Liquation Cracking Susceptibility in the HAZ of High Nitrogen-Containing Austenitic Stainless Steel Welds

Insu WOO*, Tsutomu HORINOUCHI** and Yasushi KIKUCHI ***

Abstract
This study was performed to determine the influence of nitrogen additions on liquation cracking susceptibility in fully austenitic stainless steel SUS310 welds. The nitrogen content varied from 0.023 to 0.325 mass%. Liquation cracking was investigated using bead-on-plate welding, the Gleeble test, and the isothermal liquation test. According to the cracking test, it was found that the liquation cracking susceptibility decreased with increasing nitrogen addition. The Gleeble and the isothermal liquation tests revealed that the liquation crack was closely related to the intergranular liquation. In addition, as the nitrogen addition increased, the grain growth in HAZ decreased. The degree of intergranular liquation in the high nitrogen-containing specimen was less than that of the low nitrogen-containing specimen due to the grain growth reduction effect of nitrogen, which seems to be responsible for less liquation cracking susceptibility in HAZ of the high nitrogen-containing specimen welds.

KEY WORDS: (High nitrogen-containing austenitic stainless steels) (Liquation cracking susceptibility) (Gleeble test) (Isothermal liquation test) (Intergranular liquation)

1. Introduction
The two most serious problems encountered in the welding of high nitrogen-containing austenitic stainless steels (HNS) are solidification cracking in the weld metal and liquation cracking in the heat-affected zone (HAZ). In many studies examining the solidification cracking behavior of austenitic stainless steels, HNSs may be susceptible to solidification cracking. Nishimoto, et al., reported that the nitrogen addition and the primary austenite solidification do not improve the solidification cracking susceptibility of SUS304 laser welds. Similar results are also given by Mastuda, et al., and Brooks.

In contrast, very little information is available on the nitrogen dependence of liquation cracking susceptibility in the HAZ. Liquation cracking susceptibility is dependent on the amount of residual liquid phases and thermal strain occurring in grain boundaries. This susceptibility is increased by factors, such as coarsed grain, S, P and Si that promote the formation of liquid phases in grain boundaries. However, relatively few quantitative research efforts have so far been mounted to determine the relationship between the liquation cracking susceptibility in HAZ and alloying element nitrogen, many aspects concerning the mechanism of liquation cracking in HAZ of HNS welds remain to be clarified.

The present work was undertaken to examine the effect of nitrogen addition on liquation cracking susceptibility in fully austenitic stainless steel SUS310 welds. Special attention has been paid to the effect of nitrogen on hot ductility, grain boundary liquation and grain growth in HAZ during welding thermal cycles.

2. Materials and Experimental Procedures
The chemical composition of HNS (S310N-1, S310N-2 and S310N-3) used in the present study is shown in Table 1. All experimental ingots were hot forged at 1473K to about 30 mm thick, hot rolled at 1473K to 6 mm thick and 150 mm wide. All test specimens were then annealed at 1373K for 3.6ks, which produced a uniform grain size of about 30 μm.

A TIG welder was used to perform bead-on-plate welding. Welding was performed in the longitudinal direction of the plate thickness. The adopted welding
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Table 1 Chemical composition of high nitrogen-containing austenitic stainless steel (mass%).

<table>
<thead>
<tr>
<th>Materials</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Al</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>S310N-1</td>
<td>0.048</td>
<td>0.33</td>
<td>0.80</td>
<td>0.024</td>
<td>0.0010</td>
<td>19.8</td>
<td>25.1</td>
<td>0.005</td>
<td>0.023</td>
<td>0.0105</td>
</tr>
<tr>
<td>S310N-2</td>
<td>0.048</td>
<td>0.32</td>
<td>0.80</td>
<td>0.024</td>
<td>0.0009</td>
<td>19.9</td>
<td>25.1</td>
<td>0.007</td>
<td>0.194</td>
<td>0.0084</td>
</tr>
<tr>
<td>S310N-3</td>
<td>0.048</td>
<td>0.31</td>
<td>0.84</td>
<td>0.024</td>
<td>0.0010</td>
<td>20.1</td>
<td>25.0</td>
<td>0.008</td>
<td>0.325</td>
<td>0.0057</td>
</tr>
</tbody>
</table>

conditions were a welding current of 150A, an arc length of 2 mm and a welding speed of 3.3 mm/s. After welding, four cross sections of specimens cut perpendicularly to the welding direction were examined by optical microscopy to determine the circumstances of weld cracking.

