1. 前言

Stainless steel has been widely used in various industries due to its useful properties, such as corrosion resistance, oxidation resistance and high strength maintenance at high temperatures. In particular, the austenitic stainless steel welding technology has been adopted for key components of fuel cells, steam power, and nuclear equipment. However, austenitic stainless steel is potentially susceptible to solidification cracking, governed by the $\text{Cr}_{eq}/\text{Ni}_{eq}$ ratio and the P+S content of steel. The 310S stainless steel has a higher susceptibility to solidification cracking than other types of stainless steel materials, as it contains residual $\delta$-ferrite from solidification due to its fully austenitic structure; further, the presence of any impurity elements such as P and S greatly influence solidification cracking. The susceptibility to solidification cracking during welding is a disadvantage for any application of 310S stainless steel, because the fractures in the material due to solidification cracking are directly related to safety issues.

The initiation behavior of solidification cracking during arc welding of stainless steel and its cracking mechanism have been studied previously. Lippold reported that the cracking is associated with a shift in weld solidification conditions. Shinozaki reported that a coarse columnar grain size in the weld metal shows a high solidification cracking susceptibility compared with a fine grain size. However, a quantitative assessment of a solidification cracking prediction is not adequate. In order to predict solidification cracking occurrences, a high temperature ductility curve and knowledge of the thermal strain curves according to welding conditions are necessary. Depending on the presence of any intersection between these two curves, solidification cracking could be predicted.

In this study, to predict the occurrence of solidification cracking during gas tungsten arc welding (GTAW) of 310S stainless steel in a U-type hot cracking test, the high temperature ductility curve and thermal strain curves were calculated. The critical strain rate ($\dot{\varepsilon}_{CSR}$) of the high temperature ductility curve was measured by an in-situ observation technique. The solidification initiation and completion temperature were calculated by the Kurz-Giovanola-Trivedi (KGT) and solidification segregation models respectively. The thermal strain curve was calculated using a finite element simulation model. The solidification cracking occurrence in the actual U-type hot cracking test during the arc welding corresponded with the prediction results estimated from the metallurgical and thermal elastic-plastic analysis models.

Key Words: Stainless steel, Arc welding, Solidification cracking, Supercooling, Solidification segregation, Finite element simulation model

2. Experimental procedure

In this experiment, 2 mm 310S austenitic stainless steel was used. The chemical composition of the steel is shown in Table 1. The gas tungsten arc welding (GTAW) was used during the U-type hot cracking test. The conditions of the GTAW and the U-type hot cracking test were...
cracking test are shown in Table 2. The solidification cracking was occurred by U-type hot cracking test under the different loaded stress condition (Figure 1). The U-type hot cracking test was conducted three times under each stress conditions and the same results were observed. Fracture surface of the material in the weld bead was observed by scanning electron microscope (SEM). Thermal strain curves were calculated by finite element simulation model (Quick welder software program). A high-speed camera was used to measure the critical strain rate during the U-type hot cracking test (shooting speed: 1000 fps). The images taken using the high-speed camera were converted to the strain curve using the DippMotionPro2D software program. Thermocouple was used to measure the temperature history of the molten pool. Thermo-Calc. software program was used to convert segregation concentration into temperature in the solidification completion temperature calculation.

Table 2 The conditions of the GTAW in the U-Type hot cracking test

| Parameters          | Values |
|---------------------|--------|
| Welding speed (mm/s) | 5      |
| Arc current (A)     | 110    |
| Arc length (mm)     | 1      |
| Loaded stress (kN)  | 12–17  |
| Shield gas          | Ar     |
| Gas flow rate (l/min)| 20    |

3. Results and discussion

3.1 Solidification cracking occurrence in the U-type hot cracking test

Figure 2 shows the weld bead surface according to the stress conditions. The cracks did not occur in the condition of 11 kN, but under the conditions of 13 – 17 kN, the length of the cracks increased as the stress increased.

Figure 3 shows the typical microstructure of a crack surface that occurs during the U-type hot cracking test according to the loaded stress conditions (13 – 17 kN) using SEM. The fracture morphologies in the high temperature area indicate a dendritic structure, which is regarded as solidification cracking. The dendrite structure is also observed in the lower temperature area. From the all figure, dendrites are observed on the fracture surface, which confirms the occurrence of solidification cracking.

3.2 Thermal strain curve calculation using finite element simulation model

3.2.1 Finite element model design

Thermal strain curves according to the bead location and stress conditions during GTAW were calculated using the finite element...
simulation model (software: quick welder). The half size analysis model was designed to reduce the calculation time (Figure 4).

