Analysis of Triangle Heating Technique using High Frequency Induction Heating in Forming Process of Steel Plate

KEYWORDS: Steel-plate forming, Induction heating, Triangle heating, Transverse shrinkage, Finite element analysis, Rotational path

Triangle heating technique using a gas flame is used to deform steel plate in ship construction. However, in the flame heating process, the heat source is often difficult to control and parts cannot be deformed efficiently. In this study, a numerical model is developed to study the triangle heating technique with the more controllable heat source of high-frequency induction heating and to analyze the deformation of steel plate in the heating process. To simplify the many complex trajectories of the triangle heating technique, a rotational path of inductor is suggested and then a 2-dimensional circular heat input model is proposed. The heat flow and transverse shrinkage in steel plate during triangle heating with the induction heat are analyzed. The results of the analyses are compared with those of experiments to show the good agreement. The heat source and thermo-mechanical analysis models proposed in this study were effective and efficient for simulating the triangle heating technique in the forming of steel plate in shipbuilding.

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1. Introduction

Various shapes of curved steel plates for ship-hull production are obtained by the forming process of steel plates. In the forming process, line heating and triangle heating techniques have been mainly used, and one of them can be selected depending on the heating purpose. The line heating technique heats a plate along straight lines to mainly fabricate saddle-type curved plates. Forming process based on heating has been widely studied with the line heating technique. The triangle heating technique, in which the heating length is increased continuously from the start to the end of heating to form a triangle shape of the heated area, can be applied to contract steel plate in the transverse direction with concentrated heating along the edge of the steel plate.[1] The triangle heating technique is mainly applied to make convex-type curved plates, which are to be located at the front and rear parts of a ship's hull. In this technique, the heating torch rotates and travels simultaneously to prevent excessive heating of the edge of the steel plate by the heat concentration. The process control of this technique entirely depends on the skill of the workers, who need to input much working time because of complicated characteristics of the process, including irregular multi-pass heating trajectories and various heating conditions. For the triangle heating technique with a gas-flame heating torch, the thermo-mechanical behavior of steel plate was analyzed using a disc-spring model and the inherent strain method to simplify the complicated phenomena.[2,3] A numerical model on the thermo-mechanical behavior of steel plate in the heating process was also developed, and this model, together with a commercial package program, was used to predict plate deformation.[1] To deal with the continuous decrease of the number of the skilled workers and low productivity of the triangle heating technique, this technique needs to be automated and mechanized. To automate a heating process, the heat source needs to be controlled in advance. Therefore, high frequency induction heat has been studied as a new heat source instead of the flame heat, whose intensity is difficult to control. To increase the productivity of the induction heating process and to automate the process, an analysis model for the process is first required. In addition, to develop automated equipment for the induction heating forming process, a heating plan, based on the prediction of the deformed shape with the heating process, is needed. When information on a desired curved plate is given, process parameters such as the heating method, heating position, etc. can be specified[4,5] in advance so that the process can carry out its procedures automatically. First, an analysis model of the heating process is developed to predict final shape of the plate with specified heating parameters. The analysis model of the line heating technique with high frequency induction heating has been studied extensively.[6,7] However, there have been few studies on the analysis model of the triangle heating technique with induction heating, and with this lack of information on the analysis model makes it difficult to predict the deformed shape with the heating parameters of the triangle heating technique.

In this study, to predict the deformation of steel plate in the induction heating process with the triangle heating technique, a heat-source model is proposed by an effective simulation of the technique, and then, a finite element (FE) analysis model to predict heat flow and deformation is developed. For the triangle technique, it is completely ineffective and time consuming to simulate the actual heating process itself by considering every situation. Therefore, an idealized model is used to describe the actual heating process.[1] In this study, a rotational heating scheme is suggested for the triangle heating technique and a simplified heat source model to simulate the proposed scheme is developed to easily analyze the triangle heating technique. Based on assumption that the rotational heating speed is much faster than the heat conduction speed, a two-dimensional (2-D) circular heat source is proposed, which generates the same heat along the circular direction in the same amount of time as the continuous heat input along the circular direction in an actual rotational heating process. In the triangle heating technique with the suggested rotational heating scheme, the amount of heat generated is calculated by electromagnetic analysis; the heat flow from the heat generated is analyzed to obtain the temperature distribution; and the deformation of the plate is predicted by FE analysis with the obtained temperature distribution. The results on the temperature distribution and the deformation of the plate by induction heating with the triangle heating technique are compared with experimental results to verify the proposed model on the heating process of the triangle heating technique.

