Numerical Modeling for Systematization of Line Heating Process

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Abstract

Sculptured surface structures such as ship hulls are traditionally formed up to the required double curved shape by line heating method. The nature of the line heating process is a transient thermal process, followed by a thermo-elastic-plastic stress field. The permanant shape is dependent on many factors involved in the process. Among them are torch speed and path, supplied heat type and amount, and plate size. Thus, the work is essentially leaded by experts with lots of experiences. However, in order to effectively improve productivity through automation, each factor should be clearly examined how much it affects the final shape. This can not be done only by experiments, but can be achieved by a mechanics-based approach.
In this paper, we propose a conceptual configuration for plate forming system, and then present simulations of the line heating process with numerical data in practices and suggest a computerized process of the line heating for practical applications. The modeling of heating torch, water cooling, and the plate to be formed is proposed for the finite element analysis after the mechanics of line heating is studied. Parametric studies are given and discussed for the effects of plate thickness, torch speed and initial curvature in forming a saddle typed surface.

1 Introduction

The line heating process, a forming technique of double-curvature shells in shipbuilding industries, is very complicated in a sense that it involves many factors affecting final deformed shapes. They includes heating paths, their order, torch speed and height, heat input, plate dimensions, cooling environments. At present, bending plates by line heating is primarily done manually and is based on experience rather than systematic approach. Thus only experts lead the forming work based on their experiences. In order to improve the productivity, an automated procedure would be preferrable. The automation can only be feasible when both theoretical analysis of the line heating process and database of experiences are available. To make such a database practical, it should be decided which entities are extracted from the abstract experiences. Experiments and theoretical solutions can help establish the useful database.
Since the nature of the line heating process is a transient thermal process, followed by a three-dimensional thermo-elastic-plastic stress field, the analytical solution of the process is not possible. Rather a finite element approach is more practical to explore the mechanism of the process.
In this paper, we first propose a conceptual configuration for ship production system of plate forming. And the modeling of heating torch, water cooling, and plate to be formed is proposed for the finite element analysis. Since the temperature and stress fields can be

uncoupled in this problem, we first excute the temperature distribution caused by the heating torch. The validity of the present modeling is checked by comparing results of temperature fields with published theoretical ones. It is found that the modeling gives good results. Next, stress analysis are performed based on the calculated temperature distribution. Temperature-dependent material properties, such as yield stress and elastic modulus, are employed. A saddle-type shell is generated by the proposed modeling.

2 Proposed system configuration of plate forming

The plate forming which is largely dependent on accumulated experience workers has been carried out by their inspection. Automation of the plate forming process has not made progress due to difficulties in theoretical and quantitative analyses of bending mechanism by line heating. Consequently, a greater part of the bending work has been dependent upon experienced and skilled workers for long time. Still now on, the plate forming process depends entirely on the private experiences of technicians, which can not be organized to the reliable technical data base at all. A knowledge representation of the skills and a mechanical model from the mechanics of line heating are perhaps a milestone on the way to a plate forming system since an accurate and efficient system will be required for forming hull plates composed of complicated curvature.
The system configuration for plate forming of ship hull that is proposed in this paper is conceptually outlined in Fig. 1.

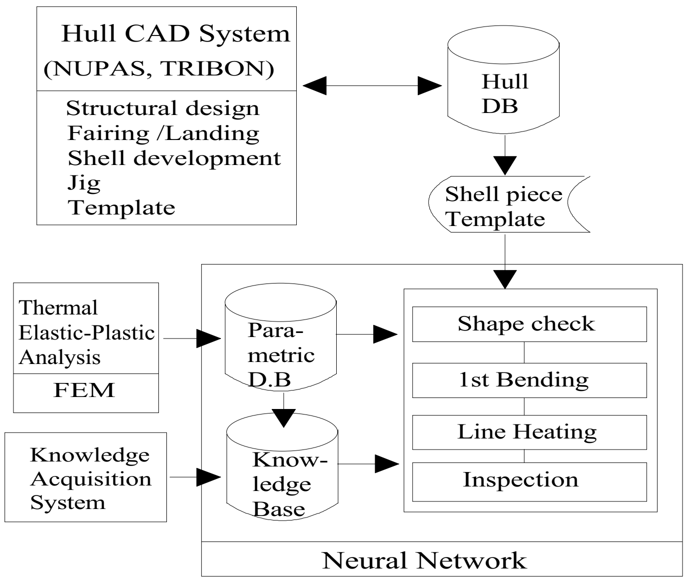


Fig. 1 System configuration of plate forming

2.1 Interface with shell lofting data

The process of hull construction is divided into various steps according to complexity of each procedure such as designing, lofting, cutting, forming and assembling. One of the earliest activities in hull construction is modeling and lofting the hull surface. It is important that the model of hull surface is created with such a quality that all subsequent lofting operations such as seams and longitudinal landing, shell plate development, templates and jigs etc. can be carried out with an accurate result. Curved hull members of different kinds are generated from the hull surface. Seams, butts and traces for longitudinals and transversal frames are generated using the hull surface. Lofting and production informations which are all necessary hull piece cutting, forming and manufacturing can be created by hull CAD system such as NUPAS, TRIBON and AUTOKON. Work instructions prepared by a loft are crucial for effective performances by plate forming workers.

