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CASE HISTORY—PEER-REVIEWED

Failure of a Dissimilar Metal Braze in an Expansion Joint

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Abstract The failure of a hot water expansion joint in the heating system of a high-rise office building resulted in a catastrophic water leak. Brittle cracking occurred at a dissimilar braze joint between copper and stainless steel components. Failure analysis and instrumental characterization revealed that an incompatible phosphorus-containing, copper-based braze alloy had been used. The brazing operation created a hard, brittle intermetallic phase at the stainless steel component interface in the complex dissimilar metal joint. Although brazing filler metal guidelines highlight this incompatibility, there is a dearth of information concerning the nature and metallographic appearance of this deleterious phase. The purpose of this case history presentation was to detail the failure investigation and to characterize the composition and microstructure of this brittle phase.

Keywords Brazing · Intermetallic · Brittle fracture

Introduction

Fracture of the expansion joint was sudden, as it occurred only several hours or a few days after the system had been completed and put into service. A high pressurization event was hypothesized as a necessary contributory cause, probably in the form of a hydraulic shock. Hydraulic shock, often called water hammer, can result in severe vibration and even pipe collapse. This pressure surge or wave is created when the liquid momentum changes as it is forced to stop or change direction suddenly. Fracture occurred through a complicated brazed joint between a copper elbow and an austenitic stainless steel expansion joint. The water leak was not immediately detected because it happened over a weekend when the building was vacant. This incident resulted in substantial flooding damage and financial loss.

For the purposes of metallurgical failure analysis, the cracked expansion joint was provided. The materials of construction and assembly methods were not identified for this investigation. It is assumed that the system had been hydrostatic tested prior to service, but this was not confirmed.

Expansion Joint Configuration

The exact design of the expansion joint assembly cannot be provided here, but similar units are fabricated by many companies in a large variety of configurations. These joints are intended to accommodate repetitive thermal and mechanical forces including axial extension, axial compression, lateral deflection, torsional deflection, angular deflection and vibration. Expansion joints like the failed component are routinely used in hot water, chilled water, steam, chemical, fire suppression, exhaust and a combination of service applications. They are also an integral part of piping design for earthquake-prone locations. These constructs can be linear, circular, U-shaped, etc., depending upon the directions and magnitudes of expansion forces anticipated during engineering design. In addition, they are available in a variety of materials, including copper alloys, stainless steels and nickel alloys for specific applications.

A diagram of the failed end of the expansion joint is provided in Fig. 1. The joint is not a typical braze where a

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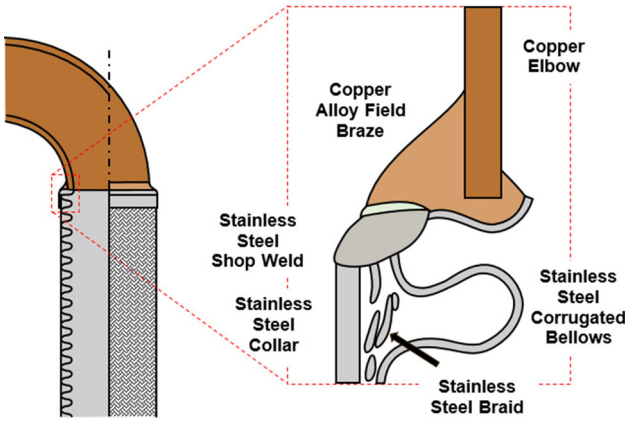

Fig. 1 Diagram of the failed joint with identifications of the components and materials. Partial cutaway (left) shows the general assembly with the inset image (right) showing the installed braze weld joint

