ADVANCES IN STAINLESS STEEL WELDING FOR ELEVATED TEMPERATURE SERVICE

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SME/ERA Welding and Joining Workshop
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TITLE OF PAPER: ADVANCES IN STAINLESS STEEL WELDING FOR ELEVATED TEMPERATURE SERVICE

PAGE NUMBER: 2
An extensive program to characterize the microstructures and determine the mechanical properties of stainless steel welds is described. The amount, size, shape, and general distribution of ferrite in the weld metal was studied in detail. The effects of electrode coatings on creep-rupture properties were determined as were the influence of slight differences in analyzed contents of carbon, silicon, phosphorus, sulfur, and boron. Using the above information, a superior commercially-produced electrode was formulated which took advantage of chemical control over boron, titanium, and phosphorus. This electrode produced deposits exhibiting superior mechanical properties and it was successfully utilized to fabricate a large nuclear reactor vessel.

INTRODUCTION

Austenitic stainless steels are candidates for vessels, piping and other components for advanced nuclear reactor, chemical processing, petrochemical, and coal liquefaction and gasification systems. 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 made available 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 (1).

As a result of the low creep ductility and the intense need for additional data for high-temperature design, an extensive stainless steel welding study is under way at the Oak Ridge National Laboratory. It involves several aspects: ferrite morphology characterization, effects of electrode coatings, and effects of slight compositional differences on structure and properties.

Using information developed in the study, an optimized electrode was produced commercially and used to successfully fabricate a large nuclear reactor vessel.

STUDIES LEADING TO OPTIMIZED ELECTRODE

Ferrite Morphology

The relative amount of ferrite in the austenite matrix is known to depend upon the specific composition of the weld deposit. Also the size and distribution are known to vary with welding process and operating conditions within a given process. It therefore seemed appropriate to characterize the microstructure present in several different types of austenitic stainless steel weldments, considering in particular detail the method of characterization, and to determine whether or not at least part of the observed property variations can be attributed to microstructural differences (2).
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PAGE NUMBER 1
The quantitative television microscope (QTM) was used extensively and found to be a precise method for measuring ferrite contents in metallographic cross sections of the weldments. It was noted, however, that metallographic etching technique affected the reproducibility of the results, as did several equipment variables including the discrimination threshold setting.

The difference in chemical composition of the filler metals used for each of four typical welds caused the overall mean ferrite content to vary from 3.1 to 8.2% as measured by the QTM. These results could not be accurately predicted from the existing Schaeffler, McKay, or similar diagrams. Further investigation revealed substantial variations in ferrite content from weld to weld produced under identical conditions (Fig. 1) from location to location along the center line of a particular weld, and from point to point within a particular transverse weld cross section (Fig. 2).

In addition to ferrite content, the distribution of ferrite present was also seen to vary substantially in each of the mentioned locations. In all instances, the ferrite was located at dendritic or cellular dendritic substructure boundaries, forming a more or less continuous network. The

![Variation in ferrite distribution in submerged-arc welds. Percent ferrite values were measured by quantitative television microscopy, 300x. Etchant: KOH,K₃Fe(CN)₆. For each microstructure shown, the percentages give the average, minimum, and maximum ferrite contents.](image-url)
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Variation in ferrite distribution in one cross section of a gas metal-arc weld sample. 300×. Etchant: KOH,K3F·(CN)6.

Average dimensions and appearance of this network were highly variable from weld to weld and from location to location within a particular weld.

Mechanical properties tests indicated that the ferrite distribution plays a major role in the fracture process at elevated temperatures. The fracture path almost exclusively follows the austenite-ferrite boundaries, producing a fracture surface reproducing the solidification substructure in detail.

Type of Electrode Coating

Shielded metal-arc electrode coverings are first evaluated on such practical grounds as ease of deposition, bead contour, arc stability, deposition efficiency, and ease of slag removal. Satisfactory bend and tensile properties of the weld are also mandatory. The collection of sufficient long-time data in the creep range has not been of major concern in the past because the applications have not required such data. Furthermore, the influence of particular flux coverings on the creep-rupture properties has received minimal attention. For this reason, ORNL obtained creep data at 1200°F (649°C) on type 308 stainless steel weld metal deposited with the three most common types of E308 covered electrodes (3).
Figure 2
Variation in ferrite distribution in one cross section of a gas metal-arc weld sample. 300x. Etchant: KOH, K₃Fe(CN)₆.

