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Effect of Heating Spacing on Deformation Distribution of Line Heating Process

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Ship hull plate forming with line heating technique is an important process in the shipbuilding industry. An automatic line heating control system needs an accurate database of various processing parameters. In this study, a numerical model, calibrated and verified using experiment results, was used to study the deformation distribution of a plate corresponding to different heating line spacing. This paper presents the results based on a single-torch and multiple-torch process. The deformation distributions in the heating and nonheating regions were analyzed. The impacts of coupling effect among heating lines were deliberated.

Keywords: line heating; thermal analysis; plate forming; heating spacing

1. Introduction

Line heating is an efficient plate forming process for many applications, such as ship hull forming, molding car body, and other curved objects. In the shipbuilding industry, this method is mainly used to create double-curved ship hull plates, especially for those plates near the bow and stern. Line heating is a complex nonlinear thermal process that involves thermodynamics, elastic–plastic mechanics, and metallurgy. Many researchers have conducted studies on the mechanism of line heating process to predict the final shape of the metal plate according to the heating conditions and mechanical properties of the plate (Moshaiov & Vorus 1987; Ueda et al. 1994a, 1994b, 1994c; Ji & Liu 2001); others performed numerical analysis with thermal elastic–plastic models to determine the parameters in line heating process (Jang et al. 1997; Yu et al. 1999, 2001; Yu 2000; Wang et al. 2006). Many experimental works were carried out to verify the thermal elastic–plastic models (Moshaiov & Shin 1991; Liu et al. 2006; Zhou et al. 2014a). The effects of parallel and cross heating lines were discussed recently (Zhou et al. 2014b; Vega et al. 2015). Residual stress among the steel plate was studied to reveal the relationship of different heating conditions.

Different heat sources have been used in line heating process, and they include gas torch (Tomita et al. 2001; Jong & Jong 2003),

laser beam (Kyrzanidi et al. 1999), welding arc (Kitamura et al. 1996), and high-frequency induction heating (Ogawa et al. 1994; Lee & Hwang 2014). In all heat sources, gas torch is most frequently used as it was and still is the cheapest and most readily available heating source in most shipyards.

Despite the many studies, the plate forming process is still far from being a fully automated process for all the ship hull plate because of a lack of knowledge, especially on the relationship of heating parameters and final steel plate deformation. The processing for forming ship hull plate near the bow or stern require dense and closely spaced heating lines because of the requirement of large deformation. It is also for this application that placement and distribution, including distance between heating lines, become a very important factor in achieving the desired deformation.

This paper analyzes the parameter of the heating line spacing on the final deformation achieved. The interactions between heating lines were investigated and in particular, the effect of a heating line on the earlier or later heating lines, or all heating lines being used at the same time was elaborated.

2. Numerical procedure and experimental validation

The line heating process may be modeled as three dimensional nonlinear transient analyses. The governing equation of heat conduction is described as (see Rosenthal 1946)

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$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + \dot{Q}$$

where c is specific heat; ρ is density; λ is thermal conductivity; T is temperature; $\dot{Q}$ is heat source; t is time. These parameters λ , ρ , and c change with temperature.

The analytical solution of line heating process is very difficult to obtain as it is a coupled thermal-mechanical phenomenon. In this study, a three-dimensional finite-element model has been established to simulate the plate forming process. The engineering simulation software ANSYS was used to simulate the forming process. The finite element model of the steel plates was meshed as shown in Fig. 1. To obtain accurate temperature and stress gradients and reduce the computer run-time, fine and coarse meshed plates were used in the numerical model. The heat transfer and structural analyses were carried out based on the same mesh.

During the line heating process, heat generated by plastic deformation of the plate may be neglected. Thermal analysis was carried out to create the temperature field, which was then applied as thermal loading in the structure analysis. The material properties of mild steel plate, which vary with temperature, are shown in Fig. 2.

The accuracy of modeling heat source is perhaps the most important segment of work in the simulation. In this study, the Gaussian energy distribution was selected as the most preferred mode for line heating as the temperature distribution obtained in the analysis agreed well with the experiment result published by others (Rykalin 1960; Shin et al. 2003; Zhou et al. 2009, 2013). The Gaussian distribution may be expressed as

$$q(x, y) = q_M \cdot \exp[-K(x^2 + y^2)] = q_M \exp[-Kr^2]$$

where $q(x, y)$ is heat flux density of point (x, y) [$\text{J}/\text{m}^2 \cdot \text{s}$];

$$q_M = \frac{\eta \cdot Q \cdot T_v \cdot K}{3600\pi} \text{ is the peak value of heat flux density } [\text{J}/(\text{m}^2 \cdot \text{s})];$$

$K = \frac{3}{r_0^2}$ is the concentration coefficient of energy [L/m^2]; η is the thermal efficiency, which is typically taken as 0.2 ~ 0.35;

Q is the flux of oxyacetylene (m^3/h); T_v is the combustion heat of oxyacetylene (W/m^3);

Fig. 1 Finite element model of cylinder plate

Fig. 2 Material properties of carbon steel and their variation with temperature

r_0 is the radius of the heat resource, about 95% of the total energy is in the inner circle.

