

Stress-Assisted Corrosion of a Superheater Tube: The Role of Thermal Fatigue Cracking and Crevice Corrosion in the Failure Mechanism

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ABSTRACT

This paper discusses the results of a failure examination of superheater tubes from a boiler. The superheater tubes failed along steamside fissures associated with external surface welds attaching finger bars to adjacent tubes. The morphologies of the fissures were consistent with stress-assisted corrosion (SAC). In addition, cracks typical of thermal fatigue were present on some ID surfaces and at the tips of some fissures. The elemental compositions of corrosion products within the wide SAC fissures, determined using Scanning Electron Microscopy (SEM)/Energy Dispersive X-ray Spectroscopy (EDXS), support the possibility that crevice conditions led to accelerated corrosion during cool down periods, resulting in pit-like areas along the fissures. Failed and unfailed superheater tubes were examined using standard metallographic techniques. The results were used to develop a theory of the role of thermal fatigue cracking and crevice corrosion in SAC fissure initiation on the steamside surfaces of the superheater tubes and propagation through the tube walls.

Key words: stress-assisted corrosion, superheater tubes, crevice corrosion, thermal fatigue, welded attachments

INTRODUCTION

Stress-assisted corrosion (SAC) is a form of corrosion initiated by tensile stresses that fracture the otherwise-protective magnetite layer on water-touched surfaces of steel boiler tubes. These stresses are typically applied by external attachment welds. Steel exposed by the crack in the magnetite corrodes until a healing magnetite layer is formed. Cyclical stresses produce a fissure beneath the initial crack in the magnetite. Such fissures typically initiate within waterside pits, show signs of discontinuous growth and are blunt tipped (Figs. 1 and 2).¹ Typically, multiple waterside fissures form continuous or discontinuous lines that are either parallel lines and linear or concentric ovals elongated

in the long direction of the external weld. The fissures propagate radially outwards through the tube wall as shown in Figures 1 and 2.

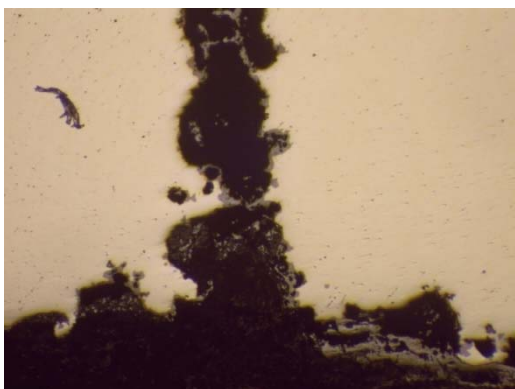


Figure 1: Typical SAC Fissure: ID Surface⁽¹⁾

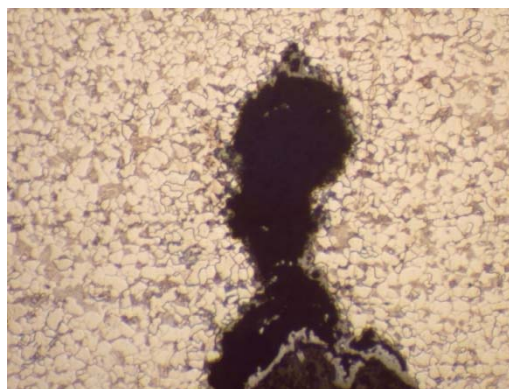


Figure 2: Typical SAC Fissure: Blunt Tipped⁽¹⁾

History

Leaks where external attachments were welded to water-filled tubes in utility boilers were reported as early as the 1960s.² The Electric Power Research Institute (EPRI) found that such leaks were a primary cause of availability loss in utility boilers.³

Although SAC is not confined to boilers in particular industries,⁴⁻⁶ the pulp and paper industry has paid particular attention to this damage mechanism because water leaks in black liquor recovery boilers can cause catastrophic smelt-water reactions.⁷ A smelt-water explosion caused by SAC in 1991 and the subsequent discovery of SAC in many other recovery boilers led to the development of radiographic procedures to classify the severity of SAC damage.⁸

Fitness-for-Service

Perhaps surprisingly, burst tests of tubes removed from recovery boilers suggest that the strength imparted by external attachment welds more than compensates for the weakening effects of waterside SAC fissures they contain.⁹

Initiation and Propagation of Stress-Assisted Corrosion

Waterside corrosion of boiler tubes occurs where chemical dissolution or mechanical fracturing of the magnetite film exposes bare steel.¹⁰ Tensile stresses in the steel exposed by a crack in the magnetite film tend to accelerate its corrosion and the large ratio of the cathodic (undamaged magnetite) area to the anodic (fissure) area also promotes corrosion.¹¹⁻¹⁴ Eventually, if the concentration of dissolved oxygen in the boiler water is not too high, a porous film of magnetite will form on the exposed steel.¹⁵ Magnetite cracking and corrosion of exposed steel may occur simultaneously or consecutively.¹ The healing film can be re-cracked by lower tensile stresses than the original magnetite film.¹¹

Repeated inspections of many boilers operated with shallow SAC fissures have shown that the fissures propagate slowly. It typically takes one or more decades to produce through-wall leaks. SAC has not

⁽¹⁾ NACE International. Paper presented at the NACE Conference, CORROSION 2004, paper no. 04520 (New Orleans, LA: NACE 2004).
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been reported in recovery boilers that have been in service for less than about seven years. The rate of propagation of the fissures appears to increase with the number and severity of thermal cycles experienced by the tube and its external attachments.

