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ORIGINAL ARTICLE

A study on thick plate forming using flexible forming process and its application to a simply curved plate

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Abstract In this study, design and fabrication of a flexible forming machine are carried out for the purpose of manufacturing a prototype of curved plate block for hull structure used in shipbuilding industry. Flexible forming dies which consist of numbers of punches in an array form for upper and lower sides are designed in view of thick plate forming. A punch has formation of male and female screws to adjust its length with regard to a given surface, and all punches are supported by each other in punch housing. Software for process configuration and punch control are developed to operate the novel flexible forming machine. The software are composed of the punch height calculation part which uses an offset surface scheme. Prior to manufacturing of a prototype, numerical simulations for a saddle-typed thick plate forming process including metal forming and spring-back analyses are carried out to predict the forming performance. Experiments are also carried out to validate and confirm the feasibility of flexible forming technology in view of practical application of thick plate forming process. Curvature radii observed in the simulation and experiment are investigated and compared. Consequently, development and practical application of flexible forming technology to the thick plate forming process are described from design of the forming machine to manufacturing of the prototype. It is confirmed that the flexible forming technology suggested in this study has enough feasibility in new application of thick plate forming in shipbuilding structures which has been formed through expensive and laborious conventional line heating.

Keywords Flexible forming process · Flexible die · Reconfigurable die · Thick plate forming · Finite element analysis · Shipbuilding

1 Introduction

Nowadays, demand of advanced manufacturing technology especially related with higher value-added ships has been increased in shipbuilding industry. Nevertheless, until now, various types of large curved blocks used in hull structure have been made by conventional line heating method which is based on inefficient manual trial-and-error procedure by experts. Heat source is used in line heating method to induce thermal deformation due to residual stress after heating along specified heating lines on the plate [1]. However, it has low productivity because it is dependent on the experience of experts. In addition, unexpected errors in dimension such as curvature radii on a deformed plate can be accumulated during the process because it is entirely based on experience of technical experts. Recently, manpower required for the manual manufacturing process is an additional burden in shipbuilding industry because its working environment is quite poor by reason of flash, noise, and heat.

Desirably, a forming process using matched dies is the best way to solve the problems of time consumption and quality control in manufacturing. However, the die forming

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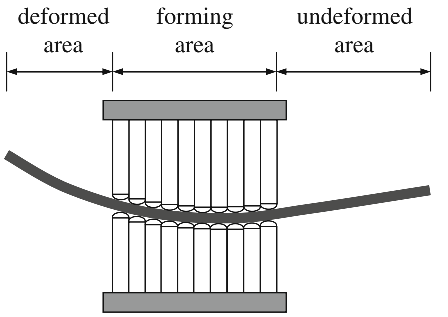
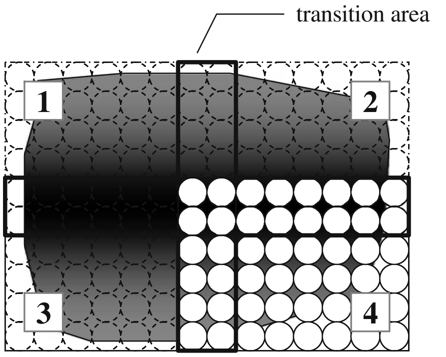
method is appropriate for mass production such as in the automobile industry because tooling cost for a part is expensive. Thus, it cannot be adapted to shipbuilding which is based on small quantity batch production. Normally, various curved plates used in hull structure are huge and heavy but those have slight deformation due to large curvature radii but also thickness of the blank is maintained as uniform level. For that reason, flexible forming technology for curved plates which have large curvature radii was arisen in previous researches to apply the die forming method to small quantity production industry as shown in Fig. 1 [2]. In a flexible forming die, punches are used to form an equivalent discrete forming surface which is made up of contact points at the tips of punches instead of the one-pieced die. The most remarkable advantage of the flexible forming technology is the flexibility that makes it easier to change the tool shape during the repeated tryout procedures in the manufacturing fields to obtain required configuration considering the compensation of spring-back amount without additional machining and cost in contrast to the conventional one. Moreover, numerous kinds of curved plates can be manufactured by using only one forming machine. Large blocks, which have larger area in comparing with forming area of the flexible die, can be also manufactured by adopting the sectional forming process as shown in Fig. 2 [3].

Previous studies related with the flexible forming technology dealt with several topics for thin plate forming processes including process design, sectional forming process using non-uniform rational B-spline, path-forming process, implementation of finite element method, and application to thin sheet metal forming process using blank holder [3–9]. As for an analogous approach, Zhang proposed multi-point sandwich-forming process using die sheet, multi-point die, elastic upper die, and interpolator as shown in Fig. 3(a) [10–12]. In the process, too many tool sets are required and some of them such as die sheet and elastic upper die are only able to be used once because a metallic die sheet would be deformed permanently and various shapes of elastic upper die should be designed for different parts. In a different way, an incremental roll-forming method focused on the doubly curved thick plate forming process for manufacture of the hull structures was proposed as shown in Fig. 3b [13, 14]. In the forming process, a movable center roll which bends a blank and four adjustable bearing type support rolls were used as a set of tools. Because the forming method is similar with simple bending process, forming shapes would be limited within the convex and saddle-type except the twist type plate. Park also proposed similar forming process using upper flexible die which consists of equivalent die surface and lower fluid or elastomer die which sustains forming load instead of solid die [15]. However, implementation of thick plate forming for practical application to shipbuilding has not been included in the previous studies. In this study, development of flexible forming apparatus and

