Chapter 20

Welding Defects

Locations

A large, utility-size boiler may contain more than 50,000 welds. Each weld is a possible defect site. Largely as a result of the rigorous ASME code requirements for pressure vessels, weld failures account for only 2½% of boiler failures. Because of the relatively severe environments present in superheater and reheater sections, many of the weld failures that do occur happen in these regions.

General Description

The purpose of a weld is to join two metals by fusing them at their interfaces. A metallurgical bond is formed that provides smooth, uninterrupted, microstructural transition across the weldment. The weldment should be free of significant porosity and nonmetallic inclusions, form smoothly flowing surface contours with the section being joined, and be free of significant residual welding stresses.

A complete listing of possible weld defects is well beyond the scope of this manual. Rather, only the more common weld failures will be presented.

Critical Factors

All weld defects represent a departure from one or more of the features described above. However, it should be realized that welds are not perfect.

In consideration of this fact, all major welding codes allow for welding defects, but set limitations on the severity of the defect. An acceptable weld is not one that is defect-free, but one in which existing defects do not prevent satisfactory service.

Porosity

Identification. *Porosity* refers to the entrapment of gas bubbles in the weld metal resulting either from decreased solubility of a gas as the molten weld metal cools, or from chemical reactions that occur within the weld metal (Fig. 20.1). Generally, porosity is not apparent from the surfaces of the weldment. The distribution of pores within the weldment can be classified as *uniformly scattered porosity, cluster porosity,* or *linear porosity.* Porosity near surfaces seems to have a significant effect on mechanical properties of the weld.

Elimination. Porosity can be limited by using clean, dry materials, and by maintaining proper weld current and arc length.

Slag inclusions

Identification. The term *slag inclusions* refers to nonmetallic solids trapped in the weld deposit, or between the weld metal and base metal. Slag forms by a high-temperature chemical reaction, which may occur during the welding process. These inclusions may be present as isolated particles, or as continuous or interrupted bands. Figure 20.2 illustrates a linear slag

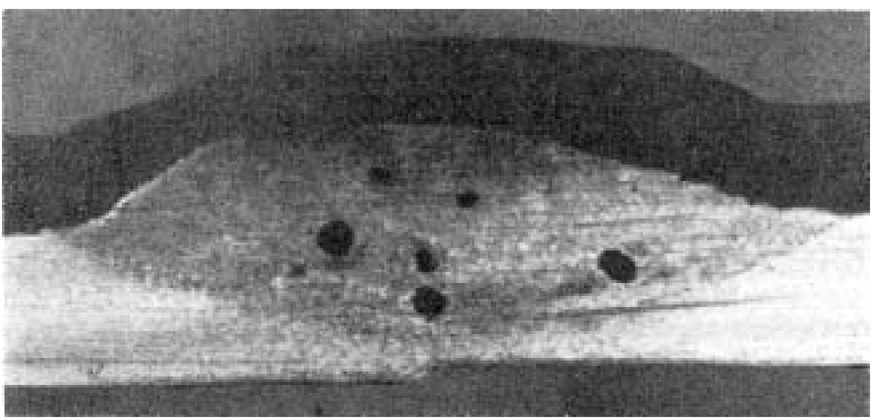

Figure 20.1 Cross section through weld showing severe porosity. This weld had been in low-pressure service for 40 years without failure. (Magnification: 2X.) *(Reprinted with permission from Helmut Thielsch,* Defects and Failures in Pressure Vessels and Piping, *New York, Van Nostrand Reinhold, 1965.)*

