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Analysis and Prediction of Parallel Effect on Inherent Deformation during the Line Heating Process

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Abstract: This paper describes the effect of previous heating on inherent deformation by following heating, more specifically, the case of two heating lines applied parallel to each other. The novelty of the work lies in revealing the parallel effect and how, factors such as, for example, the heating condition and the plate geometry, influence the resulting inherent deformation of parallel 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.

Keywords: Line heating, parallel heating lines, parallel effect, FEM, plate forming, shipbuilding.

1 Introduction

Perhaps the most significant development in shipbuilding would be a fully automated system able to generate any three dimensional shape, (independently of size and thickness) from flat plates. In recent years, significant efforts have been dedicated to understanding the mechanism of plate forming by line heating, which is the process seen to have the most potential for achieving this goal (Branco et all (2005), Chang et all (2005) and Wang et all (2006)).

While the advantages of the line heating process are well recognized, the benefits often have not been entirely inquired due to a significant increase in 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, especially on the relationship between the heating process and the resulting plate deformation (Bao et all (2001), Cheng et all (2005), Magee et all (1997)).

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 (Vega et all (2008), Vega (2009), Vega et all (2011)).

The authors wish to explore the impact that residual stresses, appearing during the heating cycle, has over the inherent deformation induced by following heating. Moreover, the understanding of such influences depends on a multitude of variables. 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 is going to be published separately.

In addition, it is necessary to mention 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 (Osawa et all (2007), Zhang et all (2012)). It is also important to mention that modeling the line heating by FEM is restricted to small plate models which at best do not constitute a good example of ship hulls' plates.

In this paper, we are focusing on the contribution that residual stress has on the deformation produced by parallel heating lines. Hereafter, parallel refers to two heating lines that maintain constant the gap between them while parallel effect refers to the influence on inherent deformation that previous heating has on the following. The main purpose is to provide detailed characterization of the parallel effect, contributing to the automation of the line heating process. Results of a wide range of cases are presented, which include different plate thicknesses and heating conditions.

2 Numerical analyses of the line heating process

The same FEA developed in Vega (2011) has been used to study the influence of parallel heating lines on inherent deformation. The main characteristics of that FEA are as follows: speed (v) = 3 mm/sec, Heat input (Q) = 3125 J/mm. For those cases where the heat input and/or the speed of the heating source were varied, then values of heat input from 2000 to 10000 J/mm and of speed from 1 to 25 mm/sec, were studied. All analyses are carried out using rectangular flat plates of 2000x2000xh (mm). Values of plate thickness (h) equal to 20, 30, 40, and 50 mm are used. The highest temperature on the surface in the heating area is kept at about 850˚C. Cooling is defined relative to natural cooling in air. Thermal, physical and mechanical properties of steel are considered and also mild temperature dependence, including; Young's modulus, thermal conductivity, specific heat, Poison ratio and yield stress. Necessary constraints are added to eliminate rigid body motion. An inhouse finite element code, based on the iterative substructure method, is employed to achieve the thermal and mechanical analyses. More details of this code are found in Nishikawa, Serizawa and Murakawa (2005).

The resulting inherent deformation of the plate is given by four main components: longitudinal shrinkage (δ_x), transverse shrinkage (δ_y), longitudinal bending (θ_x) and transverse bending (θ_y) expressed by equation 1 to 4;

$$\delta_x^i = \int \varepsilon_x^* dydz/h \tag{1}$$

$$\delta_y^i = \int \varepsilon_y^* dydz/h \tag{2}$$

$$\theta_x^i = \int \varepsilon_x^* (z-h/2)/(\mathrm{h}^3/12)dydz \tag{3}$$

$$\theta_y^i = \int \varepsilon_y^* (z-h/2)/(h^3/12)dydz \tag{4}$$

More details of the FEA as well of the heating condition or/and the material properties are found in Vega et al (2011).