2. Modeling and Numerical Analysis of Triangle Heating Technique

2.1 Circular heating model

In the triangle heating process of steel plate, heating is performed from inside the edge to the edge of the plate while the heated part is repeatedly heated. The heated length is short at the start of heating, but it becomes continuously longer, reaching the edge of the plate to form a triangular heated part. Therefore, in an analysis of the process, the initial temperature of the part to be heated should be considered, because the vicinity of the heated path would be affected by heat. In addition, because the actual heating path is long, an analysis trying to simulate the whole actual process would take excessive computing time. Therefore, a more simplified model is required. In this study, one of triangle heating techniques in which the heating torch rotates along a circle at a constant radius as the torch travels was selected to be simplified as a model. As shown at the right side in Fig. 1, in the selected technique, after the heat source rotates several times along a circle at a radius of 25 mm, it travels then along a zigzag path as shown at the left side in the figure. Although the heating length is short at the start of heating, the heating length becomes longer to the end of heating at the edge of the plate.

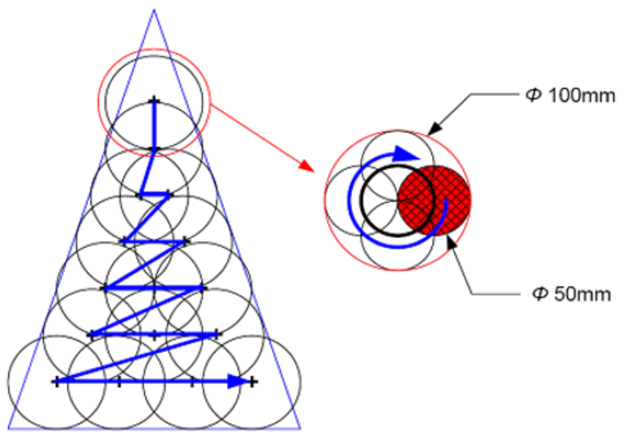


Fig. 1 Rotation method and heating path of inductor in triangle heating region

The heating method consisting of repeated rotating heating and zigzag travel path is a complex heating procedure that requires excessive computing time. Therefore, in this study, to simplify the heating process, a simple 2-D circular heat source of uniform heat intensity along the circumferential direction was proposed to model each rotation of heating, based on the assumption that when the moving speed of the heat source in the circular direction is much faster than heat conduction rate of the plate, the heat input along the circular path becomes uniform.[8] For the assumed 2-D heat source in this proposed method, the heat input was assumed to be uniformly distributed along each circular path for a rotation of heating and the heat intensity over a place changes with time as the heat source moves to another place in the heating path. The 2-D circular heat source travels in the desired path as shown in Fig. 1. Therefore, a place is first heated by the fore part of circular heat source, and finally heated by the rear part of the heat source as the source passes over the plate.

In the triangle heating technique, the heat source rotates at least 2 times with respect to the center point. Therefore, a part heated already by the previous circular pass of heat has a higher initial temperature than the ambient temperature, and this makes the part a different heat generation by the further heating by the circular heat source. The temperature on the surface of the steel plate was preheated to 20 °C, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, respectively, and each plate was then heated by the inductor. The heat generation on the surface of each plate is shown in Fig. 2. The results show that the higher the preheated temperature, the lower the expected heat generation. This is because the permeability of the steel plate becomes continuously low as the temperature of the plate approaches the Curie point where the electromagnetic property diminishes. Because the distribution of heat generation

