 CMES, vol.90, no.2, pp.147-163, 2013

Analysis and Prediction of Overlapping Effect on Inherent Deformation During the Line Heating Process

Adan Vega, Alexandra Camaño, Amaly Fong, Sheriff Rashed, Hidekazu Murakawa

Abstract: The inherent deformation produced by two or more overlapped heating lines is not equal to that obtained when individual deformations are simply added. Thus, the effect of overlapping on inherent deformation, need to be clarified in order to achieve full understanding of the phenomenon of plate forming by line heating. In this paper, a 3D thermal-elasto-plastic FEA has been performed to study this problem in details. Using this FEA, the influence of previous heating on the inherent deformation of overlapped heating lines, considering various conditions, is clarified. From the results of this study, a method to determine the overlapping effect is developed. Using this method, the overlapping effect, for a wide range of plate thickness and heating conditions, is easily obtained, been this, another important step toward the automation of the line heating process.

Keywords: Plate forming, line heating, inherent deformation, overlapped heating lines, overlapping effect, FEM.

1 Introduction

After more than five decades, the mechanism to create three-dimensional curved plates using the line heating process still has been an active research topic in manufacturing, especially in shipbuilding. Although, there is plenty of research done by people that aim to explain the process of plate forming by line heating, they are not successful due to a well known bottleneck; the relationship between applied heat and final plate deformation is still not clear. As a result, the process of plate forming by line heating is not fully automated.

Many researchers have presented theories to explain the problem. Sawada, Tomita, Osawa and Hashimoto (2007) developed a combustion model suited to the thermal fluid simulation of line heating process, and showed that the measured and estimated gas temperatures are in agreement. Shin and Woo (2003) proposed a numerical procedure that comprised a non-combustion thermal fluid analysis and an iterative heat conduction analysis to estimate the heat transfer rate during a spot heating test. More recently, Chang, Liu, and Chang (2005), Ling and Atluri (2006), Liu (2006), Liu, Liu, and Hong (2007) investigated the heat transfer problem in line heating. Osawa et al (2007) proposed a new theory of heat transmission during line heating. They also developed a technique to identify the distribution of the temperature of the gas adjacent to the plate surface and the local overall heat transfer coefficient. The inherent strain method has become one of the most effective methods to predict plate deformation (Ueda, Murakawa, Rashwan, Okumoto and Kamic (1994)). The relationship between bending deformation, heating parameters and plate thickness has been developed as empirical models (Masubichi, Imakita, Miyashi, and Miyaki (1988)). Additional information, such as the influence of strain hardening, edge effect, and size effect have also been reported in experimental and numerical investigations (Cheng, Yao, Liu, Pratt and Fan (2005), Bao and Yao (2001), Magee, Watkins, Steen, Calder, Sidhu and Kirby (1997)). In the last decade, more papers have been published on laser formation than those on flame or induction forming have been reported (Mucha, Hoffman, Kalita and Mucha (1997), Edwardon, Abed, Bartkowiak, Dearden and Watkins (2006).

More recently, the authors proposed a method considering influential factors such as the geometry, the heating and cooling condition, the location of heating, and so on, see Vega, Osawa, Rashed and Murakawa (2011), Vega (2009) and Vega, Rashed, Tango, Ishiyama and Murakawa (2008).

This paper focuses on the case of heating lines applied in the same position as others before, which is known as overlapped heating lines. First, a finite element analysis developed before (See Vega, Osawa, Rashed and Murakawa (2011)), is used to analyze the problem. Different circumstances are evaluated in detail. The heating condition, as well as the plate geometry, is varied in order to capture every detail. Based on the results, the effect of overlapped heating lines is determined. Furthermore, the overlapping effect is briefly introduced and its mathematical relationship with heating conditions and plate geometry is presented. Finally, the conclusions are derived of this study.

2 Analysis of the heat induced deformation during line heating

The deformation of the plate is given in terms of the inherent deformation, which is defined as the integration of the plastic strain over the cross section of the plate of thickness h. Inherent deformations are classified into longitudinal shrinkage (δ_x), transverse shrinkage (δ_y), longitudinal bending (θ_x) and transverse bending (θ_y) as follows;

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

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

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

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

2.1 Numerical analyses

An in house finite element code, based on the iterative substructure method, was employed to achieve the thermal and mechanical analyses (Nishikawa, Serizawa and Murakawa (2005)). In this FEA, 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 stress through thermal expansion, as well as temperature-dependent thermo-physical and mechanical properties.

