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Development of Computer Aided Process Planning System for Plate Bending by Line-Heating (Report IV)†

— Decision Making on Heating Conditions, Location and Direction —

Yukio UEDA*, Hidekazu MURAKAWA, Ahmed Mohamed RASHWAN***, Ryoichi KAMICHIKA****, Morinobu ISHIYAMA**** and Jun-ichiro OGAWA******

Abstract

The plate bending process is considered as a process to form three-dimensional shapes by introducing the permanent strain (inherent strain) into a plate through proper means. It has been shown that it is very important to utilize both inplane and bending inherent strains for effective bending. The authors have studied the inherent strain necessary to produce the final shape to be formed and the relation between the heating condition and the inherent strain created by single heating line in the previous work.

Although the general idea of generating process plan or heating instructions was proposed, the detail was not discussed. Therefore, methods to generate the information on where, in which direction and how to heat are discussed in this report. Their effectiveness are examined through numerical examples.

KEY WORDS: (Line-Heating) (Inherent Deformation) (Heating Condition) (Orthogonal Compressive Inherent Strain) (Shrinkage) (Finite Element Method)

1. Introduction

The line-heating method is widely employed in shipyards to form the shell platings of ship structure. The main advantage of this method is its capability to form complicated three-dimensional shapes which may not be achieved using other mechanical methods. In the line-heating method, the plate is bent under the influence of the plastic deformation created by the thermal expansion or shrinkage during the heating and the cooling processes. The resulting shape of the plate bent by the line-heating method is difficult to predict in advance due to the complex nature of the process. Thus, the skills and the experience of workers are indispensable elements to carry out the plate bending by the line-heating. However, high average age of skilled workers and a decrease in their number have become crucial problems for the shipbuilding industry. In order to get an insight into the unrevealed skills and experiences of skilled workers, advanced techniques such as the computer simulation by the Finite Element Method can be used. Once the necessary information about the forming process by the line-heating method can be accumulated with the aid of computer simulation, mechanization of the process can be put into a practical use in shipyards.

To achieve an efficient plate forming, the inplane and the bending inherent strains should be combined properly in the plate forming process. The authors studied the contribution of the inplane and the bending inherent strains given to a plate so as to achieve the final form[1,2]. In addition, the relation between the inherent deformation produced by a single heating line and the heating conditions has been reported[3]. However, the heating condition to create inplane or bending inherent deformation was examined with an ideal flat plate through a single heating line. To examine the effect of residual deformations created by the roll or press process and the line-heating in the preceding process, the effect of initial curvature and residual stress on the inherent deformations are examined in this report.

Knowing the distribution and the magnitude of both inplane and bending inherent strains for a given geometry of the plate, the general procedures for the forming process can be determined. However, the line-heating process produces only shrinkage and the shear mode of deformation along the heating line is not

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* Professor
** Associate Professor
*** Graduate Student
**** Ishikawajima-Harima Heavy Industries Co., Ltd.

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produced. Thus the inherent strain distribution satisfying this condition must be generated. For this purposs, a method to generate an orthogonal compressive inplane inherent strain is proposed in this report. Further, procedures to concentrate the distributed compressive inplane inherent strain into the form of heating lines distributed in the forms of grid and parallel lines are proposed.

2. Effect of Initial Curvature and Stress on Inherent Strain

2.1 Effect of initial curvature

In the most cases, each line-heating in the plate forming process is done on the plate with initial curvature and residual stress created through the preceding processes. The curved shell plating is formed usually by rolling in one direction to obtain the appropriate bending deformation. Afterwards, the plate is heated to obtain the required shrinkage, and additional heating lines are applied to adjust the geometry to the final configuration. Therefore, the effect of the initial curvature on the inherent deformation produced by a single heating line is examined and compared with that for a flat plate.

The Finite Element Method is employed to get the plate with initial curvature. The plate is forced to deform into a cylindrical form as a first step. Then, the plate is removed from the external constraints. The deformation in this process corresponds to the spring back of the plate and residual curved shape and stresses in the natural state without external forces are determined. The dimension of the model used to study the effect of the initial curvature is shown in **Fig.1**. The direction of the heating line is assumed to be normal to the axis of the cylinder since the influence of the curvature is expected to appear most. The maximum curvature used for the real shell plating of ship is nearly 1/3000 and the curvature for the present case is about 1/2260. The shape of pressed plate after releasing the spring back is shown in **Fig.2**.