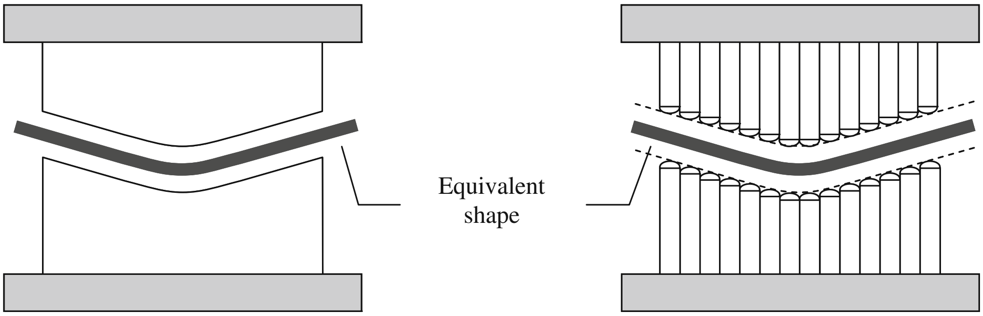


(a) illustration of sectional forming process



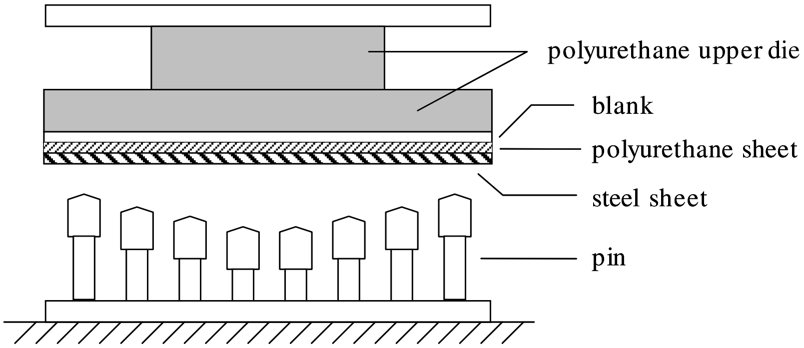
(b) concept of sectional forming 1,2,3 and 4 with transition area

Fig. 2 Schematic diagram of sectional forming process using flexible die for manufacturing of large plate

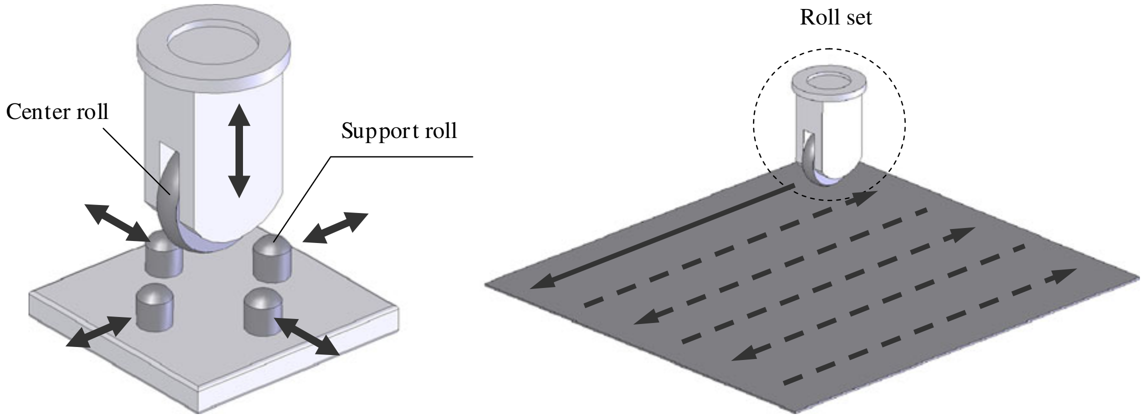


(a) conventional die forming (b) flexible forming

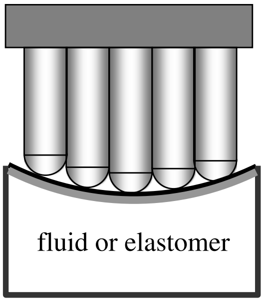
Fig. 1 Schematic diagram of flexible forming process in comparing with conventional die forming



