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Analysis of cross effect on inherent deformation during the line heating process – Part 1 – Single crossed heating lines

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ABSTRACT

This paper describes the effect of previous heating on inherent deformation by a subsequent heating line, more specifically, the case of two heating lines intersecting (crossing) each other. The paper has been divided into two parts. In the first part, the case of single crossed heating lines is studied in detail. The second part of the paper, discusses the case of more than one crossed heating lines. The novelty of the work lies in revealing the cross effect and how, factors such as, for example, the heating condition and the plate geometry, influence the resulting inherent deformation of crossed heating. In addition, relationships to easily get these influences are provided. The results are suitable for a wide range of heating conditions and plate thickness.

1. Introduction

While the advantages of the line heating process for plate forming are well recognized, the benefits often have not been entirely acquired due to a significant increase on costs related to unwanted rework. Unfortunately, there is some evidence to suggest that the line heating process is far from being fully automated due to a lack of knowledge, specifically, on the relationship between the heating process and the resulting plate deformation [1,2,3,4,5,6]. On the other hand, without a doubt, we can suggest

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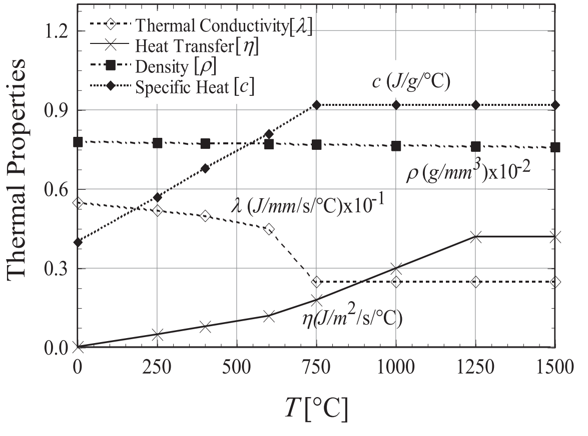

Fig. 1. Thermal and physical properties of mild steel [12].

that the most significant development in shipbuilding will be a fully automated system able to generate any three dimensional shape, independent of the size and thickness, from flat plates. In recent years, significant efforts have been dedicated to understand the mechanism of plate forming by line heating, which seen to be the most potential process, for achieving this goal [7,8,9,10].

It has been demonstrated that the plate deformation is not only dependent on the heat input, the speed and the plate thickness. It depends on secondary factors such as the plate size, method of cooling, plate initial curvature, sequence of heating, edge effect, residual stresses, and others [11,12,13,14].

In addition to the above, it is necessary to stated that in order to achieve such analysis, the finite element method (FEM), over experimentation and other numerical methods, is commonly recommended due to its versatility in modeling the uncoupled heat transfer and mechanical problem [15,16,17]. Despite this, it is important to mention that modeling the line heating by FEM is restricted to small plates models which at best do not constitute a good example of ship hulls plates.

The authors wish to explore the impact that residual stresses, appearing during the heating cycle, has over the inherent deformation induced by subsequent heating. Moreover, the understanding of such influences depends on a multitude of variable. Therefore, it has been necessary to divide the study into three different cases as follows: overlapped, parallel and crossed heating lines. The result of each of these have been published separately [14].

In this paper, we are focusing on the contribution that residual stress has on the deformation produced by crossed heating lines. Hereafter, the studied cases of crossed heating lines are only for orthogonal lines while cross effect refers to the influence on inherent deformation that previous heating has on the following. The main purposes are to provide a detailed characterization of the cross effect, contributing in this way to the automation of the line heating process. Results of a wide range of cases are presented, which includes different plates thickness and heating conditions.

2. Formulation of the 3D thermal elastic–plastic model

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 Ref. [18].

