Boiler tubing for ultra-supercritical coal-fired power generation plants must maintain strength while resisting corrosion at high temperatures.

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Ultra-supercritical coal-fired boilers can generate electric power with very low emissions even while burning high-sulfur coal, and can provide efficiency of 46 to 48%, compared with today’s ~41%. The challenge is to develop boiler tubing alloys that provide at least 100,000 hours creep strength at 750°C (1380°F)/100 MPa (14.5 ksi); and that provide coal-ash corrosion resistance of less than 2 mm (0.079 inches) metal loss in 200,000 hours. Only an alloy with aerospace strength properties coupled with the corrosion resistance of the best of the high-nickel solid solution alloys could meet these new requirements.

The effect of improvements in plant efficiency is shown in Fig. 1. Raising steam temperature provides far greater benefits to efficiency than raising steam pressure, as is clearly shown in this graph. Unfortunately, raising steam temperature disqualifies even the most advanced ferritic tube steels at temperatures much above 600°C (1110°F), because of their lack of strength and resistance to coal ash corrosion. The best of the current austenitic solid solution alloys enables raising the steam temperature to 650°C (1200°F), but steam pressure is limited to about 295 bar (4350 psi). Resistance to coal-ash corrosion is also questionable for many of these alloys.

This article covers the composition of advanced nickel alloys, and details the development of Inconel alloy 740, which is designed for applications in the very hottest section of the superheater. It also describes clad tubing and discusses several successful applications in power plants.

Advanced nickel alloys
Advanced nickel-base high strength alloys are traditionally composed of nickel and chromium. Elements such as molybdenum, tungsten, and cobalt are added to confer additional solid solution strengthening. These alloys, such as Inconel alloy 617, are relatively easy to weld and generally do not require post-fabrication heat treatment.

However, these materials lack the creep strength for long life in service as an advanced ultra-supercritical superheater tubing alloy. Aluminum, titanium, and niobium are added to provide high-temperature strength via precipitation hardening. Alloys such as Inconel alloy 718, Nimonic alloy 263, and Waspaloy are typical examples.

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Fig. 2 — A. This graph shows chromium content versus wastage rate. (Logarithmic fit.) B. This graph shows chromium+ nickel content versus wastage rate. (Linear regression fit.)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Nominal composition of Inconel alloy 671 and Incoloy alloy 800HT</th>
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<tbody>
<tr>
<td>Alloy</td>
<td>C</td>
</tr>
<tr>
<td>671</td>
<td>0.05</td>
</tr>
<tr>
<td>800HT</td>
<td>0.08</td>
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Where tubing must resist coal ash corrosion, increased levels of chromium are mandated for most nickel-base superalloys. The contribution of chromium to coal ash corrosion resistance has recently been demonstrated in the study “Coal Ash Corrosion Resistant Materials Testing Program.” This study was conducted by the Babcock & Wilcox Company, the U.S. Department of Energy, and the Ohio Coal Development Office at the Reliant Energy plant in Niles, Ohio.

To carry out the study, a test panel was placed in the superheater section of this 120 megawatt supercritical plant. The plant burns coal containing 3 to 5% sulfur, and operates at 593°C (1100°F). The panel was evaluated after 21,200 hours of operation (11,288 hours of exposure at full temperature). Figure 2 plots the metal loss in mils/year vs. chromium content in 2A, and vs. chromium-plus-nickel in 2B. Chromium is a strong indicator of life expectancy, as shown by the results of 2A. Figure 2B suggests that an even better predictor of service life may be the sum of chromium plus nickel.

**Clad tubes**

Higher chromium content enables alloys to resist corrosion better than those with less chromium, as shown in Fig. 2. The best resistance is provided by alloys containing 50% chromium/50% nickel.

On the other hand, excellent strength at elevated temperature is provided by Incoloy alloy 800HT (UNS N08811), an iron-nickel-chromium alloy. It has served successfully as a boiler tube alloy under moderately corrosive conditions. However, its chromium content of 21% is not sufficient to resist fuel ash corrosion under the conditions anticipated for future ultra-supercritical boilers.

Obviously, an alloy offering the corrosion resistance of alloy 671 along with the strength of alloy 800HT would be ideal for this service. Incoclad 671/800HT was designed by Special Metals to offer just this combination of properties.

Incoclad tubes are produced by co-extrusion of a duplex billet. The process creates a metallurgical bond between the Incoloy alloy 800HT substrate and the Inconel alloy 671 cladding. The clad tube provides good heat transfer properties and sufficient ductility for cold fabrication. The nominal cladding thickness is typically 1.9 mm (0.075 in). The compositions of both alloys are shown in Table 1.