Fig. 2 Close-up photograph of a typical region of the fracture surface

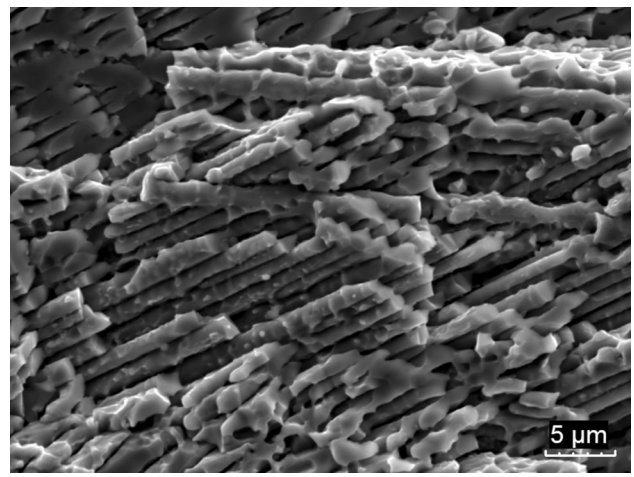

Fig. 3 Electron image of a representative fracture region

relatively tight joint is filled by capillary action. A large gap was created where the elbow was nested into the last convolution in the assembled bellows. Large volume joints like this are usually called braze welds. Due to the liquidity necessary to fill this braze joint, it is considered likely that it could only be brazed in the horizontal orientation depicted, otherwise the liquefied braze alloy would run out of the joint.

No information was provided concerning the fabrication of the expansion joint. Based on the appearance and the application, it was surmised that the stainless steel expansion joint was created as an assembly with a shop arc weld securing the stainless steel collar around the protective wire braid and the interior convoluted or corrugated hose. The precise alignment of the collar, braid and hose section would require pre-weld fixturing not usually feasible in field welds. The expansion joint was likely installed as a field weld in the high-rise building by a pipe fitter by brazing it in position to pipes and elbows as appropriate. This was likely a torch brazing operation as this technique is the most portable and versatile.

Visual and Microscopic Observations and Failure Analysis

Separation occurred through the brazement adjacent to the stainless steel expansion joint weld. The color of the braze alloy was grayish brown, suggestive of a copper alloy filler metal. The fracture appeared macroscopically brittle, without any permanent plastic deformation. There was no impact evidence or macroscopic brazing or fabrication flaws. A representative region of the fracture is shown in Fig. 2. The features were dull and did not exhibit the normal matte appearance of ductile rupture which would be expected for a copper alloy braze. Some angular features were evident at low magnification. No gross incomplete braze fusion was identified.

SEM Fractography

Excised regions of the opened joint crack surface were examined in a scanning electron microscope. The fracture specimens were cleaned in a laboratory detergent solution followed by rinsing with ethyl alcohol. No strong solvent or acidic cleaning was performed. Representative images of the fracture morphology are provided in Figs. 3 and 4. A variety of different features were observed in regions of the opened crack. None of the fracture features could be classified as those characteristically expected for cracking in a metallic material.

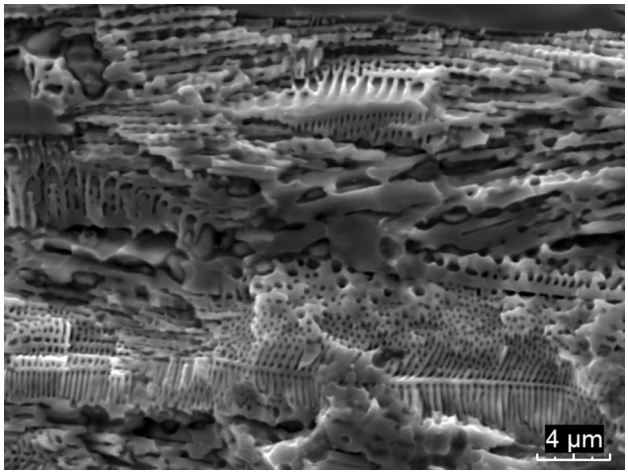

Fig. 4 Electron image of another fracture zone which exhibited different morphologies