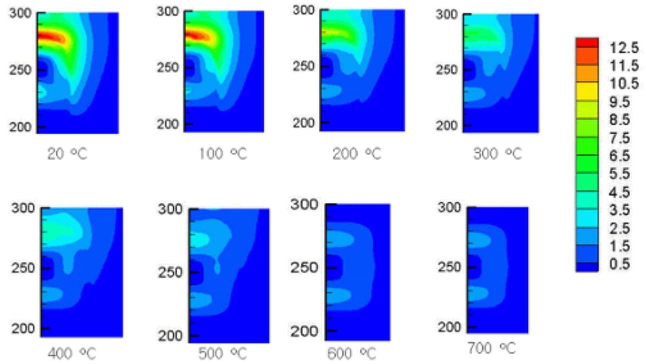


Fig. 2 Generated heat distribution on upper surface with preheating temperature in induction heating (W/mm^3)

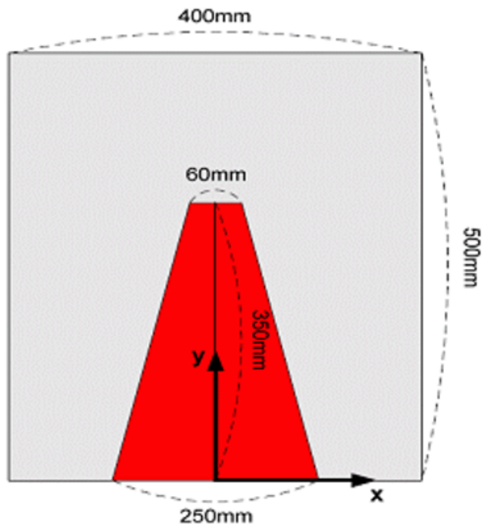


Fig. 3 Steel plate and triangle heating region

above 700 °C does not change further, results above 700 °C may be considered to be similar to that of 700 °C. To account for the effect of initial temperature, average temperature for the heated area before application of the circular heat was calculated, and then the distribution of heat generation was calculated based on the average temperature.

2.2 Analysis of heat flow and deformation

At the start part of triangle heating, the heated part has a short length and at end of the heating, it has a longer length to form a trapezoidal shape. To model this triangle heating technique, a trapezoidal shape which had an upper length of 60 mm, a lower length of 250 mm, and a height of 350 mm was used as an area to be heated. With the proposed model of the heat source and heating scheme, heat flow and deformation analyses were performed for a steel plate as shown in Fig. 3 with the trapezoidal heating region. The commercial program package ABAQUS[9] was used for the analyses, and the solution domain was divided into nearly 50,000 finite elements as shown in Fig. 4. The plate to be analyzed was made of mild steel and had a width of 400 mm, a length of 500 mm, and a thickness of 35 mm. The heating rate was 6.25 mm/s. The circular path of the inductor had a radius of 25 mm and 2 rotations were performed at each stationary position. In the analysis with the

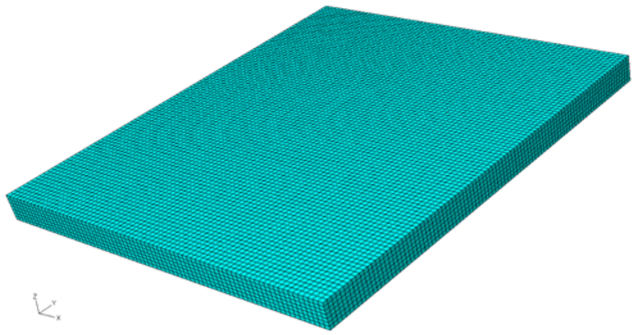


Fig. 4 Solution domain for FE analysis of triangle heating

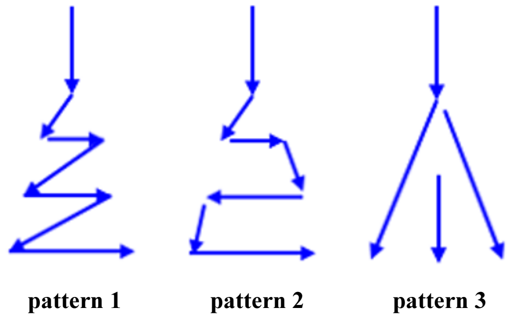


Fig. 5 Three patterns of heating paths in triangle heating region

proposed model, each stationary position then received a 2-D cylindrical heat input corresponding to the heat input by 2 rotations of induction.

