Analysis and Prediction of Crossing effect on Inherent Deformation during the Line Heating Process – Part 2 – Multiple Crossed heating lines

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Abstract

During the plate forming by line heating, large amount of heat is applied to the metal surface in order to attain certain curvature. Although this is the best way existing to bend a thick three dimensional steel plate, the lack of knowledge about the mechanism causes delay and over cost, thus automation is needed. In this paper, the effect of previous heating on inherent deformation by following heating, more specifically, the case of heating lines intersecting (crossed) each other is studied in details. The case of single crossed heating lines was studied in details in the first part. This second part, discusses the case of more than one crossed heating lines. The influence of multiple crossing in inherent deformation is explained and new relationship between deformation and crossing effect are presented. The case of non-perpendicular crossed heating lines is also studied in this paper.

Key words: Line heating, crossed heating lines, crossing effect, multiple crossed heating lines, non-perpendicular heating lines, plate forming.

1 Introduction

Line heating is one of the most important plate forming processes used in the shipbuilding industry. However, the line heating process is far from been fully automated causing delays in production, even when some attempts have been made. 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)). However, most of these researches have been focused on the numerical analysis of single heating lines applied over small plates, which may result in unreliable results. In the last year, the authors have improved the existing method for predicting plate deformation considering a series of factors affecting the plate forming by line heating such as: geometry of the plate, cooling condition, location of the heating, heat-induced curvature, residual stresses, material properties, and inter-heating temperature (See Vega et all (2009) and Vega et all (2011)). Real plate sizes and heating condition were implemented. Results of numerical analysis and experiment show better agreement when those factors were considered when compared with previous reported studies. More recently, a series of paper considering multiples heating lines, such as the case of overlapped and parallel heating lines were published (Vega et all (2013)). In this paper, our attention is given to the case of multiple heating lines intersecting each other.

In part 1 of this paper, our discussion focused on the crossing effect produced by two crossed heating lines. However, in plate forming by line heating, multiple heating lines are applied in different directions until the plastic strain necessary to form the plate is attained. On the other hand, when two or more heating lines are applied close to each other, the resulting deformation depends on the separation between heating lines. Therefore, the crossing effect produced by multiple heating lines may differ from that of single heating lines. This, is studied in details in this paper.

2 Formulation of the 3D thermal elastic-plastic model

The same FEA developed in the first part of the paper has been used to study the influence of crossing on inherent deformation of multiples crossed heating lines. Plate geometry as well heating and cooling conditions are similar to those used in the first part. More details of the FEA, the heating and cooling condition, and the material properties are found in the first part of the paper and in Vega et all (2011).

3. Plate deformation due to multiple heating lines

Figure 1 shows the distribution of residual stress obtained after applying six parallel heating lines to a flat steel plate of 3000 x 3000 x 40 mm. The first heating line is applied at 500 mm from plate side edge and the following lines are applied parallel, spaced at 400 mm from each other. The distribution of residual stresses produced by each heating line is expected to be similar to that shown by plotting the residual stress distribution of a single heating line. However, when parallel heating lines are applied closely to each other, the existing residual stress is influenced by the thermal cycle of the new heating line and therefore a new pattern of residual stress, different to the one produce by single heating appear. Similar behavior is observed by application of additional parallel heating lines. At the end, it may be observed that at the position of the last heating line, the tensile residual stress is similar to that of single heating, applied alone, while at earlier heating lines, it is smaller (see Figure 1). It may also be observed that in between parallel heating lines, compressive residual stress in x-direction and tensile residual stress in y-direction are larger than in case of single heating line. The variation of residual stress changes with the separation between parallel heating lines as shown in Figure 2 where the case of parallel heating lines spaced 200 mm from each other is shown. Here it can be seen that for smaller separation between parallel heating lines, larger amount of residual stresses accumulate.

