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A study on the thermal deformation characteristics of steel plates due to multi-line heating

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Abstract

This paper is mainly concerned with developing the formulae of predicting thermal deformation of steel plate due to multi-line heating. By investigating the results of line heating test and numerical analysis, reasonable heat flux model has been defined. Formulae of predicting the transverse shrinkage and the angular distortion as the dominant thermal deformation types in plate forming by line heating have been derived based on the results of line heating test and numerical analysis with varying plate thickness, heating speed and distance between torches. This paper illustrates how the derived formulae are used in investigating the effect of multi-line heating upon the thermal deformation and how they can be used in defining the limit distance with that there is no interacted effect between torches. This paper ends with describing the extension of the present study.

Keywords: Interaction between torches; Limit distance between torches; Multi-line heating; Productivity in plate forming process; Thermal deformation prediction formula

1. Introduction

Heating method is usually used in plate forming of ship's curved shell plates found in bow and stern area. As it is well appreciated, the plate forming process is one of the key processes in shipbuilding. Lots of researches have been carried out for the last several decades, and many researches are also in progress nowadays to enhance productivity. For example, Nomoto et al. (1990) and Shin (1992) developed simulator for plate forming and showed a couple of application examples on curved surface. Lee (1996, 1997) proposed an algorithm of generating heating line information by line heating based on mechanical model. Lee et al. (2002) suggested a simple prediction model for thermal deformation of steel plates by line heating and triangle heating through experiments. Jang et al. (2001) conducted studies on deformation characteristics due to heat forming, and Ha (2001) and Jang et al. (2002) carried out experimental studies to predict deformation with considering phase transition due to weaved heating and water cooling effect.

This paper is primarily concerned with adopting the concept of multiple line heating to enhance the productivity in plate forming process. For this, line heating test with single and/or multi-torch has been carried out with varying the parameters affecting the deformation due to line heating, say, plate thickness, heating speed and distance between torches. In addition to this, thermo-elasto-plastic analysis has been carried out to generate information beyond the region of real test aimed at deriving the formula for the transverse shrinkage and angular distortion (transverse bending deformation), which are supposed to dominantly affect the deformation due to line heating. Based on the results of the present line heating tests and the numerical analysis, formulae for the transverse shrinkage and the angular distortion have been developed through the regression analysis procedure. With the formulae

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derived in this study, the effect of distance between torches and number of torches affecting to any particular heating line are investigated. As far as the present results are concerned, due to the interaction between torches, transverse shrinkage and angular distortion become greater as the distance between torches become smaller. This paper also deals with the limit distance which is defined as the distance between torches such that there is no interaction between torches. This paper ends with describing the further study about the application of the present results to devote to enhancement of productivity in the plate forming process in shipyard.

2. Experiment and numerical studies with multi-torch

As the preliminary study, in order to investigate the physical and mechanical phenomenon, the present authors have carried out line heating test and thermo-elasto-plastic analysis with multi-torch. The models and experiment conditions for the multi-line heating are listed in Tables 1 and 2, respectively, and material is mild steel. The test conditions in Table 2 were determined by trial and error so that the heating apparatus produces the highest efficiency during heating. As it can be seen, multi-line heating test have been conducted with changing the distance between torches, d_{torch} as 100, 150, and 200 mm. Eleven k-type thermocouples are attached between ‘Torch 1’ and ‘Torch 2’ on the opposite side to the heating side to measure the temperature during heating as shown in Fig. 1. Fig. 2 shows the attached thermocouples with equal space when the distance between torches, d_{torch} is 100 mm, and so the distance between thermocouples is 10 mm. And when distance between three torches is 150 mm and 200 mm, the distance between thermocouple is 15 and 20 mm, respectively. With the measured temperature, thermal interacting effect between heating torches can be investigated. The cooling method is the air cooling and the temperature of the opposite side is measured until the temperature is less than 200 °C. For the present experiment, torch tip 3000 is used. Fig. 3 shows the multi-line heating test scene with three torches. We can see the interaction of flame between torches.

For the present numerical analysis of line heating, double Gaussian heat flux model proposed by Tsuji and Okumura (1988) is used to take into account the effect of the 1st and 2nd flame. The flux model is given as:

$$q(r) = \frac{6\eta Q}{R_1^2 + \beta R_2^2} e^{-\left(\frac{6r^2}{R_1^2} + \beta\frac{6r^2}{R_2^2}\right)} \quad (1)$$

where η is the heat efficiency, R_1 and R_2 are the first and second heat flux frame length, β is second heat flux over first heat flux, and Q is the generated heat due to chemical reaction. With the heating conditions listed Table 1, half section of the distributed shape of heat flux has the form shown in Fig. 4. When single torch was used, the thermos-elasto-plastic analysis procedure with the above double Gaussian heat flux model was already verified (Lee and Lee, 2012).

When the multi-torch is used for the line heating, it is firstly necessary to investigate the physical and mechanical phenomena to define the heat flux model since the interaction between torches is expected depending on the distance between torch, d_{torch}. As it is mentioned before, line heating test with multi-torch is carried out for three models shown in Table 1. Two types of flux model can be suggested as follows:

Table 1
Multi-line heating test models.

Plate size (mm)	Plate thickness (mm)	Heating speed (mm/min)	Distance between torches (mm)
1000 × 740	19	300	100, 150, 200

Table 2
Test condition of multi-line heating.

Item		Value
Flow rate (L/min)	LPG	23
	O_2	50
Pressure of flow (kgf/cm^2)	LPG	1.7
	O_2	4
Distance from torch tip to plate surface (mm)		50
Torch tip no.		3000

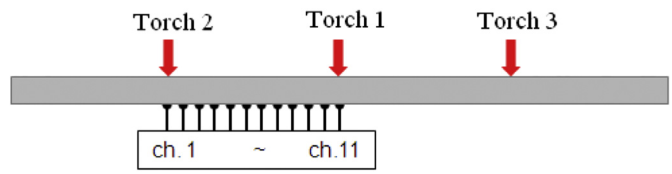

Fig. 1. Torches and locations of thermocouples.

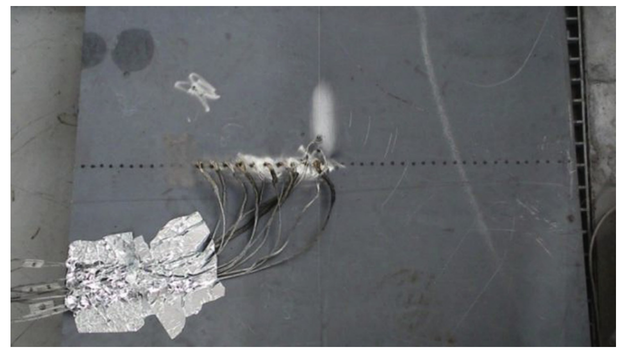
Fig. 2. Test specimen at which thermal couples are attached: d = 100 mm.


Fig. 3. Scene of multi-line heating test with three torches.

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