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RESEARCH PAPER

Finite element analysis of deformation in early stage of multi-pass circumferential dissimilar welding of thick-walled pipes with narrow gap

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Abstract Three-dimensional thermal elastic-plastic finite element analyses were conducted in order to reveal the mechanism of gap shrinkage in early stage of multi-pass narrow gap welding of thick-walled dissimilar pipes and thick plates. The gap shrinkage up to the 8th pass indicates that the shrinkage of plates becomes to be much larger than that of pipes with increasing the weld passes. In addition, through the decomposition of gap shrinkage to transverse shrinkage and angular distortion, it is found that the gap shrinkage of pipes is mainly governed by the transverse shrinkage, while the shrinkage of plates is influenced by both the transverse shrinkage and angular distortion. Moreover, the serial computational results with various groove shapes suggest that the transverse shrinkage of pipes almost linearly increases with increasing the weld pass, and its increment can be predicted by a linear approximation function obtained by the transverse shrinkage of plates regardless of the groove shape.

Keywords (IIW Thesaurus) Gap · Multirun welding · Distortion · Transverse shrinkage · Finite element analysis · Circumferential welds · Dissimilar materials · Tubes and pipes

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1 Introduction

A narrow gap welding with hot wire addition has been widely employed for joining thick-walled pipes or plates in power generation, petrochemical and nuclear power, because there are many advantages such as minimum joint volume, low heat input, small heat affected zone, small distortion, and so on [1–6]. Although there have been many reports about the welding residual stress after the multi-pass welding with narrow gap [3, 7–13], the shrinkages of gap width in the early stage of welding passes have not been examined precisely since this deformation is largely affected by the welding conditions such as heat input, geometry of structures, restraint condition, and so on [5, 6]. During the multi-pass welding, the restraint condition changes with increasing the passes so that the restraint in the early stage of welding passes is considered to be small and the welding distortion would be influenced by the geometry of the gap. In addition, as one of the practical problems for the narrow gap welding, it is known that the shrinkage of the gap might prevent the insert of TIG torch to the narrow gap [1, 14].

On the other hand, in order to reduce the time and cost for finding the appropriate welding conditions for the multi-pass narrow gap welding of thick-walled pipes, the mock-up tests for butt welding of thick plates with the strong external restraint or the numerical analyses using finite element method (FEM) would be employed [4–6]. However, the detailed method for the external restraint have not been revealed theoretically and the huge computational time is still needed for conducting the three-dimensional thermal elastic-plastic finite element simulation for the multi-pass welding of thick-walled pipes in spite of the recent rapid progress in the computational technologies. In addition, in the case of the multi-pass welding of dissimilar thick-walled pipes, the mixing behavior of two materials is uncertain and its effect on the gap shrinkage is also unknown. So, in this study, the gap shrinkage in the early stage of multi-pass circumferential butt welding of thick-walled dissimilar pipes and thick dissimilar plates were studied by using FEM.

2 Experimental result of gap shrinkage

Figure 1 shows the previous experimental results of gap shrinkage of multi-pass circumferential butt welding of various thick-walled pipes with narrow gap, which are provided by Dr. Fujita et al. This figure indicates that the gap shrinkage of multi-pass narrow gap welding of thick-walled pipes can be divided into two stages and the shrinkage at the first stage was generated until the thickness of weld metal achieved to be about 20 mm. In addition, the shrinkages at the first stage were about 70 % of the total deformation so that it can be concluded that the establishment of the prediction method of the shrinkage at the first stage is one of the most important issues in the multi-pass narrow gap welding of thick-walled pipes.

3 Method for analysis

The three-dimensional models for circumferential welding and butt welding of two dissimilar metal materials are examined. As one example for the multi-pass narrow gap welding of thick-walled pipes, the pipe of case 3 in Fig. 1 is selected as a target model for the dissimilar pipe joint, whose outer and inner diameter are 700 and 400 mm, respectively. According to our previous numerical researches about the three-dimensional finite element analysis of circumferential welding of thick-walled pipes, whose outer and inner diameter were 600 and 240 mm, respectively, it was found that the length of the pipe should be longer than 150 mm for predicting the shrinkage of the gap numerically [4]. So, the cross-sectional view of butt-welded pipes and butt-welded two plates was assumed to be the same as shown in Fig. 2, where the total width was set to be 300 (=150 × 2) mm. On the other hand, the length and thickness of plate are set as 300 and 150 mm, respectively. Based on the experimental result shown in Fig. 1, the weld metal up to 20 mm from the inner or bottom face was modeled in order to reduce the number of nodes and elements. Figure 3 shows an enlarged view of the initial groove shape and a height of the root face is 2.5 mm. In addition, the groove angle changes at the point which is 20 mm from the bottom. The analyses were carried out up to the 8th pass when the thickness of deposited filler metal became 20 mm. In order to demonstrate the temperature distribution near the weld metal precisely, the minimum size of element in cross-sectional plane was set as 1.25 mm, while that along circumferential axis was assumed to be 1.5° so that the circumferential length of element at 20 mm from bottom was about 5.76 mm. On the other hand, the length of the element in the plate model was 5 mm. Then, the total number of elements for FEM models of butt-welded pipes and plates were 275,520 and 68,880, respectively, as shown in Fig. 4.

