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# Composite Tube Cracking in Kraft Recovery Boilers: A State-of-the-Art Review

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# Composite Tube Cracking in Kraft Recovery Boilers: A State-of-the-Art Review

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# EXECUTIVE SUMMARY

Beginning in early 1995, a multidisciplinary research program funded by the U. S. Department of Energy was established to investigate the cause of cracking in coextruded tubes and to develop improved materials for use in water walls and floors of kraft recovery boilers. One portion of that program, a state-of-the-art review of public- and private-domain documents related to coextruded tube cracking in kraft recovery boilers is reported. Sources of information that were consulted for this review include tube manufacturers, boiler manufacturers, public-domain literature, companies operating kraft recovery boilers, consultants and failure analysis laboratories, and failure analyses conducted specifically for this project.

Cracks in coextruded tubes can generally be divided into two distinct types: (1) those found at smelt-spout and port openings in walls and (2) those found in floor tubes and portions of wall tubes exposed to the smelt bed. Much of the information contained in this report involves cracking problems experienced in recovery boiler floor and wall tubes exposed to the smelt bed as well as those aspects of spout and air-port-opening cracking not readily attributable to thermal fatigue. Most cracking caused by thermal fatigue is clearly related to construction and design details of the particular boiler in which cracking has occurred, and there is generally good understanding of the changes required to reduce the likelihood of such cracking. In contrast, the mechanisms governing cracking in floor and wall tubes exposed to the smelt bed appear more complex, and even relatively detailed and complete investigations have failed to establish a consistent cause.

The collected information indicates that it is likely that all 304L/SA-210 coextruded tubes exposed to the smelt bed in a kraft recovery boiler are susceptible to cracking in service. No strong mitigating factors have been discovered that might exclude these tubes from cracking. Both decanting and sloped-bottom boilers are susceptible to floor-tube cracking.

A thorough review of both private- and public-domain documents pertaining to cracking of coextruded tubes in recovery-boiler floors was unable to positively identify a failure mechanism. Some cracks, particularly those found at port openings, are caused by thermal fatigue. The mechanism of cracking for most cracks is unknown but appears to be a form of environmentally assisted cracking (EAC). Furthermore, there is still insufficient information available to select a material combination for coextruded tubes that will guarantee crack-free service over the predicted lifetime of the boiler. Laboratory testing and accumulated service history for coextruded tubes made from Alloy 825 indicate that an improvement in tube life over 304L can be expected, but cracking of these tubes has already been reported in smelt-spout opening tubes.

*Keywords:* carbon steel, composites, cracks, failure, fracture, kraft mills, recovery furnaces, smelts, stainless steel, tubes, alloy

# INTRODUCTION

The Tomlinson kraft recovery furnace, invented in 1934, is a critical component of a modern kraft mill. It has enabled the pulp and paper industry to achieve a high level of energy self-sufficiency and to significantly reduce the impact of its effluent on the receiving waters for the mills. The fuel for the furnace is concentrated black liquor, which consists of an aqueous mixture of inorganic cooking chemicals and dissolved lignin. This fuel is burned to recover the reduced inorganic cooking chemicals from the fuel and to burn the organic lignin to generate process steam. Gaseous, liquid, and solid phases coexist at high temperatures within the boiler, a condition that poses a significant challenge to boiler manufacturers in their attempts to prevent corrosion of the fireside boiler surfaces.

Early recovery boiler designs used refractory linings to protect the boiler walls, but there was a rapid evolution toward the use of water-cooled carbon steel wall and floor tubes.[1] Surface temperature of the boiler wall tubes was quickly found to be the key parameter that governed corrosion; consequently, kraft recovery boilers were designed to operate at very low steam pressures relative to power utility boilers. This compromise had little effect on the ability of the furnace to recover the inorganic cooking chemicals but significantly reduced the efficient recovery of energy from the process steam.

Beginning in the mid-1960s, increasing energy costs in Finland and Sweden made energy recovery more critical to the cost-effective operation of a kraft pulp mill. Boiler designers responded to this need by raising the steam operating pressure, but almost immediately the wall tubes in these new boilers began to corrode rapidly. Test panels installed in the walls of the most severely corroding boiler identified austenitic stainless steel as sufficiently resistant to the new corrosive conditions, and discussions with Sandvik AB, a Swedish tube manufacturer, led to the suggestion that coextruded tubes be used for water wall service in kraft recovery boilers.[2] An extensive Finnish-Swedish research program conducted in response to the problem was later able to establish that 304 stainless steel was very resistant to the highly sulphidizing environment in the boiler.[3,4] The first test panel with coextruded tubing was installed in a Finnish boiler in 1967 and was followed in 1972 by the installation in Sweden of the first complete wall panel with coextruded tubes.[5] The success achieved in Nordic countries with coextruded wall panels led to the introduction of coextruded floor tubes in 1978. Acceptance in North America came more slowly; it was not until 1978 that the first coextruded water wall was installed in a North American boiler and not until the mid-1980s that a coextruded tube floor was installed.

Replacement of carbon steel by coextruded tubes has solved most of the corrosion problems experienced by carbon steel wall tubes[6]; however, these tubes have not been problem-free. Preferential corrosion of the outer stainless steel layer in recesses around port openings has been a problem.[7,8] Another has been cracking of the outer stainless steel layer at air ports, at spout openings, and in floor or wall tubes covered by the molten smelt bed at the bottom of the boiler.[7,9]

The latter problem quickly became a concern in both Europe and North America that a crack might propagate through the tube wall and cause a water leak into the smelt bed. Initially, cracking was attributed to thermal fatigue, particularly at air ports and spout openings, where cracks usually occurred in areas subjected to variable thermal fluxes and in the presence of severe physical constraint imposed by crotch plate and attachment welds.[5,7,10] However, as reports of cracking in coextruded tubes became more widespread, particularly in floor tubes and as cracks were found more frequently in areas not associated with welds, it became clear that much less was understood about the cause of cracking than had been thought. Consideration of mechanisms turned to corrosion fatigue and stress corrosion cracking (SCC) as well as to thermal fatigue.[11–14]

Beginning in early 1995, a multidisciplinary research program funded by the U. S. Department of Energy was established to investigate the cause of cracking in coextruded tubes and to develop improved materials for use in water walls and floors of kraft recovery boilers. One portion of that program, a state-of-the-art review of public- and private-domain documents related to coextruded tube cracking in kraft recovery boilers is reported here. Sources of information that were consulted for this review include the following:

- tube manufacturers,
- boiler manufacturers,
- public-domain literature,
- companies operating kraft recovery boilers,
- consultants and failure analysis laboratories, and
- failure analyses conducted specifically for this project.

In addition to obtaining written documentation from these sources, visits were made by members of the research team to manufacturing facilities for the tubes and boilers and to mill sites during operation of the boilers and on shutdowns, when the equipment was available for inspection. University laboratories and consultants' offices were also visited. An overview of information obtained to date from each of these sources is outlined.

Much of the information contained in this report involves cracking problems experienced in recovery boiler floors and those aspects of spout and air-port-opening cracking not readily attributable to thermal fatigue. Most cracking caused by thermal fatigue is clearly related to construction and design details of the particular boiler in which cracking has occurred, and there is generally good understanding of the changes required to reduce the likelihood of such cracking.[7,9] In contrast, the mechanisms governing cracking in floor tubes appear more complex, and even relatively detailed and complete investigations have failed to establish a consistent cause.[12–14]

# MANUFACTURE OF COEXTRUDED TUBES

There are two principal manufacturers of coextruded tubes worldwide–Sandvik AB from Sweden and Sumitomo Metals from Japan. Other, smaller manufacturers also exist, but they sell very little material to the pulp and paper market. Currently no North American suppliers sell this type of tubing. The bulk of coextruded tubes sold in North America comes from Sumitomo. Sandvik does have a significant presence in North America but sells most of its product in Europe.

Coextruded tube manufacture consists of preparing and mating two billets of material, one inner and one outer. The combined billet is then extruded through a die at high temperature to form a continuous tube. Many details of the billet preparation process and extrusion conditions are considered trade secrets by the manufacturers, but some information has been placed into the public domain.[15–19]

The billets are generally joined by press-fitting the inner billet into the outer one; alternatively, the Japanese supplier claims to join some billets by means of a cold extrusion-expansion process. Sumitomo additionally claims to apply a nickel plate (for press-fit billets) or a nickel foil wrap (for the cold extrusion-expansion process) onto the outside surface of the inner billet to prevent carbon migration from the carbon steel into the outer stainless steel. Sandvik has not considered it necessary to apply a nickel diffusion barrier to their coextruded tubes; nor did the only British manufacturer of coextruded tubes (purchased by Sandvik in the late 1980s). It has been common to seal-weld the ends of the billets to prevent air incursion into the space between the billets and subsequent oxide formation at the interface during extrusion, but this practice is not always followed. Before extrusion, a glass lubricant is applied to both the inside and outside surface of the joined billets. After extrusion, the tubes are air-cooled. Both manufacturers cold finish the tubes after extrusion. Sumitomo does not indicate whether the tubes are subjected to a final annealing or normalizing heat treatment; this is apparently a common, but not universal, practice for Sandvik. It has also been suggested, but not confirmed, that Sumitomo has shot-peened the external stainless steel layer after fabrication to ensure that residual compressive stresses are present to inhibit crack initiation. A 100% ultrasonic inspection of the interface to check for internal bond integrity in the finished tube is common to both Sandvik and Sumitomo.

Other processes may also be used to make the billets for production into coextruded tubes.[17] Sandvik has utilized the "Osprey" process to produce tubes from some grades of difficult-to-extrude materials. In this process, the alloy comprising the outer, corrosion-resistant layer is melted and sprayed using a gas atomizer onto the surface of a rotating collector (e.g., a carbon steel tube). The "ospreyed" tube is subsequently peel-turned and pull-bored to final dimensions. Cold pilgering and a final anneal may also be specified. Commercial quantities of coextruded tubes for the pulp and paper industry have not been produced by this process. The production of bimetallic tubes via a centrifugal casting process has been evaluated recently, but these tubes are not yet available as a commercial product.[20]

Weld-overlaid tubes have also been manufactured for use by the pulp and paper industry. The overlay may be applied longitudinally on one surface of a wall panel only, or individual tubes may be spiral-welded around the entire circumference. Although there is some operating history for field-applied corrosion-resistant weld overlays in recovery boilers, the circumferentially weld-overlaid tubes have had no significant application as wall or floor tubes in kraft recovery boilers. Test panels containing circumferentially weld overlaid tubes have been installed within the past year, and a substantial portion of a boiler floor was installed in the fall of 1996.

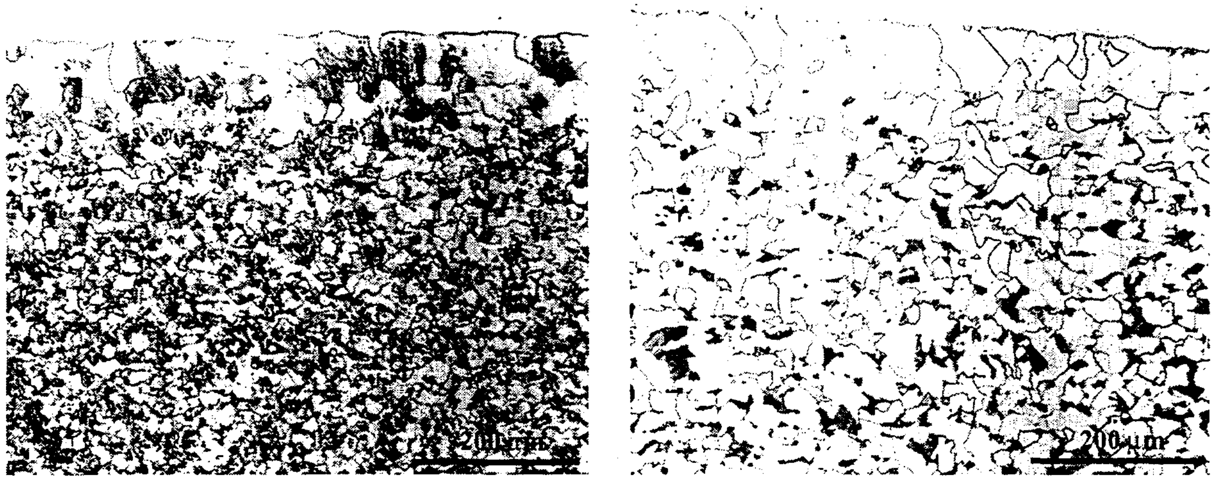
For water-wall and floor-tube service in recovery boilers, the inner layer is composed of SA-210 carbon steel or equivalent and is used to provide the strength and pressure-handling capabilities of the tube. Sandvik originally used a grade of 304 stainless steel containing ~0.05% carbon for the outer layer, but all coextruded tubes manufactured by them since about 1982 have been to a low carbon 304L specification (<0.03% C). More recently, tubes with an outer layer of Alloy 825 or equivalent composition (Sanicro 38™) have been introduced into water wall and floor tube service.[16,21,22] Other alloy combinations have also been made for applications in pulp and paper as well as other industries.[17]

Regardless of the alloys, typical tube thicknesses used in the pulp and paper industry are about 6 mm (0.25 in.) total thickness, with the outer corrosion-resistant layer being about 1.6 mm (0.065 in.) thick. The thickness of the inner carbon steel layer is likely based on boiler code calculations of the highest operating pressures to which these tubes might be exposed; the thickness of the outer stainless steel layer may be based on an extrapolation of worst-case corrosion rates of 304L in boiler environments to give an economic lifetime to the tubes (25–30 years). Tubes for the pulp and paper industry are produced with external diameters of either 76 mm (3 in.) or 63.5 mm (2½ in.), with the latter being standard for many modern boilers.