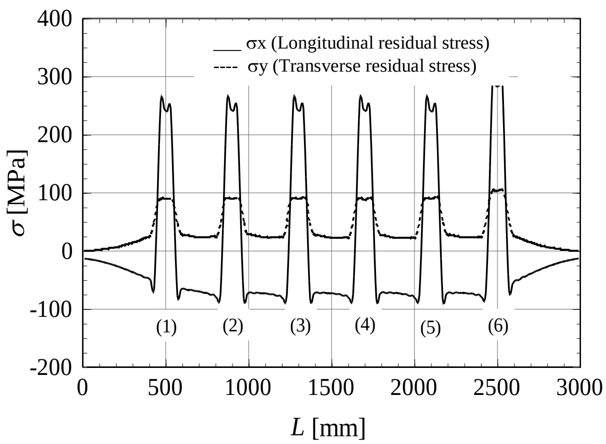


Figure 1 Distribution of residual stresses produced by parallel heating lines spaced 400 mm

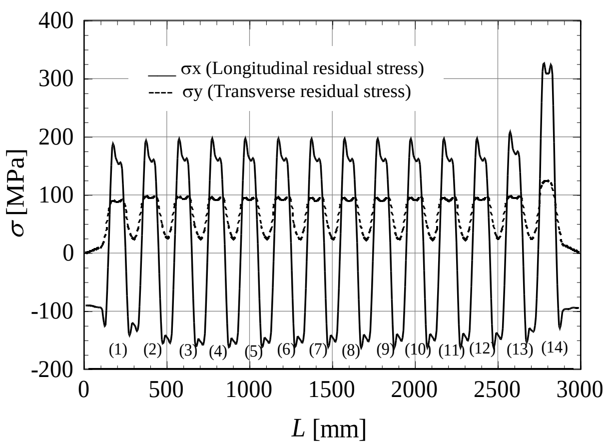


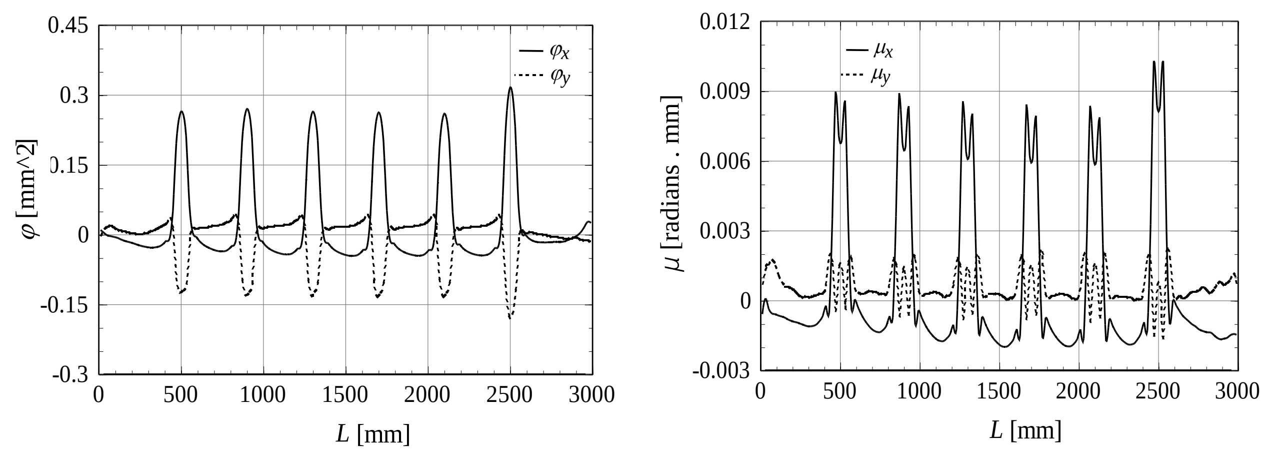
Figure 2 Distribution of residual stress due parallel heating lines spaced 200 mm