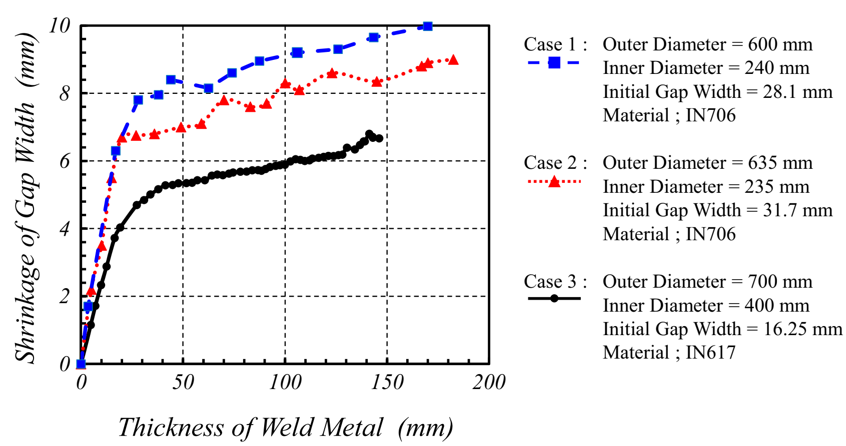


Fig. 1 Shrinkage of gap width at the surface during multi-pass narrow gap welding of thick-walled pipes

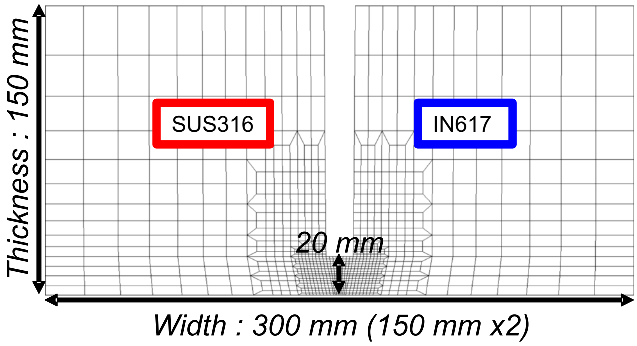


Fig. 2 Cross-sectional view of finite element models for butt-welded pipes and plates

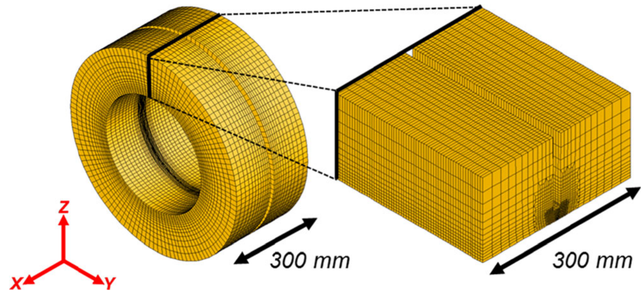


Fig. 4 Finite element models of butt-welded pipes and plates

In this research, as one example of the corrosion-resistant components, the dissimilar materials were assumed to be SUS316 and IN617. As shown in Fig. 2, the left and right parts were set to be SUS316 and IN617, respectively. In the practical manufacturing process, the filler metal might be selected as IN617 due to the weldability of SUS316 and IN617. However, in this research, the weld metal was assumed to the following three cases as shown in Fig. 5. Namely, the weld metal in the first model was simply divided into SUS316 and IN617 which is case A. In case B, the physical properties of the weld metal were assumed to be the average values of SUS316 and IN617, and the weld metal was set to be only IN617 in case C. So, the temperature-dependent materials properties of SUS316, IN617, and the average were set as shown Fig. 6 according to our experimental measurements and the information provided by Dr. Fujita et al. The work hardening was not taken into account in this research since the work-hardening behavior does not so affect the welding distortion. In addition, the welding conditions were set as shown in Table 1 according to the previous experimental test conducted by Dr. Fujita et al.

As for the thermal elastic-plastic finite element analyses, an in-house code was employed based on ISM (Iterative Substructure Method) [15, 16] in this research, and the accuracy of our code is already revealed through the comparison with not only experiments but also other commercial codes, where the element type was set as linear [4, 17, 18]. In order to demonstrate the multi-pass welding numerically, the elements representing the filler metal in the groove were deactivated before the welding, and when the weld bead was deposited, the corresponding elements were activated [12]. The heat input was set as the volumetric heat sources and the outdoor temperature was assumed to be the room temperature. As for the narrow gap TIG welding with hot wire, both the filler metal from the hot wire and the arc of shielding gas give heat energy to the base metal. So, in the thermal analysis, not only the elements representing the weld metal but also the elements near the weld metal were selected as the heat input area according to our previous study as shown in Fig. 7 [4–6]. As for the mechanical boundary conditions

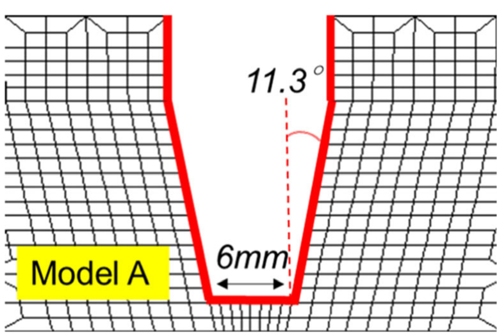


Fig. 3 Groove shape for multi-pass narrow gap welding in finite element model of Fig. 2 (model A)