The thermo-mechanical behavior of the 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 different sizes (from 400 to 4000 length). FEM solid mesh models, using 8 nodes hexahedron elements, are being employed. 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 [9] is considered, including thermal conductivity, specific heat, Young's modulus, Poison ratio, and yield stress (see Figs. 1 and 2). Phase Transformation was not considered due to the fact that its influence in plate distortion, the main goal of our research, is not critical (See Ref. [9]). 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/s, Heat input (Q) equal to 3125 J/mm. For those cases where the heat input and/or the speed of the heating source was varied, values of heat input from 2000 to 10,000 J/mm and values of speed from 1 to 25 mm/s 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}) (See Refs. [19] and [20] for more details about generating of out-plane deformation from in-plane deformation). These four fundamental components of inherent deformation can be determined by integrating the inherent strain over the cross section of the plate of thickness has follows (See Ref. [11]):

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

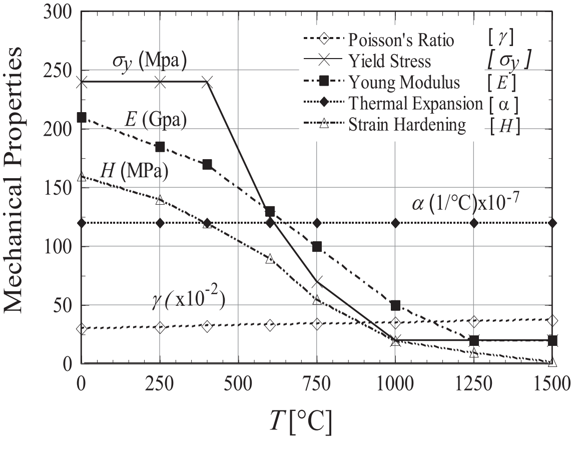

Fig. 2. Mechanical properties of mild steel [9].

$$\delta_{yy} = \iint \varepsilon_{yy}^{p} \mathrm{d}y\mathrm{d}z/\mathrm{h} \tag{2}$$

$$\theta_{xx} = \iint \varepsilon_{xx}^{p} (z - \mathrm{h}/2) / \left(\mathrm{h}^3/12\right) \mathrm{d}y\mathrm{d}z \tag{3}$$

$$\theta_{yy} = \iint \varepsilon_{yy}^{p} (z - \mathrm{h}/2) / \left(\mathrm{h}^3/12\right) \mathrm{d}y\mathrm{d}z \tag{4}$$

3. Inherent deformation produced by crossed heating lines

Fig. 3 shows two typical cases of a heating pattern. In the first case (Fig. 3(a)), a heating line is applied; inherent deformation and residual stresses are produced as explained before. After the plate cools down to room temperature, a second heating line, under the same heating and cooling conditions, is applied. The rise of inherent deformation produced by this new heating line varies due to the influence of residual stresses [13]. However, it depends on the case. Consider that the additional heating line is applied from the plate edge toward the middle of the plate and stops just before it reaches the plastic strain region of the first heating line. Here, the transverse shrinkage produced by the second heating line is increased while that in the longitudinal direction decreases. This is due to the existing residual stresses produced by previous heating, as shown in Fig. 4. These residual stresses are relatively small and, therefore, the difference of inherent deformation is small too.

A different situation is exposed in Fig. 3(b), where a second heating line is applied under the same heating and cooling condition to the first heating. However in this case, the subsequent heating line is applied from the plate edge toward the center of the plate, crossing the plastic strain zone of the first heating line and stopping at the opposite edge of the plate. At the beginning, the same situation described in the first case occurs. However, by the time that the area in which heating lines intersect (crossed area) is at high temperature, the existing residual stress is transformed into additional strain during the thermal cycle. Then, when the plate cools down, the components of inherent deformation are significantly affected, especially in the longitudinal direction as shown in Fig. 5. In addition, due to the compressive residual stress existing at the exit edge of the second heating line (See Fig. 4), additional compressive strain in the transverse direction is produced along the second half of the second heating line.

Fig. 5 also shows a comparison between the total inherent deformation obtained after simulating two (crossed) heating lines (Fig. 3(b)) and that obtained by simple superposing inherent deformation of individual heating lines (assuming that the total deformation is the result of the addition of the deformation produced by each heating separately). Noted that the second case is unrealistic, however is the way the prediction is done nowadays. From these figures, it may be concluded that the inherent deformation of crossed heating lines cannot be determined by superposing inherent deformation of individual heating lines. In following, the inherent deformation produced by crossed heating lines is examined in detail.