Fig. 3 Thermal distribution attributable to a heat source having a Gaussian energy distribution

Fig. 4 Experiment of line heating process

Figure 3 shows the thermal distribution of a heat source which follows the Gaussian energy distribution. Free convection and radiation boundary conditions were satisfied on all surfaces. In the mechanical analysis and to avoid the rigid body movement, these boundary conditions were constrained to zero displacement at endpoints of the central lines of the metal plate.

Laboratory experiments were performed to validate the accuracy of the numerical model, as shown in Fig. 4. The size of steel plate is $1000 \times 1000 \times 20$ mm. The length of heating lines was 300 mm, and the velocities (V) of heat source were set as 3, 2.5, 2, and 1.5 mm/sec. Surface shrinkage along the heated line was measured. Surface shrinkage is the displacement between test points on the both side of the heat line after the line heating process. The layout of the measure points is as shown in Fig. 5. There are five pairs of test points arranged evenly along the heating lines.

Infrared thermography system was used to capture the temperature field, see Fig. 5. It can be seen from Fig. 5 that the distribution of the temperature field shows an elliptical shape. As the heat source moves along the plate, the front isotherm line is denser, and the temperature gradient is greater there. The temperature field moving with heat source becomes a quasi-steady state.

The simulated results of temperature distribution both parallel and perpendicular to heating line are compared with those measured from experiments, as shown in Fig. 6. The degree of deviations for

Fig. 5 Experimental measurement of temperature field

Fig. 6 A comparison of temperature distribution based on the measured and simulated results

the peak temperatures was less than 5%. The shrinkage results are shown in Fig. 7. It could be seen that the simulated results agree well with the measured results with a variation of 5–10%. The temperature and residual deformation obtained through numerical analysis are in reasonable agreement with those obtained from experimental measurements. The proposed numerical model is useful and has a precision that meets the engineering requirement.

3. Analysis of spacing effects

After it was validated using the experimental results, the numerical model was then used to carry out a series of simulations to study the influence of spacing between heating lines on the residual deformation distribution in the line heating process. In this study, the writers used a flat plate as an example. The geometrical dimensions of the steel plate were as follows: length was 1400 mm, width was 800 mm, and thickness was 20 mm (see Fig. 1). There were three heating lines at the lower side of the steel plate. The length of each heating line was 300 mm and the duration of heating for each line was 120 seconds. The spacing D_h between the heating lines was set as 100, 120, 150, 200, 300, and 400 mm. The effects of

Fig. 7 A comparison of shrinkage distribution based on the measured and simulated results

heat line spacing based on a single-torch and multiple-torch process (all heating lines are heated at the same time) were also investigated.

3.1. Effect of heating line spacing using a multiple-torch process

Figures 8 and 9 show the deformation distribution after the application of line heating using multiple torch for $D_h = 100$ and 400 mm. The difference between the line spacing of 100 and 400 mm can be discerned readily. Figures 8A–B show the displacements in the Z direction at the upper and lower surface. It can be seen that the top surface depicted larger displacement than that at the bottom surface. The same phenomenon could also be seen in Fig. 8C which indicates that the Z displacement along the material thickness shows the same distribution. This displacement will create angular deformation in the heating line area. Figure 8D is the residual strain along the Z direction. It can be seen that the residual strains are mainly located on the heating lines. The same displacement trend is displayed in Fig. 9 with the peak values of UZ displacement for $D_h = 100$ mm being larger than those for $D_h = 400$ mm. For example, the maximum UZ values at the upper surface were .762 and .580 mm for $D_h = 100$ and 400 mm, respectively. The difference was about 31.4%. And the difference in strains was about 15.4%. Therefore, one may conclude that the heating line spacing produces significant impact on the heating line process.

