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Finite Element Method for Hot Cracking Using Temperature Dependent Interface Element (Report II) †

- Mechanical Study of Houldcroft Test -

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Abstract

Based on the interface element proposed for crack propagation problems, a finite element method (FEM) using a temperature dependent interface element is developed. The proposed method is applied to the analysis of the formation and the propagation of hot cracking in welding. In particular, the hot cracking extending from the starting edge of the narrow trapezoidal plate under bead welding is examined using the proposed method. From the present study, the following conclusions are drawn. In case of the trapezoidal specimen with welding from the narrower side, the crack length becomes longer when the welding speed and the heat input is large. This agrees with the phenomenon observed in experiments. In the case of the specimen with welding from the wider side, the welding speed and the heat input influence in the opposite manner.

KEY WORDS: (Hot Cracking) (Houldcroft Test) (Interface Element) (BTR)

1. Introduction

There have been many studies on hot cracking. For example, Senda *et al.*[1] proposed a parameter CST (critical strain rate for temperature drop) under the trans-varestraint test, which is considered as one of the most important parameters indicating the sensitivity to hot cracking. Most of the previous reports were experimental works and empirical formulae were proposed based on the experiments. However, their mechanical meaning was not fully explained. Thus, in this study, the numerical code of a finite element method (FEM) is developed to clarify theoretically the mechanism of hot cracking.

It is impossible to analyze hot cracking by a simple thermal elastic-plastic FEM code, such as has been used for analysis of the deformation and residual stresses under welding[2]. Conventional FEM models behavior of the volume by its nature. Hot cracking involves the formation of a new surface, which must be modeled as a surface problem. Thus, it is essential to model the mechanical behavior of the surface in addition to that of the volume in order to analyze the formation and propagation of the hot crack. Recently, an interface element[3] was proposed based on the fact that the crack propagation can be considered as the formation of new surfaces. But the effects of the temperature on the strength of the interface element were not taken into account. Therefore, in this research, a new temperature dependent interface element is developed and it is applied to analyze the hot cracking problem.

2. Theoretical Formulation

2.1 Modeling of high temperature brittleness

Since the crack is formed when the opening stress exceeds the bonding strength of the grain boundary or the interface, the brittleness of the material at elevated temperature is modeled through the temperature dependent bonding strength of the interface element. Both bonding strength and the yield stress are assumed to be temperature dependent. The BTR is modeled as the temperature range in which the bonding strength becomes smaller than the yield stress as shown in **Fig.1**. In this example, the BTR is between 1200 and 1450℃. The critical strength σ_{cr} is smaller than the yield stress σ_Y in this range.

2.2 Temperature dependent interface potential

To analyze the crack propagation under the applied load, a method using the interface element has been

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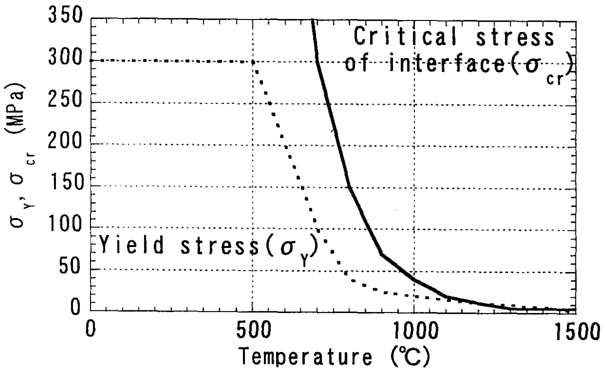


Fig.1 Temperature dependent yield stress (σ_Y) and critical strength (σ_{cr}) of interface element.

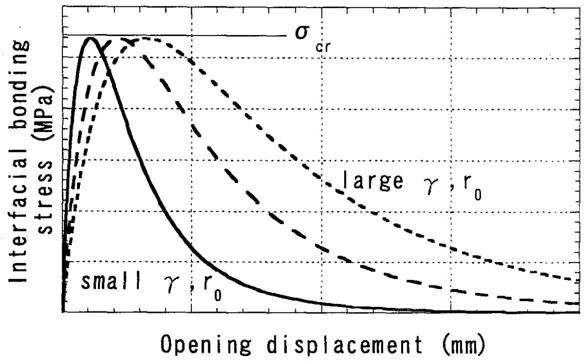


Fig.2 Stress-opening displacement curves of interface element.

proposed. In this method, the formation and the propagation of the crack are modeled by the interface element. The mechanical behavior of the interface element is governed by the interface potential ϕ per unit area of the crack surface. The requirements of the interface potential function are

(1) It involves the surface energy γ, which is necessary to form the new surface as a material constant.

