Chapter 15

Corrosion-Fatigue Cracking

Locations

Corrosion fatigue can occur in any location where cyclic stresses of sufficient magnitude are operative. Corrosion-fatigue failures most frequently occur in boilers that are in "peaking" service, used discontinuously, or otherwise operated cyclically. Rapid boiler start-up or shutdown can greatly increase the susceptibility to corrosion fatigue. Some serious corrosion-fatigue problems have been eliminated merely by sufficiently modifying start-up and shutdown rates.

Common locations of corrosion-fatigue cracks include wall tubes, reheater tubes, superheater tubes, economizer tubes, deaerators, and the end of the membrane on waterwall tubing. In addition, corrosion fatigue is common at points of attachment or rigid constraint, such as connections to inlet or outlet headers, tie bars, and buckstays.

Cracks have also been observed at grooves along the internal surfaces of boiler tubes that have been only partly full of water (cracks usually run across the grooves), at points of intermittent steam blanketing within generating tubes, at oxygen pits in waterlines or feedwater lines, in welds at slag pockets or points of incomplete fusion, in soot-blower lines where vibration stresses are developed, and in blowdown lines.

General Description

Corrosion fatigue is a form of deterioration that can occur without concentration of a corrosive substance. The term refers to cracks propagating through a metal as a result of cyclic tensile stresses operating in an environment that is corrosive to the metal. The term and definition above are somewhat misleading in the case of boilers, since normal oxidation of metal to magnetite is sufficient to induce corrosion fatigue in the presence of sufficient cyclic tensile stresses.

Cracks develop according to the following sequence:

- During the first phase of cyclic stress, the tube wall undergoes expansion. Since the oxide layer is brittle relative to the tube wall, the oxide layer may fracture, opening microscopic cracks through the oxide to the metal surface.

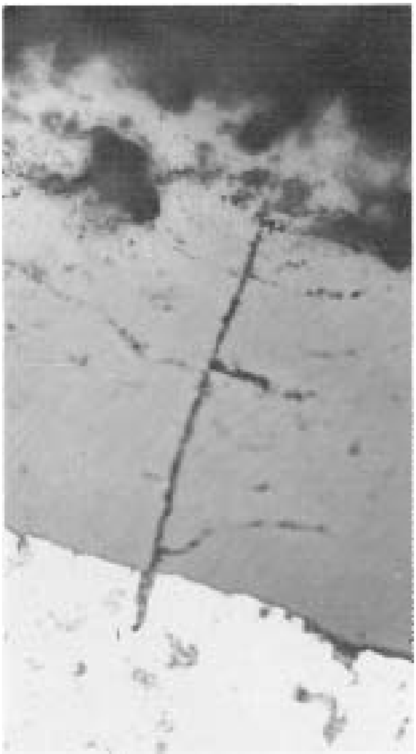

Figure 15.1 Incipient corrosion-fatigue crack formed at base of cracked layer of iron oxide. (Magnification: 400×. Etchant: Picral.) *(Courtesy of National Association of Corrosion Engineers.)*

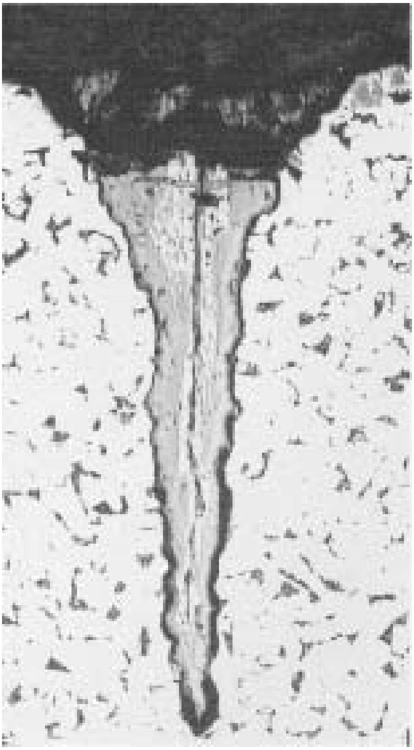

Figure 15.2 Mature corrosion-fatigue crack. (Magnification: 200×. Etchant: Nital.) *(Courtesy of National Association of Corrosion Engineers.)*

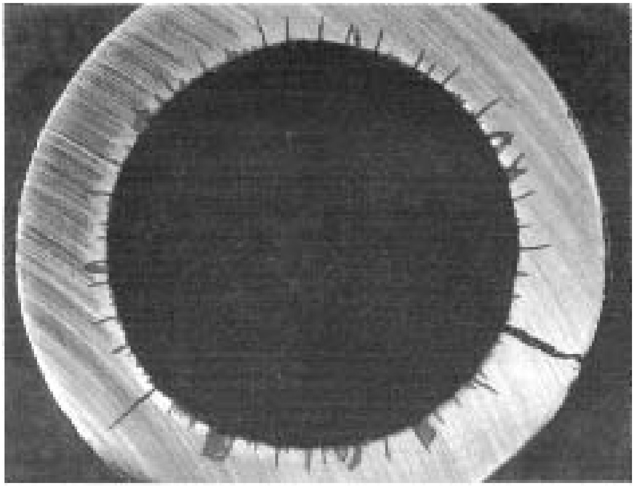

Figure 15.3 A family of longitudinal cracks resulting from fluctuation in internal pressure. *(Courtesy of National Association of Corrosion Engineers.)*

Figure 15.4 Transverse cracks originating on the internal surface.

