The Effects of Heat Input and Weld Process on Hot Cracking in Stainless Steel

BY G. M. GOODWIN

The Sigmajig test was used to quantify the hot-cracking response of Type 316 stainless steel welded with the GTAW, EBW and LBW processes.

KEY WORDS
Sigmajig Test
316 Stainless Steel
Hot Cracking Response
Heat Input
Electron Beam Welding
Pulsed Laser Welding
GTA Welding
Cracking Resistance
Threshold Stress
Argon Shielding

ABSTRACT. The Sigmajig cracking response of a single heat of 0.010-in.-thick (0.25-mm) Type 316 stainless steel was determined as a function of welding process and parameter variations within a process. It was found that changes in welding parameters resulted in changes in cracking response, even when gross energy input was maintained constant. Higher travel speeds and elongated weld pool shapes increased the cracking response, as did increased heat input. Cracking responses for all three welding processes, gas tungsten arc (GTA), electron beam (EB), and pulsed solid-state laser (LB), were found to follow a common relationship with net heat input. Both EB and LB welds showed higher cracking resistance than GTA welds.

Introduction

The initial application of the Sigmajig test (Ref. 1) used a standard set of welding parameters with the GTA process to evaluate the dependence of cracking sensitivity on heat-to-heat compositional effects in stainless steels. In this work, a specific, relatively crack-sensitive heat of Type 316 stainless steel was used to study the effect of heat input variations on cracking sensitivity using three welding processes: gas tungsten arc, electron beam, and pulsed solid-state laser.

There are numerous examples in the literature documenting the effects of heat input on hot cracking. Typically, an increase in heat input increases cracking sensitivity, but often, there are also complicating factors to be considered, including changes in solidification mode (Refs. 2-4) or compositional effects (Refs. 5-7). Solidification growth morphology has also been shown to be an important factor (Refs. 8, 9). Few studies have attempted to isolate the effect of individual parameters (Ref. 10), and fewer yet have addressed process-to-process variations (Ref. 11). In this study, we have intentionally selected a single crack-sensitive heat of material known to solidify as primary austenite for the processes and parameters investigated. The variations in response are thus attributable as nearly as possible to changes in stress at the trailing edge of the weld pool, which are determined by heat input, heat flow, thermal gradients, and weld pool geometry.

Experimental Conditions

A single heat of 0.010-in.-thick (0.25-mm) Type 316 stainless steel was used throughout the experiment. Its composition is given in Table 1. Previous work (Ref. 1) established a threshold cracking stress of 18 ksi (124 MPa), as compared with other commercial heats ranging from 15 to 53 ksi (103 to 365 MPa). It has a reasonably high P + S content (0.042 wt-%), a Cr-Ni ratio of 1.47 (Ref. 12), a predicted ferrite number (FN) of 0 (Ref. 13), and, as typified in Fig. 1, invariably solidifies as primary austenite with a small amount of residual eutectic ferrite.

Gas tungsten arc welds were produced under argon with a constant arc length of 0.035 in. (0.88 mm). Using DCEN and a 1/16-in. (1.6 mm) diameter thoriated tungsten electrode with a 45-deg included angle and a 0.010-in. truncation, arc current and travel speed were systematically varied above and below the standard conditions of 20 A and 35 ipm (14.8 mm/s) (Ref. 1). Five specimens were run at each combination of parameters.

Threshold cracking stress, \( \sigma_{\text{thr}} \), is defined in Ref. 1 as the applied stress above which cracking first occurs.

Fig. 1—Typical microstructure of gas tungsten arc weld in Type 316 stainless steel, Heat 828013. Solidification mode is primary austenite with a small amount of eutectic ferrite. Murakami's etch.
Table 1—Composition of 0.25-mm-Thick Type 316 Stainless Steel (Heat 828013)

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition (wt-%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.018</td>
</tr>
<tr>
<td>Mn</td>
<td>1.70</td>
</tr>
<tr>
<td>P</td>
<td>0.032</td>
</tr>
<tr>
<td>S</td>
<td>0.010</td>
</tr>
<tr>
<td>Si</td>
<td>0.34</td>
</tr>
<tr>
<td>Ni</td>
<td>12.16</td>
</tr>
<tr>
<td>Cr</td>
<td>17.04</td>
</tr>
<tr>
<td>Mo</td>
<td>1.98</td>
</tr>
<tr>
<td>Cu</td>
<td>0.05</td>
</tr>
<tr>
<td>N</td>
<td>0.047</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cr/Ni ratio&lt;sup&gt;a&lt;/sup&gt;</th>
<th>1.47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted FN&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0</td>
</tr>
<tr>
<td>Primary solidification&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Austenite</td>
</tr>
</tbody>
</table>

(a) Calculated from Ref. 12.
(b) Predicted from Ref. 13.
(c) Based on metallographic observation; see Fig. 1.

