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Application of flexible forming process to hull structure forming[†]

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Abstract

The conventional line heating method has been applied for the manufacture of various curved blocks used for hull structures in the ship-building industry. However, it has low economical efficiency and productivity because most of its processes are based entirely on the skillful experience of experts. In this study, a flexible forming process is proposed and utilized to substitute for the conventional manual process. In the proposed process, numbers of punches which have round shapes on the contact tip are adopted to configure an equivalent forming surface according to the arbitrarily curved objective surface. A simple punch height determination algorithm that considers the discrete surface and its spatial planar equations is applied to determine the discrete forming surface composed of the adjusted punches. Punch height data are transferred to a numerical simulation model using ANSYS parametric design language, and finite element analysis is conducted to check the formability of the process. Further, experimental investigations are carried out to verify the feasibility of the process using a flexible forming apparatus. Consequently, it is confirmed that a double-curved thick plate could be obtained by the flexible forming process.

Keywords: Flexible forming; Reconfigurable die; Shipbuilding; Hull structure; Thick plate forming

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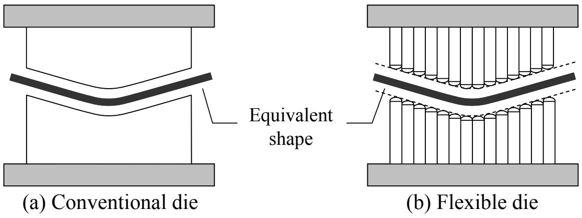
1. Introduction

Large curved plate blocks are widely used to construct hull structures in the shipbuilding industry. Until recently, most blocks were manufactured using the conventional manual line heating method. In the process, flat or slightly curved plates are heated along specified lines on the plates and then are deformed by residual stress due to thermal deformation [1]. This procedure, however, has low productivity, is ineffective, and is economically taxing because all the processes involved in the procedure are done by experts based on their experience. Moreover, the supply of new manpower required for the manufacturing process has been given great consideration as well.

A flexible forming process using a number of movable punches which have round tips was proposed to solve these problems [2-5]. The flexible die concept was proposed to substitute for the various conventional one-shot milled dies as shown in Fig. 1. In this process, the curved plates are manufactured by a high-pressure hydraulic press as a general sheet forming process using matched dies [6, 7]. The punches would be controlled to determine an equivalent forming surface for an arbitrary objective surface [8]. This has remarkable advantages in view of flexibility and productivity. The flexible forming apparatus has a reconfigurable die. Thus, various forming shapes could be configured by only adjusting the heights of the punch elements. Real time modification of the die shape during the forming process could be achieved by its reconfigurability. Moreover, large plates which have larger areas than those of the once-forming areas of the forming apparatus could also be manufactured by adopting the repeated sequential forming process. In this study, a relatively simple punch height calculation algorithm is developed. In this algorithm, virtual offset surfaces and planar equation are considered to determine the punch heights. Furthermore, numerical and experimental approaches are implemented to verify the feasibility of the forming process. From the results, curvature radii and deformed shapes are compared. Consequently, it was confirmed that the proposed flexible forming



(a) Conventional die
(b) Flexible die

Fig. 1. Schematic diagram of conventional solid and equivalent flexible dies.

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technology has enough feasibility as a new approach for application in thick plate forming in shipbuilding structures as compared to the expensive and laborious conventional line heating method.

2. Flexible forming tool

The flexible forming apparatus includes a number of arrayed punches, which configure to the forming surface, instead of the conventional matched die set. As shown in Fig. 2, each punch has a partial hemi-spherical shape to cover various contact angles. The punch has a screw type assembly that consists of an inner bolt and an outer nut. Thus, its length could be adjusted by revolving the bolt type structure. Four punches can be adjusted at once by adopting the movable control module.

The punch tip radius, ***r***, and punch width, ***w***, are both 50*mm*, and the stroke length could be adjusted by about 200*mm*. The net forming area of the apparatus is about 800×600mm^2, with 192 (16×12) punches for each die. Thus, a total of 384 punches were used in the forming apparatus. The flexible die sets are equipped with a 2,000*k*N hydraulic press unit that can be used to bend thick steel plates with thicknesses of up to 25.0*mm*.

3. Determination of the punch height and its application in the finite element analysis model

3.1 Punch height calculation

In the case of contact between the punch tip and objective surface, every punch tip surface can be considered as an inscribed circle or sphere as shown in Fig. 3.

On this occasion, the centers of each punch are to be aligned on specific spatial surfaces designated as virtual surfaces, which are obtained from the objective surfaces by offsetting the distance of the punch tip radius, ***r***. Thus, punch height data can be calculated when all punches are in contact with the objective surface by considering the geometrical relationship between the centers of all punches and the virtual offset surface.