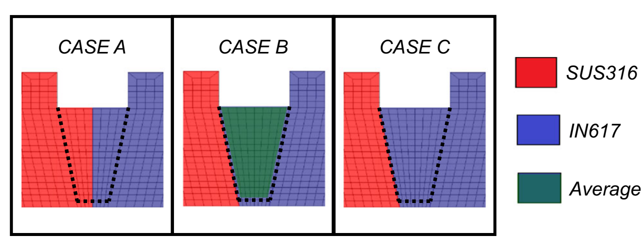


Fig. 5 Schematic illustration of weld metal types studied

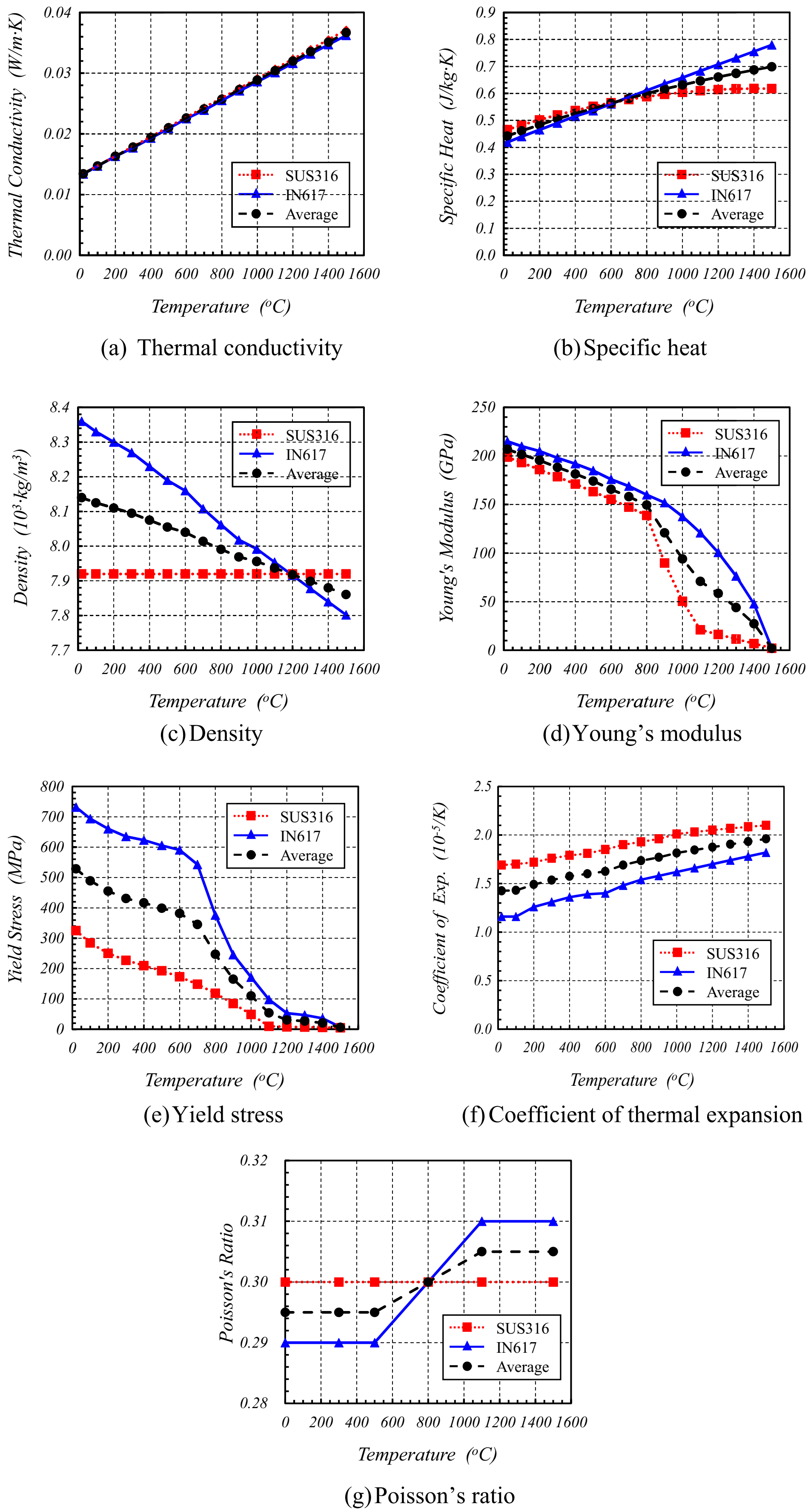


Fig. 6 Temperature-dependent material properties of SUS316, IN617, and average used for thermal elastic-plastic finite element analyses

Table 1 Welding conditions of multi-pass narrow gap welding up to the 8th pass

Number of passes	Current (A)	Voltage (V)	Welding Speed (mm/min)
1	205	9.6	72
2	160	9.4	80
3	160	9.4	80
4	160	9.4	119
5	160	9.4	63.5
6	160	9.4	63.5
7	160	9.4	63.5
8	160	9.4	63.5