Two types of heating conditions, the bending and the inplane types of heating conditions, are considered. The bending type of heating condition is to create dominant angular distortion. On the other hand, the inplane type of heating condition is to produce dominant shrinkage. The details of the two heating conditions are given in **Table 1** together with the inherent deformation produced by a single heating line applied to a flat plate. The bending and the inplane types of the heating conditions are characterized by δ/θ which is the ratio between the shrinkage and the angle of distortion. This ratio should be small for bending type of heating and vice versa. For the two heating conditions considered, as examples, the ratio δ/θ is 22.2 for the inplane type of heating and 2.34 for the bending type of heating.

The angular distortion and the shrinkage produced by the line-heating in cases of plate with initial curvature and the flat plate for both the bending and the inplane types of heating are given in **Table 2**. For the bending type of heating, the angular distortion is the most important. While the shrinkage is the primary one to be created by the inplane type of heating. Comparing the results of the angular distortion for the plate with the initial curvature and the flat plate, it is found that the

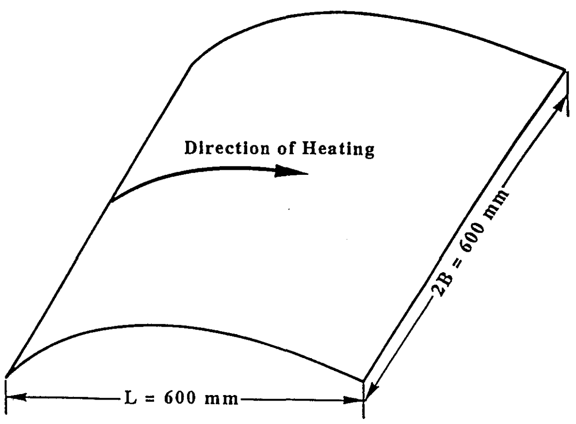


Fig.1 Line-heating model with initial curvature.

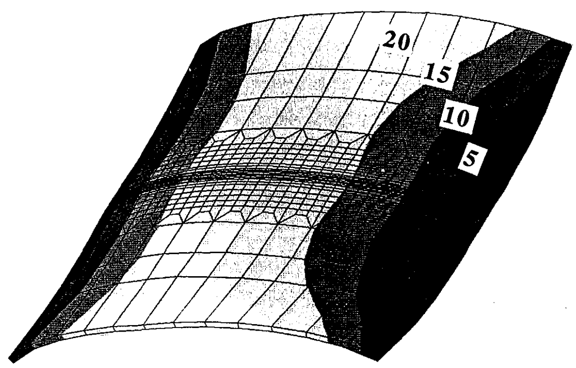


Fig.2 Shape of preseed plate after spring back.

Table 1 Heating conditions and inherent deformation.

Type of heating	Bending type	Shrinkage type
Heat input rate : Q (cal./sec.)	2475.0	350.0
Moving speed : v (mm/sec.)	50.0	1.0
Angular distortion (rad)	5.0×10^{-3}	18.9×10^{-3}
Transverse shrinkage (mm)	0.0117	0.42

Table 2 Effect of initial cruvature on the inherent deformation.

Type of heating	Curvature	Angular distortion	Transverse shrinkage
Bending type	0 1/mm	5.0×10^{-3} rad	0.0117 mm
	1/2260 1/mm	4.2×10^{-3} rad	0.0050 mm
Shrinkage type	0 1/mm	18.9×10^{-3} rad	0.42 mm
	1/2260 1/mm	28.6×10^{-3} rad	0.40 mm

angular distortion by the line-heating is decreased by about 15 % due to the assumed initial curvature. However, since the assumed curvature is the maximum value which is expected in the real practice, the change in the angular distortion due to the initial curvature is considered to be small. Hence, the information about the bending inherent deformation predicted for a flat plate can be used for the plate with initial curvatures in planning the line-heating procedure.

As for the inplane heating type, it can be seen from the table that the shrinkage is less sensitive to the initial curvature. The ratio between the shrinkage produced by line-heating in the plate with initial curvature and the flat plate is 95 % , i.e. shrinkage decreases by about 5 %. This suggests that the inplane type of heating is insensitive to the initial curvature of the plate. Thus, the information about the inplane inherent deformation predicted for a flat plate also can be used as a an approximation in planning the line-heating procedure.