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Fig. 2—Gas tungsten arc weld macrostructures. A—Standard conditions: 20 A, 35 ipm (14.8 mm/s), \( \sigma_{\text{min}} = 18 \text{ ksi (124 MPa)} \). B—Low current: 16 A, 35 ipm, \( \sigma_{\text{min}} = 31 \text{ ksi (214 MPa)} \). C—High travel speed: 20 A, 49 ipm (20.7 mm/s), \( \sigma_{\text{min}} = 31 \text{ ksi} \). D—Round weld pool: 12 A, 21 ipm (8.9 mm/s), \( \sigma_{\text{min}} = 37.5 \text{ ksi (259 MPa)} \). E—Elongated weld pool: 28 A, 49 ipm, \( \sigma_{\text{min}} = 7 \text{ ksi (48 MPa)} \).
Electron beam welds were made in a 7.5-kW Hamilton Standard hard vacuum unit operating at 100 kV. Variations in travel speed were accompanied by compensating changes in beam current and focus.

Pulsed solid-state laser beam welds were made under argon shielding using a 400-W Raytheon Model SS-500, with pulse rates, travel speeds, and power levels varied such that the weld pattern ranged from overlapping spots to a continuous pool.

**Results and Discussion**

**Gas Tungsten Arc Welds**

The standard conditions of 20 A and 35 ipm (14.8 mm/s) travel speed gave a Sigma jig response of about 50% cracking at 30 ksi (207 MPa). Figure 2 shows the various GTA weld macrostructures. As plotted in Fig. 3, independently decreasing the current caused a reduction in cracking until at 16 A, which still results in a full-penetration weld, cracking ceased. Increasing current increased cracking, with 100% cracking (specimen separation) occurring at 26 A. The high standard deviation for high cracking percentages results from the fact that data between about 60 and 100% cracking do not occur, as noted in Ref. 1.

Variations in travel speed at constant current caused comparable variations in cracking response, as detailed in Fig. 4. Decreasing travel speed increased cracking, with 100% cracking at 24.5 ipm (10.4 mm/s), and increasing travel speed decreased cracking, with zero cracking at 49 ipm (20.7 mm/s).

Both of the above effects are consistent with results observed in actual practice, and both are explained by noting that increasing heat input results in a wider zone of plastic yielding and causes a larger volume of metal to expand and subsequently contract, increasing shrinkage stresses.

Maintaining essentially constant heat input by varying both current and travel speed proportionally resulted in the data plotted in Fig. 5. At 12 A and 21 ipm (6.9 mm/s) and with a nearly circular weld pool, no cracking was observed. Cracking increased as both current and travel speed increased, and 100% cracking occurred at 28 A and 49 ipm and with an elongated crenulate weld pool shape.

Although the change in weld pool shape itself clearly affects the observed cracking response through geometric stress concentration and alteration of solidification growth morphology at the trailing edge of the pool, two other possible contributions should be noted. First, examination of Fig. 2 shows that the weld width increases roughly 30% going
from the circular to the elongated weld pool shape. This is undoubtedly due to the effect of the copper chill bar on which the specimens are welded. Although the arc heat input is maintained constant, slower travel speeds allow a higher fraction of this total heat input to be extracted through the copper, resulting in a lower effective heat input to the specimen (Refs. 14, 15). As noted above, lower heat input reduces cracking. Secondly, as pointed out by Chihoski (Ref. 16), changes in weld speed strongly affect the stress distribution within the weld pool. Without an extensive stress analysis, which is beyond the scope of this work, and clearly beyond the capabilities of the author, it should be noted that the local transverse stress at which hot cracking initiates behind a weld pool must be exceedingly low, limited by the composite strength of liquid plus solid near its melting point. Thus, when the normally predicted compressive stress in that location is offset by the preapplied test stress, the onset of cracking should be expected to be sensitive to shifts in the stress distribution, as detailed by Chihoski.