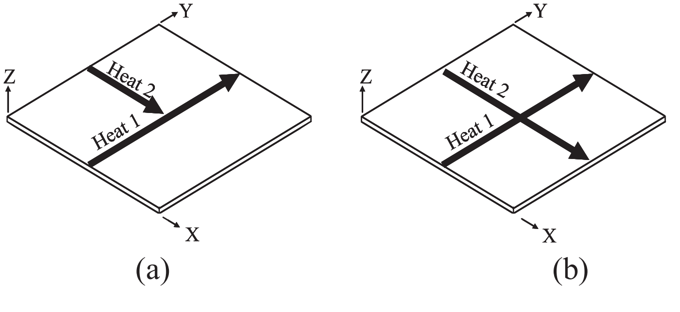

Fig. 3. Schematic of orthogonal heating, (a) Uncrossed and (b) Crossed.

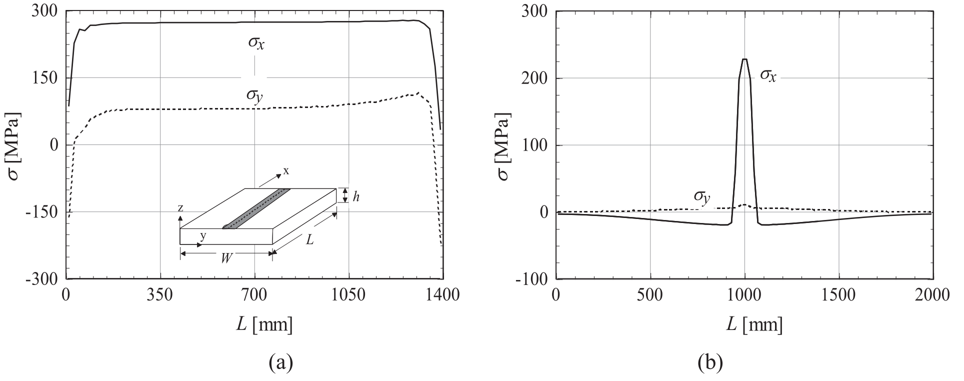

Fig. 4. Residual stresses distribution at the plate surface (a) along the heating line (W/2), (b) transverse to the heating line (L/2).

4. Crossing effect on inherent deformation

Residual stresses produced by previous heating lines influence the inherent deformation produced by crossing heating lines as shown in Fig. 5. In order to quantify this difference and take it into account in the analysis of plate deformation, we compare the inherent deformation produced by crossed