(a) multi-point sandwich forming



(b) incremental roll forming



(c) fluid dieless forming

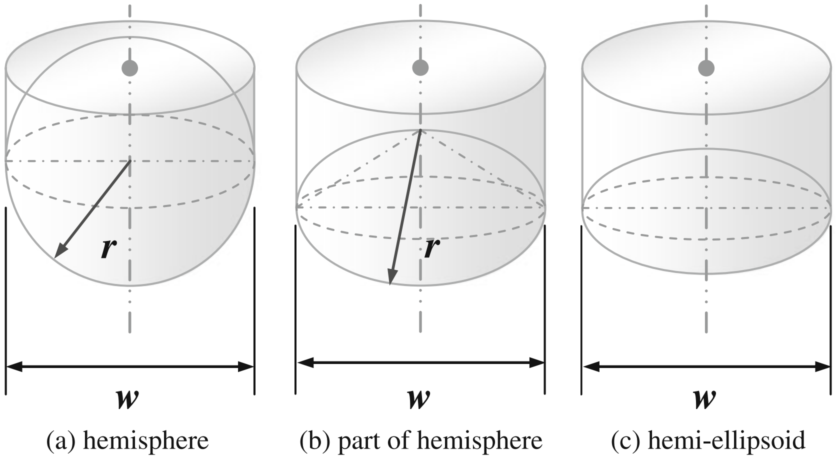
Fig. 3 Various flexible forming methods for manufacturing of curved plate [10–15]

numerical and experimental confirmation for a saddle-typed prototype focused on manufacturing of thick-curved steel plates used in hull structures are conducted.

2 Design and fabrication of flexible forming equipment

2.1 Development of flexible forming apparatus

There are two major forming methods in conceptual design level of flexible forming [3]. The first one is fixed punch forming process in which punches are adjusted to the determined height to form an equivalent forming surface before the forming process is started. The other is varying path flexible forming process in which punches are adjusted during the whole forming process and it would be moved to equivalent surface level at the end of the process. In view of formability, the varying path flexible forming process would be better because contact between punches and blank material is maintained during the forming process so that forming load can be transferred more smoothly and uniformly in comparing with the fixed punch forming process. So dimpling on the blank would occur less in varying path flexible forming process due to decentralization of forming load. However, complicated mechanical systems, such as separately operated hydraulic servo



(a) hemisphere (b) part of hemisphere (c) hemi-ellipsoid

Fig. 4 Configuration of various punch tip shapes

equipments for every punch to control punch speed during the forming process is required because both the accurate punch height and sustainable forming load should be controlled simultaneously. Even if the complicated control system is developed, too high tooling cost will be needed to fabricate the apparatus because a number of control hardware should be equipped with all punches to adjust the punches separately. On the other hand, tooling cost in fixed punch forming process would be decreased because control equipments for adjusting the punch height should not be equipped with all punches. In the process, punches are fixed during the forming process, thus only one punch or several punches can be adjusted along longitudinal and width-wise directions at once before the forming process although it might have the possibility of forming load concentration due to sequential contact. In this study, the fixed punch forming method is selected on account of controllability and economic application.

In flexible forming process, contact between blank material and die is dominated by point-to-surface contact in contrast to conventional die forming in which surface-to-surface contact occurs. Therefore, smooth punch tip shape such as hemisphere, partial hemisphere or hemi-ellipsoid can be used to cover various contact angles at the contact points as shown in Fig. 4a to c. In case of hemisphere-type punch tip (see Fig. 4a), dimpling would be observed more easily on the blank surface due to relatively small curvature radius of the punch tip although it has easier machining for production than the hemi-ellipsoidal one. On the contrary, it is difficult to machine the varying curvature shape in case of the hemi-ellipsoid type punch tip, although it covers various contact angles due to varying curvature radii on the tip. In addition, calculation algorithm of punch height to form an equivalent surface with regard to arbitrarily curved one is simpler in case of spherical punch tip. On that