(2) It is a continuous function of opening displacement δ.

Among many functions satisfying these requirements, a Lennard-Jones type potential ϕ is employed. For application to hot cracking problems, the temperature dependency is introduced into the interface element through the surface energy γ. Thus, the interface potential energy ϕ is defined by the following equation.

$$\phi(\delta,T) = 2\gamma(T)\left\{\left(\frac{r_0}{r_0+\delta}\right)^{2n} - 2\left(\frac{r_0}{r_0+\delta}\right)^{n}\right\} \qquad (1)$$

where $\gamma(T)$ is the surface energy per unit area which is temperature dependent. n and r_0 are constants independent of the temperature.

The derivative of ϕ with respect to the crack opening δ, as shown in the following equation, gives the bonding strength per unit area of the crack surface.

$$\sigma = \frac{\partial\phi}{\partial\delta} = \frac{4\gamma n}{r_0}\left\{\left(\frac{r_0}{r_0+\delta}\right)^{n+1} - \left(\frac{r_0}{r_0+\delta}\right)^{2n+1}\right\} \qquad (2)$$

Further, the bonding strength per unit area becomes a maximum under the following condition.

$$\frac{\delta}{r_0} = \left(\frac{2n+1}{n+1}\right)^{\frac{1}{n}} - 1 \qquad (3)$$

The maximum bonding strength σ_{cr} is given by,

$$\sigma_{cr}(T) = \frac{4\gamma n}{r_0}\left\{\left(\frac{n+1}{2n+1}\right)^{\frac{n+1}{n}} - \left(\frac{n+1}{2n+1}\right)^{\frac{2n+1}{n}}\right\} \qquad (4)$$

where σ_{cr} gives the critical strength at temperature T.

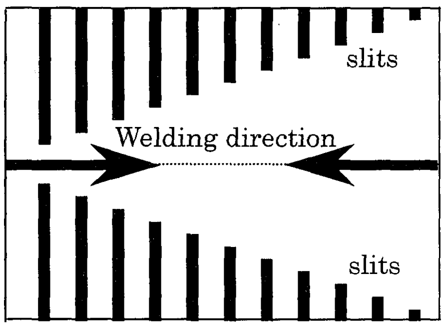


Fig.3 Two types of Fish Bone specimens.

Since σ_{cr} is proportional to $\gamma(T)$ as shown by Eq.(4), the temperature dependency of the surface energy γ is directly reflected on the critical strength σ_{cr}. The relation between the bonding strength s and the opening displacement δ is presented in **Fig.2**. As, it is shown in the figure, the parameter r_0 is a scale parameter. When r_0 is large, the opening displacement at the formation of crack increases. Further, assuming that the surface energy is temperature dependent, the BTR (Solidification Brittleness Temperature Range) can be modeled as shown in Fig.1. In the analysis of hot cracking, the interface elements derived based on the interface potential ϕ[4] are arranged along the path of crack propagation. Then the formation and the propagation of the crack can be simulated naturally without any decision on the behavior of the crack.

3. Experiment

To evaluate the hot cracking susceptibility, Varestraint test and Houldcroft test are widely used. **Figure 3** shows the two types of Houldcroft test using Fish Bone specimen. The difference between the two tests is the choice of the direction of welding. In case of the original test, the edge with shallow slits is selected as the starting edge. In both types, the hot cracking susceptibility is evaluated by the crack length. Though the difference between the two tests are not clearly understood theoretically they are widely used.

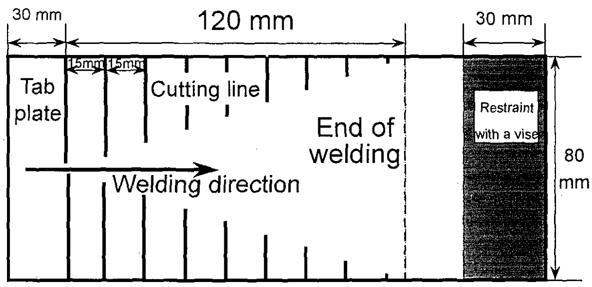


Fig.4 Fish Bone type specimen used for experiment.

