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Influential Factors Affecting Inherent Deformation during Plate Forming by Line Heating (Report 1) †

– The Effect of Plate Size and Edge Effect –

VEGA Adan*, RASHED Sherif, SERIZAWA Hisashi*** and MURAKAWA Hidekazu******

Abstract

The authors aim to propose an accurate and practical method to predict the deformation of actual plates of large size such as those used in shipbuilding. This method is to be used to improve the accuracy of an automatic plate forming process. In this first report, the influential factors affecting inherent deformation are outlines. Numerical investigations of the influence of plate length and plate width of large plates are presented. The edge effect on inherent deformation of such large plates is also investigated. The investigations have shown that the influence of plate length and plate width on inherent deformation, including edge effect, of large plates is small and can be neglected. Therefore, when the distribution of inherent deformation of a large plate is known along the heating line, the inherent deformation of smaller plates, with the same thickness and formed under the same heating and cooling conditions, can be accurately and easily predicted.

KEY WORDS: (Line Heating) (Inherent Deformation) (Residual Stress) (Plate Length Effects) (Plate Width Effects) (Edge Effect)

1. Introduction

Plate forming by line heating is a process routinely performed in many shipyards. Forming takes place in a metal whenever it is subjected to stresses greater than the yield stress so that the deformation moves from the elastic to the plastic range. When a plate is being formed by heating, plastic deformation is produced by the thermal stresses generated during localized heating and subsequent cooling of the plate. During this process, only one side of the plate is heated while the other side remains cooler. The temperature gradient across the thickness causes a gradient of thermal expansion and the plate bends in one direction, convex at the heated surface. In the mean time, the expanded metal is constrained by the surrounding cooler metal leading to compressive plastic strain gradient that is larger in hotter metal at and near the heated surface. When the heating source is removed, the plate cools down and the metal contracts. Compressive plastic strain gradient causes the plate to bend and assume an equilibrium state in the direction opposite to that when it was heated, that is concave at the heated surface.

Forming by line heating has been an active research topic in manufacturing, especially in shipbuilding. Theoretical research on the mechanism of line heating process aimed to predict the final shape of metal plates when given the heating conditions and mechanical properties of the plate material (see references[1-4] for examples). The finite element method or simplified beam or plate theory are usually applied. Research on design of the proper heating and/or cooling process (see references[5-9] for examples) has been based on the experience of forming small rectangular plates into simple geometry. Strain or curvature analysis has been employed to determine the locations of heating lines. The inherent strain method[5,6] is very promising as an accurate and practical method to predict the deformation. However it requires accurate inherent strain data bases in order to get accurate predictions. The relationships between bending deformation and heating parameters, material properties, and plate thickness have been developed in empirical models and inherent strain data bases. Additional information, such as influence of strain hardening, strain rate effects, edge effect, and size effects, have also been reported in experimental and numerical

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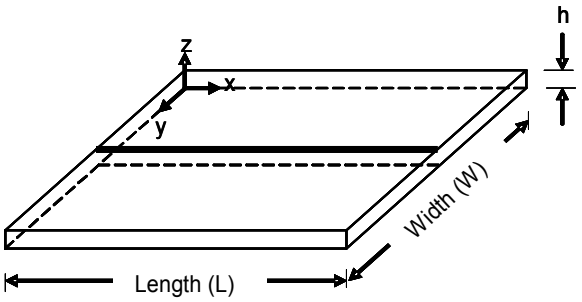

Fig.1 Schematic of the plate model.

investigations[10].

Experimental observations have shown that many factors influence the forming process. However, only a few investigations have explored these factors other than those induced by heat input and plate thickness. Most of the investigations have focused on the deformation produced by single heating lines on small plates. Inherent strain data bases derived from single heating lines on small plates are available. No empirical methods or inherent strain data bases has been developed for actual size plates, taking into account the influence of multiple heating lines. At present a practical method to accurately predict the deformation of a plate formed by line heating does not exist.

The authors aim to propose a practical and accurate method to predict deformation of actual size plates taking into account factors such as plate geometry, heating condition, location of heating lines and multiple heating lines. In this first report, the main factors affecting the deformation of plates formed by line heating are outlined. Through a 3D thermal-elastic-plastic finite element analysis using an iterative substructure method[11], the effect of plate length, plate width and proximity to the edge (edge effect) on inherent deformation are investigated and clarified. Following reports will investigate the effect of other influential factors of the line heating process and clarify their effect on inherent deformation. This will help to better understand the phenomenon, quantify the effect of these factors on inherent deformation and finally present an accurate and practical method to predict the deformation of actual ship plates when formed by line heating.

