Development of a New Hot-Cracking Test—The Sigmajig

Using a preapplied transverse stress, hot-cracking susceptibility was quantified on thin sheets of stainless steel

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ABSTRACT. The development of a new hot-cracking test and its application to 12 heats of austenitic stainless steel are described. The test involves application of a transverse stress, sigma (hence the name), to a 50-×-50-mm (2-×-2-in.) square sheet specimen, followed by autogenous gas tungsten arc welding. As the preapplied stress is increased specimen by specimen, cracking eventually occurs.

Testing to date has concentrated on 0.25-mm (0.01-in.) thick Types 304 and 316 stainless steel. Threshold stress values at the onset of cracking were found to range from 15 to 53 ksi (103 to 365 MPa). Ranking of the heats agrees completely with prior results from both the Lambert test and the ORNL Circular Patch test, and it provides quantitative indices unavailable from the other tests.

Data analyses indicate a dependence of cracking sensitivity on total sulfur plus phosphorus content for the Type 316 heats.

Future work will involve extension of the test to other thicknesses, alloys and processes.

Introduction

Studies of the hot cracking of austenitic stainless steels and other alloys constitute a major segment of the welding technical literature. A 1964 review (Ref. 1) cited 257 references on weldment cracking and an additional 43 references on cracking tests.

In the mid to late 1960’s, the Varestraint and Tigajig were introduced, and they have become the most utilized weldability tests for evaluation of hot-cracking sensitivity (Ref. 2). Both use the principle of augmenting strain during welding, and neither is usable on material less than about 3 mm (0.12 in.) thick.

The three currently existing thin-sheet tests (Houldcroft (Ref. 3), Lambert (Ref. 4), and ORNL Circular Patch (Ref. 5)) rely on self-imposed restraint. A recent review (Ref. 6) suggested the need for variable loading.

The initial intent of this work was thus to develop a test conforming with the usual guidelines, i.e., to be reproducible, sensitive, economical, and generally applicable, that would also quantitatively rank thin-section (0.25-mm/0.01-in.) Types 304 and 316 stainless steel.

Test Development

The Sigmajig test fixture is shown schematically in Fig. 1, photographically in Fig.

KEY WORDS

Hot-Cracking Test
Sigmajig
Thin-Sheet Cracking
Transverse Stress
Crack Sensitivity
Crack Susceptibility
Test Monitoring
Load Response
Centerline Cracking
Weld Pool Edge
2, and with the other components that make up the test system in Fig. 3. The fixture holds a 50×50-mm (2×2-in.) square specimen between hardened steel grips and applies a transverse stress, sigma, prior to welding. Larger specimens can be used if desired. The load is applied by a pair of strain-gaged bolts and maintained by stacks of Bellville washers in the load train. This approach avoids the inherent limitations of applying deadweight loads as suggested by Boudreau (Ref. 7) and furthered by Ramsey, et al. (Ref. 8), in that the washers provide an adjustable spring constant. The loading system was calibrated with strain-gaged specimens; it has a repetition accuracy of ±0.1% and a resolution of 1 lb (0.45 kg) of load.

After preloading, an autogenous gas tungsten arc (GTA) weld is produced along the specimen centerline using a welding current of 20 A DCE, an arc length of 0.88 mm (0.034 in.), and a travel speed of 15 mm/s (0.6 in./s). As the stress is increased specimen by specimen, a level is reached where centerline cracking initiates. At a higher stress level, specimen separation occurs.

The general appearance of the cracking is shown macroscopically in Fig. 4 and at higher magnification in Fig. 5, confirming by the presence of a prior liquid film that the mechanism is classic hot cracking.

To establish the performance of the test, 12 heats of 0.25-mm-thick austenitic stainless steel, 6 each of Types 304 and 316, were evaluated. All were cold worked 25 to 50% following final anneal. With the exception of Heat 13301, which is a high-purity laboratory heat, all are commercial heats, and the compositions presented in Table 1 are an average of multiple analyses by at least two independent organizations.

The testing was performed in a two-step procedure. In the first step, six specimens of each heat were tested in random order in the range 25 to 50 ksi (172 to 345 MPa) at 5-ksi (34-MPa) intervals. On the basis of the results, the second step relocated and further subdivided the stress intervals to more closely define the stress for the onset of cracking.

