A Case Study on Using Corrosion Analysis in Forensic Engineering

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Journal of Failure Analysis and Prevention

ISSN 1547-7029
Volume 17
Number 4

J Fail. Anal. and Preven. (2017)
17:642-646
DOI 10.1007/s11668-017-0293-4

Springer

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CASE HISTORY—PEER-REVIEWED

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Submitted: 26 May 2017 / Published online: 26 June 2017

Abstract Material failures occur in products due to changes in the original characteristics that prevent satisfactory performance of a functional system for its intended purpose and could produce losses to human life and economic infrastructure. Metals' characteristics change due to cyclic stress, strain, and corrosion. This paper presents a case study that deal with the application of corrosion fundamentals in the determination of the origin of failures in a metallic part—galvanic corrosion failure in a water supply plumbing system. Metallographic examination, chemical analysis of the parts, and fractography were conducted, and the cause of failures was determined as a galvanic corrosion.

Keywords Corrosion failure analysis · Galvanic corrosion · Copper · Steel

Introduction

The early stages of a metallurgical engineering forensic analysis include the collection of background information and the selection of appropriate samples for laboratory testing. Additional steps should include site inspection, a timeline of the failure, material specifications, review of maintenance and repair records, information on past failures for the same component, and any material substitutions made. A visual examination of the failed part or structure, non-destructive testing of the component, and photographic documentation should be performed first. The selected failed parts for laboratory testing and analysis should be carefully stored or protected during transport to prevent any damage to the fracture surfaces from humidity, dust, dirt, and contamination from human contact.

A macroscopic visual examination of the fracture surface and external surfaces of the part typically begins the investigation and will be followed by microscopic examinations. An optical stereo microscope examination at magnifications of 50× or less will help to reveal fracture surface details, confirm fracture initiation locations and mode of failure, and reveal possible evidence of surface damage at the locations of fatigue crack initiation. There are differences observed in fatigue fracture surface appearances caused by the magnitude of the applied stress and remaining cross-sectional area when the fracture passes through each area. The main differences are observed by macroscopic visual fractography. Fatigue fracture surfaces typically show two distinct regions: the fatigue crack initiation and propagation region, and the final overload region. In the final overload region, the presence of slanted 45° shear zones and their elongated fibrous dimpled structure or brittle cleavage features are indicative of rapid loading conditions [1].

Metallographic examination by optical light microscopy in the range of 100× to 1000× is required to identify the microstructure and heat treatment condition of the material and any possible defects originating from material processing or heat treatment. Many fatigue cracks can initiate from small defects. Scanning electron microscopy (SEM) assists in the characterization of the type of fracture and helps pinpoint the source of crack initiation. Chemical analysis of the component will help to determine if the material has been heat treated for higher strength as resistance to fatigue generally increases with increasing strength. The presence of alloying elements could be

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ascertained by scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy (EDS) for elemental analysis. Mechanical properties should be verified and compared with specifications when available. Verification of mechanical properties assumes that the original design and material selection were correct but rules out incorrect material substitutions. Tensile tests should be performed if the size of the sample is sufficient. Hardness or microhardness testing can also be performed in lieu of tensile testing if the components are small or if surface decarburization or carburization are present [2].

Analysis of the evidence collected is the final stage of a failure investigation. Identification of the fracture initiation site, defects, or imperfections (if present), size of the fatigue propagation zone compared with the size of the final failure zone, and material properties can be used to provide recommendations for corrective action. A final report, including all relevant data, analysis, and recommendations, may be compiled and presented to the client. In litigation investigations, the client may not be interested in the recommendations section of the report.

Case Review: Galvanic Corrosion in a Water Supply Plumbing System

Background

The potential for environmental degradation of material performance has been known for centuries. Scientific understanding of the process has helped to engineer different technologies for preventing or postponing the

