Evaluation of Backfilled Solidification Cracks in Austenitic Stainless Welds in Relationship to Evaluation of Hot Cracking

It is important to control chemical compositions of hot crack resistant materials so the solidification mode will be primary ferritic

BY C. D. LUNDIN, C. H. LEE AND C. Y. P. QIAO

ABSTRACT. This paper describes the significance of the backfilling phenomenon in solidification cracks on the evaluation of the weldability of stainless steels. Backfilling of solidification cracks was systematically evaluated in terms of:
1) Primary solidification mode (austenitic or ferritic).
2) Augmented strain levels (2 & 4% Varestraint Test).
3) Type of stainless steel (316 and 347).
4) Location in the weld and length of solidification cracks.

The extent of backfilling was found to be a function of the location of the crack in the weld and the solidification crack length, such that the shorter and narrower the crack, the greater is the potential for backfilling. The greatest extent of backfilling occurs at the center of the weld where the temperature gradient is the most shallow. Weld solidification in a primary ferritic mode has a greater potential for backfilling as compared to weld solidification in the primary austenitic mode. The applied strain level does not appear to significantly influence the degree of backfilling.

The concept of capillarity can be successfully used in explaining the backfilling phenomenon. In austenitic stainless steel the backfilled region is rich in chromium and/or nickel compared to the surrounding area depending on the primary solidification mode. Silicon is also segregated in the liquid during solidification and thus was detected in the backfilled solidification cracks.

The formation of a Nb rich liquid, along the fusion zone grain boundaries during the solidification process, which forms a NbC-austenite eutectic, can play a role in the backfilling of cracks in Type 347.

KEY WORDS
Solidification Crack
Austenitic Stainless
Hot Cracking
Backfilling
Weldability
Nuclear Grade Steel
Crack Geometry
Strain Level Effect
Capillary Action
Microstructure

Introduction

During the welding of stainless steels, if a sufficient strain exists, hot cracks initiate at the solid-liquid interface along the trailing edge of the weld pool and propagate along the liquated solidification boundaries and then along migrated grain boundaries. When hot cracks propagate, liquid just ahead of the solid-liquid interface is drawn into the cracks by capillary action and thus the high temperature end of the cracks are "backfilled." Because of unique segregation characteristics which depend upon the material solidification behavior, backfilled cracks are usually distinguishable from the solidification boundaries after etching.

The first reported observation of the backfilling phenomenon in solidification cracks in stainless steel weld metal is dated as early as the 1950s. Medovar (Refs. 1, 2) found that when welding a high silicon containing austenitic stainless steel, extensive formation of the Ni-Si eutectic resulted in a reduced extent of hot cracking caused by healing of interdendritic cracks and refinement of the structure. In a later paper, Medovar (Ref. 3) further mentioned healing of cracks such that in the welding of 18-8 austenitic stainless steel which had a high Nb content (1-2%), the hot cracking resistance was improved, as compared to a medium Nb content of 0.6-
However, since the 1950s, few investigators have reported on backfilling of hot cracks and only their observations of backfilled cracks were reported. Recently, some investigators (Refs. 4, 5, 6, 7) have begun to pay attention to the phenomena of backfilled solidification cracks. However, these investigators have examined only the microstructural characteristics and elemental distributions around the backfilled region in terms of the solidification mode without emphasizing the potential importance of backfilling on the evaluation of the weldability of materials.

Therefore, in this study, backfilled solidification cracks were systematically investigated in terms of: the primary solidification mode (ferritic vs. austenitic), applied strain levels, and types of stainless steel (316 vs. 347). Further, the extent of backfilling was also evaluated as a function of the location in the weld and the temperature gradient in the weld heat-affected zone (HAZ).

Materials and Experimental Procedure

Materials

The materials investigated in this study include two heats of Type 316 and one heat of Type 347 austenitic stainless steel. The complete chemical composition of these alloys is given in Table 1. Heat 316-D has a primary austenitic solidification mode, while heats 316-B and 347-E have primary ferritic solidification modes and thus have some residual ferrite at ambient temperature.