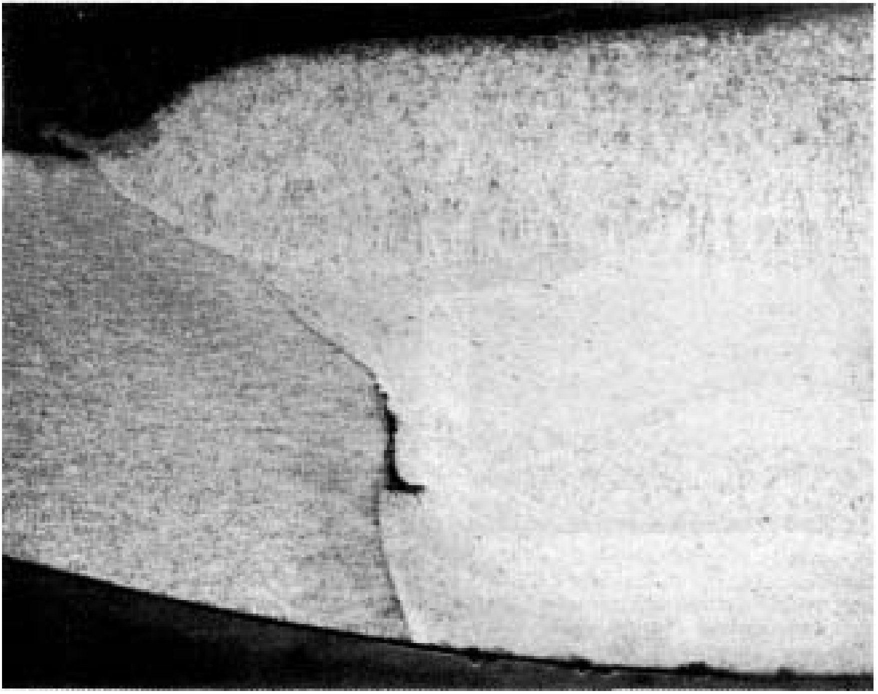

Figure 20.2 Cross section through a linear slag inclusion. This weld had been in 650-psi (4.5-MPa) service for 25 years. (Magnification: 5×.) *(Reprinted with permission from Helmut Thielsch,* Defects and Failures in Pressure Vessels and Piping, *New York, Van Nostrand Reinhold, 1965.)*

inclusion located at the weld-metal/base-metal interface. Slag inclusions are not visible unless they emerge at a surface.

Service failures are generally associated with surface-lying slag inclusions, or inclusions that are of such size that they significantly reduce cross-sectional area of the wall.

Elimination. The number and size of slag inclusions can be minimized by maintaining weld metal at low viscosity, preventing rapid solidification, and maintaining sufficiently high weld-metal temperatures.

Excess penetration (burnthrough)

Identification. The term *excess penetration* refers to disruption of the weld bead beyond the root of the weld. This disruption can exist as either excess metal on the back side of the weld, which may appear as "icicles" (Fig. 20.3), or concavity of the weld metal on the back side of the weld, sometimes referred to as "sink" (Fig. 20.4).

Figure 20.3 Burnthrough resulting in icicles on the underside of a butt weld. *(Reprinted with permission from Helmut Thielsch,* Defects and Failures in Pressure Vessels and Piping, *New York, Van Nostrand Reinhold, 1965.)*

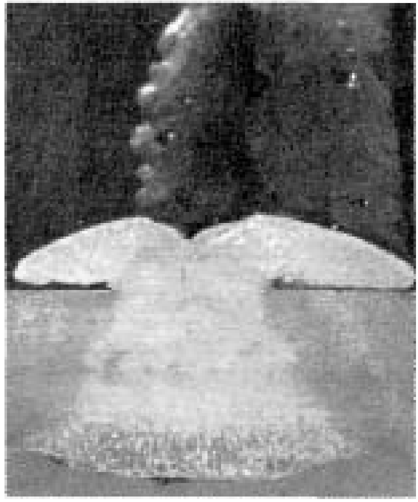

Figure 20.4 A burnthrough cavity formed on the backing ring of a tube weld. *(Reprinted with permission from Helmut Thielsch,* Defects and Failures in Pressure Vessels and Piping, *New York, Van Nostrand Reinhold, 1965.)*