2. Thermal Elastic-Plastic Finite Element Analysis

An outline of the procedure applied to compute plate deformation using 3D thermal-elastic-plastic finite element analysis is presented in this section.

2.1 Geometry, finite element models and analysis procedure

All analysis cases are carried out using rectangular flat plates as shown in **Fig.1**. Finite element models as

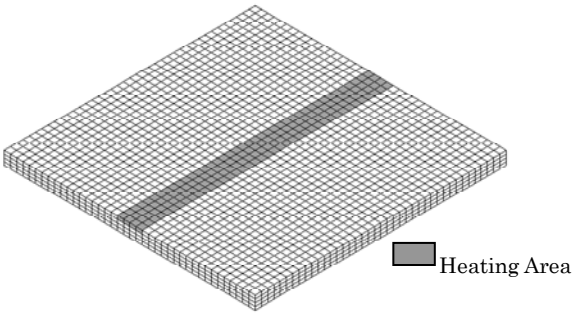

Fig.2 Example of the finite element model.

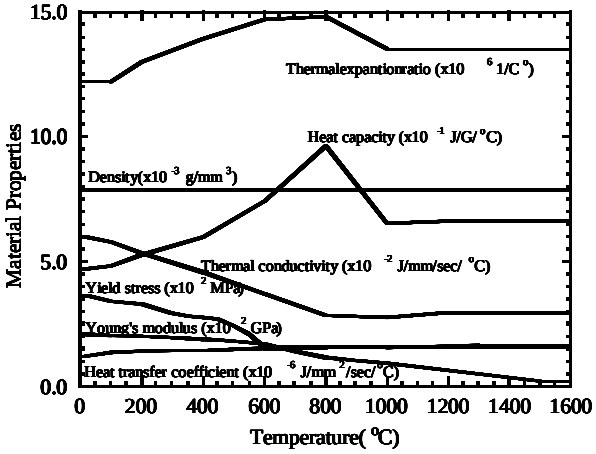

Fig.3 Mechanical properties of mild steel.

shown **Fig.2** are employed. Heating is applied over a moving zone that consists of two elements in the longitudinal (moving) direction, 4 elements in the transverse direction, and one element in the thickness direction (80x40x10 mm). In each case, the transient temperature distribution resulting from the moving heat source is computed using a 3D thermal FE analyses. Heat input per unit length of the heating line is adjusted such that the highest temperature on the surface in the heating zone is kept at 800°C. Cooling is defined corresponding to natural cooling in air. Mild steel thermal properties with temperature dependency as shown in **Fig.3** are used. The plate is heated along the X direction on the top surface. No melting is involved in the heating and cooling process. Thermal analysis is followed by a transient mechanical analysis. Necessary constraints are added to eliminate rigid body motion. Mechanical material properties with temperature dependency as shown in Fig.3 are used. The transient temperature distribution history obtained from the thermal analysis is applied and stresses, strains and displacements are evaluated.

To clarify the influence of plate length, plate width and proximity to the edge (edge effect) on inherent deformation, the analysis cases shown in **Table 1** are used. As shown in Table 1, cases from 1 to 4 are used to

Table 1 Heating conditions and plates models.

Heating Conditions			
Heat Input (J/mm)	**Traveling Speed (mm/s)**	**Surface Temperature (°C)**	**Back Surface Temperature (°C)**
5,000	3.0	800	260
Plate Models Used to Study the Plate Length Effect			
CASE	**L (mm)**	**W (mm)**	**h (mm)**
1	400	800	40
2	800	800	40
3	1400	800	40
4	3000	800	40
Plate Models Used to Study the Plate Width Effect			
CASE	**L (mm)**	**W (mm)**	**h (mm)**
5	800	400	40
6	800	800	40
7	800	1400	40
8	800	3000	40

study the influence of plate length. Cases 5 to 8 are used to analyze the influence of plate width.

2.2 Method of analysis

An in-house three dimensional thermal elastic-plastic finite element code based on an iterative substructure method[11] is employed. The iterative substructure method (ISM) takes full advantage of the fact that the region under plastic-loading which exhibits strong nonlinearity is limited to a very small area compared to the size of the model to be analyzed and the remaining part is mostly linear. Therefore a model is divided into a non-linear region and the remaining linear region. Continuity of traction on the boundary between the linear and the nonlinear regions is maintained throughout an iterative procedure.