2.2 Effect of residual stress

There are different sources of the residual stress generated in the plate such as the residual stress caused by forming the plate using the roll or the press and line-heating processes. Since the effect of the residual stress coming from the bending deformation was partly discussed in the previous section, the effect of residual stress caused by preceding heating lines is considered here. The residual stresses caused by the line-heating process can be classified into local and global residual stresses according to the zone in which the residual stress exists. The local residual stress exists in the region near the heating line and has the large magnitude reaching the yield stress of the material. On the other hand, away from the heating line, the residual stress with relatively small magnitude distributes in the wide area. In the plate forming by line-heating method, the heating lines are usually distributed in parallel manner. Even when they are crossing each other, overlapped area of heating lines is relatively small. Since, the effect of local residual stress can be expected to be very small, the influence of the global residual stress on the inherent deformations is examined here.

The dimensions of the model considered to study the effect of the residual stress are shown in **Fig.3**. The flat plate is loaded by force applied on the edge of the plate to introduce the specified value of stress. Then, the line-heating process by the gas torch is simulated. The direction of the heating is perpendicular to the direction of the stress. When the heating is completed and the temperature of the plate reduced to the room temperature, the applied force is released and the residual deformations are examined. The range of membrane residual stress, σ_R , is from -5 to +5 kgf/mm^2. Also, the two types of heating which are the same as the case with initial curvature are used for the plate with initial stress.

The distributions of the transverse plastic strain on the middle section of the plate are shown in **Fig.4** for three values of initial stress. These distributions of plastic strain shown in Fig.4 are the computed results for the inplane type of heating. It can be seen that there is a slight change in the plastic strain distribution with the membrane residual stress of $\pm$ 5.0 kgf/mm^2.

The change in the inherent deformation produced by the heating line with the membrane initial stress are

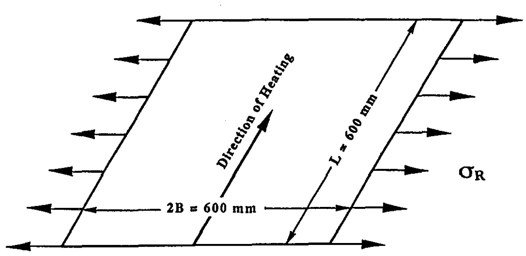


Fig.3 Line-heating model with initial stress.

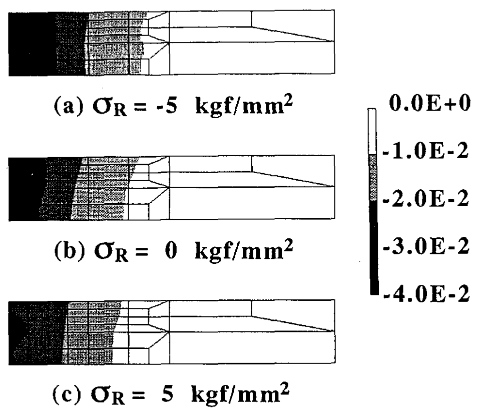


Fig.4 Distribution of plastic strain componentsin transverse direction created by line-heating under stress.

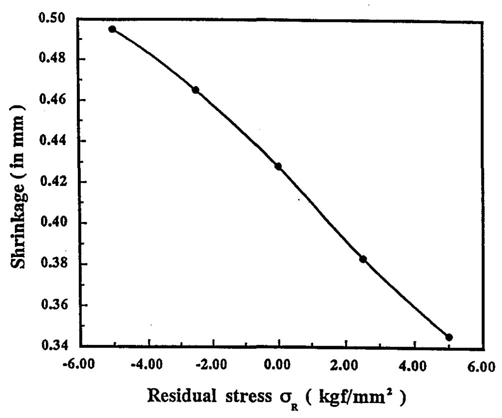


Fig.5 Effect of initial stress on shrinkage created by line-heating.

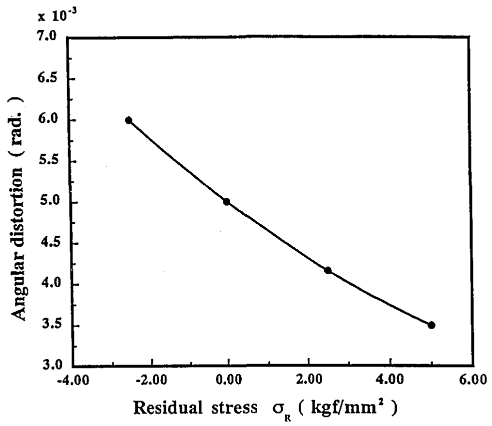


Fig.6 Effect of initial stress on angular distortion created by line-heating.