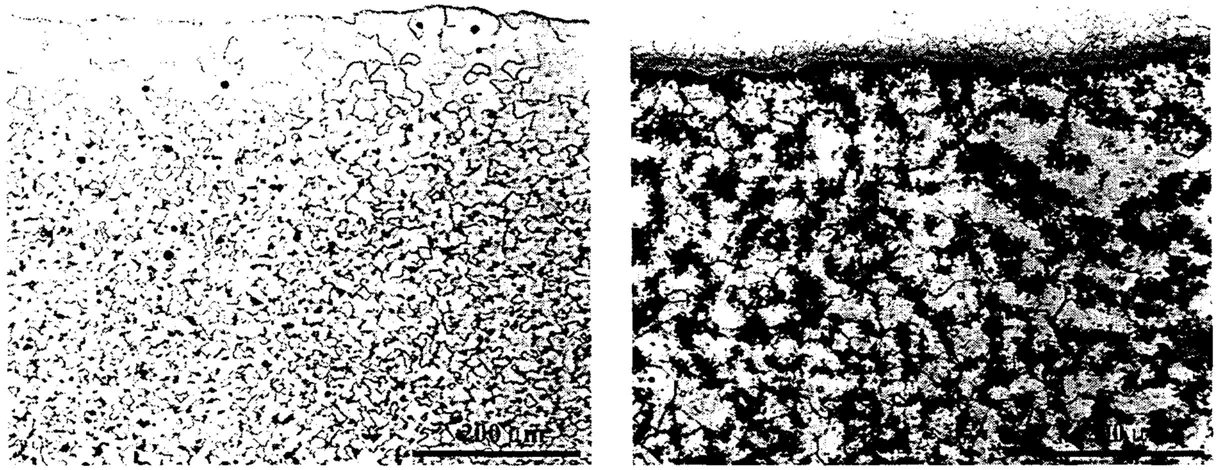
The cross-sectional appearance of the tubes produced by the two different manufacturers have very similar characteristics (Fig. 1). Typically, a hard, carbide-rich region exists in the stainless steel layer adjacent to the interface, which can be as thick as 40 μm (Fig. 2). A matching 80–100-μm-thick decarburized layer can usually be found in the carbon steel adjacent to the interface. This was true even for the Sumitomo tubes examined in this program. Electron microprobe examination of two samples failed to find evidence of the nickel interlayer on these tubes. Either the nickel layer was not applied during the manufacture of these tubes or it is not effective at preventing carbon migration into the outer alloy layer. Although the carbon steel composition in all coextruded tubes meets similar specifications, there is actually a wide variation in the grain size and phase distribution, which suggests different heating and processing histories are possible (Fig. 3).

The above description of tube-manufacturing techniques should be considered a general overview. Both manufacturers have modified and streamlined the processes used to make coextruded tubes since they were first introduced to the market. Variations or exceptions to the above descriptions may also apply for particular grades of tube, or tubes produced for a specific market.

It is important to note that despite the differences in the details of manufacture of coextruded tubes between the Swedish and Japanese suppliers, observations of cracking in boilers suggest that the source of the tube (Sandvik or Sumitomo) has little or no influence on the tendency of the tube to crack or on the severity of cracking experienced by the tube in service.



(*a*) Sandvik 3R12/4L7 (304L/SA-210) (*b*) Sandvik Sanicro 38/4L7 (Alloy 825/SA-210)



(*c*) Sumitomo 304L/SA-210 (*d*) Sumitomo Alloy 825/SA-210

**Fig. 1. Photomicrographs of the cross section of unexposed 304L/SA210 and either Sanicro 38/SA-210 or Alloy 825/SA-210 coextruded tubes.** Stainless steel was etched with aqua regia; carbon steel was etched with 2% nital. The outer stainless steel layer in each tube appears at the top of each micrograph; the carbon steel is at the bottom.

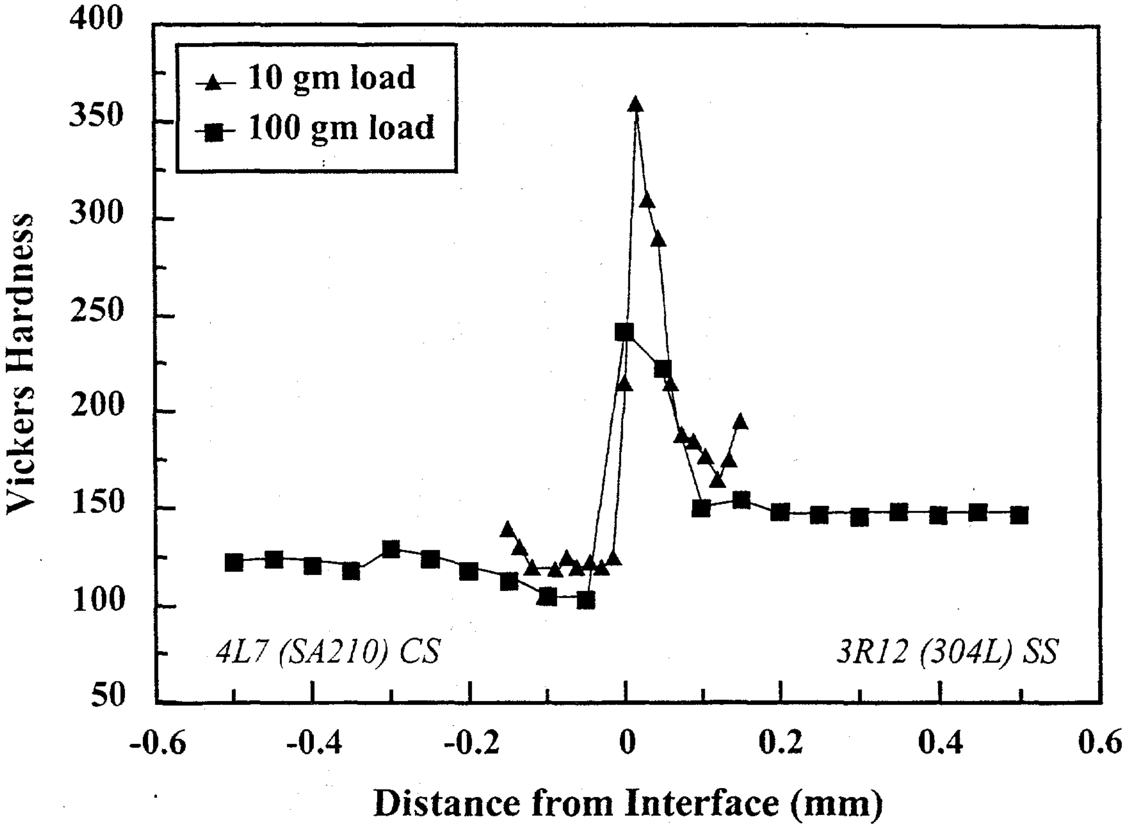
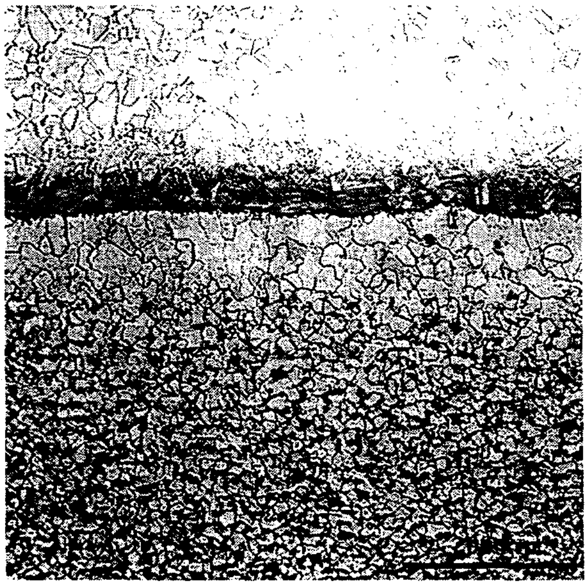


Fig. 2. **Vickers hardness profile across the cross section of a Sandvik 304L/SA-210 coextruded tubes.** Similar data were obtained from a Sumitomo tube.

(*a*) Sandvik 3R12/4L7 (304L/SA-210) (*b*) Sumitomo 304L/SA-210



(*c*) Sumitomo Alloy 825/SA-210

**Fig. 3. Comparative photomicrographs of the cross section of different coextruded tubes.** Note the variation in grain size and phase distribution across these samples as well as those included in Fig. 1. Stainless steel was etched with aqua regia; carbon steel was etched with 2% nital. The outer stainless steel layer in each tube appears at the top of each micrograph; the carbon steel is at the bottom.

## BOILER CONSTRUCTION

Six boiler manufacturers compete for most of the worldwide recovery boiler sales. In North America, the principal suppliers are ABB-Combustion Engineering (ABB-CE) and Babcock & Wilcox (B&W). Kværner (Goteverken) produces recovery boilers in Sweden, while Ahlstrom and Tampella are based in Finland. (In early 1996, Kværner and Tampella announced that they planned to merge their operations.) Mitsubishi is a prominent Japanese boiler manufacturer.

Procedures for the construction of boiler wall and floor panels are similar, but not identical, for the surveyed manufacturers. In all cases, tubes are received and cleaned prior to welding or panel assembly. Metal ball blasting is employed by one manufacturer to clean coextruded tubes of external scale and debris. Some shops have dedicated floor space and special facilities for handling coextruded tubes and panels, while others utilize the same facilities regardless of whether a carbon steel or coextruded panel is being assembled.

Individual tubes are sized and then assembled in a jig of four or more sets of tubes and membranes. In some shops, smaller subpanels are made first and then joined into larger panels, while in other shops, complete panels are made in one jig. Joining of tubes and subpanel sections is accomplished primarily by multiheaded, automatic welding processes, but manual welding is used as required. The width of the shop-assembled panels is generally dictated by that required for convenient shipment to the mill site. Roll-clad material is most commonly used for membranes, but solid 304L membranes are also specified. Details of the welding procedures vary by manufacturer and are considered proprietary. Tube bends are made at ambient temperatures, although heat may sometimes be applied to assist in forming and straightening tubes when making difficult openings. It would not be normal practice for any manufacturer to stress relieve wall panels after fabrication, but at least two manufacturers heat treat (either stress relieve or normalize) spout openings after fabrication.

There has been considerable variation in design of spout and air-port openings, not only between manufacturers, but by individual manufacturers over a period of time. Changes have been made for reasons of process improvement or improved manufacture, but many were also made in response to corrosion and cracking problems encountered in the field.[23]

Floor designs of existing boilers fall into one of two general categories: decanting and nondecanting bottoms (Figs. 4 and 5). Decanting-bottom boilers are either completely flat (ABB-CE) or are built with a very slight angle of between 1 and 2½° (Ahlstrom, Tampella). Nondecanting boilers have floor slopes of between 4 and 5° (Kværner, B&W). The height of the spout lip from the floor varies from about 10 to 30 cm (4 to 12 in.) in decanting-bottom designs, to as low as a few centimeters in nondecanting designs. The floor in all boiler designs is supported by a number of I-beams, but is allowed to move freely as the boiler expands in operation.

Depending on the manufacturer, specifications of the client, and date of manufacture, floors may be constructed of smooth or studded carbon steel tubes, a combination of coextruded and carbon steel tubes, or entirely of coextruded tubes. In boilers with coextruded tube walls and carbon steel floors, it is common to extend the coextruded wall tubes around the bend to join with the carbon steel tubes in the floor. Consequently, any boiler constructed with coextruded wall tubes will have some length of coextruded tube underneath the bed of molten smelt. In addition, sloped-floor boilers with coextruded tube walls are built with as many as 12 coextruded smelt-run tubes in the floor along either side wall.