All analyses were carried out using rectangular flat plates of 2000x2000xh (mm). Values of plate 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 speed change. 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. Mild thermal, physical and mechanical properties of steel are considered with dependence on temperature and thermal conductivity, specific heat, Young’s modulus, Poison ratio and yield stress. 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 cases 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. Other variables use during the simulation as well material properties and other are similar to those used in Vega et al (2011).

3 Inherent deformation produced by overlapped heating lines

Let us consider a straight heating line applied along the length of the plate. This heating line produces inherent deformation and residual stresses. An example of the distribution of residual stress is shown in Figure 1. In this figure, the distribution of residual stresses (σ_x and σ_y) at the heated surface, plotted along the heating line, is shown. After the heated area cools down to room temperature, a second (overlapped) heating line, under identical conditions, is applied. In this new situation, when the surface temperature is high, existing residual stresses may cause plastic strain in addition, to that produced by the heating cycle.

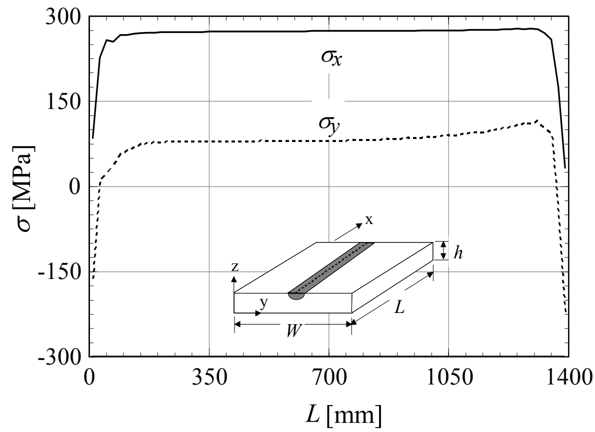

Figure 1: Residual stresses distribution at the plate surface along the heating line

Consequently, when the plate cools down to room temperature, additional inherent deformation is produced. In order to evaluate this new added inherent deformation, we compare the results obtained by simulation of overlapped heating lines with those obtained by superposition of the inherent deformation produced by individual heating lines. An example of this comparison is shown in Figure 2. As may be seen in Figures 2 (a) and (b), at both entry and exit edges of the plate, additional inherent deformation in y-direction is produced while, at the central region, it is slightly reduced. The reason of this difference is found in the distribution of residual stress in y-direction, shown in Figure 1. As seen in this figure, compressive residual stress in y-direction (σ_y) appears at both edges of the plate while, at the central region of the plate, tensile residual stress (σ_y) is observed.

As shown in Figure 2 (c), there is almost no additional longitudinal shrinkage at the central region of the plate produced by an overlapping heating line, if compared with that produce by single heating. This is because the tensile residual stress existing in the central region of the plate is large (close to the yield stress). Then, when the plate is heated and cools again, the new plastic strain is almost the same as that after previous heating. In the same way, at both edges of the plate, the residual stress in x-direction (σ_x) is small and, therefore, longitudinal shrinkage of the overlapping heating line is only slightly influenced as may be observed in the figure. The rise of longitudinal bending produced by overlapped heating lines shown in Figure 2d is due to two reasons, first is the tensile residual stress (σ_x) as explained above and the second is because the longitudinal bending is induced by other components of inherent deformation.