Experimental Procedures

Varestraint Hot Crack Testing

The hot cracking susceptibility was evaluated with a multipass technique using the subscale moving-torch Varestraint method which has been recently modified in the Materials Joining Research Group at The University of Tennessee (Refs. 8, 9). A schematic drawing of the Varestraint device showing the latest methodology for testing is shown in Fig. 1.

![Schematic drawing of the Varestraint test device showing the manner in which a specimen is tested.](image-url)

Table 1 — Chemical Composition

<table>
<thead>
<tr>
<th>Materials</th>
<th>Heat No.</th>
<th>FN^a</th>
<th>FN^b</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Mb</th>
<th>N</th>
<th>Nb</th>
<th>Co</th>
</tr>
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<tbody>
<tr>
<td>316-B</td>
<td>32809</td>
<td>3.2</td>
<td>4.9</td>
<td>0.011</td>
<td>0.58</td>
<td>1.06</td>
<td>0.032</td>
<td>0.013</td>
<td>16.95</td>
<td>10.30</td>
<td>2.15</td>
<td>0.078</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>316-D</td>
<td>D4C1204</td>
<td>0.1</td>
<td>0.0</td>
<td>0.010</td>
<td>0.51</td>
<td>1.60</td>
<td>0.021</td>
<td>0.001</td>
<td>17.55</td>
<td>12.95</td>
<td>2.76</td>
<td>0.113</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>347-E</td>
<td>161286</td>
<td>4.4</td>
<td>3.0</td>
<td>0.050</td>
<td>0.53</td>
<td>1.93</td>
<td>0.029</td>
<td>0.005</td>
<td>18.10</td>
<td>10.50</td>
<td>—</td>
<td>0.56</td>
<td>0.14</td>
<td></td>
</tr>
</tbody>
</table>

^a: Measured ferrite content with Magne-Gage

^b: Ferrite potential by DeLong method
The samples were extracted from the materials in the rolling direction. The sample dimension is 0.125 X 1 X 5 in. (3 X 25 X 127 mm).

After positioning the sample in the device, two 2-in. (51-mm) long parallel autogenous weld beads are made with a predetermined width between them. The third weld bead (test pass) is positioned so that it produces a base metal HAZ which overlaps the HAZ of the second pass and simultaneously produces a HAZ in the weld metal of the first pass. The augmented strain is applied as the torch passes the center of the radius block, such that the augmented strain is applied to the solidifying interface at the center of the sample directly over the crown of the radius block. Therefore, the multipass technique permits simultaneous evaluation of hot cracking susceptibility of the fusion zone, base metal HAZ and weld metal HAZ in a single sample. The welding conditions for the gas tungsten arc autogenous weld are: 100 A, 12 V, 10 in./min (4 mm/sec) travel speed with argon shielding gas. The range of augmented strains used in this study was 0.25-4%. The level of augmented strain was varied by simply using a different radius die block. That is strain = t/2R, where t = thickness of sample, R = radius of die block.

Test Evaluation

Tested samples were examined at 70X with a binocular microscope and each solidification crack was measured and recorded. In this study, only the fusion zone cracks were considered. The backfilled crack length was measured on the metallographic samples tested at 2 and 4% augmented strain. The polished samples were etched in dilute aqua-regia (1 part of nitric acid, 3 parts of hydrochloric acid and 1 part of distilled water). To investigate backfilling as a function of solidification crack length and location in the weld, the solidification cracked zone along the instantaneous solid-liquid interface at the time of strain application was divided into three equal regions (A, B, and C) as shown in Fig. 2. Region A is in the center of the weld, region C is in the fusion line area, and region B is an intermediate region between A and C. The solidification cracks found in each region were divided into four crack length groups: L1 < 0.3 mm, 0.3 mm < L2 < 0.5 mm, 0.5 mm < L3 < 0.7 mm, and L4 > 0.7 mm.

OLM and SEM equipped with EDS chemical analysis system were used during microstructural evaluations.

### Experimental Results

#### Solidification Cracking Susceptibility

A brief comparison of the materials with regard to solidification cracking is shown as a function of augmented strain in Fig. 3. (It is to be noted that the total crack length is measured on the as-welded surface, where narrow short cracks are usually not detectable.) It is to be clearly noted that the fully austenitic 316-D shows the greater total crack length at all applied strain levels as compared to the ferrite-containing heats. Even at the lowest strain (0.25%) used in this study, the total crack length of 316-D is almost the same as that of 316-B tested at 4% strain. The total crack length in 316-D appears to saturate beyond 2% strain.