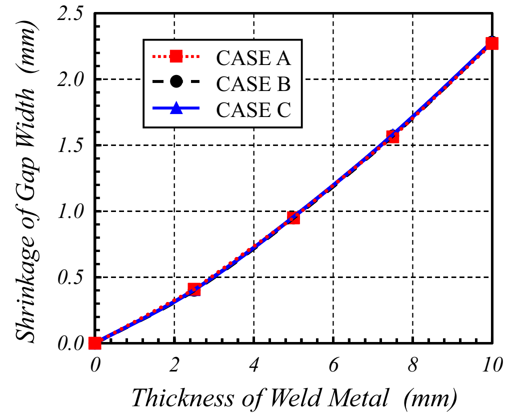


Fig. 8 Effect of weld metal type on gap shrinkage during multi-pass welding up to the 4th pass

in the elastic-plastic analyses, only the rigid body motion was prevented.

4 Results and discussions

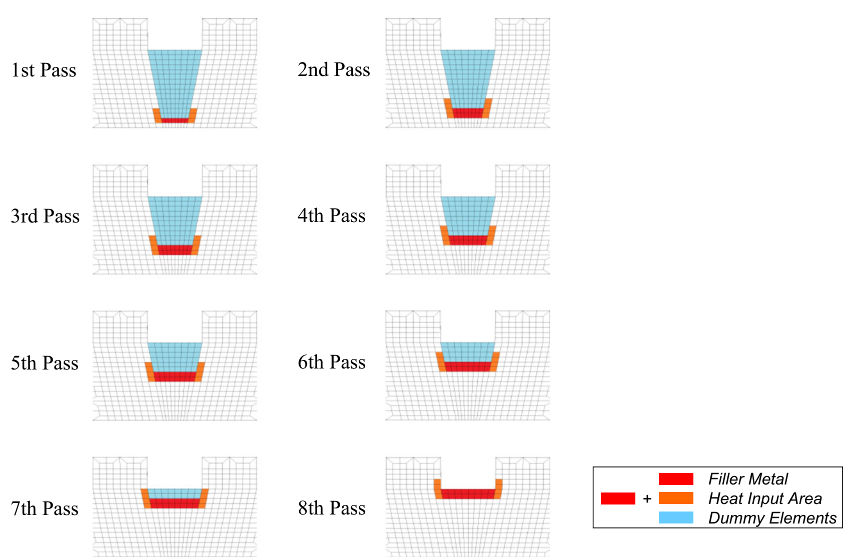
4.1 Influence of material properties of weld metal

In this research, three models were studied in order to examine the effect of weld metal type on the welding distortion in the multi-pass narrow gap welding. As the deformation in the early stage of multi-pass welding, the shrinkage of the gap at the outer surface up to the 4th pass where the thickness of weld metal achieved to 10 mm were computed and summarized in Fig. 8. The three results show almost the same value. Although the heat input might vary according to the type of filler metal in the practical process, the same heat input was assumed in the three cases so that the gap shrinkage seems to be independent of the weld metal type. Then, it can be concluded that the simple model which is case A would be enough to examine the gap shrinkage in the early stage of multi-pass circumferential butt welding of thick-walled dissimilar pipes.

4.2 Influence of joint geometry

Figure 9 shows the maximum temperature distributions near the groove at each pass on the middle point of the weld line in the butt welding of thick-walled pipes. The distributions in the butt welding of thick plates were the same as those shown in Fig. 9. From this figure, it was found that the temperature of weld metal achieved to the melting points of SUS316 (1450 °C) and/or IN617

Fig. 7 Schematic illustration of heat input area during multi-pass welding up to the 8th pass



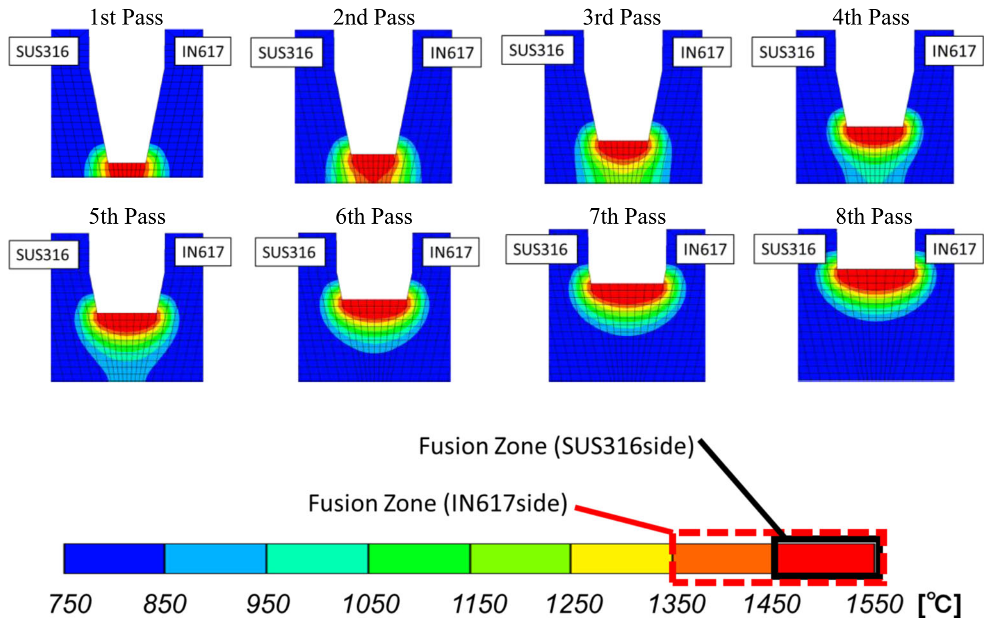


Fig. 9 Maximum temperature distributions near the gap during multi-pass welding up to the 8th pass

(1350 °C), and the slight part attaching with the weld metal was melted.