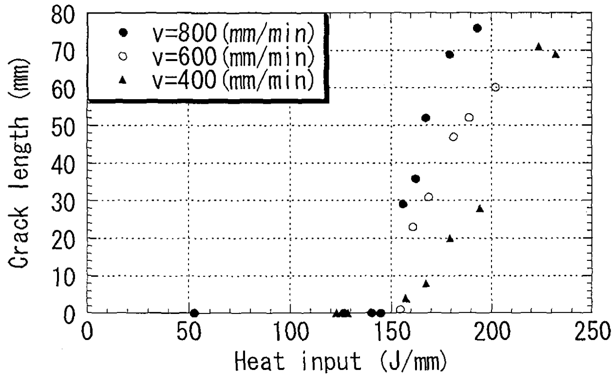


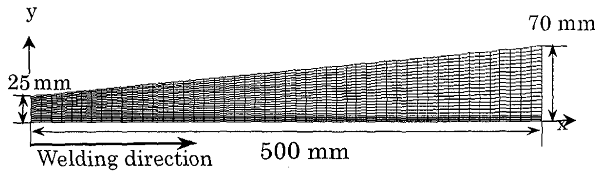
Fig.5 Effect of heat input on crack length observed in Houldcroft test.

According to the test conducted by authors using rectangular steel specimen, the hot cracking likely occur when the width of the plate is small. Thus, the reverse type Fish Bone specimen with deep slit at the starting edge is selected for experiment. As shown in Fig.3, the depth of the slits decreases toward the finishing edge so that the constraint becomes larger. The crack initiated from the starting edge stops after extending to a certain length due to the increase of constraint.

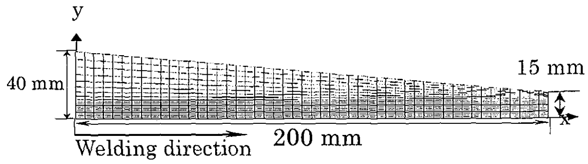
3.1 Test procedure

Figure 4 shows the reverse type Fish Bone specimen used for the experiment. The material is mild steel with 2 mm thickness. The specimen is fixed at one end by a vice and suspended in air so that the dissipation of heat is controlled. The plate is melted by the TIG torch starting from the free end toward the fixed end. A tab plate is built in the specimen with a pair of deep slits. The tab plate is designed to be melted off when the torch reaches the position of the slit. Thus, uniform heat input throughout the welding line, including the starting point, can be achieved. In the experiment, the welding speed and the heat input are systematically changed to examine the effect of these parameters. The net heat input Q is estimated from the welding current I, the welding voltage V and the welding speed v using the following equation.

$$Q = \eta(VI/v) \qquad (5)$$



(a) with welding from narrow side



(b) with welding from wider side

Fig.6 FEM mesh division for simplified Fish Bone type specimens.

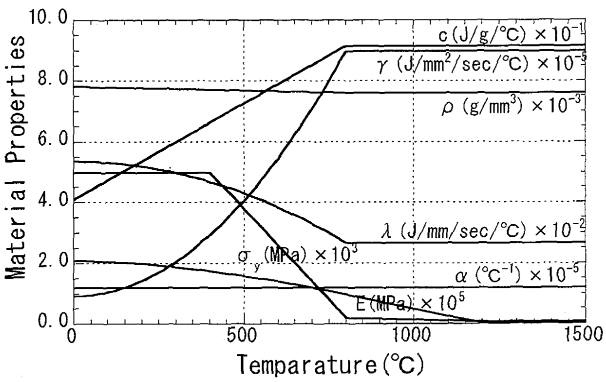


Fig.7 Temperature dependent material properties.

where, η is the heat input efficiency and it is assumed to be 0.6 for TIG welding. The length of the crack is measured by the color check.

3.2 Test results

The relation between the crack length and heat input is summarized in **Fig.5**. As shown by the figure, the cracking occurs when the heat input is greater than 150J/mm which is the minimum heat input to achieve full penetration. It is also shown that the crack length increases with the heat input and the welding speed. This result tells us that the reverse type Houldcroft test can be used for the evaluation of hot cracking susceptibility as well as the original type.

