Title	Finite Element Analysis Using Interface Element for Predicting Deformation during Butt Welding Considering Root Gap and Tack Welds(Mechanics, Strength & Structure Design)
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Citation	Transactions of JWRI. 2002, 31(1), p. 63-70
Version Type	VoR
URL	https://doi.org/10.18910/11905
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Trans. JWRI, Vol.31, (2002), No.1

Finite Element Analysis Using Interface Element for Predicting Deformation during Butt Welding Considering Root Gap and Tack Welds †

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Abstract

In shipbuilding, it is necessary to join large plates by butt-welding. It is impossible to avoid the deformation during welding. When the welding condition is not properly selected, end cracking may occur. Thus, it is very important to predict the welding deformation and the formation of end cracking. For the accurate prediction of welding deformation and cracking under real situation in shipbuilding, it is necessary to take into consideration the influence of the root gap and tack welds. In this report, a finite element method (FEM) using a temperature dependent interface element is proposed in order to analyze the influence of the root gap and tack weld. The gap is introduced into the interface element as an additional variable to represent the transient behavior of the root gap during welding. Using the proposed method, the influence of the welding condition, the tack weld interval and the tab plate on the deformation and the formation of end cracking is clarified.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: (Interface element) (Transverse shrinkage) (Tack welds) (Root gap) (Butt-welding) (BTR) (Hot cracking)

1. Introduction

Automation and robotization have recently been introduced in a large way in shipyards to improve the quality and productivity. In the case of butt-welding of large plates, the FCB (Flux Copper Backing) submerged arc welding is employed to mechanize the welding process. By using 2 to 4 electrodes, plates of 20-40 mm thickness can be welded with a single pass. Thus, productivity can be greatly improved by adopting FCB submerged arc welding. However, the tack welds and the tab plates must be arranged in an appropriate manner so that the root gap is kept within certain limits and the end cracking is prevented. Although it is expected that the opening or the closing behavior of the root gap changes with various conditions, the details of the phenomena are not yet clearly understood. To study the influence of the tack welds and the tab plates on welding deformation and end cracking, the authors proposed a FEM using temperature dependent interface element[1-5].

There are alternative methods to describe the opening or closing behavior of the root gap during the welding process[6,7]. The simplest one is to use a dummy element[8] for the groove before the welding torch reaches its location. In this way, the contact between the root surfaces cannot be considered and overlapping may occur. An alternative method is to employ contact elements, which are available in commercial FEM codes. Also, the temperature dependent interface element, which is employed to describe the crack formation, can be used to model the behavior of the root gap during the welding process. This can be achieved by introducing the gap into the interface element as an additional variable.

The proposed method is applied to examine in detail the behavior of the root gap during butt-welding. Through this analysis, the common notion that the groove opens when the welding speed is fast and it closes at low speed is numerically reaffirmed. Also, the influence of the interval between tack welds on transverse shrinkage during butt-welding is investigated. Further, the proposed method is applied to predict the formation of hot cracking at the starting and the finishing ends and the influence of the tack weld and the tab plate

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† Received on May 31, 2002

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Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan

is closely examined.

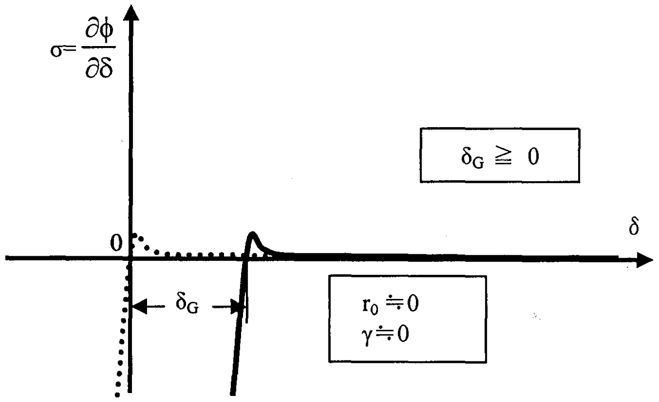
2. Modeling of Root Gap and Tack Weld

To analyze the deformation of large skin plates during butt-welding, it is necessary to model the tack weld and to consider the opening of the root gap. For this purpose, an interface element is introduced in this study. The interface elements, which can model both the opening of the root gap before welding and the joining after welding, are arranged along the welding line. The opening of root gap is represented by the gap δ_G. Thus, δ_G is fixed to be zero at the tack weld. The mechanical property of the interface element is characterized by a potential function ϕ, which is a function of the opening of the interface δ. The derivative of the potential ϕ with respect to δ gives the bonding stress σ at the interface, i.e.