Hot ductility tests were conducted using a Gleeble, which is essentially a high speed, hot tensile tester instrumented so that heating and cooling of the test specimen can be accurately programmed to reproduce the rapid thermal changes that occur during welding. The test employs a cylindrical specimen, 4 mm in diameter and 100 mm long, aligned in the rolling direction. The crosshead speed is 16.7 mm/s and 2 samples at each temperature are tested. The data of interest in the test evaluation are the percentage reduction in area at a specific temperature for on-heating. Reduction in area is the ratio between the fractured surface area (calculated from the measured average diameter of a fractured surface under a low magnification microscope) and the original cross section area of a specimen.

To simulate the grain boundary liquation phenomena occurring in the HAZ, the specimens were heated in an He gas atmosphere at a heating rate of 100K/s in a Gleeble tester in such a way as to produce rapid heating at the corresponding peak temperature, being held for 5s at the peak temperature. Thermal cycling was thereafter applied through rapid water cooling. The foregoing process is referred to in this study as isothermal liquation tests. Cross section prepared at the specimen center were then examined by SEM. The lineal fraction of grain boundary liquation was evaluated by the following relationship through measurement of the total grain boundary length (\( \sum L_2 \)) and the total liquesced length at the grain boundaries (\( \sum L_1 \)) in ten arbitrary fields of view at 1000-fold magnification:

\[
\text{The lineal fraction of grain boundary liquation (\%)} = \left( \frac{\sum L_1}{\sum L_2} \right) \times 100
\]

The microstructure was studied using optical microscopy and a scanning electron microscope (SEM). The specimens were first mechanically polished with emery paper and then etched in an aqueous 10% oxalic acid solution.

3. Results and Discussion

3.1 Bead-on-plate welding test and hot ductility test results

Fig.1 shows a typical SEM micrograph of a weld crack produced in specimen S310N-1 in the bead-on-plate welding test. The weld cracks here occur, not in the weld metal, but invariably in the HAZ. These HAZ cracks show a pattern of propagation along the base metal grain boundaries in the direction perpendicular to the fusion boundary line. To examine these cracks in more detail, relatively long cracks among those occurring in the HAZ were fractographically analyzed. The fracture surface exhibits a fine, wavy pattern on the grain boundary facet, indicating the presence of a thin liquid film prior to HAZ cracking. Such patterns suggest that the crack produced in the bead-on-plate welding test resulted from liquation cracking. The total length of cracks over the bead cross sections were measured, and a plot of the values versus the nitrogen content is shown in Fig.2. The total crack length showed a decrease as the amount of nitrogen content increased. This result indicates that the liquation cracking susceptibility in HNS welds can be improved by increasing its nitrogen content.

The hot ductility behavior of HNSs in the temperature range from 1473K to 1673K is represented by the reduction in area of the fracture surface vs test
temperature relationship shown in Fig.3. The value of reduction area tends to decrease with increasing holding temperature in any of the base materials considered. As far as the amount of ductility recovery is concerned, high nitrogen-containing specimen S310N-3 shows better response compared to low nitrogen-containing specimens S310N-1 and S310N-2. The nil-ductility temperature (NDT) can be defined as the holding temperature at which the reduction of area becomes 0% in the heating process. The effect of nitrogen addition on the NDT is shown in Fig.4. It can be seen that the value of NDT had a tendency to increase with an increase in the amount of nitrogen content. Fig.5 shows examples of SEM observations of the fractured surface of S310N-1. Two modes of fracture were observed. At a temperature of 1523K, failure was primarily ductile rupture. Above 1598K, failure was intergranular. Careful examination of these fracture surfaces at higher magnification (see Fig.5 (d) and (f)) showed a fine, wavy pattern on the grain faces, and evidence of melting along grain boundaries and at triple points, indicating the presence of a thin liquid film prior to crack. These observations clearly suggested the fracture occurred by a liqation mechanism. Furthermore, the dramatic decrease in hot ductility of specimen S310N-1 at temperatures above 1598K is considered to be due to grain boundary liqation from this temperature range.