3 Inherent deformation produced by parallel heating lines

Vega (2009) demonstrated that inherent deformation produced by overlapping heating lines is influenced by residual stresses produced by former heating. These analyses were carried out by applying heating lines in the same area (100% overlapping). In addition to that, there are cases in which the centerline of heating lines is separate from each other. In these cases, and depending on the separation between heating lines, the analysis has to be done by separating the effect of partially overlapping and that of parallel heating lines. These types of heating lines are studied in detail in this paper.

Figure 1 shows a typical distribution of residual stresses produced by a separate heating line at the heated surface and plotted transverse to the heating line at the middle of the heating line (L/2). By simple inspection, it may be noted that if a second heating line is applied parallel to the existing one, the inherent deformation produced by this new heating line will be influenced by the residual stresses shown in the figure.

Figure 2 shows a comparison between the inherent deformation, obtained by FEM, and that obtained by superposing the inherent deformations (individual heating lines plus the one produced by two parallel heating lines). In Figure 2 (a) and (b), it may be seen that the transverse components of total inherent deformation produced by two parallel heating lines are affected (reduced) by the tensile residual stress existing in the area in which the following heating line is applied (see Figure

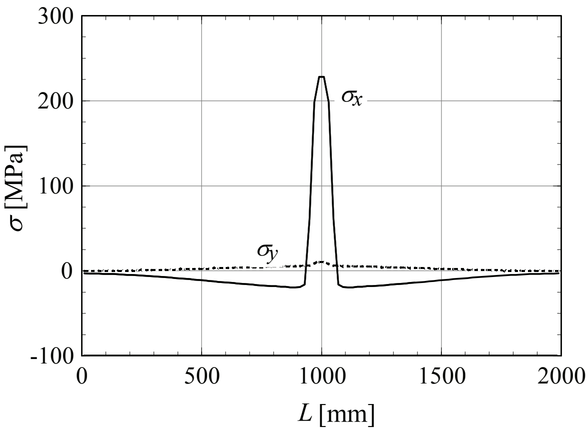


Figure 1: Residual stresses distribution at the plate surface, transverse to the heating line (L/2)

1). In the same way, the compressive residual stresses in the longitudinal direction existing in the area in which the parallel heating lines are applied cause the longitudinal components of inherent deformation to increase as shown Figure 2 (c) and (d). This variation of inherent deformation produced by parallel heating lines may vary with heat input, plate thickness, and plate size and may increase with the number of parallel heating lines. These are analyzed in the following sections.

4 Parallel effect on inherent deformation

Residual stresses, produced by previous heating lines, may cause both, increase or decrease, of the total inherent deformation, produced by parallel heating lines, as it is shown in Figure 2. In order to quantify this variation and take it into account in the analysis of plate deformation, we compare the inherent deformation produced by parallel heating lines with that calculated by superposing inherent deformation produced by the same heating lines each applied alone on a non stressed plate. The deferential ratio of these two inherent deformations is named as the *parallel effect, by the authors*. The parallel effect has four components; on longitudinal shrinkage (λ_x), on transverse shrinkage (λ_y), on longitudinal bending (γ_x), and on transverse bending (γ_y). These four components are defined in Equation 5 to 8.