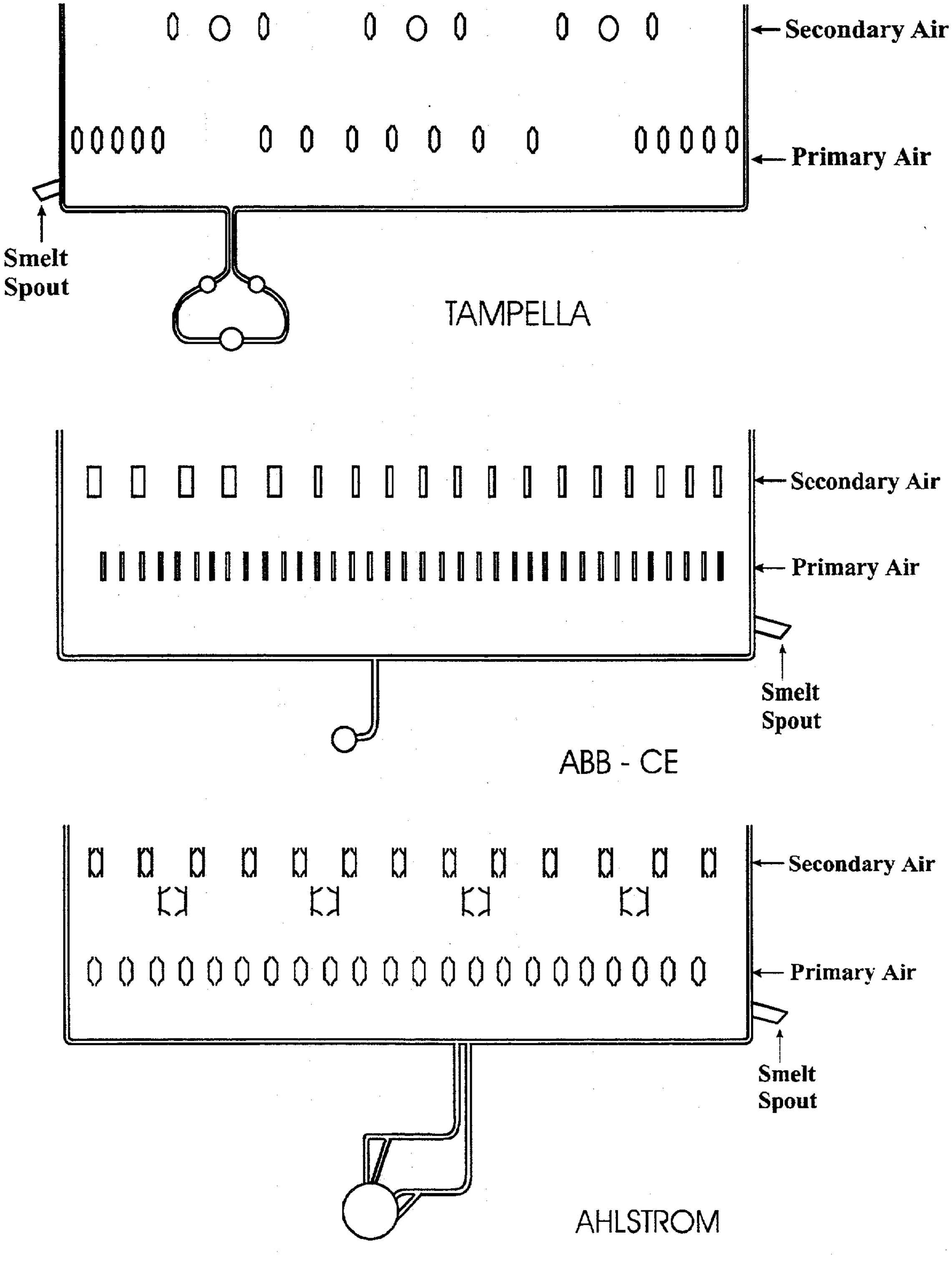
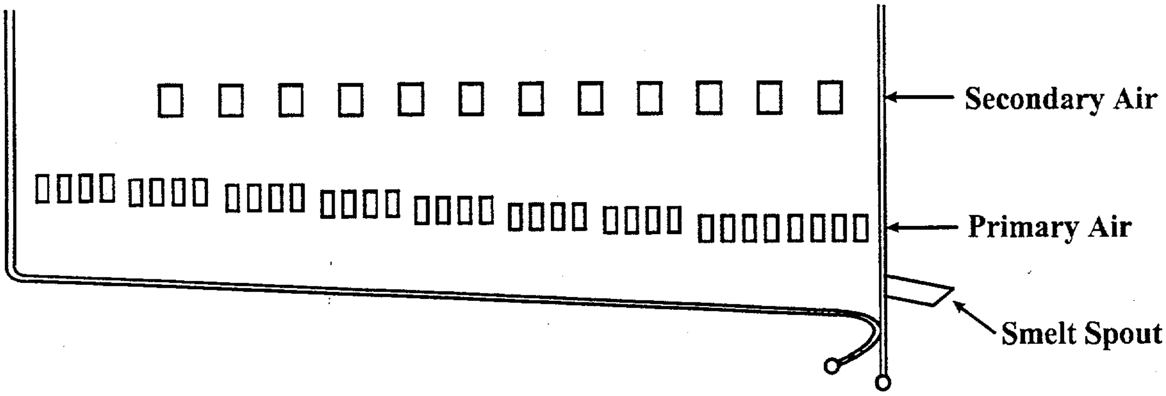
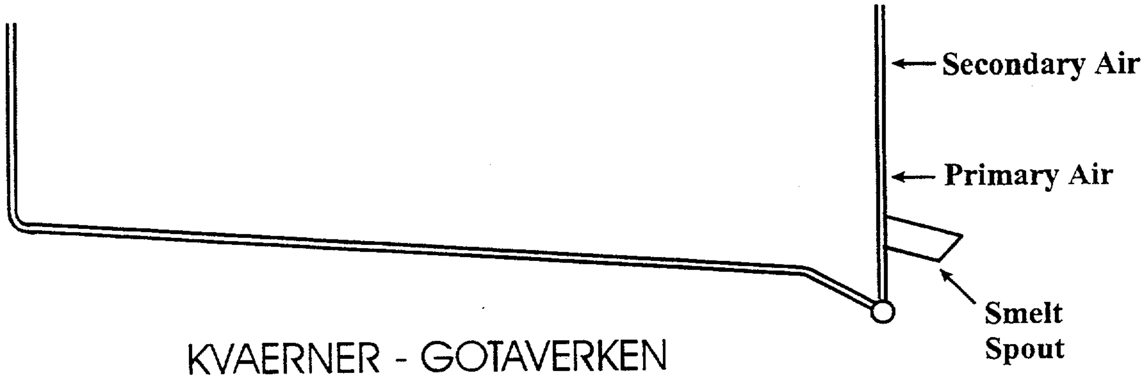


**Fig. 4. Cross-sectional schematic drawings of decanting-bottom boilers showing differences in floor design between the major boiler manufacturers (based on original drawings provided by manufacturers and Coast Testing/Bacon Donaldson & Associates, Vancouver, B.C.).**



B & W



KVAERNER - GOTAVERKEN

Fig. 5. Cross-sectional schematic drawings of nondecanting boilers showing differences in floor design between the major boiler manufacturers (based on original drawings provided by manufacturers and Coast Testing/Bacon Donaldson & Associates, Vancouver, B.C.).

# CRACKING OF COEXTRUDED TUBES IN KRAFT RECOVERY BOILERS

At present, approximately 340 kraft recovery boilers operate in North America. Of these, about 65 are reported to have been built or retrofitted with coextruded floor tubes (Table 1). An additional number (15–20) have coextruded tubes in one or more walls but not in the floor. The largest portion of North American boilers built with coextruded floor tubes have sloped floors. However, a number of decanting-bottom boilers have been retrofitted with coextruded floor tubes. In contrast, most of the 56 recovery boilers in Nordic countries (34 in Sweden and Norway and 22 in Finland) have coextruded tube walls, and more than half have coextruded floor tubes. A much larger proportion of the Nordic boilers that have coextruded floor tubes are decanting-bottom-design boilers than is the case in North America.

The cracking of coextruded tubes is common at three locations within the lower furnace of the recovery boiler: air ports, smelt-spout openings, and floors. Records of cracking at air ports and spout openings in North American and European boilers began to appear around 1983.[5,7,9,23] The European reports of cracking in these locations appear later than in North America, relative to the date of first installation of coextruded tubes in walls. Access to mill inspection and repair documents similar to those used for reference to cracking in North American boilers would likely reveal that cracking in these locations was observed earlier than the public records indicate.

By 1984, about 8 years after the first installation of coextruded tubes in floors, researchers in Finland were aware of cracking in coextruded floor tubes.[24] By 1992, about one half of the boilers with coextruded floor tubes in Finland had reported cracking in these tubes.[14] In contrast to the Nordic countries, recognition of floor-tube cracking in North America is a quite recent phenomenon. Reports of cracked floor tubes began about 1993, with a spate of further instances reported in 1994. As late as early 1996, fewer than a third of North American boilers had reported cracking in coextruded floor tubes, or in wall tubes underneath the level of the bed. This figure is in stark contrast with European experience, where the number of boilers reporting cracked floor tubes is now closer to two thirds of the total. However, the total number of boilers reporting cracked tubes in North America continues to increase as inspection techniques mature and as information on the problem circulates among the operating companies.

The following sections summarize experience with cracking in these three locations. Information is primarily drawn from interviews and inspection/failure reports obtained during the course of this work. European experience, particularly with floor-tube cracking, has been summarized in the open literature.[11–14]

**Table 1. Summary of boilers with composite tube walls and floors by manufacturer (includes as-supplied new and retrofits)[a]**

| Manufacturer | Number of boilers with composite tube panels: Walls | Floors |
|---|---|---|
| ABB-CE | 30 | 2 |
| Ahlstrom | 33 | 28 |
| Babcock & Wilcox | 52 | 41 |
| Kværner | 59 | 33 |
| Tampella | 58 | 16 |

[a]Note: based on data supplied by manufacturers as of August 1996.

## FLOOR TUBES

All boiler manufacturers report significant cracking of coextruded floor tubes. Cracking has also been detected in boilers with coextruded wall tubes extending for a short distance into the floor before joining carbon steel floor tubes (Fig. 6). In such boilers, cracking may occur on the portions of tubes underneath the smelt bed. Cracks have also been observed at the butt welds between the coextruded tubes and the carbon steel tubes.

The time from installation to first cracking for floor tubes has been as short as 4 months.[25] In most cases, it appears that cracking will be evident by 48 months, but longer times to the first observation of cracking have been reported. In North America, higher-pressure boilers (1200-1500 psi steam pressure) were the first to report cracks, but are also more likely to have been constructed with coextruded tubes in the floor. Many low-pressure boilers (600–900 psi) now report cracked floor tubes. Initial reports in North America led to the mistaken belief that cracking was restricted to boiler designs with a sloped floor. This early lead in reports of cracked floor tubes was partly because sloped-floor boilers are inspected relatively easily and because most coextruded floor tubes used in North America were supplied to sloped-floor boilers.

Boiler floor design (decanting vs. nondecanting) is thought to influence the locations at which cracks are found in floor tubes, although exceptions exist to this generalization. The most severe cracking in nondecanting or sloped-floor boilers commonly occurs within two meters (6.5 ft) of the wall containing the smelt spouts, underneath the retained inventory of molten smelt in the bed. In some boilers, the worst cracking has been reported to be located just before the downward bend to the header. Severe cracking is sometimes found in the floor tubes immediately in front of a spout. Cracking has occurred in front of both blocked-off and operating spouts. Cracks are also often found directly underneath the outer edge of the nose arch in the boiler. Recent inspection experience suggests that cracking may also be randomly distributed across the floor.[26]

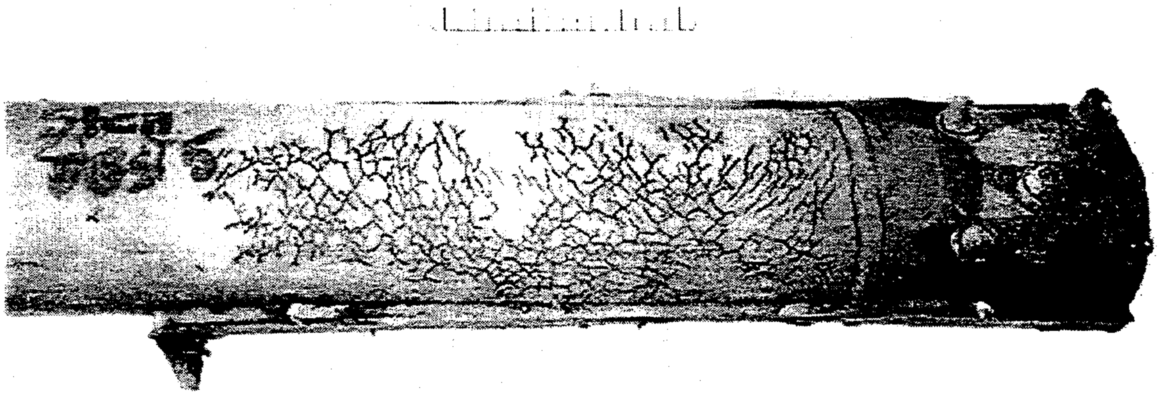


**Fig. 6. Boilers with carbon steel floors and coextruded wall tubes are susceptible to cracking.** This portion of coextruded tube from a European boiler formed the lower bend of a coextruded wall tube at the point where the tube is butt-welded to a studded carbon steel floor tube.

Floor-tube cracks in decanting-bottom boilers are generally randomly distributed across the floor. Because many North American decanting-bottom boilers have coextruded tube walls but not coextruded floors, reports often describe cracking in the wall-tube bends underneath the smelt bed. For boilers with coextruded floor tubes, the portion of the boiler floor directly underneath the nose arch is also often sensitive to cracking. One manufacturer of decanting-bottom boilers correlated a reduction in the height of the spout lip in their more recent boiler designs (and thus a lower smelt-bed level in the furnace) to increased severity of cracking in the floor tubes.

In some cases, cracking has been confined just to the membrane, but it appears more common for cracks to be present in the adjacent tube and the tube-to-membrane weld (Fig. 7). Cracking in the crowns of the tubes is also observed. In many instances, the cracking has been so severe that the outer layer of stainless steel had spalled in chunks, exposing the inner carbon steel core (Fig. 8).

In late 1996, through-thickness cracking of a coextruded smelt-run floor tube was reported in the bend leading to the floor header of a sloped-bottom boiler. Cracks in two adjacent coextruded tubes were almost through-thickness. Similar cracking was also found in the carbon steel tube nearest to the cracked coextruded smelt run tubes. The cracks apparently initiated at the toe of the membrane-tube fillet welds, on one side of the tubes only. The most severe cracks were underneath the refractory packing between the spout wall tubes and the floor tubes. The cause of cracking was attributed to fatigue, but a final report was not available for review at the time of release of this report.

Reports on boiler inspections and tube failures generally do not provide detailed information about boiler operation, and the available reports offer no clear consensus regarding the factors that may influence floor-tube cracking.