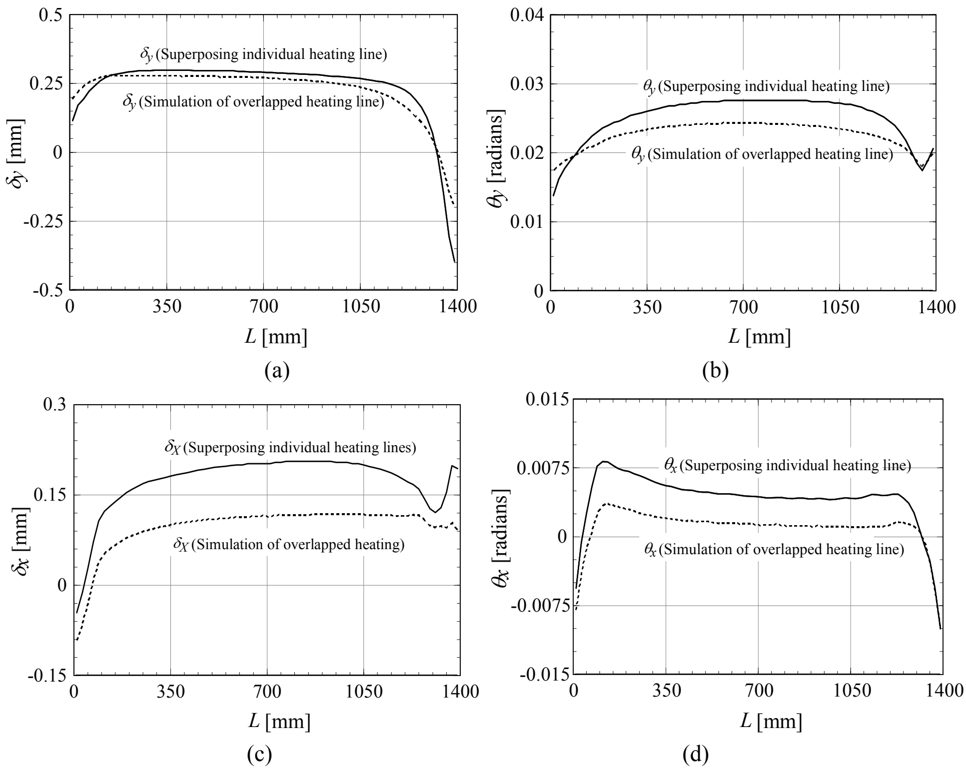

Figure 2: Comparison between results of inherent deformation produced by overlapped heating lines, and by superposing individual heating lines (a) Transverse shrinkage, (b) Transverse bending, (c) Longitudinal shrinkage, and (d) Longitudinal bending

4 Overlapping effect on inherent deformation

Residual stresses produced by former heating lines cause an increase or decrease of the absolute inherent deformation produced by overlapping as it is demonstrated already. It is a fact that the distribution of residual stresses depends on the applied heat, the plate thickness, and on the plate size. It is also a fact that residual stresses accumulate in the plate, therefore, their effect on inherent deformation, besides the factors mentioned above, varies with the number of heating lines. In order to quantify this difference and take it into account in the analysis of plate deformation, we compare the inherent deformation produced by overlapping heating lines with that calculated by superposing inherent deformations produced by the same heating lines if applied separately on a non stressed plate (Figure 2 for example). The deferential ratio of these two inherent deformations is named by the authors as the *overlapping effect* (See Vega (2009)).

According to the authors, the overlapping effect has four components; overlapping effect on longitudinal shrinkage (β_x), overlapping effect on transverse shrinkage (β_y), overlapping effect on longitudinal bending (ζ_x), and overlapping effect on transverse bending (ζ_y). These four components can be determined from the total inherent deformation (obtained from thermo-elastic-plastic analysis or experiments (δ_x^t, δ_y^t, θ_x^t and θ_y^t)), and the inherent deformation calculated by superposing inherent deformation of individual heating lines (simple addition ($\Sigma\delta_x^i$, $\Sigma\delta_y^i$, $\Sigma\theta_x^i$ and $\Sigma\theta_y^i$)) as follows;

$$\beta_{xx} = \frac{\sum \delta_{xx}^i - \delta_{xx}^t}{\sum \delta_{xx}^i} \tag{5}$$

$$\beta_{yy} = \frac{\sum \delta_{yy}^i - \delta_{yy}^t}{\sum \delta_{yy}^i} \tag{6}$$

$$\zeta_{xx} = \frac{\sum \theta_{xx}^i - \theta_{xx}^t}{\sum \theta_{xx}^i} \tag{7}$$

$$\zeta_{yy} = \frac{\sum \theta_{yy}^i - \theta_{yy}^t}{\sum \theta_{yy}^i} \tag{8}$$

It is appropriate to mention that the overlapping effect varies along the heating line, especially at the edges of the plate. However, for large plates, the overlapping effect is almost constant along most part of the heating line. Hereafter, positive values of overlapping effect mean reduction of inherent deformation.

4.1 Variation of the overlapping effect with heat input

Figure 3 compares the residual stresses in x-direction (σ_x) produced by different values of heat input, plotted through the plate thickness. In this figure, it is clearly observed that residual stress varies with the applied heat. In the same way, the four components of overlapping effect significantly vary with the heat input as shown Figure 4. For small amounts of heat input, the overlapping effect on longitudinal shrinkage, on transverse shrinkage and that on transverse bending is larger and decreases with the increase of heat input. While, the overlapping effect on longitudinal bending almost linearly increases with the increase of heat input.