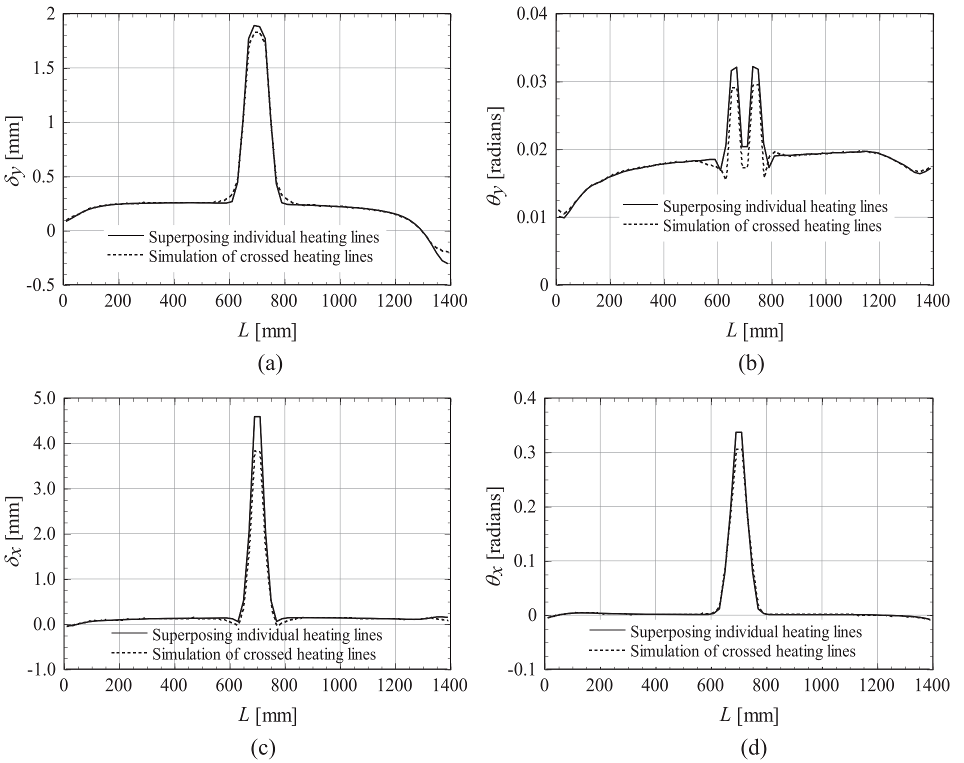

Fig. 5. Comparison between results of inherent deformation obtained from simulation of crossed heating lines and by superposing individual heating lines (a) Transverse shrinkage, (b) Transverse bending, (c) Longitudinal shrinkage, and (d) Longitudinal bending.

heating lines with that calculated by superposing inherent deformations produced by the same heating lines each applied alone on a stress-free plate. The difference between these two inherent deformations is named by the authors as the *crossing effect*. Fig. 6 shows the distribution of crossing effect on inherent deformation plotted along the first and second heating line, respectively. In this figure, positive values of crossing effect mean reduction of the inherent deformation while negative values represent an increase. As seen in this figure, the crossing effect is larger at the crossed area while, in the area far from the intersection, it is small, and can be neglected.

Since the distribution of crossing effect along the heating line is complex and difficult to record into a database, we introduce the concept of total inherent deformation, which is given by integration of plastic strains over the volume of the plate as shown in Eqs. (5)–(8).

$$\delta^t_{xx} = \iiint \varepsilon^p_{xx} \mathrm{dxdydz/h} \ \left(\mathrm{mm}^2\right) \tag{5}$$

$$\delta^t_{yy} = \iiint \varepsilon^p_{yy} \mathrm{dxdydz/h} \ \left(\mathrm{mm}^2\right) \tag{6}$$

$$\theta^t_{xx} = \iiint \varepsilon^p_{xx} (z - \mathrm{h}/2) \Big/ \left(\mathrm{h}^3 / 12\right) \mathrm{d}x\mathrm{d}y\mathrm{d}z \ \left(\mathrm{Radians.\ mm}\right) \tag{7}$$