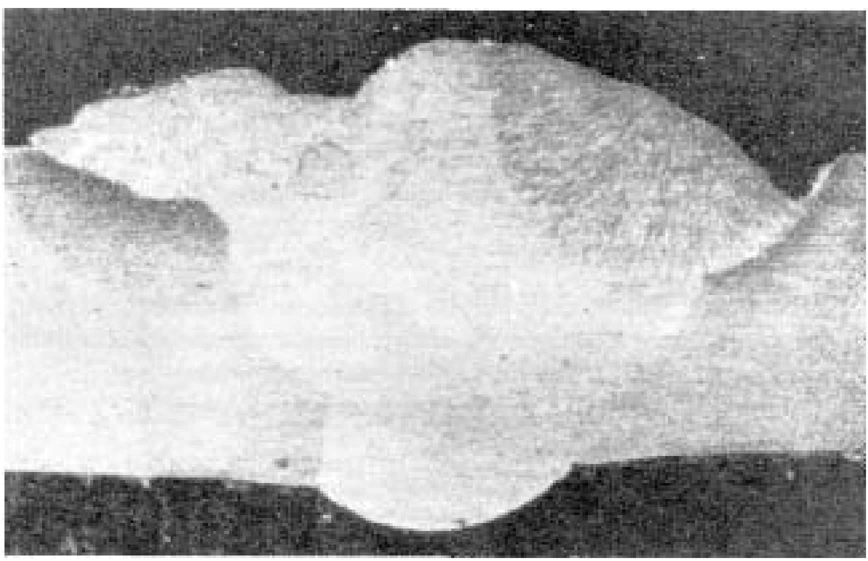

Figure 20.5 Cross section of welds containing severe undercut. (Magnification: 1.5×.) *(Reprinted with permission from Helmut Thielsch,* Defects and Failures in Pressure Vessels and Piping, *New York, Van Nostrand Reinhold, 1965.)*

The first of these is undesirable because the excess material can disrupt coolant flow, possibly causing localized corrosion downstream of the defect (water tube), or localized overheating downstream of the defect (steam tube).

The second of these, if severe, can cause root-pass cracking. Such cracks may not be revealed by radiographic examination. Concavity can also substantially reduce fatigue life, and excess concavity has been involved in thermal-fatigue failures.

Elimination. Since disruptions of this type are frequently inaccessible for repair, elimination consists largely in preventing them from occurring in the first place. Excess penetration is frequently caused by improper welding techniques, poor joint preparation, and poor joint alignment.

Incomplete fusion

Identification. *Incomplete fusion,* as the term implies, refers to lack of complete melting between adjacent portions of a weld joint. It can occur between individual weld beads, between the base metal and weld metal, or at any point in the welding groove.

Failures resulting from incomplete fusion of internal surfaces of the weld are infrequent, unless it is severe (amounting to 10% or more of the wall thickness). Incomplete fusion at surfaces, however, is more critical and can lead to failure by mechanical fatigue, thermal fatigue, and stress-corrosion cracking.

Elimination. Incomplete fusion can occur because of failure to fuse the base metal or previously deposited weld metal. This can be eliminated by increasing weld current or reducing weld speed. Incomplete fusion can also be caused by failure to flux nonmetallic materials adhering to surfaces to be welded. This circumstance can be eliminated by removing foreign material from surfaces to be welded.

Related problems. See the section titled Inadequate Joint Penetration in this chapter.

Undercut

Identification. The term *undercut* refers to the creation of a continuous or intermittent groove melted into the base metal at either the surface (toe of the weld) (Fig. 20.5) or the root of the weld. Depending upon depth and sharpness, undercutting may cause failure by either mechanical or thermal fatigue.