When a new heating line is applied in the direction transverse to the existing ones (crossing heating line), the influence of residual stress on inherent deformation (crossing effect) in each crossing area is smaller (except in the last parallel heating line) than that of two crossed heating lines previously discussed in part one of the paper. However, the residual stresses existing in between parallel heating lines significantly increase and influence the inherent deformation of the crossing heating line. In order to clarify this, the crossing effect needs to be separated into two: that caused by the residual stress in the crossing area, and that caused by the residual stress existing in between parallel heating lines. Both of them change with the separation between parallel heating lines as well as with heat input, plate thickness, location of crossed area and plate aspect ratio as is shown in part one of the paper and in following sections.

4. Crossing effect due to multiple crossing heating lines

Figure 3 shows the distribution of the crossing effect on inherent deformation of multiple heating lines in case of parallel heating lines spaced 400 mm from each other. The same trend can be observed in Figure 4 where the crossing effect on inherent deformation is shown in case of parallel heating lines spaced 200 mm from each other. Compared with the crossing effect produced by single crossing, there is a significant variation that needs to be considered. Note that only three figures are used as example. For other components of crossing effect, similarity is observed.

In order to clarify this phenomenon a parametric study considering different combination of crossing and separation between parallel heating lines on a 2000x2000x40 mm plate was performed. The results of this study shows that the crossing effect can be related to the separation between parallel heating lines as shown in Figure 5. Note that in the figure, the crossing effect is separate into two components: that produced at the crossing area (solid lines) and that produced outside the crossing area along the heating line toward the plate edges (in dashed lines). In both cases, for each component of crossing effect, except in the case of the longitudinal bending which is nearly zero. The main reason why the crossing effect is separate into two components is the fact that the crossing effect at the crossing area is much larger than at the rest of the heating line, so it is advisable to separate it in order to not over predict the inherent deformation (Vega (2009)).



(a) (b)

Figure 3 Distribution of crossing effect on inherent deformation for heating lines spaced 400 mm (a) On inherent shrinkage, and (b) On inherent bending

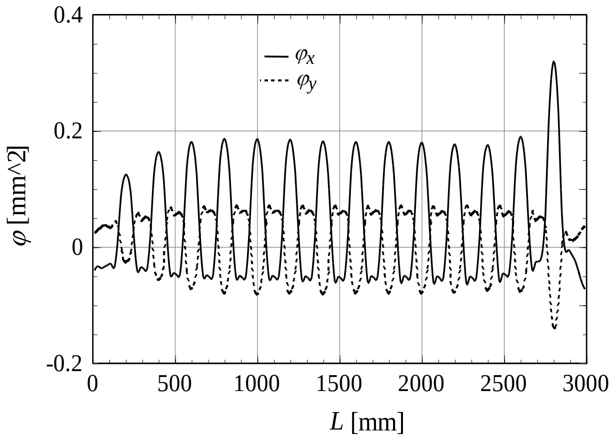
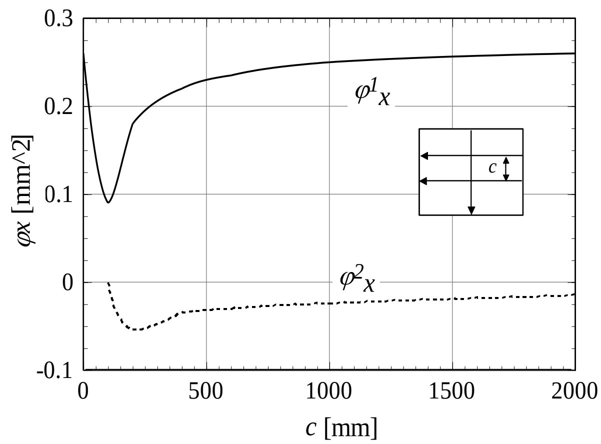
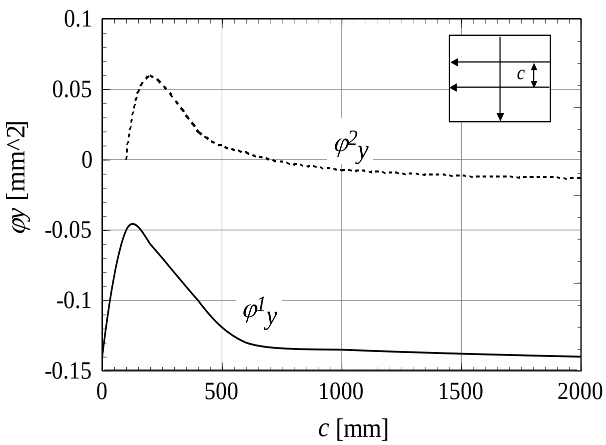