To analyze the heat flow and the contraction deformation of a steel plate with the change of the heating path, 3 different heating paths were selected as shown in Fig. 5 at the heating rate of 15 mm/s for heating of a plate with width of 500 mm, length of 500 mm, and thickness of 30 mm.

3. Results and Discussion

3.1 Temperature distribution

Before being applied directly for triangle heating, the proposed heat source model was first used to analyze a simple rotational heating on the surface of a steel plate as shown in Fig. 6, and an experiment with the same process parameters as triangle heating was then performed to verify the feasibility of the model. The center of the heat source moved along the path of 4->5->2->6->4 in the heated zone to make a radius of rotation of 25 mm. The steel plate used for the analysis and experiment had a width of 400 mm, a length of 400 mm, and a thickness of 19 mm. The traveling speed of the heat source was 15 mm/s (0.607 rad/s in angular speed) and the power of the heat source was 40 kW at 2400 A. To simulate repeated heating at the same location, heat flow analyses and experiments were carried out for 1 rotation, 2 rotations, and 4 rotations, respectively. The different temperatures of the plate were measured during circular heating by thermocouples attached on the bottom surface of the plate at point 1, point 2, and point 3, respectively, which were related to center of rotation, radius of rotation, and outskirt of rotation, respectively.

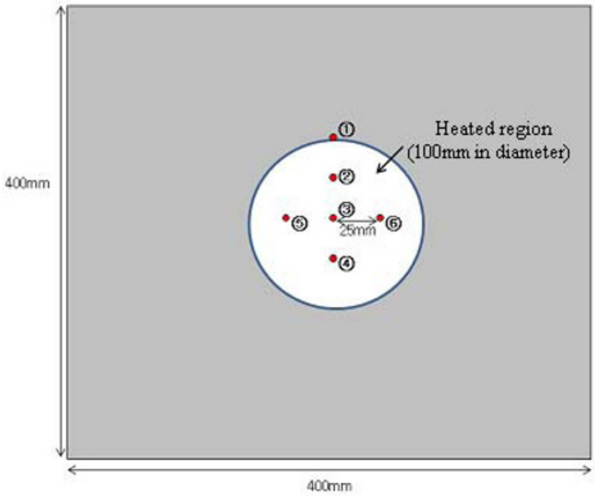


Fig. 6 Heating path of rotation method for triangle heating

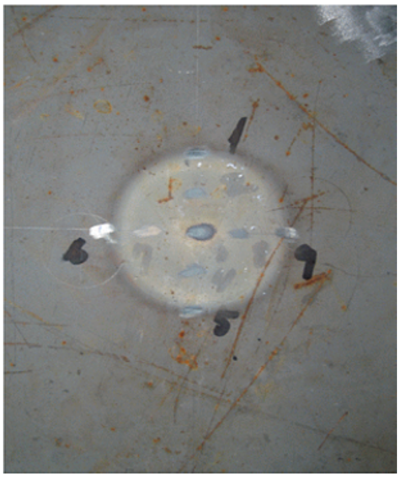