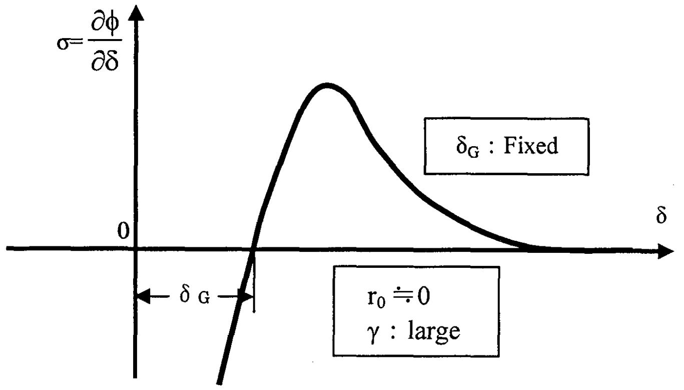
$$\sigma=\frac{\partial\phi}{\partial\delta}=\frac{4\gamma n}{r_0}\left\{\left(\frac{r_0}{r_0+(\delta-\delta_G)}\right)^{n+1}-\left(\frac{r_0}{r_0+(\delta-\delta_G)}\right)^{2n+1}\right\} \quad (1)$$

The potential involves four parameters, namely γ, r_0, n and δ_G. γ is the surface energy, which is necessary to separate the interface. r_0 and n are scale and shape parameters of the potential function. δ_G represents the gap. By selecting proper values for these parameters, different states of the welding joint, such as the condition existing before and after welding can be described. The first type potential models the root gap before the arrival of the weld torch by allowing δ_G to change freely. In this case, there is only a negligibly small resistance against the opening of the root gap while the interface strongly resists the closure of the root gap. The second type is the potential which models the root gap after it is filled with the weld metal and is cooled down. In this case, the root gap δ_G is fixed and the interface can strongly resist both opening and closing deformations.

The first type potential is used until the welding torch reaches the position and it is replaced with the second type potential when the interface element enters the cooling stage. In this way, it is possible to analyze not only the cracking but also the behavior of the root gap during butt-welding considering the root gap and the tack weld.



(a) Potential type- I (before welding)



(b) Potential type- II (during and after welding)

Fig.1 Stress- displacement curve of interface element.

3. Analysis of Welding Distortion

3.1 Behavior of root gap during butt-welding

To clarify the behavior of the root gap during welding, a butt-welding model as shown in **Fig.2** is analyzed. The portion 400 mm from the edge is assumed to be joined by continuous tack welding. Thus, the butt-welding starts from x=400 mm. The residual stress and deformation due to the tack weld are ignored in the present analysis. The following two welding conditions with high and low welding speeds are considered.

case-A : welding speed v=1500 mm/min, heat input Q/h= 320 J/mm^2

case-B : welding speed v= 100 mm/min, heat input Q/h= 900 J/mm^2

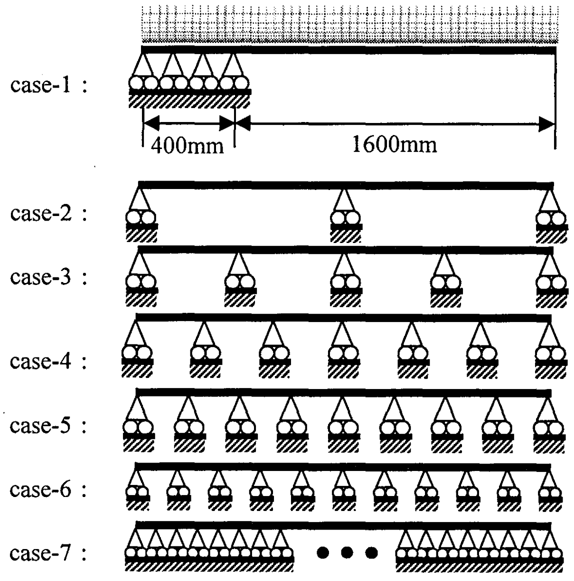
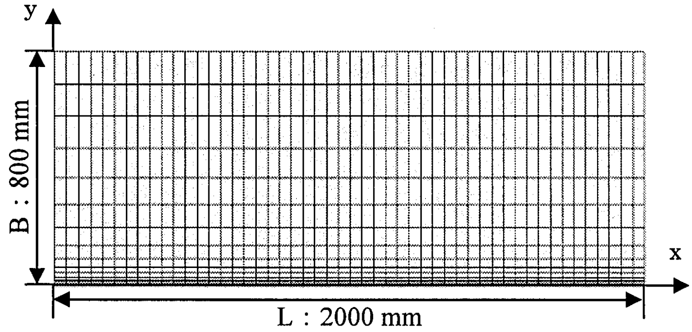


Fig.2 Seven cases of position of tack welds.