$$\lambda_x = \frac{\sum \delta_x^i - \delta_x^t}{\sum \delta_x^i} \tag{5}$$

$$\lambda_y = \frac{\sum \delta_y^i - \delta_y^t}{\sum \delta_y^i} \tag{6}$$

$$\gamma_{xx} = \frac{\sum \theta_x^i - \theta_x^t}{\sum \theta_x^i} \tag{7}$$

$$\lambda_y = \frac{\sum \theta_y^i - \theta_y^t}{\sum \theta_y^i} \tag{8}$$

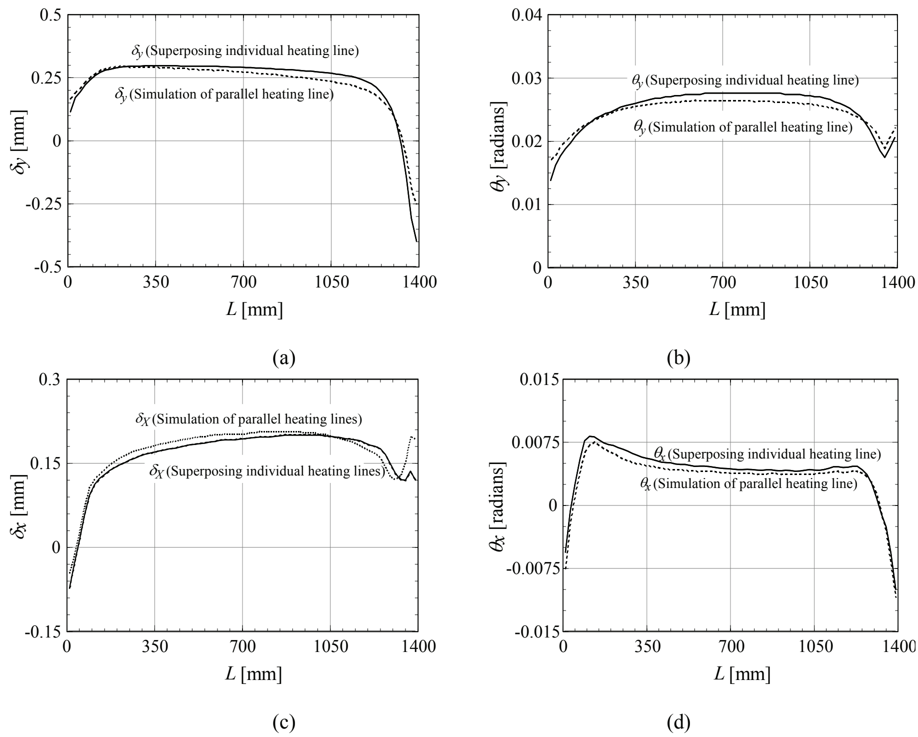


Figure 2: Comparison between results of inherent deformation obtained from simulation of parallel heating lines and by superposing individual heating (a) Transverse shrinkage, (b) Transverse bending, (c) Longitudinal shrinkage, and (d) Longitudinal bending

4.1 Variation of parallel effect with the separation between heating lines

Figure 3 shows a typical cross section of the distribution of plastic strain at the center of the plate. Now, if a second parallel heating line is applied at a distance equal to or smaller than approximately two times of the width of the inherent strain distribution (a_x or a_y as shown in Figure5.17), measured from the center of the heating lines, the resulting inherent deformation is influenced by partial overlapping as well as by the parallel effect. This is because once the second heating line partially overlaps the region of previous heating existing plastic strain is replaced by that produced by the new heating. In the case that the gap between parallel heating lines is larger than this value, only the effect of residual stress (parallel effect) may be considered. Figure 4 shows the variation of the parallel effect with the separation between two parallel heating lines. It is clearly seen that in those cases when the gap between parallel heating lines is smaller than approximately 150 mm for longitudinal components and 100 mm for transversal components (in the case of width of heating line equal to 80 mm), the parallel effect includes the effect of partial overlapping heating lines.

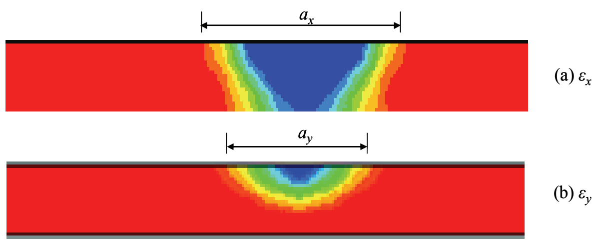


Figure 3: Typical cross section of the plastic strain distribution at the center of the plate

Note that parallel effect on longitudinal components of inherent deformation becomes smaller with the increase of the separation between parallel heating lines, while that on transverse component does not significantly differ. The cause of that is found in the effect of plate geometry. Figure5.8 is obtained when parallel heating lines are applied over a square plate; thus the effect of residual stress on parallel heating (parallel effect) exists even when the distance between heating lines is increased (see Figure5.19a). Similar phenomenon occurs in case of rectangular plates with length larger than width (see Figure5.19b).

