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Analysis and Prediction of Edge Effect on Inherent Deformation of Thick Plates Formed by Line Heating

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Abstract: A three dimensional thermal-elasto-plastic FEA has been performed to predict the heat induced (inherent) deformation produced in thick steel plates formed by line heating. Using this FEA, the edge effect on inherent deformation is clarified. From the results of this study, a method to predict the edge effect is developed. Using this method, the edge effect on inherent deformation, for a wide range of plate thickness and heating condition, can be easily predicted, been this, an important step toward the automation of the process.

Keywords: Line heating, inherent deformation, FEM, edge effect, side edge effect, induction heating.

1 Introduction

Line heating using torch, induction or more recently laser heating is one of the most important plate forming processes used in the shipbulding industry (Kyrsanidi, Kermanidis and Pantelakis (1999), Moshaiov and Latorre (1985), Moshaiov and Vorus (1987), Tsuji and Okumura (1989)). However, the line heating process is far to be fully automated causing delays in production, even when some intends have been made not fully automatic machine for plate forming exist (eg. Ueda, Murakawa, Rashwan, Okumoto and Kamichita (1993 and 1994), Jang and Moon (1998)). The main reason of this is the fact that the relation between applied heat and final plate deformation, the key to automate the process, is too complicate to analyze by using simple mechanical models.

Aiming to solve this, many researchers has presented theories to explain both the thermal and mechanical problem (eg. Jang, Seo and Ko (1997), Chang, Liu, and Chang (2005), Ling and Atluri (2006), Osawa, Hashimoto, Sawamura, Kikuchi, Deguchi, and Yamaura (2007), Liu (2006), Liu, Liu, and Hong (2007), Terasaki, Kitamura and Nakai (1999), Moshaiov and Shin (1991)). However most of these researches have been focused on the analysis of single heating lines applied over small plates.

More recently the authors proposed a method which considers all the influential factors affecting the process such as: geometry of the plate, cooling condition, location of the heating, multi-heating lines, heat-induced curvature, residual stresses, material properties, and inter-heating temperature (See Vega (2009) and Vega, Rashed, Tango, Ishiyama and Murakawa (2008).

In fact the inherent deformation produced at plate edges does not behave in the same way as that at the central region of the plate (Bao and Yao (2001), Cheng, Yao, Liu, Pratt and Fan (2005), Magee, Watkins and Steen (1997)). In addition, the region close to the plate edges, which presents complex distribution of inherent deformation, is small compared with that at the interior of the plate. On the other hand, in forming of spherical shapes by line heating it is necessary to apply large amount of plastic (inherent) strain at the plate edges. In those cases, the usage of simple straight heating lines may not be enough because the plastic (inherent) strain produced by straight heating varies along the plate length (been smaller at the plate edges). This variation of plastic strains with the length of heating influences the four components of inherent deformation reducing the accuracy of the existing predictive method. This variation of inherent deformation along the heating line is studied in details in this paper. At the end, a new method to predict edge effect on inherent deformation is presented.

2 Formulation of the 3D thermal elastic-plastic FEM

2.1 Method of analysis

Thermal and mechanical analyses were undertaken using a proprietary finite element code, based on the iterative substructure method. This approach aims to reduce the computational time for complex thermal-elastic-plastic analyses by separating the model into regions which are linear or weakly nonlinear and those which are highly nonlinear. An iterative approach is used to ensure continuity of tractions between the linear and nonlinear regions. Further details may be found in Nishikawa, Serizawa and Murakawa (2005).

The thermo-mechanical behavior of plate forming by line heating is analyzed using uncoupled formulation. However, the uncoupled formulation considers the contribution of the transient temperature field to stresses through thermal expansion, as well as temperature-dependent thermo-physical and mechanical properties. The solution procedure consists of two steps. First, the temperature distribution history is computed using transient heat transfer analysis. Second, the transient temperature distribution history obtained from the heat transfer analysis is employed as a thermal load in a subsequent mechanical analysis. Stresses, strains and displacements are then evaluated.

2.1.1 Mesh generation and process parameters

All analyses were carried out using rectangular flat plates of 2000x2000xh (mm). Values of thickness (h) equal to 20, 30. 40 and 50 mm were used. By holding the line heating energy constant, the input energy per unit length along the heating line is kept unchanged even though power and velocity change. The highest temperature on the surface in the heating zone is kept at about 850˚C. Cooling is defined corresponding to natural cooling in air. Mild steel thermal, physical and mechanical properties with temperature dependency is considered, including thermal conductivity, specific heat, Young's modulus, Poison ratio, and yield stress (see Figure 1 and 2). Necessary constraints are added to eliminate rigid body motion. The same finite element model used in the thermal analysis is employed in mechanical analysis. The analysis conditions for most of the studied case are as follows: speed (v) equal to 3 mm/sec, Heat imput (Q) equal to 3125 J/mm. For those cases where the heat input and/or the speed of the heating source were varied, values of heat input from 2000 to 10000 J/mm and values of speed from 1 to 25 mm/sec were studied.