Double-curvature shells can not be developed exactly, and although many kinds of developing method have been presented, they will always suffer from deviation from the intended sculptured surface due to unavoidable approximation in the development technique. The developing method must, in some way, be dependent on the plate forming process which may be regarded as the inverse function of the development technique. Because a double-curvature shell cannot be developed into a two-dimensional flat plate without expansion or contraction, the development technique takes the amount of streching or shrinking at the line heating process into consideration[1,2]. It is essential that the plate forming methods are good enough to bring back the develped plate into its double-curvature shell with minimum manufacturing costs.

2.2 Plate forming process

Formation of a double-curvature shell from a flat plate, after primary bending by a press or a roller, is traditionally carried out to the required double-curvature shape by the line heating method. The plate to be formed inevitably involves some degrees of elastic and plastic deformations. Special classes of shells which have developable surfaces can be readily manufactured from flat plates because they require only bending of the plates. However, developability is a highly restrictive geometric property, and there are many functional considerations on the ship hull forms that may exclude the use of developable surfaces.

Because the forming of double-curvature shells requires any degree of plastic deformation, the line heating process have been found useful for applications in the manufacturing of ship structures, primarily for parts involving double curvature, and generally used in shipbuilding industries. Line heating is the process of forming curved shapes from flat plates by controlled heating and cooling. By moving a torch or laser beam repeatedly along straight lines on top of a plate, residual bending is achieved.

Checking shape types of plates is also a target of systematization for determining the detailed sequence of plate forming steps required to choose the forming method. Even though the complete automation of process planning is almost impossible in hull plate forming, the process plans can be generated if the process plans of the similar parts already exist. For this purpose, the concept of group technology has been proposed to organize similar plate parts into family. In accordance with the surface patterns, the shell can be devided into four kinds such as flat, self-weight curvature, single curvature and double curvature. The shell plate with self-weight curvature is the plate whose curvature is small and slowly changing can be bent under its own weight. Single curvature means geometrically developable with zero Gaussion curvature and no need of line heating in shaping. Double curvature is geometrically undevelopable shell with plus Gaussian curvature and line heating implemented in both longitudinal shell boundaries and geometrically undevelopable surface with minus Gaussian curvature a saddle one and a twist one. For the inspection of curved surface geometry, templates will be placed to the shell plate surface. The information of templates is calculated for each plate parts in hull CAD system and must be interfaced to plate forming system.

2.3 The knowledge representation of plate forming

In the plate bending process by the line heating, the decisions as to which part and in which direction of the plate should be heated are usually made by skillful workers. Thus only experts lead the forming work based on their experiences. In order to improve the productivity, an automated procedure would be preferrable. The automation can only be feasible when both theoretical analysis and experiences of line heating process are available. To make such a knowledge-based system practical, it should be established using experiences of experts and theoretical solutions of mechanical analysis.
In order to apply theoretical solution, we constructed a mechanical model which was proposed for a line heating. Neural network is applied to the construction of parametric database which reduce the amount of computer time required to solve a mechanical analysis of line heating problem.
Hence, to reduce the numerous iterations of the simulation for heat paths by the line heating, such bending skills should systematically be analyzed to be applicable for a knowledge-based system. The fact that the obtained knowledge is utilized by the worker only, causes the waste of time which is needed for training new skilled worker. Therefore, it is the purpose of developing an expert system that a user makes the best use of the knowledge of expert by sharing the knowledge as much as possible, and that the constructed knowledgebase is flexible for modification, maintenance, and extensibility[4].
To develop a knowledge-based system for the line heating skill, the skill must be represented as knowledge, and the knowledge must be stored in the computer in the form of expressions. Knowledge representation means describing problems in a solvable form, and the knowledge to be used for that purpose in a form that allows processing by the computer. Knowledge can be represented in the forms of production rules, semantic network, frame, and script, for example. For the automation of a plate forming, much attention should be paid to these technologies.