A number of companies in Europe and North America have made measurements of the temperature of floor tubes with surface or chordal thermocouples. In some cases, the smelt

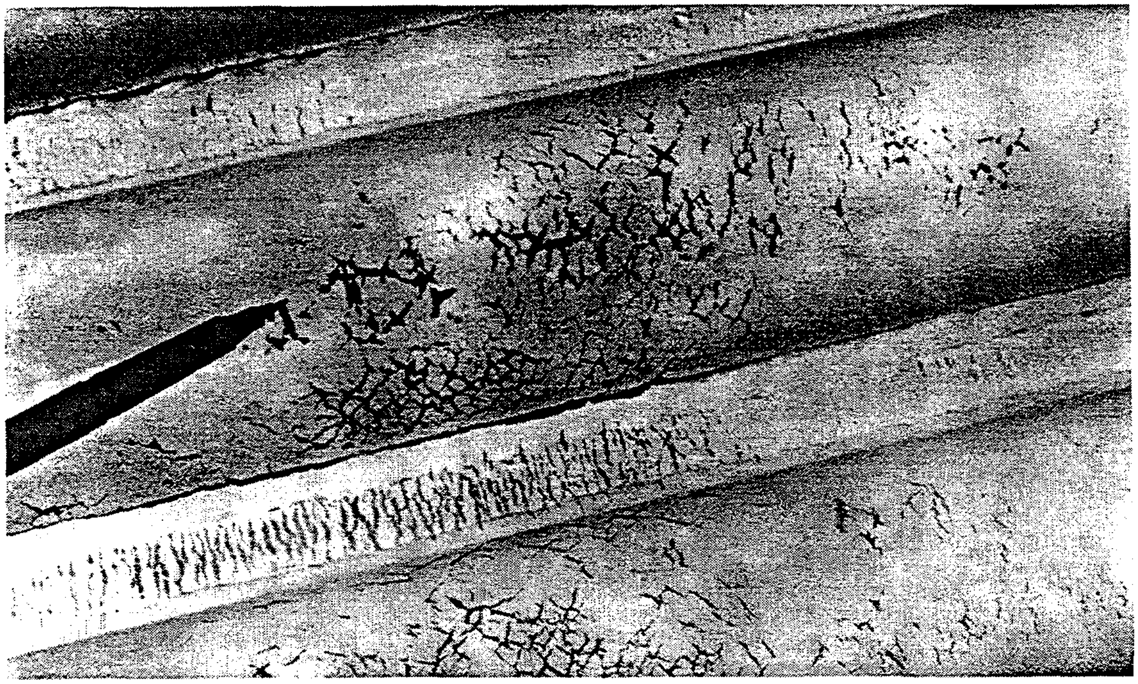


**Fig. 7. Floor-tube panel from a North American boiler showing cracking in coextruded tubes.** Cracks have been highlighted by dye-penetrant inspection. Cracks can be observed on the tube crown, at the tube-membrane interface, and in the membrane.

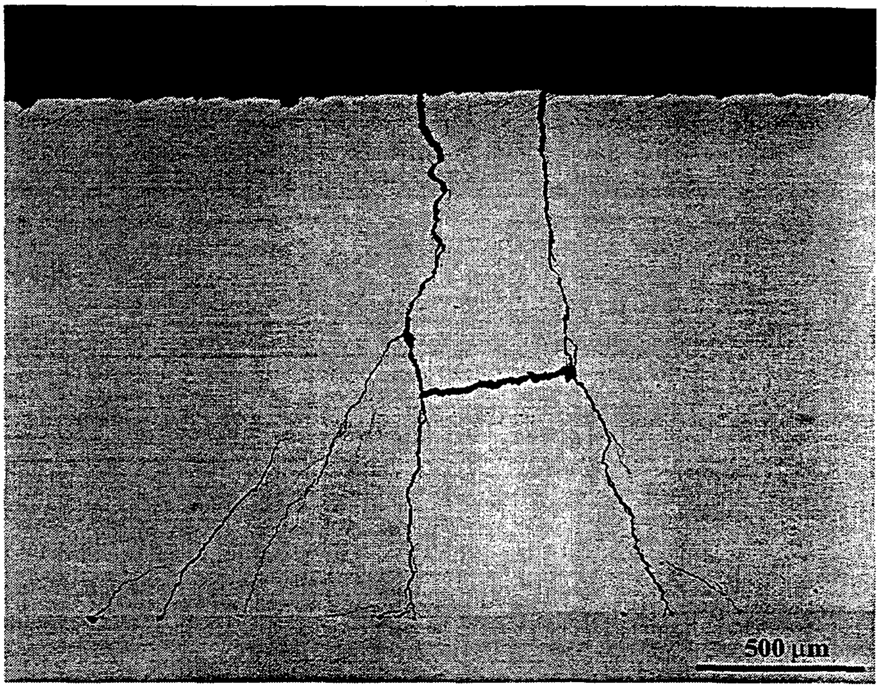


**Fig. 8. Severe cracking can lead to spalling of the outer stainless steel layer and can leave exposed carbon steel underneath.**

temperature above the floor has been measured by thermocouples inserted through the membrane. Interpreting the data from such installations is often difficult because of uncertainty about the correct performance of the thermocouples. However, some trends appear consistent between most sets of measurements.

On average, the surface temperature of the boiler floor tubes (whether measured directly or inferred by measurements of smelt temperature adjacent to the surface) appears to be within expected limits. In cases in which more than one thermocouple has been installed in a boiler floor, occasional periods of hot operation have been detected by one thermocouple but not the others in the floor. Differences of almost 100° C have been measured by thermocouples located only 20 cm (8 in.) apart. High-temperature excursions are invariably short lived (a few minutes to a few hours) and infrequent (once every 2–3 months) but have been reported to be as high as 600° C (1100° F) for a thermocouple inserted into a stud mounted on a membrane. More typically, temperature excursions up to 370 to 400° C (700 to 750° F) are reported for tube surface-mounted thermocouples. Short-term temperature excursions of 10-20° C occur more frequently than the extreme measurements reported.

Explanations for the high-temperature excursions tend to focus on momentary high heat flux to the floor caused by a thin bed, cracks in the frozen smelt layer, or nonuniform smelt contents.[27,28] The former explanation in particular has been the focus of attention as a result of a number of recent carbon steel floor tube failures caused by overheating.[28] In all cases, the formation of a highly corrosive liquid or molten phase on the outer surface of the tubes is postulated.

Although there has been considerable speculation about the presence of molten salts at the surface of the floor tubes, little actual data are available from which to draw conclusions. Ahlstrom, in particular, has tried hard to correlate changes in boiler operation and smelt chemistry with floor-tube cracking.[11] Attempts have been made to take a core sample from the smelt bed down to the surface of the floor.[29] Significant enrichment of potassium (from 7 to 12 wt %) and sulphur (from 26 to 48 wt %) from the top of the bed to the layer immediately above the floor was measured in one sample. Ahlstrom has theorized that the combined effect of higher loading of potassium, chlorine, and sulfur in the bed along with higher furnace temperatures promotes a lower smelt viscosity and thus a lower bed level at some points inside the boiler. At the same time, the formation of low melting eutectics is promoted by the presence of these elements. Research at the Abo Akademi has identified possible eutectic temperatures as low as 300°C when polysulphide is present in the smelt, but cannot yet explain how the oxygen-free, extremely reducing conditions necessary for polysulphide formation could exist at the tube surface.[30] The subject of polysulphide formation in the smelt and its possible contribution to coextruded tube cracking is the subject of a combined research program in Finland.[31]

Inspection, repair, and replacement guidelines for cracked floor tubes vary by country, boiler manufacturer, mill, number of affected tubes, severity of cracking, and the date at which cracking was first discovered in a given boiler. An inspection and repair guideline specifically addressing floor-tube cracking has been prepared by the Finnish Recovery Boiler Committee,[24] but no equivalent document exists in North America. General guidelines for inspection of recovery boilers, and one specifically for the inspection of coextruded tubes in recovery boilers, have been issued by the Technical Association of the Pulp and Paper Industry (TAPPI) and the National Association of Corrosion Engineers (NACE) respectively, but neither deals with cracking in floor tubes.[10,32]

The initial response to finding cracked floor tubes, both in Scandinavia and North America, was generally to repair or replace affected tubes as soon as was practical. To some extent, this response followed from the fact that proper inspection for floor-tube cracking was uncommon until recently, and often many years of operation had passed from the time of installation of the tubes to the time they were first inspected. Cracking in these cases was usually found unexpectedly, and often was quite severe. Many companies, particularly those in Scandinavia, have since adopted a more relaxed policy of leaving shallow cracks in place and watching from shutdown to shutdown until engineering judgment dictates either repair or replacement. Repair procedures adopted by different companies have included some or all of the following:

- inspect for cracking at regular intervals and document the location, but otherwise leave cracks in place, particularly if they are very shallow;
- remove shallow cracks with light grinding;
- remove more severe cracks by grinding no further than the stainless-carbon steel interface;
- remove severe cracks by grinding to the stainless-carbon steel interface and manually weld repairing with 309L or equivalent electrode;
- replace severely cracked portions of tubes with lengths of new 304L/SA-210 tube;
- replace a portion or all of the boiler floor with new 304L/SA-210 coextruded tubes;
- replace all 304L/SA-210 coextruded tubes in the floor with carbon steel tubes; and
- replace a portion or all of the boiler floor with alternative tube materials or compositions, including coextruded Alloy 825 or Sanicro 38™ and circumferentially weld-overlaid Alloy 625 tubes.

Accurate data on time to initiation and rates of crack propagation are not readily available and vary considerably from mill to mill and by location in the boiler. It is therefore difficult to judge the effectiveness of these various repair procedures.

The less-intrusive management procedures (inspection and/or light grinding) may, in some cases, serve adequately over the short term, but assumptions are made about the crack path and crack propagation rates that may not be substantiated as more information about cracking in coextruded tubes is acquired. In particular, it is commonly assumed that floor-tube cracks will turn at the stainless-carbon steel interface and will not propagate into the carbon steel. Although this is true for many cracks, in a small number of cases cracking into the carbon steel has been observed.

Short-term experience in both Scandinavia and North America is that recracking only occurs on a small percentage of stainless steel pad-weld repairs. Replacement of cracked 304L/SA-210 coextruded tubes in kind is generally ineffective, and cracking of new tubes has occurred in as short an interval as 4 months. Based on laboratory fatigue testing and some service experience, Alloy 825 appears more resistant to in-service cracking than 304L, but recent reports of cracks in 825/SA-210 spout-opening tubes suggest that it is not a complete solution to the problem.[33]

## SMELT-SPOUT OPENINGS

There are numerous records of cracking of 304L/SA-210 coextruded tubes at spout openings dating from 1983 to the present.[5,9] In most cases, the lifetime was less than 4 years and frequently it was less than a year. Some short-lived openings have had to be changed after 4 months, and in at least one case, cracks were detected within 2 months. Boiler design plays a clear role in the location and severity of cracking in tubes that form spout openings. Boilers with spouts that butt up against the outside of the boiler wall are almost exclusively at risk of developing cracks in the tubes that form the spout. Spout-opening tubes in these boilers are exposed to thermal fluctuations caused by variations in the smelt flow through the spout. They are also subject to damage from rodding, a common procedure used to clear spouts of solidified smelt. Star-burst cracks have often been found to initiate at sites where rodding damage has occurred (Fig. 9). Cracking of spout-opening tubes has been reported for at least one boiler in which an insertable spout was used. The general lack of cracking at spout-opening tubes with insertable spouts may be because the tubes are protected from direct contact with the out-flowing smelt. Cracking at spout-openings is most often attributed to thermal fatigue, although failure reports sometimes suggest stress corrosion cracking as a failure mechanism.

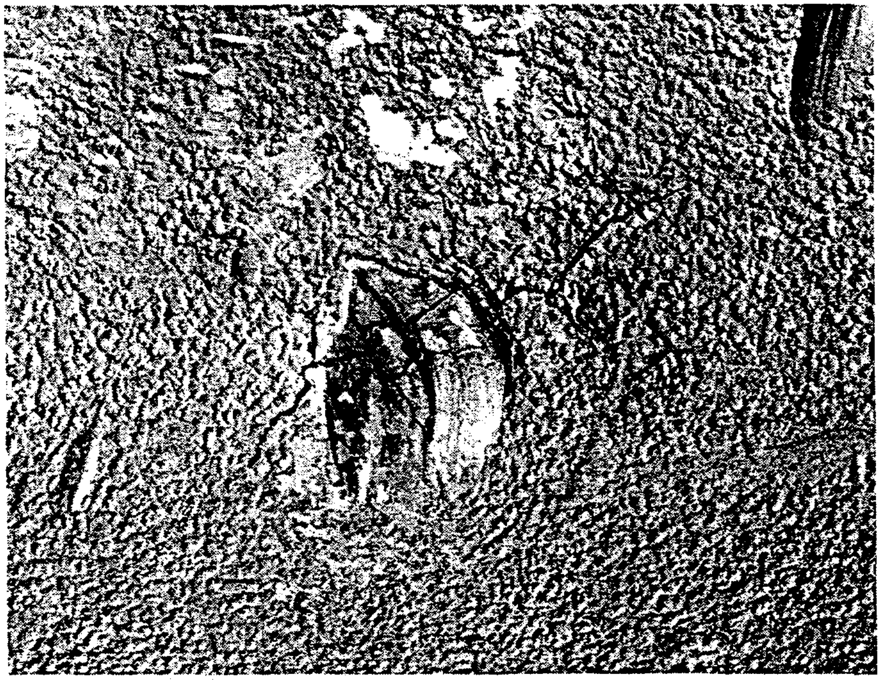


**Fig. 9. "Star-burst" crack on surface of spout opening tube damaged by rodding.**

When cracking of spout-opening tubes occurs in a boiler, it is not always the case that all spout openings are affected in the same manner. Frequently one or two spout openings exhibit more damage than the others; in some cases complete loss of cladding has been observed, while neighboring openings were barely affected. In other cases, all the spout openings have had to be replaced. Cracking has occurred in the upper, lower, and central portions of spout openings. In many cases, cracking is associated with the presence of weld metal; for example at membranes, seal bars, crotch plates or stud plates, rodding protection welds, or stack studs. Cracking of tube surfaces has also occurred in areas that were not adjacent to welds. This usually happens toward the center of the opening on the inside or fireside surface of the bent tube.

