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Case study

Failure analysis of a machinable brass connector in a boiler unit installation

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ABSTRACT

Cracking of hexagonal brass connector of a boiler tubing assembly caused leakage and interruption of the function of a water heating circuit. Destructive damage was provoked after two years in service. Visual examination, light and scanning electron microscopy coupled with local elemental energy dispersive X-ray spectroscopy (SEM/EDS) were used as the principal analytical techniques for the present investigation. The collected investigation findings suggest that failure was induced via progressive cracking, attributed probably to fatigue initiated from surface flaws existed on the thread root surface. Recommendations mainly concerned revision of the alloy selection and quality assurance of tubing assembly procedure during installation.

1. Introduction and background information

Machinable brass alloy series cover a broad spectrum of applications of manufacturing of machine components varying from electrical/mechanical to chemical process equipment. Such components include nuts, bolts, connectors and many kinds of fittings, which are produced by automatic machining processes or hot stamping of extruded and drawn brass rods. Conventional machinable alloys containing lead (Pb) with nominal compositions approximately 2–3%, depended on the application, offer superior efficiency in high-speed machining. The major in-process and in-service failures of brass rods and related manufactured components, as well as their typical microstructural and mechanical characteristics together with their major fracture mechanisms were presented in relevant references [1–3].

A failure of brass hexagonal threaded connector (nominal Across Flats = 33 mm) consisted of transverse cracking, was the reason for extensive leakage and interruption of water heating installation, being for almost two years in-service (Fig. 1). Operating conditions of boiler circuit are reported in Table 1. Visual inspection, light microscopy and SEM/EDS analysis were used as the principal analytical methods in the present investigation.

2. Experimental procedure

Low-magnification inspection of fracture surface was performed using a Nikon SMZ 1500 stereomicroscope. Microstructure examination was conducted in mounted cross-sections prepared by standard grinding, using abrasive SiC papers up to #1200 grit, followed by fine polishing using diamond and silica suspensions. Metallographic observations carried out after final polishing and also after immersion etching in $FeCl_3$ solution. Metallographic analysis was performed

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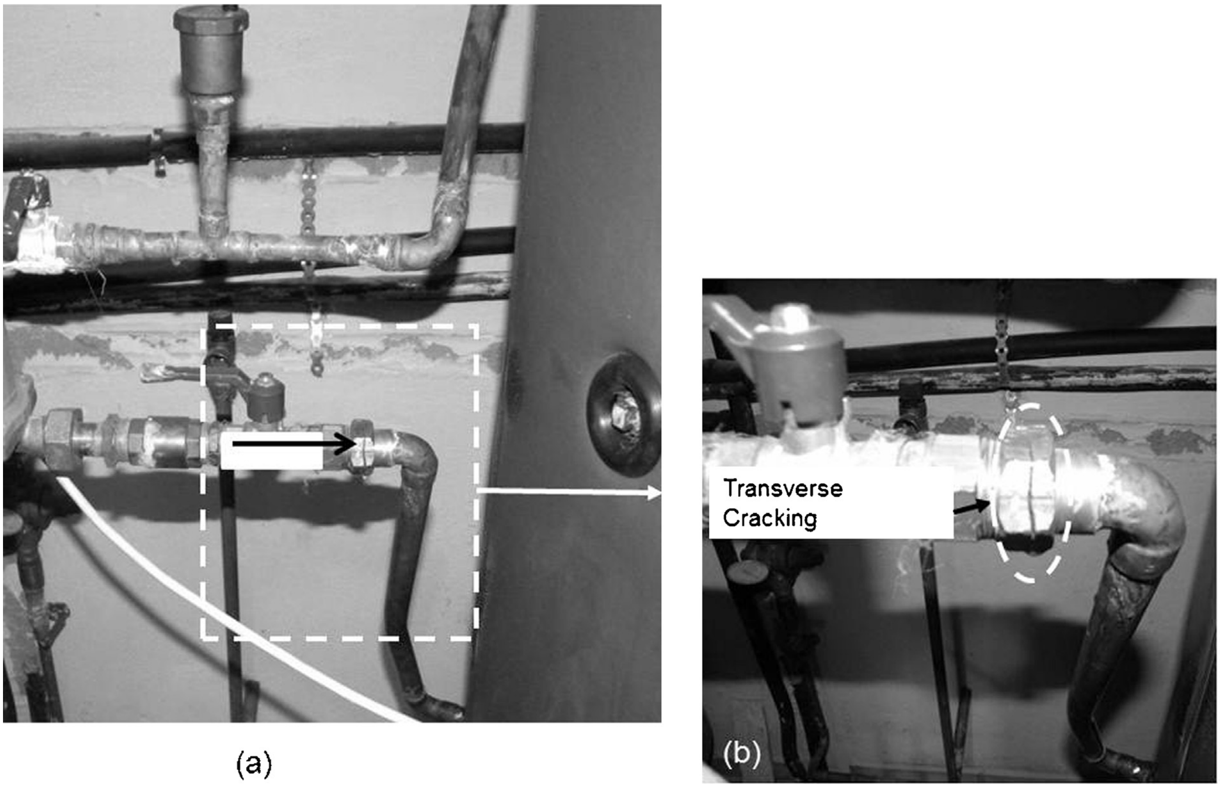