In order to identify the difference of gap shrinkage between the multi-pass narrow gap welding of thick-walled pipes and thick plates, the gap shrinkages in the early stage up to the 8th pass were computed and the results were summarized in Fig. 10. The result of butt welding of pipes is the average of the shrinkages at each 30° from the start to the end of the weld line. On the other hand, the gap shrinkage of the plates is that at the middle point of the weld line because the shrinkage slightly and linearly increased with increasing with weld line. Figure 11 shows the distributions of the gap

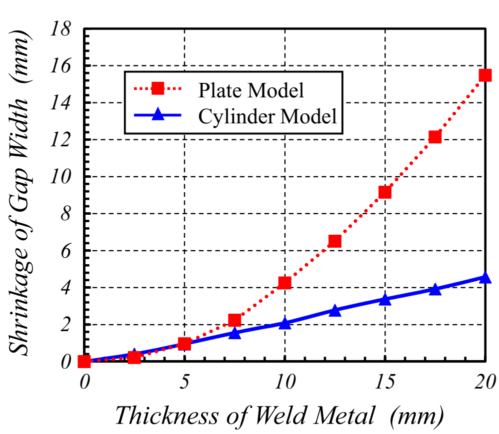


Fig. 10 Effect of joint geometry on gap shrinkage during multi-pass welding up to the 8th pass

shrinkage of thick-walled pipes and thick plates after the 8th pass along the weld line. Figure 10 indicates that the gap shrinkage of plates became to be much larger than that of pipes with increasing the welding passes, although the shrinkage of plates was well coincident with that of pipes until the 2nd passes. In order to identify the main reason of this difference, the shrinkage of gap was decomposed to be the sum of transverse shrinkage and angular distortion according to Fig. 12 from the engineering viewpoint [4, 6]. The transverse shrinkage and angular distortion decomposed were summarized in Figs. 13 and 14, respectively. As shown in Fig. 14, the angular distortions of SUS316 and IN617 can be separately decomposed. Figure 13 indicates that the transverse shrinkage of pipes has a very good agreement with that of plates until the 4th pass. So, it can be concluded that the transverse shrinkage of pipes might be predicted by that of plates if the welding conditions and the cross-sectional views are same. In addition, Figs. 10 and 13 suggest that about 98 % of gap shrinkage was contributed to the transverse shrinkage in the case of butt welding of thick-walled pipes. On the other hand, the angular distortion of plates drastically increased with increasing the welding pass after the 2nd pass, while that of the pipes almost did not change regardless of the materials. Then, the main reason of the difference of the gap shrinkage shown in Fig. 10 seems to be the difference of internal restraint between pipes and plates.

Moreover, from Fig. 13, it is considered that the transverse shrinkage of pipes might be predicted by

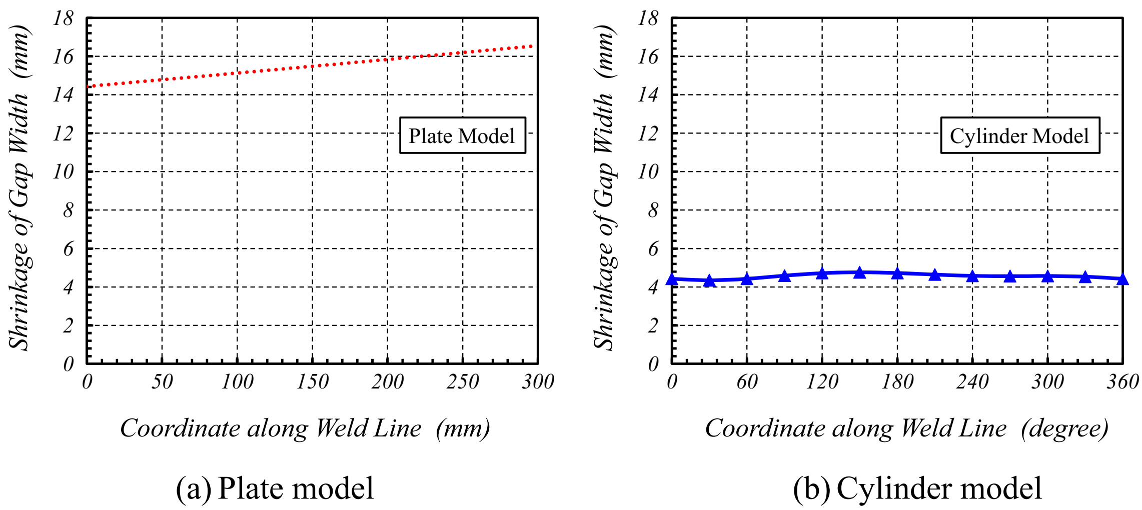
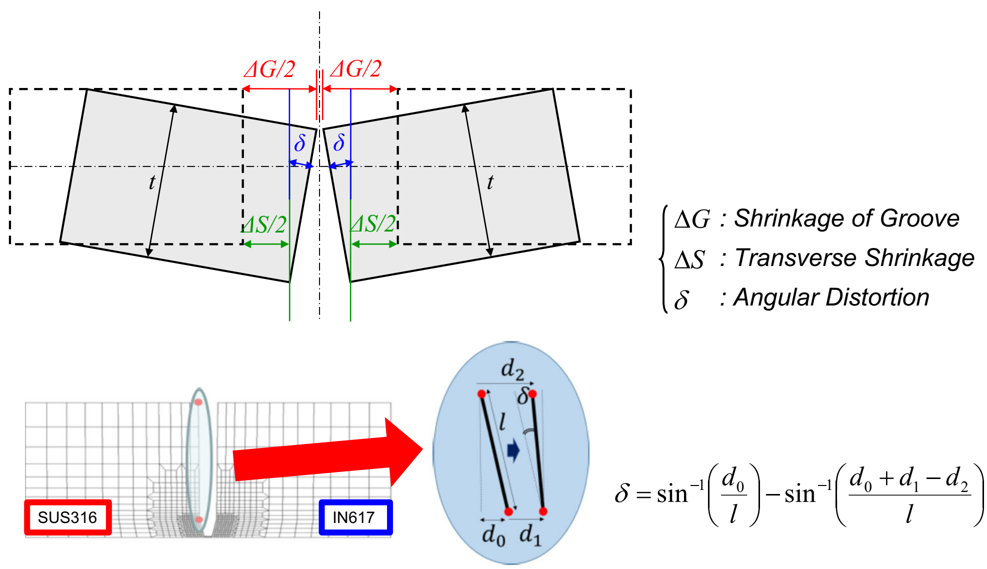