The displacements in the Z direction at the upper surface at different spacing are shown in Fig. 10. The displacement curves depict stepwise distribution. In Fig. 10, the midpoints of each stage corresponded to the positions of heating lines. For example, point A, B, and C are the heating line locations for $D_h = 400$ mm. The local shrinkage and strain could be calculated according to the displacements measured. One may see from Fig. 10 that the maximum and minimum displacements for line spacing (D_h) of 400, 300, 200, and 150 mm were distinct. The maximum and minimum values are about .6 mm. But when $D_h = 120$ and 100 mm, the maximum displacements become about 0.83 and 0.77 mm, respectively. The observation indicates that the shrinkage could increase when the spacing decreases, see e.g., at $D_h = 120$ mm. However, it does not mean that the shrinkage would increase all the time. The shrinkage for $D_h = 100$ mm was found to be smaller than that for $D_h = 120$ mm. In the analysis, the thickness t of the steel plate was 20 mm, and D_h/t was taken as the normalized parameter for heating line spacing. When D_h/t is more than 7.5, the shrinkages were basically the same. For $D_h/t < 7.5$, the shrinkage was observed to rise, peak, and then decrease. It can be seen in Fig. 10 that when $D_h/t = 6$, the shrinkage becomes much larger than that at other D_h/t . One may then deduce that multiple-torch process is a possible way to increase the shrinkage.

Because the heating lines were arranged symmetrically, the deformation patterns were also symmetrical. The results of three heating lines could be taken as one with a central and two side heating lines in the analysis. Figure 11 shows the shrinkages of all the scenarios compared with that of a single heating line. The

Fig. 8 The residual deformation of $D_h = 100$ mm for multiple torch, (A) UZ of top surface (B) UZ of bottom surface (C) UZ of side surface (D) residual strain of top surface

nomenclature adopted in Fig. 11 is as follows: Side (Top) and Side (Bot) means the distribution for side heating line at the top and bottom (back) surface. The same nomenclature is adopted for the middle heating line and single heating line. The solid lines are the results for the top surface and dashed lines are those for the lower surface.

As can be seen in Fig. 11, the shrinkages at the top surface of multiple-torch scenarios are smaller than those for single heating line except for line spacing $D_h = 120$ mm, whereas the shrinkages for the lower surface are larger than those of single heating line. When D_h is less than 120 mm, the shrinkages at the bottom surface are greatly affected by the combined effects of multiple heating lines. The effects is most distinct especially at the middle heating line, at which the shrinkage could reach more than two times the maximum value of that of a single heating line. For example, when $D_h = 120$ mm, the maximum shrinkages at the bottom surface for the “Middle,” “Side,” and “Single” heating line were .53, .34, and .22 mm, respectively, whereas for the top surface, the maximum shrinkages were .59, .55 and .49 mm, respectively.

As line spacing D_h increases, the shrinkage of “Side” and “Middle” heating lines are much closer to the value of the “Single” heating line. The effects of multiple heating lines decrease with the increase of spacing D_h . Whereas $D_h \geq 300$ mm, the difference is less than 10%. So one may deduce that when the spacing D_h is large enough, the deformation distribution of multiple torch is identical with that of a single torch.

The relationship of maximum shrinkage and maximum strain with D_h for the side and middle heating lines are shown in Fig. 12. For $D_h < 150$ mm, the maximum shrinkage and maximum strain of heating lines changed rapidly. For $300 \text{ mm} > D_h > 150$ mm, the trend becomes relatively flat. For $D_h > 300$ mm, the differences of maximum shrinkage and maximum strain between the “Sides” and the “Middle” heating lines are less than 10%.

From the viewpoint of engineering application, a difference of less than .1 mm may be considered small, and the results are basically identical. Based on the previous results using multiple torch (for three heating lines), the impact of multiple heating

Fig. 9 The residual deformation of $D_h = 400$ mm for multiple torch, (A) UZ of top surface (B) UZ of bottom surface (C) UZ of side surface (D) Z strain of top surface

lines on steel deformation could be ignored when the heating line spacing is larger than 200 mm.

3.2. Effect of heating line spacing on single torch process

The same analysis used for multiple torch described previously was also performed to study the effects of line spacing based on a single-torch process. Figures 13 and 14 show the deformation distribution of single torch process for $D_h = 100$ and 400 mm. It can be seen that the peak values of UZ displacement for $D_h = 100$ mm are also larger than that for $D_h = 400$ mm. For example, the maximum values of $D_h = 100$ and 400 mm are .689 and .567 mm, respectively. Comparing Figs. 13 and 14 with Figs. 8 and 9, one can see that the peak UZ values for a single-torch process are slightly lower than those for a multiple-torch process. But the overall deformation distributions are generally similar.