The size of the plate and the mesh divisions are shown in **Fig.3**. The problem is analyzed as a plane stress problem. The material is assumed to be mild steel and its yield stress is 300 MPa. The material properties are assumed to be temperature dependent.

The transient distribution of the longitudinal component of the stress σ_x and the transverse component σ_y in case-A at 40 second after the start of welding are plotted in **Figs.4(a)** and **4(b)**, respectively. Similarly, those for case-B at 560 second are shown in **Figs.5(a)** and **5(b)**. In case of the fast welding (case-A), it is clearly seen that the root gap ahead of the torch opens. As is seen from the fact that compressive stress σ_x distributes over a wide area behind the torch, the opening is caused by the thermal expansion in the region near the welding line as illustrated by **Fig.6(b)**. On the contrary, the root gap immediately ahead of the torch is closed when the welding speed is slow (case-B) as shown in Fig. 5(a). Since the tensile stress distributes in the area behind the torch, closing is caused by the thermal contraction as illustrated by **Fig.6(a)**. These computed results reaffirm the understanding that the root gap tends to open when the welding speed is fast and tends to close when the speed is slow. Thus, to prevent the opening of root gap, slow welding speed is preferable.



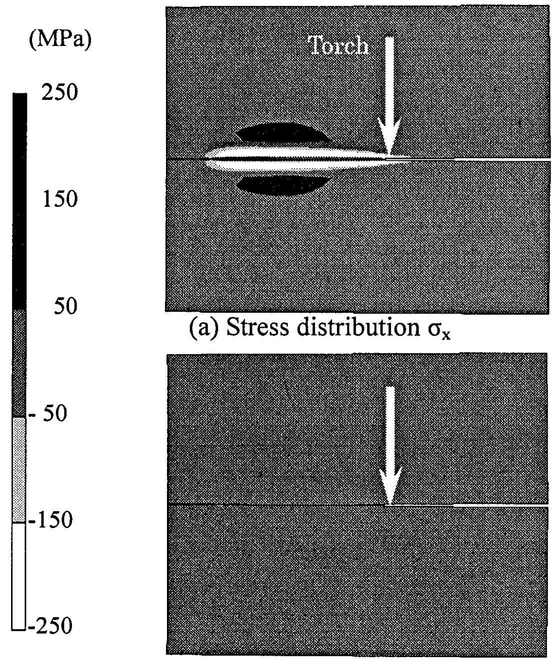
Thickness: 20 mm

Fig.3 FEM mesh divisions.

3.2 Mechanisms of root gap and transverse shrinkage formations

To clarify the mechanisms of root gap and transverse shrinkage formations, their time histories are closely examined and plotted in **Figs.7～10**. Figures. 7 and 8 show those of the root gap for both case-A and case-B. Similarly, those of the transverse shrinkage are shown in Figs. 9 and 10. The abscissa in these figures represents the distance from the edge of the plate normalized by the plate length.

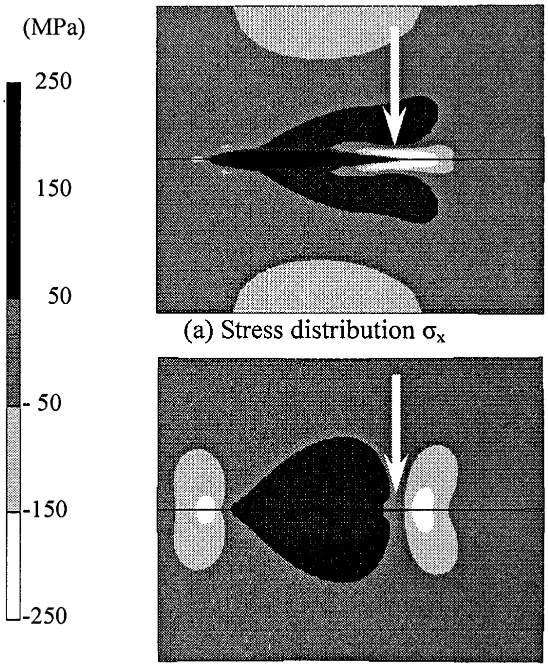
As seen from Fig. 7, the root gap ahead of the torch in case-A generally opens except for the first stage of the welding until the torch reaches the position of x/L=0.6. This may be attributed to the constraint by the tack weld. The effect of the constraint becomes smaller as the welding proceeds and the root gap starts to open. In case of real practice, a small root gap can be tolerable since it



(a) Stress distribution σ_x

(b) Stress distribution σ_y

Fig.4 Stress distribution under high speed welding (t=40sec).



