In-situ Observation of Solidification Cracking of Laser Dissimilar Welded Joints*

by Peng Wen**, Kenji Shinozaki***, Motomichi Yamamoto***, Yasutaka Senda**, Tomoko Tamura**, Norio Nemoto****

This study is purposed to develop an evaluation method of solidification cracking susceptibility for laser DWJ of different dilution ratios. By using U-type hot cracking test with in-situ observation, the critical strain for the initiation of solidification cracking was measured locally near the crack rather than the macro strain measured in most other hot cracking tests. Meanwhile, the temperature history during laser welding at the trailing region of the molten pool was measured experimentally. The high temperature ductility curve was achieved based on the above test results of the critical strain and the temperature history. The critical strain rate of temperature drop (CST) was used to evaluate the solidification cracking susceptibility. Moreover, the residual liquid metal at the solidification front during laser welding was observed directly by using in-situ observation with an optical microscope lens. Consequently, all the results showed that solidification cracking susceptibility is the highest when the ratio of Inconel600 takes up roughly 40% in the weld bead among the used Inconel600/SUS347 laser DWJ.

Key Words: Solidification cracking, Dissimilar welded joint, Laser welding, In-situ observation, critical strain

1. Introduction

Dissimilar welded joints (DWJ) have been widely used, but the occurrence of solidification cracking is one of important welding problems in practical applications. Since laser welding is usually adopted without feeding filler wires, the chemical composition of laser DWJ is determined by the dilution ratios of two base metals. So solidification cracking susceptibility is dependent on the dilution ratio of base metals¹-²). However, few published reports have been found on the quantitative evaluation of solidification cracking for laser DWJ so far.

There have been many theories on the occurrence of solidification cracking, and all of them embody a concept of the low ductility of solidifying weld metal due to a coherent interlocking solid network with the residual liquid along the grain boundary³). When the tensile strain developed across the adjacent grains exceeds the low ductility, solidification cracking happens. Various hot cracking tests can supply some indexes, which are regarded as the criterion of the ductility of solidifying weld metal, to evaluate the solidification cracking susceptibility³-⁵). However, most of the indexes, like the length of crack, the crack ratio at the cross section, the critical value of the augmented load, etc, do not have a direct relationship with the solidification cracking.

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Based on the concept of deformation energy, the Trans-Varestraint test is well known to provide the ductility curve of weld metal and be able to comprehensively evaluate solidification cracking susceptibility⁵-⁶). However, the strain obtained is the macro strain of the test piece in the Trans-Varestraint test, which neglects the strain concentration at the trailing edge of the weld pool. The true critical strain for solidification cracking should be the local strain happening near the trailing edge of molten weld pool and within the temperature range between the liquidus and the solidus. By Measurement by means of In-Situ Observation (MISO), Matsuda studied the local strain in the vicinity of solidification cracking tips during TIG welding⁷). It was found that the Trans-Varestraint test can not provide the appropriate strain in the vicinity of cracks.

In this paper, the 2-wire GTA welding process was used to make up specimens of Inconel600/SUS347 DWJ with different dilution ratios. By using the U-type hot cracking test with in-situ observation, the high temperature ductility curve, based on the critical strain at the location where solidification crack occurred, was accurately achieved for the used DWJ. The critical strain rate of temperature drop (CST) was used to evaluate the solidification cracking susceptibility. Meanwhile, since the solidification cracking is directly related to the residual liquid metal during solidification, the residual liquid metal at the trailing edge of the molten pool was observed directly with high magnification during laser welding by using the in-situ observation of an optical microscope lens.
2. Experimental procedure

2.1 Materials and DWJ specimens used

Table 1 shows the chemical compositions of materials used in this study. Inconel600/SUS347 dissimilar welded joints with various dilution ratios were produced by using the 2-wire GTA welding method. By changing the respective ratios of feeding speed of two filler wires of Inconel600 and SUS347, different dilution ratios were obtained as 16%, 36%, and 55% as Inconel600 in the weld metal. The specimens produced by the 2-wire GTA welding method were machined to a standard size as shown in Fig.1. The middle part in the specimen is the dissimilar weld metal. The machined specimens were used for U-type hot cracking test. According to the dilution ratio, the DWJ specimens are named as IS16, IS36 and IS55 respectively in this paper.

2.2 U-type hot cracking test with in-situ observation

The U-type hot cracking test with in-situ observation was carried out during laser welding to measure the critical strain of solidification cracking. The IPG YLR-3000 fiber laser unit was used to perform welding. Table 2 shows the welding condition. Figure 2 shows the setup of experimental equipments. The DWJ specimen was fixed into a U-type hot cracking tester. The solidification cracking behavior was observed just behind the molten pool by using a high-speed camera with a macro lens. A metal halide lamp was used for lightening. The shooting speed was 500fps.