2.3 Obtained results

In all cases, nodal displacements, element stress components and elastic and plastic strain components are obtained. The deformation of the plate is expressed using the inherent deformation method which consists of the integration of the plastic strain over the cross section of the plate. The inherent deformation can be divided into four components; longitudinal shrinkage (δ_x^i), transverse shrinkage (δ_y^i), longitudinal bending (θ_x^i), and transverse bending (θ_y^i). These four components are defined by the following equations:

$$\delta_x^i = \int \varepsilon_x^i dydz / h \quad (1)$$

$$\delta_y^i = \int \varepsilon_y^i dydz / h \quad (2)$$

$$\theta_x^i = \int \varepsilon_x^i (z - h/2)/(h^3/12) dydz \quad (3)$$

$$\theta_y^i = \int \varepsilon_y^i (z - h/2)/(h^3/12) dydz \quad (4)$$

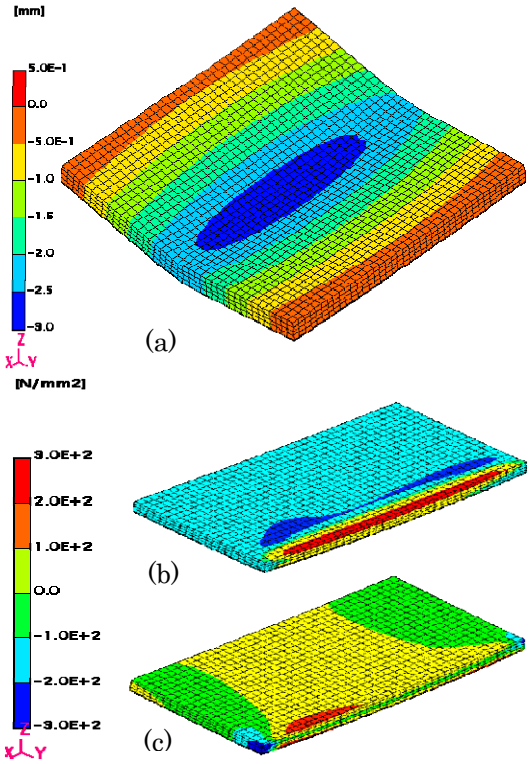

Fig.4 Schematic of (a) the plate deformation, (b) residual stress in x-direction and (c) residual stress in y-direction.

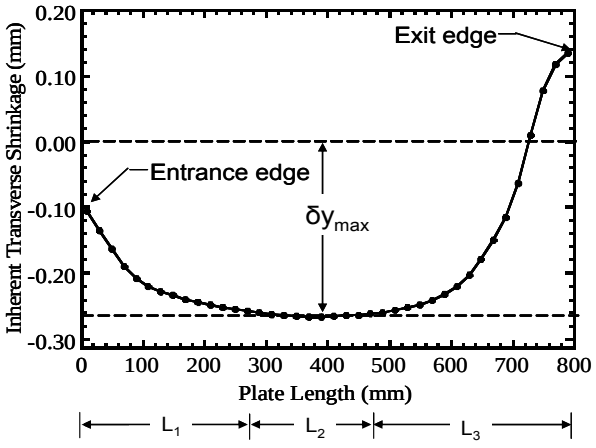

Fig.5 Schematic of inherent transverse shrinkage distribution.

3. Influential Factors Affecting Inherent Deformation

Heat-induced deformation is affected by many complex and uncertain factors that make it difficult to obtain accurate predictions required by automatic forming systems. In order to identify important factors affecting inherent deformation, let us consider a formed plate such as that shown in **Fig.4(a)**, formed by applying a heating line along x-direction in the middle of the plate. An example of analysis results is shown in **Fig.5** which presents the inherent transverse shrinkage distribution along the x-direction (heating direction).

A primary factor influencing inherent deformation is the *heating method*. The four components of inherent deformation are strongly related to variables such as the heat input (Q), size of the heating zone and the heating source speed. Inherent deformation almost proportionally increases with the heat input and decreases with the heating source speed. *Cooling method* is another important factor. Inherent deformation is directly dependent on the rate of cooling. Rate of cooling can be increased by using water leading to an increase of transverse shrinkage and a slight decrease of longitudinal shrinkage (tendon force). The location and area of application of water cooling affects all 4 components of inherent strain. Also, increasing the rate of cooling, the variation on inherent deformation along the heating line decreases.

As shown Fig.5, inherent transverse shrinkage varies along the heating line. At and near both the entrance and the exit edges (regions L_1 and L_3), inherent deformation is smaller than that in the middle region of the plate (L_2). The same tendency can be observed in the other three components of inherent deformation. The variation of inherent deformation at and near the edges from the maximum inherent deformation near the middle of the plate is another important factor known as the *edge effect*. When the same heating line is applied in the same x-direction but close to one side of the plate, the inherent deformation becomes smaller. This variation of inherent deformation is called the *side effect*.

