A Study of Ferrite Morphology in Austenitic Stainless Steel Weldments

Variations in ferrite distribution are related to weld heat input, joint strength properties and the problem of measuring ferrite content

By G. M. GOODWIN, N. C. COLE, AND G. M. SLAUGHTER

ABSTRACT. The limited amount of data available on the stress-rupture properties of austenitic stainless steel weldments show a large scatter in ductility; much of the data show less than 10% total elongation. It seems highly probable that the ferrite morphology significantly influences creep ductility and that variations in morphology account for much of the scatter in data.

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 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 using the existing Schaeffler, McKay, or similar diagrams. Further investigation revealed substantial variations in ferrite content from weld to weld produced under identical conditions, from location to location along the center line of a particular weld, and from point to point within a particular transverse-weld cross section.

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

Initial results show that mechanical behavior can be correlated with ferrite morphology and that the scatter in properties can be reduced considerably by its consideration.

Introduction

To minimize the possibility of hot cracking during welding of the austenitic stainless steels, it is common practice to produce welding filler metals of such composition that the weld deposit contains a small amount (in the order of 5%) of delta ferrite. The relative amount of ferrite in the austenite matrix is known to be very dependent upon the specific composition of the weld deposit; however...
ever, very little has been reported concerning the influence of welding process and welding parameters on ferrite morphology. The morphology of the ferrite refers not only to relative amount, but also to size, shape, and general distribution.

The design and construction of several types of modern nuclear reactor plants, including the Liquid Metal Fast Breeder Reactor (LMFBR) concept, are dependent upon the use of austenitic stainless steels at elevated temperatures. The behavior of weldments of these materials in the creep range is currently of great interest to those associated with reactor design and fabrication.

The limited amount of data available on the stress-rupture properties of austenitic stainless steel weldments shows a large scatter in strength and, particularly, in ductility. Figures 1 and 2 summarize the available stress-rupture data for Type 347 stainless steel weld metal tested at 1200°F (650°C) (refs. 3, 4). Note that all welds were prepared using the shielded metal-arc process, and each symbol represents a different source of data.

It is significant that in spite of the fact that these data are all obtained from the same grade of materials, welded under typical conditions, there is substantial scatter, especially in ductility values. The arbitrary scatter band shown in Fig. 1 indicates that, from these data alone, little useful information can be obtained when considering the allowable design stresses for long-term service (> 100,000 hr) in this temperature range.

The data shown are for Type 347 stainless steel weld metal, merely because there are more data available for this type. The data for Type 308 stainless steel weld metal, for example, show a similar degree of scatter, but are far less numerous.

From these simple observations, it is apparent that the creep-rupture properties of a particular type of austenitic stainless steel weld metal are highly variable, excluding the effect of welding process selection and test temperature. It seems appropriate, then, to characterize the microstructure present in several different types of austenitic stainless steel weldments, considering in particular the method of characterization and to determine whether or not at least part of the observed property variations can be attributed to microstructural variations.

Experimental Procedure

The welds investigated were deposited on 1-in.-thick Type 304 stainless steel plate, using the joint geometry shown in Fig. 3. Four commonly used processes were studied: submerged-arc, shielded metal-arc, gas metal-arc, and gas tungsten-arc. In each case, welding parameters, filler metals, fluxes, and shielding gases were used which were typical of commercial practice. The welding conditions used for each weld are summarized in Table 1.

Measurements of ferrite content were made primarily using a quantitative television microscope (QTM).

Results and Discussion

Macroscopic cross sections of the subject welds are shown in Fig. 4. The variation in the number of passes used in each weld is clearly evident. Microscopic views of the center section of each cross section are shown in Fig. 5. Here, the distribution of

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Table 1—Summary of Conditions for Producing Test Weldments Using Four Different Welding Processes

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Submerged-arc</th>
<th>Gas metal-arc</th>
<th>Shielded metal-arc</th>
<th>Gas tungsten-arc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current, amp</td>
<td>600</td>
<td>290-320</td>
<td>170</td>
<td>187-250</td>
</tr>
<tr>
<td>Voltage, v</td>
<td>35-37</td>
<td>35-37</td>
<td>25</td>
<td>10-5-12</td>
</tr>
<tr>
<td>Travel speed, in./min</td>
<td>18</td>
<td>11.3</td>
<td>7.5-8.5</td>
<td>12-14.6</td>
</tr>
<tr>
<td>Filler metal</td>
<td>5/32-in.-diam type 308 stainless steel</td>
<td>1/16-in.-diam type 308L stainless steel</td>
<td>1/16-in.-diam 16Cr-8Ni-2Mo covered stainless steel</td>
<td>1/16-in.-diam type 308 stainless steel</td>
</tr>
<tr>
<td>Number of passes</td>
<td>14</td>
<td>18</td>
<td>35</td>
<td>108</td>
</tr>
<tr>
<td>Interpass temperature, F</td>
<td>&lt; 350</td>
<td>&lt; 350</td>
<td>&lt; 350</td>
<td>&lt; 350</td>
</tr>
<tr>
<td>Polarity</td>
<td>dcrp</td>
<td>dcrp</td>
<td>dcrp</td>
<td>dcrp</td>
</tr>
<tr>
<td>Shielding gas</td>
<td>90% He—5% Ar—2.5% CO₂</td>
<td>90% He—5% Ar—2.5% CO₂</td>
<td>90% He—5% Ar—2.5% CO₂</td>
<td>90% He—5% Ar—2.5% CO₂</td>
</tr>
</tbody>
</table>

(a) Welds made in flat position with no preheat. Cleaned between passes with carbide rotary file and stainless steel brush.

