Simulation of Welding Deformation for Accurate Ship Assembling (Report II)†

– Influence of Initial Geometrical Imperfection on Butt Welded Plate –

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Abstract

Welding deformation is one of the main problems to be solved in the automation and mechanization of ship assembly. In the previous report[1], the in-plane transverse deformation of one-sided automatic welding on large real size plate is investigated by experiments and thermal-elastic-plastic FEM analyses. The effects of various factors, such as welding sequence, initial stress (stress existing in plate before welding), types of tab, pitch of tack welds and local heating have been clarified. It was concluded that the local heating affects the deformation significantly near the heated region. Welding sequence also has a fairly large influence on the distribution of transverse shrinkage. The most considerable finding is, however, that certain pattens of initial stress could change the deformation significantly. Therefore, it is important to clarify the effects of the initial stress in various forms.

In this paper, main work is focused on the investigation of the influence of correcting groove gaps, which is one of the major causes of initial stress. To begin with, the straightness and the shapes of skin plates after parallel gas cutting are statistically surveyed to obtain types of gap and possible maximum gap. The practical methods to correct the gap are studied. Finally, the influence of the corrections is computed using thermal-elastic-plastic FEM method. The following conclusions are drawn;

(1) *Most measured plates have fan-shapes or s-shapes after gas cutting. The mean value of the out of straightness is 0.87 mm.*
(2) *Correcting gap by gas heating or by a proper choice of tack welding sequence results in quite high initial stress in widespread area of the plate before welding.*
(3) *This kind of initial stress produces an undesirable effect on the transverse deformation after welding. It causes the irregular deformation and increases the shrinkage more than two times compared to the case without initial stress.*

KEY WORDS: (Butt Welding) (Welding Deformation) (In-plane Shrinkage) (Initial Deformation) (Finite Element Method) (Initial Gap) (Residual Stress) (Gas cutting)

1. Introduction

To realize the automation and mechanization of assembly process, ship parts are required to have very high accuracy. As most assembling processes in shipyards consist of cutting and welding the accuracy of these processes must be controlled to achieve the required precision. Also it is important to set up the tolerance limit at reasonable levels, because unrealistically sever limit will push up the cost unacceptably high. The appropriate approach to these problems is predicting the deformation precisely and taking some measures to control key factors. The transverse shrinkage is investigated as the first step because the in-plane deformation is one of the main problems needed to be solved for mechanization. A thermal-elastic-plastic FEM, which was proved to be a reliable method in the previous report, is employed to analyze the welding deformation. Special effort are made to simulate the phenomena as close as possible to the real situation. Real welding conditions and plates with large size have been taken into account in the modeling. Various practical factors such as local heating, different welding sequences and various constraint conditions have also been considered and their effects are investigated. To clarify the effect of initial stress (stress existing in plate before welding) the residual stress produced by the

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welding of end tab and last five tacks is taken as initial stress for the welding deformation calculation. The investigations show that the local heating and the welding sequences have significant influence on the welding deformation locally near the seam. The effect is alleviated with the distance form the seam. In the case in which the residual stress due to the welding of the tab and tacks are considered, large influence on the deformation is observed up to the outer edge which is 3 meters away. The phenomena show that internal stress before welding could be an important factor that affects the welding deformation.

In this report emphasis is placed on the further investigation of the initial stress and the extent of its effect on the distribution and magnitude of transverse welding deformation. The initial stress can be introduced in various processes such as the rolling and the cooling in steel plate production, gas cutting, the welding of tacks and tabs, etc. Since relatively high and widespread stress is expected to result in larger influence, the following two processes are chosen as the influential sources of initial stress. One is that due to the plate cutting and the other is that due to the gap correction. Gas cutting is the common cutting method used in shipyards. The gas cutting is usually accompanied by the deformation and the residual stress. Thus the groove gap will occur if the edge along the cut line is not straight due to cutting error. When the gap exceeds certain limit, proper measure, such as gas heating or sequential tack welding is taken to close the gap in order to achieve sound weld bead. To obtain the information on the shape of the gap and its possible magnitude, the accuracy of gas cutting is investigated first. Also the methods commonly used in the shipyard to close the gap are studied. Based on these information, the residual stress caused by correcting the gap is reproduced by numerical simulation. By taking this computed stress and strain as initial conditions, the deformation due to the initial gap is investigated through FEM analysis. Also the effect of the initial stress produced by the gas cutting upon the deformation is analyzed.

2. Preparations for Butt Welding

2.1 Accuracy of gas cutting

Ship blocks are the welded structures composed of huge plane blocks with many longitudinal and transverse stiffeners. Each plane block is built independently by welding skin plates together and stiffeners are welded afterward. The skin plates are welded in the following manner. Pieces of plates are arranged in the proper positions. Welding of tabs and tacks are then done manually to fix the plates. Next, welding is carried out by an one-sided automatic submerged welding machine.

As a first step, skin plates are required to be sized and slopes of grooves are needed to be formed. In the present shipyards, the sizing and the forming of the groove are completed at the same time by using a NC gas cutting machine.

The geometrical error in the straightness of the plate along the edge cut by NC gas cutting machine is mainly caused by the following factors categorized in three groups:

(1) Mechanical cause
- Straightness of rails
- Motion of the cutting machine running on rails
- Positioning and operating error of cutting torches
- Accuracy of NC data

(2) Related to cutting phenomena
- Accuracy of the torch nozzle
- Flame instability caused by variation of gas pressure and gas flow
- Instability of the cutting process itself

(3) Thermal deformation
- In-plane and out-of-plane deformation

To clarify the mechanical influence of category (1), the positions of the gas cutting machine when it was running on the rails have been measured. **Figure 1** shows the results for a round trip on the rails. The magnitude of the error is about 0.2 mm and the difference is observed between forward and backward runs. The measurements are considered as a resultant error including the effects of two rails and the motion of the machine.