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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. Table 1 gives approximate ingredients one might expect to use in the formulation of the three basic types of stainless steel electrode coverings. Each manufacturer has his own proprietary formulations, but generally the lime-type covering contains more calcium carbonate (limestone) and calcium fluoride (fluorspar) than the titania-type covering, and the titania-type covering contains more titanium dioxide (titania). The lime-titania covering is somewhat of a compromise between the other two types.

Table 1. Typical Covering Compositions for Stainless Steel Electrodes

<table>
<thead>
<tr>
<th>Covering Type</th>
<th>Ingredient, %</th>
<th>Alloy Additions and Other Ingredients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calcium Carbonate</td>
<td>Calcium Fluoride</td>
</tr>
<tr>
<td>Lime</td>
<td>37</td>
<td>33</td>
</tr>
<tr>
<td>Lime-titania</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Titania</td>
<td>25</td>
<td>20</td>
</tr>
</tbody>
</table>

*Ferromanganese, ferrosilicon, binders, etc.

Table 2 summarizes the creep-rupture data at 1200°F (649°C) for specimens tested at three stress levels. The lime-covered electrode weld metal generally had the shortest rupture times and the greatest total elongation at each stress level. The lime-titania- and titania-covered electrode deposits behaved nearly identically, rupturing with low ductility in long-term tests. They strained less than 1% in tests lasting about 600 hr. The differences

Table 2. Creep-Rupture Test Results on Experimental Covered Electrode Deposits at 1200°F (649°C)

<table>
<thead>
<tr>
<th>Covering Type</th>
<th>Rupture Time, hr</th>
<th>Total Elongation, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25,000 psi</td>
<td>20,000 psi</td>
</tr>
<tr>
<td>Lime</td>
<td>27</td>
<td>135</td>
</tr>
<tr>
<td>Lime-titania</td>
<td>44</td>
<td>363</td>
</tr>
<tr>
<td>Titania</td>
<td>26</td>
<td>322</td>
</tr>
</tbody>
</table>

*Stresses are 172, 138, and 124 MPa.
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<td>Calcium Carbonate 37</td>
<td>Sodium Silicate 15</td>
</tr>
<tr>
<td>Lime-titania</td>
<td>Calcium Carbonate 30</td>
<td>Sodium Silicate 5</td>
</tr>
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in creep behavior at long times include nearly all of the strain-time characteristics. Figure 3 shows that the minimum creep rate and the tertiary creep behavior of the lime-covered electrode deposits differ markedly from the titania- and lime-titania-covered electrode deposits at the lowest stress. 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.

Figure 3

Elongation versus time for experimental stainless steel deposits at 1200°F (649°C) and 18,000 psi (124 MPa).

When the total elongation data, however, were plotted as a function of time it became apparent that the ductilities of all three deposits tend to approach zero total elongation for rupture times in the order of 1000 hr.

Slight Compositional Variations

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 (4), we determined the effects of various amounts of these same elements on the 1200°F (649°C) creep-rupture properties of type E308 weld deposits. Boron was also included in the experiments because it
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has been reported (5) to improve the creep resistance of various ferrous alloys.

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. That is, several batches of experimental electrodes were made by an industrial electrode manufacturer from the same heat of type 308 stainless steel core wire, upon which several slightly different covering formulations were applied. 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 A5.4-69).

Table 3 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

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<th>Compositional Variables</th>
<th>Rupture Time (hr)</th>
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<tbody>
<tr>
<td>Std lime-titania covering</td>
<td>363</td>
<td>2.0</td>
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<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>
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<tr>
<td>Silicon, %</td>
<td></td>
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<tr>
<td>Low, 0.29</td>
<td>127</td>
<td>15.7</td>
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<tr>
<td>High, 0.73</td>
<td>651</td>
<td>1.3</td>
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<tr>
<td>Phosphorus, %</td>
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<td></td>
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<tr>
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<td>166</td>
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<tr>
<td>Low, 0.006</td>
<td>333</td>
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<td>292</td>
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</tr>
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<td>1167</td>
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\[a\] 0.044% C, 0.47% Si, 0.012% P, 0.016% S, 0.001% B.
Time changes in electrode covering formulation. That is, several batches of experimental electrodes were made by an industrial electrode manufacturer from the same heat of type 308 stainless steel core wire, upon which several slightly different covering formulations were applied. 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 A5.4-69).