Fig. 1. Image showing the boiler installation and cracked hexagonal brass connector.

using a Nikon Epiphot 300 inverted light optical microscope. Hardness testing on various areas of threads was conducted using an Instron Wolpert microhardness tester under a 200 g (1.96 N) applied load. In addition, high magnification observations of the microstructure and cracking mode were conducted to Au-sputtered mounts, employing a FEI XL40 SFEG Scanning Electron Microscope and Energy Dispersive X-ray Spectroscopy using an EDAX detector for elemental microanalysis.

3. Investigation findings

The failed brass connector was examined after disassembly from tubing and appropriate sectioning to expose the fracture surfaces. Metallographic sampling was also made normal to the direction of crack propagation. Macro-fractographic examination showed intense surface damage due to the accumulation of corrosion deposits and dezincification phenomena (red-coloured areas) attributed to and post-fracture processes (Fig. 2a–c). However, slight dezincification processes were noticed on the outer connector surface at the leakage area. No macroscopic plastic deformation was involved. These preliminary stereo-microscopic observations advocate that crack was initiated most probably on the inner threaded area and propagated towards the outer showing a characteristic shear-lip as the final fracture area (Fig. 2b). The inner threaded surface did not show significant corrosion damage (Fig. 2d).

Metallographic observations confirmed the hypothesis of the inside-out crack propagation (Fig. 3a). Moreover, the crack was initiated at the thread root due to local stress concentration and at the transition area from engaged thread to the connector shank. Crack initiation shows a slight deflection due to the associated shear stresses applied at final thread cutting or fastening during installation period (Fig. 3b). The main crack front manifests principally a radial transgranular

Table 1
Operating conditions of the boiler hydraulic circuit.

Process parameter	Value
Operating pressure (bar)	8
Maximum pressure (bar)	12
Maximum temperature (°C)	50
Service period (yr)	2