It is very difficult to quantify the effects of the factors belong to category (2). Many factors such as the deterioration of the flame torches, the fluctuation of gas pressure, uncertainty of kerf width and the change of bevel angle of torches could affect the accuracy of cutting. Maintenance problem or unsuitable cutting conditions also decreases cutting accuracy.

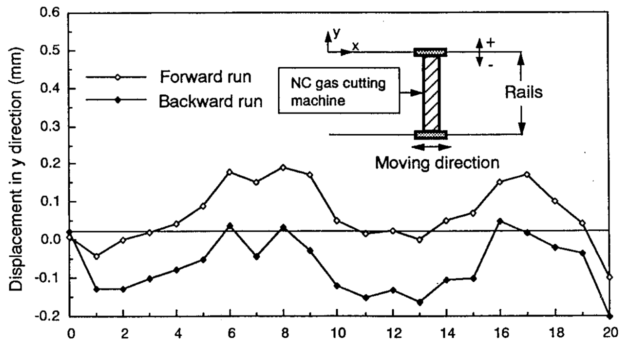

Fig. 1 Measured movement of NC gas cutting machine on rails.

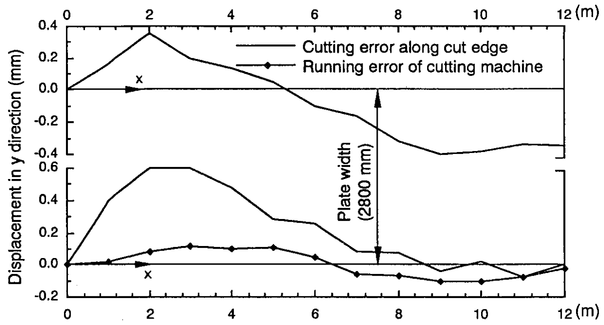

Fig. 2 Measured error along cut edges.

Table 1 Patterns of edge shape after gas cutting.

Type	Patterns of edge shape	Remark	Frequency
1		fan-shape	26
2		s-shape	15
3		partial s-shape	11
4		anti-barrel -shape	6
5		irregular local error (one side)	5
6		irregular local error (both sides)	9

Concerning the thermal deformation of category (3) it is well known that simultaneous parallel cutting produces least error because of geometrical and thermal symmetries. But relatively large deformation occurs if groove shapes are different between two cut edges. In this case heat input is different between two edges and it causes unsymmetrical thermal deformation and large cutting error. Out-of-plane deformation becomes dominant when thin and narrow plate is considered.

Stress in the plate before cutting is another factor which possibly influence the cutting accuracy significantly. Especially in the case of TMCP type high strength steel, stress introduced in the steel making process may become large.

Though the numerical simulation of the deformation in gas cutting has been reported[2], it is difficult to predict the geometrical error along the cutting line. Measurements are done to get the information on the total error in the cutting. **Figure 2** shows an example of measured cutting error along the edges cut by the machine accuracy of which is show in Fig. 1. The same measurements are made on 72 pieces of plates to investigate the tendency of edge shape. The material and the size of the plates are shown as follows:

Material : 36 kgf/mm^2 (353MPa) high strength steel (TMCP steel)
Thickness : 12-23 mm
Length : 9-23 m
Width : 2.1-3.5 m

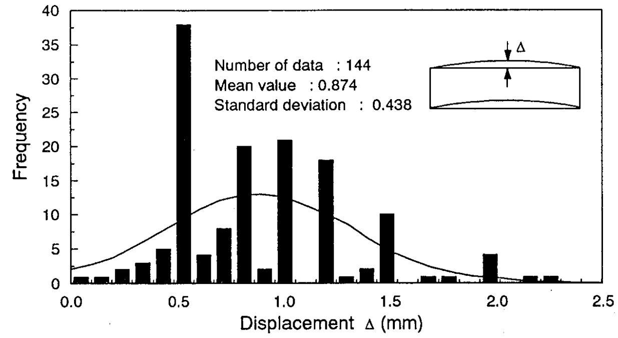

Fig. 3 Statistical distribution of the measured maximum error along cut edges.

Table 1 summarizes the measured results. The pattens of the edge shapes can be roughly classified into six types. The irregular local deformation of type 5 or 6 is relatively less and the majority have certain shape. The most frequently observed one is the fan-shape of type 1. The second is s-shape of type 2 followed by partial s-shape of type 3.

The statistical distribution of the straightness (maximum transverse deformation) of the cut edges is shown in **Fig. 3**. It is observed that the error of 0.5 mm has the highest frequency and the distribution extends to 1-2 mm. The mean value is 0.87 mm while the maximum value is 2.3 mm. The standard deviation of the data is 0.4 mm. It implies that the variation of the error is fairly large.

By facing together these deformed plates, gaps appear in the groove. If the gaps are large, the sound weld bead can not be achieved. Therefore, gaps larger than 2 mm must be corrected before welding. The correction is usually carried out in the stage of tack welding.

2.2 Gap correction

As discussed in the above, most plates after gas cutting have fan-shapes of type 1. When two plates with fan-shape are faced together for welding, a gap is formed in the middle if the edges of two plates are concave and gaps occur at the ends when both edges are convex. Plates of types 2-4 can also cause gaps in the middle or at ends of the groove depending on the combination of the types.