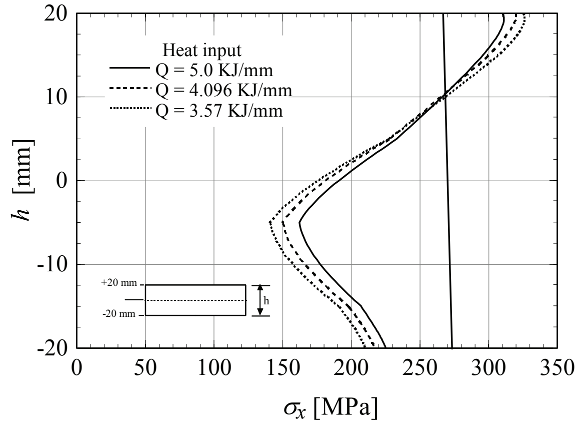

Figure 3: Distribution of residual stresses (σ_x) through plate thickness for different heat input

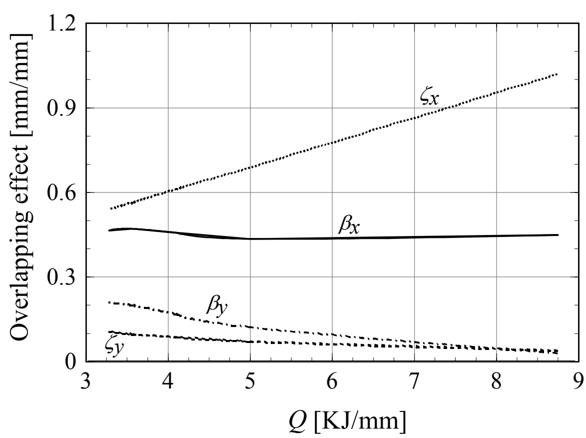

Figure 4: Variation of overlapping effect with heat input

4.2 Variation of overlapping effect with plate thickness

In the analyses performed to explain the variation of overlapping effect with heat input, we use one value of plate thickness as a representative case. If plates with different thicknesses are analyzed, the energy needed to achieve the plate deformation, must be changed in order to get similar temperature at the plate surface. As mentioned above, if the heat input varies, residual stress also varies (this may be clearly observed in Figure 5, where the distribution of residual stress through the plate thickness for different plate thickness is compared). Because of this, the overlapping effect varies with plate thickness as may be observed in Figure 6.

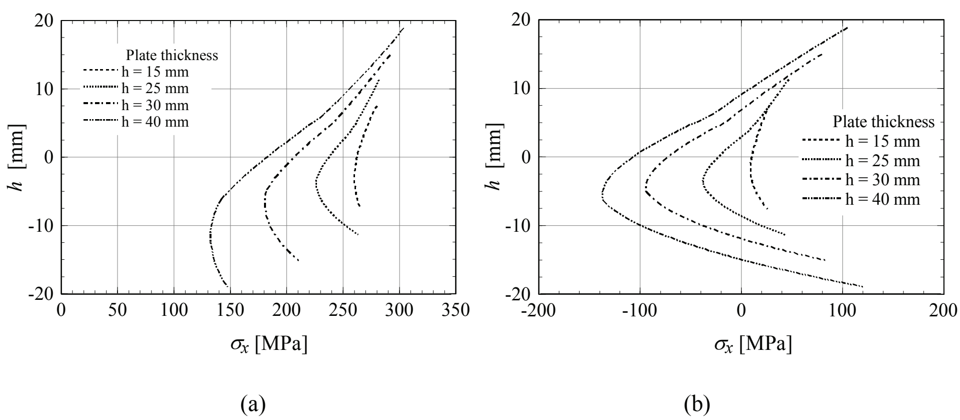

Figure 5: Distribution of residual stresses for different plate thickness (a) σ_x and (b) σ_y

The variation of residual stresses through the thickness also influences the overlapping effect of overlapping heating lines applied over the opposite surfaces as may be noted in Figure 7. It is clearly seen that for thin plates, the overlapping effect on both, the longitudinal and the transverse components of inherent shrinkage of heating lines applied over the opposite surface is the same as those obtained when both heating lines are applied over the same surface. On the other hand, for thick plates, the overlapping effect of heating lines applied over the opposite side is significantly smaller than those obtained when both heating lines, are applied over the same surface. The reason of that is found in the distribution of residual stress shown in Figure 5.

Figure 8 compares residual stresses at the heated surfaces of plates with different length. In this figure, it may be seen that residual stresses decrease with plate length up to approximately one meter, then for larger plates, it is almost constant. This