2.1.2 Computed results

The deformation of the plate is expressed in terms of the inherent deformation, which is defined as the integration of the plastic strain over the cross section of the plate. Generally, inherent deformations are classified into longitudinal shrinkage (δ_{xx}), transverse shrinkage (δ_{yy}), longitudinal bending (θ_{xx}) and transverse bending (θ_{yy}). These four fundamental components of inherent deformation can be determined by integrating the inherent strain over the cross section of the plate of thickness h as follows,

$$\delta_{xx} = \int \varepsilon^{p}_{xx} dydz/\text{h} \tag{1}$$

$$\delta_{yy} = \int \varepsilon^{p}_{yy} dydz/\text{h} \tag{2}$$

$$\theta_{xx} = \int \varepsilon^{p}_{xx}(z-\text{h}/2)/(\text{h}^3/12)dydz \tag{3}$$

$$\theta_{yy} = \int \varepsilon^{p}_{yy}(z-\text{h}/2)/(\text{h}^3/12)dydz \tag{4}$$

3 Inherent deformations produced at plates edges

Figure 3a shows a typical distribution of inherent transverse shrinkage produced by a straight-line heating along the heating line. In this figure, it may be observed

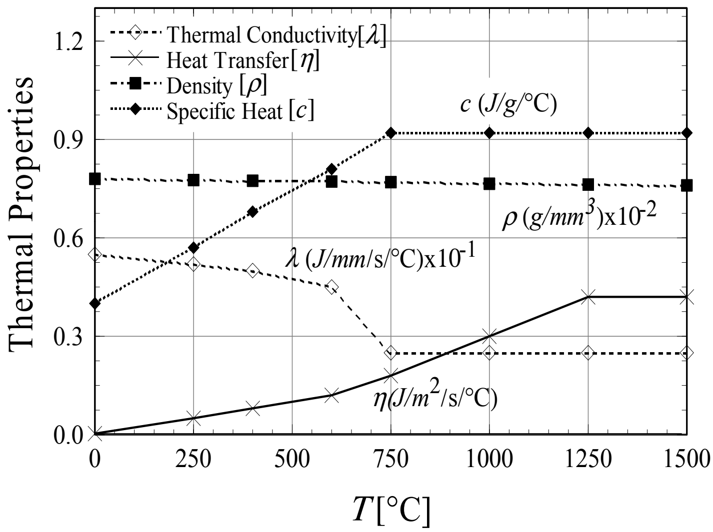

Figure 1: Thermal and physical properties of mild steel

that if the heating line is long enough, the distribution of transverse shrinkage is almost uniform in the interior of the plate. However, close to the edges transverse shrinkage decreases and exhibits a complex distribution. Similar tendency can be observed in the other three components of inherent deformation (see Fig. 3b, 3c and 3d). This is an undesirable effect in plate forming because it causes deviations from the original design. To understand the causes of the variation of inherent deformation along the plate length let us examine the process of forming inherent deformation.

3.1 Transverse components of deformation

First, let us study the process of forming transverse components of inherent deformation using the three bars model show in Figure 4. The heating and cooling process of each bar is given by state (1) to (2). Where, bars (a), (b) and (c) represent the entrance edge, the center and the exit edge of the plate, respectively. The process of forming inherent transverse deformation in each state is described as follows:

- In the initial state (state (1)), heating is applied to the bar (a). In this state,

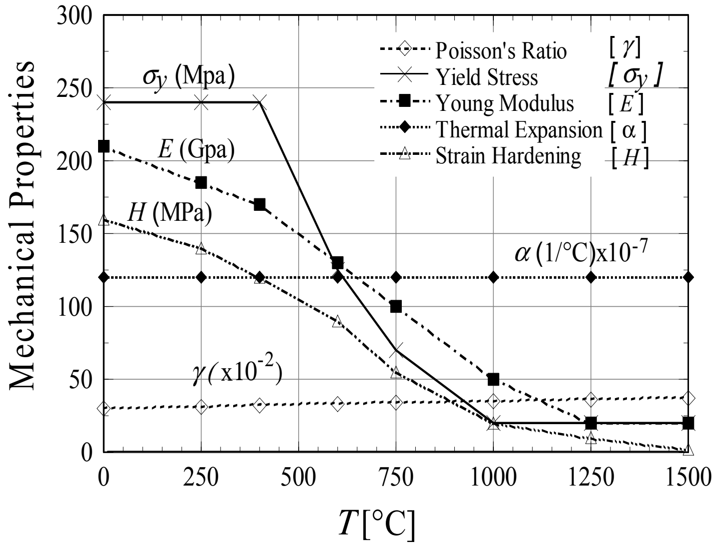

Figure 2: Mechanical properties of mild steel

since the heat is applied at the plate edge, large amount of heating is quickly dissipated and therefore the maximum temperature is lower. When bar (a) is at high temperature, it tries to expand however it is pushed back due to the large restraint. Then, while the heating source is moving toward the plate center, bar (a) is cooling down, and thermal expansion of the bar (a) is fully transformed into transverse deformation. However, this deformation is small due to the lower temperature caused by the heat lost at the plate edge.