Table 2 Methods for correcting gap.

Type	Before tack welding	Size of gap	Procedure of correction
Middle -gap		About 5 mm	Heat shaded areas. Weld tacks right after gas heating. Close the gap up to about 2-3 mm.
		2-3 mm	Weld tacks from the ends to the middle of the gap. Close the gap up to 1-2mm.
End-gap		About 5 mm	Heat shaded areas. Weld tacks after the plate is cooled down. Close the gap up to about 2-3 mm.
		2-3 mm	Weld tacks from the middle to the ends of the gap. Close the gap up to 1-2mm.
Double -gap			Weld tacks from the place in contact to the middle of gap. Close the gap up to 2-3 mm.

Plates after cutting are usually arranged without taking edge shapes into account. Consequently, two types of gap are common. One is a long gap in the central part of the plates and another is two gaps developing from the center to the ends. The maximum gap is expected about 5 mm in the worst case which is 2 times of the maximum error in straightness of 2.3 mm shown in Fig.3. When the type 5 or type 6 happens to be faced each other two gaps may appear along the groove. The above three types of gap are named here as middle-gap, end-gap and double-gap.

Table 2 shows an example of procedures to correct the gaps being used in shipyards. If a gap reaches about 5 mm, gas heating with an equal interval along the welding line is employed. In case of a middle-gap, tack welding is carried out right after the gas heating when the plate is under thermal expansion whereas for an end-gap, tacks are welded after the plate is cooled down. Gas heating is not necessary for relatively small gaps of 2-3 mm. Alternatively, a series of tack welding in a proper sequence are used for correction. For a middle-gap, tacks are welded from the ends to the middle of the gap whereas for an end-gap, tacks are welded from the middle to the ends . The final gap before welding is kept under 2 mm in this way.

Usually the workers in shipyards decide how to correct gap according to their experiences. Sometimes both gas heating and a proper sequence of tack welding are used. Depending on the situation,they also heat the place along non-welding edge and make tack weldings in an opposite sequence compared to that discussed in the above.

3. Numerical Analysis

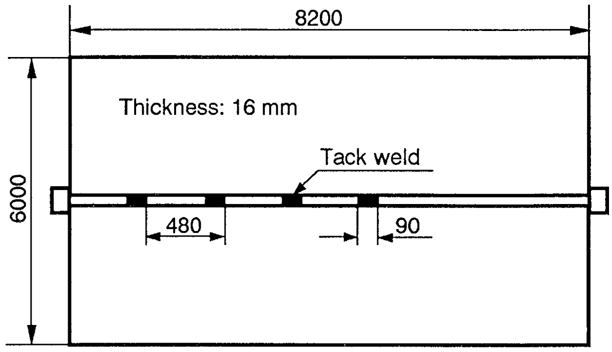

Fig. 4 Preparations for butt welding.

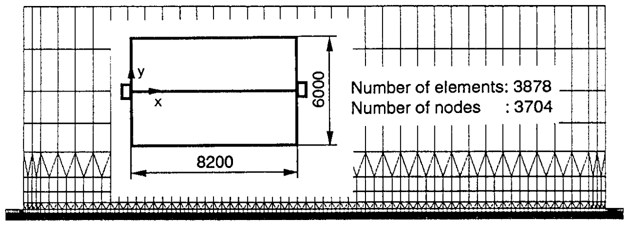

Fig. 5 FEM model for numerical analysis.

3.1 Method of analysis

Reducing gap in groove through gas heating and tack welding is effective to obtain welds of good quality. But at the same time the correction leaves residual stress in the plate as initial stress for the following welding. Moreover, different gaps and various correction procedures make the stress change greatly from case to case. If the stress is large and exists in wide area, it will significantly affect the welding deformation and result in irregular distribution of the shrinkage. In the correction process, deformation also occurs in addition to the residual stress. Such complicated processes starting from the correction of the gap to the final welding are numerically simulated.

The FEM method as described in the 1st report[1] is used. The transient temperature fields are obtained through solving the heat conduction equation. Using the computed temperature fields, stress and deformation are calculated through thermal-elastic-plastic analysis. Temperature dependency of thermal and mechanical properties is considered. The computations have been done on the workstation (TITAN). A FEM program named JWRIAN-W90 is used, which is developed by the authors' research group specially for the butt welding problem.

Computations include ideal welding (no gap and initial stress), welding after correcting the three types of gap and the welding with residual stress of gas cutting.

Table 3 Welding conditions.

Type of welding	Electrodes	Current (Amp)	Voltage (Volt)	Speed (mm/min)	Efficiency (%)
F C B welding	L	1180	33	680	85
	T_1	1130	37		
	T_2	830	39		
Tack welding	–	500	20	250	95

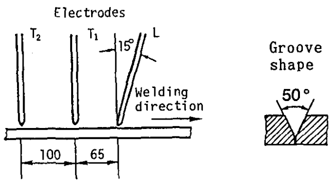

Table 4 Cases of numerical simulation.

Computed case	Gap pattern	Shape of gap	Maximum gap δ (mm)	Remark
C 1	No gap	—	0	No initial stress
C 2	Middle-gap		2	Ideal correction
C 3			4	
C 4	End-gap		2	
C 5			4	
C 6	Double-gap		2	
C 7	Middle-gap		2	Correcting gap by tack welding
C 8			3	Correcting gap by gas heating
C 9	No gap	—	0	Considering stress due to gas heating

The shape of the gap is assumed as a circular arc. The residual stress produced by the rolling process is ignored in the simplification.