The region (L_2) showed in Fig.5, increases in the case of a larger plate while L_1 and L_3 only slightly changes. In the case of short plates, L_2 almost disappears and the inherent deformation at center becomes smaller as the plate becomes shorter. This decrease of inherent deformation is called the *plate length effect*. In large plates, L_2 is large and this effect becomes negligible. In a similar way, in narrow plates the inherent deformation decreases with plate width. This decrease of inherent deformation is called the *plate width effect*. Both, plate length effect and plate width effect depend on plate edge restraint and are observed only in small plates.

The transverse shrinkage distribution shown in Fig.5 is obtained from the analysis of a 40 mm thick plate. With a smaller plate thickness, the inherent deformation increases. The edge effect also increases while the middle region L_2 decreases. These variations are called the *plate thickness effect*.

Figures 4(b) and **4(c)** show the residual stress distribution of one half of the deformed plate model shown in Fig.4(a). High tensile and compressive residual stresses appear in and close to the heating area while far from the center of the plate, residual stresses are small.

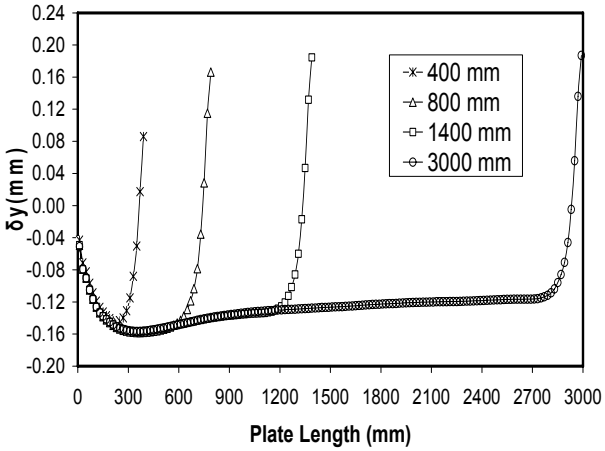

Fig.6 Effect of the plate length on transverse shrinkage.

Now, let us consider a second heating line applied parallel to the first heating line. The total inherent deformation after the two heating lines is not a simple addition of that produced by each heating line when applied alone[12]. The same is observed when the second heating is applied at the same position of the first heating line (overlapped heating) or when the second heating line is applied in the transverse direction of the first heating line (crossed heating). In these three cases, the inherent deformation produced by the second heating line is greatly affected by the residual stresses produced by the first heating line. In this paper, the difference of the final inherent deformation from the simple summation of the inherent deformation of two heating lines in each of these three cases is called, the *effect of parallel heating lines*, the *effect of overlapped heating lines* and the *effect of crossed heating lines* respectively. In the case of multiple heating lines, the *heating sequence* also influences the inherent deformation. In additional to the above mentioned influential factors, the inherent deformation is affected by the residual stresses produced by the cutting process and by the initial curvature of the plate.

4. Effects of Plate Size and Edge Effect

In the previous section a brief introduction of the influential factors that affect inherent deformation is presented. In this section the effect of plate length, the effect of plate width and the edge effect are discussed and clarified. Other factors are discussed and clarified in following reports.

4.1 Effect of plate length

Figure 6 shows the variation of inherent transverse shrinkage with plate length while plate width and thickness are kept constant. Heat conditions and heat

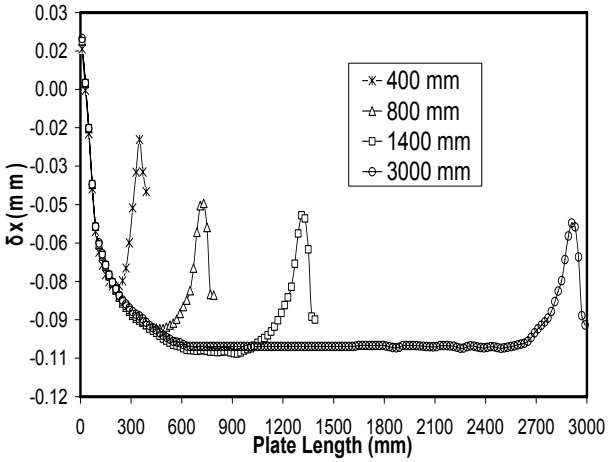

Fig.7 Effect of the plate length on longitudinal shrinkage.