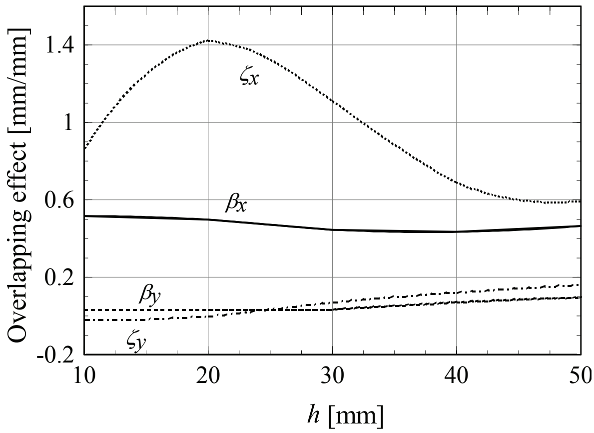

Figure 6: Variation of overlapping effect with plate thickness

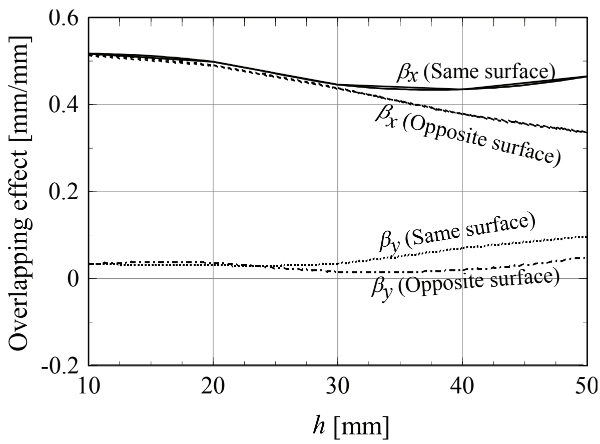

Figure 7: Variation of overlapping effect at different plate surface

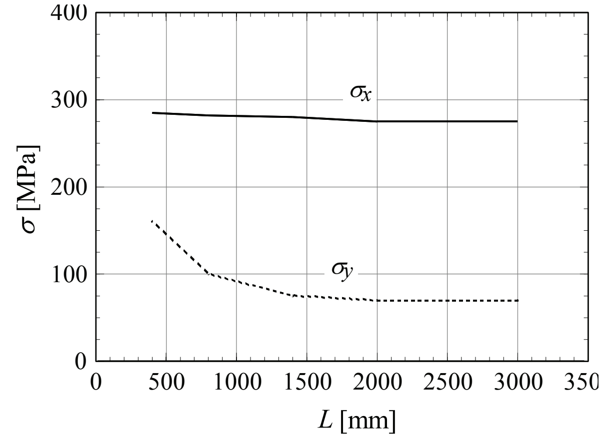

Figure 8: Residual stresses at the heating surface for different plate length

is because in the case of small plates the edge effect significantly influences the residual stress distribution (see Figure 1 for example). Figure 9 shows the variation of overlapping effect with plate length. It may be observed that, for large plates, the overlapping effect is not depending on the plate length. In case of a large plate, the overlapping effect is only influenced by the applied heat and plate thickness. Similar behavior is observed when varying the plate width.

4.3 Overlapping effect of various overlapping heating lines

Figure 10 shows the residual stress at the heated surface after applying additional overlapping heating lines. In this figure, it may be observed that certain additional amount of residual stresses accumulate in the plate after each other overlapped heating. Because of the increase of residual stresses, in those cases when more than two heating lines are applied over the same location, the overlapping effect increases as shown in Figure 11. However, this increase of overlapping effect becomes smaller with the number of overlapping heating lines.

5 Inherent deformation databases of overlapped heating lines

In order to create an inherent deformation database for overlapped heating lines, the overlapping effect is related to the heating conditions as shown in Figure 12. Values given in this figure can be used to make corrections to the inherent deformation given in Figures 4, 6, 7, 9 and 11. In case of overlapped heating lines applied by opposite surfaces, the consideration of overlapping effect is also needed. In that case, if the plate thickness is smaller than 30 mm, values given in Figure 12 can be

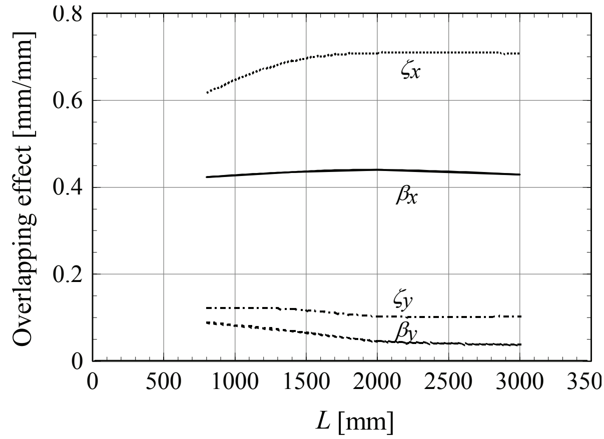

Figure 9: Variation of overlapping effect (Center of the plate) for different plate length