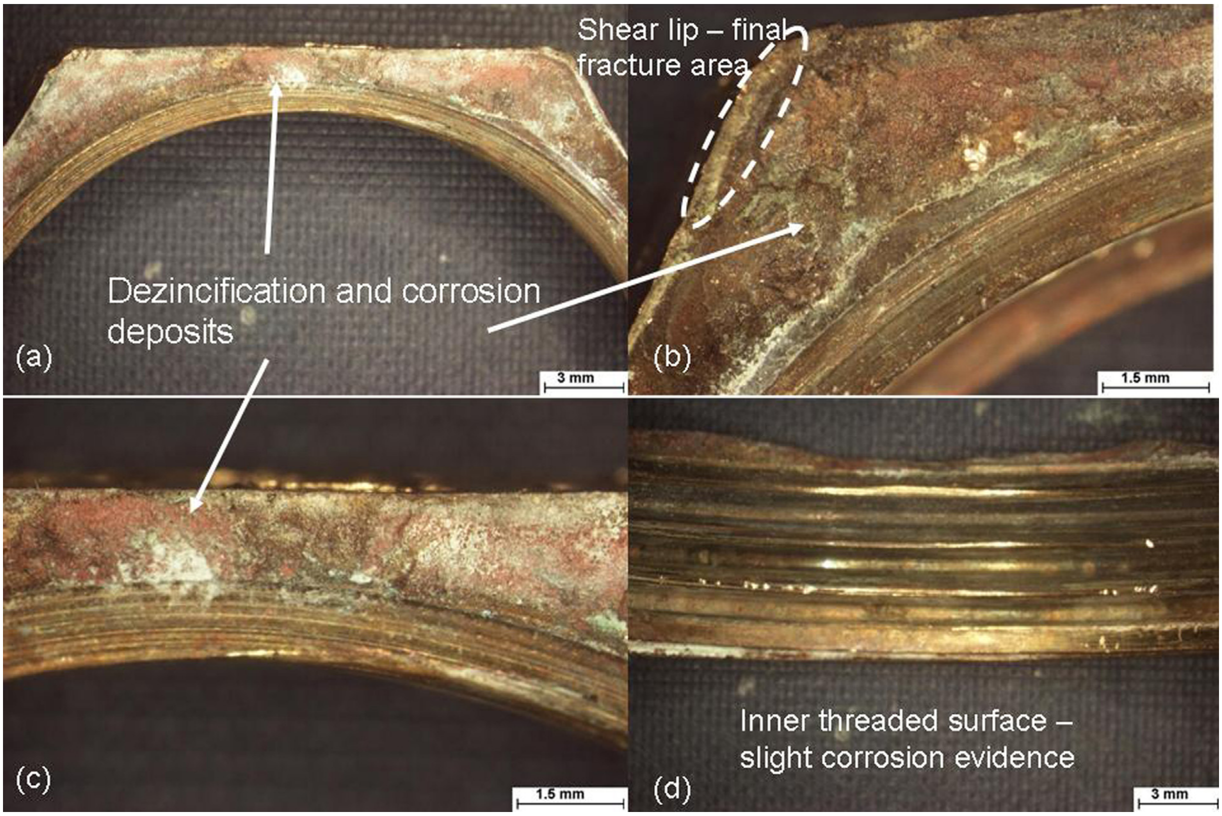

Fig. 2. Optical stereo-micrographs showing the fracture surface of the brass connector. Note intense corrosion scale accumulation and evidence of dezincification phenomena. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

propagation mode accommodating secondary crack branches (Fig. 3b and c). The microstructure is typical of α–β machinable brass manufactured by extrusion and drawing showing an almost uniform Pb-particle distribution (Fig. 3c). Hardness values are in a relative narrow range, i.e. 127–139 $HV_{0.2}$ from outer to threaded surface area respectively, consistent to half hard temper. Localized plastic deformation occurred close to the crack tip (Fig. 3c).

SEM observations and semi-quantitative EDS microanalysis suggest that the alloy used for connector matches approximately to CuZn40Pb2/CuZn39Pb3 grades which are commonly used for the production of machined components for hydraulic installations (Fig. 4). Close observations of the principal crack revealed surface damage and localized plastic deformation while coarse Pb particle concentration is noticeable at the crack initiation area. Mechanical damage and high local Pb concentration may constitute inherent weaknesses assisting crack initiation (Fig. 5a). Secondary intergranular branches may be originated from stress-corrosion-cracking occurred as a post fracture process, inducing radial stress relaxation (Fig. 5b). Searching adjacent thread root areas, surface flaws constituting prominent areas for crack initiation were discovered (Fig. 5c and d).

4. Discussion

The examination of the background information for this case history allows the hypotheses of progressive damage mechanisms rather than sudden mechanical overload. Two major classes of failure mechanisms together with their combination comply with this hypothesis for the specific certain application: corrosion and fatigue. Operating environment involves tap city water which is considered as non-harmful for mild conditions of usage. Severe general corrosion attack was not noticed on the inner threaded area, apart from local dezincification. Minor secondary crack branching possess a typical form of stress-corrosion-cracking (SCC). SCC is a delayed failure mechanism exhibiting mostly intergranular propagation mode with multiple secondary branches. The activation of SCC mechanism is based on the synergistic effect of service environment, internal or applied tensile stress and susceptible material. Relevant studies of SCC failures in brass components are also presented in [4,5]. Liquid ammonia is one of the characteristic environmental factors stimulating the occurrence of SCC. Evidence of multiple intergranular cracking and ammonia was not retrieved during the present investigation.