Fig. 11 Distributions of gap shrinkage along weld line after the 8th pass

Fig. 12 Schematic illustration of the decomposition method of gap shrinkage to transverse shrinkage and angular distortion



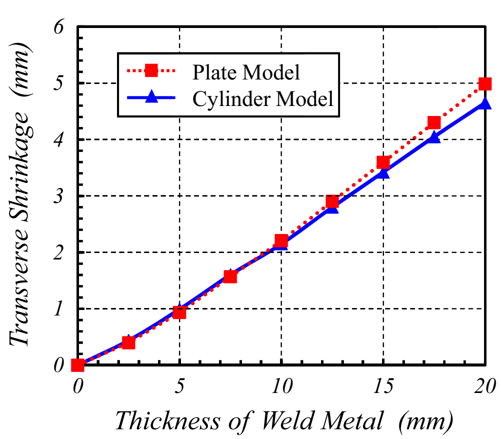


Fig. 13 Effect of joint geometry on transverse shrinkage during multi-pass welding up to the 8th pass

using a simple linear equation based on the result of plates because the transverse shrinkages of pipes and plates almost linearly increased with increasing the weld passes. So, the linear function was obtained from the transvers shrinkage of plates up to the 4th pass and the approximation was plotted in Fig. 13 as shown in Fig. 15. This figure indicates that this approximation has a very good agreement with the transverse shrinkage of pipes up to the 8th pass. Namely, this simple method is considered to have a good potential for predicting the transverse shrinkage of butt welding of pipes from the shrinkage of butt welding of plates obtained not only numerically but also experimentally.

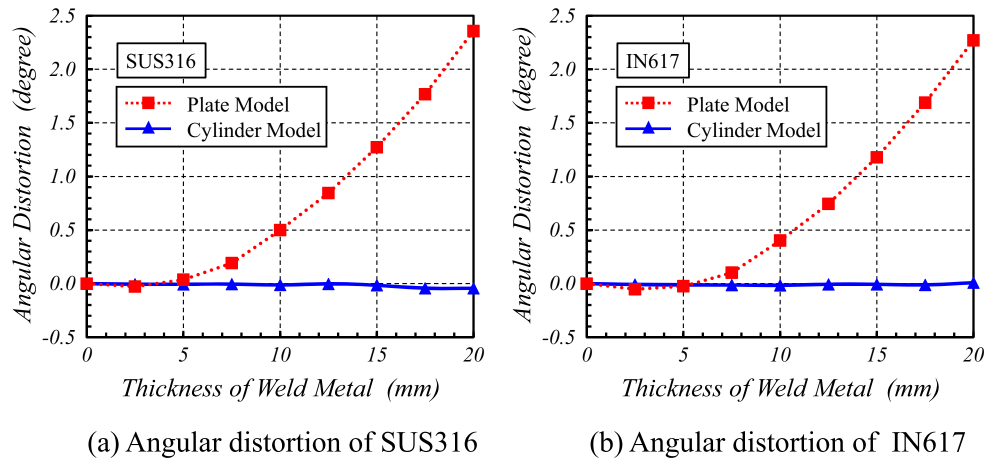


Fig. 14 Effect of joint geometry on angular distortion during multi-pass welding up to the 8th pass