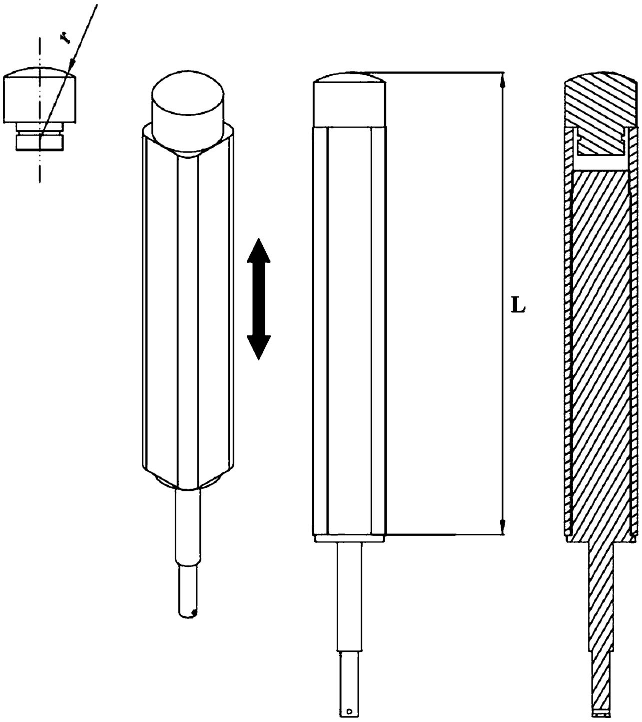


Fig. 5 Configuration and sectional shape of punch

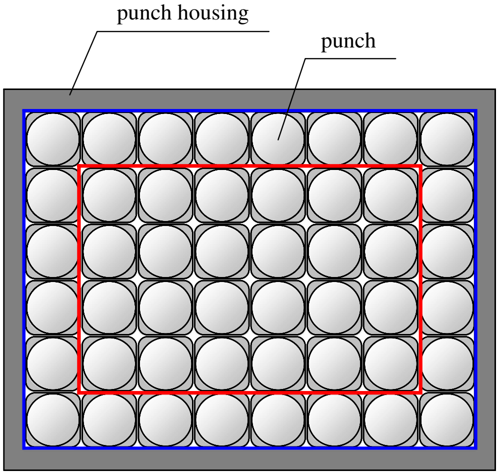


Fig. 6 Constraint condition of punches in flexible die

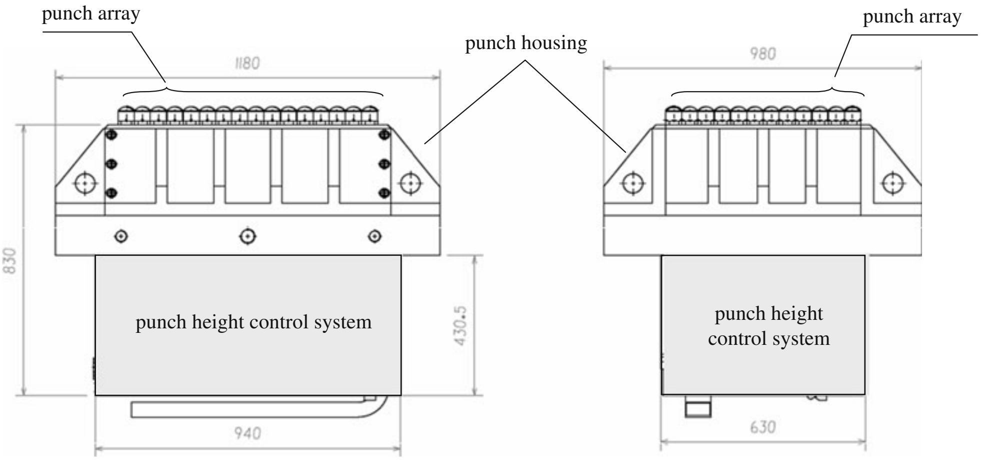
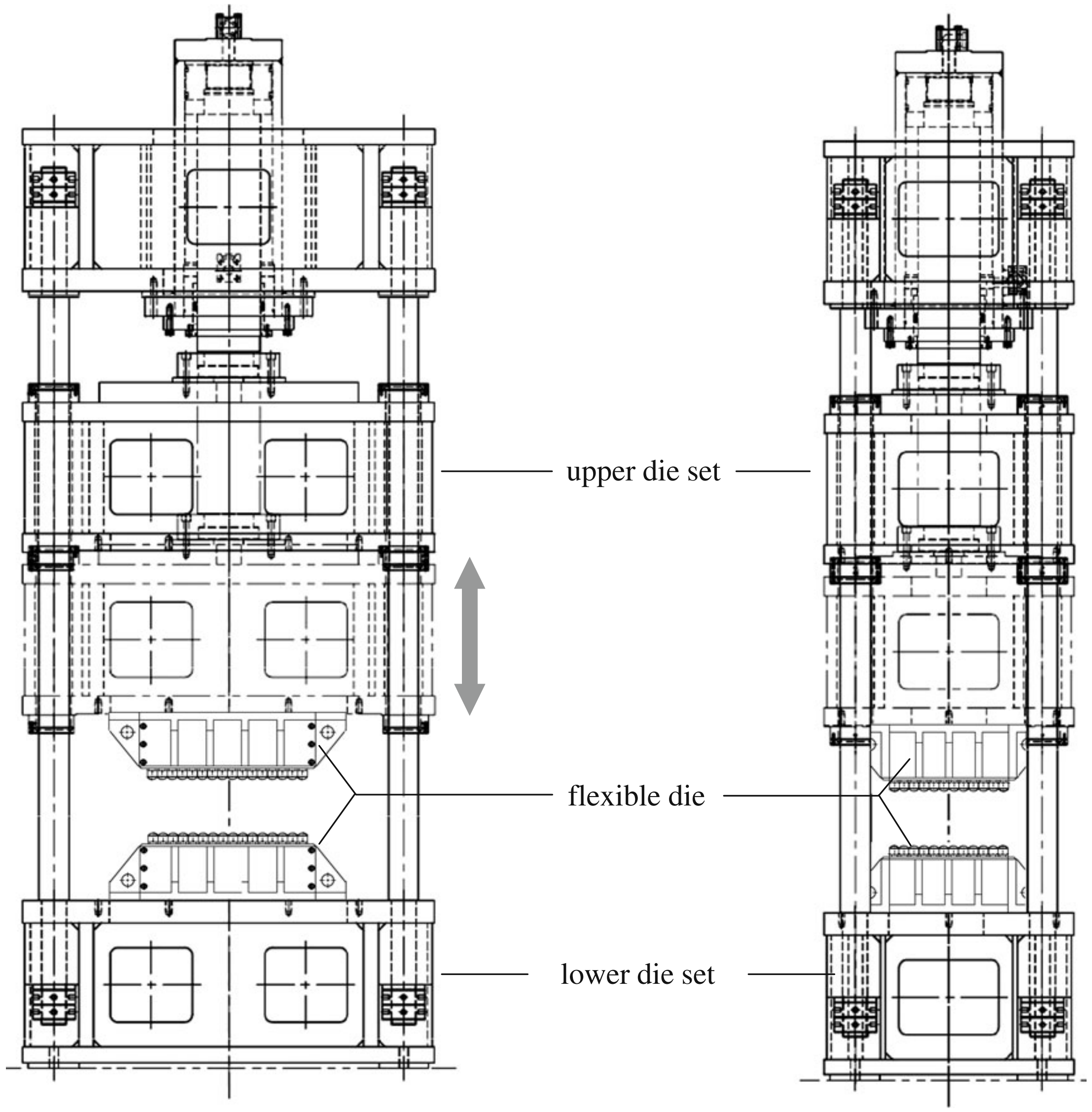