Figure 4 shows the model of butt welding and tack arrangement. Welding is done on the two pieces of plates with the size of 8200 mm in length, 3000 mm in width and 16 mm in thickness, same as that was used in the 1st report. Considering the geometrical symmetry, half of the model is analyzed. FEM mesh division is shown in **Fig. 5.** Welding conditions and the conditions of tack welding are shown in **Table 3.**

3.2 Models to be analyzed

Nine cases shown in **Table 4** have been computed. Case C1 is an ideal case without gap and initial stress. Case C2 to case C6 are the models to investigate the influence of the gaps with different forms. Cases C2 and C3 are for the middle-gap, cases C4 and C5 for the end-gap and case C6 is for the double-gap. In these cases, the correction process of the gaps is idealized. The gap is assumed to be closed by forcing the nodes at tacks in the groove to move to the welding line. The process can be regarded as a kind of simultaneous tack welding, without considering the local heat effect (ignoring the local deformation and stress caused by tack welding). The details of the computing procedure are given in the following:

Stage 1

To obtain the inherent strain for deforming the plate into the shape of the gap, the plate is forced to deform to the fan or "s" shapes. The strain at all elements are saved as the inherent strain $\{\varepsilon^*\}$.

Stage 2

Fix all the nodes belong to tack welds in y direction. At the same time the strain $\{\varepsilon^*\}$ calculated in the previous step is introduced into the plate as inherent strain (initial strain).

The elastic strain and stress exiting in the plate are determined by the following equation:

$$\{\varepsilon^e\}=\{\varepsilon(u)\}-\{\varepsilon^*\}$$

$$\{\sigma\}=[D]\{\varepsilon^e\}=[D](\{\varepsilon(u)\}-\{\varepsilon^*\})$$

where

u = displacement

$\{\varepsilon(u)\}$ = total strain vector

$[D]$ = stress-strain relation matrix

Stage 3

Thermal-elastic-plastic FEM simulating the butt welding is done on the plate with the initial stress obtained from stage 2.

Differing from the ideal correction in the above 5 cases, the processes of the gap correction in cases C7 and C8 are simulated by thermal-elastic-plastic FEM analyses. C7 is the case to simulate the sequential tack welding shown in Table 3 to close a 2 mm middle-gap. The stress and strain due to the welding of tabs and tacks are obtained by repeatedly applying the thermal-elastic-plastic FEM. C8 is the case to simulate the gap correction by gas heating. The whole calculation is done by numerical simulations of gas heating, tab and tack weldings and the final butt welding successively. By considering the strain caused by gas heating and tab and tack welding as initial strain the welding deformation is computed. C9 is the case considering the residual stress caused by gas cutting.

3.3 Influence of gap shape on welding deformation

Figure 6 shows the stress distribution due to correcting the middle-gap of the case C3 as an example. The size of the gap is assumed to be 4 mm in this case. Figure 6(a) shows the normal stress in x-direction and (b) gives the Mises equivalent stress. Though the stress in most area keeps quite low, large stress is observed near tacks and it reaches about 10 kgf/mm^2 (98MPa). Assuming such initial stress distribution, the

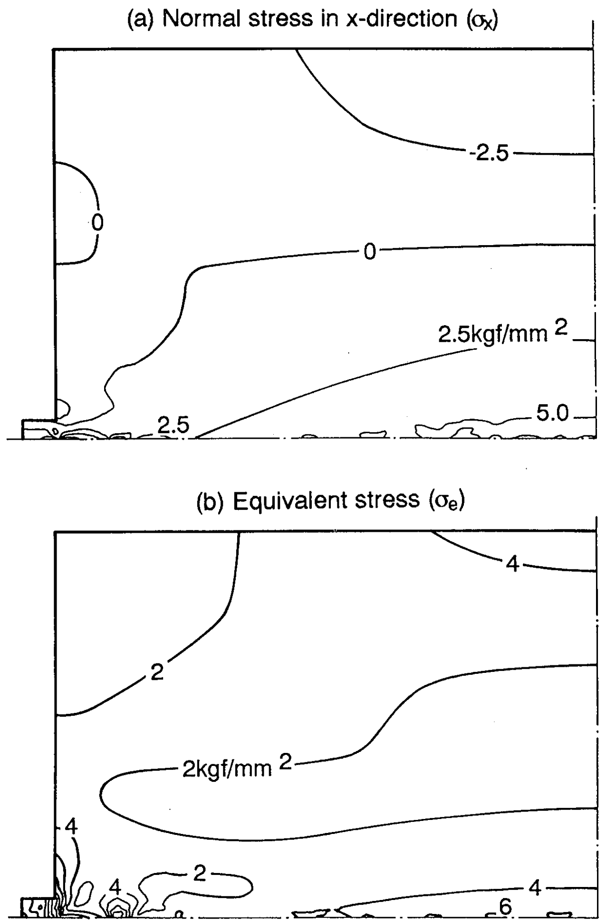

Fig. 6 Stress distribution due to correcting middle-gap of case C3.

computation of welding is done and the results are shown in **Fig.7**.

Figure 7(a) describes the displacement in y-direction (plate width direction) along the line 50 mm away from the seam and the displacement along the outer edge is shown in Fig.7(b). Abscissa indicates the distance from the start point of the welding. The case without initial stress (C1) and the case with a 2 mm gap (C3) are also plotted in Fig.7.