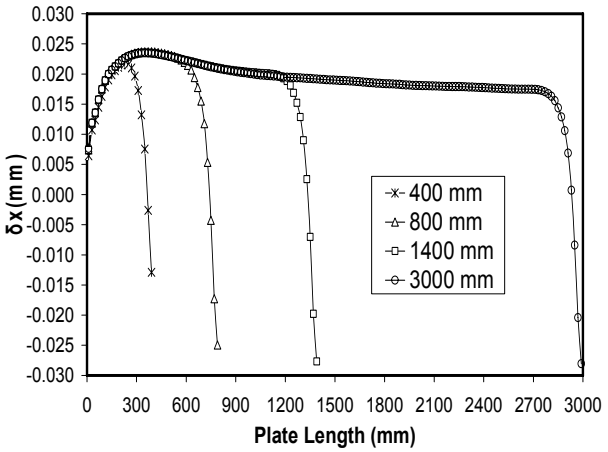

Fig.8 Effect of the plate length on transverse bending.

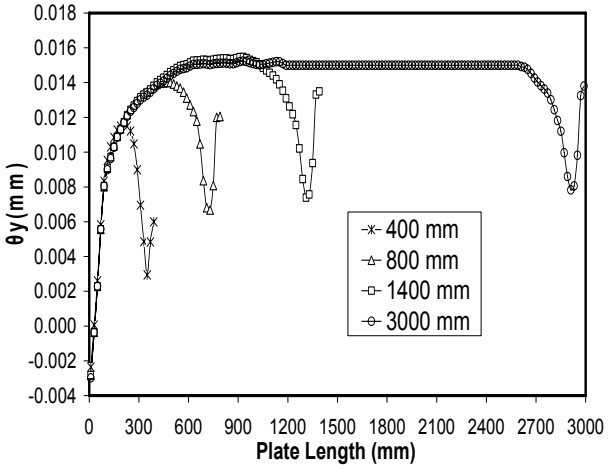

Fig.9 Effect of the plate length on longitudinal bending.

source speed are also kept constant. It may be seen that the maximum inherent transverse shrinkage (described in Fig.5) in small plates, changes with plate length. However, for plates larger than about 800 mm, maximum inherent transverse shrinkage is almost the same. The central region of the plate (L_2) increases with

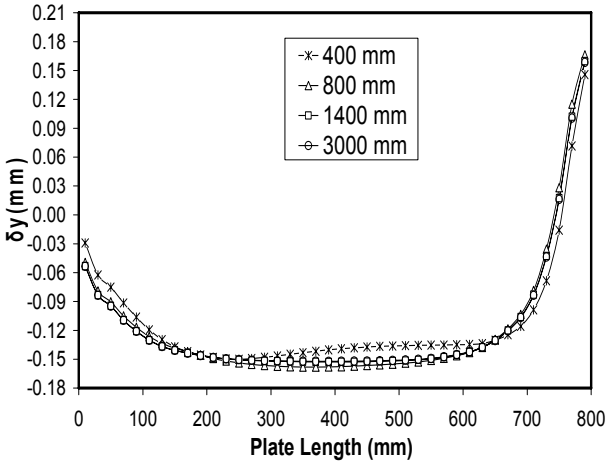

Fig.10 Effect of the plate width on transverse shrinkage.

plate length, and the distribution of inherent transverse shrinkage is almost flat.

The same characteristics are also observed in **Figs.7, 8** and **9** which present the variation of distributions of inherent longitudinal shrinkage, inherent transverse bending and inherent longitudinal bending respectively. Although, the inherent deformation varies along plate length, only in the case of small plates, a considerable decrease of maximum inherent deformation is observed. In shipbuilding, such small plates are not usually formed by line heating. Therefore, in actual shipbuilding plates, it may be said that the inherent deformation and its distribution along the heating line in region L_2 is not a function of plate length.

4.2 Effect of the plate width

Figure 10 shows the variation of inherent transverse shrinkage with plate width while plate length and thickness are kept constant. It is observed that in the case of narrow plates, there is a small reduction of the maximum inherent transverse shrinkage compared with that obtained from wide plates. From the figure it may be seen that this reduction is small and can be neglected. This reduction is also observed in **Figs.11, 12** and **13** which present the variation of inherent longitudinal shrinkage, inherent transverse bending and inherent longitudinal bending along plate length with different plate widths.

Therefore it may be said that the distribution of inherent deformation along the heating line for real ship plates is not a function of plate width.