- The exposed metal surface at the root of the crack oxidizes, forming a microscopic notch in the metal surface (Fig. 15.1).
- During the next expansion cycle, the oxide will tend to fracture along this notch, causing it to deepen.
- As this cyclic process continues, a wedge-shaped crack propagates through the tube wall (Fig. 15.2), until rupture occurs or the tube wall is penetrated.

The cracks always propagate in a direction perpendicular to the direction of the principal stress. Hence, if the principal cyclic stress is produced by fluctuations in internal pressure, longitudinal cracks are produced (Fig. 15.3). If the principal cyclic stress is a bending stress produced by thermal expansion and contraction of the tube, cracks will be transverse (Fig. 15.4). Corrosion-fatigue cracking commonly occurs adjacent to physical restraints. Cracks may originate on the external surface, the internal surface, or both simultaneously. Cracks originating on the internal surfaces are often associated with pits. The pit site serves as a stress-concentrating notch, making it a preferred site for initiation of corrosion-fatigue cracks.

Critical Factors

Cyclic tensile stresses and an environment that will cause spontaneous oxidation of a bare metal surface are two critical factors that govern susceptibility to corrosion fatigue. Two common sources of cyclic tensile stresses are cyclically fluctuating internal pressure, and constrained thermal expansion and contraction.

In addition to an environment that will cause spontaneous oxidation of a bare metal surface, other factors that may provide a significant contribution are pH level and dissolved-oxygen content. Operation at low-pH levels or with excessively high levels of dissolved oxygen may induce pitting. The pits act as stress concentrators for the initiation of corrosion-fatigue cracks.

Identification

Corrosion-fatigue cracks are typically straight and unbranched. They are needle- or wedge-shaped, and propagate perpendicularly to the metal surface. They often occur in families of parallel cracks (Figs. 15.3 and 15.4), and are frequently very tight, making them difficult to see without very close examination. At times, they may appear to be only shallow grooves in the magnetite covering. Typically, they do not run long distances along the tube surface. It is not unusual for corrosion-fatigue cracks to develop simultaneously within two or more components of similar location.

Nondestructive methods for crack identification include ultrasonic surveillance, radiographic surveillance, dye penetrant, and magnetic-particle inspection.

Elimination

Elimination or reduction of corrosion-fatigue cracking is realized by controlling cyclic tensile stresses, controlling environmental factors, and boiler redesign. Reducing or eliminating cyclic operation of the boiler as well as extending start-up and shutdown times may help eliminate or reduce corrosion-fatigue cracking.

Elimination of the oxidation process occurring at a newly exposed crack tip is not feasible. This oxidation will occur spontaneously even at very low levels of dissolved oxygen. Controlling pH and excessive levels of dissolved oxygen can be useful in eliminating pitting corrosion, which will eliminate a common point of initiation for corrosion-fatigue cracking.

In persistent cases of corrosion-fatigue cracking, measures such as contouring of welds and redesign of tube attachments may be required to eliminate or reduce constraints to thermal expansion and contraction.

Cautions

Complete fractures resulting from corrosion-fatigue cracking are typically thick-walled and show very little, if any, ductility. These fractures might conceivably be confused with other failure modes that typically produce thick-walled fractures, such as stress rupture, cracking caused by hydrogen damage, stress-corrosion cracking, and some types of severe overheating. Corrosion-fatigue cracks are frequently difficult to see since they are often filled with dense iron oxides. At times they may appear as short, shallow grooves in the magnetite layer covering the tube.

Related Problems

See also Chap. 2, “Long-Term Overheating”; Chap. 3, “Short-Term Overheating”; Chap. 14, “Hydrogen Damage”; and Chap. 16, “Stress-Corrosion Cracking.”

CASE HISTORY 15.1

Industry:	Utility
Specimen Location:	Cold reheat line 20 in. (50.8 cm) from turbine discharge
Specimen Orientation:	Horizontal
Drum Pressure:	350 psi (2.4 MPa)
Tube Specifications:	14 in. (35.6 cm) outer diameter, seamless

The cracks illustrated in Fig. 15.4 were confined to zones 5 to 10 ft (1.5 to 3.0 m) on either side of a coupling in the reheat line. Failures had not occurred, but similar cracking had been observed in a sister unit previously. The transverse fissures and cracks were accompanied by, and associated with, a population of small pits (Fig. 15.5). Reddish iron oxides were present on this surface.