It can be observed from Fig.7(a) that when the initial stress is absent the displacement along the line is uniform except near the start and the end parts of the welding. While for the case with initial stress the displacement is not uniform. Larger shrinkage appears in the end parts and the shape of the curve looks like a letter w inclining up toward the right as shown in Fig. 7(b). Rapid changes near the ends are alleviated with the distance from the seam and the distributions of the shrinkage along the outer edge becomes convex and they are slightly inclining up in the right. The magnitude of the shrinkage increases with the size of the gap in the order C1, C2, C3.

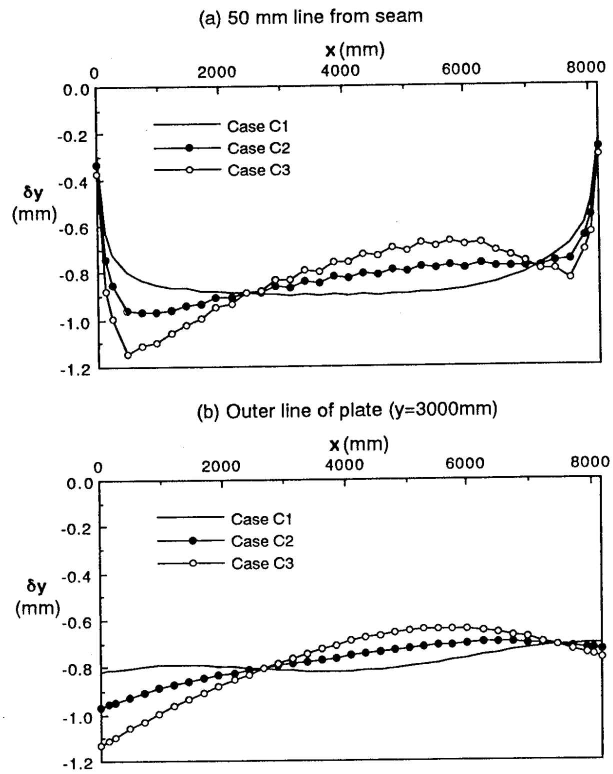

Fig. 7 Welding deformation considering the influence of residual stress produced by correcting middle gap (C2,C3).

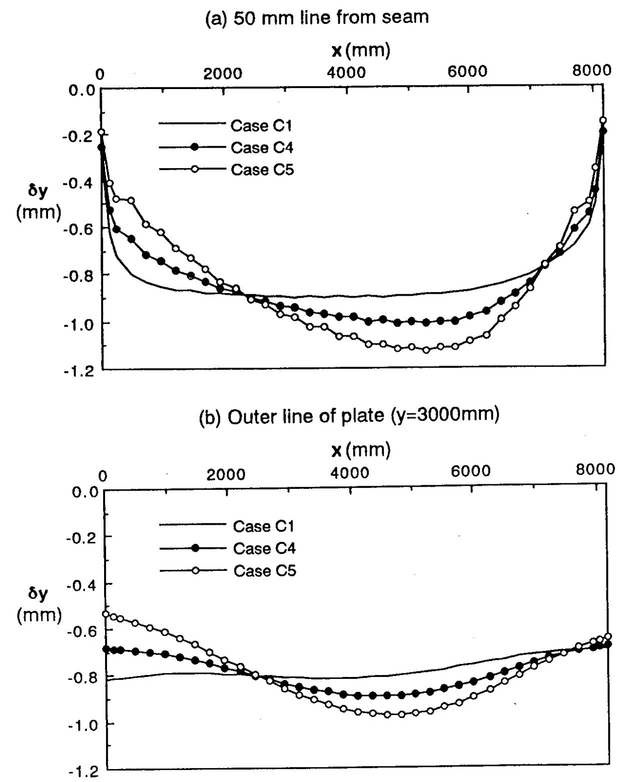

Fig. 8 Welding deformation considering the influence of residual stress produced by correcting end-gap (C4,C5).

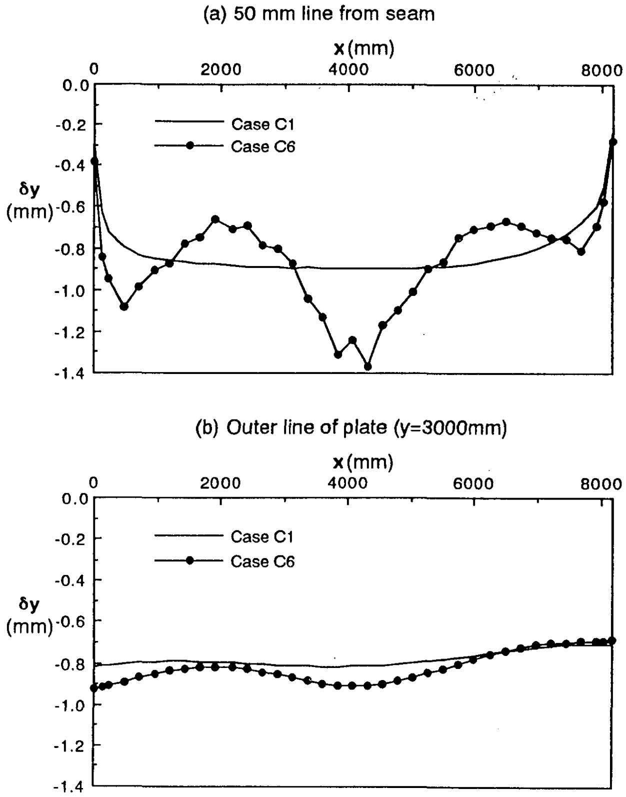

Fig. 9 Welding deformation considering the influence of residual stress produced by correcting double-gap (C6).

