Hot cracking susceptibility in laser weld metal of high nitrogen stainless steels

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Abstract

High nitrogen stainless steels are used as structural materials required to possess high strength and fracture toughness at low temperatures. The solidification mode in weld metals of stainless steels is generally designed to be the primary ferrite solidification mode to prevent hot cracking. The weld metals in some high nitrogen stainless steels, however, exhibit the primary austenite solidification mode because of an austenitizing effect of nitrogen, which enhances hot cracking susceptibility. In addition, laser welding provides the primary austenite solidification mode in weld metals of stainless steels due to the high solidification rate. Therefore, the laser weld metal of high nitrogen stainless steels likely occurs hot cracking.

This study was conducted to make clear an effect of nitrogen and the solidification rate on hot cracking susceptibility in the laser weld metals of type 304 stainless steels varied with nitrogen content. The hot cracking susceptibility was examined by the preloading tensile strain (PLTS) cracking test. The PLTS test results showed that hot cracking susceptibility was remarkably increased with increase in the solidification rate and the nitrogen content. On the other hand, the solidification mode in the weld metal was changed from the primary ferrite to the primary austenite, as the solidification rate was raised. The primary austenite solidification mode was also observed in the weld metals with higher nitrogen content at lower solidification rate conditions. The experimental results indicated that the increase in hot cracking susceptibility is in agreement with the transition of solidification mode from the primary ferrite to the primary austenite in the weld metal. The transition of solidification mode in the weld metals of high nitrogen stainless steels could be predicted by the calculation using the modified Kurz–Giovanola–Trivedi model considering the effect of nitrogen.

Keywords: Hot cracking; Laser welding; Weld metal; High nitrogen stainless steel; Solidification mode

1. Introduction

High nitrogen stainless steels are used as structural materials for many kinds of equipments and apparatuses due to their outstanding mechanical properties and resistance to corrosion and oxidation [1]. Recently, the content of nitrogen alloyed in austenitic stainless steels can be reached to the level of 0.7%, which is more than the maximum soluble content at the melting point of steels, by pressurized electroslag remelting method [2] and the properties of high nitrogen stainless steels have been improved. However, high nitrogen stainless steels have problems like nitrogen loss, pore formation and hot cracking during welding [3–5]. The risk of hot cracking in welding is known to be enhanced in austenitic stainless steels solidified with primary austenite. High nitrogen stainless steels are prone to solidify with primary austenite by the austenite forming effect of nitrogen. On the other hand, in modern welding processes like as laser welding, an increase in cracking tendency of austenitic stainless steels has been predicted at high traveling velocity, because the weld metal was solidified with primary metastable austenite [6]. These facts suggest that the hot cracking susceptibility in laser welds of high nitrogen stainless steels may be enhanced by primary austenite solidification due to not only rapid solidification during laser welding but also the austenite forming effect of nitrogen. The weld cracking behavior in high nitrogen steels in laser welding is, however, still unknown.

The present study has been conducted to make clear the hot cracking behavior of high nitrogen stainless steels in laser welding. Special attention has been paid to
the effect of nitrogen on solidification mode in the weld metal. Hot cracking susceptibility in laser welds was discussed in terms of the nitrogen content and the solidification mode.

2. Materials and experimental procedures

The materials used in this study were type 304 austenitic stainless steels which varied in the nitrogen content at seven levels from 0.024 to 0.34 mass%. The chemical compositions of the materials are indicated in Table 1. The preloading tensile strain (PLTS) cracking test was used for evaluation of hot cracking susceptibility in these stainless steels. Schematic illustrations of the PLTS test and the specimen used are shown in Fig. 1. Specimens were set on the jig with loaded tensile stress prior to welding on the PLTS test. The augmented stress in the PLTS test was varied from 12 to 18 kg/mm². Welding was performed using a CO₂ laser generator with the maximum power of 2.5 kW. Laser welding conditions are indicated in Table 2. The microstructure was studied using an optical microscopy and a scanning electron microscope (SEM). Nitrogen content in the weld metal was measured by the LECO analyzer and an electron probe microanalysis (EPMA).

3. Hot cracking susceptibility of the laser welds

To elucidate the effect of nitrogen on hot cracking susceptibility in the laser welds, the PLTS test was performed. Fig. 2 shows the surface appearance of the laser welds after the PLTS test. A main crack is observed at the center of the weld metal. Some small additional cracks are also observed connecting with the center crack, as shown in Fig. 2. Cross sectional observation of the weld metal indicated that the crack preferentially propagated along the grain boundaries of the columnar crystals, as shown in Fig. 3. The surface of the cracks are shown in Fig. 4, which is characterized by dendritic pattern. These facts apparently indicates that cracks occurred in the welds by the PLTS test are solidification cracks.