3 The numerical modeling of the line heating process

3.1 The mechanical model of line heating

As the first step in the analysis of the line heating problem, the heat conduction problem is assumed to be unaffected by the stress strain field and therefore the temperature field can be evaluated beforehand. Then, the stress-strain field follows. Before the thermo-elastic-plastic analysis is applied, the time history of the temperature distribution during the process should be determined. The temperature gradients cause residual strains and change the material properties as well. In particular the increase of temperature results in a decreasing yield stress and Young's modulus, both of which have a substantial effect on the thermo-elastic-plastic bending characteristics. The calculated temperature field is used as a loading condition that creates the residual strain[5].

3.2 The heat conduction equation

The temperature distribution in a steel plate heated by the line heating method can be obtained by solving the following heat conducton equation.

$$\frac{\partial}{\partial x}\left[k\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right]=\rho c\frac{\partial T}{\partial t} \qquad (1)$$

Here, k is thermal conductivity coefficient $[\mathrm{cal/mm\cdot sec^\circ C}]$, ρ denotes density $[\mathrm{g/mm^3}]$, $c = c(x,y,z,t)$ denotes specific heat $[\mathrm{cal/g\cdot^\circ C}]$, and the value of the material properties are dependent on temperature.

3.3 The modeling of thermal energy input

The moving torch flame cannot be accurately modeled by a moving point heat source, but by a disributed heat flux load. Rykalin made various studies and proposed a mathematical for the distribution of heat flux from the heating torch. He assumed that the torch is at right angles to the plate and at a radius r the heat flux $q''(r)$ is given by a Gauss normal distribution as shown in Fig. 2 [6]. The heat flux equation can be written by

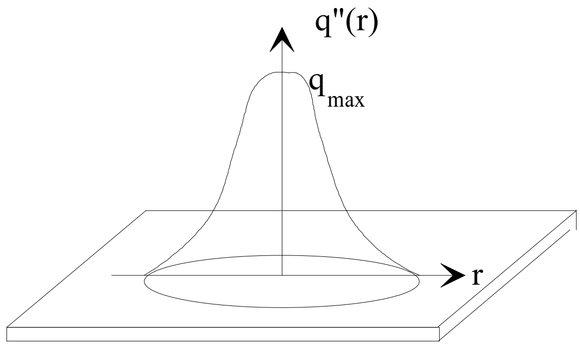


Fig. 2 Gaussian distributed heat source

$$q''(r) = q_{max}\exp(-\gamma r^2) \qquad (2)$$

$$q_{eff} = \int_0^\infty q''(r) r d\theta dr \qquad (3)$$

where, γ is the concentration coefficient $[\mathrm{cm^{-2}}]$, q_{eff} is an effective flame power [cal/sec] .

3.4 The modeling of the cooling troch

Line heating process involves a cooling as well as a heating. This cooling process can be modeled as the heat convection condition that appears as a boundary condition in the solution of heat conduction problems. This condition is given by

$$q'' = h\left(T_\infty - T_s\right) \qquad (4)$$

Here, q'' denotes convective heat flux $[\mathrm{cal/mm^2\,sec}]$, h denotes film coefficient $[\mathrm{cal/mm^2\,{}^\circ C \cdot sec}]$, T_∞ denotes fluid temperature $[{}^\circ\mathrm{C}]$ and T_s denotes surface temperature $[{}^\circ\mathrm{C}]$. In the solution of such problems we presume heat convection coefficient h to be known, using typical values given in [7].

3.5 Thermo-elastic-plastic incremental equation

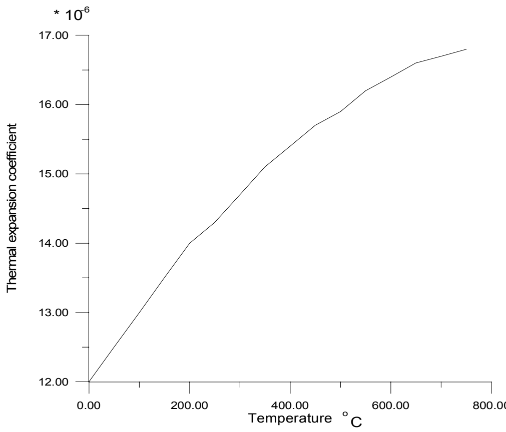
Thermo-elastic-plastic analysis requires appropriate constitutive relations. The stress-strain relations are needed here to evaluate the plastic strain increment. The residual stresses and strains are produced due to non-uniform temperature distribution and temperature-dependent material properties. The increment of the total strain is assumed to be a superposition of increments of the elastic strain, thermal, and plastic strains. Incremental constitutive equations employed to analyze the thermo-elastic-plastic problems is written as follows.