347-E shows a behavior intermediate between 316-B and 316-D. At strain levels below 2%, both 316-B and 347-E have an almost identical behavior; however, when the applied strain is increased to 4%, 347-E has a greater susceptibility to solidification cracking than 316-B, revealing the detrimental influence of niobium in the Type 347 alloy.

Figure 3 further reveals the influence of the primary solidification mode on the extent of hot cracking. Welds solidifying in a primary austenitic mode (316-D) are more susceptible to solidification cracking than those solidifying in a primary ferritic mode (316-B and 347-E).

### Backfilled Solidification Cracks

The extent of backfilling in each solidification crack was carefully measured using a calibrated scale at 100–200X OLM on the mounted samples tested at 2 and 4% strain. The measured average solidification crack length and backfilled crack length, number of cracks in terms of the solidification crack length groups (L1, L2, L3, and L4) and the position in the weld (regions A, B, and C), are given in Tables 2–5. The percentage of the average backfilled crack length to average solidification crack length is also given in the tables. The average of each column and row is given in the last column and row, respectively.

#### Table 2 — Extent of Backfilled Cracks in 316-D at 4% Strain

<table>
<thead>
<tr>
<th>Crack Length</th>
<th>Region</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>—</td>
<td>S: 0.33 mm</td>
<td>B: 0.19 mm</td>
<td>S: 0.61 mm</td>
<td>B: 0.28 mm</td>
<td>0.18 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 57</td>
<td>%: 9</td>
<td>%: 46</td>
<td>%: 44</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>NO 2</td>
<td>S: 0.21 mm</td>
<td>B: 0.19 mm</td>
<td>S: 0.68 mm</td>
<td>B: 0.35 mm</td>
<td>0.24 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 69</td>
<td>%: 45</td>
<td>%: 40</td>
<td>%: 44</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>NO 6</td>
<td>S: 0.19 mm</td>
<td>B: 0.11 mm</td>
<td>S: 0.65 mm</td>
<td>B: 0.18 mm</td>
<td>0.11 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 30</td>
<td>%: 41</td>
<td>%: 27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>S: 0.20 mm</td>
<td>S: 0.27 MM</td>
<td>B: 0.12 mm</td>
<td>S: 0.65 mm</td>
<td>B: 0.18 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 60</td>
<td>%: 44</td>
<td>%: 27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A: Average solidification crack length; B: Average backfilled crack length

### Table 3 — Extent of Backfilled Cracks in 347-E at 4% Strain

<table>
<thead>
<tr>
<th>Crack Length</th>
<th>Region</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>—</td>
<td>S: 0.33 mm</td>
<td>B: 0.19 mm</td>
<td>S: 0.61 mm</td>
<td>B: 0.28 mm</td>
<td>0.18 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 57</td>
<td>%: 9</td>
<td>%: 46</td>
<td>%: 44</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>NO 2</td>
<td>S: 0.21 mm</td>
<td>B: 0.19 mm</td>
<td>S: 0.68 mm</td>
<td>B: 0.35 mm</td>
<td>0.24 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 69</td>
<td>%: 45</td>
<td>%: 40</td>
<td>%: 44</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>NO 6</td>
<td>S: 0.19 mm</td>
<td>B: 0.11 mm</td>
<td>S: 0.65 mm</td>
<td>B: 0.18 mm</td>
<td>0.11 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 30</td>
<td>%: 41</td>
<td>%: 27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>S: 0.20 mm</td>
<td>S: 0.27 MM</td>
<td>B: 0.12 mm</td>
<td>S: 0.65 mm</td>
<td>B: 0.18 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>%: 60</td>
<td>%: 44</td>
<td>%: 27</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The tables clearly reveal that, in general, when the solidification crack length is small, the percentage of backfilled crack length to solidification crack length is greater. Further, the center of the weld (region A) shows the greatest extent of crack backfilling and thus the highest percentage of backfilled crack to solidification crack length as compared to regions B and C. All the above-mentioned characteristics are true for all materials tested and at all strain levels.