As can be seen in Fig. 15, stepwise displacement distributions similar to those of multiple-torch process are also observed. The midpoints of each stage are the positions of heating lines. According to the sequence of heating process,

the heating lines are named as line 1, line 2, and line 3 correspondingly. For $D_h > 150$ mm, the maximum values are about

Fig. 10 Displacements of three heating lines at different spacing

Fig. 11 Shrinkages corresponding to multiple-torch process set at different heating line spacing

.6 mm and the minimum values are about -0.6 mm. A comparison of Figs. 10 and 15 show significantly large difference for $D_h/t = 5$. The maximum values of single-torch and multiple-torch process are .69 and .77 mm, respectively. This large difference is probably due to the fact that the coupling effect of multiple torch would be much higher than that of a single torch when $D_h \sim 100$ mm. As can be seen in the temperature distributions, and when the heating lines are placed closer to one another, the maximum temperature corresponding to multiple torch is slightly higher than that of a single torch.

Figure 16 shows the shrinkages of all the heating lines compared with those of a single heating line. Similar to Fig. 11, solid lines are the results at the top surface and dashed lines are those for the bottom surface. For $D_h/t \geq 15$, the differences of all

the heating lines from that of a single heating line are less than 10%. For $D_h/t < 10$, the shrinkage of line 1 is closest with that of a single heating line, followed by line 3 and line 2, a result of the boundary condition imposed on the process. Line 1 would be expected to be the same with that of a single heating line as it was processed under similar conditions. However, the result of lines 1 is slightly different because of the affection by subsequent heating of line 2 and line 3.

The maximum values (top and bottom surface) of line 1 are less than those of single heating line. It could also be seen in Fig. 16 that the effects of line 2 and line 3 could be ignored when D_h is large enough; e.g., when $D_h/t > 10$. The condition of line 2 is little complex as it was affected by an earlier (line 1) and later heating line (line 3). But line 3 is only affected by the previous heating line. The maximum values at the top surface of line 3 are

F16

Fig. 12 The relationship of maximum shrinkage and maximum strain with line spacing D_h

less than that of a single heating line, whereas the maximum values at the bottom surface are larger.

As can be observed by comparing Figs. 11 and 16, the results of a single-torch process are closer to that of a single heating line than

those for multiple-torch process. Based on practical engineering precision consideration of .1 mm, one may conclude that the results of a single-torch and multiple-torch process are basically identical if the spacing is more than 150 mm ($D_h/t > 7.5$).

Fig. 13 The residual deformation of $D_h = 100$ mm for single torch, (A) UZ of top surface (B) UZ of bottom surface (C) UZ of side surface (D) residual strain of top surface

Fig. 14 The residual deformation of $D_h = 400$ mm for single torch, (A) UZ of top surface (B) UZ of bottom surface (C) UZ of side surface (D) strain of top surface

The relationship of maximum shrinkage and maximum strain with D_h for single torch are shown in Fig. 17. Similar to a multiple-torch process, the maximum shrinkage and maximum strain due to a single-torch process changed rapidly when $D_h < 150$ mm. The peak values of line 2 are largest at both the top and bottom surfaces. For $300 \text{ mm} > D_h > 150$ mm, the trend becomes relatively flat. For $D_h > 300$ mm, the differences in maximum shrinkages are less than 10%.

4. Conclusions

Based on the findings of the studies, the following conclusions may be drawn.

- 1) For heating line spacing D_h , when $D_h < 150$ mm, maximum shrinkage and maximum strain of heating lines change rapidly. For $300 \text{ mm} > D_h > 150$ mm, the trend become relatively flat. For $D_h > 300$ mm, the differences of maximum shrinkage and maximum strain between that of single-torch and multiple-torch processes are less than 10%.

Fig. 15 Displacements of three heating lines at different spacing

Fig. 16 Shrinkages of single torch at different heating line spacing

Fig. 17 The relationship of maximum shrinkage and maximum strain with D_h

2) From the viewpoint of practical engineering consideration, one may conclude that if the spacing is 150 mm ($D_h/t = 7.5$), the results of single-torch and multiple-torch processes are basically identical. The impact of coupled heating effects between the heating lines on steel deformation could also be ignored. The findings of the study show that multiple-torch process is an effective method for forming steel plates using line heating process.

3) For $D_h/t < 7.5$, the shrinkages corresponding to multiple-torch process are larger than those of a single-torch process. Therefore, the multiple-torch process is a possible way to increase the deformation, especially for ship hull plates of bow or stern areas.

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