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{E} + d\varepsilon_{ij}^{t} + d\varepsilon_{ij}^{P} \tag{5}$$

$$\begin{aligned} d\sigma_{ij} = {} & \frac{\nu}{(1+\nu)(1-2\nu)} dE\varepsilon_{\mu\mu}\delta_{ij} + \frac{\nu E}{(1+\nu)(1-2\nu)} d\varepsilon_{\mu\mu}\delta_{ij} + \frac{1}{1+\nu}\varepsilon_{ij} dE + \frac{1}{1+\nu} d\varepsilon_{ij} \\ & - \frac{1}{1-2\nu}\left(\alpha T \cdot dE + ET \cdot d\alpha + E\alpha \cdot dT\right)\delta_{ij} - \frac{E}{1+\nu}\sigma'_{ij} d\lambda \end{aligned} \tag{6}$$

ε_{ij}=total strain	ε_{ij}^{E}=elastic strain	ε_{ij}^{t}=thermal strain
ε_{ij}^{p}=plastic strain	σ_{ij}=stress	ν=Poisson's ratio
E=Young's modulus	δ_{ij}=Kronecker's delta function	T=temperature
α=thermal expansion coefficient		σ'_{ij}=deviatoric stress
$d\lambda = 3/2 \cdot d\bar{\varepsilon}^{p}/\bar{\sigma}$	$\bar{\sigma} = \sqrt{3/2\,\sigma'_{ij}\sigma'_{ij}}$	$\bar{\varepsilon}^{p} = \sqrt{2/3\,\varepsilon_{ij}^{p}\varepsilon_{ij}^{p}}$

The material properties are taken as temperature-dependent, such as thermal expansion coefficient and Young's modulus, yield stress, as shown in Fig. 3.



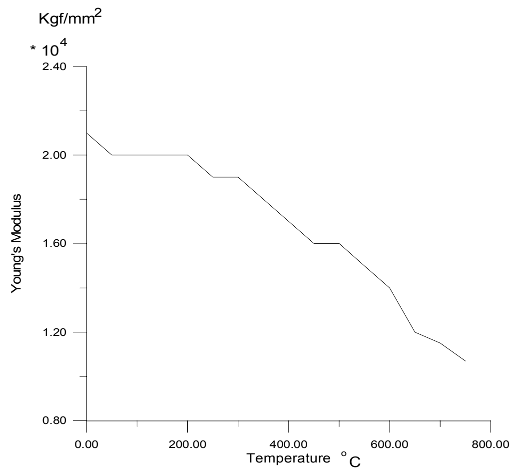


Fig. 3(a) Thermal expansion coefficient

Fig. 3(b) Young's modulus

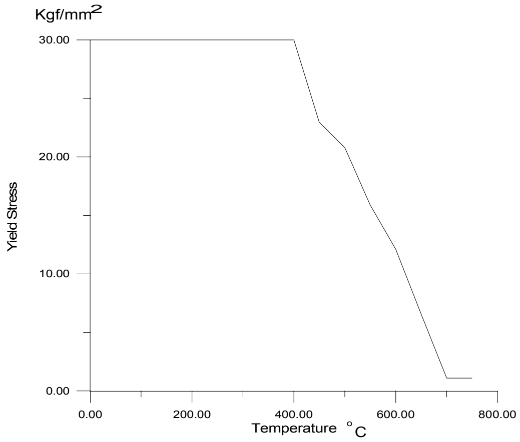


Fig. 3(c) Yield stress

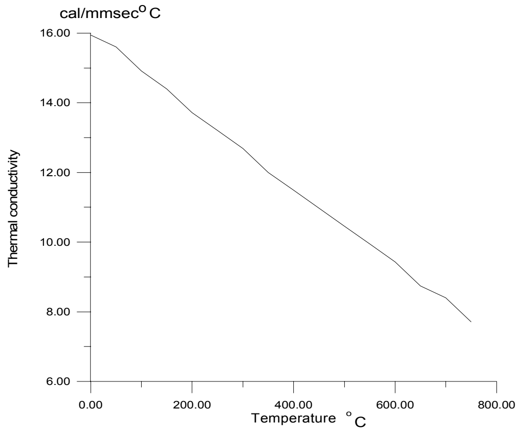


Fig. 3(d) Thermal conductivity coefficient

4 Numerical simulation

4.1 Procedure of finite element modeling and analysis

We performed both the temperature distribution analysis and the stress strain analysis sequentially. This procedure is shown in Fig. 4.