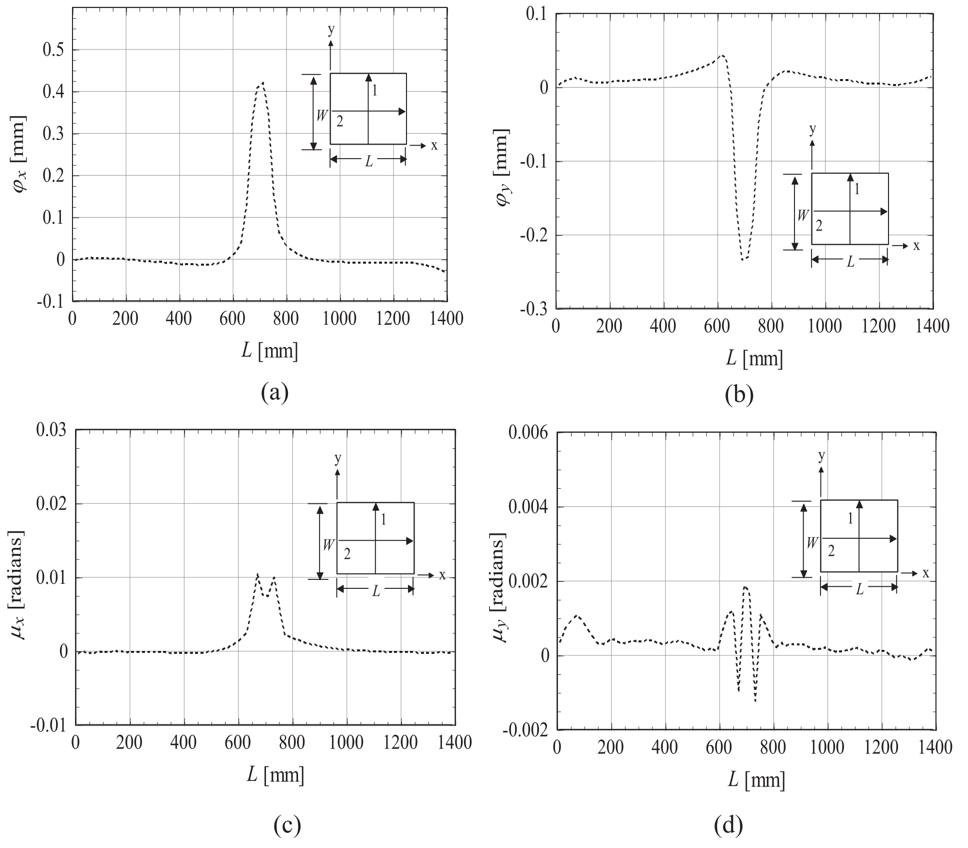

Fig. 6. Crossing effect on inherent deformation, (a) On longitudinal shrinkage, (b) On transverse shrinkage, (c) On longitudinal bending, and (d) On transverse bending.

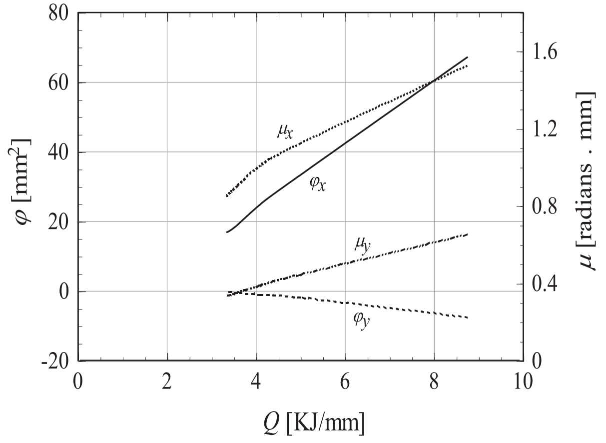

Fig. 7. Variation of crossing effect with heat input.

$$\theta^t_{yy} = \iiint \varepsilon^p_{yy}(z - \mathrm{h}/2) \Big/ \left(\mathrm{h}^3/12\right) \mathrm{d}x\mathrm{d}y\mathrm{d}z \ \ (\text{Radians. mm}) \tag{8}$$

where z represent the distance from the plate neutral axes.

By using the total integration of inherent deformation, the crossing effect, for each heating condition, is achieved. Then, these values of crossing effect can be added to the inherent deformation of individual heating line by concentrating them into the crossed area only. Then, it is possible to separate the crossing effect into four components; crossing effect on longitudinal shrinkage (φ_x), crossing effect on transverse shrinkage (φ_y), crossing effect on longitudinal bending (μ_x), and crossing effect on transverse bending (μ_y). These four components of crossing effect can be defined as follows:

$$\varphi_x = \delta^{tc}_x - \delta^{t1}_x - \delta^{t2}_x \left(\mathrm{mm}^2\right) \tag{9}$$

$$\varphi_y = \delta^{tc}_y - \delta^{t1}_y - \delta^{t2}_y \left(\mathrm{mm}^2\right) \tag{10}$$

$$\mu_x = \theta^{tc}_x - \theta^{t1}_x - \theta^{t2}_x \ (\text{Radians. mm}) \tag{11}$$

$$\mu_y = \theta^{tc}_y - \theta^{t1}_y - \theta^{t2}_y \ (\text{Radians. mm}) \tag{12}$$

Where, the superscript c implies the inherent deformation of crossed heating lines 1 plus 2, the other terms of the equation are the same as in Eqs. (5)–(8).