The shape of penetration in laser welds varied with the laser welding parameters. Fig. 5 shows two typical types of penetration in laser welded specimens for the conditions indicated in Table 2. One is the thermal conduction type of penetration and the other is the keyhole type of penetration. Then, hot cracking behavior was examined for each typical type of penetration.

Effects of the nitrogen content and the laser traveling velocity on hot cracking susceptibility were shown in Fig. 6. The hot cracking susceptibility in laser welds was markedly increased with an increase in the laser traveling velocity and the nitrogen content in both types of penetration. However,
there is some difference in the critical condition on which hot cracks occurred between weld metals of thermal conduction type and the keyhole type penetrations. That is, the critical condition that hot cracks occurred in the keyhole type weld metal was shifted to the higher nitrogen content range than that in the thermal conduction type weld metal.

Fig. 7 shows that effects of the nitrogen content and the laser traveling velocity on the solidification mode and the hot cracking susceptibility. The solidification mode in the weld metal was changed from primary $\delta$-ferrite (FA mode) to primary $\gamma$-austenite (AF mode), as both nitrogen content and the laser traveling velocity were increased. The critical condition of hot cracks occurred in the weld metal of the thermal conduction type penetration was consistent with the condition of transition from FA mode to FA + AF mode. On the other hand, as to the weld metal of the keyhole type penetration, the critical condition on which hot cracks occurred was consistent with the transition condition of solidification mode from FA + AF to AF.

In order to elucidate the cause of the difference in the relationship between the hot cracking behavior and the solidification mode in laser welds with different penetration shapes, microstructure in the weld metal was further investigated by SEM observation.

Fig. 8 shows the distributions of solidification mode in the weld metal of thermal conduction type and the keyhole type penetrations. In Fig. 8(a), in the case of the thermal conduction type, FA mode was observed along the fusion line and AF mode at the bead center. On the contrary, it was found that AF mode existed along the fusion line whereas FA mode was situated at the center part of the bead in the weld metal of the keyhole type penetration, as shown in Fig. 8(b). That is, even in the weld metal of the keyhole type penetration, hot cracks have occurred in the condition on which solidification mode at the bead center changed from FA to AF.

These results suggested that the enhanced hot cracking susceptibility in laser welds can be attributed to the change in solidification mode from FA to AF at the center part of the bead where cracks mainly occurred.

The reason why there is difference in distribution of the solidification mode between the keyhole type weld metal...
and the thermal conduction type one was next considered. Fig. 9(a) shows that the distribution of the nitrogen content measured by EPMA. The nitrogen content is almost even in the case of the thermal conduction type weld metal. However, in the keyhole type weld metal, the nitrogen content at the bead center was less than that along the fusion line, as indicated in Fig. 9(b). As nitrogen promotes primary austenite solidification, such unevenness in the nitrogen content in the weld metal of the keyhole type penetration seemed to be responsible for that FA mode formed at the center part of bead and not along the fusion line. Although, the reason for the decrease in the nitrogen content at the center part in the weld metal with keyhole type of penetration is not uncertain, it seems to be caused by the nitrogen vaporization due to an increase in surface temperature and the area of the molten pool in this type of penetration.

4. Theoretical analysis for the transition of solidification mode in laser welds

As previously described, the difference in the distributions of the solidification mode between laser welds with the keyhole type and the thermal conduction type of penetration seems to be attributed to unevenness of the nitrogen content in each weld metals. Therefore, in order to clarify more in detail the effect of nitrogen on the solidification mode in laser welds with different types of penetration, a theoretical analysis on the determining
factors of the transition of the solidification mode in weld metals was carried out with taking the effect of nitrogen into consideration.

4.1. Theoretical model and calculations

In the case of high cooling rate process such as laser welding, the metastable austenite is formed in the weld metal as a primary solidification phase, even if the solidification mode has been FA in weld metal using ordinary welding methods. The Kurz–Giovanola–Trivedi (KGT) model is known to be applicable for such rapid solidification process as the transition of the primary phase on solidification might occur. Recently, the modified KGT model which is extended to alloys with multicomponents has been developed [7,8]. The modified KGT model was used for the analysis on the transition of solidification mode in the weld metal of stainless steels. The theories used for the analysis are outlined as follows. According to the model, the functional relationship among dendrite tip radius, \( R \); dendrite growth velocity, \( V \); the liquid concentration at the dendrite tip, \( C_l \); and the undercooling related to the tip radius, \( \Delta T \), was expressed as the following equations

\[
\frac{\pi^2 \Gamma}{P^2 D} V^2 + \frac{mC_0(1-K)\xi_c}{D[1-(1-K)I_{\xi}(P)]} V + G = 0 \tag{1}
\]

\[
C_i = \frac{C_0}{1-(1-K)I_{\xi}(P)} \tag{2}
\]

\[
\Delta T = m(C_0 - C_i) + \frac{2\Gamma}{R} \tag{3}
\]

where \( \Gamma \) is the Gibbs–Thomson coefficient, \( P \) is the Peclet number, \( D \) is the liquid interdiffusion coefficient, \( m \) is the liquidus slope. \( C_0, C_i \) are the initial and liquidus compositions, respectively. \( K \) is the partition coefficient, \( G \) is the temperature gradient, \( I_{\xi}(P) \) is Ivantsov’s solution, \( V \) is the dendrite growth velocity and \( \xi_c \) is the absolute stability coefficient determined by a following equation.