Corrosion damage originating at cracks in the magnetite film can produce several different damage morphologies: open-mouthed pits, carrot-shaped fissures that look like corrosion fatigue cracks, and oxide-filled cracks.^{7, 16} In utility boilers, waterside oxide fractures typically produce narrow, sharp-tipped cracks.¹¹ In industrial boilers, the waterside fissures are typically wider, blunt-tipped and often contain subsurface cavities that appear bulbous in cross-section, as if they had been formed during distinct cycles of corrosion.

Effects of Water Composition

Feedwater quality in industrial boilers is generally lower than in utility boilers, causing more rapid corrosion of exposed surfaces that widens SAC fissures and blunts their tips.^{7, 17, 18} The propagation of SAC fissures can be accelerated by pH depressions, caused by phosphate hideout or by dissolution of CO₂ in the feed water during boiler outages, or by the use of lower-pH water for hydrostatic testing.¹⁸⁻²¹ In boilers using phosphate water treatments, increasing the concentration of dissolved oxygen decreased the number of thermal cycles required to initiate waterside cracking tenfold and reduced the magnitude of the strain required to initiate SAC.^{22, 23} Oxygen concentrations in industrial boilers should be kept below 5-10 ppb to minimize oxygen pitting that could provide initiation sites for SAC.^{21, 23, 24} A previously published SAC case history concluded that the most likely cause of the failures was cycles of oxygen corrosion during out-of-service periods coupled with thermal stresses associated with shutdown and startup operations.¹

Factors Relating to Superheater Design and Operation

Superheater tube assemblies contain parallel steam circuits in pendant tubes that take steam up and down in the flue gas path before exiting through the roof.²⁵ Various approaches have been taken to hold the tubes together in planar assemblies, including tube-to-tube welds or welds to 3" (76.2 mm) long square or round section "finger bars" laid between the tubes. Fireside cracks at the toe of welds attaching finger bars prompted new designs with smaller attachment welds that produced less tube shrinkage, lower residual stresses, smaller differential thermal expansion stresses and fewer leaks.²⁵ The greatest thermal stresses occur where cooler tubes and hotter tubes are welded together in a platen.

Superheater tubes have also been joined by hinge pin attachments designed to allow up-and-down movement and slight rotation between adjacent tubes. Superheater platens are designed to expand and contract together when heated up and cooled down at rates specified by the boiler designer. However, fouling and corrosion can cause hinge pins to seize, so that relative movement produces out-of-plane distortion. Also, excessively rapid temperature changes can produce front-to-back distortion when front tubes and rear tubes heat and cool at different rates. Out-of-plane distortion of superheater tubes can be caused by four additional factors: water entering superheater tubes from the attemperator, water carried over from the drum into the low temperature superheater, and condensate or hydrostatic testing water that has not been blown out of tube loops during start up. Out-of-plane tubes experience more severe thermal cycling than planar tubes and are therefore more vulnerable to both fatigue cracking and overheating.

A 1998 recovery boiler case history documented tube leaks on the sides of the first two superheater bends downstream from the drum.²⁶ This boiler was filled with city water during maintenance outages and hydrostatically tested with the same water before start-up. The authors concluded that axial through-wall SAC fissures on the sides of superheater tube bends initiated from steam-side corrosion pits formed among alkaline deposits and were not associated with corrosion thinning. Un-pitted steam-side surfaces were covered by a magnetite scale that was black, adherent and thin. The magnetite had cracked where high tensile residual stresses were augmented by start-up operational stresses that were highest along the neutral axis of the tube bends. The authors also suggested that the SAC fissures probably propagated when the tubes were filled with water during outages.

The exact mechanism of SAC is still unknown. The current paper discusses the examination of superheater tubes from a recovery boiler that recently leaked. Features of the failure indicate distinct steps during the formation of SAC fissures.

FAILURE ANALYSIS

Failed and unfailed superheater tube samples from a 40-year old black liquor recovery boiler were examined metallographically. Outlet steam conditions from the superheater are 4.55 MPa (660 psig) and 399 to 410 °C (750 to 770 °F). The tubes are 30 to 40 years old. Superheater tubes in this boiler had experienced many leaks over the years from thermal fatigue cracks formed on the fireside surface at the ends of attachment welds. These cracks posed no danger of sudden rupture and had been repaired during routine maintenance operations. The most recent failures, discovered during hydrostatic testing, were associated with multiple, parallel, axial fissures that initiated midway between a pair of external attachment welds (finger bar welds), which are used to maintain proper alignment of superheater tubes within the platen assembly. A typical design of the platen superheater assembly with finger bar welds and potential problems associated with this design are discussed in Reference 25.