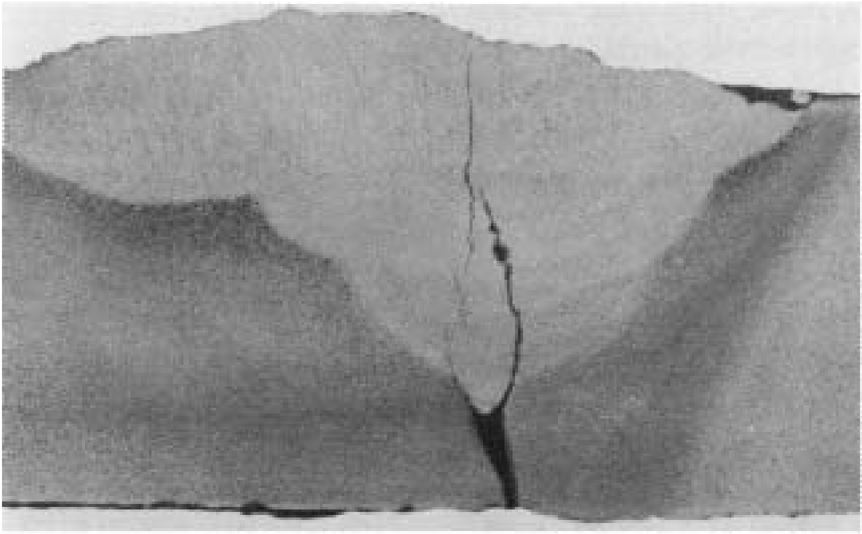

Figure 20.6 Lack of penetration in the root of a butt weld in a boiler feedwater line. Sodium hydroxide concentrating in the resulting crevice led to caustic stress-corrosion cracking. Note fine cracks emanating from crevice. *(Reprinted with permission from Helmut Thielsch,* Defects and Failures in Pressure Vessels and Piping, *New York, Van Nostrand Reinhold, 1965.)*

Elimination. Serious undercutting may be repaired either by grinding or by depositing additional weld metal. Undercutting is generally caused by using excessive welding currents for a particular electrode or maintaining too long an arc.

Inadequate joint penetration

Identification. Inadequate joint penetration, as the name implies, involves incomplete penetration of the weld through the thickness of the

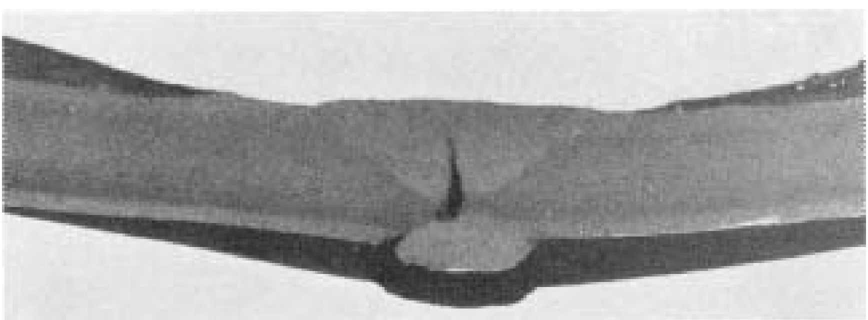

Figure 20.7 Cross section of circumferential butt weld. *(Reprinted with permission from Helmut Thielsch,* Defects and Failures in Pressure Vessels and Piping, *New York, Van Nostrand Reinhold, 1965.)*

joint (Fig. 20.6). It usually applies to the initial weld pass, or to passes made from one or both sides of the joint. On double-welded joints, the defect may occur within the wall thickness (Fig. 20.7).

Inadequate joint penetration is one of the most serious welding defects. It has caused failures in both pressure vessels and tube welds. Failures by mechanical fatigue, thermal fatigue, stress-corrosion cracking, and simple corrosion have been associated with this defect.

Elimination. Inadequate joint penetration is generally caused by unsatisfactory groove design, too large an electrode, excessive weld travel rate, or insufficient welding current.

Related problems. See the section titled Incomplete Fusion in this chapter.

Cracking

Identification. Cracks appear as linear openings at the metal surface. They can be wide, but frequently are tight. Such cracks are typically thick-walled and exhibit very little, if any, plastic deformation. Cracking of weld metal can be critical and has led to frequent service failures. Base-metal cracking (toe cracking, underbead cracking) is also critical and has caused service failures. Cracking may be either transverse or longitudinal (Fig. 20.8).