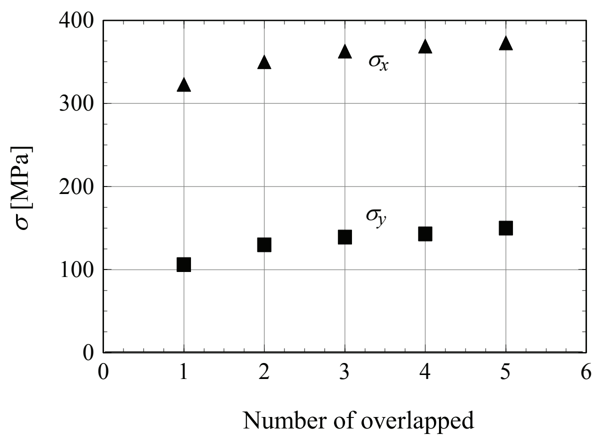

Figure 10: Residual stresses at the heated surface for various overlapped heating lines

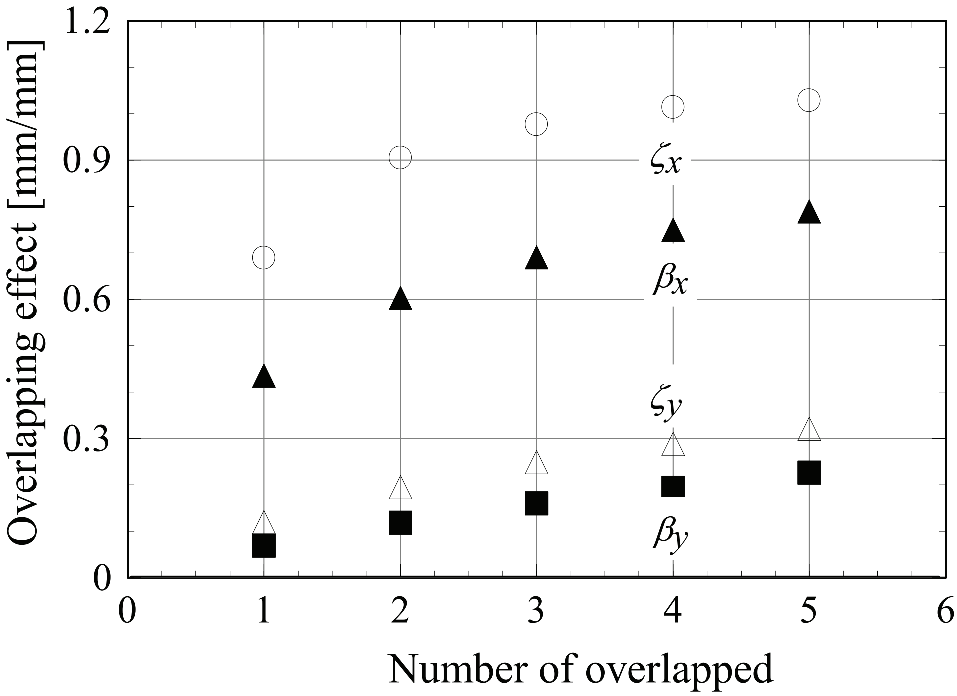

Figure 11: Overlapping effect for various overlapped heating lines

used directly.

In case of more than one overlapped heating line, corrections are needed as is explained in section 4.4. Figure 13 shows the relationship between overlapping effect and heat input parameter $Q/h^2$for cases having more than one overlapped heating line. In this figure, it is observed that the overlapping effect on inherent deformation increases with additional overlapping. In case of shrinkage components of overlapping effect, the growth of overlapping effect is mostly linear as shown in Figures 13 (a) and (b). On the other hand, in case of bending components it is smaller, been negligible in case of heat input parameter larger than approximately 8.0.