The influence of solidification mode on the extent of backfilling is compared graphically in Fig. 4. In all weld regions, the 316-B weld, solidifying in the primary ferritic mode, has a longer absolute backfilled crack length and thus a greater ratio of backfilled to solidification crack length than the weld solidified in the primary austenitic mode (316-D). Figure 4 further illustrates that when the solidification crack length is less than 0.3 mm (0.012 in.), the primary ferritic solidification mode shows complete backfilling at the center of the weld (region A). As seen in Tables 2-5, smaller backfilled cracks (<0.5 mm or 0.02 in.) formed in the primary ferritic welds as compared to the primary austenitic weld.

The effect of the augmented strain level on the degree of backfilling in 347-E is given in Fig. 5. There is almost no difference in the absolute backfilled length between 2 and 4% strain. However, the percentage of the backfilled length to the solidification crack length at the 2% strain level is slightly greater than that at the 4% strain level because the solidification crack length at the higher strain level is generally longer than that for the samples tested at lower strain levels.

Microstructural Evaluation of Backfilled Region

A typical backfilled crack in 316-D, which solidified in a primary austenitic mode, is shown in Fig. 6A. The solidification crack occurred intergranularly. The grain boundary can be easily distinguished by the different cell orientation in the grains at either side of the grain boundary. The backfilled crack extends about two grain boundary lengths from the position of the instantaneous solid-liquid interface. The instantaneous solid-liquid interface position is shown by the dotted line. The distinctly different etching characteristic of the backfilled region gives easy discrimination from the adjacent regions and other grain boundaries. The backfilled cracks sometimes appear as narrow cracks at low magnification as shown in Fig. 6A. However, at higher magnification, as shown in Fig. 6B, it can be clearly seen that the crack was completely healed by a liquid. The width of this particular healed crack is approximately 8-10 μm. Formation of delta ferrite along the center of the back

<table>
<thead>
<tr>
<th>Crack Length Region</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>NO 2</td>
<td>NO 8</td>
<td>NO 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S: 0.28 mm</td>
<td>S: 0.36 mm</td>
<td>B: 0.28 mm</td>
<td>B: 0.33 mm</td>
<td>%: 100</td>
<td>%: 77</td>
</tr>
<tr>
<td>B</td>
<td>NO 4</td>
<td>NO 7</td>
<td>NO 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S: 0.24 mm</td>
<td>S: 0.39 mm</td>
<td>S: 0.51 mm</td>
<td>B: 0.21 mm</td>
<td>B: 0.25 mm</td>
<td>%: 71</td>
</tr>
<tr>
<td>C</td>
<td>NO 21</td>
<td>NO 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S: 0.13 mm</td>
<td>S: 0.37 mm</td>
<td>B: 0.11 mm</td>
<td>B: 0.18 mm</td>
<td>%: 86</td>
<td>%: 48</td>
</tr>
<tr>
<td>Average</td>
<td>S: 0.22 mm</td>
<td>S: 0.37 mm</td>
<td>S: 0.51 mm</td>
<td>B: 0.18 mm</td>
<td>B: 0.22 mm</td>
</tr>
</tbody>
</table>

S: Average solidification crack length, B: Average backfilled crack length
%: (B/S) X 100 NO: Number of cracks
L1 < 0.3 mm, 0.3 mm ≤ L2 ≤ 0.5 mm, 0.5 mm ≤ L3 ≤ 0.7 mm, L4 > 0.7 mm
filled area can also be noted. The different etching characteristics indicate that the elemental distribution along/across the backfilled crack may be different from the adjacent area. The chromium and nickel profiles across the backfilled crack at region A-A in Fig. 6B are given in Fig. 7. The backfilled region is richer in chromium and slightly depleted in nickel as compared to the adjacent region. This is strong evidence of backfilling. Because 316-D has a primary austenitic solidification mode, Cr, a ferrite stabilizer, is rejected into the liquid at the dendrite interstices and grain boundaries. Further, the impurity elements (P+S together with Si), which have a lower solubility in austenite and a small distribution coefficient (k << 1), will also segregate to the remaining liquid. Therefore, the effective solidus temperature of the remaining liquid along the grain boundary is depressed below the bulk solidus temperature. If a sufficient strain is present or is applied, hot cracks form and when cracking initiates and a crack propagates, the Cr enriched liquid just ahead of the advancing solid-liquid interface is drawn into and fills the crack. Therefore, the formation of a ferrite along the backfilled crack is a product of solidification of Cr enriched liquid. No evidence of S and P segregation in the backfilled region was found in this study with EDS. Only a small extent of Si segregation was detected.