(b) A 1/8-in. diam. 2% thoriated tungsten electrode (AWS EWTh-2) was used.

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Fig. 1 — Available data for stress-rupture strength at 1200F (650°C) of type 347 stainless steel weld metal deposited on type 347 stainless steel plate. Each type of symbol represents a different source of data taken from data sheets of Ref. 3 (pp 97-100)

Fig. 2 — Available data for stress-rupture ductility at 1200F of type 347 stainless steel weld metal deposited on type 347 stainless steel plate. Each type of symbol represents a different source of data taken from data sheets of Ref. 3 (pp 97-100)
ferrite (dark staining phase) in the austenitic matrix is revealed for each of the welds. The ferrite is in all cases located at the solidification substructure boundaries, in the areas which in a single-phase alloy are the last to solidify. Note that the shielded metal-arc weld, produced with 16Cr-8Ni-2Mo type filler metal, shows a much smaller amount of ferrite with a more discrete, less continuous distribution.

From the other three welds of Fig. 5 (all made with Type 308 stainless steel filler metal), it appears that the "coarseness" of the ferrite distribution depends primarily upon the substructure size, that is, essentially upon the relative weld energy input utilized. It should be noted that substructure size is in fact dependent only upon composition, solidification growth rate, and the thermal gradient in the liquid at the solid-liquid interface. It is common practice, however, to relate substructure size to energy input, realizing that, in the usual case, a higher energy input affects the growth rate and thermal gradient such that a coarser substructure results.

The views shown in Fig. 5 were selected as "typical" after careful observation of a large area in the central portion of the weld cross sections; the necessity of such a technique is justified by Fig. 6. These photomicrographs were taken at random from the central portion of three cross sections — two (% in. apart) from the same submerged-arc weld and the third from a second weld, produced under presumably identical conditions. The ferrite contents noted represent a mean of 20 QTM readings, with the range of readings shown. Figure 7 further illustrates the situation; here, "typical" areas have been selected within four general areas of a single weld cross section. Again note the variation in amount and distribution of the ferrite phase. This is pointed out to emphasize the perhaps obvious fact that, due to the inherent heterogeneity of the weld-metal solidification process, large variations in ferrite content occur locally which cannot be observed by the usual bulk nondestructive ferrite measuring techniques such as the Magnegage. The authors suggest that differences in ferrite content and morphology and local variations in content and morphology may help to explain some of the scatter observed in elevated-temperature mechanical properties values.

The subject of ferrite measurement is in itself an area of considerable discussion and should not be ignored here. Gania and Ratz recently recommended in their excellent review
Fig. 6 — Variation in ferrite distribution in submerged-arc welds. Percent ferrite values were measured by quantitative television microscopy.

Fig. 7 — Variation in ferrite distribution in one cross section of a gas metal-arc weld sample. Etchant: KOH, K$_3$Fe(CN)$_6$

Fig. 8 — Effect of etchants on measured amount of ferrite; single specimen lightly repolished between etchings.

Fig. 9 shows test results at 1200°F for two welds of essentially identical composition and nominal ferrite content. The submerged-arc weld, prepared with a relatively high energy input, exhibits a coarse ferrite distribution and lower strength than the lower heat-input shielded metal-arc weld which has a relatively fine ferrite distribution. Other factors such as "heat treating" of the individual passes by subsequent passes may account for a small amount of the observed strength difference; but it is predominantly due, the authors feel, to the overall differences in ferrite distribution and associated microscopic compositional variations.

It is also quite evident that the ferrite distribution plays a major role in the fracture process at elevated temperatures. Figure 10 shows a scanning electron fractograph of a specimen tested in stress rupture at 1200°F. Note that the fracture path almost exclusively follows the austenite-ferrite boundaries, producing a fracture surface reproducing the solidification substructure in detail. Figure 11 further emphasizes this
Table 2—Variation of Ferrite Measurements (Day to Day) with Shielded Metal-Arc Process

<table>
<thead>
<tr>
<th>Day</th>
<th>Number of Readings</th>
<th>Range</th>
<th>Mean</th>
<th>Confidence Level, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/14</td>
<td>12</td>
<td>6.3-13.5</td>
<td>9.9</td>
<td>8.6-11.2</td>
</tr>
<tr>
<td>10/16</td>
<td>12</td>
<td>5.5-12.2</td>
<td>8.0</td>
<td>6.7-9.2</td>
</tr>
</tbody>
</table>

Summary and Conclusions

From the above discussion, several conclusions can be drawn:

1. Published stress-rupture data for austenitic stainless steel weld metal show a high degree of variability for the same grade of material.
2. The amount and distribution of ferrite present in austenitic stainless steel weld metal are highly variable from weld to weld and from location to location within a particular weld.
3. The distribution of ferrite present is, in general, dependent upon the solidification substructure size, that is, essentially upon the energy input utilized.
4. Measurement of ferrite content, even by a very precise method such as the QTM, may not be sufficiently accurate unless control is exerted over such variables as etching technique and instrument adjustments.
5. Stress-rupture tests of weldments with equivalent composition and ferrite content exhibit significant variations in strength, attributable at least in part to variations in ferrite distribution.

6. The fracture path in stress-rupture specimens of ferrite-containing weld metals is dependent upon the ferrite distribution essentially following the austenite-ferrite boundaries.

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References