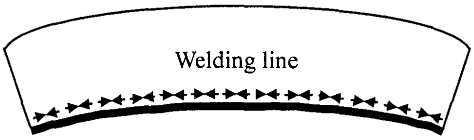
(a) Stress distribution σ_x

(b) Stress distribution σ_y

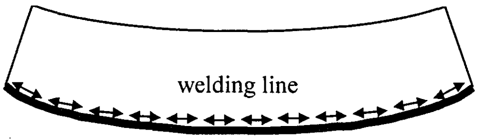
Fig.5 Stress distribution under low speed welding (t=560sec).

can be filled up with the filler metal. However, welding cannot be continued when the root gap exceeds a critical limit.

When the welding speed is small, the root gap behind the torch closes though it opens slightly at a small distance ahead of the torch. As for the transverse shrinkage, the plate expands by the magnitude corresponding to the root gap when the welding speed is fast. In case of slow welding, the transverse shrinkage increases towards the end of the plate. As observed here, both the behavior of the root gap and the transverse shrinkage vary with the welding speed.



(a) Shrinkage type



(b) Expansion type

Fig.6 Modes of welding deformation.

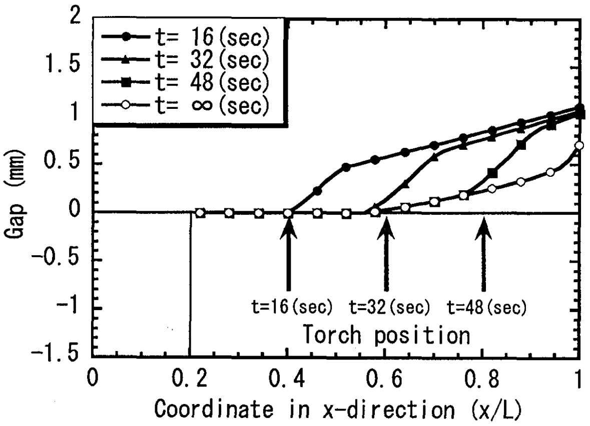


Fig.7 Transient behavior of root gap (v=1500 mm/min).

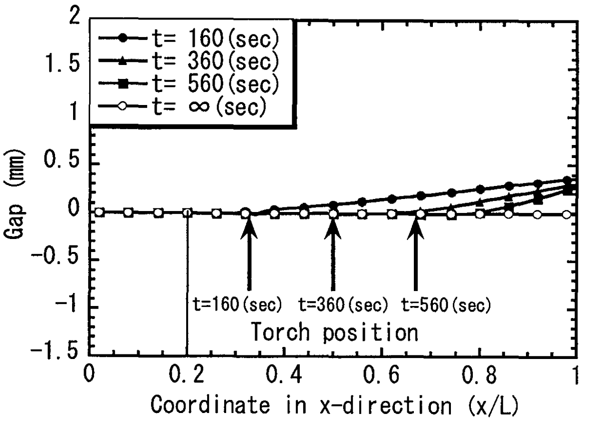


Fig.8 Transient behavior of root gap (v=100 mm/min).

3.3 Influence of tack weld interval on transverse shrinkage

In case of a fast welding speed, the root gap tends to open and a large gap can be produced. To prevent an excessive gap, tack welds are done before welding. The tack weld has an influence, not only on the root gap, but also on the transverse shrinkage. In this section, the influence of the tack weld interval on the transverse shrinkage is examined. The plate to be analyzed is ten times longer than that in the preceding section. The plate length is 20,000 mm. The width and the thickness are 800 mm and 20 mm, respectively. The six cases from case-2 ~ case-7 with different tack weld interval as shown in Fig. 2 are analyzed. The welding condition is the same as case-A.

Figure 11 shows the distribution of the computed transverse shrinkage along the plate for six cases. When the tack welds are dense or continuous as given in case-7, the plate shrinks uniformly along the length. However when only three tack welds are given (case-2, the plate expands in the transverse direction by more than 1 mm at around x/L=0.75 instead of shrinking. This is due to the

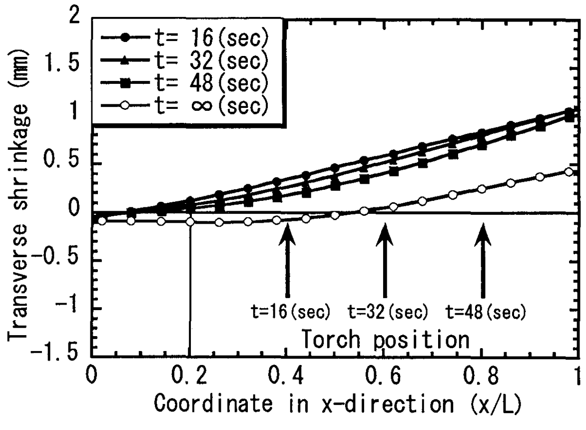


Fig.9 Transient behavior of transverse shrinkage (v=1500 mm/min).