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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 (124 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.

Figure 4 summarizes the effect of composition on the creep ductility of the type E308 deposits studied in this investigation. If one would imagine the lines missing, it would become apparent how difficult it is to assemble good creep ductility data on a certain type of weld deposit, such as type E308. Nevertheless, it can be seen from Fig. 4 that the boron-doped deposit (0.004% B) demonstrates the best creep ductility for any given rupture life.

![Figure 4](image)

Effect of composition on the creep ductility of shielded metal-arc welds at 1200°F (650°C).

The high-phosphorus deposit (0.034% P) was the next best, followed by the low-silicon deposit (0.29% Si). Somewhat disquieting was the fact that all the deposits tended toward zero ductility with extended rupture lives. Again, the boron-doped deposits, as well as the high-phosphorus and low-silicon deposits, appeared to be most resistant to this phenomenon.
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Interestingly, the standard composition curve falls at the lower boundary of the family of curves.

BEHAVIOR OF OPTIMIZED ELECTRODE

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. We conducted an extensive mechanical properties and metallographic investigation of welds deposited on 2 3/8-in.-thick (60 mm) type 304 stainless steel plate (6).

The test specimens were categorized according to distance from the nearest plate surface regardless of the side of the midplane from which they came (Fig. 5).

![Location and orientation of standard specimens in the test weld. Hour-glass shaped region represents weld metal.](image)

The superiority of the type 308 CRE stainless steel composition is evident in Fig. 6. All the total strain data are contained in a scatter band when plotted against rupture time and are compared with standard commercial weld metal and earlier developmental welds in the ORNL program. The lowest observed total creep strain for a CRE all-weld-metal specimen is 13%. Internal cracks did not develop at interphase boundaries, as they tended to do in standard stainless steel weld metal.

The microstructure varied systematically through the thickness of the weld. In the initial passes at the center of the weld, dislocation densities are...
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The test specimens were categorized according to distance from the nearest plate surface regardless of the side of the midplane from which they came (Fig. 5).

The superiority of the type 308 CRE stainless steel composition is evident in Fig. 6. All the total strain data are contained in a scatter band when plotted against rupture time and are compared with standard commercial weld metal and earlier developmental welds in the ORNL program. The lowest observed total creep strain for a CRE all-weld-metal specimen is 13%. Internal cracks did not develop at interphase boundaries, as they tended to do in standard stainless steel weld metal.

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TITLE OF PAPER: ADVANCES IN STAINLESS STEEL WELDING FOR ELEVATED TEMPERATURE SERVICE

PAGE NUMBER 8
Ductility in creep-rupture tests of type 308 stainless steel welds.

Dislocation loops form, cell structures form, and $\text{M}_2\text{C}_6$ carbides precipitate on austenite-ferrite interfaces as a result of numerous thermal and mechanical cycles experienced during welding. The carbide precipitate density, loop density, and dislocation density decrease gradually toward the surface of the weld, where less thermal and mechanical cycling occur. Near the surface few dislocation loops and no precipitate are present, and the dislocation density is about a factor of 2.8 lower than near the center of the weld. The dislocations near the surface are generally straight, with only a hint of crude cell structure. These characteristics are shown in Fig. 7.

The systematic variations in creep properties at small and large strains and in tensile properties are at least partly attributable to these
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Figure 7
As-welded microstructure of type 308 CRE stainless steel weldment. (a) Macrostructure; (b) weld metal contained in L1 specimen; (c) weld metal contained in L3 specimen.

Microstructural variations. Weld metal from initial passes is stronger than weld metal in the final passes.

This optimized electrode was successfully used in the construction of a large nuclear reactor vessel.

ACKNOWLEDGEMENT

The breadth and duration of the efforts described in this paper preclude individual recognition of each of those who have contributed to its progress. Some who are highly involved in the early stages of the work are not now involved in the continuing study or are with other companies. Additionally, the cooperation and counsel of staff members of Combustion Engineering, Nuclear Division, have been invaluable through many phases of the program. Within the Oak Ridge National Laboratory, members of many groups, including Welding and Brazing, Mechanical Properties, Metallography, Electron Microscopy, and the Reports Office have contributed.

REFERENCES

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