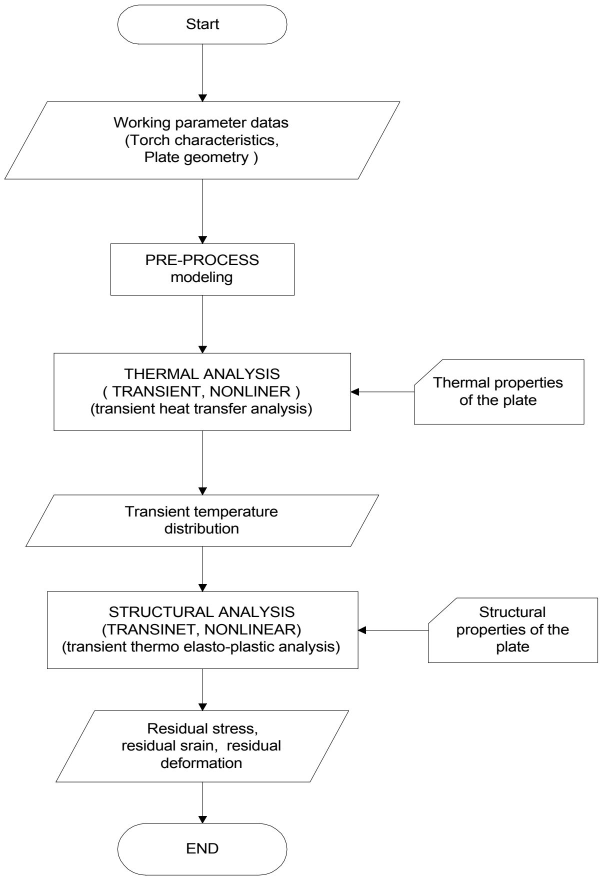


Fig. 4 Schematic diagram of the analysis

The heated line of the torch was taken at the center of the plate, and a calculation was carried out for the half-side as shown in Fig. 5. A 3-dimensional 8-node solid element of ANSYS was chosen to model the plate.

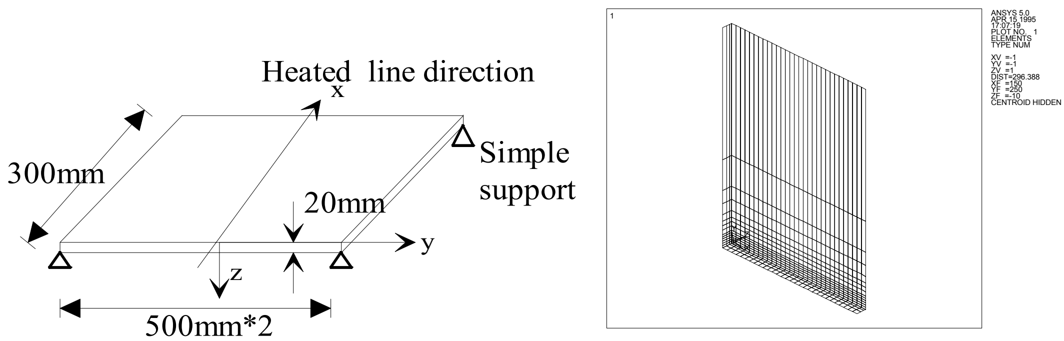


Fig. 5 Coordinate system and the finite element analysis model

In the line heating process, not only air-cooling but also water-cooling is used to cool the heated plate. In the case of water-cooling, it is assumed that the water outlet is located at about 50 mm backward the heated region. The water-cooling can be modeled as a distributed heat convective boundary condition. The characteristics are shown in Fig. 6.

$$h(r) = h_{max} * 0.9^{r/10}, r = [mm] \tag{7}$$

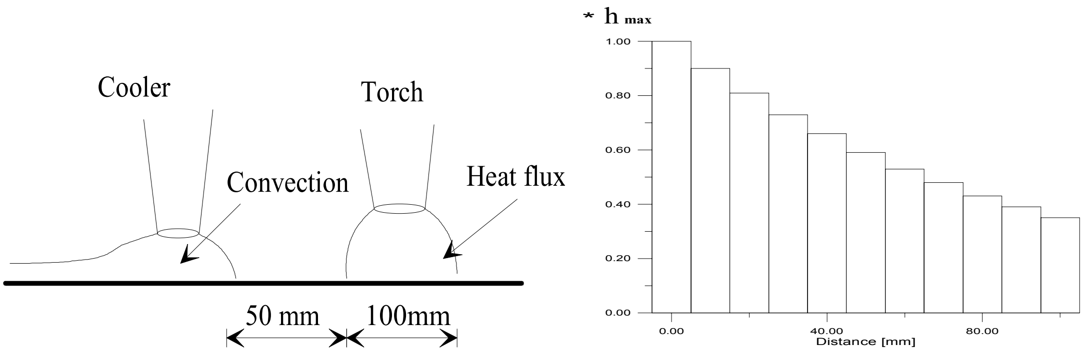


Fig. 6 Heat convection coefficient distribution

Table 1 summarizes the data used in the following numerical study. The material properties are assumed to be temperature dependent values[8].