\[
\xi_c = \begin{cases} 
1 - \frac{2K}{\left(1 + \left(\frac{2\pi}{P}\right)^{1/2}\right)^2} & \left( P \leq \frac{\pi^2}{K^{1/2}} \right) \\
\frac{\pi^2}{K P^2} \left( P > \frac{\pi^2}{K^{1/2}} \right) 
\end{cases} \tag{4}
\]

In general, the phase, which has the higher dendrite tip temperature, has an advantage to be primary phase on solidification. Therefore, the primary phase in stainless steels can be predicted by comparing dendrite tip temperatures \( T^* \) of \( \delta \)-ferrite and \( \gamma \)-austenite, by using the numerical analysis with the modified KGT model developed for multicomponents.

Dendrite tip temperature, \( T^* \), is given by the following equation

\[
T^* = T_L + \sum (m_{c,i}C_{i}^* - m_{0,i}C_{0,i}) - \frac{2\Gamma}{R} - \frac{V}{\mu} - \frac{GD}{V} \tag{5}
\]

where \( T_L \) is the liquidus temperature, \( m_{c,i} \) is the velocity dependent liquidus slope, \( C_i \) is the liquid concentration at the dendrite tip, \( \Gamma \) is the Gibbs–Thomson parameter, \( R \) is the dendrite tip radius, \( V \) is the dendrite growth velocity, \( \mu \) is the growth kinetic coefficient, \( G \) is the mean temperature gradient at the interface and \( D \) is the liquid interdiffusion coefficient.

The velocity dependent liquidus slope, \( m_{c,i} \) is determined by following equation

\[
m_{c,i} = m \left( \frac{1 + k_c - k(1 - \ln(k/k_c))}{1 - k_c} \right) \tag{6}
\]
where $k$ is the velocity dependent partition coefficient and is formulated by Aziz as follows

$$k = k_e + \left(\frac{a_0 V}{D}\right) \left(1 + \left(\frac{a_0 V}{D}\right)\right)$$

(7)

where $k_e$ is the equilibrium partition coefficient, and $a_0$ is a length scale related to the interatomic distance.

On the basis of the theories described above, the dendrite tip temperature was calculated with solving Eq. (5), using the dendrite tip radius obtained by solution of Eqs. from (1) to (3). The parameters used for the calculation of the dendrite tip radius and the temperature at the dendrite tip are listed in Table 3.

4.2. Transition of solidification mode (results of numerical analysis)

The transition of primary phase in solidification was calculated by using the theoretical equations described in Section 4.1. Fig. 10 shows the calculated transition line of solidification mode from FA to AF as a function of the Cr/ Ni-equivalent and the dendrite growth velocity in stainless
steels. Nitrogen content is included in Ni-equivalent with the factor of nitrogen being 18 [9]. The dendrite growth velocity on which the solidification mode transition from FA to AF occurred increases with an increase in Cr/Ni-equivalent. Namely, nitrogen alloying has an effect to reduce the dendrite growth velocity which provide

Fig. 9. Distribution of solidification mode in the laser welds; (a) penetration type of thermal conduction (SUS304N2), laser power: 2.0 kW, laser traveling velocity: 25.0 mm/s, distance between focal point and specimen: 4.0 mm and (b) penetration type of keyhole (SUS304N2), laser power: 1.6 kW, laser traveling velocity: 25.0 mm/s, distance between focal point and specimen: 0.0 mm.

Table 3
Parameter values for numerical analysis

| Parameter                      | $\delta$ | $\gamma$ |
|--------------------------------|----------|----------|
| $T_L$ liquidus temperature (K) | 1721.7   | 1719.1   |
| $K_C$ partition coefficient of Cr | 0.99     | 0.83     |
| $K_N$ partition coefficient of Ni | 0.77     | 1.0      |
| $K_N$ partition coefficient of N | 0.195    | 0.435    |
| $m_C$ liquidus slope for Cr (K/mass%) | $-1.2$   | $-4.9$   |
| $m_N$ liquidus slope for Ni (K/mass%) | $-6.9$   | $-6.7$   |
| $m_N$ liquidus slope for N (K/mass%) | $-6819$  | $-4585$  |
| $\Gamma$ Gibbs–Thomson coefficient (mK) | $2.6 \times 10^{-7}$ | $3.2 \times 10^{-7}$ |
| $\Delta S_f$ entropy of fusion (J mol$^{-1}$ K$^{-1}$) | 5.6188   | 6.4409   |

Fig. 10. Calculated phase selection between primary $\delta$-ferrite and primary $\gamma$-austenite in Fe–Cr–Ni–N quaternary system.
the primary phase transition from ferrite to austenite in solidification by lowering Cr/Ni-equivalent.