The crack propagation mode indicates principally the operation of fatigue mechanism in conjunction with secondary SCC and dezincification corrosion. The internal stresses imposed during installation, added to the working stresses, increase stress amplitude facilitating crack-growth during service. Crack initiation is found on the inner threaded area at the grooved

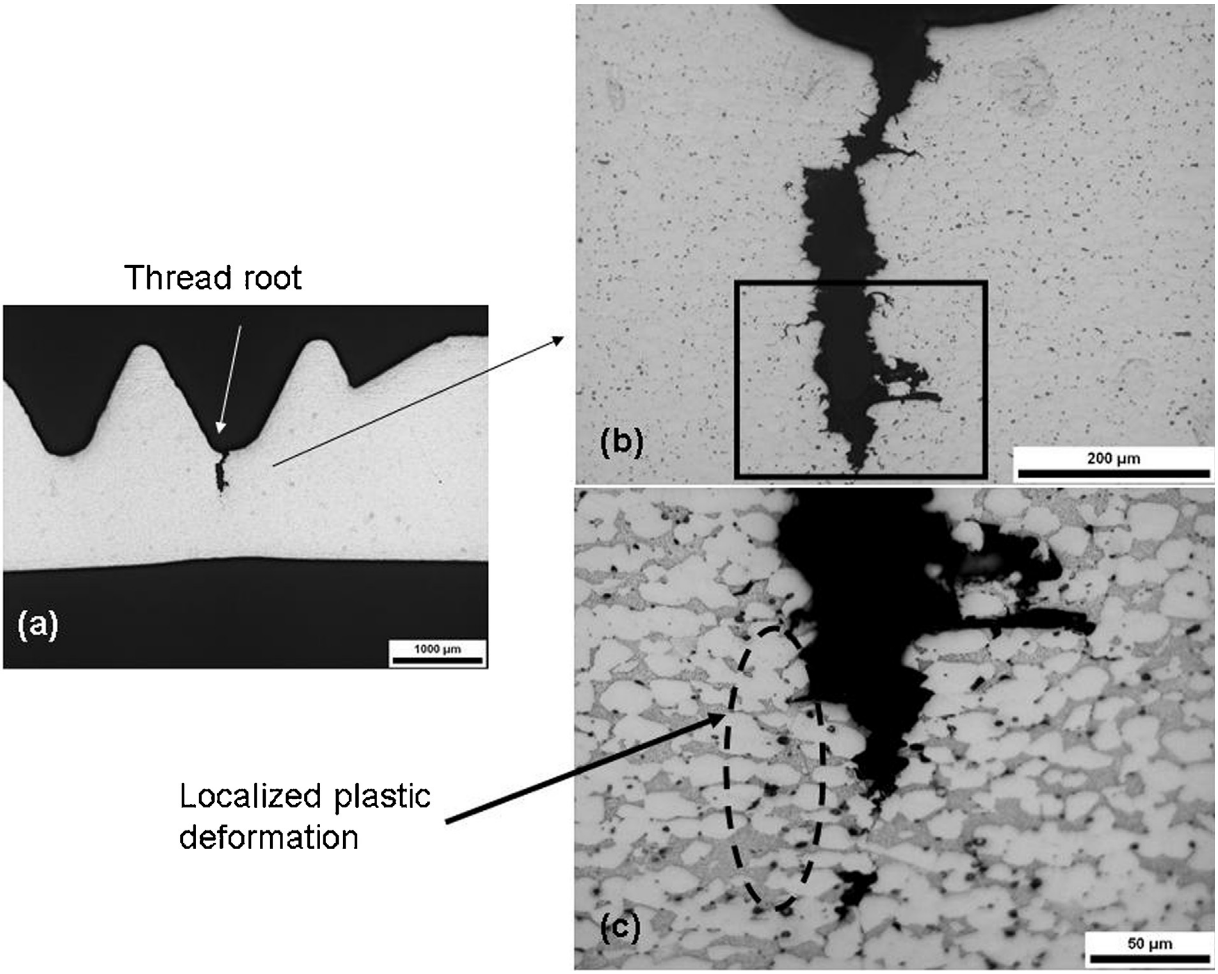

Fig. 3. (a) Optical micrograph of the transverse section showing the origin of crack, emanating from the inner thread root; (b) and (c) details of (a) showing the cracking mode. Note the presence of α (light areas) and β phase (dark areas) together with uniform Pb particle distribution (black dots).