4.3 Edge effect

In previous sections it may be seen that when the heating line is long enough, the distribution of the inherent deformation in the interior of the plate (region L_2) is almost uniform. It may also be seen that in all

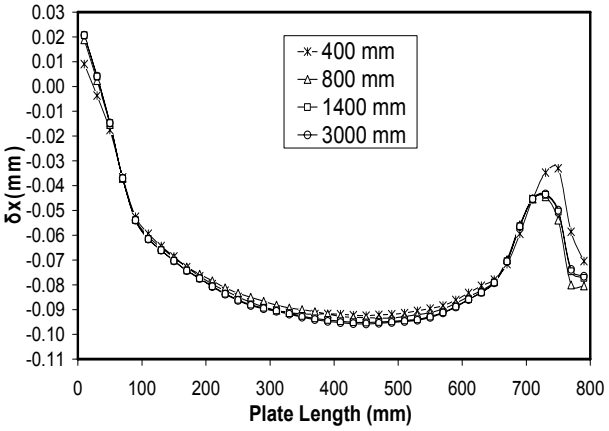

Fig.11 Effect of the plate width on longitudinal shrinkage.

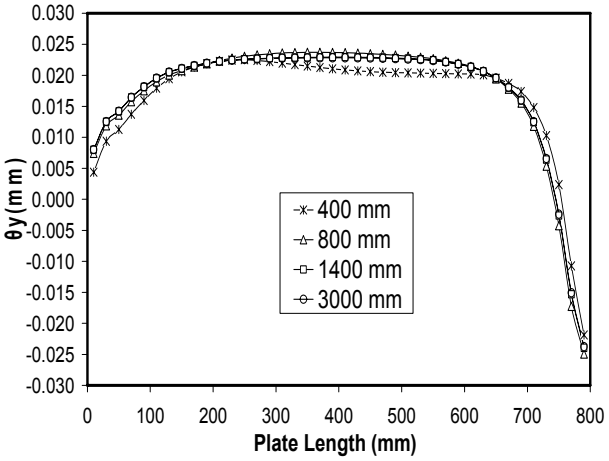

Fig.12 Effect of the plate width on transverse bending.

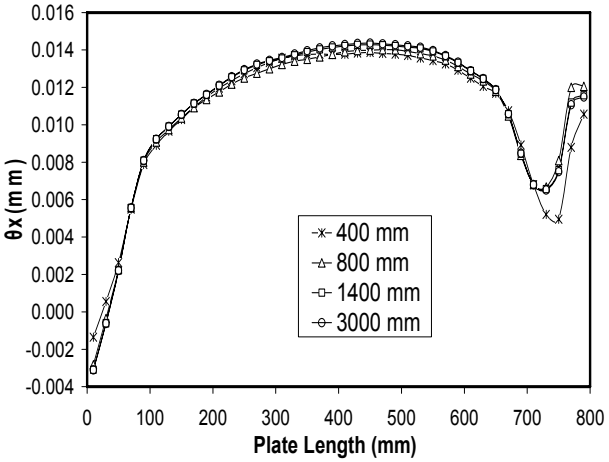

Fig.13 Effect of the plate width on longitudinal bending.

cases, the distribution of inherent deformation at the entrance edge (region L_1) does not differ while at the exit edge (region L_3), slightly changes. In this paper, the decrease of inherent deformation at both, the entrance and the exit edge of the plate is referred to as the edge effect.

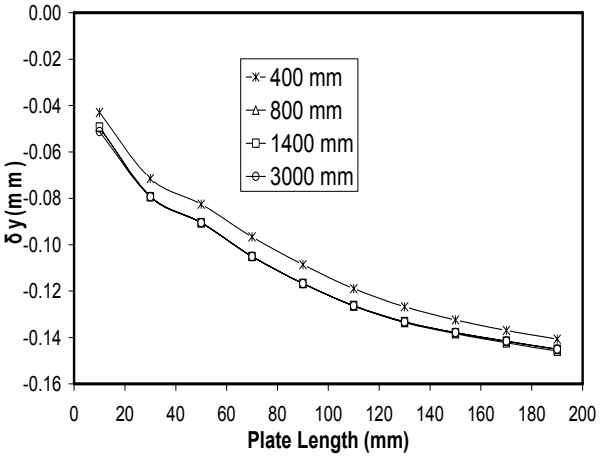

Fig.14 Entrance edge effect on transverse shrinkage.

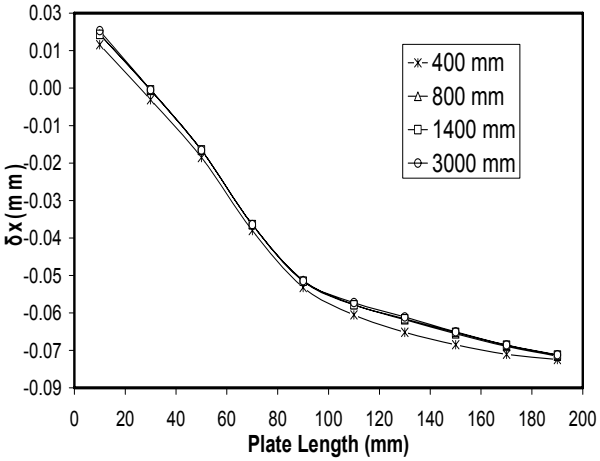

Fig.15 Entrance edge effect on longitudinal shrinkage.