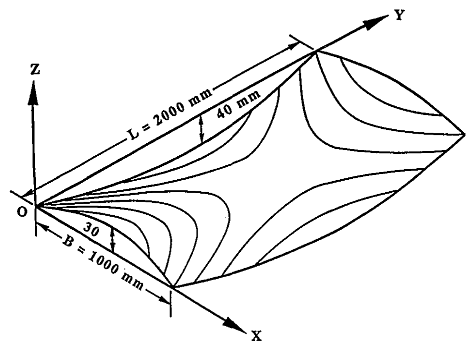


Fig.7 Shape of curved plate to be achieved by line-heating.

summarized in **Figs.5** and **6**. The effect of the initial stress on the shrinkage created by the inplane type of line-heating is shown in Fig.5. It can be seen from this figure that the maximum effect of the membrane residual stress, in the case of $\sigma_R = 5$ kgf/mm^2, can reach about 20 % of that for ideal plate without residual stress. Similarly, the effect of membrane initial stress on the angular distortion created by the bending type of line-heating is shown in Fig.6. The influence of membrane initial stress on the bending deformation is relatively large. If the initial stress σ_R is equal to 5 kgf/mm^2, the angular distortion decreases by about 30 % than that without residual stress. However, the magnitude of the membrane residual stress in the real situations is smaller than the value assumed here. Therefore, the effect of the membrane residual stress on the bending inherent deformation is expected to be small. Thus, the information about inherent deformations predicted for flat plate without residual stress can be also used as an approximation for the plates with residual stresses.

3. Method to Generate Orthogonal Compressive Inherent Strain

3.1 Example model and inherent strain distribution

A saddle shape is chosen as an example and the dimensions of the model are 2000 × 1000 × 16 mm as shown in **Fig.7**. The deflection of the saddle shape is given by the following equation,

$$w(x,y) = g(y)\, f(x) + h(y) \tag{1}$$

where,

$$g(y) = 1 - 0.16666667\times10^{-3}\times y$$
$$f(x) = (-4.897459443\times10^{-8}) \times(x-1000)(x+1925)\ x$$
$$h(y) = (8.162432405\times10^{-9}) \times(y-2000)(y+3850)\ y$$

The Finite Element Method is used to get the inherent strain distribution. The plate is forced to deform to the final shape and the bending and the inplane inherent strains are computed. The distributions of the principal bending and inplane inherent strains, ε^b and ε^m, for the saddle shape are shown in **Figs.8** and **9**, respectively. The direction of the bending inherent strain is nearly in one direction and it is assumed that this bending inherent strain can be produced by mechanical forming process. As seen from the inplane inherent strain shown in Fig.9, compressive strain component is observed in the middle of the plate. Such compressive component can be created using the line-heating method. However the tensile component in y-direction appearing along the edges is impossible to produce by the line-heating method. Consequently, a method to generate orthogonal compressive inplane inherent strain, eliminating the tensile and the shear inherent strains which is not obtainable by the line-heating, must be developed.

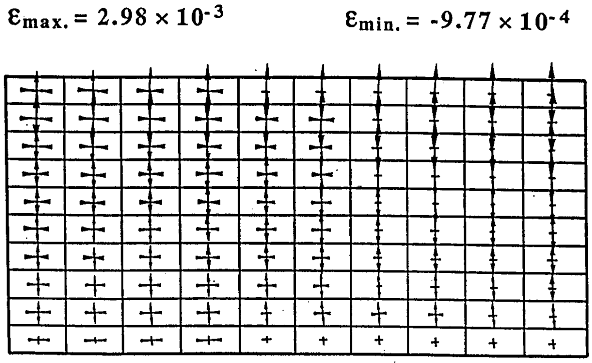


Fig.8 Bending inherent strain distribution which is necessary to form plate.

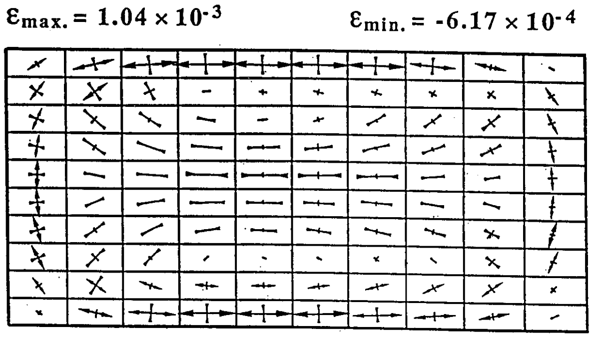


Fig.9 Inplane inherent strain distribution which is necessary to form plate.