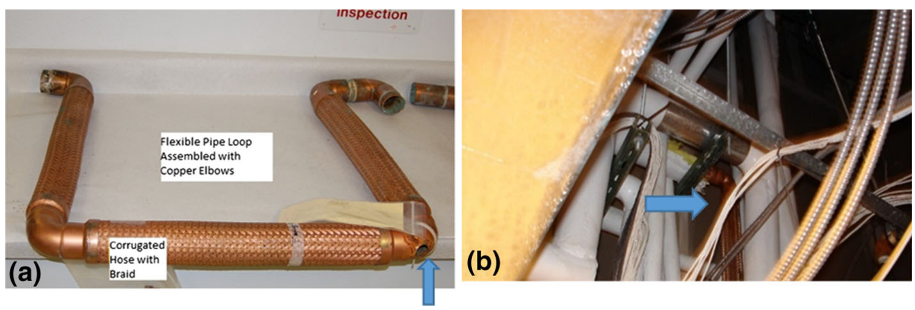

Fig. 1 (**a**) Flexible corrugated hose pipe connector and location of a drainage port on copper elbow. (**b**) Location of a flexible pipe in the plumbing structure of building

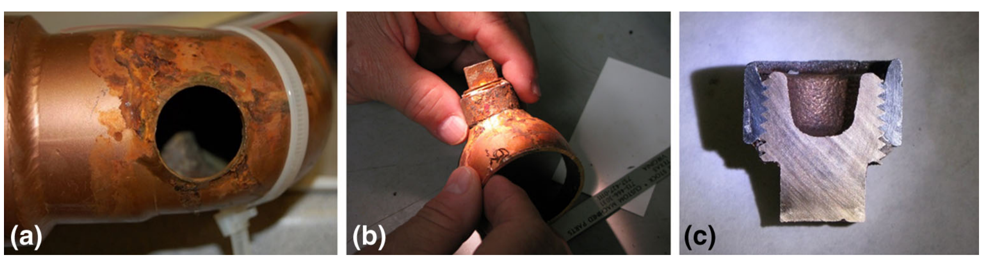

Fig. 2 Failed copper joint (**a**), the brazed steel coupling with plug (**b**), and cross section of coupling with plug

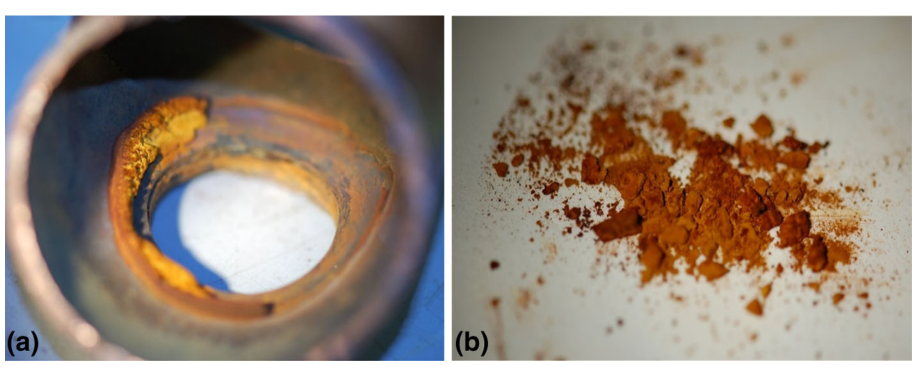

Fig. 3 Inside of the corroded copper elbow (**a**) and corrosion powder product (**b**)

damaging effect in products and parts. Engineers who are responsible for design and manufacturing of components and systems should consider adverse effects of material degradation on safety of the products [3].

Galvanic corrosion of metals, which has been called dissimilar metal corrosion, is a process by which one metal corrodes another one in contact through an electrolyte. An example of galvanic reaction is manifested in batteries to produce a voltage. The phenomenon has been recorded in detail in the literature, and engineering approaches to avoid galvanic process have been presented in engineering and technology curricula [4, 5]. The following case presents a matter in which a lack of adherence to materials engineering knowledge in decision making for altering a design created failure and damages [6].

Water piping systems in multi-story buildings may require different configurations and flexibility for various passages in the design of the system. Applications utilizing corrugated copper hose assemblies are popular in both conventional and advanced plumbing designs. Flexible corrugated metallic pipe loops were originally patented in the US in 1998 (US Patent 5,803,506). Challenges of customizing pre-assembled hose systems to meet local building code requirements require a good knowledge-based background and experience in corrosion science and technology to successfully modify the original design of the hose.

A large water leak caused major damage in a high-rise building. The water leak was due to failure of assembled drain couplings on copper elbows in flexible braided hose connectors. Figure 1 shows one of the flexible corrugated hose pipes and its location in the building.