Fig. 11 shows comparison of the transition of the solidification mode calculated with the experimental results. The calculated transition line of the solidification mode from FA to AF seems to be good agreement with experimental results.

5. Discussion

The hot cracking susceptibility in the weld metals was found to enhance remarkably as the nitrogen content and the laser traveling velocity increased. Comparison between the transition behavior of the solidification mode and the hot cracking susceptibility has shown that the transition of the solidification mode from FA to FA + AF was consistent with the condition on which hot cracking occurred in the case of the thermal conduction type weld metal. In laser welds with this type of penetration, the AF mode region is formed at the center part of the weld metal solidified with FA + AF mode. On the other hand, in the laser welds of the keyhole type penetration, the transition of the solidification mode from FA + AF to AF was better coincident with the condition on which the hot cracking occurred. The FA mode region was found to yield at the center part of the weld metal of the keyhole type penetration, which solidified with FA + AF mode. These results indicate that the difference in the effect of solidification mode on hot cracking susceptibility in laser welds with different types of penetration can be attributed to the mode transition on solidification at the center part of the weld metal.

In general, the higher solidification rate and the lower thermal gradient are obtained at the center part of weld metals. Such condition is preferable for the primary austenite solidification mode; AF or A mode. However, in the keyhole type weld metal, FA mode is preferentially formed in the center part of the weld metal solidified with FA + AF mode. As previously shown, the decrease in the nitrogen content was detected in the center part of the weld metal with keyhole type of penetration. Therefore, the transition of solidification mode was theoretically analyzed by considering the distribution of nitrogen in the weld metal. The distribution of nitrogen in the weld metal of Steel N2 (N:0.0943%) was measured by EPMA, which is indicated in Fig. 12. By using the measured nitrogen content, the transition of the primary phase on solidification was determined by calculation. Thus obtained result is shown in Fig. 12. The distribution of solidification mode seems to be fairly consistent with the experimental result. Then next the relationship between the hot cracking behavior and the theoretically determined solidification mode at the center part of the weld metal was considered for laser welds with the thermal conduction type and the keyhole type of penetration. As the result, as shown in Fig. 13, the condition on which hot cracking occurs seems to coincide with the theoretical transition of solidification mode from FA to AF at the center part of the weld metal in both type of welds.

On the basis of these results, it can be said that hot cracking susceptibility in laser welds of high nitrogen stainless steels can be predicted by the theoretical analysis with taking the distribution of nitrogen in the weld metal into the consideration.

6. Conclusions

The effects of the solidification mode on the hot cracking susceptibility in laser welds of high nitrogen stainless steels were investigated. Hot cracking susceptibility was examined by the PLTS cracking test. Transition of the solidification mode in the weld metals of high nitrogen stainless steels was theoretically analyzed
using the modified KGT model, which is extended to multicomponents. Conclusions obtained in this study are summarized as follows:

1. The transition of solidification mode from primary δ-ferrite to primary γ-austenite in the weld metals of high nitrogen stainless steels was affected by not only the solidification rate but also the nitrogen content. As the results, it occurred at the lower laser traveling velocity than that of ordinary austenitic stainless steels due to the austenite forming effect of nitrogen.

2. The distribution of the solidification mode in the weld metal solidified with FA + AF mode was differed depending on the shape of the penetration; FA mode was formed along the fusion line and AF mode at the center part in the weld metal of the thermal conduction penetration, whereas AF mode was formed along the fusion line and FA mode at the center part in the weld metal of the keyhole type penetration.

3. Difference in the distribution of the solidification mode between weld metals of the keyhole type and the thermal conduction type penetration is attributed to unevenness of the nitrogen content in each weld metal.

4. Hot cracking susceptibility in the laser welds of high nitrogen stainless steels is remarkably enhanced by formation of the region solidified with primary γ-austenite in the weld metals.
The transition of solidification mode from primary δ-ferrite to primary γ-austenite in the weld metals of high nitrogen stainless steels could be predicted by calculation using the modified KGT model considering the effect of nitrogen.

The distribution of the solidification mode in the weld metals solidified with FA + AF mode could be estimated by the calculation using the developed KGT model by taking the distribution of nitrogen in weld metals into the consideration.

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