Fig. 5 One cross section of the expansion joint brazement is pictured. An intermetallic phase was identified (arrow) between the braze and the stainless steel weld (potassium dichromate etch)

Metallography

Several radial cross section specimens were prepared through the dissimilar metal braze joint in regions that had cracked and regions that were not visibly cracked. Microscopic evaluation was performed in the as-polished condition and after etching to reveal the microstructures. Inspection was performed at magnifications up to 1,000X. It should be noted that due to the substantial relative differences in etching response (corrosion resistance) between the different materials in this dissimilar joint it was necessary to try a variety of different etching procedures and etchants. No single combination of etchant and etching technique was successful in properly etching all regions of interest. Figures 5 and 6 show cross sections through the joint in regions that were partially cracked.

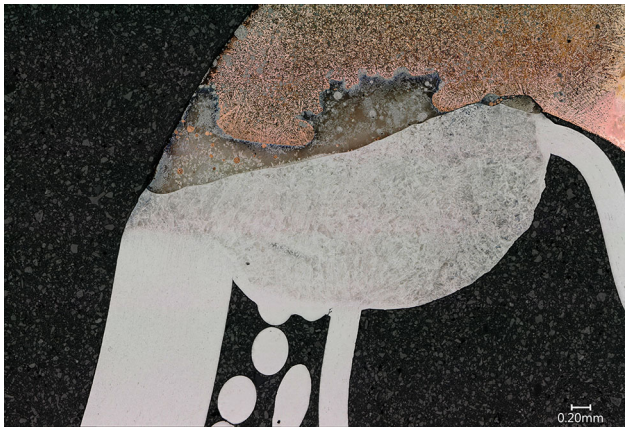

Fig. 6 An additional cross section revealed a more irregularly shaped intermetallic phase (10% oxalic acid electrolytic etch)

The microstructure of the copper elbow was considered typical, comprised of equiaxed alpha copper grains with twin boundaries from prior annealing. Regions of the elbow adjacent to the braze exhibited gross grain growth. In addition, some of the elbow was melted into the brazement. This was suggestive of excessive temperatures and/or extensive heating time during the braze welding process. Copper braze alloys are formulated to have melting temperature ranges substantially lower than the melting point of copper, so this is further evidence of excessive brazing temperature. The adjacent braze alloy exhibited a normal dendritically solidified structure in regions adjacent to the copper elbow.

Metallographic evaluation of the weld, bellows, collar and braid wires revealed normal microstructures for austenitic stainless steel. The stainless steel weld microstructure was typical, consisting of dendritically solidified austenite with ferrite. The wrought components had normal annealed microstructures with fine grain sizes and annealing twin boundaries. No welding fusion flaws or thermal degradation to the stainless steel components were identified.

All of the cross section specimens contained an irregular phase that formed between the braze alloy and the stainless steel weld. This phase was continuous, from the OD to the ID of the joint. The features suggested this was an intermetallic phase rather than trapped flux or slag. Cracking was isolated to this intermetallic phase and did not follow a particular structure. Higher-magnification images of the intermetallic phase are included in Figs. 7–10. Various etchants were used singly and in succession, but Waterless Kallings and 10% oxalic acid (electrolytic) revealed the intermetallic microstructure best. Copper spheres were evident in the intermetallic, a condition which is often observed in brazing intermetallic layers. The unusually thick intermetallic contained both lamellar and somewhat