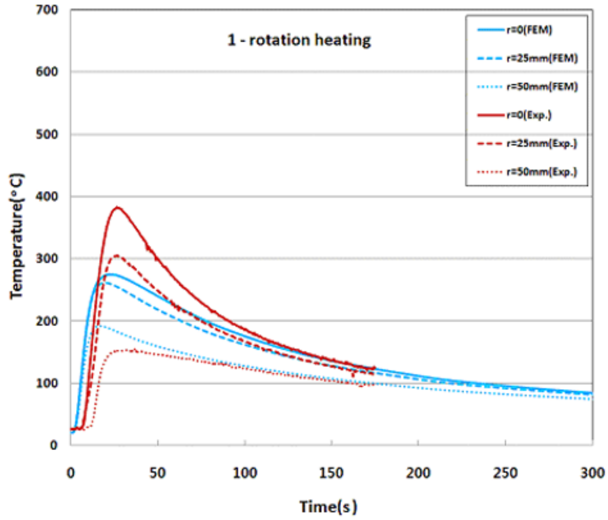
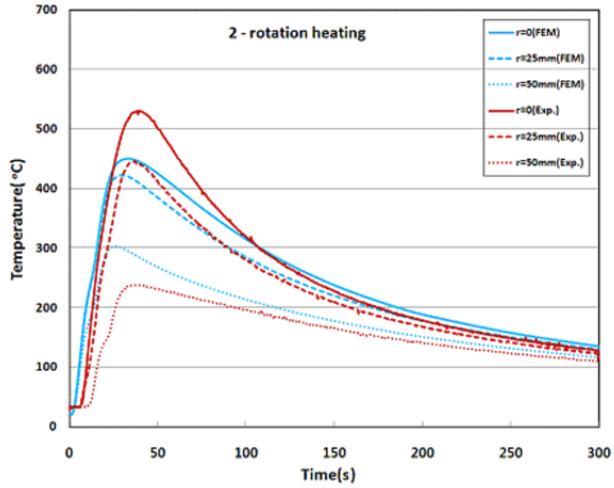


Fig. 7 Heated specimen of rotation method for triangle heating

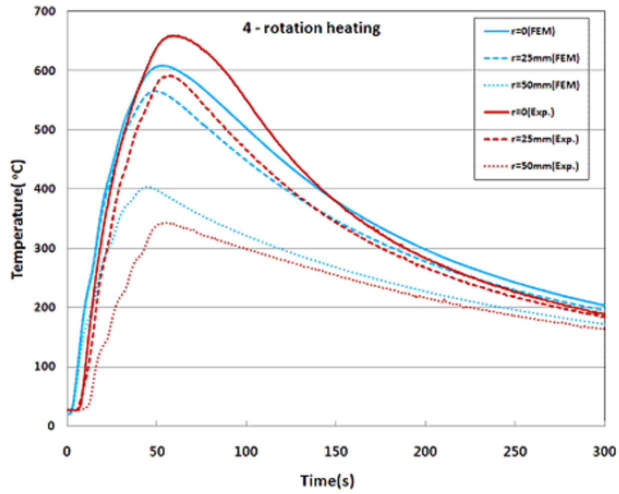
Figure 7 shows the result of circular heating on a steel plate. The results of the temperature distribution by the analysis of heat flow are illustrated and compared with results of experiments in Fig. 8(a), (b), and (c) for the heating process of 1 rotation, 2 rotations, and 4 rotations, respectively, to verify the proposed heat source model. A higher temperature than expected was measured at the center of the rotation (r=0 mm), whereas a lower temperature than expected was measured at the outskirt of the rotation (r=50 mm). This could be from the fact that the inductor had the shape of a channel of 20 mm in width and 20 mm in length. In rotational heating, the center of the rotation (r=0 mm) had a higher heat input than the center of the inductor (r=25 mm) itself, and the heat conduction from the center of rotation to the vicinity area could be blocked somewhat by the distributed heat input, whereas outside the heat source (r=50 mm) there could be a normal heat conduction to surround. Therefore, the center part of the rotational heating had a higher temperature than the other parts. In the analysis using the model of the 2-D circular heat source, where uniform heat intensity was imposed on the surface of the steel plate, the thermal conduction effect as the heat source made a circle in actual heating could not be considered. Therefore, the temperature differences existed between relative positions to the heat source.