3.2 Proposed method

The proposed method of generating the orthogonal compressive inplane inherent strain distribution is based on the idea that the inherent strain distribution to produce the given geometry is not unique. Thus, if the orthogonal inplane strain field without tensile and shear components which produce the desired geometry without residual stress is generated, such inherent strain field is the one which can be realized by line-heating method.

The Finite Element Method is used to prove the possibility of generating orthogonal compressive inplane strain which is attainable by the line-heating. The created compressive components of the inplane strain, in x and y directions, given in Fig.9 are taken as the first approximation and modified through iterative computation as described as follows:

(1) The plate is deformed elastically from its initial shape to the final geometry to be achieved using the Finite Element Method and the components of the inplane strain are computed. Only the negative orthogonal components, in x and y directions, are taken as the first approximation of the inherent strain, ε^*_{mx} and ε^*_{my}, and the other components are set equal to zero such as,

$$
\begin{aligned}
\varepsilon^*_{mx} &= 0.0 && \text{when} \quad \varepsilon_{mx} > 0.0\\
\varepsilon^*_{my} &= 0.0 && \text{when} \quad \varepsilon_{my} > 0.0\\
\varepsilon^*_{mx} &= \varepsilon_{mx} && \text{when} \quad \varepsilon_{mx} < 0.0\\
\varepsilon^*_{my} &= \varepsilon_{my} && \text{when} \quad \varepsilon_{my} < 0.0\\
\gamma^*_{mxy} &= 0.0
\end{aligned}
$$

(2) The orthogonal compressive inplane inherent strain components ε^*_{mx} and ε^*_{my} obtained at the preceding step are applied to the plate as the initial strain and the plate is forced to deform elastically to the final shape at the same time. If the inherent strains, ε^*_{mx} and ε^*_{my}, are compatible and produce the given geometry, no elastic strain or stress in the inplane direction is produced in this process. Thus, the elastic strains produced, $\Delta\varepsilon_{mx}$, $\Delta\varepsilon_{my}$ and $\Delta\gamma_{mxy}$, in this process are considered as the correction to the inherent strain ε^*_{mx} and ε^*_{my}. In this correction, only the compressive components of $\Delta\varepsilon^*_{mx}$ and $\Delta\varepsilon^*_{my}$ are considered such that,

$$
\begin{aligned}
\Delta\varepsilon^*_{mx} &= 0.0 && \text{when} \quad \Delta\varepsilon_{mx} > 0.0\\
\Delta\varepsilon^*_{my} &= 0.0 && \text{when} \quad \Delta\varepsilon_{my} > 0.0\\
\Delta\varepsilon^*_{mx} &= \Delta\varepsilon_{mx} && \text{when} \quad \Delta\varepsilon_{mx} < 0.0\\
\Delta\varepsilon^*_{my} &= \Delta\varepsilon_{my} && \text{when} \quad \Delta\varepsilon_{my} < 0.0\\
\Delta\gamma^*_{mxy} &= 0.0
\end{aligned}
$$

Then, the new values of the inherent strains are obtained as,

$$(\varepsilon^*_{mx})_{new} = (\varepsilon^*_{mx})_{old} + \Delta\varepsilon^*_{mx} \tag{2}$$

$$(\varepsilon^*_{my})_{new} = (\varepsilon^*_{my})_{old} + \Delta\varepsilon^*_{my} \tag{3}$$

(3) Repeating step (2) till the magnitude of the correction as well as the residual stress become negligible. The inherent strain obtained through this procedure is orthogonal, compressive and compatible. If the strain is compatible, all the strain is transformed into the deformation and no residual stress is produced.

3.3 Numerical example

To examine the validity of the proposed method, the saddle shape is considered here. Applying the same procedure described in the preceding section, the computed results of the orthogonal compressive inplane inherent strain distribution is shown in **Fig.10**. It is clear from this figure that only two components of the compressive inplane inherent strains, ε^*_{mx} and ε^*_{my}, are generated. The tensile and the shear strain components are removed. While, the bending inherent strain distribution and its magnitude are kept unchanged. Applying both the bending and the orthogonal