Table 1: Summary of the heating and cooling conditions

Torch speed	$v = 7.5$ [mm/sec]
Equivalent heat transfer rate	$q_{eff} = 2200$ [cal/sec]
Concentration coefficient	$\gamma = 0.180\ [cm^{-2}]$
Maximum convection coefficient	$h_{max} = 1.e\text{-}3\ [cal/mm^2\,^\circ C \cdot sec]$

At first step, a temperature distribution was evaluated by using ANSYS program. The validity of the present modeling is verified by comparing temperature distributions with theoretical one in [5]. Fig. 7(a) illustrates the transient temperature distribution in the x-direction. In this figure, the temperature is plotted against the distance x from the edge at the center of the plate surface (y=z=0 mm) for varying time t. At time t=0 sec the torch center is behind the edge. Fig. 7(b) illustrates the temperature distribution at x=150 mm along z-direction at t=26.7 sec, 29.0 sec, 40.0 sec.

The temperature distribution obtained in the previous step was used as a load for the stress-strain analysis. Fig. 8(a) illustrates the residual deflection along y-direction at x=150 mm, z=0 mm. The maximum deflection at the center line was 2.84 mm. Fig. 8(b) shows the residual strains along the plate thickness at the mid-plate.

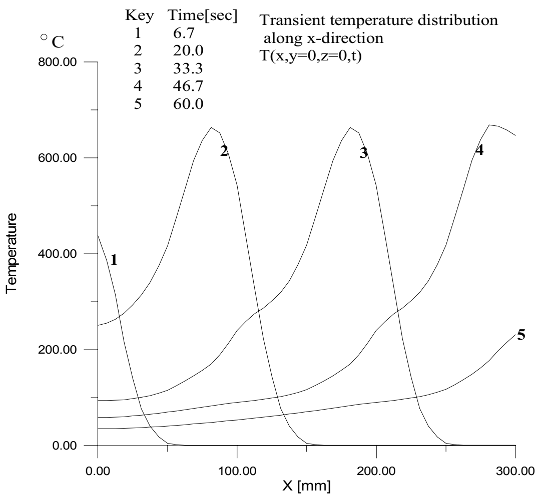


Fig. 7(a) Transient temperature distribution along x-direction

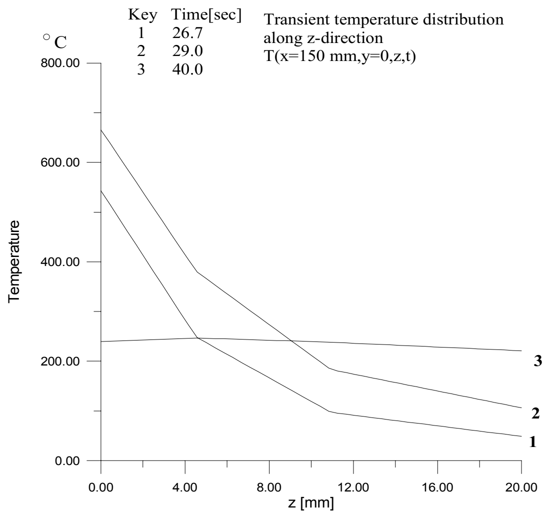


Fig. 7(b) Transient temperature distribution along z-direction

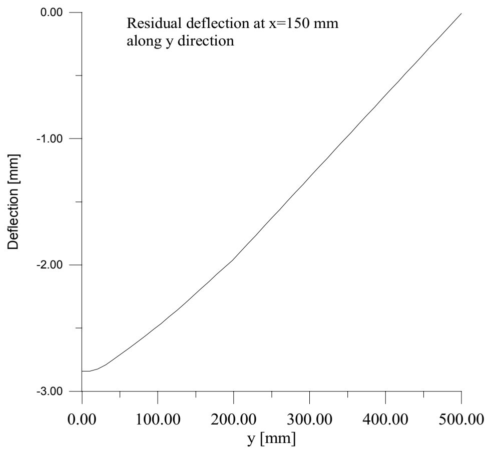


Fig. 8(a) Residual deflection along y-direction

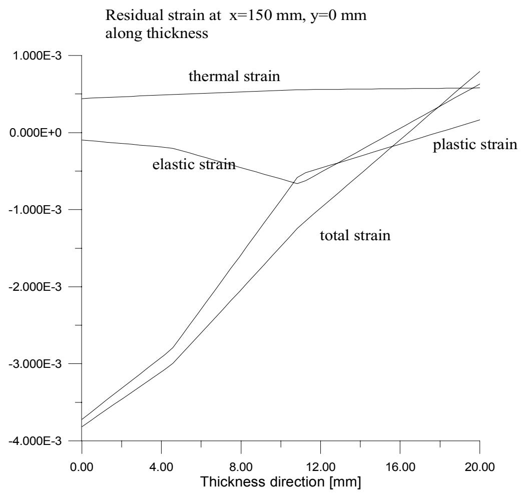


Fig. 8(b) Residual strain at mid-plate

4.2 Parametric study

(1) Influence of torch speed

To examine the effect of the torch speed, thermo elastic plastic analysis were performed for various torch speeds with all the other input parameters remaining unchanged. The q_{eff} was 2200 cal/sec, γ was 0.180 cm^{-2}, and h_{max} was 1.e-3 $cal/mm^2\,{}^\circ C\cdot sec$.