The tubes provided for the examination were from the high temperature and intermediate temperature superheaters. As an example, a sketch of the high temperature superheater platen assembly is shown in Figure 3. A schematic representation of finger bar welds between the tubes and the location of the axial fissures are depicted in Figure 4.

It will be shown that the finger bar attachment welds played a critical role in the stress-assisted corrosion that produced the axial steamside fissures found midway between the finger bars on the side of a superheater tube in contact with the flue gases passing alongside a superheater platen (Left and/or Right Sides in Figure 4). Therefore, all examined tubes were split longitudinally to separate the left and right sides as shown in Figure 4.

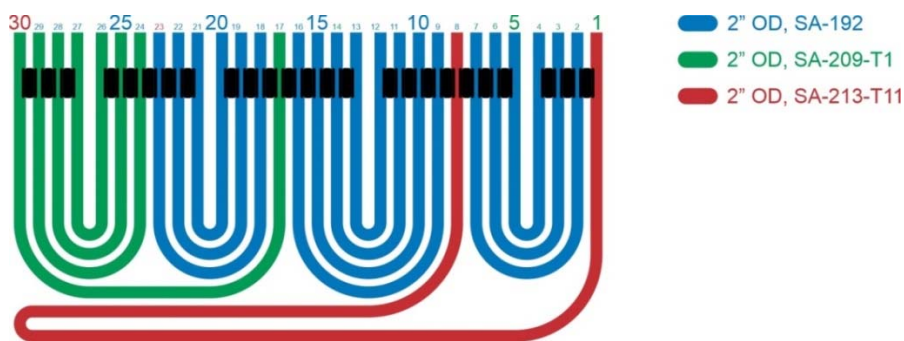


Figure 3: Schematic of Tubes in the High Temperature Superheater Platen

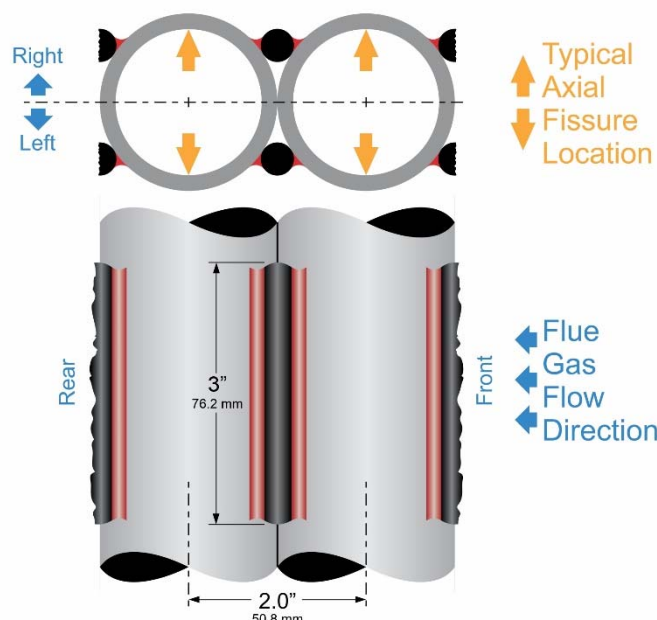


Figure 4: Schematic Representation of Finger Bar Welds in this Recovery Boiler

Visual Examination

Several carbon steel U-bend tube samples removed from high temperature superheater (HTSH) and intermediate temperature superheater (ITSH) platens were examined. The as received conditions of the external surfaces in the vicinity of the welded attachments for two adjacent U-bends are depicted in Figure 5. The tubes exhibited some in-plane distortion indicating large internal thermal stresses due to non-linear temperature gradients across the superheater.²⁵ Figure 6 shows typical damage found on the steamside surfaces of superheater tubes with all four 3-inch (76.2 mm) long finger bar welds on the external surface of the tube. Multiple axial fissures were present in two groups on each side of the tube. In each case, these axial fissures were located midway between the finger bar welds and extended up to 0.5-inch (12.7 mm) above or below the ends of the finger bar weld elevations as shown in Figure 6. Fissures are filled with freshly formed, yellow iron oxyhydroxide (FeOOH) indicative of active corrosion following removal from service and exposure to moisture and air. The adjacent, unaffected surfaces were covered with a protective grey scale layer of magnetite (Fe_3O_4) typical of steam-touched tubes. Yellow rust will form only in the areas where the protective magnetite layer has cracked, and the fresh metal surface was exposed to an oxygenated moist environment potentially containing other corrodents.

For all examined tubes, the damage on the internal surfaces was localized and associated with the welded attachments present on the external tube surfaces. As a result, it was concluded that during non-linear temperature gradients across the superheater the finger bar welds are responsible for producing the circumferential tensile stresses necessary for the axial fissure to initiate on the steamside surface. The role of finger bar welds in fissure formation was further confirmed by the absence of any fissures on one side of a tube with a missing finger bar. Figure 7 shows that both finger bar welds were present on the Right Side of the examined tube but only one finger bar was welded to the Left Side of this tube. The corresponding internal surfaces are depicted in Figure 8. It is evident that in the absence of two finger bar welds on the same side of the external tube surface no axial fissures were formed on the internal surface of the tube. Fissures filled with fresh corrosion products (yellow iron oxyhydroxides),