- When the moving heat source reaches bar (b), the large restraint has similar influence on the thermal expansion, however in this case the heat input has reached the steady state and therefore the temperature is larger, thus shrinkage increases (state (2)).

- When the moving heating source reaches bar (c), bars (a) and (b) are cooling down and therefore they are shrinking. The thermal contraction along the heating line during the cooling of bars (a) and (b), allows the area of the plate under high temperature (bar (c)) to freely expand in the transverse direction (state (3)).

- In the last state (state (4)), the restrain in the transverse direction of the plate

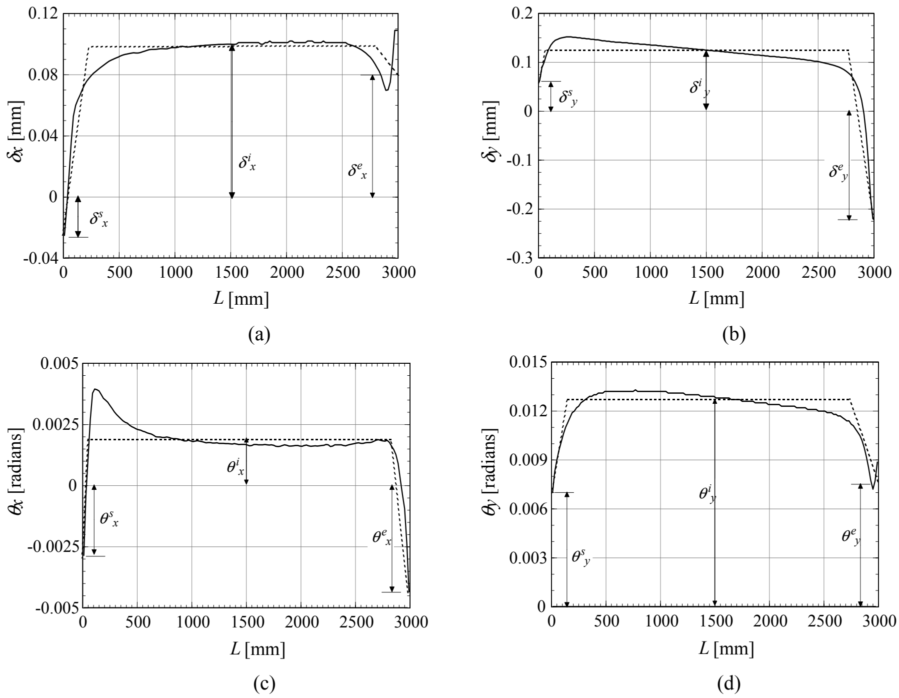

Figure 3: Comparison between computed and assumed distribution of inherent deformation (a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending and (d) Transverse bending

have become small (the gradient of temperature between bars (a), (b) and (c) is small) and therefore no significant additional plastic deformation in the transverse direction is produced at the plate exit edge. In addition, the expansion created in state (c), creates negative transverse shrinkage (transverse expansion).

3.2 Longitudinal components of deformation

The process of forming longitudinal components of inherent deformation is described using the mechanical model shown in Figure 5. Where, bar (b) represents the heating area while bars (a) and (c) represent the area of the plate that is not heated. The process is as follows:

- At the beginning of heating, the thermal expansion of the plate is smaller due

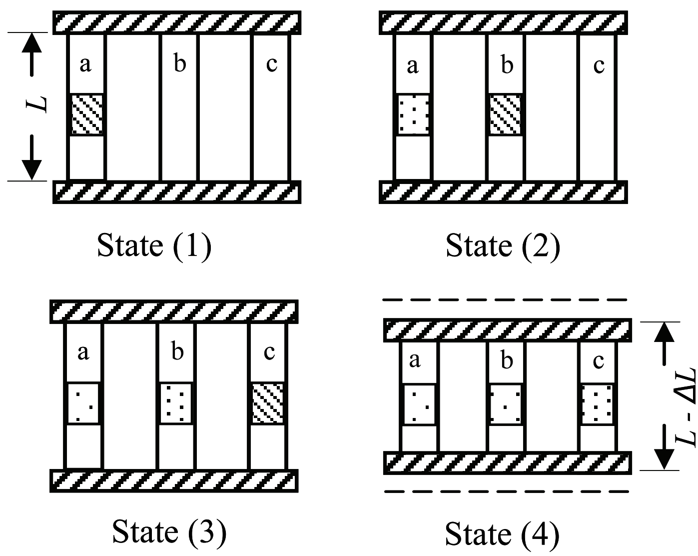

Figure 4: Mechanical model used to analyze the transverse component of inherent deformation

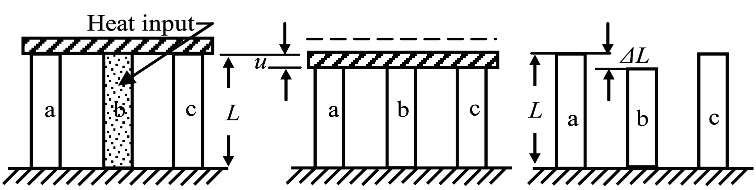

Figure 5: Mechanical model used to analyze the longitudinal components of inherent deformation

to the heat lost and the small restraint of the plate, similar to the explanation given in previous section.