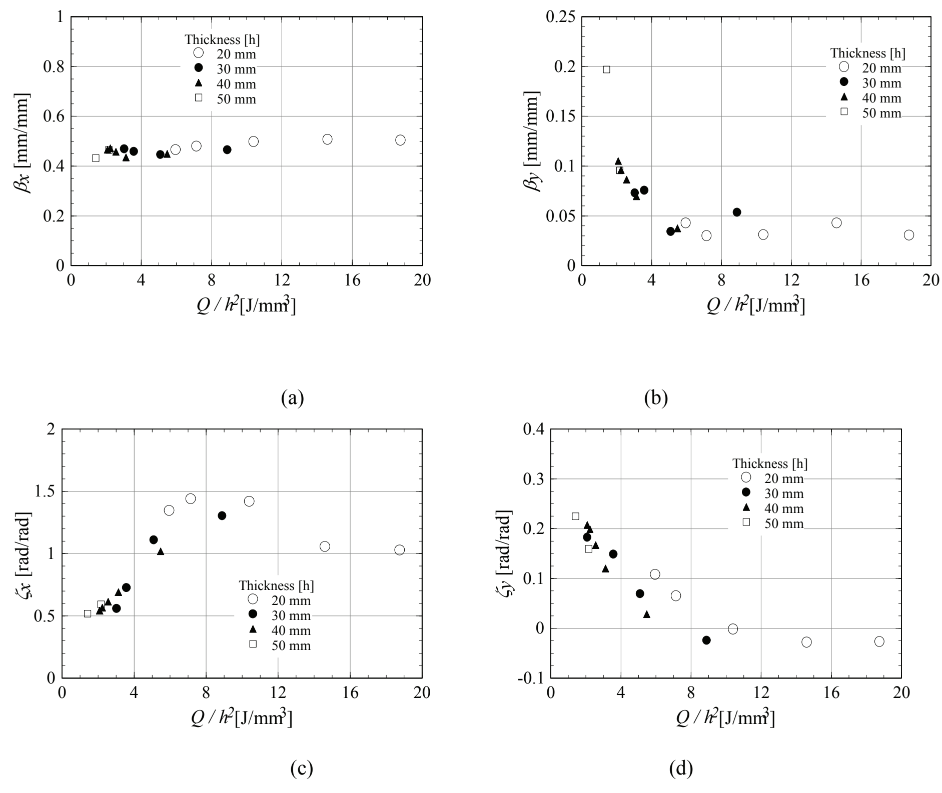

Figure 12: Relation between overlapping effect and heat input parameter Q/h^2 on, (a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending, and (d) Transverse bending

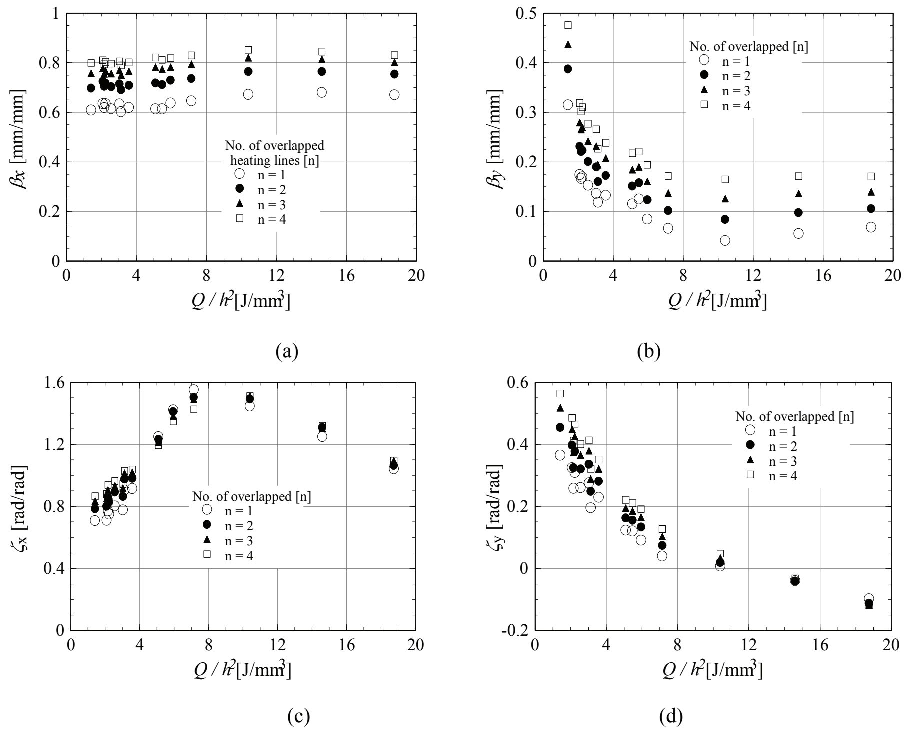

Figure 13: Relation between overlapping effect and heat input parameter Q/h^2 for several overlapped heating lines on,(a) Longitudinal shrinkage, (b) Transverse shrinkage, (c) Longitudinal bending and (d) Transverse bending

6 Conclusions

After completing this study on the effect of overlapped heating lines on the prediction of inherent deformation, the following conclusions can be drawn:

1. A finite element analysis has been developed in order to analyze the impact of overlapped heating lines on inherent deformation during line heating.
2. It has been demonstrated that the variation of inherent deformation with overlapped heating lines is due to existing residual stresses produced by former heating lines.
3. The concept of overlapping effect is introduced and explained in detail.
4. The relationship between overlapping effect and influential factors is determined.
5. Based on the analysis performed here, a database of overlapping effect is presented.

Acknowledgement: Financial support from The Secretary of Science and Technology (SENACYT) of The Government of The Republic of Panama and by Class IBS is gratefully acknowledged.