$\varepsilon_{min.} = -2.07 \times 10^{-3}$

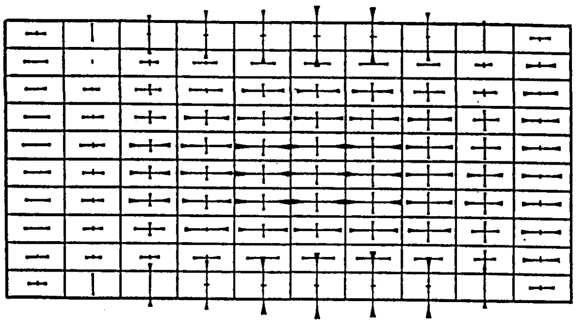
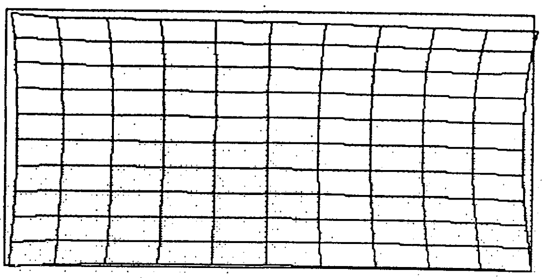


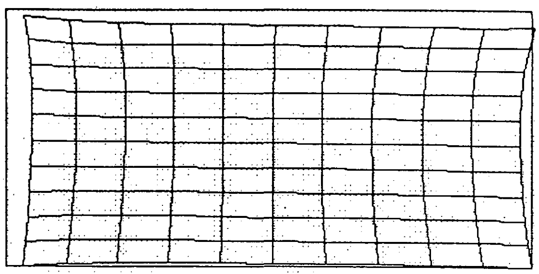
Fig.10 Distribution of orthgonal compressive inplane inherent.

Table 3 Error in geometry in plate with distributed inherent strain under free deformation.

Models	Desired shape	Distributed inherent strain without shear	Absolute value of error in geometry
w_{max} (mm)	30.0	29.98	0.067 %
w_{min} (mm)	-40.0	-39.64	0.900 %



(a) Under forced deformation.



(b) With orthogonal inplate inherent strain.

Fig.11 Inplane shrinkage of plate.

compressive inplane inherent strains to the flat plate, the geometrical error of the plate under stress free state is 0.90 % as shown in **Table 3**. The produced deformation in the in-plane direction due to the new distribution of orthogonal inplane inherent strain is shown in **Fig.11** compared with that of the plate under the forced elastic deformation. The magnitude of the inplane deformation in the length direction for the forced deformation is 1.6 mm and that produced by the orthogonal distribution is 3.5 mm. This means that the change in the inplane deformation is negligibly small compared to the deflection of the plate. Thus, the proposed method can be used to determine an orthogonal compressive inplane strain distribution.

The distributions of Mises stress produced by simply forcing the plate to deform to the final geometry and by giving the orthogonal inplane inherent strain and the bending inherent strain to the plate in the force free state are shown in **Figs.12** and **13**. The maximum value of the Mises stress for the case of forced deformation, σ_{max} , is 22.0 kgf/mm^2, as shown in Fig.12. On the other hand, the maximum value of Mises stress caused by the orthogonal inplane strain distribution is equal to 0.947 kgf/mm^2. This means that a stress free state can be achieved using the orthogonal compressive inplane inherent strain. The number of iterations, N, to get this value of the residual stress is 100. The relation between the number of iterations, N, and Mises residual stress, σ_{max}, is shown in **Fig.14**. It

σ_{max} = **22.0 kgf/mm²**

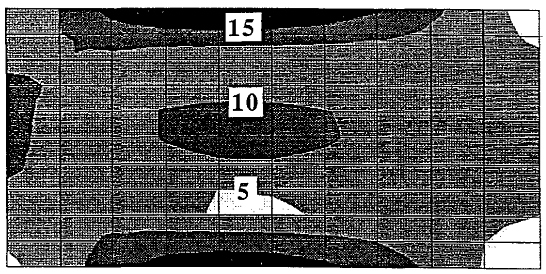


Fig.12 Distribution of Mises stress in plate under forced deformation.

σ_{max} = **0.947 kgf/mm²**

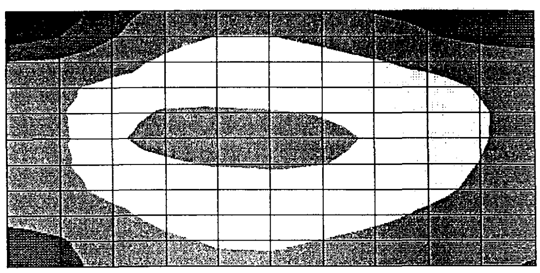


Fig.13 Distribution of Mises stress in plate with orthogonal inplate inherent strain under free deformation.