Due to the fact that inherent deformation does not significantly change with plate width, in this section, we only examined the relation between edge effect and plate length. **Figure 14** shows the distribution of inherent transverse shrinkage at the entrance edge (region L_1). In this figure it is observed that the edge effect at the entrance edge does not depend on the plate length. The same tendency is observed in **Figs.15, 16** and **17** which present the distribution of inherent longitudinal shrinkage, inherent transverse bending and inherent longitudinal bending, respectively.

Figure 18 shows the distribution of inherent transverse shrinkage at the exit edge of the plates (region L_3). These distributions follow the same tendency. However, there are differences between these distributions for different plate lengths, especially in the case of plate length equals to 400 mm. For plates about 800 mm or larger, these differences become very small and may be neglected. The same tendency is observed in **Figs.19, 20** and **21** which present the distribution of inherent longitudinal shrinkage, inherent transverse

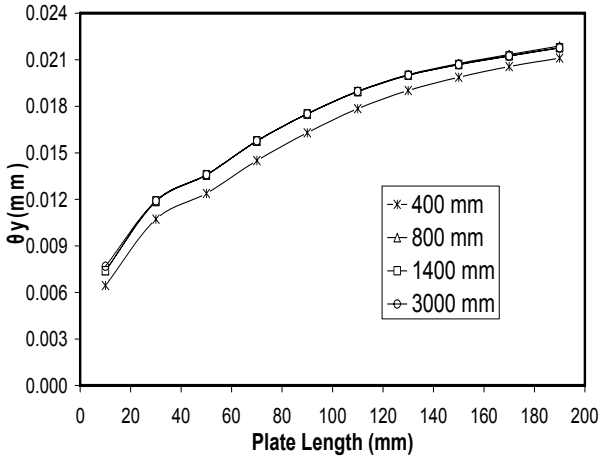

Fig.16 Entrance edge effect on transverse bending.

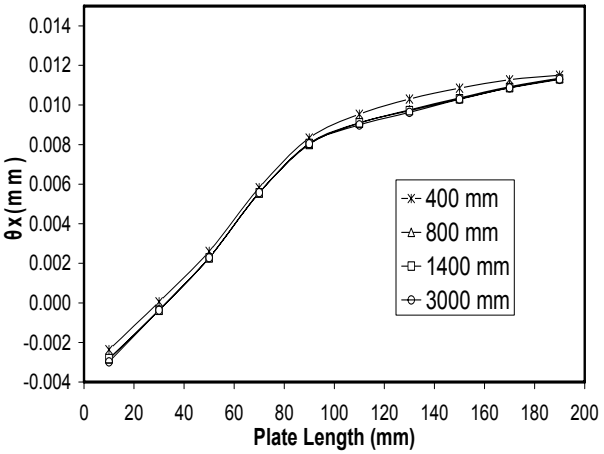

Fig.17 Entrance edge effect on longitudinal bending.

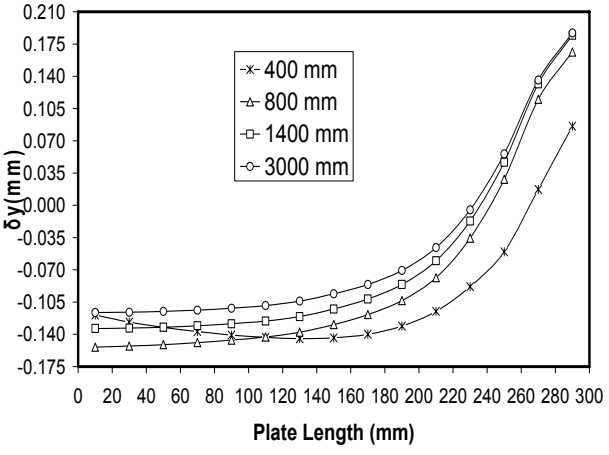

Fig.18 Exit edge effect on transverse shrinkage.

bending and inherent longitudinal bending at the exit edge, respectively.