- When the moving heating is approaching the plate center, the restraint of the plate decreases meanwhile the area behind the heating, is contracting. Due to this, the longitudinal deformation at the interior of the plate increases compared with that at the entrance edge.

- When the moving heat source reaches the exit edge of the plate, the restraint in the longitudinal direction has decreased. However, no significant change in the distribution of longitudinal shrinkage is observed. Moreover, the longitudinal bending decreases at the exit edge. The reason why the longitudinal bending decreases at the exit edge is because the longitudinal bending is strongly influenced by the combination of other components of inherent deformation and thus it may vary when other components vary.

4 Edge effect on inherent deformation

The inherent deformation produced by straight heating lines applied from edge to edge varies along the plate length as is explained in previous sections. In order to quantify this variation and consider it in the analysis of plate deformation, we define the ratio between the maximum and the minimum inherent deformation at the entrance and exit edges of the plate as edge effect. Under this, the edge effect has four components: edge effect on longitudinal shrinkage (τ_{xx}), edge effect on transverse shrinkage (τ_{yy}), edge effect on longitudinal bending (ψ_{xx}) and edge effect on transverse bending (ψ_{yy}). In addition, the edge effect at the entrance edge is different to that at the exit edge of the heating line as explained above. Therefore, it is necessary to separate them into eight (8) components given as follows:

$$\tau_{xx}^{s} = \frac{\delta_{xx}^{i} - \delta_{xx}^{s}}{\delta_{xx}^{i}} \tag{5}$$

$$\tau_{xx}^{e} = \frac{\delta_{xx}^{i} - \delta\delta_{xx}^{e}}{\delta_{xx}^{i}} \tag{6}$$

$$\tau_{yy}^{s} = \frac{\delta_{yy}^{i} - \delta\delta_{yy}^{s}}{\delta_{yy}^{i}} \tag{7}$$

$$\tau_{yy}^{e} = \frac{\delta_{yy}^{i} - \delta\delta_{yy}^{e}}{\delta_{yy}^{i}} \tag{8}$$

$$\psi_{xx}^{s} = \frac{\theta_{xx}^{i} - \theta\theta_{xx}^{s}}{\theta_{xx}^{i}} \tag{9}$$

$$\psi xx^{e} = \frac{\theta_{xx}^{i} - \theta\theta_{xx}^{e}}{\theta_{xx}^{i}} \tag{10}$$

$$\psi_{yy}^{s} = \frac{\theta_{yy}^{i} - \theta\theta_{yy}^{s}}{\theta_{yy}^{i}} \tag{11}$$

$$\psi_{yy}^{e} = \frac{\theta_{yy}^{i} - \theta\theta_{yy}^{e}}{\theta_{yy}^{i}} \tag{12}$$

Where the superscripts s, i, and e are the starting, middle and finishing part of the heating line, respectively.

It is important to note that the inherent deformation at the interior of the plate is not exactly uniform therefore; average of inherent deformation along the interior of the plate is used in these relations. Henceforth, positive values of edge effect mean decrease while negative values mean increase of inherent deformation.

4.1 Variation of edge effect with heat input

Figures 6 (a) shows the variation of edge effect with heat input at the entrance edge of the plate. It is noted that the edge effect on longitudinal shrinkage, transverse shrinkage and transverse bending do not significantly changes with heat input (slightly decrease) while the edge effect on longitudinal bending slightly increases. The reason of this small variation is the fact that when the heat input is changed, the peak temperature of the heated surface varies and therefore the inherent deformation (see Vega (2009)). The increase of edge effect on longitudinal bending is due to the same reason explained in previous section.

Figure 6 (b) shows the variation of edge effect with heat input at the exit edge of the plate. It is noted that up to Q equal to approximately 3.5 kJ/mm when the plate thickness is 40 mm, the edge effect on longitudinal shrinkage and transverse bending decreases while that on transverse shrinkage and longitudinal bending increases. It is also noted that for larger values of heat input, the edge effect does not significantly change (slightly decreases). The increase of edge effect on transverse shrinkage with heat input is associated with a reduction of peak temperature at the heat surface. As mentioned, peak temperature is lower at the lower velocity due to the more time for heat dissipation. Because of this, the restrain in the transverse direction of the plate become small (state (d) in Fig. 4) and therefore the edge effect on transverse shrinkage became larger. At the lower velocity, the difference between the temperature at the top and bottom surface is also smaller than that at higher velocity for the same reason. Because of this, the edge effect on transverse bending decreases with heat input. In case of edge effect on longitudinal shrinkage, it decreases with heat input because the decrease of restraint in the longitudinal direction caused by the lower speed. The variation on edge effect on transverse shrinkage, longitudinal shrinkage and transverse bending may cause increase of the edge effect on longitudinal bending as shown in the figure.