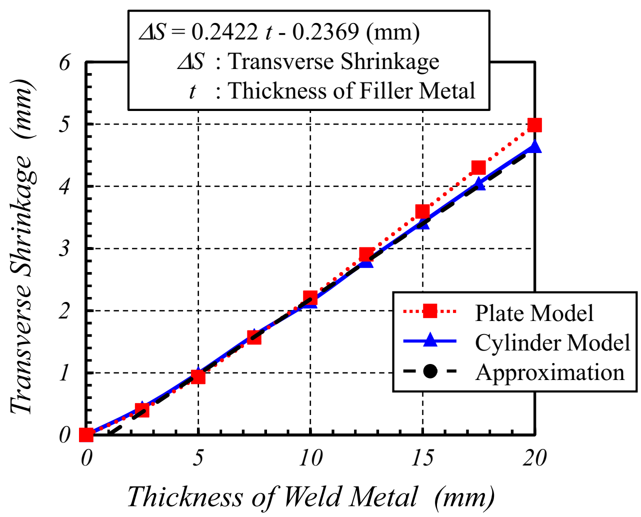


Fig. 15 Approximation of transverse shrinkage during multi-pass welding of butt-welded pipes based on butt-welded plates

4.3 Influence of groove shape

In the practical manufacturing process of multi-pass narrow gap welding, the groove shape are varied based on the previous experience in each companies and the effect of groove shape on the gap shrinkage in narrow gap welding have not been revealed theoretically. In addition, as a result of the above discussions, there would be a simple method to predict the transverse shrinkage in the multi-pass narrow gap welding of thick-walled pipes based on the result of the narrow gap welding of thick plates. So, in this section, an applicability of the simple method is examined by changing the groove shape.

Figure 16 shows the groove shapes studied in this study, where the shape of model A is the base model employed in the above section. The differences are the groove angle and initial gap width at the bottom as shown in Table 2. In all cases, the groove angle was set to change at the point which is 20 mm from the bottom and the analyses were carried out up to the 8th pass when the deposited filler metal achieves to this point.

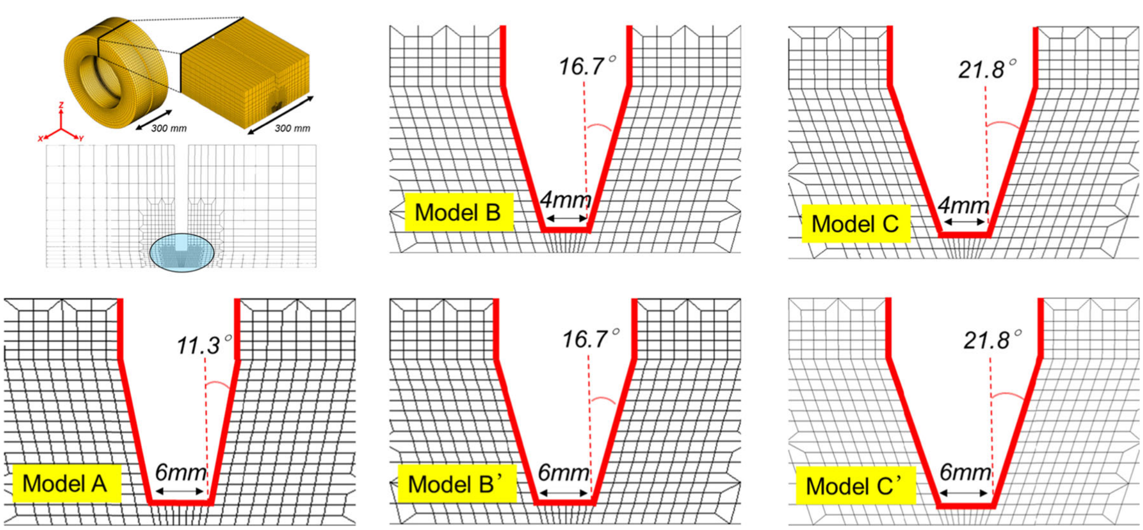
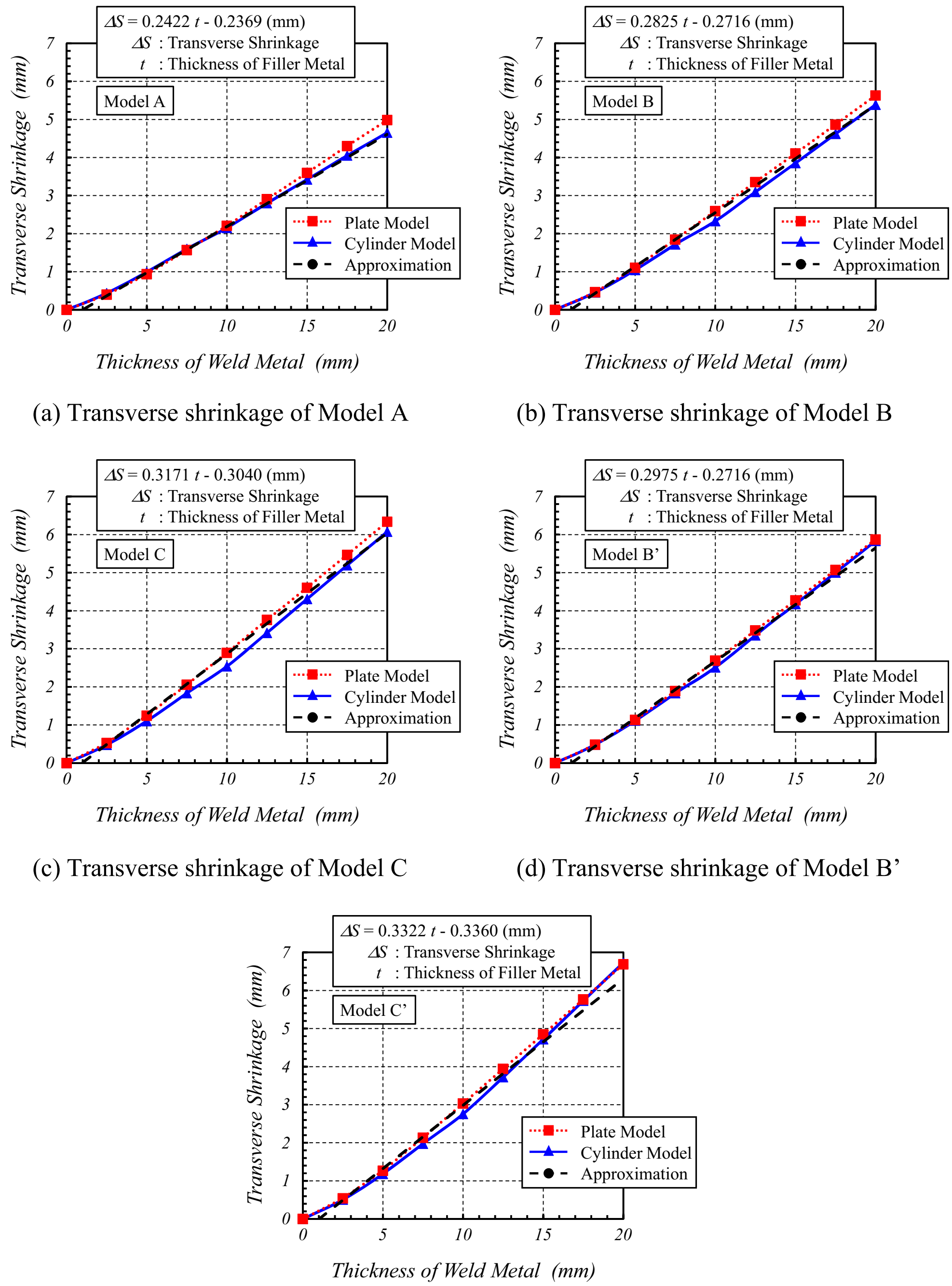