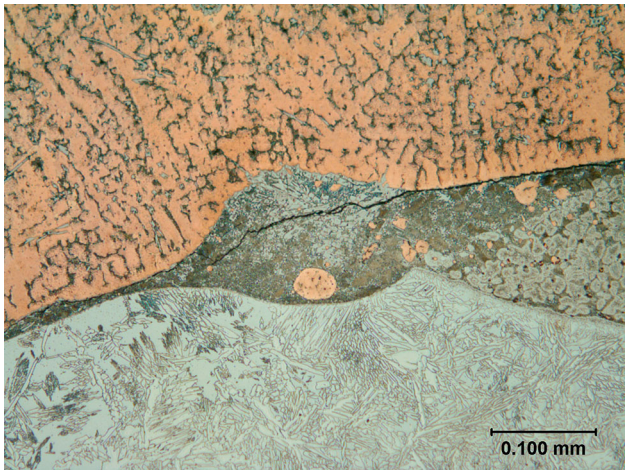

Fig. 7 Photomicrograph of cracking which was isolated to the intermetallic layer between the copper braze (top) and the stainless steel weld (bottom) (Waterless Kalling's reagent etch)

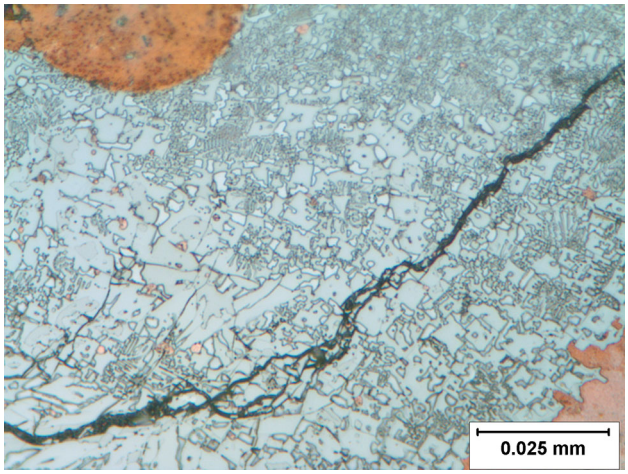

Fig. 8 Additional image of cracking through the intermetallic showing that the cracks did not follow any unique features (Waterless Kalling's reagent etch)

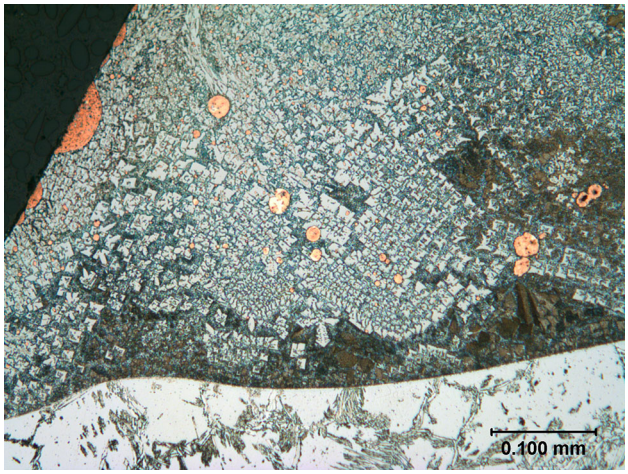

Fig. 9 Moderate magnification image showing the unique microstructure of the intermetallic layer (oxalic acid/Waterless Kalling's reagent etch)

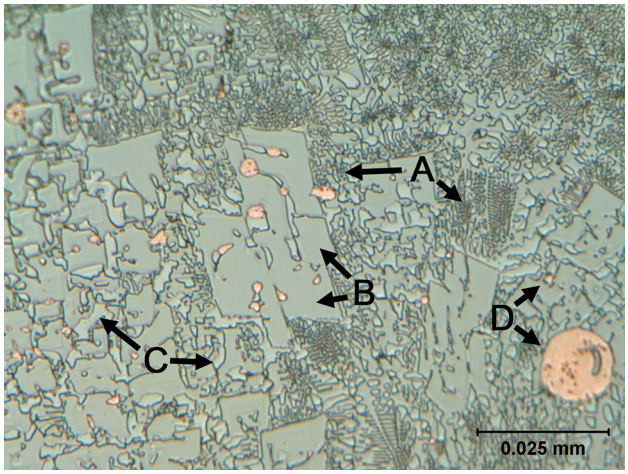

Fig. 10 High-magnification image showing the intermetallic microstructure. A number of phases were apparent, including a lamellar phase (**a**), a somewhat cubic blocky phase (**b**), a lighter hued irregular phase (**c**) and copper spheroids (**d**) (oxalic acid/Waterless Kalling's reagent etch)

cubic appearing structures, consistent with the unusual fracture morphology. Comparison of microstructure images could not be found in the literature.