By adjusting the deflection of two restraint beams of the U-type tester, different initial tensile loads were applied on the specimen in order to reproduce different solidification cracking. Moreover, two kinds of U-type jigs (U-type 1 and U-type 2) with different rigidity were used in this research, and the applied strain rate in U-type-2 is higher than that of U-type 1. Thus, various critical strains can be obtained during a wide temperature range with applying different initial loads under the two U-type testers, which guarantees a detailed high temperature ductility curve.

2.3 In-situ observation during laser welding with high magnification

By using an optical microscope lens, the residual liquid metal at the solidification front was directly observed during laser welding. Figure 3 shows the setup of the in-situ observation system. The high speed camera was set vertical to the specimen in order to observe the solidification front clearly at the surface of the specimen. The coaxial lightening device with a half mirror was used to provide the enough lightening. The shooting speed was 3000fps. The used specimens were as the same as those used in U-type hot cracking test. The thickness of the dissimilar welded part in the specimen was manufactured to 1mm. Table 2 shows the welding condition.

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Table 1 Chemical composition of materials used (mass %)

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Ni</th>
<th>Fe</th>
<th>Nb</th>
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<tbody>
<tr>
<td>Inconel600</td>
<td>0.04</td>
<td>0.2</td>
<td>0.2</td>
<td>-</td>
<td>0.001</td>
<td>15.4</td>
<td>8.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inconel600 Wire</td>
<td>0.04</td>
<td>0.25</td>
<td>0.24</td>
<td>0.006</td>
<td>&lt;0.001</td>
<td>15.68</td>
<td>6.4</td>
<td></td>
<td></td>
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<tr>
<td>SUS347</td>
<td>0.05</td>
<td>1.51</td>
<td>0.58</td>
<td>0.031</td>
<td>0.01</td>
<td>19.01</td>
<td>9.93</td>
<td>Bal.</td>
<td>0.56</td>
</tr>
<tr>
<td>SUS347 Wire</td>
<td>0.05</td>
<td>2.3</td>
<td>0.38</td>
<td>0.02</td>
<td>0.01</td>
<td>19.5</td>
<td>10.3</td>
<td>Bal.</td>
<td>0.7</td>
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</table>

Table 2 Welding condition for the U-type hot cracking test

<table>
<thead>
<tr>
<th>Laser power [kW]</th>
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<tr>
<td>Welding speed [m/min]</td>
<td>0.4</td>
</tr>
<tr>
<td>Shape of penetration</td>
<td>Full</td>
</tr>
<tr>
<td>Defocus [mm]</td>
<td>0</td>
</tr>
<tr>
<td>Shielding gas rate [l/min]</td>
<td>Top 50 (Ar)</td>
</tr>
<tr>
<td>Back 15 (Ar)</td>
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</tbody>
</table>

Table 3 Welding condition for in-situ observation of the residual liquid metal

<table>
<thead>
<tr>
<th>Laser power [kW]</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding speed [m/min]</td>
<td>0.18</td>
</tr>
<tr>
<td>Shape of penetration</td>
<td>Full</td>
</tr>
<tr>
<td>Defocus [mm]</td>
<td>0</td>
</tr>
<tr>
<td>Shielding gas rate [l/min]</td>
<td>Top 50 (Ar)</td>
</tr>
<tr>
<td>Back 15 (Ar)</td>
<td></td>
</tr>
</tbody>
</table>

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Fig. 1 DWJ Specimen for the U-type hot cracking test
Fig. 2 Setup of U-type hot cracking test with in-situ observation
Fig. 3 Setup of system for in-situ observation of the residual liquid metal
3. Results and discussion

3.1 Achievement of high temperature ductility curve

With locating the focus of high speed camera near the trailing edge of the molten pool, Fig. 4 (a) shows a snap of images obtained by the in-situ observation. From the picture, the solidification crack is observed clearly behind the well-defined trailing edge of the molten pool. The critical strain of solidification cracking can be measured by using the pictures obtained by the in-situ observation. The measurement method was shown in Fig. 4 (b).