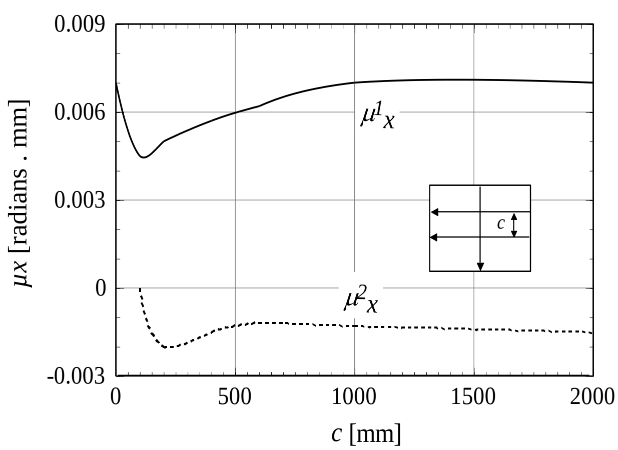
Figure 4 Distribution of crossing effect on longitudinal shrinkage of heating lines spaced at 200 mm



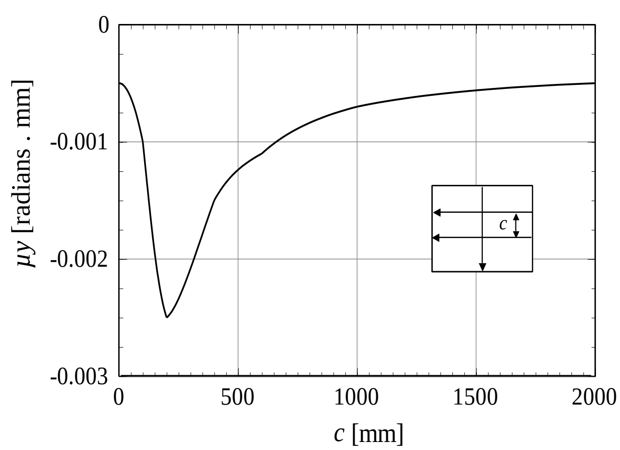
(a)



(b)



(c)



(d)

Figure 5 Relation between crossing effect on inherent deformation and separation between parallel heating lines for both, at the cross area (solid lines) and at outside of the cross area (dashed lines) (a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending and (d) Transverse bending

5. Variation of crossing effect with the angle of intersection

Up to now, our discussion has been focused on the analysis of crossing effect produced by single and multiple perpendicular heating lines. However, in plate forming by line heating, heating lines are applied in different direction. Therefore, it is necessary to consider the variation of crossing effect with the angle of intersection between the heating lines. Figure 6 compares the crossing effect on longitudinal shrinkage for three different values of angle of intersection between crossed heating lines. The case of angle equal to 90º corresponds to those previous discussed. It may be seen that the crossing effect on longitudinal shrinkage at, and far from the crossing area decreases with increasing the angle of intersection between crossed heating lines. This is mainly because the area of the first heating line that is affected by the crossing is larger in case of a small angle, therefore, more residual stress is diminished and more crossing effect is produced.