Considering the similarity of inherent deformation at the entrance edge and at the exit edge of plates with different lengths larger than about 800 mm, the distribution of inherent deformation for a shorter plate

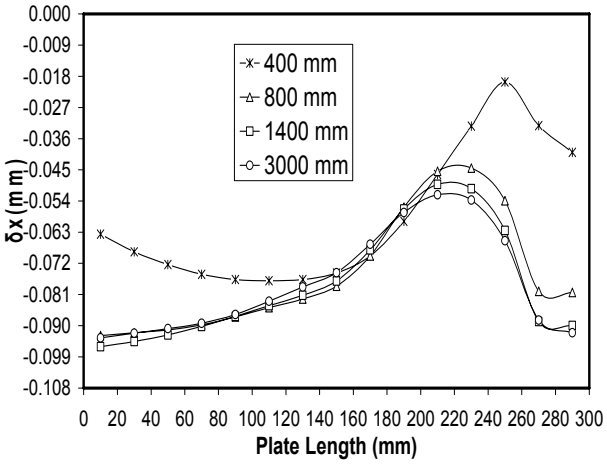

Fig.19 Exit edge effect on longitudinal shrinkage.

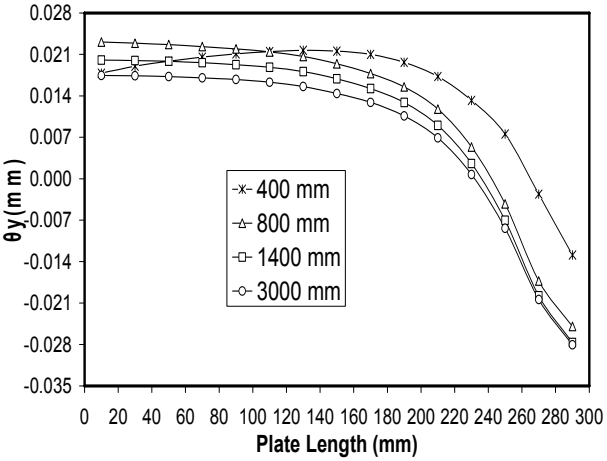

Fig.20 Exit edge effect on transverse bending.

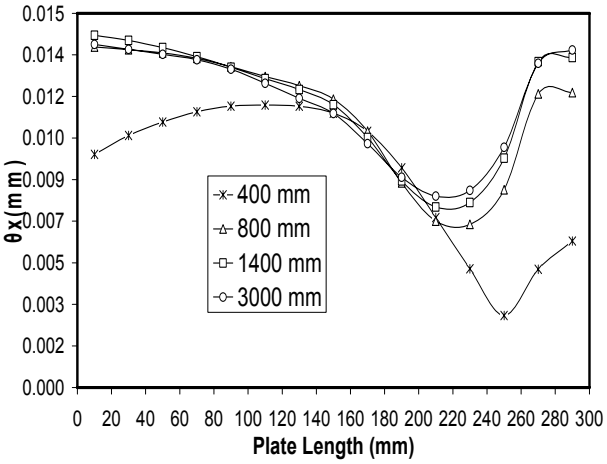

Fig.21 Exit edge effect on longitudinal bending.

length (same thickness) can be obtained by superposing the distribution of inherent deformation of both, the entrance and the exit edges (L_1 and L_3), obtained from the analysis of a larger plate. The value of the inherent strain in the central region (L_2) stays almost unchanged.

In a previous report[13] the authors demonstrated that the edge effect mainly depend on heating condition, heat source speed and plate thickness. The authors also examined methods to reduce the edge effect. They concluded that triangular heating and edge heating are the most effective methods to increase the inherent deformation at plate edge.

5. Conclusions

In the above, influential factors affecting inherent deformation in plate forming by line heating are outlined. Investigations of plate length effect, plate width effect and edge effect are presented. Through these investigations the following conclusions are drawn.

(1) In small plates, inherent deformation increases with both, plate length and plate width. However, when plate dimensions become larger than about 800 mm (for a 40 mm thick plate), the effects of plate length and plate width on inherent deformation become negligible. Therefore, for real ship plates, both plate length and plate width do not appreciably influence the inherent deformation.

(2) Edge affect at entrance edge (region L_1) does not change with neither plate length nor with plate width.

(3) The edge effect at the exit edge (region L_3) slightly changes with the plate length. However, for plates larger than about 800 mm, the change is small and may be neglected.

(4) For plates longer than about 800 mm, the distribution of inherent deformation for a shorter plate length (same thickness) can be obtained by superposing the distribution of inherent deformation of both, the entrance and the exit edge (L_1 and L_3), obtained from the analysis of a larger plate. The value of the inherent strain in the central region (L_2) stays almost unchanged.

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