Fig. 16 Groove shapes for multi-pass narrow gap welding in finite element models of Table 2

Table 2 Groove angle and initial gap width at the bottom studied

	Groove angle of inner bottom (degree)	Initial groove width at inner bottom (mm)
Model A	11.3	6
Model B	16.7	4
Model C	21.8	4
Model B’	16.7	6
Model C’	21.8	6

The sizes of the pipe and plate were assumed to be the same as those studied in the above section. Namely, the outer and inner diameters of the pipes were 700 and 400 mm, respectively, and the total width of pipes was 300 mm, while the size of the plates was 300 mm in length, 300 mm in width, and 150 mm in thickness. According to Fig. 12, the gap shrinkages of the pipes and plates computed were decomposed to transverse shrinkage and angular distortion. Since the transverse shrinkage is found to be the main composition of gap shrinkage, only the transverse shrinkages were summarized in Fig. 17.



(a) Transverse shrinkage of Model A

(b) Transverse shrinkage of Model B

(c) Transverse shrinkage of Model C

(d) Transverse shrinkage of Model B’

(e) Transverse shrinkage of Model C’

Fig. 17 Effect of groove shape on approximation of transverse shrinkage during multi-pass welding of butt-welded pipes

Where, as same as Fig. 15, the approximation obtained from the transverse shrinkage of plates up to the 4th pass was also plotted. From this figure, it was found that although the approximation is affected by the groove shape, the transverse shrinkage can be well predicted by the linear function regardless of the groove shape and the difference after the 8th pass is less than 6 %. Then, it can be concluded that this simple linear function obtained from the transverse shrinkage of butt welding of plates is considered to be very useful for predicting the shrinkage of butt welding of pipes regardless of the groove shape. However, in order to reveal the influence of groove shape on the coefficient of approximation, further studies have to be needed.

5 Conclusions

In order to reveal the mechanism of gap shrinkage in the early stage of multi-pass narrow gap welding of thick-walled dissimilar pipes, three-dimensional finite element analyses for the multi-pass butt welding of thick-walled pipes and plates were conducted. The conclusions are summarized as follows.

1. Although the heat input might vary according to the filler metal type in the practical process, the gap shrinkage seems to be independent of the weld metal type because the change of heat input is considered to be small due to the narrow gap.
2. The gap shrinkage of plates became to be much larger than that of pipes with increasing the weld passes, although the shrinkage of plates was well coincident with that of pipes until the 2nd pass.
3. The gap shrinkage of pipes was found to be mainly governed by the transverse shrinkage, while the shrinkage of plates was influenced by both transverse shrinkage and angular distortion.
4. The transverse shrinkage of pipes almost linearly increased with increasing the weld passes and its linear increment seems to be predicted by the transverse shrinkage of plates regardless of the groove shape.

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