A typical backfilled crack in 347-E, which solidified in a primary ferritic mode, is shown in Fig. 8. The chromium and nickel distribution across the backfilled area (region B-B) is given in Fig. 9. The average chromium and nickel content near, and in the backfilled area, is higher than in the surrounding regions. Since the primary solidification mode is ferritic, the liquid remaining during the final stage of solidification is enriched in nickel. Thus, the liquid will solidify as an eutectic mixture of austenite and ferrite during subsequent freezing. This can be noted in Fig. 9, in which the chromium content at the center of the backfilled boundary is higher than in the adjacent backfilled area and at the same location the nickel content is slightly lower than in the surrounding matrix. However, there is no clear evidence of formation of ferrite in the center of the backfilled boundary as shown in Fig. 8. Figure 8 further shows formation of an almost continuous NbC or NbC-austenite eutectic along the backfilled crack, revealing that the formation of a low melting temperature NbC-austenite eutectic may have also played an important role in backfilling in the Type 347 alloy.

Discussion

Tables 2-5 show that the extent of backfilling is a function of location in the weld. The central region of the weld has the greatest extent (percentage and absolute length) of backfilled solidification cracks. This result indicates that backfilling is also a function of the temperature gradient because the weld centerline region has the shallowest temperature gradient as compared to other regions. A macrograph of the weld zone, shown in Fig. 10, clearly illustrates that the width of the backfilled region is the greatest at the center of the weld and becomes narrower close to the fusion line. The macrograph further reveals that when a crack is short, it is also narrow.

The backfilling of solidification cracks occurs by the liquid absorption into the cracks by capillary action (from liquid just ahead of the advancing solid-liquid interface). Therefore, the backfilling phenomenon may be explained by capillary action theory. Capillary "rise" is a function of liquid density/viscosity, column radius/length, and surface energy (tension) (Ref. 10). A schematic drawing of capillary rise is given in Fig. 11. The height (h) of the liquid drawn into the column and the velocity (V) of liquid drawing are:

\[ h = \frac{2\gamma_{LV}\cos\theta}{D_L g R} \]

\[ V = \frac{\gamma_{LV}\cos\theta}{n} \cdot \frac{R}{4L} \]

where:

- \( D_L \) = density of liquid
- \( n \) = viscosity of liquid
- \( R \) = radius of column
- \( L \) = length of column
- \( \gamma_{LV} \) = surface tension
- \( \theta \) = contact angle between liquid and column
- \( g \) = acceleration due to gravity
To apply these equations, it has to be assumed that for a given sample (material), there is no temperature gradient in the weld pool and no localized variation in the liquid viscosity and density (because an increase in temperature reduces $\gamma_{lv}$ and improves penetration (Ref. 11). This is a reasonable assumption since the liquid drawn into the cracks is only from the thin stagnant liquid layer just ahead of the solid-liquid interface along the trailing edge of the weld pool. Therefore, for a given material, capillary liquid "drawing" is only a function of crack width (column diameter) and length of the crack (column length). The surface energy term in both equations is identical for different cracks in a given material. That is, when a crack is narrower (usually the shorter crack is narrower as shown in Fig. 10), capillary "drawing" is to a greater extent. It is also known that finer pores and flaws produce a greater "suction" (Ref. 11). This may be the reason that the shorter/narrower crack has a greater extent of backfilling. Figure 4 reveals that, when a weld has a primary ferritic solidification mode (316-B), the degree of backfilling is somewhat greater than that for a weld solidified in a primary austenitic mode (316-D). The above equations may also be applicable with the same assumptions. However, in this comparison, the surface tension and liquid contact angle have to be considered. It is known that the surface energy is greater and thus the liquid contact angle is smaller for an austenite-austenite boundary than for an...
austenite-ferrite boundary (Refs. 12, 13). Before considering the surface energy term in the equations, the weld metal freezing process has to be considered. A pseudo-binary section of the Fe-Ni-Cr ternary system at 70% Fe as shown in Fig. 12 can be used to predict the solidification behavior of 316-D and 316-B.