In the case of rectangular plates (Figure5 (c)), the parallel effect on both, longitudinal and transverse components of inherent deformation become smaller (zero) when the gap between heating lines is large. In the region in which overlapping occurs, the combined effect (parallel plus overlapping effect) changes almost in proportion to the percentage of overlapping.

4.2 Variation of parallel effect with heat input

Figure 5 shows the variation of parallel effect with heat input. It may be seen that the longitudinal components of parallel effect slightly decrease with the increase of

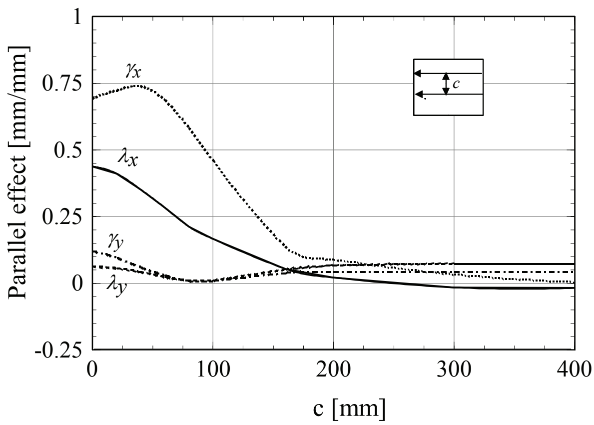


Figure 4: Variation of parallel effect with the separation between parallel heating lines

heat input while the transverse components increase. This relationship is obtained by applying parallel heating lines under the same heating condition and spacing 200 mm from each other. However, in plate forming, usually the heat input used for each heating line is different. In this case, the variation of parallel effect is not so simple.

Figure 6 shows two cases of the variation of parallel effect with different combination of heat input. In the first case, a single heating with a heat input equal to 3.3 kJ/mm is applied. Then, a parallel heating line in which the heat input is varied from 2.0 to 9.0 kJ/mm is applied. In the second case, the heat input of the first heating line is 8.8 kJ/mm and a similar approach as the first is followed. By simple inspection of these figures, it may be seen that the variation of parallel effect with heat input is complex and cannot be described simply by mathematical relationship.

4.3 Variation f parallel effect with plate thickness

In case of plates with different thicknesses, the parallel effect varies as may be observed in Figure 8. In this figure, which shows the parallel effect on longitudinal shrinkage, it is clearly seen that the plate thickness slightly influences the relationship between parallel effect and separation between parallel heating lines. However, its effect is small and can be neglected. Similar conclusion is obtained after examining the parallel effect on the other three components of inherent deformation.