The data shown in Figs. 3-5 are combined in Fig. 6 to give an overall view of the effect of current and/or travel speed on cracking response. The constant heat input (Fig. 5) data are a traverse from lower right to upper left of the figure. The standard welding conditions of Ref. 1 are at the intersection of the two bold lines in the center of the plot. The choice of a test stress other than 30 ksi, or a different heat of material, would, of course, shift the results.

The effect of variations in current and/or travel speed on cracking response can also be reported by determination of the threshold stress value, \( \sigma_{\text{th}} \), Table 2 tabulates these values for the extreme GTA conditions and compares them with values, to be discussed later, obtained with the EB and pulsed LB processes. For the GTA process, the standard conditions of 20 A and 35 ipm yield a threshold stress of 18 ksi (124 MPa). The elongated weld pool formed at 28 A and 49 ipm drops the threshold stress to 7 ksi (48 MPa), whereas the lower heat input conditions, achieved by either high travel speed (49 ipm) or low current (16 A), raise the threshold stress to 31 ksi (214 MPa). The highest cracking resistance (37.5 ksi/259 MPa) is obtained with the round weld pool (12 A and 21 ipm), at the same nominal heat input as the standard and elongated pool.

**Electron Beam Welds**

All three sets of welding parameters used with the EB process gave higher threshold stress values than any of the GTA conditions. Figure 7 shows the EB weld macrostructures. Using the same travel speed, 35 ipm, as the standard GTA condition, with beam current and focus adjusted to give approximately the same weld width, the measured threshold stress value was 57.5 ksi (396 MPa).

Increases in travel speed to 70 and 105 ipm (29.6 and 44.5 mm/s), with compensating changes in beam current and focus, reduced the threshold stress values to 55 and 50 ksi (379 and 345 MPa), respectively. As noted for the GTA welds, this effect is attributed to a reduction in heat input (see Table 2), change in weld pool shape, and change in stress distribution at the trailing edge of the weld pool.

It is interesting to note that although travel speed was varied by a factor of 3, changes in the pool shape were such that substructure size remained essentially constant; this observation was confirmed by both optical metallography and scanning electron microscopy of crack surfaces.

**Pulsed Laser Beam Welds**

As with the EB welds, all sets of welding parameters used in the pulsed LB process gave higher threshold stress values than any of the GTA conditions. The laser beam weld macrostructures are shown in Fig. 8.

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**Table 2—Sigma mj Threshold Stress (\( \sigma_{\text{th}} \)) Values for Various Welding Conditions on 0.010-in.-Thick (0.25-mm) Type 316 Stainless Steel, Heat 628013**

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Gross (ksi)</th>
<th>Net (ksi)</th>
<th>Heat Input, J/in. (J/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GTAW</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elongated pool, 28 A, 49 ipm (20.7 mm/s)</td>
<td>343 (13.5)</td>
<td>120 (4.7)</td>
<td>7.0 (48)</td>
</tr>
<tr>
<td>Standard, 20 A, 35 ipm (14.8 mm/s)</td>
<td>343 (13.5)</td>
<td>120 (4.7)</td>
<td>18.0 (124)</td>
</tr>
<tr>
<td>Low current, 16 A, 35 ipm (14.8 mm/s)</td>
<td>206 (8.1)</td>
<td>72 (2.8)</td>
<td>310 (214)</td>
</tr>
<tr>
<td>High travel, 20 A, 49 ipm (20.7 mm/s)</td>
<td>245 (9.6)</td>
<td>86 (3.4)</td>
<td>310 (214)</td>
</tr>
<tr>
<td>Round pool, 12 A, 21 ipm (8.9 mm/s)</td>
<td>343 (13.5)</td>
<td>120 (4.7)</td>
<td>37.5 (259)</td>
</tr>
<tr>
<td><strong>EBW</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 ipm (14.8 mm/s), 1.0 mA</td>
<td>171 (6.7)</td>
<td>86 (3.4)</td>
<td>57.5 (396)</td>
</tr>
<tr>
<td>70 ipm (29.6 mm/s), 1.5 mA</td>
<td>129 (5.1)</td>
<td>64 (2.5)</td>
<td>55.0 (379)</td>
</tr>
<tr>
<td>105 ipm (44.5 mm/s), 2.0 mA</td>
<td>114 (4.5)</td>
<td>57 (2.2)</td>
<td>50.0 (345)</td>
</tr>
<tr>
<td><strong>LBW</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 ipm (14.8 mm/s), 40 Hz, 64 W, 3 ms</td>
<td>110 (4.3)</td>
<td>22 (0.9)</td>
<td>80.0 (552)</td>
</tr>
<tr>
<td>35 ipm (14.8 mm/s), 100 Hz, 110 W, 3 ms</td>
<td>189 (7.4)</td>
<td>38 (1.5)</td>
<td>70.0 (483)</td>
</tr>
<tr>
<td>35 ipm (14.8 mm/s), 200 Hz, 107 W, 1 ms</td>
<td>183 (7.2)</td>
<td>37 (1.4)</td>
<td>65.0 (448)</td>
</tr>
<tr>
<td>52.5 ipm (22.2 mm/s), 200 Hz, 274 W, 1 ms</td>
<td>313 (12.3)</td>
<td>63 (2.5)</td>
<td>60.0 (414)</td>
</tr>
<tr>
<td>70 ipm (29.6 mm/s), 200 Hz, 314 W, 1 ms</td>
<td>269 (10.6)</td>
<td>54 (2.1)</td>
<td>55.0 (379)</td>
</tr>
</tbody>
</table>