Laboratory Examination

Laboratory tests were conducted on four failed flexible hoses. The tests performed were visual examination, microscopic examination, hardness measurements, and chemical analysis.

After photographic documentation, a square section was removed from the copper elbow. When the inside surface of the elbow was exposed to view, a bright orange deposit was observed nearly around the hole from which the drain port had separated. Energy-dispersive spectroscopy (EDS) analysis revealed that this material was ferric hydroxide [$Fe(OH)_3$—rust]. Microscopic examination of the inside diameter of the fracture surface of the weld metal attached to the elbow revealed a layer of reddish scale. That scale was also identified with the EDS to be rust. Figures 2, 3, 4, and 5 show the failed copper elbow, coupling and plug, surface dust, scanning electron microscopy of the failed surface, metallographic microstructure, and EDS analysis.

EDS analysis of the gray surface on the steel drain port revealed steel with no copper present. This surface had been part of the welded joint. EDS analysis of the copper-colored area above the gray area revealed a copper-filled organic coating. Quantitative chemical analysis in the optical emission spectrometer of the coupling revealed a carbon steel that does meet the compositions for carbon steel forgings for piping applications per ASTM A105 [7]. Table 1 presents chemical compositions of the drain port coupling. The steel contained high sulfur and manganese contents, like to free machining steel Table 1. The etched metallographic section through the steel connector revealed the manganese sulfide stringers typical of free machining steel. Chemical analysis of the plug identified a copper alloy with approximately 80% copper and 10% tin, Fig. 5.

A metallographic section through the elbow and the weld deposit was prepared and polished. EDS analysis of the elbow portion revealed essentially pure copper. EDS analysis of the braze deposit portion revealed copper with about 4.4 percent silicon and about 1.6 percent manganese. Average microhardness of the copper elbow was determined to be 69 HK200, and average microhardness of the weld deposit was determined to be 126 HK200.

Macroscopic examination, microscopic examination, and SEM microscopic examination revealed that the

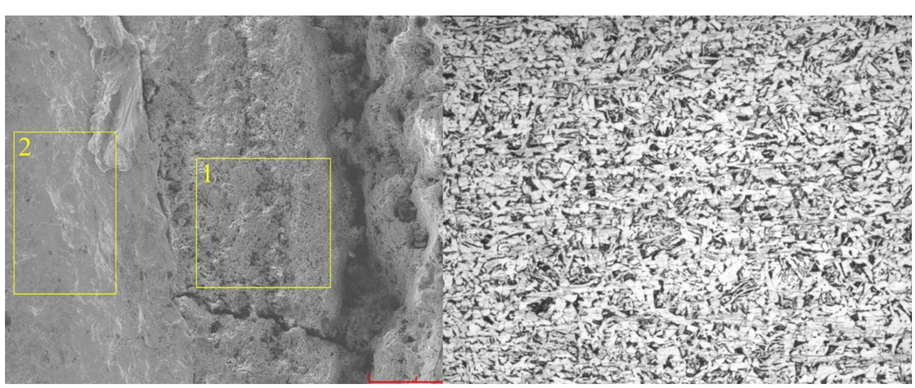

Fig. 4 Representative pictures of SEM (left) and metallography (right) of copper pipe and steel plug