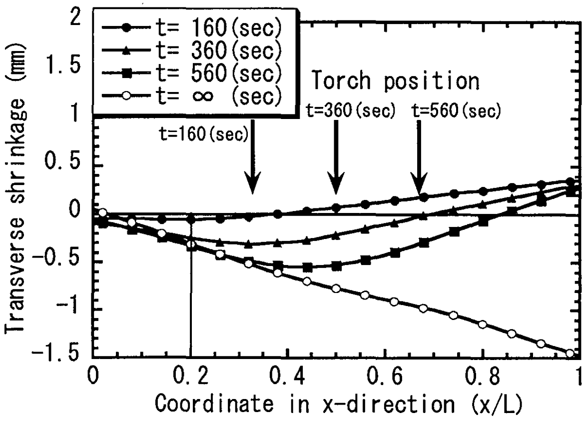


Fig.10 Transient behavior of transverse shrinkage (v=100 mm/min).

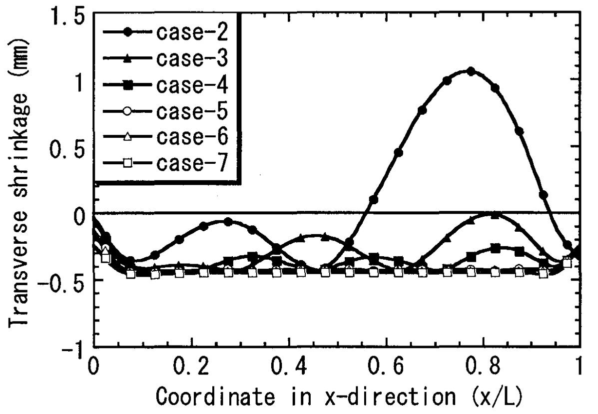


Fig.11 Effect of tack welds interval on transverse shrinkage

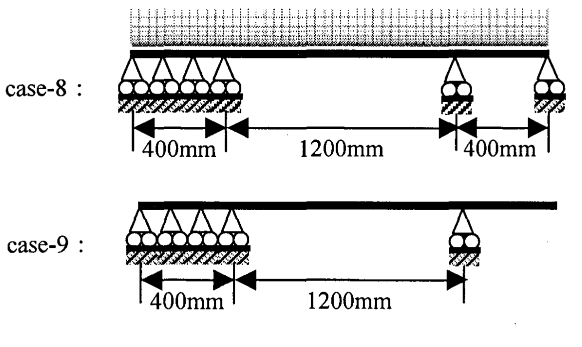


Fig.12 Two cases of tack welds.

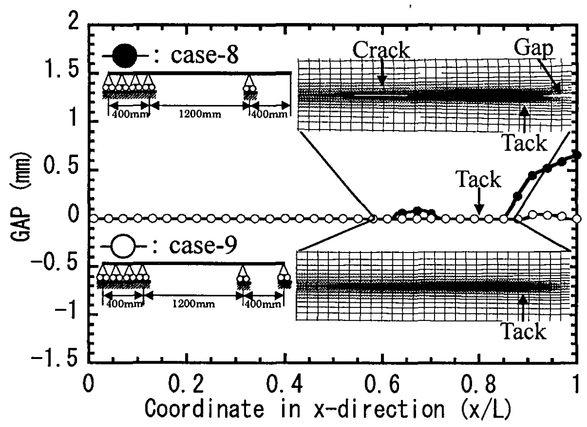


Fig.13 Effect of end tack on hot cracking.

root gap formed under small constraint. With the increase in the number of tack welds, the expansion of the plate decreases. When it is more than 6 (case-5) or 11 (case-6), the plate shrinks almost uniformly as in the case with continuous tack welding (case-7). These results show that tack welding with reasonable spacing is effective in controlling the welding deformation.

4. Analysis of Simple Hot Cracking Problem

It is known that the end cracking is observed in FCB submerged arc welding when the tack welding and the tab plate are not appropriately arranged or the welding condition is not correct. In this section, the influence of the tack weld is investigated using FEM. For this analysis, a temperature dependent interface element representing the root gap is employed. The model analyzed is shown in **Fig.12**. The half breadth of the plate is 1,000 mm. The length and the thickness of the plate are 2,000 mm and 20 mm, respectively. The same welding condition as in case-A is assumed. The temperature dependent interface element is characterized by Brittleness Temperature Range (BTR) and scale parameter $r_0$1-5).

