

## Influential Factors Affecting Inherent Deformation during Plate Forming by Line Heating (Report 3) – The Effect of Crossed Heating Lines

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### ABSTRACT

Experimental observation have shown that the heat induced deformation produced by crossed heating lines is significantly affected by the crossing especially at the cross area. Aiming to clarify this effect, through the inherent deformation theory, we numerically clarify and quantify the influence of crossed heating lines on heat induced deformation. First, it is demonstrated that the heat induced deformation of single heating lines may not be super-imposed upon one another to approximate the inherent deformation of the resultant curved surface. Then, a method to accurately predict the heat induced deformation produced by crossed heating lines is proposed.

**KEY WORDS:** Line heating; inherent deformation; crossed heating lines; parallel heating lines; cross effect; residual stress; FEM.

### INTRODUCTION

Line heating is an effective method to form curved shell plates with complex three-dimensional geometry. However, line heating process is mostly dependent on the skill of hard-to-find experienced workers. Therefore, automation is highly required. At present, no automatic system that can accurately form a plate without significant human help has been developed. The main reason of this is that the mechanism of plate forming using the line heating method is highly complicated for analysis with simple analytical models. The difficulty comes from the material and the geometrical nonlinearities as well as the variation of temperature in the spatial and time domains.

The study of thermal-elastic-plastic behavior of the line heating process has received attention of many researchers for about the past 40 years. The first attempt to use an analytical approach to simulate the line heating process was by Suhara (1958) and Iwasaki, Hirabe, Taure, Hujikura and Shiota (1975). They modeled the problem using the beam theory and the solution was obtained analytically. Due to these restrictions, their model can deal only with ideal situations. Iwamura and Rybicki (1973) also analyzed the process using a beam model normal to the heating line, employing the finite-difference approach to solve the problem. Moshaiov and Vorus (1987) developed a boundary-

element method based on thermal-elastic-plastic boundary-element theory. The limitation of their method is that only a small deflection is considered in the theory. Also, Moshaiov and Shin (1991) modified the strip method and extended it to an uncoupled thermal-elastic-plastic strip. In this modification they imposed artificial temperature and material properties to avoid the problem of coupling the bending and inplane process. Throughout the 1990s, many researchers have investigated FEA-based methods for predicting the resultant deformation generated by application of a series of heating lines [Ueda, Murakawa, Rashwan, Okumoto, and Kamic (1994), Jang, Seo, and Ko (1997), Kyrsanidi, Kermanidis, and Pantelakis (1999)]. These finite element-based simulation methods produce accurate predictions in laboratory setting. However, their practicality for use with production is limited. Further, most of these investigations have focused on the deformation produced by single heating lines on small plates and no practical methods has been developed for actual size plates taking into account multiple arbitrary heat lines.

The objective of this paper is to develop a method to predict the heat induced deformation produced by crossed heating lines. To achieve this objective, a 3-D thermal-elasto-plastic finite element analysis is performed. To validate the FEM results, we performed line heating experiments. To quantify the variation on inherent deformation produced by crossed heating lines, first we introduce the concept of cross effect. Then, a series of FEA analysis are run to cover the possible range of factors affecting the process which includes variation of the heating condition and plate geometry for single and multiples crossed heating lines. Based on acknowledges obtained from this study, a method to accurately predict the heat induced deformation produced by crossed heating lines is proposed. Finally, conclusions of this numerical study are outlined.

### PREDICTION OF PLATE INHERENT DEFORMATION

Generally, line heating plate deformation is classified into longitudinal shrinkage ( $\delta_{xx}$ ), transverse shrinkage ( $\delta_{yy}$ ), longitudinal bending ( $\theta_{xx}$ ) and transverse bending ( $\theta_{yy}$ ) as shown Fig. 1. These four fundamental components of plate inherent deformation can be determined by integrating the inherent strain over the cross section of the plate as follows,