Cracking has also been reported in 304L/SA-210 coextruded wall tubes situated beside the tubes that form the actual spout opening. On average, 4 to 5 tubes on either side of the opening are typically affected, but in some boilers the number of affected tubes has been as high as 13 tubes on either side of the opening.[26]

Cracking associated with the use of 304L/SA-210 coextruded tubes has prompted some boiler owners to experiment with nickel-base weld overlays on top of carbon steel smelt-outlet tubes as an alternative approach. Problems have been reported with cracking in the vicinity of the welds. An alternative approach has been to use coextruded tubes with an outer layer of Alloy 825. One user suggested that Alloy 825 conferred improved resistance to surface cracking but was nevertheless susceptible to cracking at the crotch welds. In another case, extensive network cracking was found in the Alloy 825 layer after 18 months in service. More boilers have now been reported to have cracking in spout-opening tubes made from Alloy 825. The time from installation to the first observation of cracking has ranged up to 6 years.

Detailed investigations of crack surfaces and corrosion products are generally lacking from available reports. A series of investigations on cracks in spout-opening tubes from three different boilers found a number of common elements.[34] Corrosion of the 304L layer was often observed to coincide with the location of cracks. Qualitative Energy Dispersive X-Ray (EDX) analysis identified a chromium-depleted, iron oxide corrosion product as predominant in some locations on the tube surfaces, while other areas were covered by a chromium- and nickel-rich sulphur-containing corrosion product. A chromium-depleted region was often found between the corrosion product wedged into the crack opening and the surrounding stainless steel substrate. In one case, where the crack tip intersected the carbon steel-stainless steel interface of a wet-polished specimen, the corrosion product on the stainless steel side was identified by EDX as being oxides of iron, nickel, and chromium while iron sulfide was identified as a corrosion product on carbon steel. Sulphur was not present in the corrosion product formed on the stainless steel.

Substantial cracking and corrosion have also been reported in one boiler on the cold side of 1-year-old coextruded tubes in locations normally protected by the seal box around the smelt-spout opening. Cracks were confined to areas that had also suffered from general corrosion of the stainless steel, and in no case were they observed further away from a weld than about 2 cm (0.79 in.). As is common for cracks in other parts of the boiler, the cracks initially propagated in a direction perpendicular to the surface but quickly branched and turned to follow the stainless steel-carbon steel interface. Cracking was transgranular. Leakage of weak wash into the seal box and subsequent evaporation to concentrated caustic was blamed for both the rapid thinning and cracking of the 304L outer layer of the affected tubes. The circumstances under which these cracks formed are unusual; it is significant that severe cracking occurred on these tubes in the absence of the thermal fluctuations suspected of playing a significant role in the cracking on the hot side of coextruded boiler tubes.

## AIR PORTS

The preponderance of cracking at air-port openings is specific to certain port designs, although not restricted to a single boiler manufacturer.[7,9,23] In most cases, cracked tubes were detected after less than 5 years of service. In one boiler, cracking was noted after only 9 months. Cracking is sometimes restricted to a small number of air ports, but on other occasions a large number of tubes have been affected at the same time. For example, in one boiler, 21 cracked tubes were found during a single inspection in 1983. In another boiler, inspected in 1993, dye penetrant testing revealed 51 indications. There were times when the cracking was reported to be worse on one particular wall. In another case, the affected air ports were located in the corners of the boiler.

Cracking at air ports usually, but not always, originates in the vicinity of weldments. Sometimes it is the tube-to-membrane weld, but cracks also develop at welds to stud plates or crotch plates, especially near the toe of a weld. Cracks have formed on bare tube surfaces at the centers of the openings, distinct from those at nearby weldments.

One reported incident of a water leak from a cracked coextruded tube took place at a primary air port opening in 1983. A failure analysis suggested that overheating had played a role, but the cause was thought to be predominantly thermal fatigue. A second incident of a tube leak took place in another boiler in 1994. The site of the failure was close to the primary windbox attachment welds, above the smelt spouts on the rear side (cold side). The cracks were longitudinal, 2.5–5 cm (1–2 in.) in length, and penetrated straight across the interface between the stainless steel and the carbon steel.

Failure analyses have attributed most cracking in air ports to thermal fatigue. Fluctuations in air flow were thought to be a factor, as was the residual stress associated with bending and welding the tubes. Very large temperature fluctuations have been measured on the surface of tubes forming air-port openings.[35] It has been reported that some of the boilers with cracked air-port-opening tubes had experienced excessively high bed levels and repeated break-through of smelt into the port opening.

# METALLOGRAPHY OF CRACKED TUBES

Regardless of whether cracking is observed in air-port, spout-opening, or floor tubes, a number of common features link many of the cracks. Cracking of coextruded tubes is most easily detected by penetrant testing (PT) on a carefully prepared surface. A "composite" example of the types of crack patterns generally observed on the surface of tubes is shown schematically in Fig. 10. Cracking may be located in or adjacent to the membrane, or may be spread across the tube surface. Cracks may be oriented either transversely or longitudinally to the tube. Cracking at the crown of the tube is less common at air-port or spout openings but has been found on numerous occasions in floor tubes.

In the early stages of degradation, short, unconnected cracks may be detected. More severe damage is characterized by longer, branched cracks or cracks that appear to meet and cross over one another. Sometimes cracks radiate in several directions from a central point, often described as "star-burst" cracking. A more severe stage of degradation shows itself as an interconnected network of cracks. This has been described as "craze cracking," "spider's-web cracking," "snake-skin cracking," or "crocodile-skin cracking." In extreme cases, chunks of stainless steel may completely lose contact with the tube when this form of cracking occurs.

More detailed information about crack morphologies can be gained by examining polished sections of cracked tubes with a metallurgical microscope. Examples of the types of cracks that may exist are displayed schematically in Fig. 10, where each sketch represents a two-dimensional section of a three-dimensional crack.

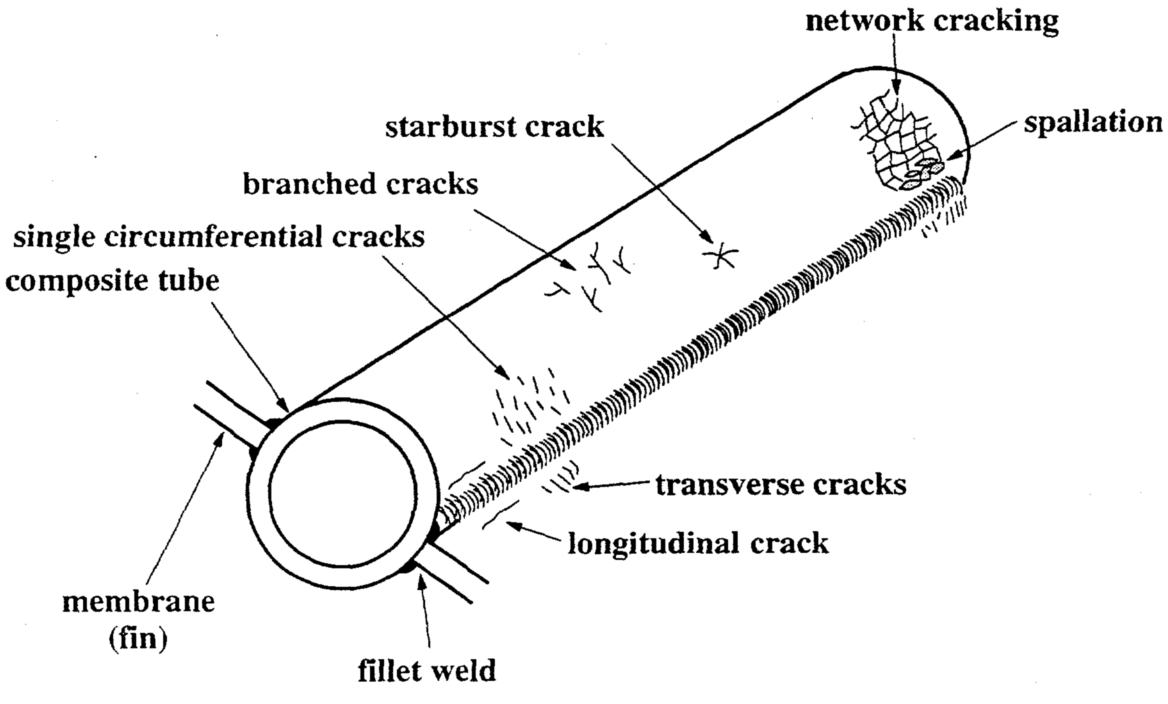


Fig. 10. A "composite" drawing showing the manifestations of the various forms of cracking found on the surface of coextruded tubes.

With fortuitous timing of an inspection, the cracks may be detected before they have penetrated through the outer layer of stainless steel cladding. The cracks are almost always initiated at the outer stainless steel surface and generally propagate perpendicularly to the surface. Sometimes single cracks are observed; in other cases, multiple cracks close together or craze cracking is found. They are mostly wedge-shaped or tapered with sharp, rather than blunt, tips. They may contain corrosion products or deposits from the boiler environment. Short cracks are usually straight and unbranched (Fig. 11*a*), but after they have penetrated some distance into the stainless steel layer, there may be signs of branching (Fig. 11*b*). The branches are generally finer than the original crack. They frequently show signs of further branching and may exhibit a multibranched morphology or "river delta" pattern (Fig. 11*c*). These cracks tend to be transgranular, rather than intergranular, but sometimes follow certain crystallographic features with frequent changes of direction giving rise to stepped crack morphologies (Fig. 11*d*).

Type 304L stainless steel is generally considered to have good corrosion resistance in a recovery boiler atmosphere. However, cases have been reviewed in which crack formation in coextruded tubes was accompanied by corrosion of the outer layer. In some cases, corrosion of the outer stainless steel layer was significant, but in other cases, it was manifested by a slight roughening and staining of the surface. There have been instances in which cracks appear to have been widened by the action of the corrosive environment (Fig. 11*e*), perhaps becoming filled with corrosion product. In contrast, highly branched cracking can sometimes initiate without developing from a wider initial crack (Fig. 11*f*).

In many cases, the cracks have already reached the interface between the stainless steel and the carbon steel before they are detected, and in many cases crack progression has been arrested at the interface. However, this is not necessarily the end of the crack path, and a series of possible mechanisms exist by which degradation of the coextruded tube may continue.

The first method, and perhaps most common, is that the path of the crack turns and proceeds along the interface between the stainless steel and the carbon steel (Fig. 11*g*). Metallography has shown cracks that proceed along the interface for distances of 2 cm (0.79 in.). In extreme cases, the loss of the bond associated with this mode of crack propagation leads to delamination and spalling of chunks of the outer stainless steel layer, exposing the carbon steel core to the boiler atmosphere.

Several examples show how corrosion of the carbon steel can occur at the point where the crack meets the interface. The cracks allow access of corrosive species that attack the carbon steel at a faster rate than they attack the stainless steel. Damage may show itself as small spots of corrosion at the crack tips (Fig. 11*h*), which eventually grow into pits of considerable size (Fig. 11*i*). The region of active corrosion can spread along the interface (Fig. 11*j*), or can produce broad corrosion pits in the carbon steel (Fig. 11*k*). There are also cases in which intergranular attack of the carbon steel has been noticed in the vicinity of the crack tip (Fig. 11*l*).

The most alarming micrographs of cracks in coextruded tubes are those that show cracks that penetrate from the outer layer of stainless steel, through the interface, into the carbon steel tube. Several such cracks have been found, primarily in air ports and smelt-spout openings. In floor tubes, the information surveyed to date has revealed a few cases of crack penetration into the carbon steel. In most cases the penetration was slight, perhaps a few thousandths of an inch into the decarburized zone of the carbon steel. However, there is at least one report of a crack progressing through 50 to 60% of the carbon steel core, although without confirming metallography. More recently, a through-thickness crack initiating at the tube-membrane weld has been found.