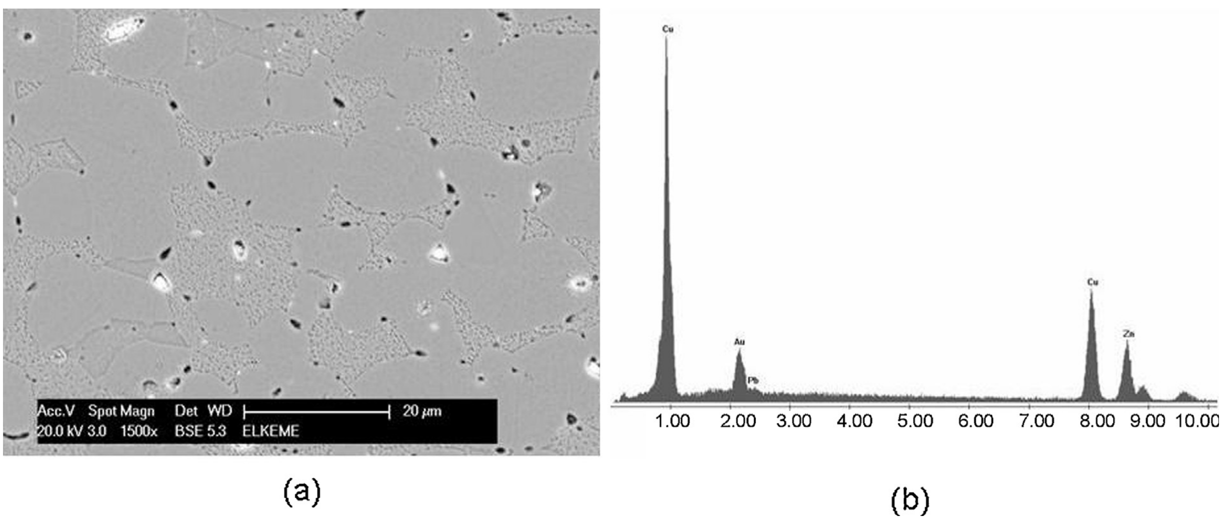

Fig. 4. (a) SEM micrograph and (b) corresponding full-frame EDS spectrum showing the elemental composition of the selected area. The semi-quantitative chemical composition indicates that the alloy matches approximately to CuZn40Pb2/CuZn39Pb3 machinable brass grades.

