High-quality welds with suitable properties for long-time elevated-temperature nuclear service are among the most critical needs in today's welding technology. Safe, reliable, and economic generation of future power depends on welded construction in systems such as Liquid Metal Fast Breeder Reactors (LMFBRs). Rapid thermal transients in LMFBR systems at coolant temperatures around 590-650°C (1000-1200°F) could cause creep and creep-fatigue damage that is not encountered in lower temperature reactor systems. The undesirable consequences of interaction between the two working fluids—sodium and steam—in the steam generators are also of major concern. Thus sound welds that have excellent reliability over a 30-year service life are essential. Several programs are actively underway at ORNL to satisfy this critical need and selected portions of three of these programs are discussed briefly in this paper.

Welding of Stainless Steels

Austenitic stainless steels are the materials of construction for vessels, piping, and other components for LMFBRs. Many of these components are of welded construction and are, or will be, used in service at elevated temperatures. Despite this wide usage, very little data have been generated concerning the high-temperature creep properties of stainless steel weld deposits. Also the limited data available show a high degree of scatter, especially in creep ductility; much of the data show less than 10% total elongation (Fig. 1).

As a result of the low creep ductility and the obvious needs for improved filler metals and data for high-temperature design, an extensive stainless steel welding study is being conducted. It involves several aspects: effects of electrode coatings, effects of slight compositional differences on structure and properties,

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development of improved filler metals for the various welding processes of interest, and generation of high-temperature mechanical properties data.

General classes of stainless steel electrode coating formulas are well known and accepted throughout the welding industry. For example, stainless steel electrodes usually have either a "lime", "lime-titania", or "titania" type covering. Fig. 2 shows that the minimum creep rate and the tertiary creep behavior of a lime-covered type 308 electrode deposit differ markedly from the titania - and lime-titania -covered electrode deposits at a stress of 18,00 psi (124 MPa) and a temperature of 1200°F (649°C). The lime-covered deposit has little "steady state" or secondary creep strain, while the lime-titania- and titania-covered electrode deposits remain in second-stage creep for relatively long periods of time with a much reduced third-stage creep.

Previous work on compositional effects on stainless steel welds have usually been concerned with the influence of such elements as S, C, P, and Si on hot-cracking tendency, tensile strength, tensile ductility, and impact behavior. In our study we determined the effects of various amounts of several elements on the 1200°F (649°C) creep-rupture properties of type E308 weld deposits. The slight differences in the chemical deposit analyses of the different electrode batches were brought about solely as a result of small one-at-a-time changes in electrode covering formulation. In all cases, the coverings were of a typical "lime-titania" formulation (ac and dc reverse polarity, all-position electrode). Moreover, in no case did the adjusted deposit composition of an experimental batch of electrodes fail to meet the specification (AWS A 5.4-69).

Table I shows the results of the creep tests run at 1200°F (650°C) under 20,000 psi (138 MPa) static stress. The differences in creep behavior of the various altered deposits become more apparent at this stress and the resulting longer rupture times, [as compared to shorter tests at 25,000 psi (172 MPa)]. The deposit
of higher carbon content proved to be much stronger than the "standard" deposit under these conditions. Lowering the carbon content below the "standard" did not appear to have any significant effect on the rupture life of the deposit, but it did increase rupture ductility. Adding boron to the type E308 deposit seemed to improve significantly both the rupture life and the rupture ductility. Lowering the amount of silicon in the type E308 deposit very markedly increased the final rupture ductility, but this effect is probably due to a corresponding loss of rupture life. There seems to be very little difference as a result of sulfur content.

At a lower stress level of 18,000 psi (125 MPa), where longer times to rupture are involved, it became apparent that additions of phosphorus and boron significantly strengthen the weld deposit and add resistance to creep embrittlement when compared with other type E308 deposits.

An optimized E308 stainless steel electrode that contained 0.007% B, 0.06% Ti, and 0.04% P was produced by an industrial manufacturer. It has been designated type 308 CRE stainless steel for the controlled residual elements it contains. An extensive mechanical properties and investigation was conducted on welds deposited on 2 3/8-in. thick (60 mm) type 304 stainless steel plate, and the electrode was successfully used in the construction of a large nuclear reactor vessel. Current work is aimed at optimizing the compositions of CRE-containing filler wires (types 308, 316, and 16-8-2 stainless steels) for the gas-tungsten arc and submerged-arc welding processes for applications involving piping, vessels, and other high-reliability components.