Mode 316-B, which lies to the right (Cr-rich side) of the eutectic triangle, solidifies as ferrite and thus nickel and other austenite stabilizing elements segregate into the remaining liquid along the dendrite subgrain boundaries. During the last stage of the solidification, a mixture of austenite and ferrite may form along the boundaries (depending on the extent of segregation) by a eutectic reaction (in the room temperature microstructure); however, usually only austenite can be observed due to transformation of ferrite to austenite during cooling to room temperature or by formation of a divorced eutectic). Likely, in the case of 316-D which solidifies in a primary austenitic mode, during the final stage of freezing the remaining chromium-enriched liquid will form a mixture of ferrite and austenite by a eutectic reaction along the dendrite interstices. Here again, the majority of ferrite will transform to austenite during cooling to room temperature and thus ferrite cannot be detected in the optical microstructures as shown in Fig. 6.

Therefore, the extent of backfilling in both solidification modes (316-D and 316-B) is again a function of crack length and width only. Tables 2 and 4 indicate that the average solidification crack length for the entire weld is greater in the primary austenitic 316-D than in the primary ferritic 316-B. Therefore, it is now clear that a greater extent of backfilling in the primary ferritic weld may not be the result of the solidification mode but because of the shorter average crack length (therefore, a narrower crack) in the primary ferritic weld metal.

Comparing the extent of backfilling between 316-B and 347-E, both solidifying in a primary ferritic mode, 347-E shows a slightly longer absolute back-
filled crack length for a given solidification crack length and location in the weld. However, the percentage of backfilled length to solidification crack length is almost identical for all regions in the weld, because the average solidification crack length in Type 347 stainless steel is greater than that in Type 316. The formation of a high Nb-containing liquid along the boundaries, which forms a low melting NbC,Ni-austenite eutectic during subsequent cooling and solidification, may have also played an important role in the extent of backfilling in 347-E. The evidence for the NbC-austenite eutectic formation along the backfilled crack is shown in Fig. 8.

The above results indicate that when a hot crack-resistant material is required, it is important to control the chemical composition so that the solidification mode is primary ferritic. In such cases, even if a solidification crack forms, it will be shorter/narrower and be healed to a greater extent. Further, when evaluating the weldability of stainless steels by measuring the solidification crack length in terms of maximum crack length (brittleness temperature range) and/or total crack length, the extent of backfilling and healing may also have to be measured and considered.

Conclusions

The evaluation of backfilled cracks in austenitic stainless steels provides the following important results:

1) Extent of backfilling is a function of location in the weld and the temperature gradient. Thus, greater backfilling occurs at the center of a weld because the shallowest temperature gradient exists at the centerline.

2) Extent of backfilling is also a function of solidification crack length and width such that the shorter/narrower the solidification crack, the greater is the backfilling regardless of the location in the weld.

3) A weld solidifying in a primary ferritic mode, as compared to the primary austenitic mode, exhibits a greater percentage of backfilled crack length to solidification crack length due to the occurrence of shorter/narrower cracks.

4) Applied strain level does not significantly influence the backfilled length but at lower strain levels a slight increase in the percentage of backfilled crack to solidification crack length at a given location in the weld was found.

5) For the same applied strain level, with a primary ferritic solidification mode, Type 347 stainless steel has a longer backfilled crack length than Type 316 at a given location in the weld. However, the ratio of backfilled crack to solidification crack length is similar because the average solidification crack length is longer in Type 347 than Type 316.

6) The formation of a Nb-enriched liquid along boundaries, which subsequently forms a low melting NbC-austenite eutectic, may play an important role in the extent of backfilling in the Type 347 alloy.

7) Backfilling is a result of capillary action. The liquid source for the backfilling is the liquid remaining during the final stage of solidification and/or just ahead of the advancing solid-liquid interface along the trailing edge of the weld pool, which is enriched primarily in chromium or nickel, depending on the primary solidification mode.

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