The external load is applied by fixing the specimen on the restraint beams with initial deflection. During GTAW, the specimen is stretched by a transverse tensile load, inducing solidification cracking at the centerline of the weld bead. However, the stress load from the restraint beam decreases due to an expansion of the specimen during welding. Therefore, the stress applied to the specimen during welding is not constant. In order to reproduce this effect, the restraint beam was included in the model. The mechanical properties of 310S stainless steel according to the temperature are shown in Figure 5 \(^\text{24}\).

3.2.2 Validation of finite element simulation model

The weld bead shape of GTAW calculated by the simulation was compared with the experimental result (Figure 6). The calculated geometry of the fusion zone was determined by the melting temperature (1673 K) of 310S stainless steel. The comparison data of the bead shape shows that the simulation and experimental results match well.

The temperature profile and thermal strain curve comparison are presented in Figure 7 and Figure 9, respectively. The thermal strain curve measurement is explained in Section 3.3. The cooling rate was measured by inserting a thermocouple into the molten pool during GTAW. As a result, it can be concluded that the finite element simulation model of GTAW is reliable by comparing the experimental and simulation results of the weld geometry, temperature history and thermal strain curve.

3.3 Critical strain rate measurement by in-situ observation technique

The \( \varepsilon_{CSR} \), which is the minimum ductility required for cracking,
was measured by an in-situ observation technique during the U-type hot cracking test under different stress conditions (11–17 kN)[25-26]. A high speed camera was focused on the trailing edge of the molten pool, and the images obtained by the in-situ observations are shown in Figure 9. Two reference points near the crack initiation were measured along the tensile direction, and the length between these two points was defined as the gage length ($L_0$). The length change $L_1$ during welding was measured, and the strain curve according to time was calculated using Equation (1).

$$\varepsilon(\%) = \frac{L_1 - L_0}{L_0} \times 100$$ (1)

The thermal strain curve according to the gage length is shown in Figure 8. The thermal strain curve measured at 2–3 mm of the gage length shows uniform values due to a uniform strain distribution caused by strain concentration at the grain boundary [27].

In addition, these results corresponded with the simulated results. Therefore, strain curves according to different loaded stresses (12–16 kN) were measured at 2 mm of the gage length (Figure 10).

### 3.4 Theoretical study of solidification cracking susceptibility of GTAW

The solidification brittleness temperature range (BTR) of the material can be expressed by the interval between the solidification initiation temperature and the solidification completion temperature. The BTR of 310S stainless steel was discussed by employing a numerical calculation of the solid/liquid coexistence temperature range. During the welding process, a segregation of the solute elements occurs in the residual liquid due to solute element diffusion from the solid (dendrite structure) to the liquid phase. Therefore, the solidification completion temperature is different from the solidus temperature. The solidification initiation temperature and solidification completion temperature were calculated by the KGT and the solidification segregation models, respectively. The validity of this metallurgical model was confirmed in our previous study [28].

#### 3.4.1 Calculation of solidification initiation temperature in the super-cooled solidification process

The solidification initiation temperature was expressed by the dendrite tip temperature. The Kurz-Giovanola-Trivedi (KGT) model, a dendrite growth theory, was extended to multiple system for the calculation [29-31].

The dendrite tip temperature ($T_{tip}$) can be expressed as the temperature decreased by supercooling ($\Delta T$) from the equilibrium liquidus temperature ($T_{l eq}$).

$$T_{tip} = T_{l eq} - \Delta T$$ (2)

$$\Delta T = \Delta T_c + \Delta T_r + \Delta T_k + \Delta T_{cell}$$ (3)

$\Delta T_c$ is the constitutional supercooling, $\Delta T_r$ is the supercooling due to curvature of solid liquid interface, $\Delta T_k$ is the kinetic supercooling and $\Delta T_{cell}$ is the cellular supercooling. The solidification initiation temperature ($T_s$) can be expressed as the following equation [28].

$$T_s = T_i^{eq} - \sum \frac{m_i^{eq}c_i^0}{1 + \frac{k_i^{eq}f_i - k_i^{eq}(1 - \ln k_i^{eq}/k_i^{eq})}{1 - k_i^{eq}(1 - k_i^{eq})} \gamma_i V_{0} \Delta H_f \frac{G}{V}}$$

$$- \frac{2\Gamma}{R} \frac{T_m^{eq}}{\Delta H_f V_0} V - \frac{GD}{V}$$ (4)

Here, $m_i^{eq}$ represents the equilibrium liquidus gradient, $c_i^0$ the initial composition, $k_i^{eq}$ the equilibrium partitioning coefficient, $k_i^{eq}$ the velocity-dependent partitioning coefficient, $I_v(P_i)$ the Ivantsov solution, $\Gamma$ the Gibbs–Thompson parameter, $T_m$ the liquidus temperature of pure iron, $\Delta H_f$ the enthalpy of fusion, $V_0$ the sonic velocity in liquid, $G$ the temperature coefficient, and $V$ the solidification velocity. The material constants used in the calculations are shown in Table 3 and 4. The calculation conditions are also listed in Table 5. The calculation result of solidification initiation temperature was 1680 K.
3.4.2 Calculation of solidification completion temperature in solidification segregation states of elements

The solidification completion temperature was based on the segregation concentration of the solute in the residual liquid during solidification. The solidification segregation model is based on the non-equilibrium solidification diffusion model proposed by Morishita et al. The finite difference method was used assuming that the dendrite cross-section is a two dimensional hexagonal (Figure 11).