Dissimilar Metal Transition Joints

Both ferritic steels and austenitic stainless steels have been commonly used in commercial fossil-fired power plants for many years. The primary boilers and heat exchangers operate at low enough temperatures and under such environmental
Conditions that ferritic steels are the best choice for materials of construction. The higher operating temperatures of the superheater and reheater tubes, headers, and the main and hot reheat steam pipes require the use of austenitic steels. Thus transition joints between the two types of materials are required. The experience with dissimilar-metal transition joints has been generally satisfactory; however, a number of failures of these joints has prompted several investigations of the problem (attempts to circumvent it) over the last two to three decades. Fig. 3 illustrates a failure in a welded transition weld joint taken from a coal-fired utility boiler after a service life of 17 yrs. The weld in the 2 1/2 in. (0.06 m) diam pipe was between 2 1/4 Cr-1 Mo ferritic steel and type 321 stainless steel and was made with Inconel 132 filler metal; the failure initiated and propagated in a narrow band in the heat-affected zone of the ferritic steel.

The potential consequences of failure of such joints, together with the severe thermal transients possible in a nuclear system such as an LMFBR, made it mandatory to initiate a program to develop even more reliable joints and to evaluate their behavior and properties. Current design for the Clinch River Breeder Reactor Plant (CRBRP), a demonstration LMFBR, calls for 42 transition joints of ferritic steel to austenitic stainless steel in piping ranging from 2 to 24 in. (0.05 to 0.6 m) in diameter. Our work recognizes the advantages of the current industrial use of nickel-base welding filler metals rather than the stainless steel filler metals used previously. However, our objective was to develop improved joints to circumvent the failures and concerns with existing technology.

The primary concern that mismatch in coefficients of thermal expansion between the ferritic and austenitic steels imposed high stresses at the interface between ferritic steel and weld metal led to an extensive inelastic stress analysis at General Electric Co. involving base metal combinations, filler metals,
and weld joint geometries. This analysis indicated that for the larger pipe sizes, stress imposed at the joint could be reduced considerably by using a transition material with an intermediate coefficient of thermal expansion between the 2 1/4 Cr-1 Mo ferritic steel and the austenitic stainless steel. Alloy 600 was selected as an appropriate intermediate material for this application. Fig. 4 shows the advantages of using the Alloy 600 since its thermal expansion coefficient of 9.4 is between 2 1/4 Cr-1 Mo (7.8) and stainless steel (10.3). One of the most critical problems encountered in this transition joint program involved the selection of a filler metal and the development of a detailed welding procedure for joining Inconel 600 to type 316 stainless steel. Various filler metals with coefficients of thermal expansion in the desired range were evaluated. These included types 309, 312, 347, and 16-8-2 stainless steel, Incoloy 88, and Inconel 82 (as a backup filler metal). Various problems were encountered, principally cracking and microfissuring. The 16-8-2 was found to be most attractive (Fig. 5), but special techniques are required to obtain the very low base-metal dilution required to prevent weld microfissuring. The hot-wire gas tungsten-arc welding process appears to be particularly advantageous from this standpoint, and it has been selected as the primary method for producing the CRMP transition joints.

Our on-going studies emphasize this process.

**Tube-to-Tube Sheet Welding**

The most critical weldments in an entire steam supply system for an LMFBR are those which join the steam generator tubes to the tubesheets. These welds are particularly important in the LMFBR because of the severe consequences of interaction between the two working fluids - sodium and steam. Traditionally, the tube-to-tubesheet connections connections have been made by passing the tubes through the tubesheet and making a fillet weld on the face side. Although this face-side
welding technique is economical and generally reliable, it has the disadvantages of producing a weld which is difficult to inspect by radiography and containing a leaky crevice between the tube and tube-sheet which may serve as a site for localized corrosion or crack initiation during service. The latter is true even if the width of the crevice is minimized by mechanical or explosive expansion of the tube inside the hole.

In order to avoid these disadvantages of the conventional face-side tube-to-tube-sheet weld, the steam generators for the Clinch River Breeder Reactor Plant (a power-plant demonstration BRP) will be built using a relatively new technique known as internal-bore-welding (IBW). In IBW the tube does not pass through the tubesheet but rather is welded to a short stub machined on the tube side of the tubesheet. This joint has the important advantages of being inspectable by radiography and eliminating the crevice; however, it is much more difficult to weld than is the face-side design. Because of the close proximity of the tubes, there is not room for an orbiting-arc welding head on the outside of the tube. Consequently, this weld must be made by welding from the inside- or bore-side of the tube. Fig. 6 illustrates the configurations and points out the advantages and disadvantages of the most common types of tube-to-tubesheet welds used industrially in steam generators and heat exchangers. The internal-bore weld is shown on the right-hand side of this figure.

A program is currently underway at ORNL to develop improved bore-side welding equipment, to gain further understanding of this technique, and to develop mechanical property data for autogenous welds in 2 1/4 Cr-1 Mo steel tube and tubesheet materials.

