Of the 50 structures inspected, the following were determined.

• The primer thickness was low on 8 structures.
• The top coat thickness was low on 5 structures and high on 5 structures.
• Mechanical damage to the coating was observed on all structures. See Figure 6.
• Weld splatter/defects were observed on 44 structures.
• Rust was observed on 46 structures. See Figure 7.
• Coating defects were observed on 34 structures.
• Coating repairs were observed on 3 structures.
Review of Coating Specifications

Before undertaking the laboratory analysis, a review of the client-supplied coating specifications for the primer or base coat and the top coat was undertaken. Important information is provided below.

- Primer or base coat – Carbozinc 859 low VOC organic zinc-rich epoxy steel 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.
- Top coat – Carbothane 133 HB 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 top coat 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 of 7x and 45x. The surfaces appeared at the highest magnification of 45x 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 1.0 to 3.0 mil. Rust spots were apparent at selected areas of the primer/base coat surface; as shown in Figure 8. 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. The 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 45x. When comparing coating thickness measurements to the specifications, it was noted that the top coat thickness on three of five samples exceed the stated specification requirement that dry film thicknesses in excess of 7 mils per coat are not recommended.

The base and top coated sides of the five paint chip samples were subjected to FTIR analysis using a Nicolet Avatar 360 FTIR spectrometer in attenuated reflectance (ATR) mode. Fourier transform infrared spectroscopic (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 Carbozinc 859. Although a definitive answer cannot be given to whether or not the top coating on the paint chip samples was, in fact, Carbothane 133 HB, the FTIR spectra are consistent in showing characteristic IR absorption
bands attributable to aliphatic acrylic-polyester polyurethane. Figure 9 presents a representative FTIR spectrum of the top coating. Also, the top coat 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 also results in sharp and recessed edges which are difficult to effectively coat.

Field and laboratory evaluation indicate the aliphatic polyurethane top coat thickness is greater than the recommended maximum of 7 mils on some structures. Too great of coating thickness 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 is evident, and is manifested at locations of inadequate coating thickness. Mechanical damage from the installation process is evident, and is 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.

CONCLUSION

This paper emphasized the basic problems and applied aspects of the failures encountered in paints and coatings. Two separate types of failures were presented, including T&D pipelines and utility structures, detailing the factors and mechanisms affecting the failures.
Figure 1: Blistering of FBE coating on steel pipe.

Figure 2: Blistering of FBE coating on steel pipe.
Figure 3: Stray current corrosion of FBE coated steel pipe.

Figure 4: Solution extraction for laboratory analysis; high alkalinity solution was present in the blister.
Figure 5: Photograph of weathering steel transmission line pole structure.
Figure 6: Photograph showing mechanical damage to paint.

Figure 7: Rust in area of paint delamination.
Figure 8: Photomicrograph of rust on underside of primer; 7x.

Figure 9: Representative FTIR spectrum of top coat.
REFERENCES