References

Bao, J.; Yao, Y. L. (2001): Analysis and Prediction of Edge Effects in Laser Bending. *Journal of Manufacturing Science and Engineering*, ASME Vol. 123:53-61.

Chang, C.W.; Liu, C.S.; Chang, J.R. (2005): A Group Preserving Scheme for Inverse Heat Conduction Problems. *CMES: Computer Modeling in Engineering& Sciences*, 10, 1, pp.13-38.

Cheng, P.; Yao, Y. L.; Liu, C.; Pratt, D.; Fan, Y. (2005): Analysis and Prediction of Size Effect on Laser Forming of Sheet Metal. *Journal of Manufacturing Process*, SME Vol. 7/No.1; 28-40.

Edwardon, S.P.; Abed, E.; Bartkowiak, K.; Dearden, G.; Watkins, K. G. (2006). Geometrical Influences on Multi-pass Laser Forming. Journal of Physics D: Applied Physics. 39, pages 382-389.

Ling, X.; Atluri, S.N. (2006): Stability Analysis for Inverse Heat Conduction Problems. *CMES: Computer Modeling in Engineering & Sciences*, 13, 3, pp.219-228.

Liu, C.S. (2006): An Efficient Simultaneous Estimation of Temperature-Dependent Thermo physical Properties. *CMES: Computer Modeling in Engineering & Sciences*, 14, 2, pp.77-90.

Liu, C.S.; Liu L.W.; Hong, H.K. (2007): Highly Accurate Computation of Spatial-Dependent Heat Conductivity and Heat Capacity in Inverse Thermal Problem. *CMES: Computer Modeling in Engineering & Sciences*, 17, 1, pp.1-18.

Magee, J.; Watkins, K. G.; Steen, W. M.; Calder, N.; Sidhu J.; Kirby, J. (1997): Edge effect in laser forming, Laser assisted net shape engineering 2, *Proceeding of the LANE'97*, Meisenbach Bamberg, pp.399-408.

Masubichi, K.; Imakita, A.; Miyashi, K.; Miyaki, M. (1988): Development of an Intelligent System for Flame Straightening Panel Structures-Devices and Algorithms to Be Used with Robots, *Journal of Ship Production*, 4(4): 219-227.

Mucha, Z.; Hoffman, J.; Kalita, W.; and Mucha, S. (1997), Laser Forming of Thick Free Plate, Laser Assisted Net Shape Engineering 2, *Proceeding of the LANE'97*, Meisenbach Bamberg, pp.383-393.

Nishikawa, H.; Serizawa, H.; Murakawa, H. (2005): Development of a Large-scale FEM for Analysis Mechanical Problems in Welding, *Journal of the Japan Society of Naval Architects*, 2, pp.379.

Osawa, N.; Hashimoto, K.; Sawamura, J.; Kikuchi, J.; Deguchi, Y.; Yamaura, T. (2007): Development of Heat Input Estimation Technique for Simulation of Shell Forming by Line-Heating. *CMES: Computer Modeling in Engineering & Sciences*, 20, 1, pp.45-53.

Shin, J. G.; and Woo, J. H. (2003): Analysis of Heat Transfer between the Gas Torch and the Plate for the Application of Line Heating. *Journal of Manufacturing Science and Engineering*.. Vol. 125, No. 4. Pages 794-800.

Sugawa, Y. N.; Osawa, K.; Hashimoto, J.; Sawamura (2007): Numerical Simulation of Transitional Heat conduction during Induction Line Heating Process, *Proceeding of TEAM'07*, pages 203-209.

Ueda, Y.; Murakawa, H.; Rashwan, A. M.; Okumoto, Y.; Kamichika, R. (1994): Development of Computer-Aided Process Planning System for Plate Bending by Line Heating, (Report 3) – relation between heating condition and deformation. *Journal of Ship Production* 10(4): 248-257.

Vega, A.; Rashed, S.; Tango, Y.; Ishiyama, M.; Murakawa, H. (2008): Analysis and prediction of multi-heating lines effect on plate forming by line heating. *CMES Journal: Computer Modeling in Engineering & Sciences, CMES*, Vol. 28, No. 1, pp. 1-14.

Vega, A. (2009): Development of Inherent Deformation Database for Automatic

Forming of Thick Steel Plates by Line Heating Considering Complex Heating Patterns. *Doctoral Thesis*. Osaka University, Japan.

Vega, A.; Osawa, N.; Rashed, S.; and Murakawa, H. (2011): Analysis and Prediction of edge effect on Inherent Deformation of Thick Plates Formed by Line Heating. *CMES: Computer Modeling in Engineering & Sciences*, Vol. 69, No. 3, pp. 261-279.