The phenomenon changes with large values of heat input as seen in the figure. The main reason of that is found in the relation between speed of the heating source and heat input as shown in Figure 7. As seen in this figure, large heat input is obtained at low speed. In addition, the relation between speed and heat input for large values of heat input is close to constant (contrary to the case of small heat input in which

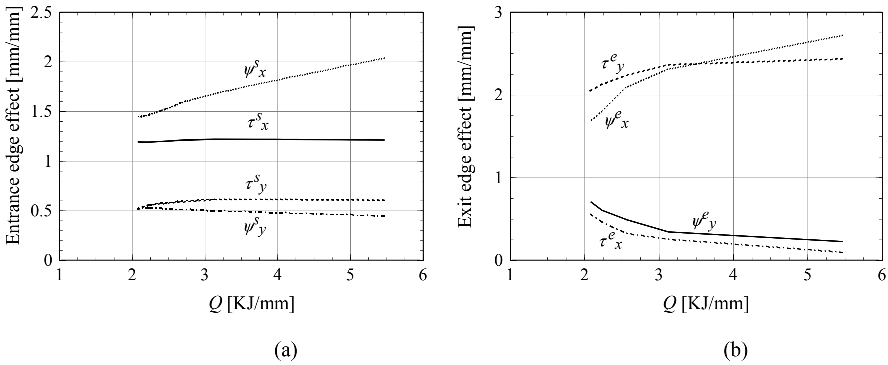

Figure 6: Variation of edge effect with heat input (a) entrance plate edge (b) exit plate edge

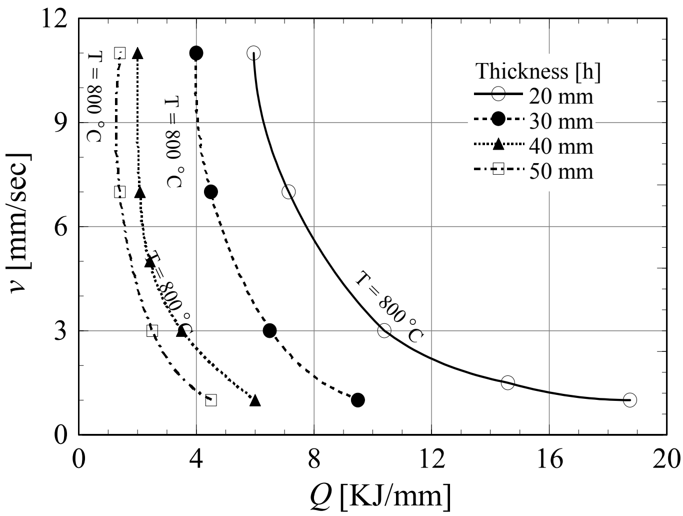

Figure 7: Relationship between neat heat input and speed of the heating source

any small change on speed produce large variation of heat input). Because of this, the peak temperature at the heated surface does not significantly changes when the heat input increases. Consequently, the peak temperature at the heated surface does not changes and therefore no visible change in edge effect is observed.

4.2 Variation of edge effect with plate geometry

Figure 8 shows the variation of inherent deformation with plate length. It is clearly seen that the inherent deformation produced at both plate edges does not significantly vary with plate length. Similar conclusion is obtained after comparing the variation of inherent deformation with plate width (See Vega (2009)). It therefore seems reasonable to conclude that the edge effect is independent of the plate size. Hence, considering the similarity of inherent deformation at the entrance and at the exit edge of plates with different lengths larger than about 800 mm, the distribution of edge effect for any plate size (same thickness), can be obtained by superposing the edge effect obtained from the analysis of a larger plate.

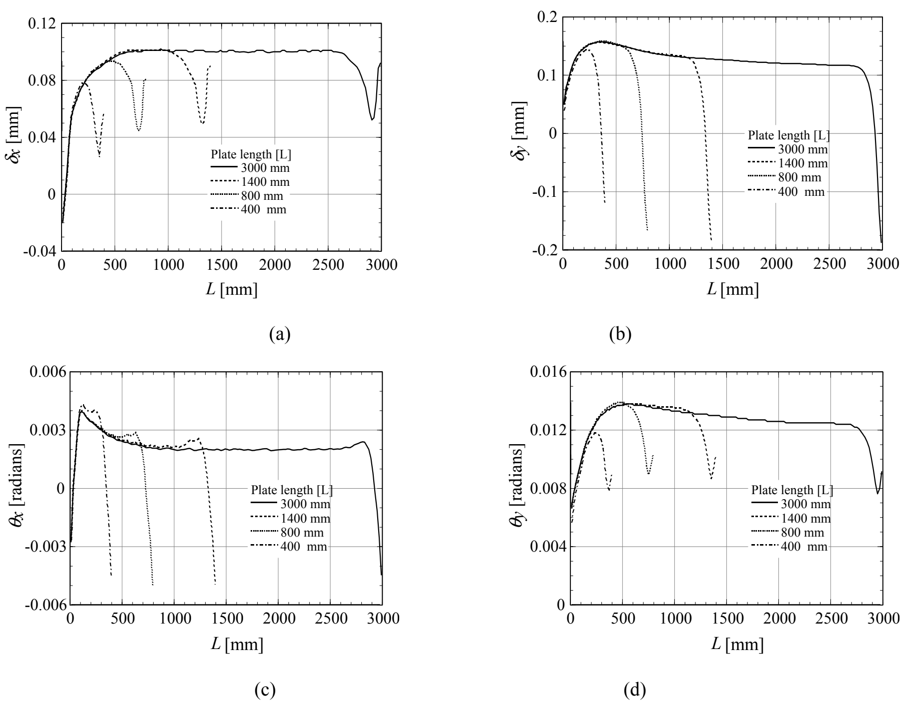

Figure 8: Variation of inherent deformation with plate length, (a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending, and (d) Transverse bending