Firstly, when the initiation of the solidification crack is just captured by the high speed camera \( (t=t_1) \), two reference points near the crack were picked up along the tensile direction and the length of the line between the two reference points was measured as \( L_1 \). Then, by rewinding the obtained video to the time \( (t=t_0) \) when the reference points moved to the end of the trailing edge of the molten pool, the length between the two reference points was measured as \( L_0 \). By comparing the \( L_1 \) and \( L_0 \), the critical strain \( \varepsilon_{cr} \) can be obtained as Equation 1 shows.

\[
\varepsilon_{cr} = \frac{L_1 - L_0}{L_0} \times 100\% \quad \text{Equation 1}
\]

Fig. 4 Measurement method of critical strain of solidification cracking
Figure 5 shows the method to obtain the high temperature ductility curve with IS16 as an example. By using the measurement method shown in Fig.4, the development of the strain with time was shown in Fig.5 (a). Since U-type 2 provided a higher external strain rate, it could be found that the crack for U-type 2 occurred earlier than that for U-type 1. Secondly, the strain-time curve was transformed to the strain-temperature curve as shown in Fig.5 (b). The temperature history at the trailing edge was measured by inserting thermocouples into the molten pool. It can be seen that the critical strains were obtained in a wide temperature range by using two kinds of U-type jigs. Then, various critical strains at different temperatures can be obtained with using different initial loads in the U-type hot cracking test.

Figure 6 shows the obtained the critical strains for IS16 specimen. The liquidus (T_L) was measured by thermal analysis, and the solidus (T_S*) was defined as the lowest temperature at which the crack occurred in the U-type hot cracking test. While the true solidus during laser welding is too hard to measure, T_L-T_S* was considered to represent BTR (Brittleness Temperature Range) approximately. Finally, by connecting the obtained critical strains, the shape of high temperature ductility curves could be achieved.

### 3.2 Evaluation of solidification cracking susceptibility

With the method described above, the high temperature ductility curves of the different DWJ specimens were obtained as shown in Fig.7. The solidification cracking susceptibility of the DWJ specimens can be evaluated by comparing the shape of the high temperature ductility curve. Usually there are three indexes used to clarifying the cracking susceptibility: $\varepsilon_{\text{min}}$, which indicates the lowest value of the ductility curve, BTR, which means the brittleness temperature range, and CST, which mentions to the critical strain rate of temperature drop. Since CST can embody both effect of $\varepsilon_{\text{min}}$ and BTR, the solidification cracking susceptibility was evaluated by the CST in Fig.8. The order of the cracking susceptibility was like Inconel600>SUS347>IS55>IS16>IS36. It means that the base metals were less susceptible to solidification cracking than the dissimilar welded joints, while the IS36 was the most susceptible to solidification cracking among the materials used in this study.

Fig. 8 Evaluation of solidification cracking susceptibility by the CST

![Graph showing CST values](image)

Fig. 9 Images of the residual liquid metal at the solidification front

![Images of liquid metal at solidification front](image)

Fig. 10 Length of residual liquid metal by the in-situ observation

![Graph showing length of liquid metal](image)

Fig. 11 T_L-T_S* by the U-type hot cracking test

![Graph showing T_L-T_S* values](image)
3.3 Residual liquid metal at the solidification front during laser welding

Figure 9 shows the images of solidification fronts during laser welding for the used DWJ specimens obtained by using the in-situ observation with high magnification. In Fig.9, the growing dendrite cell appears black and the residual liquid between the dendrite shows white at the solidification front behind the molten pool. The growth of the solidifying dendrite was clearly observed, and the coexistence of liquid and solid were clearly captured. Although it can not determine the approximate range at which liquid and solid coexist, the difference of the length of residual liquid metal can be clearly distinguished among the used materials as the arrows indicate in Fig.9.

Figure 10 shows the length of the residual liquid metal at the solidification front. The length of the residual liquid metal can be arranged as IS36>SUS347>IS16>IS55>Inconel600. The residual liquid metal in the solidifying weld metal seems the longest for IS36; while for Inconel600 the residual liquid metal appears the shortest. Figure 11 shows the comparison of TL-TS* for the used materials, which was obtained by the high temperature ductility curve according to Fig.7. It can be found that the TL-TS* of IS36 was the widest, while that of Inconel600 was the narrowest. The two results, U-type hot cracking test and the direct observation of the residual liquid metal, corresponded with each other very well. Thus, all the results show IS36 is the most susceptible to solidification cracking due to the longest existence of the residual liquid metal, which causes the low ductility of the solidifying weld metal.

4. Conclusions

(1) By using U-type hot cracking test with in-situ observation, the critical strain for initiation of solidification cracking was measured in the local position where solidification cracking happens. The high temperature ductility curve was achieved by connecting the obtained critical strain for the five DWJ specimens used in this research.
(2) The solidification cracking susceptibility was evaluated by CST based on the obtained ductility curves. It was found that dissimilar welded joints had a higher cracking susceptibility than base metals, and IS36 specimens showed the highest cracking susceptibility among the used specimens.
(3) By using the in-situ observation of high magnification, the length of residual liquid at solidification front was observed and arranged. The result was in good agreement with that of U-type hot cracking test, which explains the highest cracking susceptibility of IS36 DWJ specimen.

Reference