4.1. *Variation of crossing effect with heat input*

Fig. 7 shows the variation of crossing effect with heat input. It is clearly seen that the crossing effect on longitudinal shrinkage increases with the heat input while that on transverse shrinkage slightly decreases. In the case of bending components, the crossing effect increases with the heat input as may be notice in the figure. There are two reasons the crossing effect varies with heat input. First, it is a fact that residual stresses varies with heat input. Second, a variation of heat input means that the speed or the power of the heating source has been changed, both consequently changes the width of the heat-affected zone (HAZ). An increase of the HAZ means that the crossing area becomes larger. This expansion of the crossing area results in a variation of the crossing effect because the amount of residual stress diminished during the thermal cycle changes. The second reason is the most dominant.

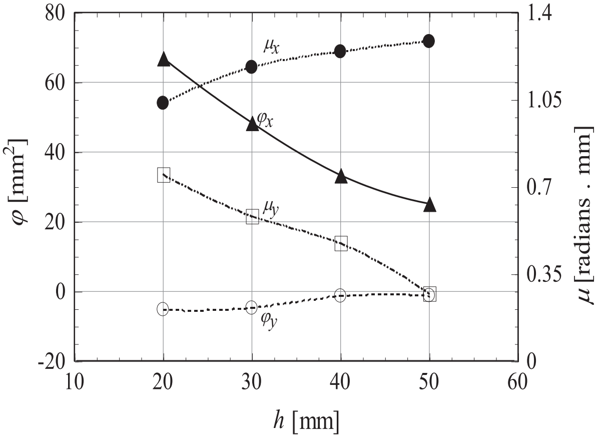

Fig. 8. Variation of crossing effect with plate thickness.

Therefore, it is necessary to consider the variation of crossing effect with heat input in case of crossed heating lines applied under different heating conditions.

4.2. Variation of crossing effect with plate thickness

The crossing effect varies with plate thickness as may be seen in Fig. 8. It may be seen that the crossing effect on longitudinal and transverse shrinkage decreases with increasing plate thickness. Similar trend is observed in the crossing effect on transverse bending while the crossing effect on longitudinal bending increase with plate thickness as is shown in the figure. In this comparison, the speed of the heating source and the heated surface temperature are the same for all cases. This implies that the heat input is different for each case due to the different plate thickness and the idealized heat input model used in this paper (See Ref. [12]).

4.3. Variation of crossing effect with plate size

The distribution of residual stress depends on the geometry of the plate, as explained previously. Because of this, the crossing effect varies with plate size as shown in Fig. 9. In this figure, the crossing effect on longitudinal shrinkage for three different plate models (See Fig. 10) is shown. In all the cases,

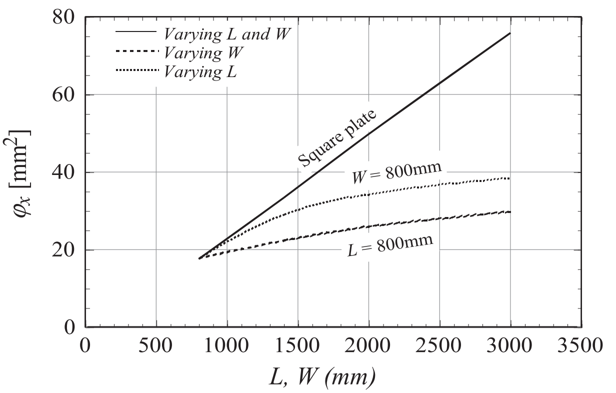

Fig. 9. Variation of crossing effect with plate size.