Figure 9 shows the variation of edge effect with plate thickness at the entrance and exit edge of the plate, respectively. As seen in the figure, the edge effect changes with plate thickness. There are two reasons for this; first, in the analysis of plates

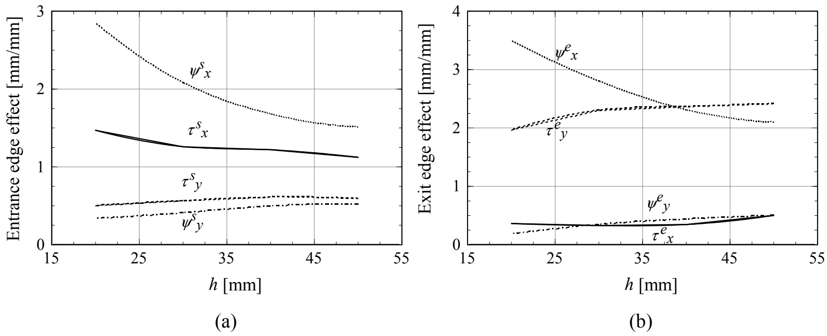

Figure 9: Variation of edge effect with plate thickness (a) entrance plate edge, (b) exit plate edge)

with different thickness, the heat input has been changed in order to attain same temperature at the heated surface (speed is kept constant). Therefore, the edge effect changes, as is explained in previous section. Second, it is a fact that thicker plates have large difference of temperature between top and bottom surface (restraint through the thickness increases with plate thickness). Thus, the edge effect may decrease. It is important to note that the variation of edge effect with plate thickness is large and therefore it may be considered in the analysis.

4.3 location of heating lines

Cheng et al (2005) performed numerical investigations aimed to clarify the side edge effect on plate deformation. They concluded that plate deformation, especially angular distortion, greatly decreases when the heating line becomes closer to a free edge. However, this conclusion is based on analysis of small plates, which do not represent the actual size of plates used in shipbuilding. In this section, a numerical study is performed to clarify the influence of side edge on inherent deformation of large plates. At first, inherent deformation of single heating lines applied at different distances from the free edge (0, 200, 400, 600, 800 and 1000 mm) is computed. Plate models (2000 x 2000 x 40 mm) as well as heating and cooling condition are the same in all cases.

Figure 10 shows the resulting inherent deformation. Here, the inherent deformation is obtained by averaging the value at the central region of the plate. It may be clearly seen that both, transverse and longitudinal component of inherent deformation decrease as the heating line becomes closer to the free edge.

For those cases that are spaced more than 300 mm (in the case of longitudinal components) and 400 mm (in case of the transverse components) from the free edge, the inherent deformation does not significantly change. Despite the fact that the reduction of inherent deformation due to side edge effect is only found in a small area of the plate, the influence is large. Therefore, in accurate prediction of inherent deformation due to line heating, the influence of plate side edge on inherent deformation must be considered.

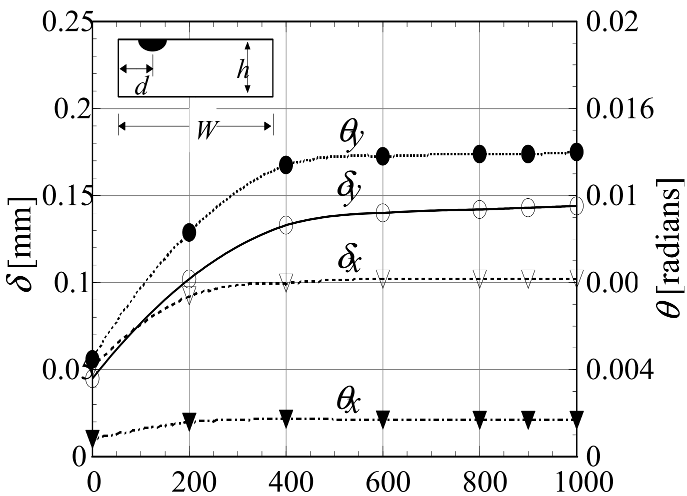

Figure 10: Variation of inherent deformation with the distance from the plate edge

4.4 Variation of edge effect with material properties

Magee et al. (1997) showed that the extent of the edge effects on angular distortion is also related to the material properties. In order to evaluate this effect on inherent deformation the influence of material properties on inherent deformation produced at plate edges is considered. Figure 11 shows the variation of edge effect on transverse shrinkage with thermal material properties. As it is clearly seen, thermal properties such as specific heat, density and thermal conductivity influences the edge effect. However, these influences are small and can be neglected. Almost similar conclusion is obtained after examining the variation of edge effect with mechanical material properties as is shown in Figure 12. In both cases, the maximum variation of edge effect is of about 10% and it happens when the material properties have been increase (compared with the original value obtained from experiment) in about 20%.