In this analysis, r_0 and BTR are assumed to be 15 μm and 1200-1450℃. The locations of the tack weld are shown in Fig. 12. The location $x/L=0\sim0.2$ is fixed with a continuous tack weld as in case-1. In addition to this, two tack welds at $x/L=0.8$ and 1.0 are added in case-8. While in case-9, the last tack in case-8 is removed. The welding is assumed to be performed to the position 450 mm from the end of the plate.

The computed results are shown in **Fig.13**. The stress distribution superposed on the deformed geometry and the gap along the welding line are shown. When welding is stopped before the torch reaches the last tack as in case-8, no cracking is observed. However when the last tack is melted by the welding heat as in case-9, hot cracking occurs. The hot cracking is produced at the area where the temperature is in between the BTR at the moment when the last tack weld is melted. This result suggests that the proposed method can be applied to analyze the hot cracking problem in practical welding processes.

5. Analysis of End Cracking during Butt Welding

To model the real situation in butt-welding of the large skin plate of a ship structure, the tab plates at both the starting and the finishing ends are considered. The size of the plate is the same as in the preceding section. The length and the width of the tab are both 300 mm as illustrated in **Fig.14**. The tack welds are placed at three places with a 500 mm pitch as shown in **Fig.15**.

The influence of the heat input and the welding speed on the formation of the hot cracking at the starting end is summarized in **Fig.16**. In case of the present model, the form of cracking can be divided into two types. One is the cracking, which starts from the tab and propagates into the main plate as shown in **Fig.17(a)**. The other is the cracking, which remains within the tab plate and does not extend into the main plate as shown in **Fig.17(b)**. The former type appears when the heat input and the welding speed are large. The latter happens when

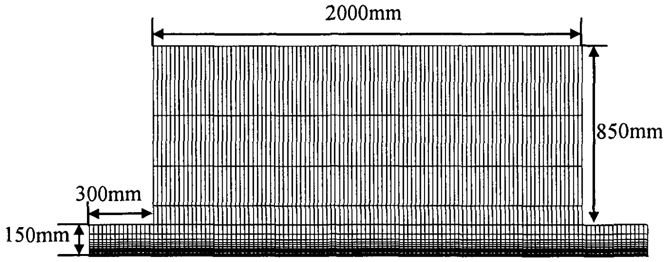


Fig.14 FEM mesh division for end cracking under butt-welding (half model).

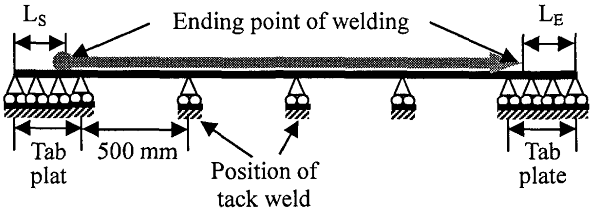


Fig.15 Schematic illustration of position of tack welds.

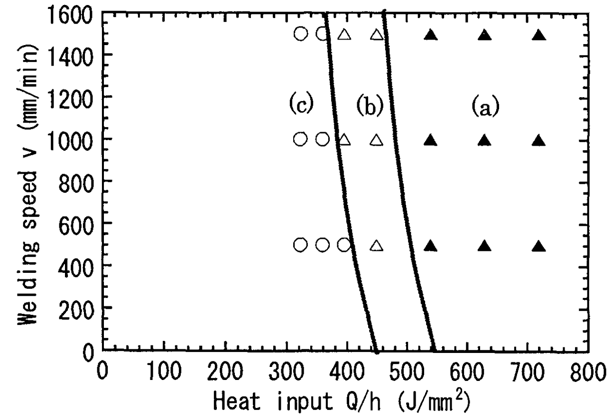
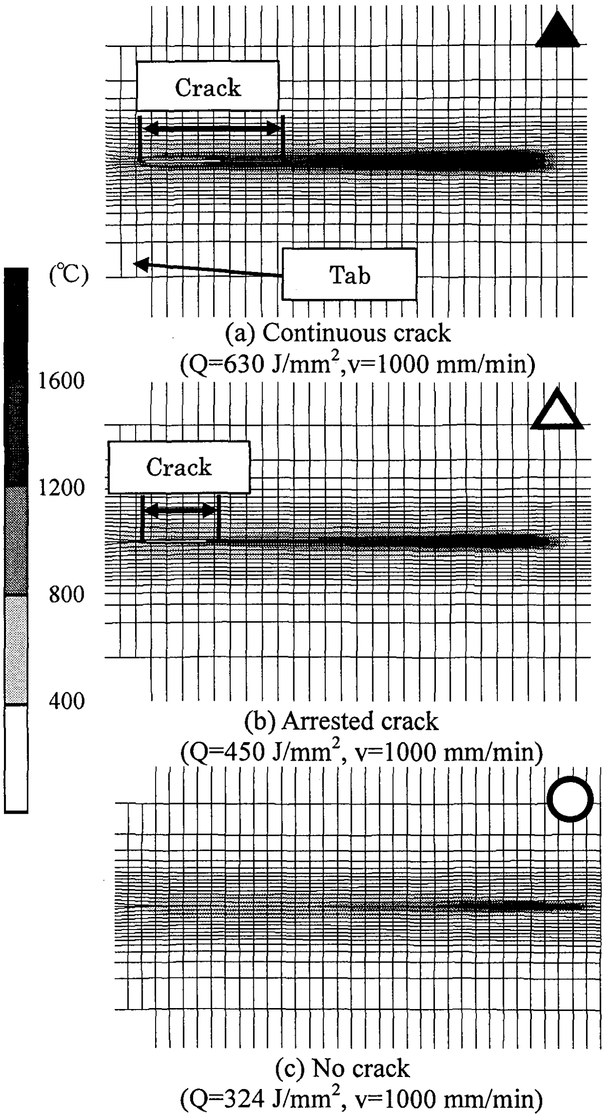