Fig. 9(a) shows the quasi-steady state temperature distributions as the speed is changed. The residual deflections along x-direction at y=z=0 mm are plotted in Fig. 9(b). As the torch speed v is increased, the value of the maximum deflection decreases. Reviewing the results, we find that a maximum deflection decreases linearly as the torch speed is increased.

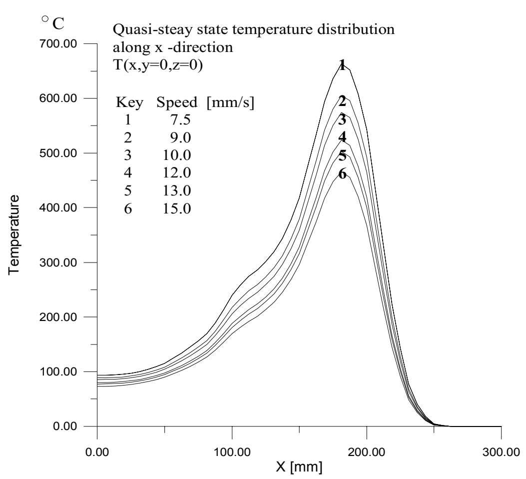


Fig. 9(a) Temperature distributions

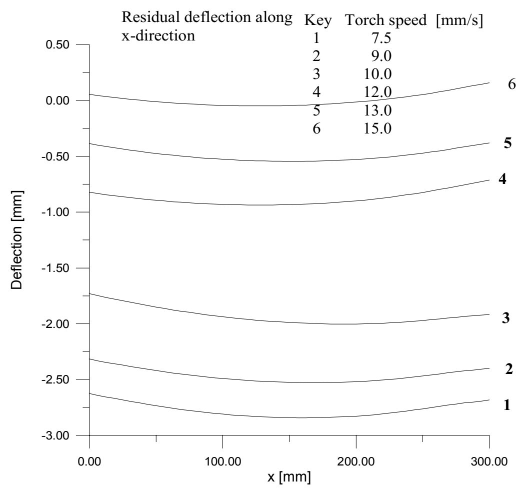


Fig. 9(b) Residual deflection along x-direction

(2) Influence of the heat convective coefficient

In the case of water-cooling, the cooling effect was regarded as a distributed heat convective boundary condition. The value of h_{max} means the strength of cooling effect on the heated plate. To examine the effects of the cooling thermo elastic plastic analysis were performed for various h_{max} with the other input parameters remaining unchanged. Torch speed was 10 mm/sec.

The temperature abruptly drops in the region cooled by water as the value of h_{max} increases as shown in Fig. 10(a). Fig. 10(b) shows that the value of maximum deflection is increased as the value of h_{max} is increased, but the differences of maximum deflection are small.