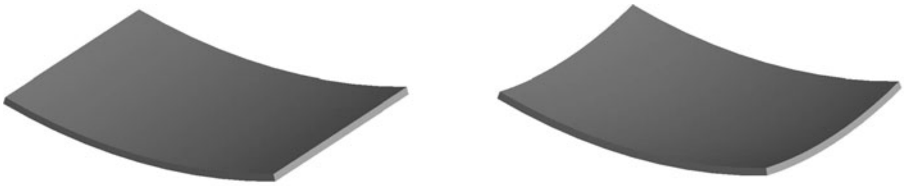
Fig. 7 Configuration of flexible die and composition of punch array [unit: mm]



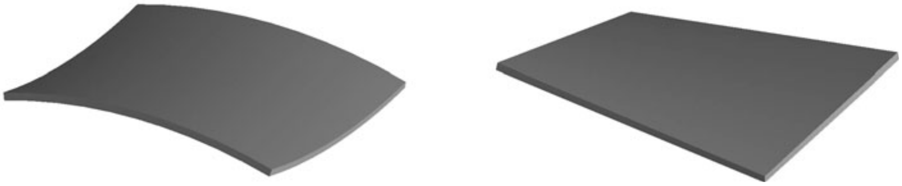
Front view

Side view

Fig. 8 Configuration of flexible forming machine equipped with hydraulic press



(a) cylinder type (b) spherical and convex



(c) saddle type (d) twist type

Fig. 9 Various curvature shapes created by developed modeling software

account, partial spherical type punch tip is selected in view of machining and formability.

Punch tip radius and shape are one of the most important variables in flexible forming process. Number of punches within fixed forming area of a flexible die is determined according to punch width. The forming die has 800× 600 mm^2 in forming area and punch width is 50.0 mm, thus the number of punches are 192 (16×12) for each die. Punch tip radius also affects the surface quality of the product and forming capacity of the machine. Dimpling defects would occur more frequently when smaller radius punches are used but curved plates which have smaller curvature radii would be produced because more punches make it possible to form more curved surface by reason of increase in number of contact points. However, forming capacity related with forming load would be limited due to sustainable structural strength of the punch.

Flexible forming process is based on the use of reconfigurable die which has a number of punches in a matrix array form. The configuration of the flexible die can be simply changed by adjusting the punch height with regard to arbitrary curved surfaces. As shown in Fig. 5, every punch has capability of adjusting the punch length by adopting male and female screw-type assembly and controllable servomotor. A punch consists of three major parts such as punch tip, punch body, and bolt. Punch tip does a role to form equivalent surface and it contacts with blank or elastic pad during the forming process. Punch tip is separately designed to minimize the replacement cost when surface defects or wear on the tip surface are observed. Punch body and bolt have matched thread of screws on the inner and outer surface, respectively, thus length of the punch can be adjusted by revolving punch bolt according to calculated revolutions. As shown in Fig. 6, punch body has rectangular outer section so inner-side punch array can be constrained by each other and boundary punches also can be constrained by a surrounded punch housing along longitudinal and width-wise directions. The punch tip utilized in this study has a curvature radius, r, of 50.0 mm. Punch body has 50.0 mm width, punch length, L, from the punch base to the punch tip is about 320 mm, which was designed to allow that maximum 200.0 mm stroke amount for adjusting the punch length and 80.0 mm joint margin for sustaining forming load. Therefore, punch length would be enlarged to about 520 mm at the maximum value. In the housing, several ribs are added to each side to enhance the structural strength against the side forces caused by bending behavior of punches during the forming process. Figure 7 shows final assembly of flexible die set which has punch array and control module below the punches. Punch control system

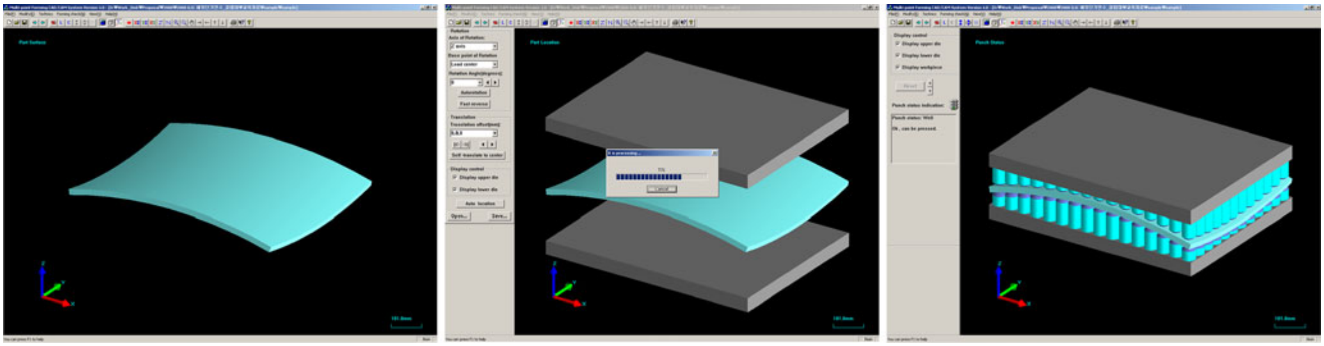


Fig. 10 Three-dimensional display of punch height calculation procedure for saddle-type surface