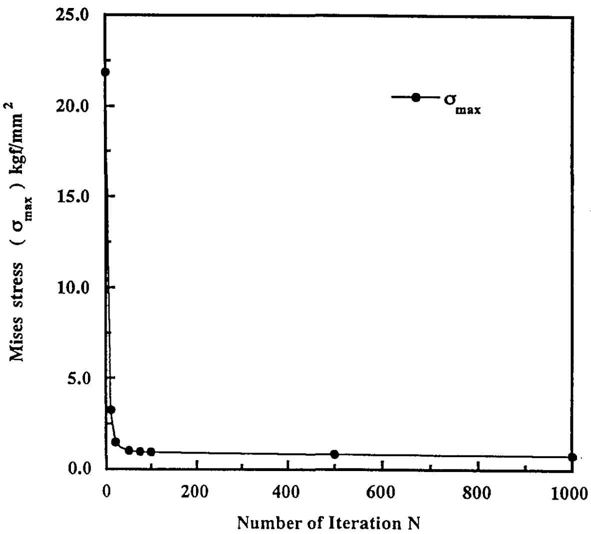


Fig.14 Relation between maximum value of residual stress and number of iterations.

$\varepsilon_{min.} = -2.21 \times 10^{-2}$

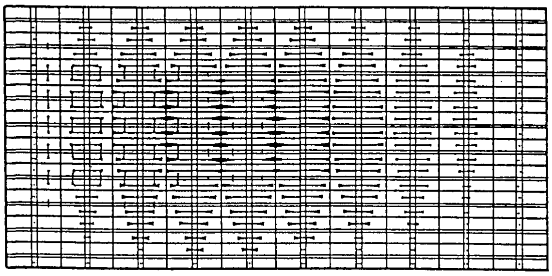


Fig.15 Compressive inplane inherent strain concentration in grid form.

Table 4 Error in geometry in plate with grid form concentrated inherent strain under deformation.

Models	Desired shape	Concentrated inherent strain in grid form	Absolute value of error in geometry
w_{max} (mm)	30.0	30.29	0.967 %
w_{min} (mm)	-40.0	-40.39	0.975 %

can be seen from this figure that the value of the residual stress decreases as the number of the iteration N increases and the orthogonal compressive inplane strain field which produces nearly stress free state can be achieved by the proposed method.

4. Concentration of Inherent Strain into Heating Lines

$\sigma_{max.} = 0.403$ kgf/mm²

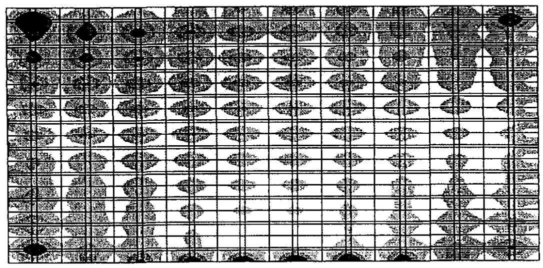


Fig.16 Distribution of Mises stress in plate with grid form concentrated inherent strain under free deformation.

The compressive orthogonal inherent strain obtained in the preceding section is continuously distributing. However, in the actual line-heating process, the inherent strain is concentrated along the heating line. Such concentrated inherent strain distribution can be obtained by FEM in the following manner. First, introduce elements representing the heating line and concentrate the inherent strain in these elements. The strain can be concentrated by assuming very small Young's modulus, such as 1/1000 of the ordinary value, for elements in the heating lines. The computation of the inherent strain is done in the same manner as described in the method proposed for generating orthogonal compressive inplane inherent strain.

4.1 Heating lines with grid form

The saddle shape is used to demonstrate the above mentioned idea. The directions of heating are supposed to be the same as the directions of x and y axes and the elements for the heating lines are distributed as a grid as shown in **Fig.15**. The same procedure applied in obtaining the orthogonal inherent strain is employed. The magnitude of the concentrated inplane inherent strain are shown by arrows in Fig.15. It can be seen from the figure that the resulting distribution of the inplane inherent strain is slightly changed compared with Fig.10. The large compressive inherent strain component ε^*_{my} along the edge is removed in Fig.15. The most inplane inherent strain are distributed along the heating lines in the width direction. Assuming that the bending inherent strain can be produced by other forming method and applying this bending inherent strain together with the concentrated orthogonal inplane inherent strain, the error in the geometry of the plate under stress free state is 0.975 % as shown in **Table 4.** The residual Mises stress distribution due to the new concentrated inplane inherent strain is shown in **Fig.16.** The maximum magnitude of the residual