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(a) Assumed efficiencies: GTAW, 35% (Ref. 13); EBW, 50% (Ref. 9); LBW, 20% (Ref. 17).
Fig. 7 — Electron beam weld macrostructures. A—35 ipm (14.8 mm/s), 1.0 mA, $\sigma_{\text{min}} = 57.5$ ksi (396 MPa); B—70 ipm (29.6 mm/s), 1.5 mA, $\sigma_{\text{min}} = 55$ ksi (379 MPa); C—105 ipm (44.5 mm/s), 2.0 mA, $\sigma_{\text{min}} = 50$ ksi (345 MPa). 400 μm, 50X
At a travel speed of 35 ipm (14.8 mm/s), a pulse rate of 40 Hz with 3 ms duration at a 64-W average power resulted in a series of spots with about 75% overlap. Since this particular heat of stainless steel did not crater crack under these conditions, the result was that each spot was essentially an independent event, and the threshold stress value of 80 ksi (552 MPa) approached the ultimate tensile strength of the base material (80.2 ksi/553 MPa in the annealed condition).

Increasing the pulse rate to 100 Hz (with 3 ms duration) and 200 Hz (with 1 ms duration) required approximately twice the power level (110 W versus 64 W) to maintain the same weld width. Threshold stress dropped to 70 and 65 ksi (483 and 448 MPa), respectively.

Increasing travel speed to 52.5 and 70 ipm (22.2 mm/s and 29.6 mm/s) at 200 Hz, with concurrent increases in power level, caused further reductions in threshold stress to 60 and 55 ksi (414 and 379 MPa), respectively. The higher speed LB welds resembled the EB welds, both in physical appearance and in threshold stress values.

Threshold Stress versus Heat Input

The threshold cracking stress values for each of the welding process/parameter combinations investigated versus net heat input are plotted in Fig. 9. In determining net heat input, the following efficiencies were assumed: GTA, 35% (Ref. 15); EB, 50% (Ref. 9); and LB, 20% (Ref. 17). It is debatable whether these efficiency values are precisely correct for the conditions of this experiment, but modest changes in assumed efficiency do not grossly affect the trend of the data. With the above noted exceptions where changes in travel speed and weld pool shape affect threshold stress independent of heat input, there is an overall relationship for all three processes between threshold stress and net heat input. Although a straight line can be fitted to the data with a correlation coef-
parameters, but further suggests that the agreement with results obtained in actual provide improved cracking resistance.

3) At least for the GTA process, manipulation of welding parameters at essentially constant heat input alters the cracking response due to changes in weld pool shape and stress distribution at the trailing edge of the weld pool.

4) Compared with the GTA process, both the EB and pulsed LB processes provide improved cracking resistance.

These observations are all in qualitative agreement with results obtained in actual practice. This not only confirms the ability of the Sigmajig test to respond appropriately to changes in the various welding parameters, but further suggests that the quantitative nature of the test will prove useful in selecting parameters (or processes) to avoid cracking, while optimizing travel speed, heat input or other variables of interest.

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