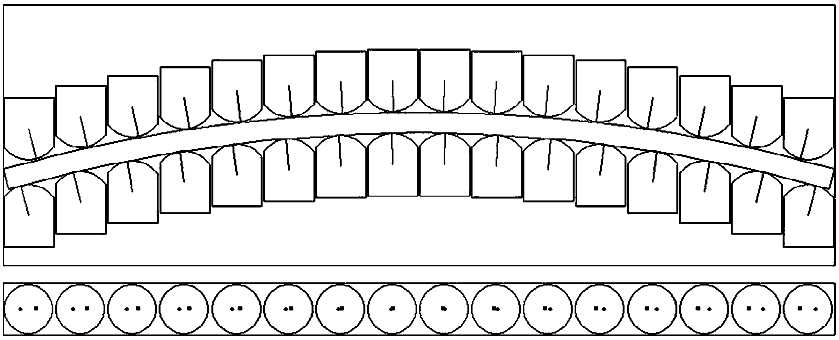


Fig. 11 Three-dimensional display of adjusted punch array for a saddle-typed surface

equipped with flexible die has a height of 430.5 mm. Figure 8 shows configuration of flexible forming press machine which has a height of 4.2 m. Both the upper and lower die sets have considerable space for the purpose of installation of flexible dies. A hydraulic press is connected with a crown at the top, and the upper die moves in the vertical direction through the four columns installed at the corners of the forming machine. The maximum forming load is set at 2,000 kN to manufacture curved steel plate blocks of hull structure which have within 25.0 mm in thickness.

2.2 Development of software programs for process configuration and machine operation

Software developed in this study are composed of two programs concerning to process configuration and machine control. In the process configuration, punch dimension, number of punches in an array, and surface information are provided as inputs and thus punch height can be calculated for the given curved surface. Firstly, a punch height calculation program is developed to figure out the equivalent forming surface with regard to a given surface. Curvature radii of the objective surface are referenced by neutral surface of the plate, and the thickness can be defined as an input. Typical modeling functions are included to create the defined forming surfaces such as cylinder, spherical and convex, saddle, and twist types. Figure 9 shows those typical types of curved plates which are defined and created in the software by using general geometry parameters. In addition, a calculation processor for arbitrary curved surface data defined by a user input is also included to figure out the punch height for any forming surfaces. After modeling the forming surface, punch height calculation is conducted and the calculated results are displayed in a software window using three-dimensional graphics. Figure 10 shows a display example of three-dimensional punch array model for the given forming surface. Sectional configuration of the punch array and contact points also can be observed along the longitudinal and width-wise directions as shown in Fig. 11. In the figure,