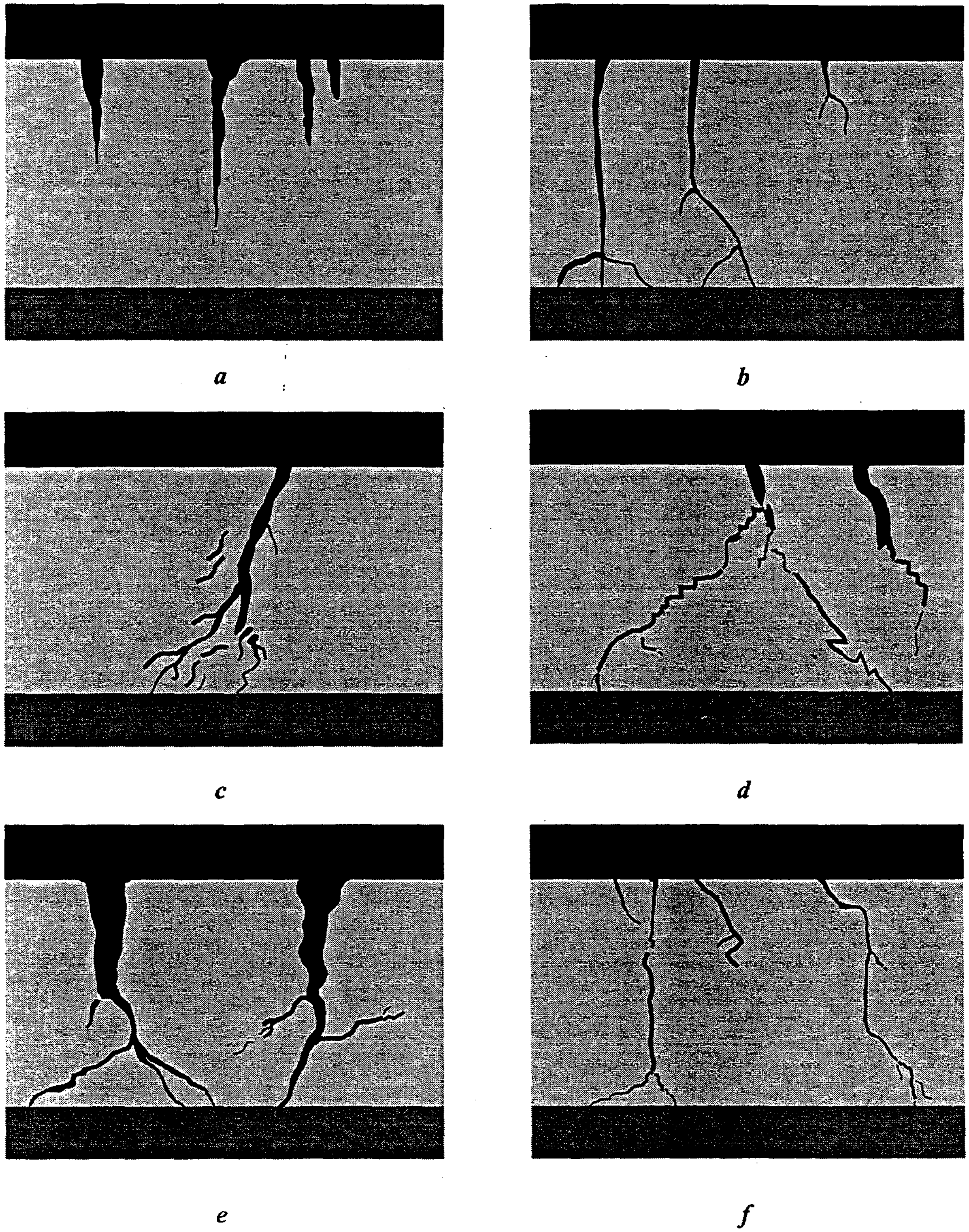
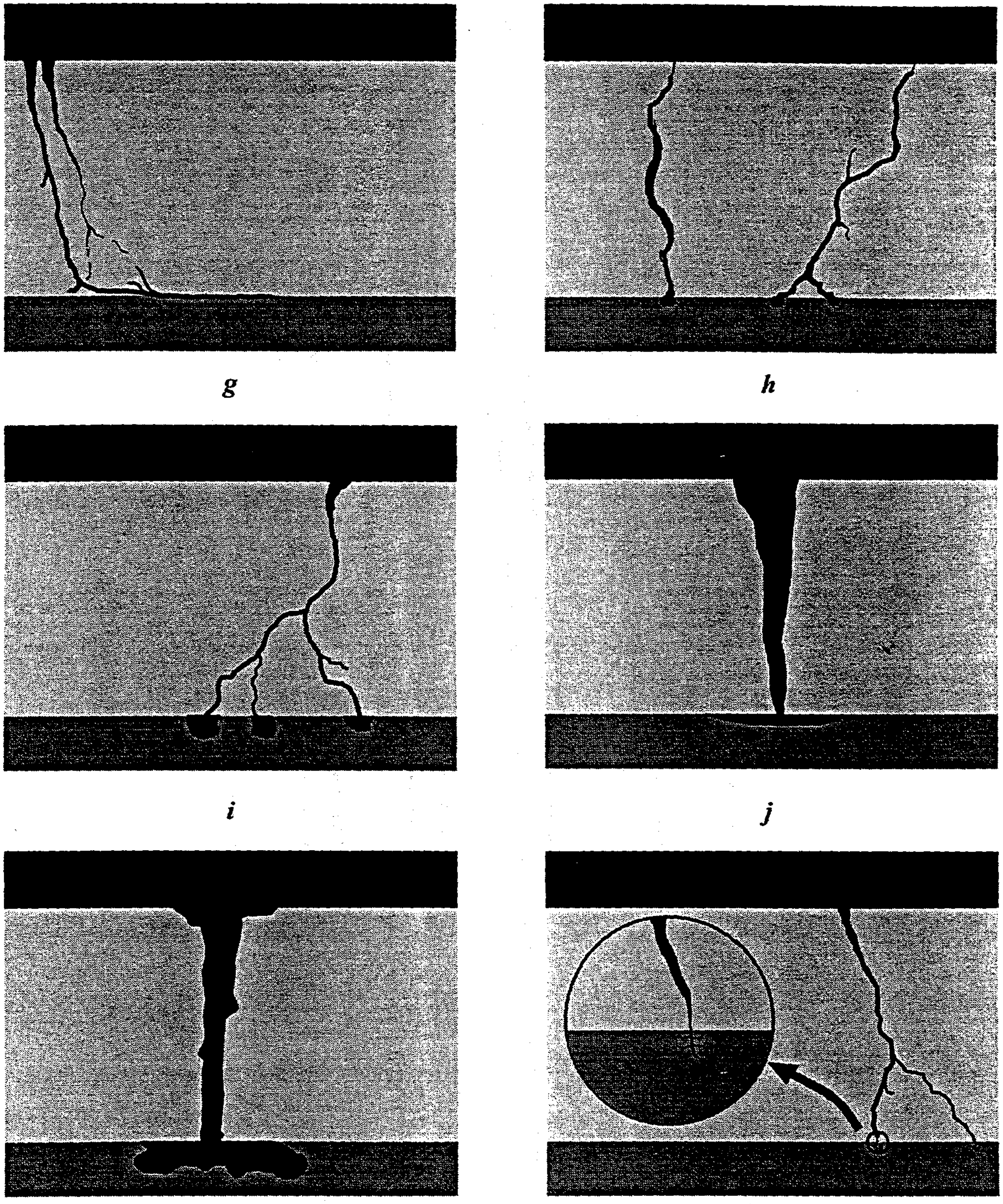


Fig. 11. Schematic drawing showing the various types of crack morphology found in coextruded tubes as cracks propagate to the interface between the carbon steel and the stainless steel.



g

h

i

j

k

l

**Fig. 11. (continued)**

The evidence reviewed suggests that the cracks that cross the interface are chiefly the straight, wide, unbranched, or carrot-shaped cracks (Fig 12*a*); however, network cracking from the crown of a spout-opening tube that penetrated into the carbon steel have been reported. Although sometimes the crack may pass directly through the interface, there have also been cases in which corrosion and widening of the crack take place at the point where it enters the carbon steel (Figs. 12*b* and 12*c*).

Up to this point, the cracks described in the stainless steel layer have been transgranular; however, there have been a few reports of intergranular cracking (Fig. 13*a*). These are unusual and can generally be attributed to sensitization of the stainless steel. In the early 1980s some tubes were manufactured from stainless steel with a high carbon content (i.e., AISI 304 instead of AISI 304L). These were susceptible to sensitization during heat treatment or during service if overheated. There is a recorded incident of an intergranular crack penetrating from sensitized stainless steel through the interface into the carbon steel core (Fig 13*b*). However, no further incidents of intergranular cracking have occurred in recent years.

As a final note, another type of crack morphology has been observed in coextruded tubes. It is not at all common, but a few cases were reported in the early 1980s. Subsurface cracks existed in the carburized zone of the stainless steel layer, adjacent to the interface with the carbon steel core. These were fine cracks, typically up to 0.05 mm (0.002 in.) in length, oriented perpendicular to the tube axis (Fig 13*c*). It was suggested that these cracks were the result of dense carbide precipitation and thermal fatigue. The phenomenon was described as "clad-interface cracking."

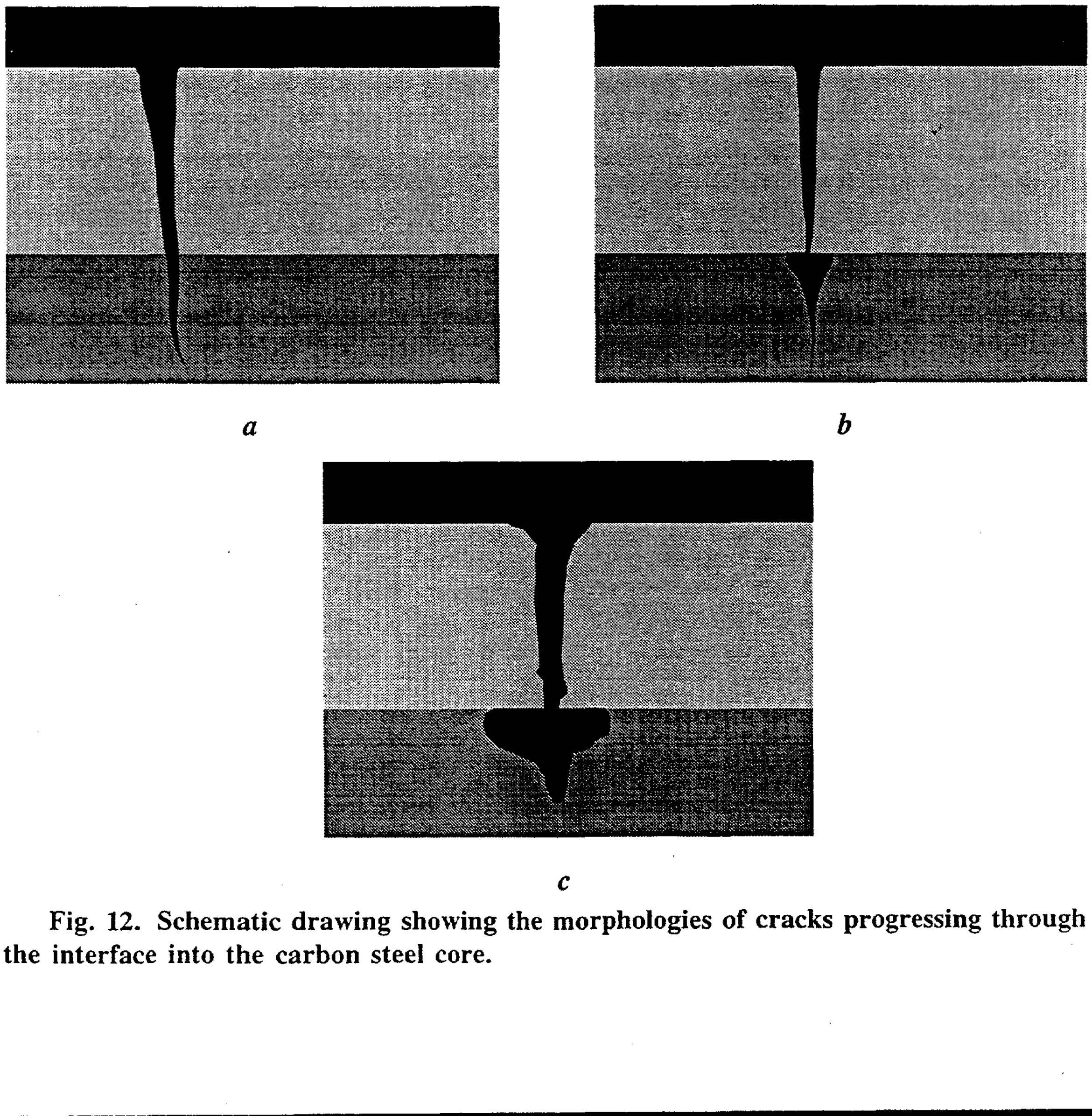
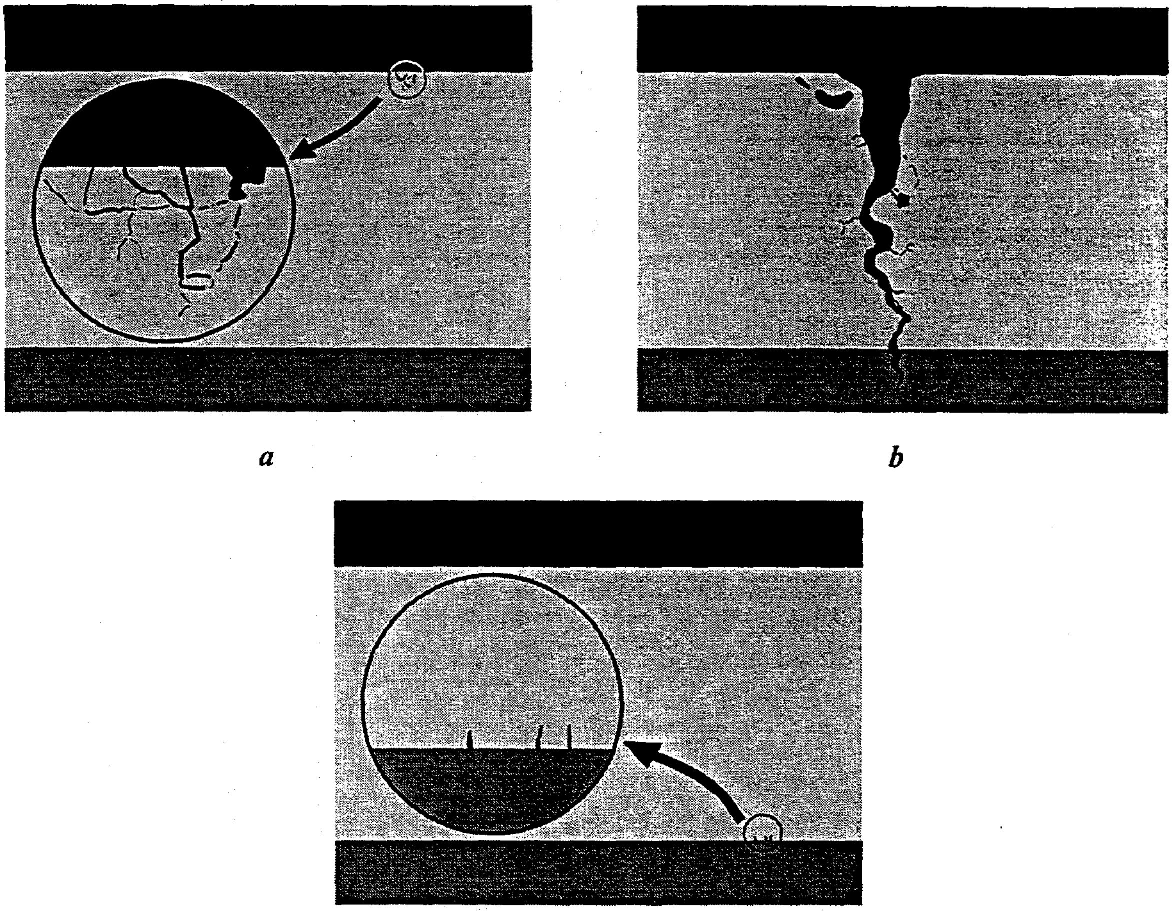