The cracking data that resulted fall into two general categories, as typified in Fig. 6. This figure plots percent cracking, defined as fraction of the specimen length cracked, versus applied stress. Crack length can be measured on the specimen with a ruler or by using an overhead projector for greater precision. Some heats, such as Heat 9938, show no cracking until very high stress levels (>40 ksi/276 MPa) are reached and then show a sharp transition (within 0–2 ksi/0–14 MPa) to 100% cracking, i.e., specimen separation. Other heats, such as Heat 59449, show the onset of cracking at
substantially lower stress levels, followed by a gradual transition to 100% cracking. The reproducibility of the test was demonstrated by repeated testing of one of the heats (Heat 828013), which shows a gradual transition at a stress midway through the transition (30 ksi/207 MPa) over a six-month period. For a total of 36 tests, the average percent cracking was 40.3, with a standard deviation of 9.7. The range was from 23 to 59% cracked.

The dynamic response of the load cells during welding was monitored with strip-chart recorders and revealed four general types of behavior, as shown in Figs. 7 through 10. The figures show load on each of the two load cells versus time; the load cell on the starting side of the specimen is the solid curve, and the one on the finishing side is the dashed curve. In Case 1 (Fig. 7), a specimen at low stress with no cracking, the first load cell responds as the arc approaches, reaches a minimum when the arc is approximately halfway along the specimen, and then recovers to essentially the starting load as the specimen cools. The second load cell responds later than the first, reaches a lower minimum, and then recovers similarly.

In Case 2 (Fig. 8), low stress with partial cracking, i.e., a crack-sensitive heat, the first load cell shows the onset of cracking as a secondary dip after the initial minimum has been reached. At high stress with no cracking (Case 3, Fig. 9), considerably more yielding occurs, and the...
In the case for 100% cracking (Case 4, Fig. 10), both load cells monotonically decrease to zero as specimen separation occurs. Figure 11 shows the remaining stress after test as a fraction of starting stress versus starting stress for all tests in which no cracking occurred. As might be anticipated, the amount of yielding that the specimen undergoes is a function of the preapplied stress. Thermal expansion and contraction are assumed to be essentially free from heat-to-heat variation within a given class of materials.

The dynamic eccentricity of the loading pattern explains why percent cracking data between about 60% and 100% do not occur. If the stress is sufficiently high, cracking initiates at the start of the weld (100% cracking), and if not, it will not initiate until the loading has shifted substantially from the second load cell back to the first as the weld progresses.

Experiments have shown that the cracking response is not a strong function of the preapplied stress.
of the system spring constant. The standard washer arrangement gives a deflection/load curve with a slope of 0.108 mils/lb (6.1 mm/mg), and changing the slope from 0.061 to 0.130 has no measurable effect. A "hard" system causes more yielding than a "soft" system, with the same net result in terms of cracking.

**Analysis of Results**

The basis of this test is the determination of the point at which a centerline crack forms at the trailing edge of the weld pool. It can be argued that this event will occur in a given material with given welding conditions at a given local stress at the site of the crack, regardless of location along the weld length. Thus, the usual debate as to which cracking variable is the key indicator can be avoided.

Although it is not possible at this time to directly calculate the dynamic stress state at the trailing edge of the weld pool, the test does provide at least part of the input needed to do so, including a precisely known starting stress, and a real-time measure of loads during and following welding. For the purpose of this analysis, the indicator used is the stress above which cracking first occurs, designated $\sigma_{\text{min}}$. In some very crack-resistant materials, this coincides with the stress at which specimen separation occurs.

Table 2 shows the value of $\sigma_{\text{min}}$ for each of the 12 heats studied. For the Type 304 heats, there is no apparent correlation between $\sigma_{\text{min}}$ and any of the usual chemical and microstructural variables. The phosphorus and sulfur contents are within a narrow range (0.033–0.040 wt-%) for all six heats, the Cr/Ni ratios are all in excess of 1.5, all heats have a predicted ferrite number of at least 3, and all solidify as primary ferrite based on metallographic observation.