(a) 1-rotation heating



(b) 2-rotation heating



(c) 4-rotation heating

Fig. 8 Comparison of temperature history by FE analysis and experiment (thickness: 19 mm, speed: 15 mm/s)

The results on the temperature distribution show much difference between the analysis and the experiment for the 1-rotation heating, but the difference becomes small for the 4-rotation heating. This is due to the fact that the heat conduction effect with

Table 1 Coordinates of rotating centers in triangle heating path

point	x-coordinate(mm)	y-coordinate(mm)
1	0	350
2	0	350
3	0	300
4	0	300
5	-15	250
6	-15	250
7	15	250
8	15	250
9	-30	200
10	-30	200
11	30	200
12	30	200
13	-50	150
14	-50	150
15	0	150
16	0	150
17	50	150
18	50	150
19	-65	100
20	-65	100
21	0	100
22	0	100
23	65	100
24	65	100
25	-80	50
26	-80	50
27	-40	50
28	-40	50
29	40	50
30	40	50
31	80	50
32	80	50

Fig. 9 Specimen of triangle heating

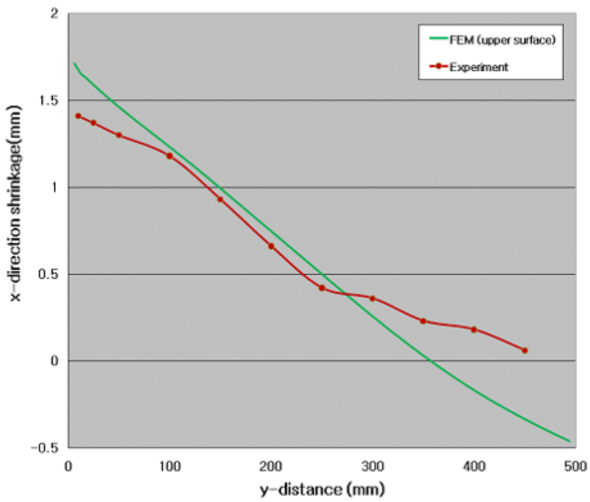


Fig. 10 Comparison of transverse shrinkage obtained by FE analysis and experiment

time can be presented in the analysis for multi-rotation heating. The results also show that the surface is not heated above the recrystallization temperature of the steel plate even in the 4-rotation heating. Therefore, 4 rotations of heat source at a location are allowable with induction heating in the triangle heating process.

3.2 Contraction of steel plate

To verify the proposed model of the triangle heating technique with the induction heating process, a numerical analysis was carried out for a geometrical model of the steel plate shown in Fig. 3 to calculate the transverse contraction of the plate, followed by an experiment with the same heating parameters as the analysis. The steel plate used for the experiment was made of mild steel and had a size of 400 mm in width, 500 mm in length, and 35 mm in thickness. The heat source traveled a circular heating path of radius of 25 mm and rotated 2 times at one place before traveling straight to another place at 6.25 mm/s. The coordinates of the center position of the heat source along the heating path are presented in Table 1, and the actual result of the heating is shown in Fig. 9. After the heating, the transverse contraction of the steel plate (x direction) along the length of the plate (y direction) are illustrated in Fig. 10. The result of analysis is in good agreement with that of the experiment. The result shows that some contraction exists at the start of heating (y=350 mm) and the largest contraction occurs at the end of heating (y=0 mm), increasing linearly along the heating path.

With the proposed model, the change of transverse contraction was analyzed with the change of heating path for a circular heat source which moved at 15 mm/s for a radius of 25 mm and 2 rotations at a place. Three heating paths were used as shown in Fig. 5 and the coordinates of the center of the heat source along the paths are presented in Table 2. The results of the analysis are shown in Fig. 11.

The transverse contractions along the length are smaller than the results shown in Fig. 10, which was obtained at a lower heating speed of 6.25 mm/s. The largest contraction is expected for the case of path 1. This shows that the path imposed with more repeated heating gives a higher heat input than the other paths. The smallest contraction is expected for path 3, which has less repeated heating to give a smaller heat input. The particular point compared to Fig. 10 is that though the contraction increases with length of heating region, it becomes constant at about y position of 200 mm. This seems to occur because the heating regions by the paths are narrower and longer than that by the path shown in Fig. 3 and Table 1.