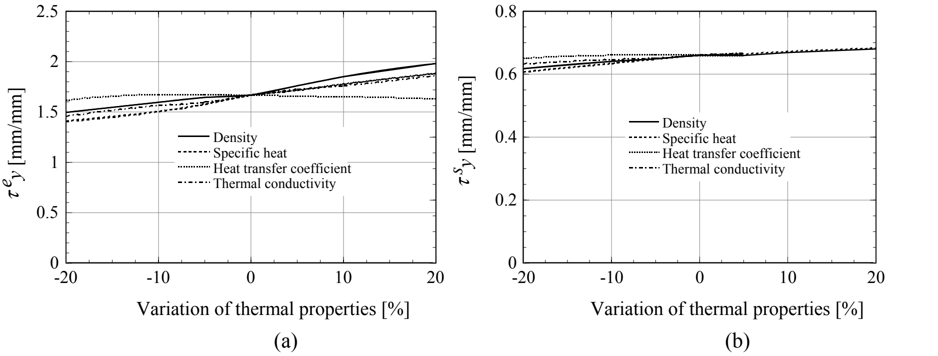

Figure 11: Variation of edge effect on transverse shrinkage with thermal properties (a) entrance plate edge, (b) exit plate edge

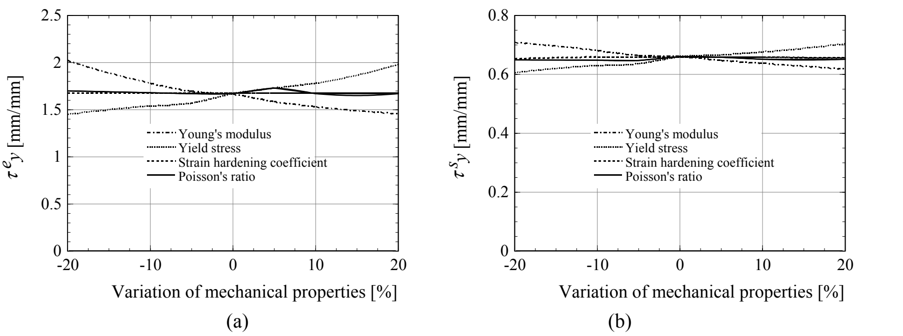

Figure 12: Variation of edge effect on transverse shrinkage with mechanical properties (a) entrance plate edge, (b) exit plate edge

5 Method to predict edge effect on Inherent deformation

As demonstrated in previous sections, the inherent deformation at the entrance and exit edge of the plate varies with the heat input, the speed of the heating source, the plate thickness and with materials properties. It has been also demonstrated that these variation can be quantified through the edge effects given in Equations 5 to12. In order to create a method of prediction that considers all these variations, the edge effects can be related to the heat input parameter Q/h^2 as shown in Figures 13 and 14. As it is seen in these figures, at the starting edge, the edge effect on longitudinal shrinkage generally increases with the heat input parameter (Figure 13 (a)). Similar behavior is observed in Figure 13 (c) where the edge effect on

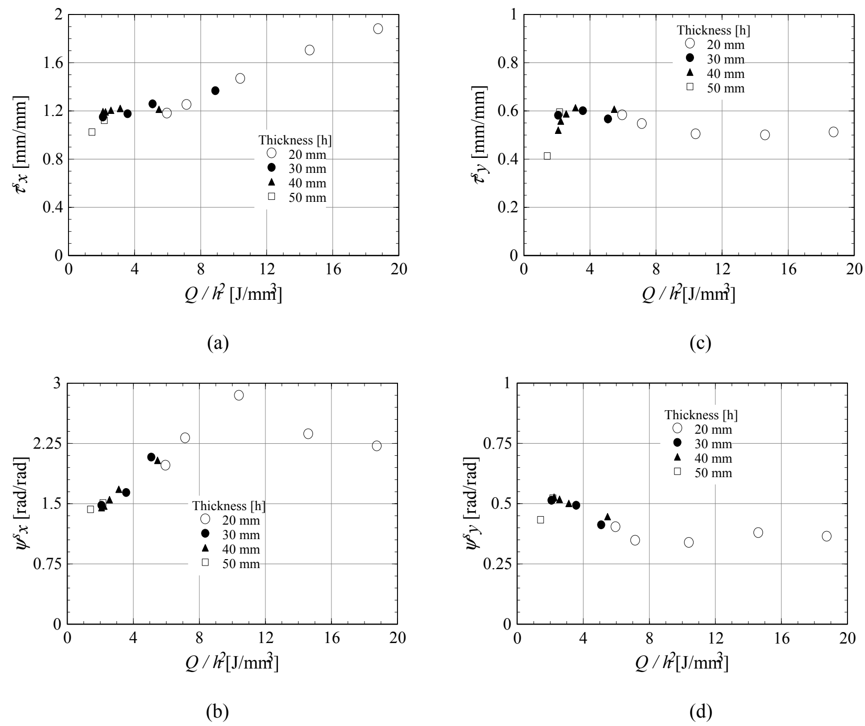

Figure 13: Relation between edge effect and heat input parameter Q/h^2 at the entrance plate edge (a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending and (d) Transverse bending