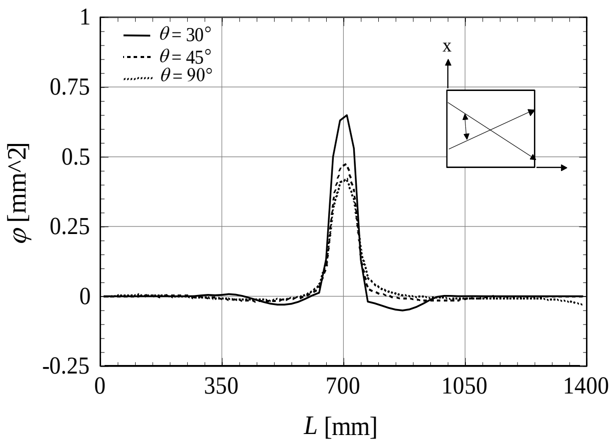


Figure 6 Crossing effect on longitudinal shrinkage

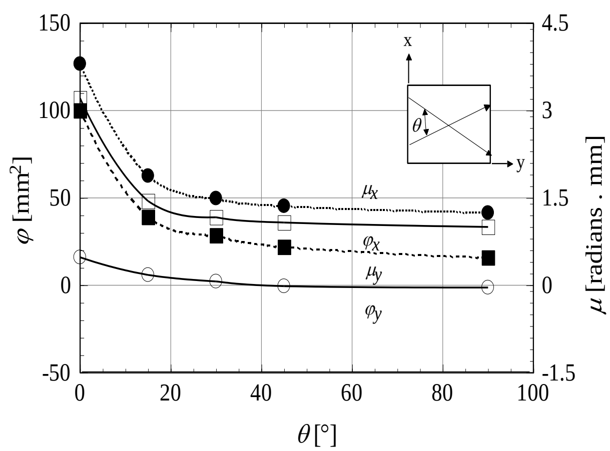


Figure 7 Variation of crossing effect for different angle of intersection between crossed heating lines

In the case of small angle of intersection, the mechanism approaches to that of overlapped heating lines where no appreciable longitudinal component of inherent deformation is produced by additional heating lines (See Vega et all (2013)). Figure 7 shows the variation of crossing effect with the angle of intersection. Here, an angle of intersection equal to zero degree corresponds to the case of overlapped heating lines. It is clearly seen that for small angles, the crossing effect increases while for angle of intersection larger than approximately 40º, the crossing effect is not significantly influenced by the angle of intersection.

6. Inherent deformation databases of crossing effect

An inherent deformation database of crossing effect can be established by relating the crossing effect to the heat input parameter Q/h^2 as shown Figure 8. Using these relationships, the crossing effect for a wide range of heating condition and plate dimension can be precisely predicted. Here it is important to mention that Figure 8 is obtained after compute perpendicular crossing heating lines only. In those cases where the angle of intersection between the heating lines is different from 90°, we need to consider the effect of angle of intersection given in Section 5.