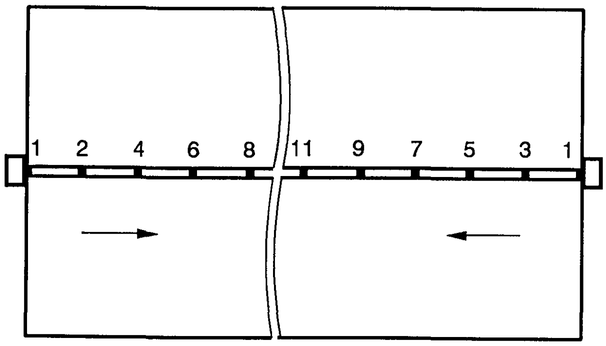

Fig. 10 Sequential tack welding to correct middle-gap.

Same computations are done on end-gap and the results are shown in **Fig 8**. The distributions are very different from middle-gap which is shown in Fig.7. As shown in Fig.8(a) the distributions of transverse displacements near the seam shapes like a letter v with its center shifted toward the ending edge of the welding. Corresponding to such displacement near the seam, the outer edge keeps v-shape as shown in Fig. 8(b). Like the case of middle-gap, the maximum shrinkage is roughly proportional to the size of the gap.

Comparing the curves in Fig.7(b) and Fig.8(b), it can be seen that the middle-gap and the end-gap make the

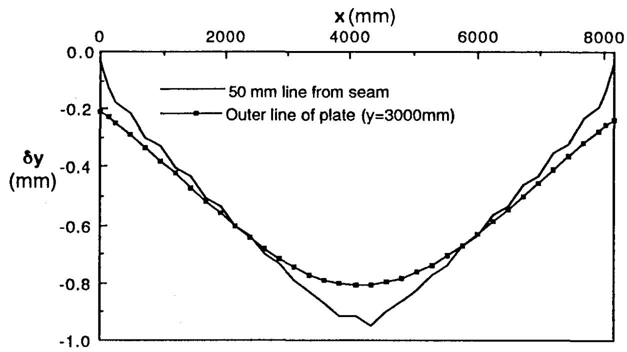

Fig. 11 Residual deformation after sequential tack welding.

plates deform in the opposite manner. Large value of shrinkage appears near the ends in the case of middle-gap while largest shrinkage is observed in the middle in the case of the end-gap.

Figure 9 shows the results for the case with double-gap. Roughly symmetrical distribution of the shrinkage is observed in the right and the left sides of the plate. The shape of the curves in each side is the same as that of the case C2, but much larger shrinkage is observed in the middle of C6 compared to the shrinkage at the right end of C2 which is shown in Fig. 7(a). Along the outer edges, the curves with and without the initial stress do not show large difference.

3.4 Correcting gap by sequential tack welding

As shown in Table 2 sequential tack welding is used to correct the gap with its maximum of 2-3 mm. Since the root gap at the present tack welding is closed by the shrinkage caused by the previous tack weld, the sequence is taken from ends to the middle for a middle-gap and from the middle to the ends for an end-gap.

To investigate its effectiveness, 2 mm middle gap is assumed to be corrected by the tack welding from the ends to the middle as shown in **Fig.10**. The interval time between each tack welding is 90 seconds.

Thermal-elastic-plastic FEM is employed to simulate the tack weldings. **Figure 11** shows the residual displacement after the tack welding. The plate is deformed in concave shape. The maximum displacement observed in the middle of the plate is about 1 mm. It means that the tack weldings with the sequence is effective and 2 mm middle-gap can be closed by the sequential tack welding.

Taking both the residual stress and the strain due to the tack welding as initial stress and initial strain, welding deformation is computed. The results are shown in **Fig. 12**. Comparing with the case C1

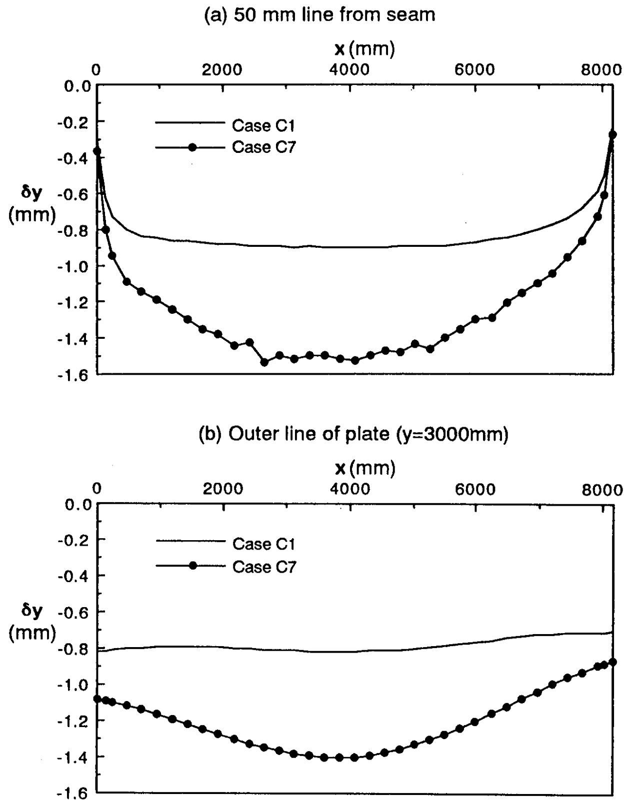

Fig. 12 Welding deformation considering the residual stress and strain due to sequential tack welding.