Fig.16 Effect of welding condition on cracking at starting end.



(a) Continuous crack
($Q=630\ J/mm^2, v=1000\ mm/min$)

(b) Arrested crack
($Q=450\ J/mm^2, v=1000\ mm/min$)

(c) No crack
($Q=324\ J/mm^2, v=1000\ mm/min$)

Fig.17 Typical modes of cracking at starting end.

the welding speed is large and the heat input is intermediate. When both the welding speed and the heat input are small, the hot cracking does not occur as the case shown in **Fig.17(c)**.

Since close relation between the mechanical behavior of the end points in the tab plates and the hot cracking formation is expected, the temperature at the end point is closely examined for the cases in which the welding speed and the starting position are changed with keeping the heat input at 360 J/mm^2. Taking the temperature at the end as the abscissa and the welding speed as the ordinate, the relation between the temperature and the hot cracking formation is summarized in **Fig.18**. The symbols ▲ and △ in the figure denote the cases with cracking extending into the main plate and that remaining in the tab plate, respectively. The symbol ○ represents the cases without cracking. Also, the position L_S where the welding starts is indicated as curves. It is seen that the hot cracking is likely to occur when the starting position of the welding becomes closer to the end of the tab. From the temperature point of view, the cracking occurs when the temperature at the end point exceeds BTR or 1,200 ℃.

Similarly the computed results are summarized for the hot cracking at the finishing end in **Fig.19**. As in the case of cracking at the starting end, the cracking is likely to occur when both the welding speed and the heat input are large. As far as the present model is concerned, the hot cracking is formed in the main plate near the connection to the tab plate as shown in **Fig.20(a)**. When

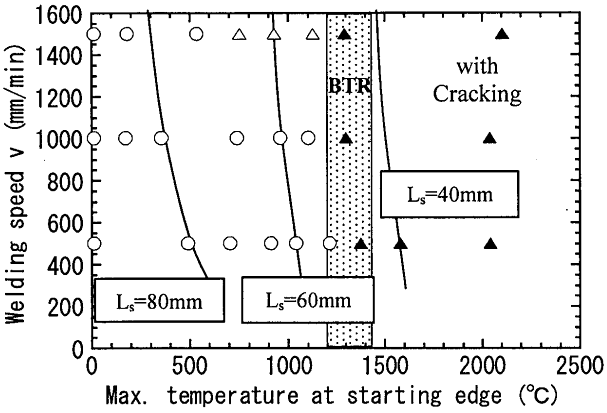


Fig.18 Starting end cracking zone in terms of welding speed and Max. temperature at ending edge.