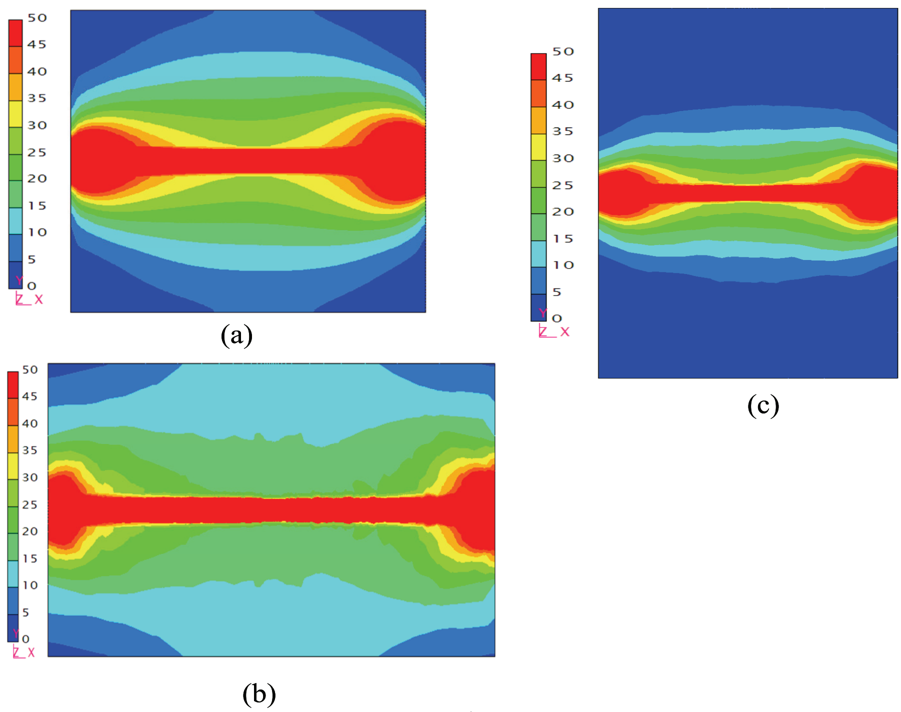


Figure 5: Distribution of residual stress (σ_x) produced by independent heating over plates with different geometry (a) Square plate, (b) Rectangular plate (L>W), and (c) Rectangular plate (W>L)

4.4 Parallel effect of multiple parallel heating lines

Figure 9 shows a typical cross section of the distribution of plastic strain, in X and Y directions, produced by parallel heating lines, spaced from each other by 200 mm. The heating and cooling conditions are the same in all cases. It may be seen that the longitudinal component of plastic strain (ε_x) slightly increases with additional parallel heating lines while the transverse components of plastic strain (ε_y), decrease. However, the parallel effect changes with the number of parallel heating lines as shown in Figure 10 where the parallel effect for multiple parallel heating lines is plotted. If the difference between parallel heating lines is larger, the parallel effect decreases as is shown in Figure 11.

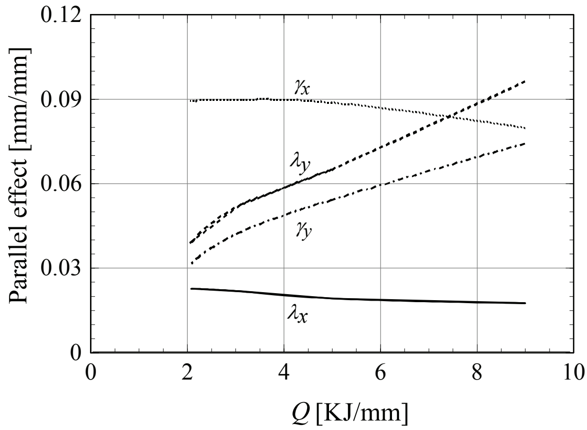


Figure 6: Variation of parallel effect with heat input (both heating lines under the same heat input)

5 Inherent deformation databases of parallel heating lines

In order to establish an inherent deformation database that considers the parallel effect it may be required to separate the problem into two sub-problems: first, cases of parallel heating lines separated from each other less than approximately 1.5 times the width of the heating lines, second, cases where the gap between them is larger than this value. The reason is the partial overlapping as above explained.

In the first case, the parallel effect is the greatest when the distance is equal to zero (overlapped heating lines), then the parallel effect decreases almost linearly as the heating lines separate from each other. Hence, the parallel effect can be directly related to the percentage of overlapping. Based on this assumption, values given in Vega (2009) can be used to determine the parallel effect. When the difference

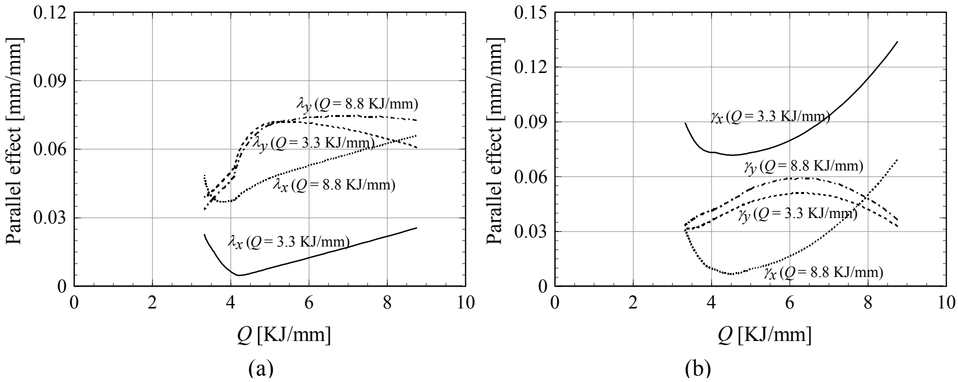


Figure 7: Variation of parallel effect with heat input (first heating constant and varying the second) (a) On shrinkage, and (b) On bending