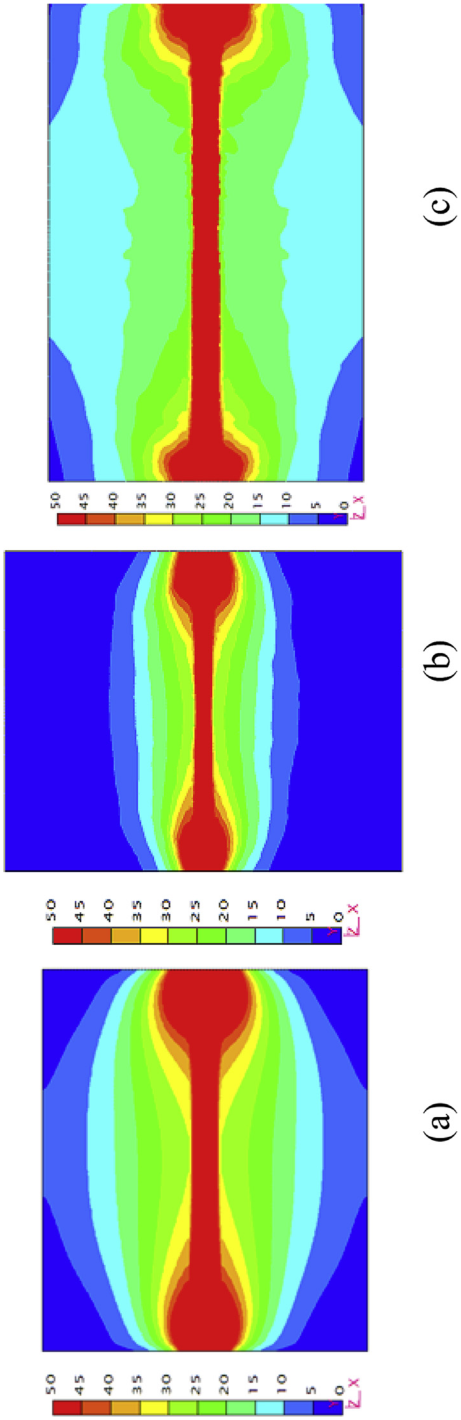

Fig. 10. Distribution of residual stress (σ_x (MPa)) produced by single heating over plates with different geometry (a) Square plate, (b) Rectangular plate (L > W), and (c) Rectangular plate (W > L). "Note that in these figures the scale has been changed in order to attain a most clear distribution of residual stresses".