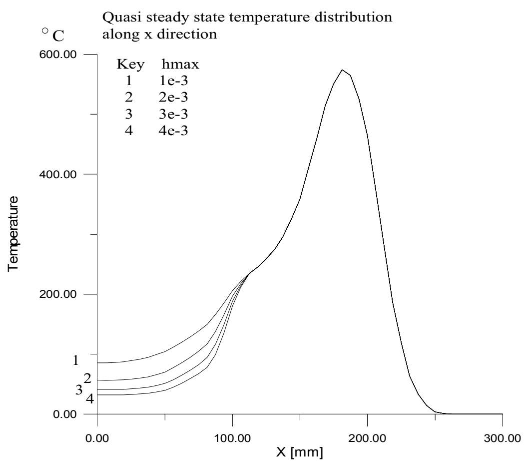


Fig. 10(a) Influence on temperature distribution by change in h_{max}

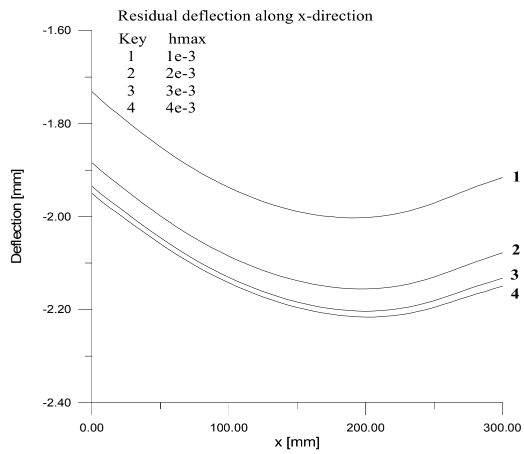
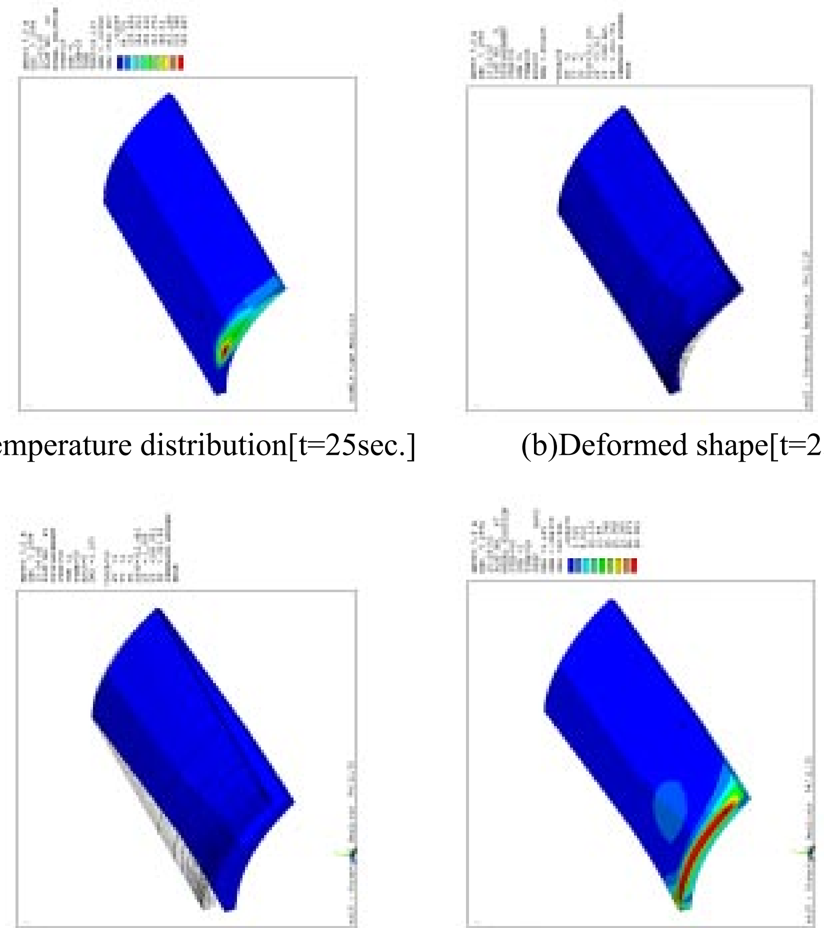


Fig. 10(b) Influence on deflection by change in h_{max}

4.3 The single curvature plate to the double curvature plate

A calculation was performed for the heated plate that had the initial curvature. The heating condition was the same as that in the flat plate. Torch speed v was 10 mm/sec, q_{eff} was 2200 cal/sec, γ was 0.180 cm^{-2}, and h_{max} was 1.e-3 $cal/mm^2{}^\circ C\cdot sec$.
With the above heating condition the maximum deflection of the flat plate was 2.0 mm. The resultant maximum deflection of the initially curved plate is 1.1 mm that is smaller than that of a flat plate. Comparing the results of the flat plate and the initially curved plate, it can be concluded that the initially curved plates are more inflexible than flat plates. The result is shown in Fig. 11.



(a)Temperature distribution[t=25sec.] (b)Deformed shape[t=25sec.]

(c)Final deformed shape (d) Residual Mises equivalent stress

Fig. 11 Simulation of line heating process for the initially curved shell

5 Conclusions

In this paper, we first propose a conceptual configuration for ship production system of plate forming. It is necessary to integrate lofting and plate forming activities for minimum thermal energy in line heating peocess.
The modeling of heating torch, water cooling, and plate to be formed is proposed for the finite element analysis after the mechanics of line heating is studeid. A three-dimensional 8-node solid elements of ANSYS were chosen for analysis. The validity of the present modeling is checked by comparing results of temperature fields with published theoretical ones. It is found that the modeling gives good results. The stress analyses are performed

based on the calculated temperature distribution.
Parametric studies are given and discussed for the effects of torch speed and cooling methods. In our calculation, the final deformation is inversely proportional to the torch speed. Finally a saddle-type shell is generated by the proposed modeling.

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