Although there was a considerable effort in the development of the internal-bore-welding technique about 5 years ago by a number of steam generator manufacturers, this work was done on approximately 1-in. diam tubing rather than the 5/8-in. OD x 0.112-in. wall tubing that will be used in the CRBRP. Because of the
small bore of this tubing, the feeding of filler wire (as was done in previous work) is not practicable so that autogenous, full-penetration welds are required. A procedure has been developed for making this weld using a commercially obtained internal-welding head, which was modified to fit the smaller tube size. Fig. 7 shows the reference design for the weld joint and the placement of the head in the tube. Fig. 8 is a photograph of the head. In our latest modification, the bent tungsten electrode has been replaced by a straight electrode whose axis is perpendicular to the axis of the head.

We have evaluated the influence of several procedural variables such as gas pressure, gas composition, and preweld cleaning methods on welding behavior and quality. Our study includes material made by three commercial melting practices, i.e., vacuum arc remelt, electroslag remelt, and air melt.

We have conducted a preliminary study to determine the response of weldments to variations in postweld heat treatment temperature. Sections of welds were given 1-hr treatments in vacuum at temperatures of 1150, 1250, 1350, and 1450°F (621, 677, 732, and 788°C), and microhardness traces were made across the weldments into the base metal. In the as-welded condition the fusion zones were considerably harder than the base metal. The hardest area in both types of material was in the HAZ near the fusion line in which the hardnesses were greater than 325 MPa as compared to base metal hardness of about 150.

Our future procedural, mechanical properties, and NDT studies will utilize prototypic tubing and forging material to be used in the actual steam generators.

The above studies demonstrate the types of welding development that have been and are being conducted at the Oak Ridge National Laboratory to ensure the high reliability and overall success of the LMFBR concept in general and the CRBR in particular.


Fig. 1. Available Data for Stress-Rupture Ductility at 1200°F of Type 347 Stainless Steel Weld Metal Deposited on Type 347 Stainless Steel Plate. Each Type of Symbol Represents a Different Source of Data.
Fig. 2. Elongation Versus Time for Experimental Stainless Steel Deposits at 1200°F (649°C) and 18,000 PSI (124 MPa).
Fig. 3. Longitudinal Cross Section of Failed Transition Joint. Y-127801.
Fig. 4. Transition Joint Configurations Under Consideration.
Fig. 5. Incoloy 800-to-Type 316 Stainless Steel Transition Joint Welded with 16-8-2 Filler Metal. Y-138238.
Typical Configurations for Tube-to-Tubesheet Welds.

**FILLET WELD**
- **ADVANTAGE** - EASY TO FABRICATE
- **DISADVANTAGES** - CREVICE, LACK OF VOLUMETRIC (UT, RT) INSPECTION

**RECESSED WELD**
- **ADVANTAGE** - EASY TO FABRICATE
- **DISADVANTAGES** - CREVICE, LACK OF VOLUMETRIC INSPECTION

**FILLET WELD TO BOSS**
- **ADVANTAGES** - EASY TO WELD, ALLOWS VOLUMETRIC INSPECTION
- **DISADVANTAGES** - CREVICE, COST OF MACHINING BOSS

**BUTT WELD TO BOSS**
- **ADVANTAGES** - ELIMINATES CREVICE, ALLOWS VOLUMETRIC INSPECTION
- **DISADVANTAGES** - COST OF MACHINING BOSS, DIFFICULT TO WELD
Reference Design for CRBR Tube-to-Tubesheet Weld.
TABLE 4. EFFECT OF COMPOSITIONAL VARIABLES ON THE CREEP PROPERTIES OF SHIELDED METAL-ARC E308 STAINLESS STEEL WELDS AT 1200°F (650°C) AND 20,000 PSI (138MPa)

<table>
<thead>
<tr>
<th>Compositional Variables</th>
<th>Rupture Time (hr)</th>
<th>Total Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std lime-titania covering</td>
<td>363</td>
<td>2.0</td>
</tr>
<tr>
<td>Carbon, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, 0.035</td>
<td>346</td>
<td>4.0</td>
</tr>
<tr>
<td>High, 0.074</td>
<td>1334</td>
<td>1.75</td>
</tr>
<tr>
<td>Silicon, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, 0.29</td>
<td>127</td>
<td>15.7</td>
</tr>
<tr>
<td>High, 0.73</td>
<td>651</td>
<td>1.3</td>
</tr>
<tr>
<td>Phosphorus, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium, 0.023</td>
<td>166</td>
<td>9.6</td>
</tr>
<tr>
<td>High, 0.034</td>
<td>1329</td>
<td>4.35</td>
</tr>
<tr>
<td>Sulfur, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, 0.006</td>
<td>333</td>
<td>2.6</td>
</tr>
<tr>
<td>High, 0.027</td>
<td>292</td>
<td>4.05</td>
</tr>
<tr>
<td>Boron, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium, 0.004</td>
<td>1167</td>
<td>7.5</td>
</tr>
<tr>
<td>High, 0.006</td>
<td>1159</td>
<td>7.8</td>
</tr>
</tbody>
</table>

*0.044% C, 0.47% Si, 0.012% P, 0.016% S, 0.001% B.*