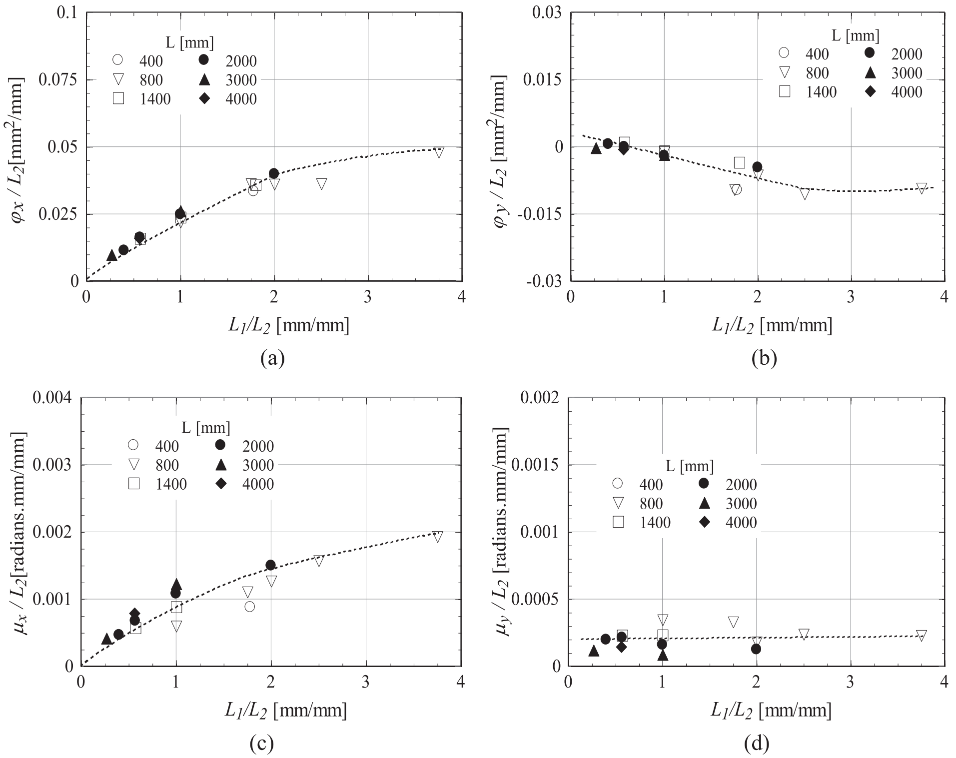

Fig. 11. Variation of cross effect with the aspect ratio of the crossed heating lines (L_1/L_2), (a) On longitudinal shrinkage, (b) On transverse shrinkage, (c) On longitudinal bending, and (d) On transverse bending.

both heating lines are applied from one edge to the other edge. The first plate model corresponds to square plates in which both, the length and width are changed. The second model corresponds to rectangular plates in which the length is changed while the width is kept constant. The last model corresponds to rectangular plates in which the width is changed with keeping the length constant. It is clearly seen that in case of square plates, the crossing effect on longitudinal shrinkage linearly increases with increasing plate size. In the case of rectangular plates, the crossing effect does not significantly changes with plate size. The reason is that the tensile residual stress, existing far from the crossed area, is also diminished due to the thermal cycle of the crossed heating line. This residual deformation cause additional crossing effect. The amount of this additional crossing effect directly depends on the relation between the lengths of both heating lines as follow:

1. In case that the length of both heating lines is the same (Square plates (Fig. 10(a)), the crossing effect increases proportionally to the length of the heating lines. An example of this is the comparison of crossing effect in square plates given in Fig. 8.
2. In case that a crossing heating line is applied over the pattern of residual stress existing in Fig. 10(b), the crossing effect does not significantly increase with the length of the first heating line (increased plate length while maintaining a constant width). This is because the additional crossing effect produced in the region far from the crossed area is not so pronounced because the plate is narrow.
3. In the case that a crossed heating line is applied over the pattern of residual stress existing in Fig. 10(c), the crossing effect does not increase with increased length of the crossing heating line (increasing plate width while keeping a constant length). This is because the residual stress in the extended area is small.

In the three cases studied above, heating lines are applied from one edge to the other edge of the plate. In the case of partial heating lines (shorter than the plate size), it follows the same tendency. However, there is a small difference due to the effect of the plate edge.

In order to acquire a better comprehension of the behavior explained above, the crossing effect produced by different combination of plate size (from 400 mm to 4000 mm) is compared in Fig. 11. In this figure, the crossing effect is plotted as a function of the aspect ratio of the heating lines (L_1/L_2), where L_1 and L_2 are the length of the first and the second (crossing) heating lines, respectively. Note that the crossing effect has been divided by the length of the second (crossing) heating line for easy understanding.

Despite the fact that, the crossing effect varies with the plate aspect ratio, for large values of aspect ratio this became neglectable. It is important to note that these figures are obtained with plates of thickness equal to 40 mm heated under the same heating and cooling conditions. Thus, if one or both are changed, these relations may vary as explained previously.

5. Conclusions

A finite element analysis has been developed in order to analyze the impact of crossed heating lines on inherent deformation during line heating. The inherent deformation on crossed heating lines is not a simply superposition of that produced by independent heating lines; thus, it has to be considered as an influential factor during the line heating process. It has been demonstrated that the variation of inherent deformation with crossed heating lines is caused by the existing residual deformation produces by former heating lines. Then, the concept of cross effect is introduced and explained in detail. The relationship between cross effect and influential factors is determined.

Acknowledgments

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