EDS Analyses

Energy-dispersive x-ray spectrometry analysis was then performed on the polished metallographic cross section specimens. Standardless EDS analysis (excluding carbon) confirmed that the expansion joint materials were generally consistent with Type 304 stainless steel, except for the corrugated bellows hose which contained sufficient titanium to suggest it was likely Type 321. Since only the interior of the bellows would be subjected to the more corrosive water service environment, Type 321 would not be an unusual selection. The copper elbow was nearly pure copper, possibly a phosphorus deoxidized alloy.

The weld, braze alloy and intermetallic layer were also analyzed, and the semiquantitative results are summarized in Table 1. The high chromium level of the weld suggested it was likely a Type 308 or 309 although compositional variation between analyzed locations revealed non-uniform dilution. The braze alloy was primarily composed of copper, silver and phosphorus. Although analysis was preferentially performed in the center of the braze metal to minimize dilution effects, significant concentrations of iron, chromium and nickel from the stainless steel weld

Table 1 Cross section EDS analysis data: relative weight percent

Element	Stainless steel weld	Copper braze alloy	Intermetallic layer
Silicon	0.4	…	0.4
Phosphorus	…	5.0	9.1
Chromium	24.1	2.1	21.6
Manganese	1.6	…	0.5
Iron	65.0	5.5	57.6
Nickel	8.9	0.9	6.0
Copper	…	71.8	4.7
Silver	…	14.7	…

Table 2 Braze alloy EDS analysis data: relative weight percent. Excluding iron, chromium and nickel from quantification

Element	Braze alloy	AWS BCuP-5 filler composition (UNS C55284) per AWS SFA-5.8 [1]
Copper	78.2	Remainder
Silver	16.3	14.5–15.5
Phosphorus	5.5	4.8–5.2
Other elements	None detected	0.15 Maximum

were detected in the braze. Re-quantification omitting these dilution elements yielded the composition as shown in Table 2. The braze alloy was consistent with the typical requirements for AWS BCuP-5 per AWS A-5.8 (ISO 17672 Type CuP 284) with 14.5–15.5% silver and 4.8–5.2% phosphorus. Due to mutual insolubility, this ternary system is normally copper, silver and copper phosphide (Cu_3P).

The composition of the intermetallic compound, in Table 1, consisted primarily of iron, chromium, phosphorus, nickel and copper, along with trace levels of silicon and manganese. This layer contained all of the elements from the stainless steel and most of the elements from the braze alloy. However, silver was absent from the intermetallic in the regions that were analyzed. The copper level was relatively low, as much of the copper appeared to have been separated into the copper-colored spheroids in the intermetallic microstructure (Figs. 8 and 9). EDS analysis of a larger spheroid revealed that its composition was greater than 90% copper. SE and BSE SEM examinations showed identifiable boundaries between the cubic-shaped and lamellar structures within the intermetallic layer, but no compositional differences could be quantified by EDS analyses. The intermetallic was likely composed of mixed metal phosphides likely M_3P–M_2P, iron, nickel, chromium and copper phosphides, but this could not be confirmed.

Microindentation Hardness Testing

Microindentation hardness testing was performed on one intact cross section through the expansion joint (Table 3). The elbow, braze, intermetallic layer, weld, bellows and collar hardness levels were all measured for comparison. The hardness levels of the copper elbow were considered typical, with a significant reduction in hardness adjacent to the braze where grain growth had occurred. The stainless steel components and weld hardness readings were also considered typical. The hardness of the braze was intermediate between the copper and stainless steel components. The intermetallic layer hardness was very high, consistent with its brittle characteristics.