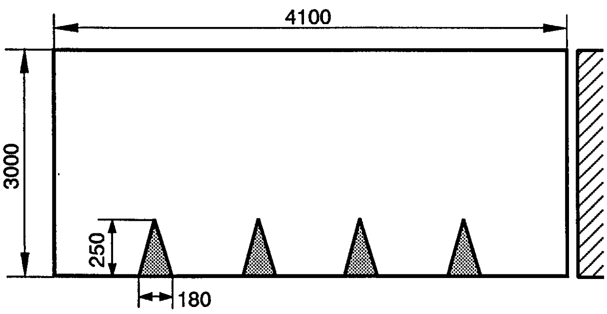

Fig. 13 Correcting middle-gap by gas heating.

without gap, the total displacement caused by gap correction and welding is about 1.5 to 2.0 times larger. Moreover, its variation along the welding direction is also increased. Such welding deformation is not desirable to achieve the precision assembly of ships.

3.5 Correcting gap by gas heating

When the size of the gap is fairly large, gas heating can be used to close the gap as shown in Table 2. The effectiveness of the gas heating is examined in this section. The model analyzed by FEM is shown in **Fig. 13**. Due to the symmetry, only half of the plate is modeled. The shaded four zones are assumed to be heated to a uniform temperature of 550 °C simultaneously.

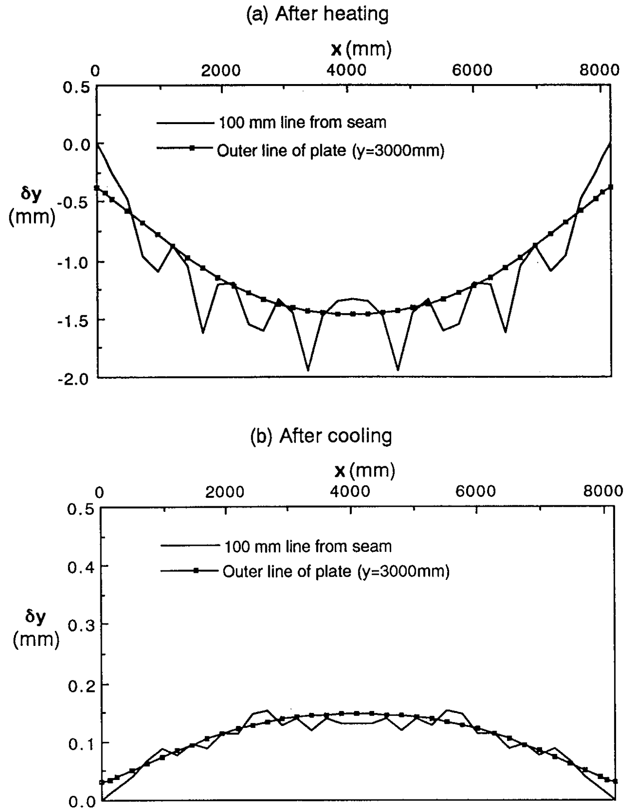

Fig. 14 Residual deformation after gas heating.

Figure 14(a) shows the deformed shape just after heating. The shape of the deformation is concave and the maximum displacement is about 1.5 mm which is observed at the center of the plate. While Fig. 14(b) shows the residual deformation after the plate is completely cooled down. The shape of the plate becomes convex and the magnitude of the deformation is only 0.15 mm. This means that gas heating is effective to correct the middle-gap but less effective for the end-gap. Gas heating can be, therefore, used to correct 3 mm middle-gap. In the case of the end gap, more effective way is to shift the gas heating to the non-welding side and make use of the convex shape of the plate while it is in expansion just after the heating.

Figure 15 shows the computed results of the deformation in correcting a middle-gap by gas heating. The thermal-elastic-plastic FEM calculation is performed in the following sequence. At first, the tack welding is done just after the plate is heated and the plate is welded by automatic butt welding. Same as Fig.12, Fig.15 shows the total displacement including gas heating, tack welding and automatic butt welding. Similar to the case C7 the shrinkage of C8 is v-shape in the distribution and its magnitude is about 2 times as large as that of C1 without initial stress.

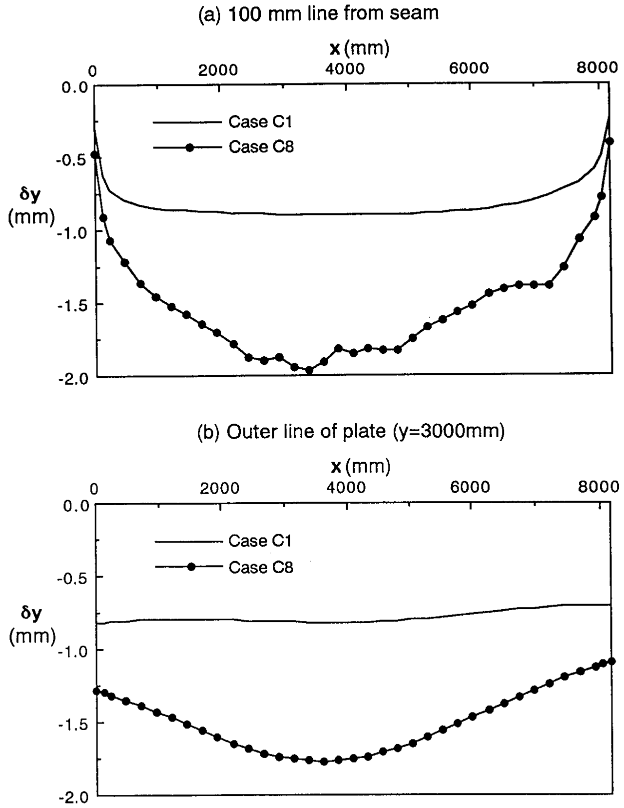

Fig. 15 Welding deformation considering the residual stress and strain due to correcting gap by gas heating.