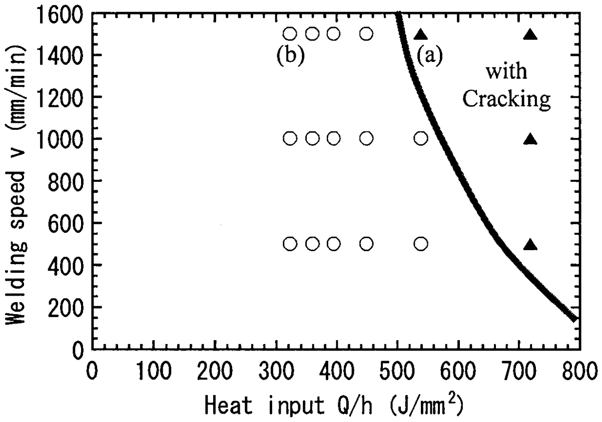
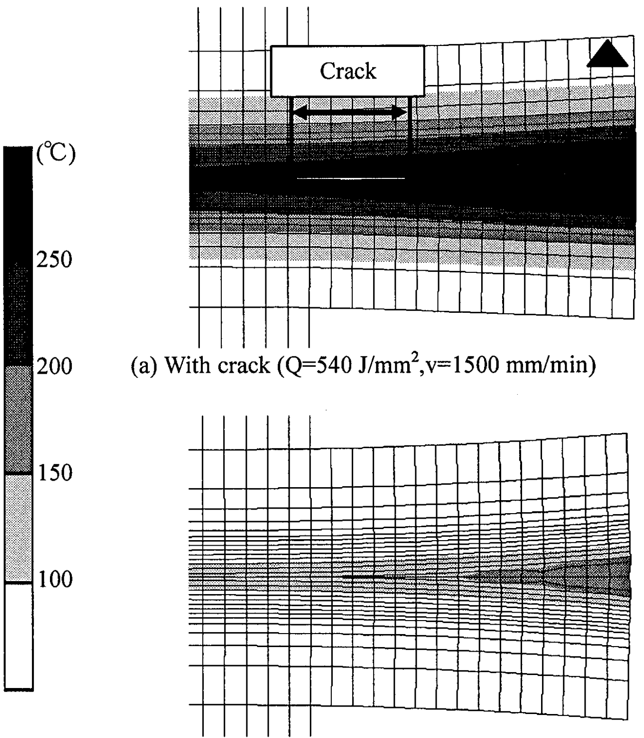


Fig.19 Effect of welding condition on cracking at finishing end.



(a) With crack (Q=540 J/mm^2,v=1500 mm/min)

(b) No crack (Q=324 J/mm^2, v=1500 mm/min)

Fig.20 Typical modes of cracking at starting end.

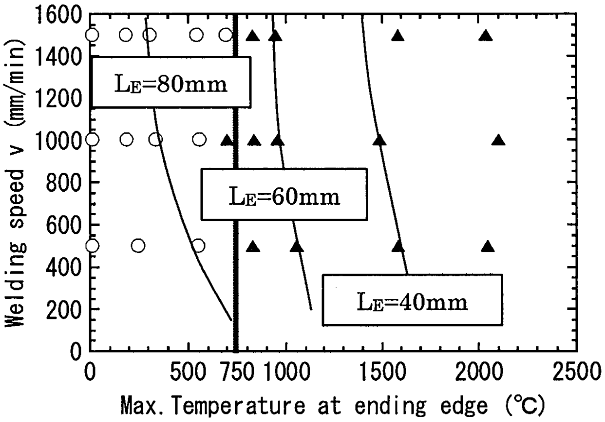


Fig.21 Effect of welding condition on cracking at finishing end.

both the welding speed and the heat input are small, the cracking is not formed as shown in **Fig.20(b)**. **Figure 21** summarizes the influence of the temperature at the end point of the tab plate. In this figure, L_E denotes the position where welding is finished. In contrast to the cracking at the starting end, the mechanical melting point is the critical temperature, which determines the formation of cracking at finishing end. When the temperature at the end of the tab plate exceeds 750℃, hot cracking occurs. These results clearly suggest that the mechanisms of hot cracking formation are different between those at starting and finishing ends.

6. Conclusions

To predict the formation of hot cracking during welding and also considering the influence of the root gap and the tack weld, a FEM using a temperature dependent interface element with root gap as an additional variable is proposed. It is applied to the FCB submerged arc welding of large plates and the influence of various factors, such as the welding condition, the tack weld and the tab plate on the welding deformation and the formation of hot cracking is investigated. Based on the present study, the following conclusions are drawn.

1. Using the proposed method, the transient behavior of the root gap during butt-welding can be analyzed.
2. It is shown numerically that the root gap opens when the welding speed is fast and it closes at low speed.
3. To control the transverse shrinkage during high speed

welding, constraint by tack welding with appropriate spacing is effective.

4. By introducing the root gap into the temperature dependent interface element, the analysis of end cracking considering gap and tab plate is possible.
5. The proposed method is applied to predict the formation of hot cracking at both the starting and the finishing ends. A series of computations are conducted to clarify the influence of the welding condition and the positions of starting and finishing of welding. Based on the computations, it is found that the formation of end cracking is closely related to the highest temperature at the end of the tab plate. In the case of cracking at the starting end, the Brittleness Temperature Range (1,200℃) is the critical temperature which determines the formation of cracking. On the contrary, the mechanical melting point (750℃) becomes the critical temperature in case of the cracking at the finishing end.

Acknowledgement

This work is the result of "Development of Highly Efficient and Reliable Welding Technology" which is supported by the New Energy and Industrial Technology Development Organization (NEDO) through the Japan Space Utilization Promotion Center(JSUP) in the program of Ministry of International Trade and Industry (MITI).

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