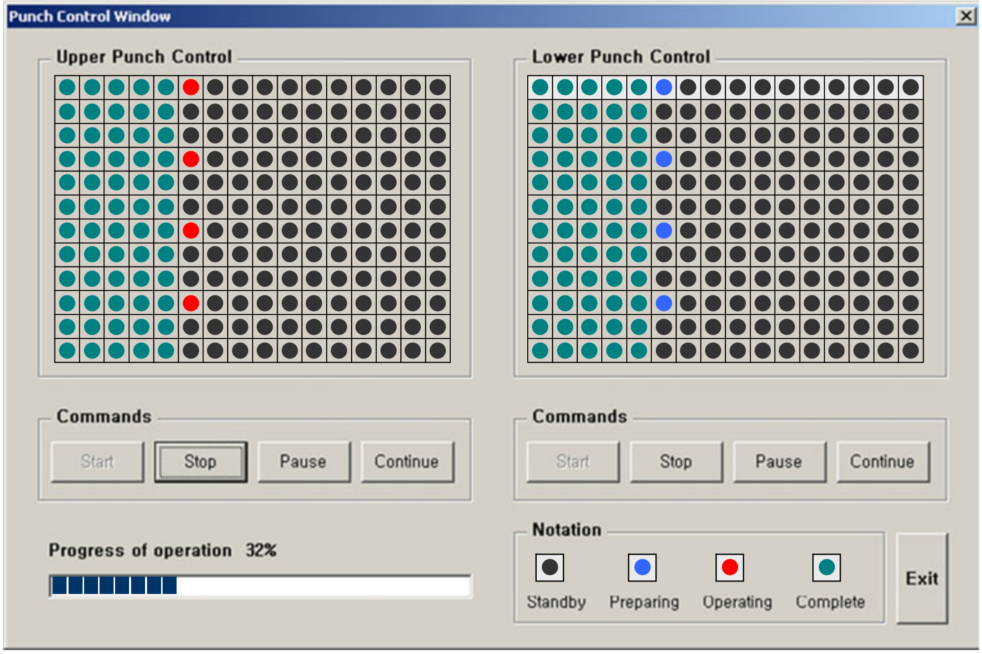


Fig. 12 Punch control monitoring shown in machine operating software

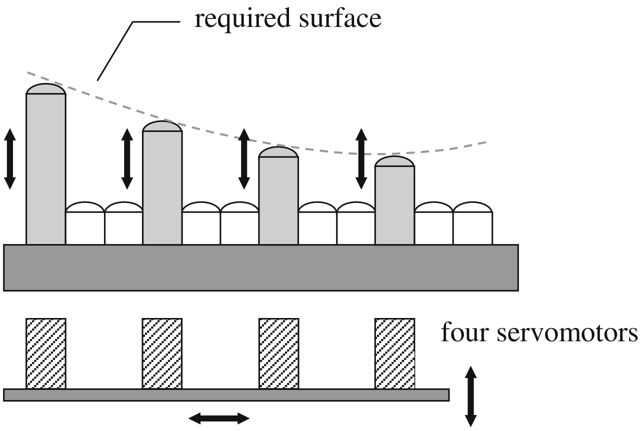


Fig. 13 Sequential punch control in control module which has four punches at uniform intervals in a row

the perpendicular lines marked on the punch surfaces depict contact points, and the top view of the punch surfaces are also shown below. Then, the calculated punch height data are transferred to the machine control software, and the punches are adjusted according to the data. The control software is connected with several servomotors which control the punch height according to specified rotation angle for each punch obtained from the punch height. Figure 12 depicts a picture of the monitoring procedure in the software to investigate the current punch control state.

2.3 Mechanism of punch height adjustment and control scheme

Punches are constrained in the punch housing, thus the bending moment caused by the eccentricity of the contact point on the punch tip surface can be sustained due to contact condition between punches. All degree of freedom of the screw bolts are fixed except the rotational one due to constraint by flange and bearing at the top and bottom of die plate. Therefore, forming load is supported by the flange of the bolt which is in contact with the die plate. Adjustment mechanism of the punch height is designed by adapting the screw assembly structure so length of the punch can be adjusted by rotating the bolt according to proper rotational angle. In this stage, calculation of rotational angle for required height should be carried out, and the angular data should be transferred to servomotors of punch control module. Displacement of the punch body (i.e., punch height) and rotational angle are expressed as the following relationship.

$$\Delta h = p \times \mathrm{Rev} \quad \text{or} \quad \mathrm{Rev} = \Delta h / p \tag{1}$$

where, Δh, p, and Rev (1 revolution=360°) denote increment of punch height, pitch length and revolution number of the bolt, respectively.

In the forming machine, the punch control system using four servomotors is developed by reason of expense for the case of full use of servomotors. Four punches are able to be controlled at once by the punch control module which has four servomotors at uniform intervals in a row as shown in Fig. 13. Therefore, movement of the module along the crossway should be controlled to adjust the punch height sequentially in a row. After finishing the adjustment of the punch height in a row, other punches in the other rows can be controlled. Therefore, the whole system of punch control module including the servomotor should be moved along the longitudinal direction. Finally, six servomotors including

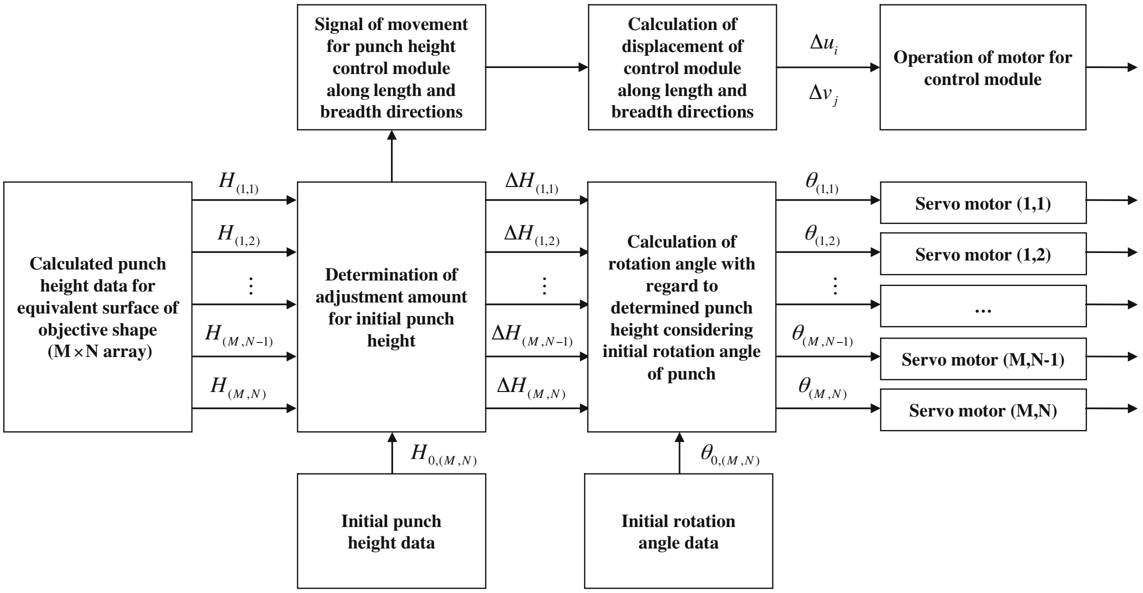


Fig. 14 Punch height control scheme for a flexible die ($M \times N$ array) using motor module and servo motors