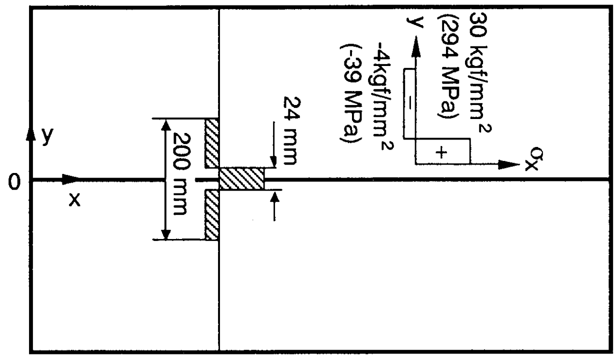

Fig. 16 Residual stress produced by gas cutting.

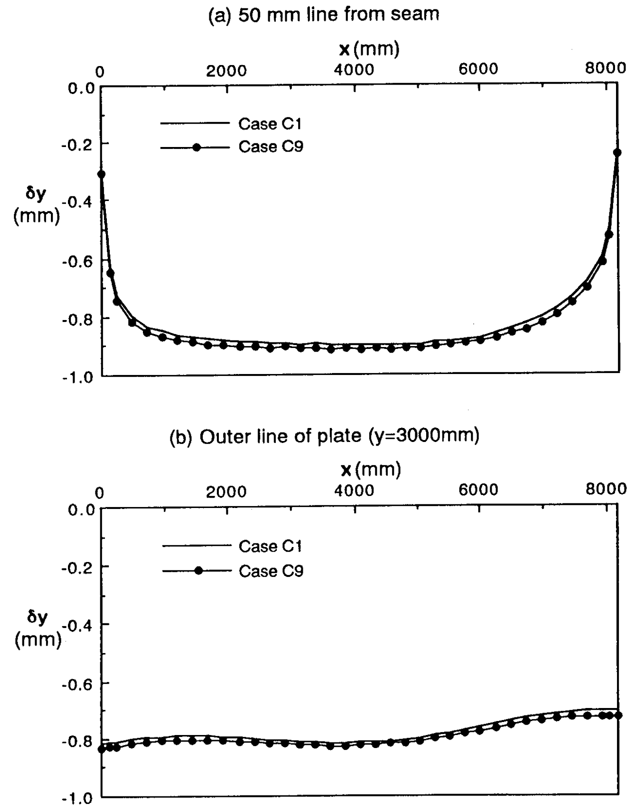

Fig. 17 Welding deformation considering the influence of residual stress produced by gas cutting (C9).

3.6 The influence of the residual stress caused by gas cutting

To investigate the influence of residual stress caused by gas cutting, a uniform stress distribution in longitudinal direction is assumed to exist in plate before welding as shown in **Fig.16**. It is also assumed that there is no gap in the groove. The thermal-elastic-plastic analyses are performed in the same manner as other cases. **Figure 17** shows the transverse shrinkage for both cases C1 and C9. Since the difference between them is quite small, it can be concluded that the residual stress due to the gas cutting has little influence on the transverse displacement.

4 Concluding Remarks

This study was motivated by the conclusion of the previous report that the initial stress may greatly affect the welding deformation. The initial stress can be introduced through various processes, such as gas cutting and closing the initial gap in groove. To clarify the effect of these, the geometrical error in the skin plates after parallel gas cutting is measured first. Also the real processes to close the gap are studied.

The effects of residual stresses introduced by various processes on the welding deformation are quantitatively studied using FEM analysis. The main conclusions drawn are as follows:

(1) Both the straightness and the shapes of real skin plates in a shipyard after gas cutting are investigated. The measured results show that most plates are fan-shaped or s-shaped with the maximum geometrical error about 2 mm.

(2) Groove gap of 4.0 mm may appear in the worst case when two plates with the geometrical imperfection are put together. Properly ordered sequential tack

welding and gas heating are used as practical correcting methods to close large gaps.

(3) The effectiveness of sequential tack welding to close the gap is proved by FEM simulation. The computed results also show that gas heating near welding line is effective to correct middle-gap but less effective to close end-gap.

(4) The correction of gap results in quite high internal stress in wide area before automatic butt welding. This kind of initial stress influences the deformation greatly after the welding. It makes the shrinkage two times larger and distribution of the transverse displacement irregular. Moreover, the shape of deformation changes according to the types of gap, such as middle-gap and end-gap.

(5) The residual stress caused by gas cutting has little influence on the deformation of automatic butt welding.

References

1) Y. Ueda, H. Murakawa, S.M. Gu, Y. Okumoto and R. Kamichika, "Simulation of Welding Deformation for Accurate Ship Assembling (1st Report)", Transactions of JWRI, Vol.21, No. 2 (1992), pp. 265-275.

2) Y. Okumoto, S. Matsuzaki and M. Shiino, "Investigation on the Building Accuracy of Hull Structure ", Technical Report of Ishikawajuma-Harima Heavy Industries, Vol. 32, No. 2 (1992), pp. 83-91 (in Japanese).