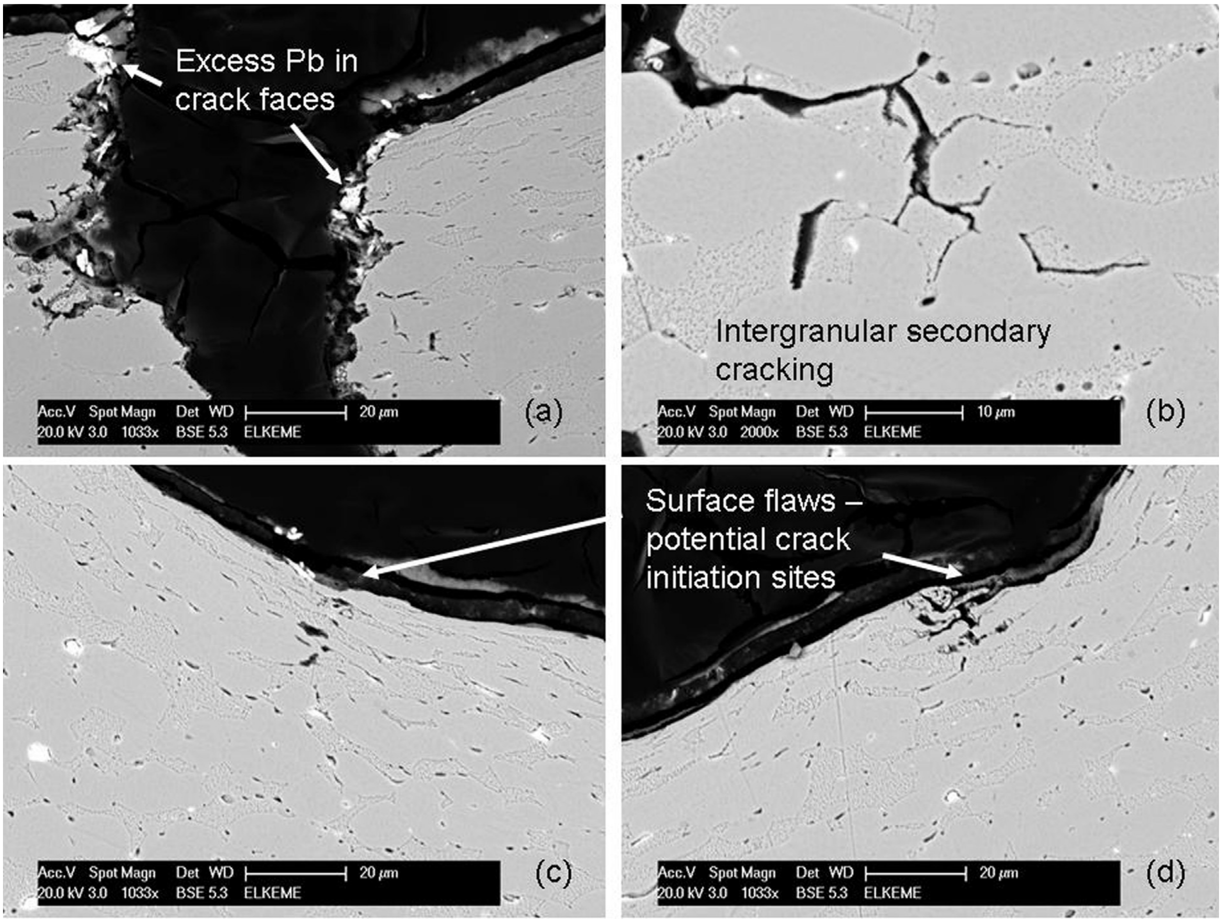

Fig. 5. SEM micrographs depicting details of cracking mode: (a) initiation area showing locally the presence of higher Pb particle size, (b) secondary intergranular branching, (c) and (d) surface flaws observed on the inner threaded surface which constitute potential crack initiation sites.

region which acts as stress raiser. In addition, the inclined form of the initiation site suggests prior existence of surface flaw that triggered the crack. The existence of coarse Pb particles on the crack faces could be an additional weakness assisting in crack initiation. Overheating incidents in metal working processes could cause hot-shortness coming from Pb particle melting and coalescence, see also [6]. However, the overall Pb distribution seems fine and uniform through the entire section examined. Surface flaws were also evident in adjacent areas of the inner thread grooves attributed to mechanical damage and/or localized dezincification (Fig. 5c and d). It is noteworthy also to mention that dezincification was also noticed on the outer surface (red-coloured areas) at the leakage region, verifying the sensitivity of the material against dezincification. Moreover, this grade of brass alloy exhibits also a considerable susceptibility in stress-corrosion-cracking (SCC), which constitutes a common in-service failure mechanism.

The substitution of the present material with an alternative brass alloy, such as the DZR (Dezincification Resistant) CuZn36Pb2As alloy will increase the dezincification resistance and reduce the SCC sensitivity. The addition of trace elements such as Sb or, in this case, As (up to 0.15%) and, on the other hand the lower amount of β-phase ($\leq$5%) provides a shielding effect against dezincification. Moreover, this alloy exhibits higher ductility and fracture toughness demonstrating, therefore, higher resistance in crack propagation. A comparison study of mechanical properties of brass alloys CuZn39Pb3 and CuZn36Pb2As is presented in [3]. Finally the assurance of proper installation following the torque and alignment specifications during assembly will keep internal stress at low level, improving the reliability of the operation of the boiler unit.

5. Conclusion and recommendations

A machinable brass connector (33 mm Hex AF) failed in a boiler unit, after almost two years in function, caused leakage and heating unit shutdown. The collected evidence suggests that failure was induced by progressive crack-growth during service, initiated from inner thread root. A plausible failure mechanism is fatigue facilitated by the action of dezincification and secondary intergranular corrosion cracking. Crack emanated at high stress concentration area assisted by the presence of surface flaws created probably by shallow mechanical damage and/or dezincification pits. Potential improvement suggestions concern the following:

- Alloy selection revision: dezincification brass alloy (e.g. CuZn36Pb2As) will offer a protective effect against dezincification and SCC together with higher ductility and fracture toughness.
- Quality assurance of the installation and assembly procedure: compliance with fastening torque and alignment requirements, foreseen by boiler unit assembly.

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