longitudinal bending is shown. However, up to Q/h^2equal to approximately 10, the edge effect on longitudinal bending starts to decrease with and increasing heat input parameter Q/h^2. On the other hand, the edge effect on transverse components of inherent deformation increases with the heat input parameter up to approximately 2, after that it slightly decreases as shown in Figures 13 (b) and (d).

At the exit edge, the edge effect on longitudinal shrinkage shows a complex distribution. Generally, it increases with the heat input parameter as seen in Figure 14 (a). Similar behavior is observed in Figure 14 (c) where the edge effect on longitudinal bending is shown. However, up to Q/h^2equal to approximately 8, the edge effect on longitudinal bending does not significantly changes with the heat input parameter Q/h^2. On the other hand, edge effect on transverse components of inherent deformation decreases with heat input parameter as shown in Figures 14 (b) and (d). Despite the fact that edge effect shows a complex distribution, it has been

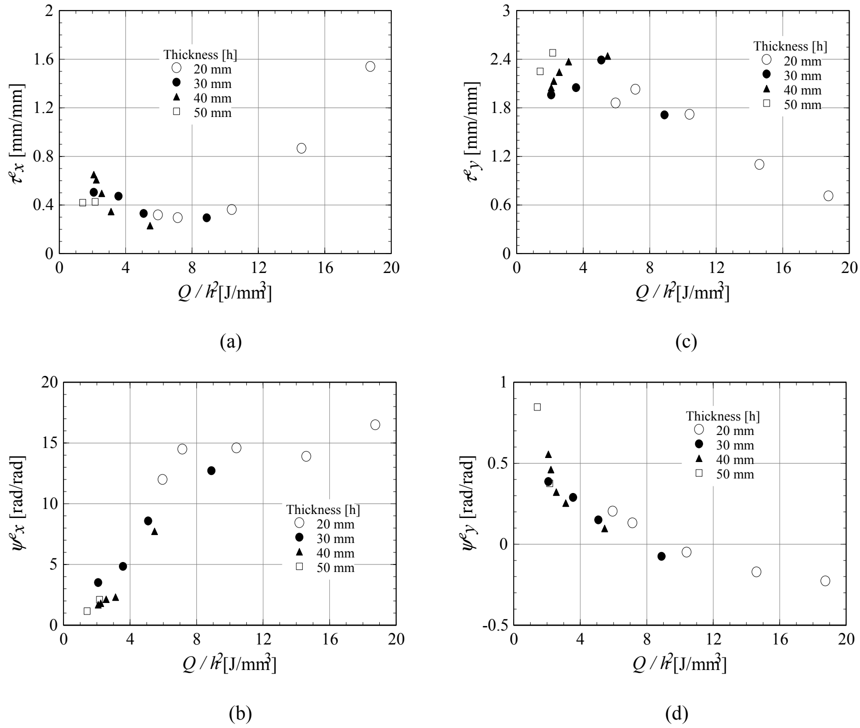

Figure 14: Relation between edge effect and heat input parameter Q/h^2 at the exit plate edge (a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending and (d) Transverse bending

demonstrated that it is possible to relate it to the heat input parameter Q/h^2. Using the relation given in Figures 13 and 14 the edge effect for a wide range of heating condition and plate thickness can be obtained.

Note that values given in these figures correspond to the value at the plate edges. However, the edge effect varies along the heating line and it decreases toward the plate center. If this distribution is approximated as uniform distribution, the accuracy of the inherent deformation is significantly reduced. To overcome this, the edge effect can be considered as a linear function of the extension of the edge effect. Examining the distribution of computed inherent deformations for cases with different conditions it was found that the extension of the entrance edge effect and the exit edge effect are approximately equal to 300 and 400 mm respectively.

6 Conclusions

It has been demonstrated that the variation of inherent deformation along the plate length (known as edge effect) need to be separated into two: that at the entrance edge and that at the exit edge of the plate. It is explained that the first is produced by the heat lost at the plate edge while the second is mainly produced by the reduction of restraint in the transverse direction of the plate during the time the plate is being heated toward the exit edge of the plate. These two types of edge effect are undesirable since they adversely affect the accuracy of the plate forming.

Through the study of the influence of some influential factors on inherent deformation produced at plate edges it has been concluded that it is necessary to consider the variation of edge effect with plate thickness and heat input in order to improve the accuracy of the predictive model. Based on the analysis performed here, a database of edge effect is presented in Section 7.2.1 of this thesis.

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