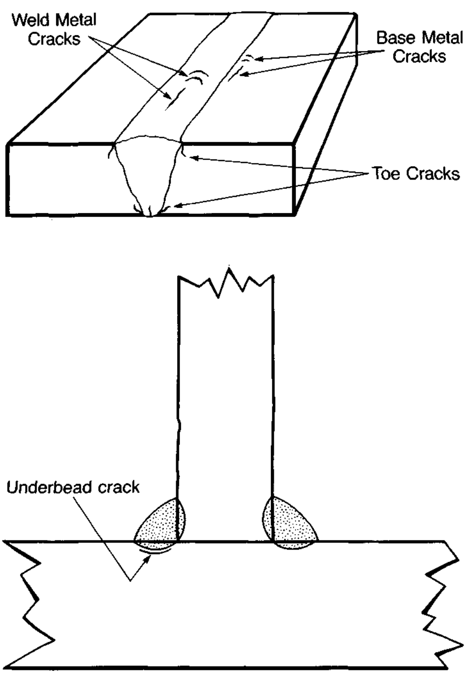

Figure 20.8 Typical crack locations in weldments.

Cracking in weldments can occur in several forms:

- **Hot cracking in weld deposit.** Forms immediately upon solidification of the weld metal.

- **Cold cracking in weld deposit.** Forms after the weld has cooled. Such cracks may form days after the welding procedure.

- **Base-metal hot cracking.** Forms upon solidification of the weld metal.

- **Base-metal cold cracking.** Forms after the weld metal has cooled.

Elimination. In general, cracking results from poor welding practice, inadequate joint preparation, use of improper electrodes, inadequate preheat, and an excessive cooling rate.

If cracking occurs in the weld metal, the following steps may prevent recurrence:

1. Decrease weld travel speed.
2. Preheat area to be welded, especially on thick sections.
3. Use low-hydrogen electrodes.
4. Use dry electrodes.
5. Sequence weld beads to accommodate shrinkage stresses.
6. Avoid conditions that cause rapid cooling.

If cracking occurs in the base metal, the following steps may prevent recurrence:

1. Preheat area to be welded, especially in thick sections.
2. Improve heat-input control.
3. Use correct electrodes.
4. Use dry electrodes.

Cautions. Final determination of the severity of a weld defect, and its influence on serviceability, requires the judgement of an experienced weld inspector.

Graphitization

Locations. Unalloyed steel and steel containing ½% molybdenum can be susceptible to graphitization. Such steels may be used in low-temperature sections of the superheater and reheater. Failures are more frequent in steam piping than in boiler tubing.

General description. The term *graphitization* refers to the spontaneous thermal conversion of the iron carbide constituent of steel to free carbon (graphite) and pure iron. This is a time/temperature phenomenon that typically occurs in a temperature range of 800 to 1200°F (427 to 649°C). The time required for graphitization to occur decreases with increasing metal temperature.

Failures due to graphitization in welded steels result from the formation of continuous chains of graphite that preferentially align along the low-temperature edge of the heat-affected zone in the base metal. These continuous chains or surfaces of graphite represent a brittle plane through which cracks may readily propagate. Unalloyed steels and steels containing ½% molybdenum can be affected. Failures by graphitization have caused substantial damage.

Critical factors. The critical factors leading to potential failure resulting from graphitization are the use of a susceptible material, welding of susceptible material, and exposure of the weldment to temperatures above the range of 800 to 1200°F (427 to 649°C) for a prolonged period.

A *susceptible material* can be defined as an unalloyed steel, or an alloyed steel containing ½% molybdenum that has been deoxidized in the steelmaking process by aluminum in amounts exceeding 0.5 lb/ton (0.226 kg/T).

Identification. Failures due to graphitization may occur in carbon and carbon–molybdenum steels that have been welded and subsequently exposed to metal temperatures between 800 and 1200°F (427 and 649°C) for a prolonged period. Fractures occur in the heat-affected base metal approximately 1/16 in. (1.6 mm) from the weld interface. A nondestructive technique for confirming the occurrence of graphitization does not exist.

Elimination. Avoiding prolonged exposure of welded metal to the temperature range over which graphitization occurs is the best method of eliminating graphitization in suspect material. Specifying nonsusceptible material in the design phase of equipment has also been useful in eliminating failures by graphitization.

Additional considerations

Welding debris. Welding debris such as weld spatter, shavings, filings, chips from grinding tube ends, and even welding tools, have found their way into tubes as a consequence of tube repair. If this debris is not removed, it can cause partial blockage of coolant flow and result in overheating failures such as stress rupture. Such failures can occur months after the completion of the repair.