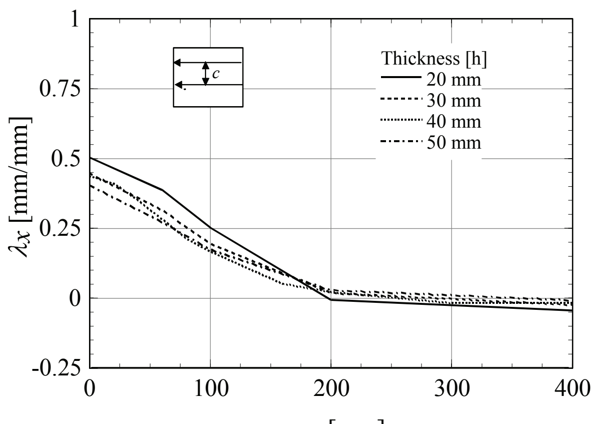
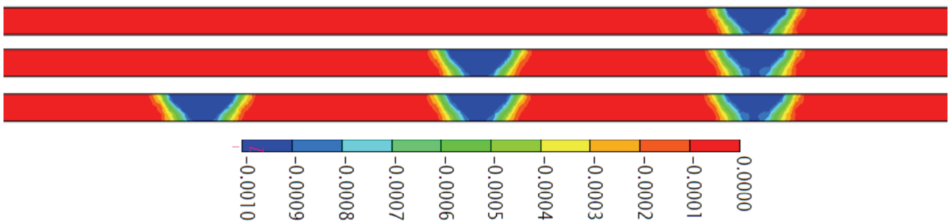
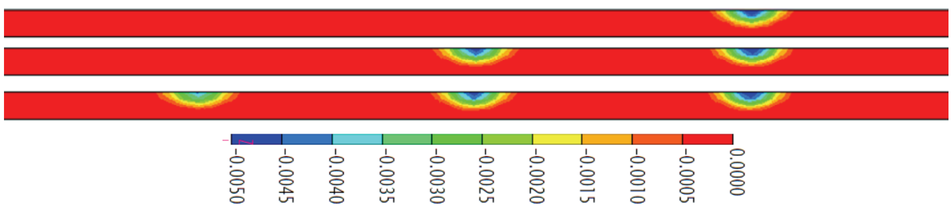


Figure 8: Variation of parallel effect on longitudinal shrinkage with the separation between heating lines for different plate thickness



(a) ε_x



(b) ε_y

Figure 9: Cross section view of the distribution of plastic strains after each heating line