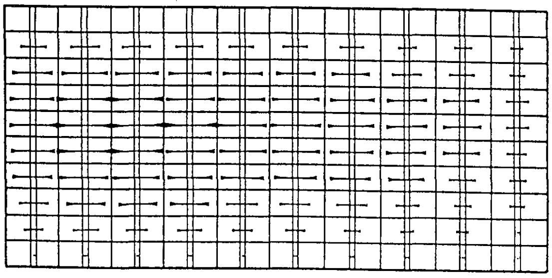


Fig.17 Parallel distribution of concentrated compressive inplane inherent strain.

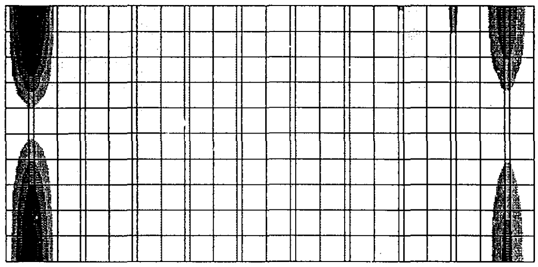


Fig.18 Distribution of Mises stress for parallel distribution of concentrated inherent strain.

Table 5 Error in geometry in plate with inplane inherent strain concentrated in parallel lines.

Models	Desired shape	Concentrated inherent strain in parallel lines	Absolute value of error in geometry
w_{max} (mm)	30.0	29.98	0.067 %
w_{min} (mm)	-40.0	-40.39	0.975 %

stress is 0.403 kgf/mm^2. A stress distribution close to the stress free state can be achieved with the inplane inherent strain concentrated along the grid.

4.2 Parallel heating lines

As observed in Fig.15, the inherent strain distributing along the width direction is dominant. The distribution of the inplane inherent strain concentrated into the parallel heating lines is shown in **Fig.17.** From this figure it is observed that the distribution is shifted slightly toward the left side and the maximum value of the concentrated inplane inherent strain is nearly the same as the grid type concentrated inherent strain. The residual stress distribution due to the concentrated parallel type of the inplane inherent strain is shown in **Fig.18.** A local concentration of the residual stress is observed. This is mainly due to forcing the inplane inherent strain to be concentrated only in one direction. However, the maximum value of residual stress is located in small area compared to the whole area of the plate and its influence may be ignored. By giving this concentrated inplane inherent strain together with the bending inherent strain, the resulting error in the obtained shape is 0.975 % as shown in **Table 5.** Thus, the inplane inherent strain concentrated to the parallel heating lines can also produce the desired form of the plate provided that the bending inherent strain is given by other methods. This agrees with the real practice of plate forming using both the mechanical and line-heating methods effectively to produce 3-dimensional curved plates.

5. Conclusions

The influence of the initial curvature and the residual stress on the inherent deformations are examined through the comparison with the flat plate without residual stress. Since only the compressive inherent strain can be produced by the line-heating, methods to generate compressive orthogonal inherent strain are proposed. The effectiveness of the proposed methods are demonstrated using a saddle shape as an example. Further, the possibility of plate bending by the orthogonal compressive inherent strain concentrated along the grid type and the parallel type of heating lines are examined. Through the present study, the following conclusions are drawn:

(1) The influence of the initial curvature on the shrinkage and the angular distortion is found to be small. Also, the effect of the inplane residual stress on the shrinkage is relatively small while its effect on the angular distortion is relatively large.
(2) Informations about the inherent deformations obtained for the case of flat ideal plate can be used as an approximation for the plates with initial curvature and residual stress in planning the line-heating procedure.
(3) Methods to generate orthogonal compressive inplane inherent stain are proposed. Inherent strains continuously distributed and concentrated in the forms of grid and parallel lines are generated by the proposed method. It is shown that the target shape can be achieved within about 1 % accuracy by these inherent strains. However, small residual stresses which may be caused by ignoring the shear component of the inherent strain are observed in the plates in force free natural state.

(4) If the small error in the geometry and the residual stress with small magnitude are allowed, both the grid type and the parallel type of the line-heating may be employed in the real practice.

(5) The distribution of the concentrated inherent strain can be used to decide the density of heating lines.

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