4. Simulation

4.1 Model for analysis

The proposed FEM employing temperature dependent interface element is applied to the analysis of hot cracking. The specimen considered is a simplified Fish Bone specimen which is a narrow trapezoidal plate without fins as shown by **Fig.6(a)**. The size and the mesh division are also shown. Comparing the original and the simplified Fish Bone specimens, they are the same in the

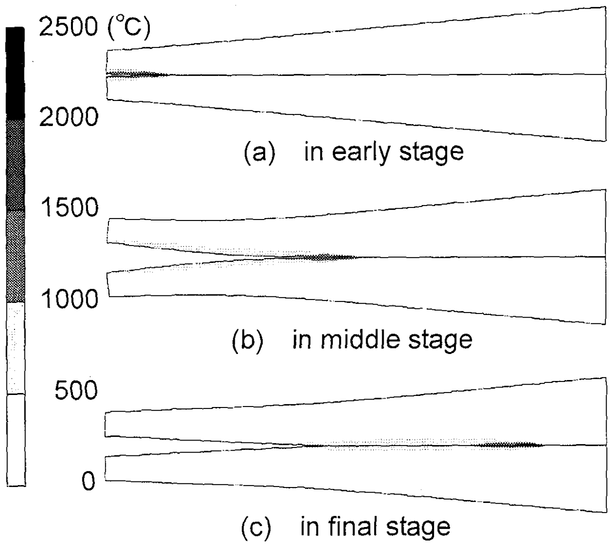


Fig.8 Transient temperature distribution and deformation (v=1500mm/min, Q=160J/mm).

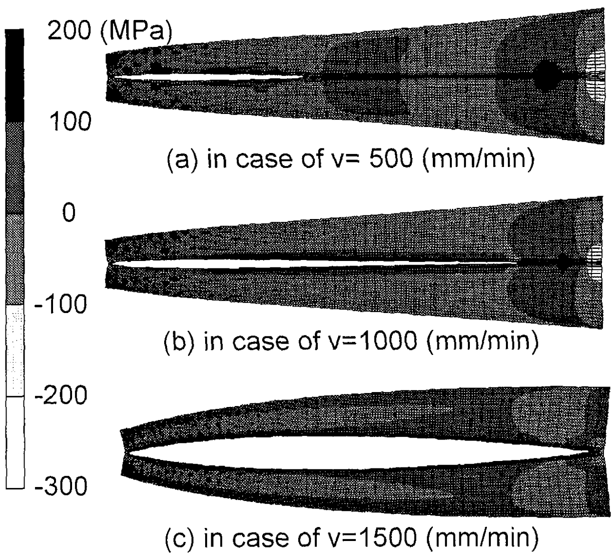


Fig.9 Distribution of stress (σ_y) and deformation after complete cooling (Q=240J/mm).

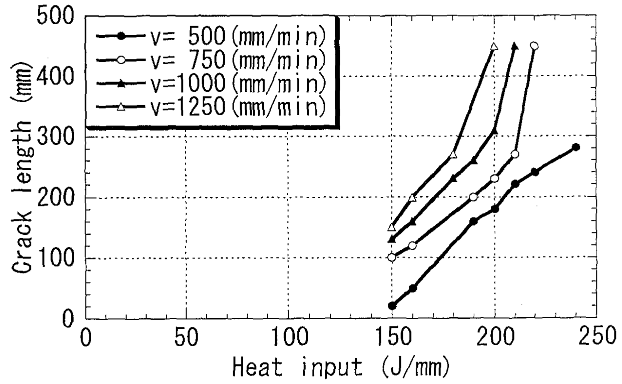


Fig.10 Effect of welding speed and heat input on crack length in Fish Bone type specimen with welding starting from narrow edge.

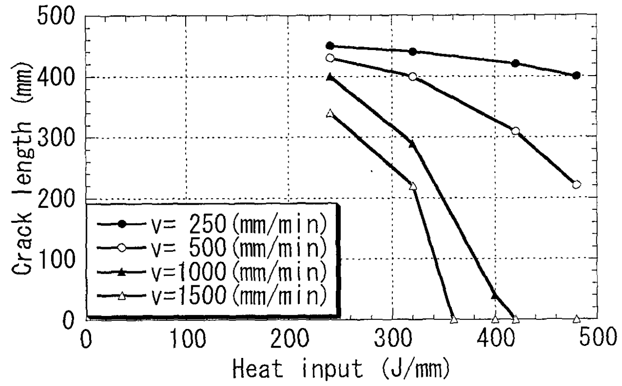


Fig.11 Effect of welding speed and heat input on crack length in Fish Bone type specimen with welding starting from wide edge.

fact that the constraint against the opening deformation of the weld changes in the welding direction. However, the thermal capacity also changes in the welding direction in case of the simplified Fish Bone specimen. The thickness of the specimen is assumed to be 2 mm and the temperature dependent material properties given in **Fig.7** are used in the analysis.