Microstructural examinations revealed families of blunt, V-shaped fissures entering the wall from the internal surface. The deepest fissures penetrated 25% of the wall thickness.

Figure 15.5 Transverse cracks and associated oxygen pits.

The cracking in this case was due to cyclic flexing of the line. Small oxygen pits, resulting from exposure of the internal surfaces to moisture and oxygen during idle times, served as nucleation sites for the corrosion-fatigue cracks.

Mitigation of this problem can be achieved by eliminating oxygen pitting during idle periods, and by reducing or eliminating the cyclic flexing of the line.

CASE HISTORY 15.2

Industry:	Utility
Specimen Location:	Drain line off reheat header
Tube Specifications:	1⅞ in. (4.8 cm) outer diameter, low-alloy steel

Deep, cross-hatched cracks and fissures are located in a distinct zone around one end of the internal surface of the drain line (Figs. 15.6 and 15.7). Cracks and fissures are not present in areas away from this end.

Microstructural examinations revealed classic thermal-fatigue cracks propagating through the wall. Evidence of mild overheating was also observed.

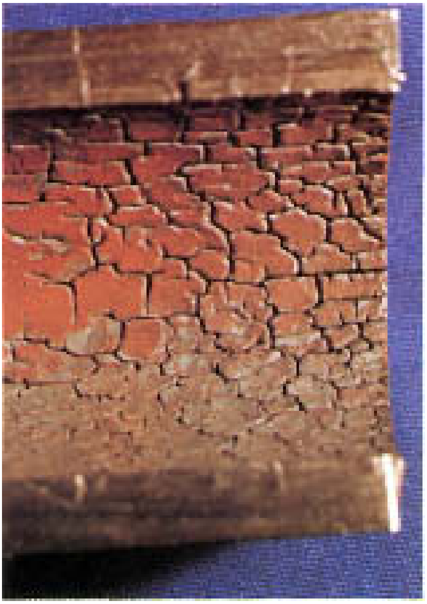

Figure 15.6 Thermal-fatigue cracks on internal surface.

Figure 15.7 Cross section through cracks.

Thermal fatigue can occur when heated metal is rapidly cooled repeatedly. Rapid cooling of the metal surface establishes high triaxial stresses that can produce cross-hatched cracks of the type illustrated in these figures. Rapid cooling may have been induced by localized exposure of the line to slugs of water. Elimination of the rapid cooling cycles is necessary to eliminate this problem.

CASE HISTORY 15.3

Industry:	Pulp and paper
Specimen Location:	Front-wall tube around primary air port, recovery boiler
Specimen Orientation:	Slanted
Years in Service:	15
Drum Pressure:	900 psi (6.2 MPa)
Tube Specifications:	3 in. (7.6 cm) outer diameter, studded

The cracking illustrated in Figs. 15.8 and 15.9 was localized to the area around the primary air port. These short transverse fissures were especially prominent near the base of studs (Fig. 15.9). Measurement revealed penetrations of 15 to 20% of the original tube-wall thickness.

Microstructural examinations of surface profiles revealed deep, wedge-shaped fissures from the external surface and shallow, sharp cracks from the internal surface.

The transverse orientation of cracks and fissures reveals that they were produced by cyclic, outward bending of the tubes resulting from thermal expansion and contraction. The prominence of the cracks at the stud bases may be due to differences in the thermal expansion and contraction charac-

Figure 15.8 Transverse fissures at and near stud bases.

teristics of the studs and the tube wall. The visual appearance of such corrosion-fatigue fissures on studded tubes has led to the term "elephant hiding," to describe the phenomenon. Experience suggests that elephant hiding occurs in areas of high heat-transfer rate, and may occur on tubes that are not covered with smelt.

Figure 15.9 Transverse fissures near stud (center). (Magnification: 6.5×.)

CASE HISTORY 15.4

Industry:	Pulp and paper
Specimen Location:	Superheater near outlet header, power boiler
Specimen Orientation:	Vertical
Years in Service:	5
Water-Treatment Program:	Coordinated phosphate
Drum Pressure:	1250 psi (8.6 MPa)
Tube Specifications:	1¾ in. (4.4 cm) outer diameter, low-alloy steel

The thick-walled circumferential fracture shown in Fig. 15.10 was the first superheater failure in this boiler. Close visual examinations of both internal and external surfaces adjacent to the fracture revealed secondary cracks (Fig.

Figure 15.10 Brittle fracture face resulting from corrosion fatigue.

15.11). Microstructural examinations of the tube wall confirmed the presence of families of unbranched transgranular cracks near the fracture both internally and externally. The circumferential orientation of the cracks reveals that the stresses responsible were cyclic bending stresses, possibly caused by thermal expansion and contraction of the tube.

Figure 15.11 Secondary corrosion-fatigue cracks on external surface. (Magnification: 6.5X.)