CASE HISTORY 20.1

Industry:	Utility
Specimen Location:	Superheater outlet header
Specimen Orientation:	Slanted
Years in Service:	7
Water-Treatment Program:	Ammonia, hydrazine
Drum Pressure:	3800 psi (26.2 MPa)
Tube Specifications:	2¼-in. (5.7 cm) outer diameter, SA-213 T22

The tube illustrated in Figs. 20.9 and 20.10 had been welded to the finishing-superheater outlet header in the penthouse. The specimen shows a brittle fracture at the weld, which apparently popped out of the header after the failure. Similar fractures had not occurred previously, but several additional cracked and leaking welds were discovered upon the inspection associated with this failure. The boiler was base-loaded and in continuous service except for yearly maintenance outages.

Visual examination of the weld and the fracture face revealed that large areas of the weld root were unfused. Radial striations on the fracture face originated at the unfused region.

The specimen had failed at the weld that joined the tube to the header. Cracks initiated at the weld root, where incomplete fusion had occurred, and propagated from this region by a corrosion-fatigue mechanism. The unfused portion of the weld formed sharp crevices, which acted as stress-concentration sites that locally elevated normal stresses.

Figure 20.9 Cross section of tube showing weld metal (top of tube).

Figure 20.10 Fracture surface showing tube wall (inner ring) and fractured weld metal (outer ring).

Cyclic stressing in this region of the boiler is frequently caused by differences in rates and directions of thermal expansion between the header and the tubes. Terminal tubes are often affected and can crack at the toe of the weld even in connections that have been properly welded. The thermal expansion and contraction stresses are often associated with start-up and shutdown.

CASE HISTORY 20.2

Industry:	Utility
Specimen Location:	Screen tube
Specimen Orientation:	45° slant
Years in Service:	20
Water-Treatment Program:	Coordinated phosphate
Drum Pressure:	1500 psi (10.3 MPa)
Tube Specification:	3 in. (7.6 cm) outer diameter
Fuel:	Coal

A "window" section had been cut out of the hot side of the tube illustrated in Fig. 20.11 and a new section welded into place from the external surface. Cross sections cut through the welded window revealed deep fissures associated with the welds (Fig. 20.12). The appearance of this defect suggests that entrapped slag, dirt, or flux prevented the formation of a sound metallurgical bond. Defects of this type can lead to through-wall fatigue cracking or corrosion fatigue due to the stress-concentrating effect of the fissure.