In this study, meshed offset surface patches are implemented to determine punch height using the above relationship. The offset surface was discretized into patches including nodal connectivity, and every patch was considered to be a spatial plane that could be determined by the planar equation based on the spatial coordinates, n_i (x_i, y_i, z_i) of the three nodal points on the patch. The target height, z, for a punch can be expressed in the following relationships using the planar equation:

$$F(x-x_1)+G(y-y_1)+H(z-z_1)=0 \quad \text{or}$$

$$z=\frac{-F(x-x_1)-G(y-y_1)+Hz_1}{H} \tag{1}$$

where $F=(y_2-y_1)(z_4-z_1)-(y_4-y_1)(z_2-z_1)$,

$G=(x_4-x_1)(z_2-z_1)-(x_2-x_1)(z_4-z_1)$, and

$H=(x_2-x_1)(y_4-y_1)-(x_4-x_1)(y_2-y_1)$.

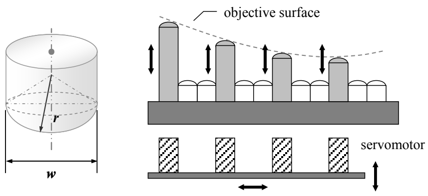


Fig. 2. Features of the punch tip shape and principal of the punch height control module including a movable servomotor.

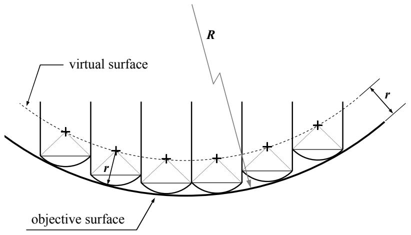


Fig. 3. Features of the punch tip shape and principal of the punch height control module including a movable servomotor.

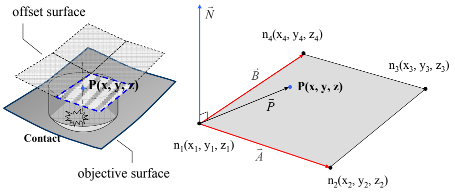


Fig. 4. Determination of punch height using the planar equation of the patch.

3.2 Construction of the finite element model

In this study, a saddle-type thick plate was selected as a candidate for part of the hull structure. Punch height data were obtained using the above algorithm and transferred to the preprocessor of ANSYS using its own parametric design language which offers a convenient handling method for array-type data in the modeling procedure. The variational formulation for the principle of virtual work could be written as follows:

$$\delta\pi=\int_V \rho\ddot{x}_i\delta x_i dV+\int_V \sigma_{ij}\delta_{i,j} dV-\int_V \rho f_i \delta x_i dV-\int_{S_t} t_i\delta x_i dS \tag{2}$$

where x_i is the current coordinate system, σ_{ij} is the Cauchy stress, ρ is the current density, f_i is the body force, and the comma denotes covariant differentiation. S_t is the traction boundary where the traction vector x_i is specified.

Fig. 5 shows the configuration of the target shape plate and its analysis model for the flexible forming process. The plate material was AH-32 steel. Its flow stress in the plastic strain region can be expressed as $\bar{\sigma}=K\bar{\varepsilon}^n$, where the plastic strength coefficient, K, and the work hardening exponential, n, are 790.5MPa and 0.168, respectively. The elastic material proper- ties, including the elastic modulus and Poisson's ratio, were 210GPa and 0.29, respectively. The generally used density of the steel material, 7.85×10^{-6}kg/mm^3, was used. The required saddle plate had doubly curved radii measuring 1,600*mm* (A-A' direction) and 1,400*mm* (B-B' direction) along the length and width, respectively. The initial blank size was

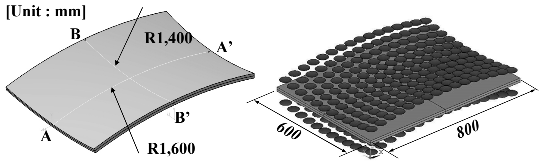
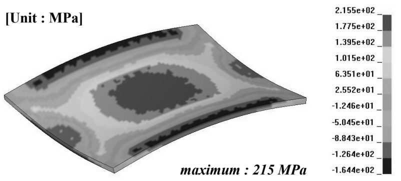
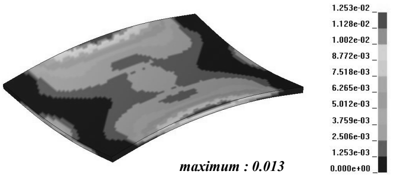


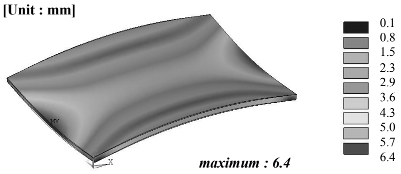
Fig. 5. Configuration of the target shape and its main dimensions.



(a) Pressure distribution



(b) Strain distribution



(c) Spring-back distribution

Fig. 6. Numerical simulation results for the flexible forming process.

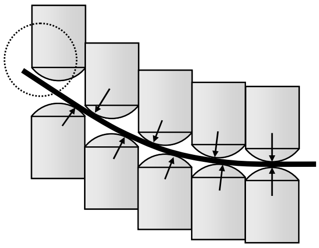


Fig. 7. Forming error due to incomplete contact at the boundary region of the plate.