![Fig. 12](image12.png)

**Fig. 12** — A — Transverse cross-section of typical Type 304 stainless steel test specimen (100X); B — Transverse cross-section of typical Type 316 stainless steel test specimen (100X)

![Table 2](image2.png)

Table 2 — Sigmajig Cracking Response of Types 304 and 316 Stainless Steel

<table>
<thead>
<tr>
<th>Heat</th>
<th>Type</th>
<th>$\sigma_{\text{min}}$ (ksi) (MPa)</th>
<th>P + S, wt-%</th>
<th>Cr/Ni Ratio</th>
<th>Predicted Ferrite Number</th>
<th>Primary Solidification</th>
</tr>
</thead>
<tbody>
<tr>
<td>11352</td>
<td>304</td>
<td>53 (365)</td>
<td>0.034</td>
<td>1.73</td>
<td>6</td>
<td>Ferrite</td>
</tr>
<tr>
<td>10749</td>
<td>304</td>
<td>49 (338)</td>
<td>0.039</td>
<td>1.64</td>
<td>3</td>
<td>Ferrite</td>
</tr>
<tr>
<td>9937</td>
<td>304</td>
<td>45 (310)</td>
<td>0.038</td>
<td>1.82</td>
<td>6</td>
<td>Ferrite</td>
</tr>
<tr>
<td>9938</td>
<td>304</td>
<td>45 (310)</td>
<td>0.033</td>
<td>1.84</td>
<td>8</td>
<td>Ferrite</td>
</tr>
<tr>
<td>11124</td>
<td>304</td>
<td>37 (255)</td>
<td>0.038</td>
<td>1.66</td>
<td>3</td>
<td>Ferrite</td>
</tr>
<tr>
<td>9643</td>
<td>304</td>
<td>35 (241)</td>
<td>0.040</td>
<td>1.87</td>
<td>8</td>
<td>Ferrite</td>
</tr>
<tr>
<td>191513</td>
<td>316</td>
<td>50 (345)</td>
<td>0.031</td>
<td>1.63</td>
<td>4</td>
<td>Ferrite</td>
</tr>
<tr>
<td>730693</td>
<td>316</td>
<td>42 (290)</td>
<td>0.036</td>
<td>1.63</td>
<td>5.5</td>
<td>Ferrite</td>
</tr>
<tr>
<td>13301</td>
<td>316</td>
<td>36 (248)</td>
<td>0.006</td>
<td>1.36</td>
<td>0</td>
<td>Austenite</td>
</tr>
<tr>
<td>99449</td>
<td>316</td>
<td>20 (138)</td>
<td>0.043</td>
<td>1.48</td>
<td>1</td>
<td>Austenite</td>
</tr>
<tr>
<td>828013</td>
<td>316</td>
<td>18 (124)</td>
<td>0.042</td>
<td>1.47</td>
<td>0</td>
<td>Austenite</td>
</tr>
<tr>
<td>12</td>
<td>316</td>
<td>15 (103)</td>
<td>0.051</td>
<td>1.53</td>
<td>3</td>
<td>Ferrite</td>
</tr>
</tbody>
</table>

Notes:
- Calculated from Ref. 9.
- Predicted from Ref. 10.
- Based on metallographic observation. See Fig. 13.

![Fig. 13](image13.png)

Fig. 13 — A — Fusion line region in Heat 191513. Solidification mode is primary ferrite (Murakami's etch). B — Fusion line region in Heat 730693. Solidification mode is primary ferrite (Murakami's etch). C — Fusion line region in Heat 13301. Solidification mode is primary austenite (Murakami's etch). D — Fusion line region in Heat 99449. Solidification mode is primary austenite (Murakami's etch). E — Fusion line region in Heat 828013. Solidification mode is primary austenite (Murakami's etch). F — Fusion line region in Heat 12. Solidification mode is primary ferrite (Murakami's etch).
The suspicion that such heats should not hot crack is confirmed by observation of the cross-section of the tested specimens, as typified by Fig. 12A. In fact, each of the six Type 304 heats fails in tension with a reduction of area greater than 90%, at an initial stress level greater than its annealed room-temperature yield strength (room-temperature tensile yield strength values for all 12 heats range from 40.9-57.5 ksi (282-398 MPa) as cold worked and from 27.9-34.0 ksi (192-234 MPa) annealed). High-temperature strength is unknown, but it is commonly presumed to be proportional to room-temperature value. This type of behavior results in a sharp transition from 0 to 100% cracking, and, in the rare instance where partial cracking occurs, it is invariably at the start of the weld only.

All six Types 316 heats exhibit classical hot cracking, as shown in Fig. 12B and in Fig. 5. Reduction-of-area values are typically less than 30%, and the transition from 0 to 100% cracking is gradual, especially for lower values of $\sigma_{\text{min}}$. Partial cracking is invariably at the end of the weld. The two different responses correlate with the typical curves in Fig. 6.