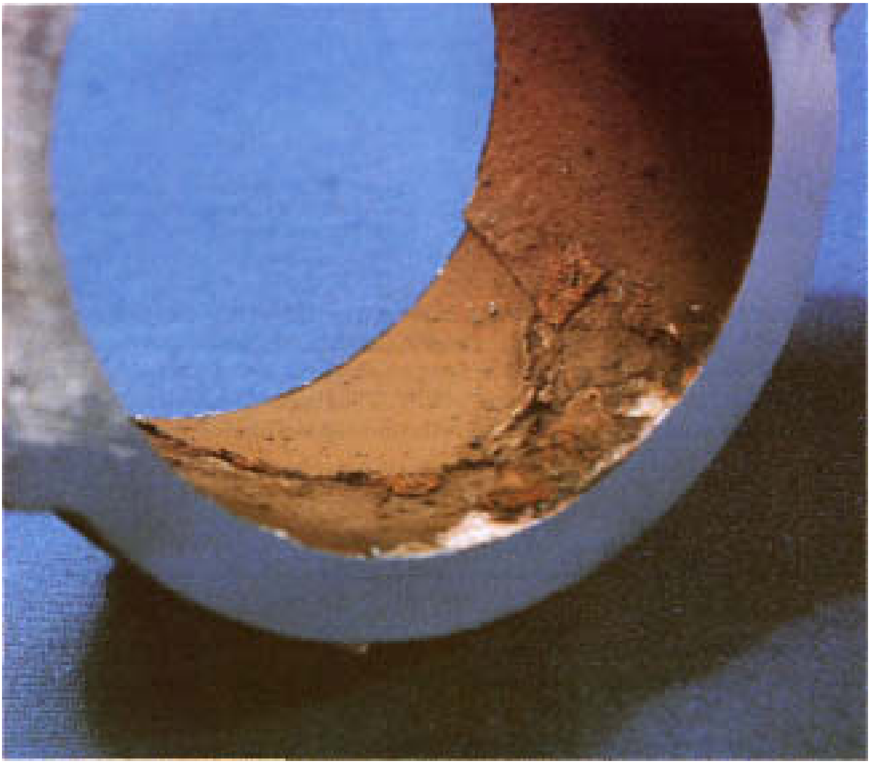

Figure 20.11 Internal surface of tube showing oval-shaped replacement window welded into place.

Figure 20.12 Cross section through window weld showing deep fissure in weld metal. (Magnification: 6×.)

CASE HISTORY 20.3

Industry:	Utility
Specimen Location:	Tube in area of cyclone burners
Specimen Orientation:	Vertical
Years in Service:	22
Water-Treatment Program:	Coordinated phosphate
Drum Pressure:	1500 psi (10.3 MPa)
Tube Specifications:	1½ in. (3.8 cm) outer diameter

The boiler from which the tube illustrated in Fig. 20.13 was taken had experienced recurrent overheating failures in the areas around the cyclone burners and the furnace floor. The boiler had been in peaking service for the last 6 years.

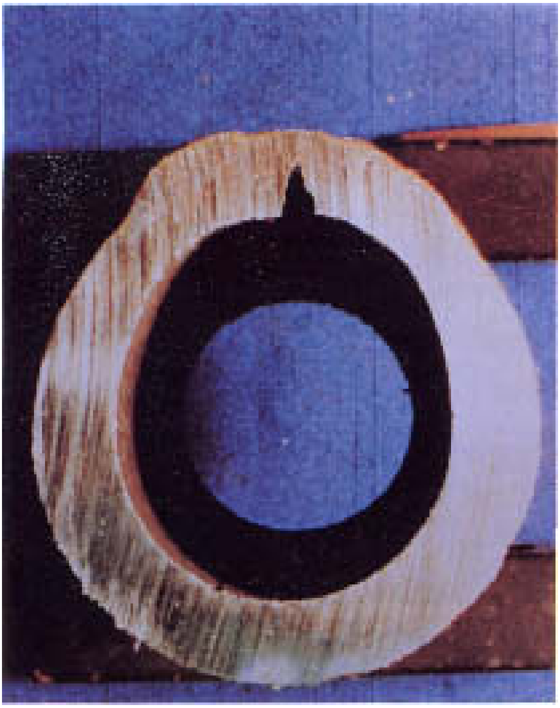

Figure 20.13 Profile of tube wall showing unfused fissure remaining after weld repair.

Failures were repaired by patch-weld overlays. The illustration indicates that the weld metal has not penetrated through the tube wall, leaving the thick-walled fissure caused by the in-service overheating unfused. These fissures operate as stress-concentration sites. Consequently, under the combined influence of normal service stresses and high operating temperatures, creep cracks (see Chap. 2, "Long-Term Overheating") formed at the tip of the fissure. Failure of the weld-repaired tube wall was imminent.

CASE HISTORY 20.4

Industry:	Utility
Specimen Location:	Screen wall
Specimen Orientation:	Vertical
Years in Service:	9
Water-Treatment Program:	Coordinated phosphate
Drum Pressure:	900 psi (6.2 MPa)
Tube Specifications:	2 in. (5.1 cm) outer diameter
Fuel:	Coal

Fig. 20.14 illustrates a massive fracture along the weld bead attaching the membrane to the tube wall. Microstructural examinations revealed an aligned chain of graphite nodules in the heat-affected zone immediately adjacent to the weld bead. The fracture had occurred through this chain. The proximity and alignment of the graphite nodules provided a weak plane where a fracture could readily propagate due to stresses imposed by internal pressure. This tube section had been exposed to metal temperatures in excess of 850°F (454°C) for a very long period of time.

Figure 20.14 Massive fracture along weld bead resulting from weld-related graphitization. *(Courtesy of National Association of Corrosion Engineers.)*