Discussion

The phosphorus-containing braze alloys were developed primarily for joining copper-based alloys. The phosphorus content provides a self-fluxing characteristic, deoxidizing the surfaces and eliminating the need for supplemental fluxes which can be more expensive and inconvenient. Fluxes must be completely removed after brazing, otherwise the halogen content typical in these fluxes can become severely corrosive. Incompatible brazing alloys are known to result in intermetallic compound formation in some circumstances. Formation of intermetallic compounds can result in brittle fracture under stress.

Much of the normal literature a failure analyst might reference to better understand this intermetallic phase does not provide a great deal of clarity or useful information. The chapter on "Products of Principle Metalworking Processes" in ASM Metals Handbook Volume 11 indicates that "braze filler metals containing phosphorus, such as AWS BCuP, BNi–6 and BNi–7, should not be used to braze any iron or nickel-based materials, because they form phosphides, which are brittle compounds" [2]. Similarly, the AWS Brazing Handbook in the chapter on Brazing Filler Metals indicates that copper–phosphorus filler metals "should not be used on ferrous or nickel-based alloys, or on copper-nickels with more than 10% nickel, to avoid formation of brittle, intermetallic phosphide compounds" [3]. Unfortunately, that is the entirety of the discussion of these materials, without any helpful guidance on the extent of the embrittlement or any microstructural identification features. Since incomplete or potentially incorrect fabrication information is often provided to the failure analyst, the inability to identify this phase may be problematic. Typical braze intermetallic compounds are thin films ($\sim$ 20 μm), but in this case, the intermetallic was very thick (up to 700 μm). This may explain the paucity of microstructural images, as thinner layers may not form a long-range

Table 3 Vickers microindentation hardness test results. Each value is the average of five individual measurements

Results	Copper elbow	Elbow near braze	Braze	Intermetallic	Weld	Bellows	Collar
Vickers hardness, HV_{500gf}	72	58	141	661	202	226	205

microstructure. The melting and grain growth of the copper elbow suggested that the brazing temperature was very high, likely contributing to the intermetallic compound thickness. The braze weld joint design would necessitate high heat input, staying hotter longer and permitting more dissolution of the stainless steel by the fluxing action of the phosphorus. Similarly, slow cooling may also have contributed to the thickness of the intermetallic layer.

Summary and Conclusions

Failure of a hot water expansion joint in newly completed heating system piping resulted in severe flooding of an office building. Cracking occurred through the braze joint securing a copper elbow and austenitic stainless steel expansion joint assembly. The proximate cause of the cracking was the use of an incompatible phosphorus-containing braze alloy which formed a complex brittle intermetallic phase which cracked. A system hydraulic shock event likely precipitated the cracking in this brittle compound, but this could not be verified. The probable root cause was inadvertent substitution of a brazing filler that was successfully used for non-fluxed copper–copper joints elsewhere in the riser system.

The literature does not provide substantial guidance for identification of the intermetallic microstructure, fractographic features or the anticipated hardness. This phase is generally so thin that long-range microstructural features may not form or may not be microscopically resolved. In the subject case, use of a braze weld joint configuration, high torch brazing heat input, and an incorrect filler metal acted synergistically to create the thick intermetallic deposit which lead to this failure. Further characterization of this likely ternary eutectic intermetallic compound and its unusual microstructure is warranted.

With regard to prevention, the prohibition of this filler metal for dissimilar metal joints between copper and stainless steel should be strictly observed. Copper and stainless steel base metal combinations may be successfully brazed using silver, nickel or gold-alloyed copper filler metals (with suitable fluxes), where deleterious intermetallic layers do not form [4]. Joining research has shown that interfacial barrier layers of nickel on stainless steel and copper on mild steel can suppress phosphide layer formation when phosphorus-bearing alloys are selected [5].

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