4.2 Reverse type test

The welding speed and the heat input are selected as influential parameters and their influence on crack length in hot cracking test is examined. **Figure 8** shows transient temperature distributions and deformations during the welding. It is clearly observed that the crack stops extending at the middle of the plate while the torch keeps moving. **Figure 9** shows the final deformations and the distribution of stress component in transverse direction after complete cool down. The results are shown for three cases with different welding speeds, namely 500, 1000 and 1500 mm/min. From the comparison among three cases, it is seen that the crack length becomes large when the welding speed is fast. Further, the influence of the welding speed and the heat input on the crack length is summarized in **Fig.10**. In the case of a simplified Fish Bone specimen with the narrower side selected as the starting side, the crack length becomes large when the welding speed and the heat input are large. This result agrees with the experiment discussed in chapter 3.

4.3 Original type test

Similarly, the specimen with the wider side selected as the starting side is analyzed using the FEM model shown by **Fig.6(b)**. To demonstrate the transition between cracking and no-cracking, a smaller size of specimen compared to that in Fig.6(a) is employed. The influence of the welding speed and the heat input on the crack length is summarized in **Fig.11**. The figure shows

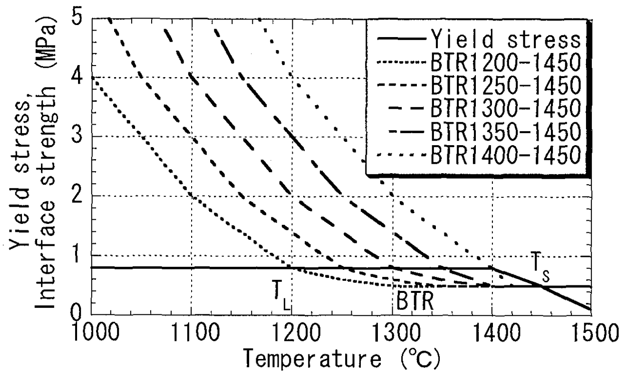


Fig.12 Temperature dependent critical interface strength to clarify effect of BTR width on crack length.

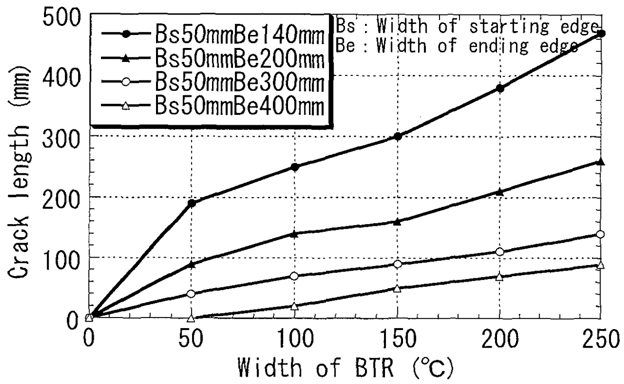


Fig.13 Influence of BTR width on crack length.

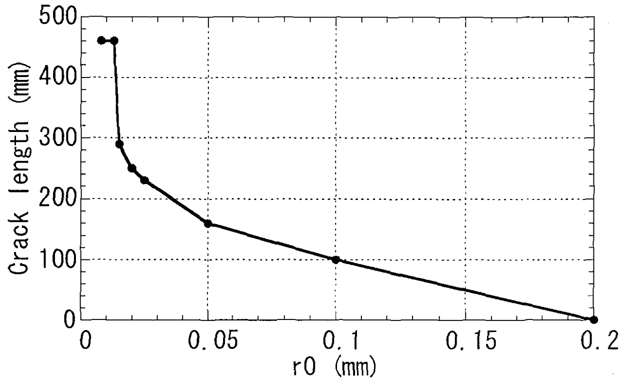


Fig.14 Influence of r_0 on crack length.