The duplex product can be formed and machined by conventional techniques. The tubing is readily weldable, and welding products are available with strength and corrosion resistance comparable to those of the tubing.

For installations constructed according to the rules of the ASME Boiler and Pressure Vessel Code, the design stresses specified by the code for Incoloy alloy 800HT should also be used for Incoclad 671/800HT. However, tube wall thickness requirements should be based only on the thickness of the Incoloy alloy 800HT substrate.

**Inconel alloy 740**

With the technical challenge of the European Thermie AD 700 project requirements in mind, Spec-
Incolad Case Study: Philadelphia Electric Co.

Philadelphia Electric Company (PEC) Eddystone Station, Unit 2, is a 350,000 kW unit with double reheat. After 37,000 hours of operation, up to 35% of the wall had been lost in the 9% Cr-1% Mo steel reheater tubes. This forced a downrating of the unit, with steam temperature lowered by 28°C (50°F) from the start-up throttle of 565°C (1050°F).

Searching for a material that would resist the environment, PEC installed Incoclad 671/800HT tubes for evaluation. Tubes were installed in an area where the risk of corrosion was highest, a location directly struck by the flue gas. A wide range of coal was burned during the exposure period. The average sulfur content was 2.44%. The coal mixture exhibited an average ash content of 10.76% and high metallic contaminants (3100 ppm iron, 330 ppm sodium, and 1190 ppm potassium).

Laboratory evaluation after nine years of service verified that the tubing had performed well. The Inconel alloy 671 cladding was essentially unaffected by coal-ash corrosion. No deterioration of the metallurgical bond between the cladding and the substrate was observed. The alloy 800HT had shown excellent resistance to steam-side corrosion and had retained good tensile properties, stress-rupture strength, and ductility. Furthermore, it was not sensitized to intergranular corrosion even after the long exposure at 595°C (1100°F).

Incolad Case Study: United Kingdom

In the United Kingdom, the Central Electricity Generating Board (CEGB) operated a trial reheater using Incoclad co-extruded tubes in a 550 MW power station for over six years. The tubes exhibited trouble-free service in previous service, stainless steel tubes corroded at the rate of 3.5 mm/y (0.04 in/y) due to the particularly aggressive fuel. The Incoclad tubing was found to have corroded at only one fortieth of this rate. This assessment led to a full replacement of 32 x 24 chevron bends on the reheater with Incoclad tubes.

Incoclad 617/800HT tubes were installed in a superheater unit operating at 570°C (1055°F) and 14.8 MPa (2,150 psi) under conditions that produced fuel ash corrosion in previous boiler tubes. The boiler, rated at 460,000 kg/h (1,200,000 lb/h) was fired by high-sulfur pulverized coal. After 32 months, a sample was removed and evaluated.

The cladding thickness remained uniform, circumferentially and longitudinally. Cladding exposed on the fire side showed only minimal corrosion, the most severe attack being pitting to a depth of 0.05 mm (0.002 in). The back side of the tube was essentially free of coal-ash corrosion and pitting. The Incoloy alloy tube interior showed only a uniform, adherent oxide layer.

A clad tube sample from the same installation was examined after 66 months. Again, the cladding thickness remained uniform with only superficial gas impingement erosion on the fire side. The worst attack showed fissures in the cladding to a maximum depth of about 0.30 mm (0.012 in). However, about 1.5 mm (0.060 in) of cladding still remained unattacked beneath the fissures. The inside of the tubing was unchanged from the earlier review and evaluation.
(1290°F) to 4000 hours. A linear projection equates to a metal loss of about 1.3 mm (0.051 in), and parabolic projection leads to a metal loss of about 0.25 mm (0.01 in), both in 200,000 hours.

Figure 6 shows weight change (in mg/cm²) in steam oxidation at 750°C (1380°F) for times up to 10,000 hours. Measurement of the scale at the end of the test revealed a surface film of about 1.22 microns thickness.

**Future boilers**
- Efforts to increase the efficiency of power generation boilers will undoubtedly result in more demanding conditions within the units. Thus, advanced alloys will be required to meet the rigors of this service.
- Inconel alloy 740 exhibits the properties required for developmental boilers designed to operate at significantly higher pressures and temperatures.
- Incoclad 671/800HT tubes have proven capable of resisting fuel ash corrosion and providing long term service (20+ years) in boilers fueled with low-grade coal.

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