Table 2 Coordinates of rotating centers in triangle heating paths with 3 different heating patterns

point	pattern-1		pattern-2		pattern-3	
	x(mm)	y(mm)	x(mm)	y(mm)	x(mm)	y(mm)
1	0	300	0	300	0	300
2	0	300	0	300	0	300
3	0	275	0	275	0	275
4	0	275	0	275	0	275
5	0	250	0	250	0	250
6	0	250	0	250	0	250
7	0	225	0	225	0	225
8	0	225	0	225	0	225
9	0	200	0	200	0	200
10	0	200	0	200	0	200
11	-19.2	145.2	-19.2	145.2	-19.2	145.2
12	-19.2	145.2	-19.2	145.2	-19.2	145.2
13	19.2	145.2	19.2	145.2	-38.3	90.4
14	19.2	145.2	19.2	145.2	-38.3	90.4
15	-38.3	90.4	38.3	90.4	-57.5	35.6
16	-38.3	90.4	38.3	90.4	-57.5	35.6
17	0	90.4	0	90.4	0	90.4
18	0	90.4	0	90.4	0	90.4
19	38.4	90.4	-38.3	90.4	0	35.6
20	38.4	90.4	-38.3	90.4	0	35.6
21	-57.5	35.6	-57.5	35.6	19.2	145.2
22	-57.5	35.6	-57.5	35.6	19.2	145.2
23	0	35.6	0	35.6	38.3	90.4
24	0	35.6	0	35.6	38.3	90.4
25	57.5	35.6	57.5	35.6	57.5	35.6
26	57.5	35.6	57.5	35.6	57.5	35.6

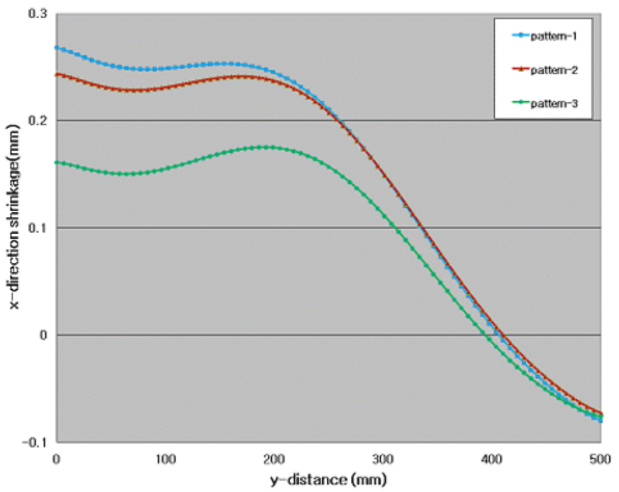


Fig. 11 Comparison of transverse shrinkages by 3 different patterns of heating paths

4. Conclusion

Triangle heating technique is mainly used to form steel plate into a curved shape by transverse contraction for the ship hull. A numerical model was proposed to analyze the transverse contraction of steel plate applied with the triangle heating scheme using the induction heating process. For this purpose, a 2-D heat source model for the rotational heating scheme in the triangle heating process was proposed and a numerical model for the analyses of heat flow and deformation was then developed. With the developed numerical model, the temperature distribution and the transverse contraction of a steel plate by the triangle heating process were predicted. The following conclusions can be drawn from this study.

(1) The predicted results were in good agreement with the experimental results, which verified the feasibility of the proposed models and the numerical analyses. 4 rotations of heat source at a location are predicted to be allowable with induction heating in the triangle heating process.

(2) The proposed model for a complex triangle heating process was used to predict to the change of the transverse contraction of the steel plate based on the heating parameters and to make a heating plan which would yield the desired shape of a plate. The heating path imposed with more repeated heating gives a more contraction of above 60%.

(3) The model can be also used in implementation of a process model to control the deformation of steel plate in real time for the automation of the heating process.

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