The two best heats of Type 316, 191513 and 730693, have low phosphorus and sulfur levels, high Cr/Ni ratios, and high predicted ferrite numbers, and both solidify as primary ferrite, as shown in Figs. 13A and 13B. Heat 13301 is a high-purity laboratory heat, and although it has a very low phosphorus and sulfur level, it also has a very low Cr/Ni ratio and solidifies as primary austenite—Fig. 13C. Its cracking sensitivity is in the middle of the range of the six heats.

Heats 59449 and 828013 have higher phosphorus and sulfur levels, Cr/Ni ratios below 1.5, and low predicted ferrite numbers, and solidify as primary austenite—Figs. 13D and 13E. Heat 12 is the most crack susceptible of the heats, and it has the highest phosphorus and sulfur level, a Cr/Ni ratio slightly greater than 1.5, and a predicted ferrite number of 3, and solidifies as primary ferrite—Fig. 13F. Apparently, the high phosphorus and sulfur level is the overriding factor.

The correlation of this test with prior results from two other tests is shown in Table 3. There is no disagreement between the three tests. Quantification of the cracking sensitivity permits ranking of the heats on an absolute basis. Such information is very useful, because production conditions seldom approximate testing conditions.

## Conclusions

1. The new hot-cracking test described here can successfully rank Types 304 and 316 stainless steel in thin (0.25-mm-0.01-in.) section.

2. The test causes cracking in even the most hot-crack-resistant heats and discriminates hot cracking from simple tensile failure.

3. None of the six Type 304 heats tested was susceptible to hot cracking. All failed at high stresses by tensile separation.

4. All six Type 316 heats exhibited classical hot cracking over a wide range of stresses.

5. Rating of the Type 316 heats by the stress above which cracking first occurs is explained by consideration of phosphorus and sulfur levels, Cr/Ni ratios, and primary solidification mode.

## Future Work

Extension of the existing system is planned in three areas: different sample thicknesses, other alloy systems, and other welding processes. Preliminary tests on 20-mil (0.5-mm) stainless steel sheet have shown less scatter than 10-mil data, presumably due to reduced potential for buckling. Random heats of Alloy 800 and 17-14 Cu-Mo have shown greater crack sensitivity than the average Type 316 heat. Pulsed laser welds in Type 316 have shown improved crack resistance over gas tungsten arc welds.

## Acknowledgments

J. D. Hudson contributed heavily to the design and fabrication of the first testing unit. J. P. Strizak gave many helpful suggestions concerning the load train. Stephen G. Zorko and Lisa M. Scibba helped with the initial trial run. C. Bayne performed many statistical analyses, most of which are still to be published. C. W. Houck did the metallurgy, K. W. Gardner typed the draft, M. L. Santella and T. M. Mustaleski provided technical review, and A. R. McDonald prepared the final manuscript. The Y-12 Development Division provided materials and financial support, and T. M. Mustaleski, R. K. Holbert, Jr., and M. Richey deserve special thanks for their guidance and counsel. The research was sponsored by the U. S. Department of Energy under contract DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

## References


5. U.S. Patent 4,499,758 and research to be published, S. A. David, Oak Ridge National Laboratory, Oak Ridge, Tenn.


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**Table 3—Comparative Cracking Results**

<table>
<thead>
<tr>
<th>Heat</th>
<th>Sigmajig, $\sigma_{\text{min}}$, ksi (MPa)</th>
<th>Lambert(a)</th>
<th>ORNL(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11332</td>
<td>53 (365)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>10749</td>
<td>43 (296)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>9937</td>
<td>45 (310)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>9938</td>
<td>45 (310)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>11124</td>
<td>37 (255)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>9643</td>
<td>35 (241)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>191513</td>
<td>50 (345)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>730693</td>
<td>42 (290)</td>
<td>2 &gt;2 cracks</td>
<td>2 cracks</td>
</tr>
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<td>36 (248)</td>
<td>2 &gt;2 cracks</td>
<td>2 cracks</td>
</tr>
<tr>
<td>59449</td>
<td>20 (138)</td>
<td>No cracks</td>
<td>No cracks</td>
</tr>
<tr>
<td>828013</td>
<td>18 (124)</td>
<td>1 crack</td>
<td>1 crack</td>
</tr>
<tr>
<td>12</td>
<td>15 (103)</td>
<td>1 crack</td>
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(a) Ref. 4.

(b) Ref. 5.