**Fig. 12. Schematic drawing showing the morphologies of cracks progressing through the interface into the carbon steel core.**



*a* *b*

*c*

**Fig. 13. Intergranular cracking and interface cracking in coextruded tubes.**

## EXPERIENCE WITH COEXTRUDED TUBES IN OTHER INDUSTRIES

In 1984, kraft recovery boilers were reported to represent the second largest use of coextruded tubes worldwide, with an estimated 250,000 m (~820,000 ft) installed.[36] The largest use for coextruded tubing in the world at the time was for superheater and furnace wall tubes in coal-fired utility boilers.[37–40] It was estimated that more than 330,000 m (~1.1 million ft) had been installed for this application, largely in English boilers operated by the Central Electricity Generating Board (CEGB). Together these two industry uses accounted for more than 90% of the known installations at the time. As of 1995, Sandvik claimed more than 1.5 million m (5 million ft) of coextruded tube in commercial service; much of the additional length was likely supplied to the pulp and paper industry.[16] Compared with kraft recovery boiler service, in which most of the coextruded tubes used have been 304L/SA-210 carbon steel, most of the coextruded tubes installed in utility boilers have been 310SS or a modified 310SS over an Esshete 1250 core for superheater applications and 310SS over carbon steel for water walls. Some 50/50 nickel chromium over Alloy 800H or Esshite 1250 coextruded tubes have been put into service as well.

CEGB has applied considerable effort to develop and qualify coextruded tubes for service in its boilers, including the development of standards for welding and bending the tubes.[41] Because of higher operating temperatures, the most common problem experienced by the CEGB with coextruded tubes has been to find sufficiently corrosion-resistant materials for the outer layer of the tubes. Furnace wall corrosion rates of 0.17 mm/year have been measured on the 310SS outer layer, compared with 0.5 mm/year for adjacent carbon steel tubes. Superheater corrosion rates have been measured as high as 1.7 mm/year on 310SS but seem more typically to be about 0.4 to 0.5 mm/year for 310SS. Because of the high corrosion rates on the coextruded tubes in the CEGB boilers, the tubes have a much thicker outer layer than is typical for recovery boiler applications; about 3 mm of 310SS over 3 mm of carbon steel or Esshete 1250. In pulp and paper tubes, the outer layer of 304L is about 1.6 mm thick over a 4.2-mm-thick carbon steel layer. The outside diameters of the wall and superheater tubes in the coal-fired utility boilers span the range used by the pulp and paper industry (33–76 mm or 1.3–3 in.).

The pulp and paper industry is the only one to report significant in-service cracking of coextruded tubes. With more than 65,000 h of operation in some boilers (as of ~1989), the only reported incidents of in-service thermal fatigue in CEGB boilers occurred when bond defects greater than 5 mm in circumferential length were present in the tubes, and heat fluxes on the affected tubes exceeded 350 kW/m$^2$.[36] No details of the nature of the cracking were given, but the problem was apparently solved early on by instituting quality control and inspection procedures that would now be considered standard for tube producers (no defects larger than 20 mm$^2$ allowed and 100% ultrasonic inspection of the tubes for bond defects).

Originally, there was concern at the CEGB that carbon migration into the outer stainless layer would limit the life of the tubes; this turned out not to be a concern. At the operating temperatures of the tubes, a slow migration of carbon from the carbon steel to the stainless steel appeared to occur (revealed by hardness traverses across the tube cross section) up to about 25,000 h. No change in the position or size of the high-hardness zone at the interface occurred during another 40,000 h of operation. These data were used to justify an early decision not to require a nickel interlayer to prevent carbon migration across the interface.[42]

Other issues addressed by the CEGB included modifying the standard composition of 310SS to improve corrosion resistance in superheater service (silicon was increased from 0.75 to 1.5 wt %, a minimum chromium content of 25 wt % was specified, and niobium was set to a minimum of eight times the carbon content). The modified 310SS was also reported to have provided better corrosion resistance for furnace tubes. A number of problems were encountered when qualifying new types of coextruded tube for production, but all were reported to have been solved.[37]. Contamination of the surface with carbon led to sensitization during extrusion and subsequent intergranular surface cracking during hot bending of superheater tubes. Alloy 671, the 50/50 nickel chromium alloy, was found to be notch-sensitive and cracked during cold bending. A coarse-ground surface finish on the tubes was identified as the cause of the problem.

Other literature deals mostly with the development of coextruded tubes and not with actual applications.[20,40,43,44] Materials evaluated for use as coextruded tubing include Fe-30Cr alloys and Sanicro 28 (28Cr-32Ni-3.5Mo) over 1¼Cr-½Mo steel;[40] 310S over 17-14CuMo,[44] and 310S or 35Cr-45Ni over 17-14CuMo, 347H, Tempaloy A-1 and Alloy 800H.[45] The Japanese programs also investigated the tensile properties and forming characteristics of a chromized coating over 17-14CuMo.

Surprisingly, thermal fatigue of the coextruded tubes in service is an issue that appears to have been addressed by only one of the above developmental programs. Resistance to thermal cycling was part of the evaluation of Fecralloy (FeCrAlY) coextruded tubes in a British program, but the projected service and test conditions were far from what might be expected for kraft recovery boiler service.[43,46,47] Triplex coextruded tubes (with both inner and outer layers of Fecralloy) were exposed to rapid thermal cycles between 930°C and about 40°C (1700 to 100°F). Bond defects and interfacial cracking were introduced into the cladding during the thermal cycling, rather than surface cracking.

The Japanese programs were aimed at evaluating materials for advanced cycle power applications, and consequently, tubes were considerably thicker and smaller in diameter than those used in recovery boiler applications. Typical dimensions were 48.6 mm OD with 13.7 mm thick substrate plus 1.5 mm corrosion-resistant alloy surface layer.[48] It is of interest that one group of researchers found that cracking from the surface through to the substrate occurred on chromized tubes when subjected to certain strain rates during hot forming at temperatures between 650 and 750°C (1200 and 1380°F).[44]

# PROPERTIES OF COEXTRUDED TUBES

## PHYSICAL PROPERTIES OF ALLOYS

A thorough review of the material properties and thermal/mechanical fatigue behavior of alloys used to produce coextruded tube panels in kraft recovery boilers has been prepared for this project.[48] A brief summary of pertinent information from the report is included in this review. Chemical composition and a summary of mechanical properties of these alloys can be found in Tables 1 and 2, respectively.

Note that physical and mechanical properties of as-deposited weld metal are generally not well characterized and, when available, exhibit a great amount of scatter caused by variations in filler metal composition, base metal composition, degree of restraint and welding process and parameters. Some properties specific to Sanicro 38™ were found, but this alloy is similar enough in composition to Alloy 825 that its mechanical and physical behavior can be considered to be the same.

A key consideration in the fabrication and use of coextruded tubes is the effect on surface residual stresses of the mismatch in the coefficient of thermal expansion between the alloys used for the inner and outer layers. Of the alloys currently considered for use as the outer corrosion-resistant layer of coextruded tubes for kraft recovery service, 304L has the greatest mismatch with the underlying carbon steel (Table 3). Within the expected temperature range of the tubes in recovery boiler service, thermal expansion of Alloy 625 is almost identical to that of carbon steel while that of Alloy 825 lies somewhere between 304L and Alloy 625. However, other properties, such as yield strength and microstructure also influence the distribution of residual stress through the thickness of a coextruded tube. The combined influence of these parameters on the residual stress distribution in coextruded tubes is the subject of both modeling and experimental work in other portions of this program.

A considerable volume of data on fatigue is available for design purposes for the wrought alloys, but little or no data exist for the as-deposited weld metals of interest to this program. Based on American Society of Mechanical Engineers (ASME) code case N-47 fatigue design curves, the performance of 304L and Alloy 825 are nearly identical. Comparison of fatigue data for 304L and Sanicro 38™ at 600° C (1100° F) shows a slight advantage for the Sanicro 38™.[16] Alloy 625 is considerably more resistant to fatigue and can tolerate either a higher total strain range for a given number of cycles or longer operation at the same total strain range than would be allowable for either 304L or Alloy 825.

The ASME design curves appear conservative when compared with fatigue data generated for these alloys. However, cyclic loading of coextruded tubes in service is much different from the simple, single-axis experiments used to produce the fatigue data. The fatigue behavior of carbon steel and 304L under multiaxial loading at ambient and higher temperatures has received extensive investigation, but data for the other alloys are lacking. A number of models to predict fatigue damage as a consequence of multiaxial loading have been proposed, but no one model fits all materials.[49,50]

For 304 stainless steel, it has been found that the equivalent strain approach outlined in ASME Sect. III Code Case 47-N produces conservative results when compared with design curves, at least for proportional loadings. However, variations in crack path have been observed as a function of shear strain amplitude in torsional fatigue, and the amount of deformation martensite formed in 304 has been observed to be a function of loading conditions. In particular, nonproportional loading produced more martensite for the same accumulated plastic strain as uniaxial loading. Nonetheless, in the absence of better information, the rules for multiaxial fatigue incorporated into ASME Sect. VIII, Div. 2 and Sect. III Code Case N-47 provide the logical first approach to the evaluation of fatigue damage in coextruded tube materials.

Table 2. Chemical composition of alloys used in the construction of composite tube panels

| Element | Alloy | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | SA-210 Gr. A-1 | 304L | 825 | Sanicro 38™ | 625 | ER312 | ER309L | ERNiFeCr-1 | ERNiCrMo-3 |
| C | 0.27 max | 0.035 max | 0.05 max | 0.025 max | 0.1 max | 0.15 max | 0.03 max | 0.05 max | 0.10 max |
| Mn | 0.93 max | 2.00 max | 1.0 max | 0.80 max | 0.50 max | 1.0–2.5 | 1.0–2.5 | 1.0 max | 0.50 max |
| P | 0.035 max | 0.040 max | | | 0.015 max | 0.03 max | 0.03 max | 0.03 max | 0.02 max |
| S | 0.035 max | 0.030 max | 0.03 max | | 0.015 max | 0.03 max | 0.03 max | 0.03 max | 0.015 max |
| Si | 0.10 min. | 0.75 max | 0.5 max | 0.5 max | 0.50 max | 0.30–0.65 | 0.30–0.65 | 0.5 max | 0.50 max |
| Cr | | 18.0–20.0 | 19.5–23.5 | 20 typ | 20.0–23.0 | 28.0–32.0 | 23.0–25.0 | 19.5–23.5 | 20.0–23.0 |
| Ni | | 8.00–13.0 | 38.0–46.0 | 38 typ | 58.0 min | 8.0–10.5 | 12.0–14.0 | 38.0–46.0 | 58.0 min |
| Mo | | | 2.5–3.5 | 2.5 typ | 8.0–10.0 | 0.75 max | 0.75 max | 2.5–3.5 | 8.0–10.0 |
| Cu | | | 1.5–3.0 | 1.7 typ | | 0.75 max | 0.75 max | 1.5–3.0 | 0.5 max |
| Fe | bal | bal | 22.0 min | bal | 5.0 max | bal | bal | 22.0 min | 5.0 max |
| Ta + Cb | | | | | 3.15–4.15 | | | | 3.15–4.15 |
| Al | | | 0.2 max | | 0.40 max | | | 0.2 max | 0.40 max |
| Ti | | | 0.6–1.2 | 1.0 max | 0.40 max | | | 0.6–1.2 | 0.40 max |

Table 3. Typical mechanical properties of alloys used in the construction of composite tube panels

| Property | Alloy | | | | | | |
|---|---|---|---|---|---|---|---|
| | Temp °C (°F) | SA-210 Gr. A-1 | 304L | 825 | Sanicro 38™ | 625 | ER309L |
| Yield Strength (MPa) | 21 (70) | 290 | 234 | 301 | as for 825 | 510 | 290 |
| | 316 (600) | 242 | 145 | 232 | as for 825 | 448 | 205 |
| | 427 (800) | 217 | 136 | 228 | as for 825 | 427 | 185 |
| Ultimate Strength (MPa) | 21 (70) | 538 | 552 | 693 | as for 825 | 965 | 620 |
| | 316 (600) | 564 | 408 | 632 | as for 825 | 931 | 520 |
| | 427 (800) | 422 | 397 | 610 | as for 825 | 896 | 495 |
| Young's Modulus (GPa) | 21 (70) | 203 | 195 | 195 | as for 825 | 208 | 200 |
| | 316 (600) | 184 | 174 | 180 | as for 825 | 192 | - |
| | 427 (800) | 167 | 166 | 172 | as for 825 | 186 | - |
| Mean Coefficient of Thermal Expansion ($10^{-6}$/°C) | 316 (600) | 13.4 | 17.2 | 15.3 | 14.9 | 13.3 | 16.6 |
| | 427 (800) | 14 | 17.7 | 15.7 | 15.1 | 13.7 | 16.7 |

Data for uniaxial and multiaxial fatigue previously outlined are based on cycles to failure. A fault-tolerant approach based on prediction of crack growth rates may also be employed. However, evaluation and prediction of crack growth rates requires a number of conditions to be met before subcritical crack-growth fracture-mechanics principles can be applied. These conditions may not be satisfied for coextruded tubes, where the cladding is relatively thin, cracks are highly branched, and the cracks change direction near the cladding-base metal interface. A thorough knowledge of the stress state at the crack tip is required for practical application of these techniques.