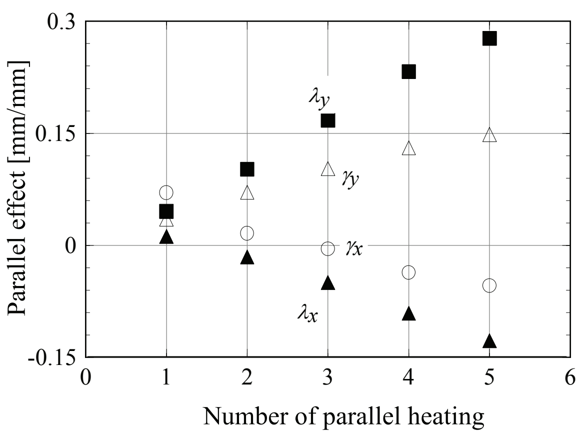


Figure 10: Variation of parallel effect with multiple heating lines

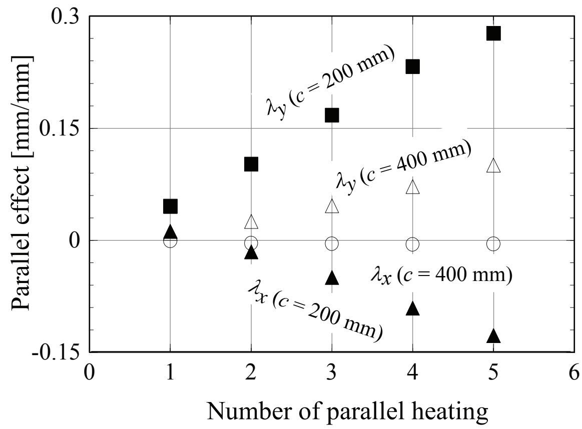


Figure 11: Influence of separation between heating on parallel effect of various parallel heating lines

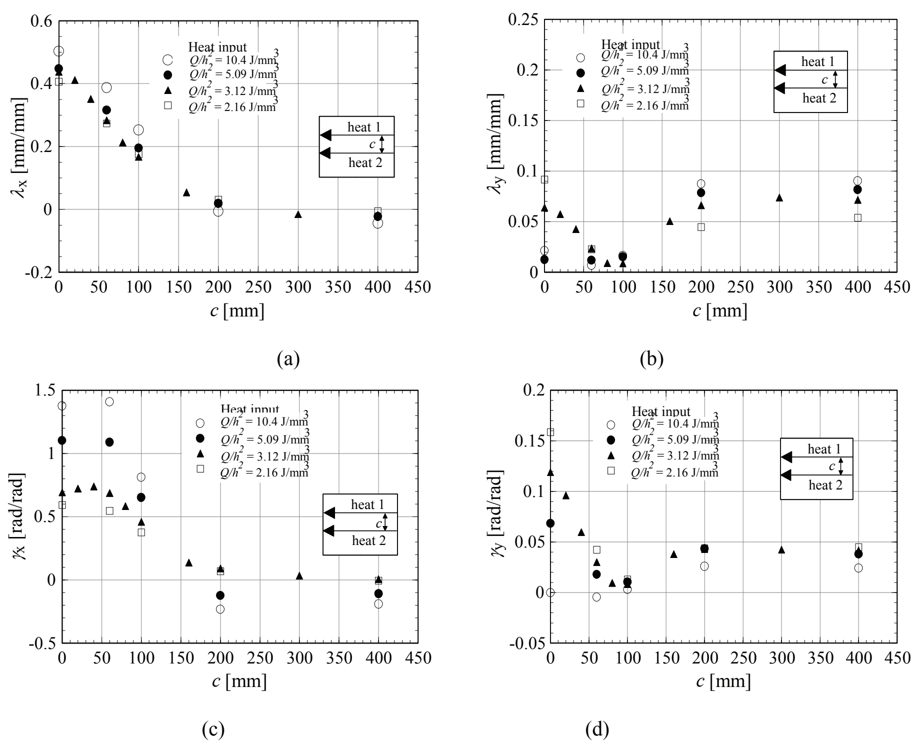


Figure 12: Relation between parallel effect and separation between parallel heating lines for different values of heat input parameter Q/h^2(a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending and (d) Transverse bending

between parallel heating lines is larger than approximately 1.5 the width of the heating line, the variation of parallel effect with heat input can be neglected and only the separation between heating lines needs to be considered as shown in Figure 12. These figures are created considering only two parallel heating lines. In case of multiple parallel heating lines, corresponding relations are needed.

6 Conclusions

A finite element analysis has been developed in order to analyze the impact of parallel heating lines on inherent deformation during line heating. The inherent deformation of parallel heating lines is not simply an addition 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 parallel heating lines is caused by the existing residual stresses produces by former heating lines. Then, the concept of parallel effect is introduced and explained in detail. The relationship between parallel effect and influential factors is determined. Finally, based on the analysis performed here, a database of parallel effect is presented.

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