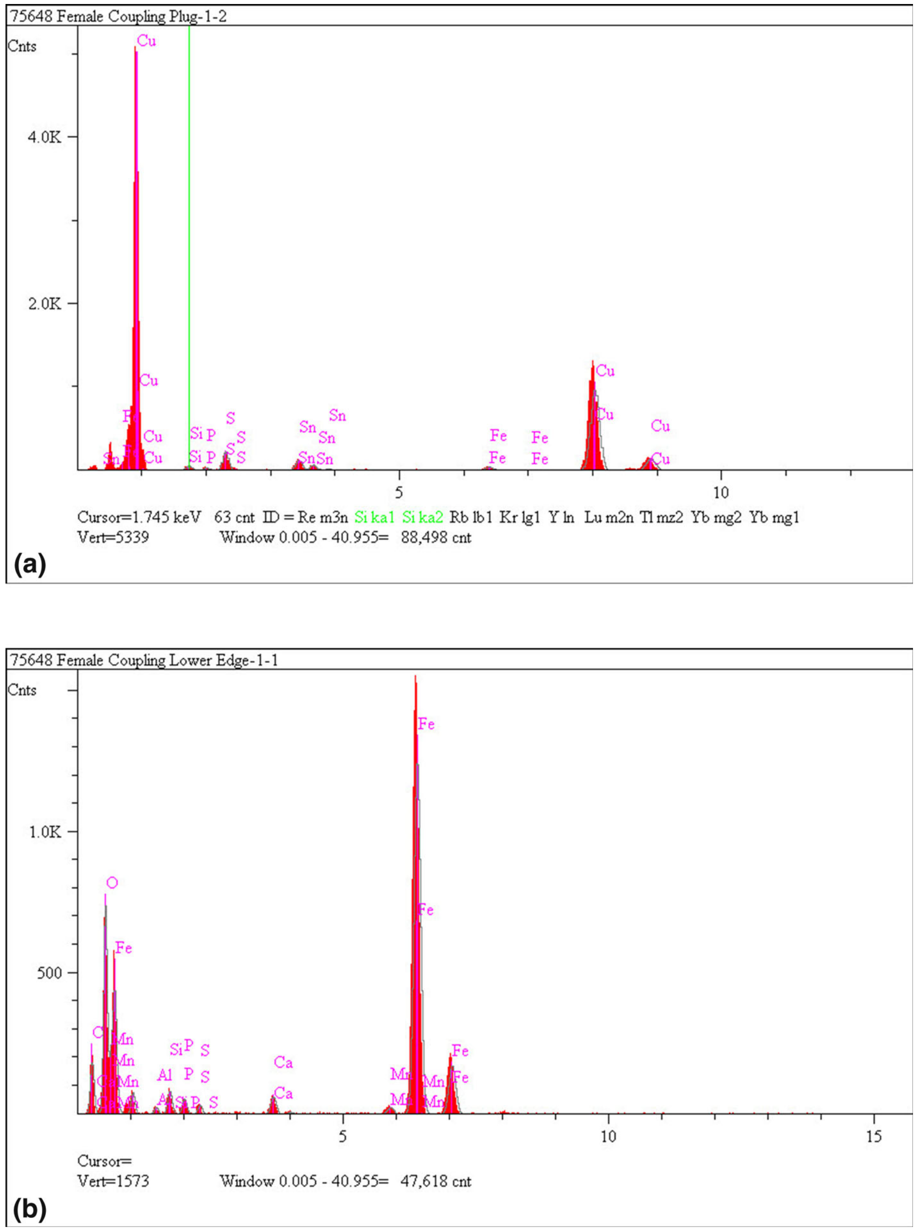

Fig. 5 Energy-dispersive spectroscopy (EDS) of (**a**) the plug, (**b**) the coupling

bottom end of the drain port was a preferred site for pitting in a manner consistent with galvanic corrosion. The metallographic section also revealed deep corrosive attack.

Discussion

There was no fracture of the braze metal or of the steel coupling. It was clear that corrosive attack penetrated along the interface between the braze metal and the outer surface of the steel coupling. That galvanic corrosion produced a scale in the interface that separated the joint, and resulted in the detachment of the drain port from the elbow under system pressure.

Exposure of relatively large area of copper with respect to iron resulted in accelerated galvanic corrosion of the iron and the destruction of the braze joint holding the steel coupling in the copper elbow. There was no corrosion of the copper. Only the steel coupling was corroded. It is concluded that installation of a steel coupling for drain port on the copper elbow was an improper decision.

Table 1 Chemical compositions of the drain port coupling

Element	wt.%
C	0.14
Mn	1.27
P	0.0519
S	0.0604
Si	0.235
Ni	0.01
Cr	0.045
Mo	0.01
Cu	0.22
V	0.007
Ti	0.003
Al	<0.003
Vb	<0.03

Conclusion

The separation of the steel coupling from the drain port on the copper elbow occurred as a result of galvanic corrosion. This corrosion mechanism is well understood. Installation of a drain port with a steel coupling on a copper elbow was an improper decision. To prevent galvanic corrosion, interaction of dissimilar metals should be avoided in a wet environment.

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