## FATIGUE AND SCC OF COEXTRUDED TUBES

Little specific data are available on fatigue, corrosion fatigue, or SCC of coextruded tubes. As part of the development and marketing process for coextruded tubes in the early 1970s, Sandvik provided thermal fatigue data on 304/SA-210 coextruded tubes.[51] A theoretical stress analysis of the tubes suggested that the outer austenitic layer would contain considerable tensile stresses in the tangential and axial directions. Full-size 304/carbon steel tube specimens about 100 mm long were subjected to repeated cycles of induction heating and air cooling. The temperature of the tube was cycled between 200 and 500°C (392 to 932°F) for 10,000 cycles. Comparison of the stress analysis with ASME Boiler and Pressure Vessel Code data suggested that the tubes should not fatigue under these conditions; this was confirmed by tests on a defect-free tube.

Two other tubes were also tested; one with an internal bond defect along the entire length of the sample, and the other with a 0.6-mm-deep notch cut transversely into the tube. A fatigue crack initiated at the surface defect, but not at the internal bond defect. Subsequent testing with notches of different depths showed that fatigue-crack initiation and growth only occurred when the depth of the surface notch exceeded 0.4 mm.

More recently, thermal fatigue of coextruded bar stock was studied to identify more resistant materials for the outer layer of coextruded tubes.[16] Each bar was subjected to a maximum of 1000 heating and cooling cycles spanning a temperature range from less than 100°C (212°F) to between 400 and 1000°C (752 and 1832°F). In these experiments, the hot bars were water-quenched, rather than air-cooled. Evaluation was based on the highest temperature reached by a material without initiation of fatigue cracks after 1000 cycles. Sanicro 38™ withstood 600°C (1100°F) without failure, while 304L, 310SS, and 2304 all failed at temperatures greater than 400°C (752°F).

Fatigue crack initiation on Alloy 825 coextruded tubes has also been studied.[52] Thermo-mechanical fatigue tests were conducted over a temperature range of 300 to 600°C (572 to 1110°F). Failure in these tests was caused by crack initiation at the inner surface of the tube (in the carbon steel) and outward propagation, so that no comparisons to the fatigue resistance of 304L coextruded tubes could be made.

Environments that cause SCC of most materials comprising both the outer and inner layers of a coextruded tubes in recovery boiler service (i.e., carbon steel, 304L, Alloy 825, etc.) are well known. Austenitic stainless steels are very susceptible to SCC in acidic, chloride-containing environments at temperatures exceeding 60° C (140° F) and in strongly alkaline solutions at temperatures over about 100° C (212° F). Nickel-base alloys are generally not susceptible to SCC in acidic chloride media but, although much more resistant than austenitic stainless steels, can also experience SCC in hot, concentrated caustic environments. Carbon steels are susceptible to SCC in alkaline environments but not in acidic environments.

Little data could be found on the resistance of coextruded tubes to SCC. In one study, ring specimens cut from coextruded tubes with a 304 outer layer were evaluated for resistance to SCC in a 45% $MgCl_2$ solution at 150° C (302° F).[53] In tests that lasted up to 240 h, cracks readily propagated through the outer stainless steel layer, but in all cases the cracks stopped when they reached the stainless-carbon steel interface in the ring specimens. The original intent of the research was apparently to simulate possible water wash conditions in a boiler, but it was stated that SCC could not be produced in the more benign simulated wash water and the considerably more aggressive $MgCl_2$ solution was used instead. Although a hot, alkaline environment can cause SCC in austenitic stainless steels as well as carbon steel, no effort appears to have been made to determine whether crack propagation through the interface might occur in such environments.

## FATIGUE OF CLAD MATERIALS

A number of studies have investigated the fatigue properties of clad or coextruded materials.[54-59] In one report, which specifically addressed the issue of fatigue-crack propagation across the interface of a clad material, it was concluded that the behavior of the crack (i.e., whether it crossed the interface, stopped at the interface, or progressed to, and then along the interface) depends on the elastic moduli of the constituent materials, thermal residual stresses, and the properties of the interface.[55] It was observed that when the fatigue crack propagated from the material with the lowest modulus to one with a higher modulus, crack propagation rate decreased as the crack tip approached the interface but then increased after crossing the interface into the second material. Another study, of explosion-clad plate with steels of similar modulus but different tensile strengths, concluded that the fatigue-crack growth rates were related to the maximum strain range at the crack tip rather than the stress intensity factor range.[56]

Fatigue-crack growth through the outer stainless steel layer in a 316L/X65 carbon steel explosion-clad plate was observed to increase as the crack approached the interface, and then drop to a constant rate in the carbon steel substrate when the change in stress intensity factor ($\Delta K$) was 15 $MPa\sqrt{m}$. At higher $\Delta K$ (20 $Mpa\sqrt{m}$), crack propagation rate was unaffected by the presence of an interface.[57] In other cases, researchers were unable to correlate $\Delta K$ to fatigue-crack growth across the interface of a 304/carbon steel-clad plate.[58] Failure of 304/carbon steel-clad material was found to increase exponentially as the total strain range resulting from the mismatch at the interface was decreased.[59]

# DISCUSSION

Based on the information collected, it is likely that all 304L/SA-210 coextruded tubes exposed to the smelt bed in a kraft recovery boiler are susceptible to cracking in service. No strong mitigating factors have been discovered that might exclude these tubes from cracking. Some circumstantial evidence collected by one boiler manufacturer suggests that a deep smelt bed over the boiler floor might offer a degree of protection for decanting-bottom boilers.

The greatest danger posed by cracking of coextruded tubes is that a through-thickness crack will allow water to leak onto the smelt bed and precipitate a smelt-water explosion. Fortunately, through-thickness cracking of coextruded tubes has been extremely rare despite the widespread occurrence of cracking in coextruded tubes. Most cracks found in coextruded tubes remain in the stainless steel outer layer and do not penetrate through the stainless-carbon steel interface. In almost every case in which continued crack propagation from the outer stainless steel layer into the carbon steel core has been documented, it has been in the presence of residual stresses along welds subject to unusually high degrees of restraint. Typical locations where crack penetration into the carbon steel occurs more readily are around the corners of air-port or spout openings. These cracks often have the appearance typical of classical thermal fatigue, but there is at least one documented case in which through-thickness cracking of a coextruded tube has been attributed to SCC.[34]

To date, there are four known reports of cracks found in the carbon steel core of a coextruded floor tube, the most serious being through-thickness cracking of smelt-run tubes that caused a water leak into the smelt bed. In one case, crack propagation into the carbon steel was identified during a boiler inspection by a process of PT to identify the crack, light grinding to chase out the crack, and additional PT to confirm removal of the crack. It was reported that about 50% of the thickness of the carbon steel was ground through before the area was indication-free.[60] The tube was not removed, and there was no confirming metallography. In two other cases, a detailed metallographic examination of tubes received for study by the Oak Ridge National Laboratory (ORNL) project team revealed cracks in the carbon steel at the base of severe cracking in the stainless steel. These cracks were not continuations of the parent cracks, which had turned to propagate along the stainless-carbon steel interface, but had initiated independently in the delaminated area at the interface. In neither case did the cracks extend deeper than the decarburized zone of the carbon steel, and the crack path was intergranular. Most recently, cracking of coextruded smelt-run floor tubes has been reported in the bend near the floor tube header of a sloped-floor boiler. One of these tubes contained a through-thickness crack that caused water to leak into the smelt bed. Adjacent smelt-run tubes also contained cracks that penetrated into the carbon steel core of the tubes. Cracking was attributed to fatigue based on appearance of the cracks, but further details were unavailable at the release of this report.

Although thermal fatigue is a clear factor in some of the cracking reported (particularly at spout and air-port openings), a careful review of available evidence does not present a convincing argument in favor of thermal fatigue as the mechanism for the balance of the cracking observed in coextruded tubes. The following are some critical observations:

- Coextruded tubes have proven resistant to fatigue in a variety of laboratory tests. Specifically, 304/SA-210 tubes were resistant to fatigue over 10,000 cycles in a laboratory test designed to simulate reasonable thermal cycles experienced by tubes in service. More recent tests, which compared thermal fatigue resistance of 304L with that of Alloy 825, subjected the test specimens to thermal shocks far beyond normal operating practice; even so, the 304L survived to 1000 cycles at a temperature difference of about 400°C.

- Thermal fatigue failures are not reported in other industries using coextruded tubes for boiler service.
- The crack paths are typically transgranular but often follow what appear to be specific crystallographic planes.
- High residual tensile stress appears to be required in addition to thermal cycling for cracks to be clearly caused by thermal fatigue. Many cracks initiate on the bare crown of tubes, which is the least likely location for fatigue cracks to be found.
- Transmission electron microscopy (TEM) examinations have found some evidence in cracked coextruded tubes for the existence of tangled-dislocation cell structures indicative of fatigue of austenitic steels, but not at the density observed in comparative samples fatigue-cracked in the laboratory.
- It is remarkable that cracking is not reported on coextruded wall tubes other than around port openings and on portions of the wall exposed to the molten smelt bed. Wall tubes should be exposed to the same (or even more severe) thermal fluctuations than those experienced by floor tubes.
- Tight, transgranular cracking has, in some cases, only occurred on portions of tubes where minor roughening of the stainless steel surface by corrosion was also observed.

The environmental factors that promote cracking in the coextruded tubes remain unidentified, principally because quantitative data on the composition and physical properties of the smelt layer adjacent to the tube surface during operation are unavailable. Attention has been given to the investigation of stress-corrosion cracking under conditions that might exist during a water wash of the boiler, but the results were inconclusive.[12,53] EAC, used here to denote both traditional stress-corrosion cracking and corrosion fatigue, typically occurs only in the presence of a small number of well-defined environments. For austenitic stainless steels, these include hot aqueous chloride solutions, acid chlorides, hot caustic, and oxygenated water at high temperatures and pressures. A molten salt containing a mixture of NaOH and $Na_2S$ has been reported to cause SCC of 304L stainless steel at typical boiler tube temperatures.[61]

A mixed-mode mechanism, whereby cracking initiates as stress-corrosion cracking and then propagates because of thermal fatigue, or vice versa, is also possible. Evidence for the existence of a thin sensitized layer on the surface of coextruded tubes exists, although primarily for tubes manufactured before about 1982. The progression of the typical crack path from a singular crack propagating perpendicular to the surface to a multiple-branched crack could indicate a change of mechanism, although such changes may only be reflecting a complex change in the orientation of the principal stresses in the interior of the tube.

The choice of an appropriate solution to cracking of coextruded tubes will depend on the crack mechanism. If fatigue processes dominate, then attention on elimination of residual tensile stresses on the tube surface during operation would be a positive step. As long as the magnitude and orientation of residual tensile stresses are appropriate, it would appear from the studies of fatigue in clad plates that crack growth across the stainless-carbon steel interface and into the carbon steel is inevitable, and that the interface should not be relied upon to halt crack propagation. EAC may be prevented by either a material change or a reduction in tensile stresses. In addition, propagation of a crack through the outer layer and across the interface into carbon steel requires an environment that will cause EAC in both the outer stainless steel layer and the carbon steel layer. The only known common environment that can cause SCC in both stainless steel and carbon steel is one that is hot and strongly alkaline.

# CONCLUSIONS

1. Based on the information collected, it is likely that all 304L/SA-210 coextruded tubes exposed to the smelt bed in a kraft recovery boiler are susceptible to cracking in service.

2. No strong mitigating factors have been discovered that might exclude these tubes in a boiler from cracking.

3. Most of the cracking found in floor and wall tubes exposed to the smelt bed has been confined to the outer stainless steel layer. Penetration of the cracks across the stainless steel-carbon steel interface is rare, and occurs predominantly near highly restrained welds at spout and air-port openings. Four instances of cracking into the carbon steel core of floor tubes have been reported, including one through-thickness crack.

4. A thorough review of both private- and public-domain documents pertaining to cracking of coextruded tubes in recovery boilers floors was unable to identify a failure mechanism for all cracks. Some cracks, particularly those found at port openings, are likely caused by thermal fatigue.

5. The mechanism of cracking for most of cracks is unknown but appears to be a form of EAC. Insufficient information exists to select a material combination for coextruded tubes that will guarantee crack-free service for the predicted lifetime of the boiler.

6. Laboratory testing and accumulated service history for coextruded tubes made from Alloy 825 indicate that an improvement in tube life over 304L can be expected, but cracking of these tubes in spout openings has already been reported.

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