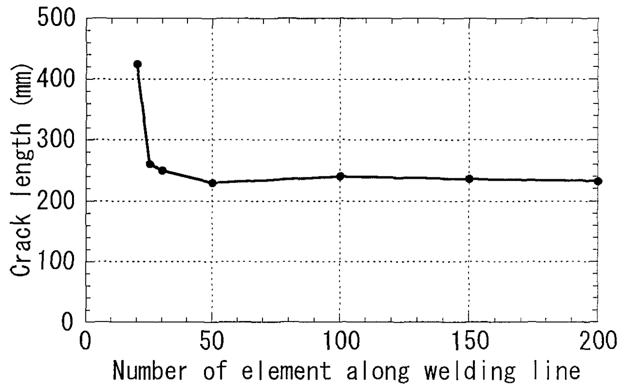


Fig.15 Influence of FEM mesh size on crack length.

that the computed results are opposite compared to the Fish Bone specimen of reverse type. When the welding speed and the heat input are small, the crack length becomes large. In general, the length of the crack in the hot cracking test is governed by the high temperature brittleness of the material and the mechanical constraint of the specimen. According to the present computed results, there is a clear difference in the mechanical constraint between the two types specimens with different welding directions. This results in the difference in the influence of welding speed and the heat input on the crack length.

5. Influence of Interface Parameters

5.1 Influence of BTR width

In the proposed method, the susceptibility to hot cracking is built in the temperature dependent interface element. As it is shown by Eq.(2), the mechanical properties of the interface element are determined by the parameters γ, r_0, n, the critical strength σ_{cr} and the BTR width. Thus, the influence of BTR width and the scale parameter r_0 on the crack length is examined in this chapter.

To examine the influence of BTR width, the cases with different BTR width as shown in **Fig.12** are analyzed and the computed crack lengths are compared. In this serial computation, the liquidus temperature T_L is fixed to 1450℃ and the solidus temperature T_S is changed from 1200 to 1350℃. The type of the specimen considered is the simplified Fish Bone specimen with welding from the narrower side. The length and the full width at the narrow side are 200 mm and 50 mm, respectively. The computations are done for four types of specimens with different width at the finishing end, namely 140, 200, 300 and 400 mm. The computed results are summarized in **Fig.13**. The figure shows that the material becomes more susceptible to hot cracking when the BTR width is large.

5.2 Influence of scale parameter r_0

As shown in Fig.2, the parameter r_0 determines the scale of opening displacement. Therefore, the opening displacement at the failure of the interface is proportional to r_0. **Figure 14** shows the influence of r_0 on the crack length when it is changed from 0.008 mm to 0.2 mm. It can be seen that the crack length decreases with the increase of scale parameter r_0. This means that the parameter r_0 must be adjusted together with the BTR width so that the temperature dependent interface element represents the hot cracking susceptibility of materials to be studied.

6. Influence of Mesh Division

It is quite often experienced in FEM analysis that the computed results depend on the mesh division. To prove the validity of the proposed method, the influence of mesh division on the crack length is clarified. The mesh division in the width direction is maintained the same as the mesh division shown in Fig.6(a). The seven levels of mesh divisions in the welding direction, namely 20, 25, 30, 50, 100, 150 and 200 divisions, are examined. The relation between the crack length and the number of mesh division is shown in **Fig.15**. The mesh size has no influence on the crack length if it is small enough compared to the BTR length, which is the length of the area with the temperature higher than the solidus temperature T_S. The BTR length is about 16 mm in this case.

7. Conclusions

In order to clarify the mechanism of the hot cracking theoretically, a FEM with a temperature dependent interface element is developed. It is applied to the analysis of Houldcroft test using simplified type Fish Bone specimen. Based on the serial computations, the mechanical properties of the interface element, which models the high temperature brittleness of the material, are examined. Also potential usefulness of the proposed method is demonstrated. The conclusions can be summarized as follows;

(1) The proposed method can be applied to the analysis of hot cracking at the starting edge in the simplified type Fish Bone specimen with bead welding.

(2) The general tendency obtained through computation agrees well with experiment.

(3) Both Houldcroft tests with opposite welding directions can be used to estimate the hot cracking susceptibility. But the effect of the welding speed and the heat input appears exactly in the opposite manner.

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References

1) K.Satoh, Y.Ueda, T.Maeda, T.Yada, R.Kamichika and Y.Kim : Studies on Deformation and Cracking in One Sided Welding (Ist Report), Bulletin of Society of Naval Architects of Japan , No.136 (1974-11).

2) K.Shinozaki : Weld Cracking of Ni-base Superalloys During Laser Welding, Preprints of the meeting of J.W.S, No.62 (1998-4).

3) T.Senda and F.Matsuda : Studies on Solidification Crack Susceptibility for Weld Metals with Trans-Varestraint Test (1), Trans of J.W.S, No.41-6 (1972).

4) M.Shibahara, H.Serizawa and H.Murakawa : Finite Element Method for Hot cracking Using Interface Element), Trans of JWRI, Vol.28, No.1, pp.47-53 (1999).