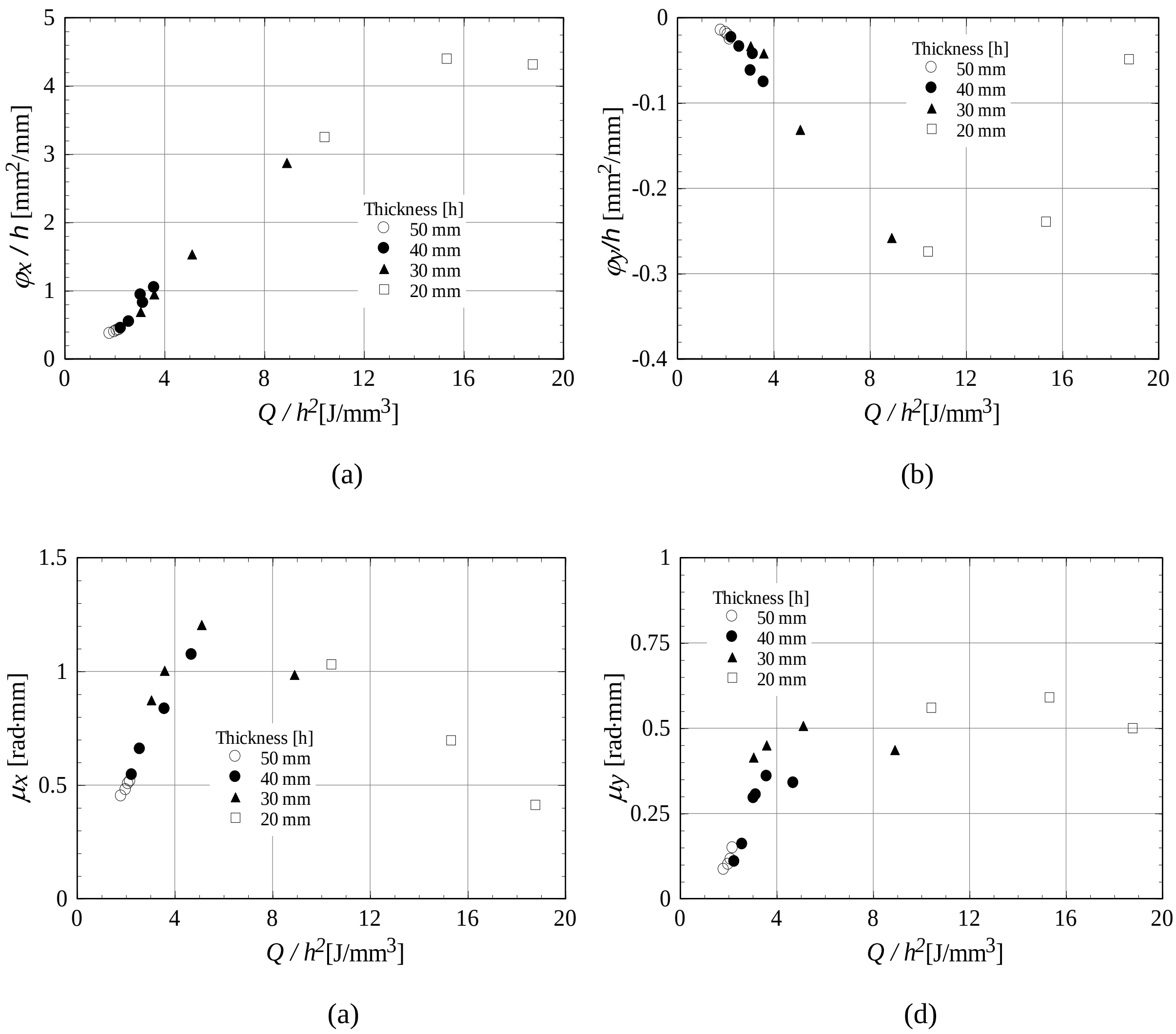


Figure 8 Relation between crossing effect on inherent deformation and heat input parameter Q/h^2
(a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending and (d) Transverse bending

7 Conclusions

The main objective of this paper was to develop a new method that can improve the precision in predicting plate deformation during the plate forming by line heating. In order to accomplished that objective a FEA has been performed to study the influence of multiple crossed heating lines on inherent deformation during the plate forming by line heating. From the results of this study the following conclusions are drawn:

1. The inherent deformation produced by multiple crossed heating lines applied close to each other is influenced by residual stresses produced by previous heating lines.
2. The concept of crossing effect proves to be useful when considering the effect of multiple crossed heating lines on inherent deformation. An inherent deformation database of crossing effect is proposed as an alternative for prediction plate deformation.
3. The crossing effect is influenced by both, the angle in between crossed heating lines and by the separation between the crossed areas.

Acknowledgments

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