This model was calculated using Fick’s first law of diffusion below equation (5).

\[
J_i = D \frac{c_{i+1} - c_i}{\Delta x}
\]  

(5)

\(D\) is the diffusion coefficient of solute, \(c_i\) is the concentration in segment \(i\) and \(\Delta x\) is the segment width. The solute concentrations of liquid and solid phase at the solid-liquid interface were calculated by the following equation (6)

\[
c_i^L = k_{net}^{sl} \cdot c_i^L
\]

\[
k_{net}^{sl}\text{ is the velocity dependent partitioning coefficient.}
\]

The variation of each solute concentration with the solidification is expressed by the following equation (7)

\[
\Delta c_i = \frac{-2D \Delta t}{\Delta x} \left( \frac{c_{i+1}^p - c_i^p}{S_i} + \frac{c_i^p - c_{i-1}^p}{S_{i-1}} \right) \left( S_i \frac{c_{i+1}^s - c_i^s}{\Delta x_i} + S_{i-1} \frac{c_i^s - c_{i-1}^s}{\Delta x_{i-1}} \right)
\]  

(7)

The \(S_i\) is the surface area from element 1 to element \(i\) (equation 8)
The segregation concentration of each solute element derived by the solidification segregation model was converted into temperature using Thermo-Calc software program and the result of solidification completion temperature was 1520 K.

### 3.4.3 Prediction of high temperature ductility curves in GTAW welding

A high-temperature ductility curve was obtained based on a combination of the solidification initiation and completion temperatures, in addition to the critical strain rate. The solidification initiation and completion temperatures in GTAW were 1680 K and 1520 K, respectively. The BTR calculated by the metallurgical analysis was determined to be 160 K. The horizontal axis of the measured critical strain rate (Figure 10) was converted from time to temperature using the cooling rate (Figure 7). The solidification initiates at 0 s in Figure 10 at a temperature of 1680 K. The time axis is then modified to a temperature axis by calculating the temperature reduction amount according to the cooling rate (420 K/s). Figure 12 shows the high temperature ductility curve of GTAW.

### 3.5 Comparison of thermal strain curve and high temperature ductility curve in GTAW

Solidification cracking can be represented by the intersection of the high temperature ductility curve and the thermal strain curve. Figure 13 shows the high temperature ductility and thermal strain curves according to bead location and loaded stress conditions (Fig. 2).

![Figure 12](image1.png)

**Fig. 12** High temperature ductility curve in GTAW.

![Figure 13](image2.png)

**Fig. 13** Comparison between the thermal strain curves and the high temperature ductility curve in the different loaded stress conditions. (a):11 kN, (b):13 kN, (c):15 kN and (d):17 kN
With each loaded stress condition, the thermal strain curves along the welding direction increased due to an increase in the amount of heat input on the specimen during welding. In addition, these curves were changed by variations in the loaded stress. For the condition of 11 kN, the intersection between the high temperature ductility curve and the thermal strain curve did not appear. However, as the loaded stress is increased, the intersection of these two curves also increases, which implies that the solidification cracking is elongated according to the loaded stress. In Figure 13 (b), at a bead location of 35 mm, the high temperature ductility curve intersects the thermal strain curves at a point when solidification cracking is expected to occur. As the stress increases, the point of intersection of these two curves increases with increasing slope of the thermal strain curve. Therefore, the length of the high temperature crack is also elongated. In Figure 13, the location and length of the solidification cracking observed during the actual U-type hot cracking test (a) were compared with the prediction result (b). Figure 14 shows the corresponding results between the actual U-Type hot cracking test (a) and the solidification cracking prediction model (b). Therefore, it is possible to predict the occurrence, as well as the length of the solidification cracking using the crack prediction model.

4. Conclusion

- A solidification cracking occurrence during the U-Type hot cracking test in the GTAW was observed through the relationship between the high temperature ductility curve and thermal strain curves.
- The high-temperature ductility curve was obtained based on a combination of the solidification initiation and completion temperatures, in addition to the critical strain rate. The thermal strain curves were calculated using the finite element simulation model.
- The intersection between the high temperature ductility curve and the thermal strain curves increased with an increase in the loaded stress. In the actual test, solidification cracking did not occur under the conditions of 11 kN, but the cracks elongated according to the loaded stress. The solidification cracking occurrence in the actual test corresponded with the prediction results.

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