3.2 Isothermal liqation test results

As described above, the behaviors of liqation cracking and hot ductility in the HAZ of HNS welds is closely related to grain boundary liqation phenomena. To clarify the cause of the liqation cracking susceptibility improved by nitrogen addition, this section describes an investigation of the grain boundary liqation phenomena affecting the specimens in the isothermal liqation test.

Fig. 6 presents the results obtained during measurements of the lineal fraction of grain boundary liqation ratio at different holding temperatures. The straight lines shown in this diagram were obtained through regression analysis of the observed values by the least squares method. These data show the lineal fraction of grain boundary liqation to increase with a rising
Fig. 5 SEM fractographs of Gleeble test specimen S310N-1;
(a) fracture surface in lower magnification of specimen tested at 1523K,
(b) high magnification of (a),
(c) fracture surface in lower magnification of specimen tested at 1598K,
(d) high magnification of (c),
(e) fracture surface in lower magnification of specimen tested at 1623K,
(f) high magnification of (e).
Fig. 6 Effect of nitrogen content and holding temperature on lineal fraction of intergranular liquation: (T_{LH}; intergranular liquation onset temperature).

Liqation also decreases in specimen S310N-1, specimen S310N-2 and specimen S310N-3 order. With regard to the grain boundary liquation onset temperatures, T_{LH} of the specimens considered, specimen S310N-3 has a value of around 1570K, and specimen S310N-1 has value of 1545K. High nitrogen-containing specimen S310N-3 thus has a grain boundary liquation onset temperature some 25K higher than the low nitrogen-containing specimen S310N-1. As grain boundary liquation onset temperature increases, the amount of intergranular liquation decreases, and results in improvement of the liquation cracking susceptibility.

During isothermal heat treatments, grain growth due to grain boundary migration may possibly occur. The grain sizes after isothermal liquation test were accordingly measured. Fig. 7 shows the results of these measurements. This diagram suggests that, for all specimens considered, the grain size increases with an increase in holding temperature. The grain size also decreased in specimen S310N-1, specimen S310N-2 and specimen S310N-3 in that order.

On the other hand, many researchers have suggested that the combination of liquid films along grain boundaries and thermal strain due to the weld thermal cycle can lead to the formation of liquation cracking in the HAZ. The fine-grained specimen has an increased grain boundary area/unit volume, which results in less area covered with the liquid compared with the coarse-grained specimen. In addition, when a fine-grained specimen is welded, the part far from the welded zone has a high yield strength so that the plastic deformation of specimen is smaller. This leads to a low local deformation in the HAZ, thereby providing decreased opportunity for crack initiation in the specimen with smaller grains. It can be concluded that the decrease of liquation cracking susceptibility by nitrogen addition is attributed to the reduction of grain boundary liquation and plastic deformation in HAZ due to the grain growth reduction effect of nitrogen during welding thermal cycles.

4. Conclusions

This study was performed to determine the influence of nitrogen addition on liquation cracking susceptibility in fully austenitic stainless steel SUS310 welds. Main results obtained in this paper are as follows.

(1) According to the bead-on-plate welding test, it was found that the liquation cracking susceptibility in HAZ decreased with increasing the nitrogen addition.

(2) The value of reduction area had a tendency to decrease with increasing holding temperature in any of the base materials considered. The ductility recovery of the high nitrogen-containing specimen S310N-3 showed better response compared to the low nitrogen-containing specimens, S310N-1 and S310N-2.

(3) The isothermal liquation test results indicated that improvement of the liquation cracking susceptibility by nitrogen addition was due to a reduction in the amount of grain boundary liquation.

(4) The decrease of liquation cracking susceptibility by nitrogen addition was attributed to the reduction of grain boundary liquation and plastic deformation in HAZ due to the grain growth reduction effect of nitrogen.
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References