800×600mm^2, almost similar to the net forming area of the forming apparatus, and its thickness is 20.0*mm*. The punch is assumed to be a rigid body, and thus only the punch tip surfaces were considered as tool models. The friction coefficient between the blank material and the punches was assumed to be 0.05. This means that the flexible forming process is almost similar to the frictionless process because flexible forming is performed by point contact, as opposed to conventional forming processes which are done by surface contact. Numerical simulations for the flexible forming process were carried out by using an LS-DYNA solver which is based on the explicit scheme. Spring-back simulations were also conducted using ANSYS based on the implicit scheme.

3.3 Numerical simulation results

Figs. 6(a), (b), and (c) show the pressure and effective strain at the end of the metal forming process and the spring-back distributions under the unloaded state. It is remarkable that the pressure distribution is not smooth but is discrete. This is likely due to the concentration of the forming load at the contact points of the punch tips (see Fig. 6(a)). Maximum pressure is concentrated at the center of the plate because the forming load is mainly transferred to the region that undergoes first contact at the beginning of the forming process. Similarly, the strain also shows a little rough distribution at the boundary of the plate because the punch array could not support the deformation observed due to considerable gaps between punches (see Fig. 6(b)).

Curvature radii along the lengthwise and widthwise directions were investigated to confirm the forming accuracy. The curvature radius in section A-A' was measured as 1,640*mm*, which has about 2.5% error with regard to the target shape. In section B-B', the curvature radius was measured as 1,518*mm*, with about 8.4% shape error. These errors could be considered as an inevitable characteristic of the “straight effect” of the flexible forming process as shown in Fig. 7. The required forming surface could not be formed accurately due to the straight effect at the boundary of the blank, which is marked with a dotted line. Another reason for the error may be attributed to a high elastic recovery due to the high bending moment along the A-A' direction. However, the curvature radii are quite large for most curved plates used in hull structures. Thus, the forming errors could be neglected. Finally, spring-back analysis was carried out by adopting an explicit-to-implicit sequential simulation scheme. As shown in Fig. 6(c), maximum spring-back displacement was observed at about 6.4*mm*. Similarly, the curvature radii of the spring-back simulation result were also measured as 1,730*mm* in section A-A’ and 2,010*mm* in section B-B'.

4. Experiments

A forming experiment using the flexible forming apparatus was carried out to manufacture a saddle-type thick steel plate. For the given saddle type surface, the punch height of each punch was calculated by using the offset scheme described above. The calculated punch height data were transferred to the servo motor control system. Each punch has a screw type assembly in which the length of the punch is adjusted by revolving the screw. Therefore, punch heights could be adjusted by revolving the punch screw of all punch elements, consider ing the relationship between the target length and the revolutions of the screw. The adjusted punches are shown in Fig. 8. In the experiment, 10.0*mm* urethane sheets, which have a shore-A hardness of 90, were inserted between the punches and the blank to prevent scratches or defects from forming on the material and the punch tips. The thickness of the elastic cushions was also considered in the punch height calculation procedure because the forming surface would be offset from the mid-surface of the objective surface. The initial blank size,

Fig. 8. Forming test for a saddle type plate using a flexible forming apparatus.

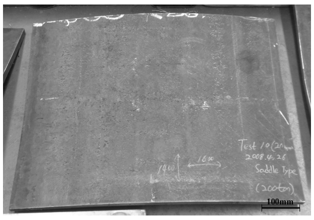


Fig. 9. Forming test for a saddle type plate using a flexible forming apparatus.

as mentioned above, was 800×600mm^2, and its thickness was 20.0*mm*. Fig. 9 shows the configuration of the manufactured saddle-type plate. No defects visible to the naked eye were observed. To compare the product with the simulation results, the curvature radii of the product were also measured. The values 1,786*mm* in section A-A' and 2,071*mm* in section B-B' were obtained. Thus, it was verified that the simulation results matched those that obtained from the experiment and that the flexible forming process can be applied for the manufacture of the slightly curved plate parts of hull structures used in ship-building.

5. Conclusions

In this study, a flexible forming process is applied for the manufacture of double-curved thick plates used in hull structures in ship-building. The flexible forming technology provides high flexibility in the configuration of the forming tool due to a number of punches involved as compared to that observed for the conventional matched die set. In the flexible forming process, punch height calculation is one of the most important parameters. Based on the geometrical relationship between an arbitrarily curved surface and spherical surface, a simple punch height calculation scheme using the discrete virtual offset surface and planar equation is developed to determine the proper height for the objective surface. As an example, a saddle-type plate was applied to verify the feasibility of the flexible forming process. Numerical simulations and experiments were carried out using a 20.0*mm*-thick steel plate. In the simulation, the “straight effect,” which causes an inevitable forming error at the boundary of the plate, was observed. The errors were negligible, however, considering the slightly curved shape of the product. Correlation between the simulation and experimental results was obtained in view of the curvature radii along both main cross sections in the mid-surface. We confirmed that the flexible forming process is capable of substituting for the conventional line heating method.

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