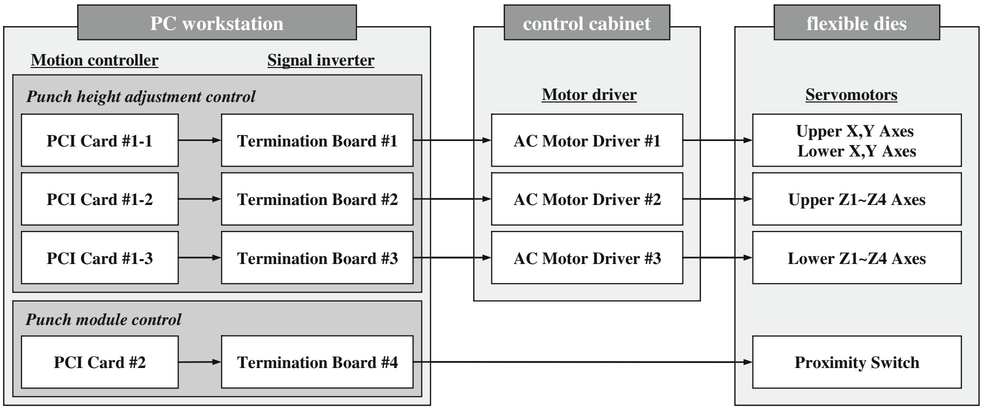


Fig. 15 Composition of punch height control hardware and signal flow in controller of flexible forming machine

four motors for controlling the punch height and two motors for longitudinal and width-wise movement are used for a flexible die set, and a total of twelve servomotors play for both the upper and the lower flexible die sets.

Figure 14 shows punch height control scheme and data flow in the punch control program. The calculated height data, $H(i, j)$, is obtained from the process configuration software, and the increments of punch height, $\Delta H(i, j)$, considering the initial punch height are determined. Then, required rotational angles of the all punches can be obtained. In this stage, initial rotation angle, $\theta_0(i, j)$, which is determined in previous forming process should be considered to find out accurate starting location of the lever pins. Then, longitudinal and width-wise displacements, Δu_i and Δv_j, of the control module are determined by using the punch position data. Figure 15 shows a brief illustration of control hardware used in the operation system and signal flow in the system. The hardware consist of three major parts of a PC workstation, a control cabinet, and flexible dies as shown in Fig. 15. Two kinds of peripheral component interconnect (PCI) cards are used in the motion controller for the purpose of punch height adjustment and punch module attachment. On the purpose of punch height control, AC motor drivers are used to assign the longitudinal and width-wise movement of punch module, X and Y, and punch height control, Z1–Z4, of the upper and the lower die punches. Punch module is designed for the punches to be attached and detached with the lever pins so that the punches could be adjusted sequentially.

3 Application to forming of thick plate in shipbuilding

3.1 Determination of punch height for arbitrarily curved surface

Spherical punch tip shape is selected for the contact surface of the punches for the ease of punch height calculation as described above. Then, punch height can be simply calculated as shown in Fig. 16. In this figure, round-tip punches are contacting with forming surface which has curvature radius, R. On that occasion, center points of all punches are to be aligned on a specified imaginary surface which is depicted in a dotted line because the perpendicular distance between the center point of the punch and the contact point on the forming surface is uniform by the punch tip radius, r. The imaginary surface has the same center position of curvature with that of the forming surface depicted in a solid line because the punch tip has a spherical surface. Therefore, punch height for arbitrary surface can be determined by using this scheme. Figure 17 depicts a schematic diagram of punch height determination method using a patched offset surface. Coordinates of punch location in X and Y directions determined by punch

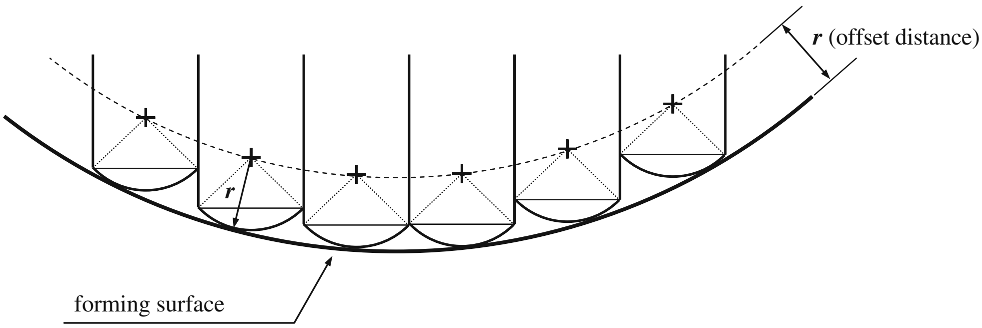


Fig. 16 Schematic diagram of contact between round-tip punches and forming surface

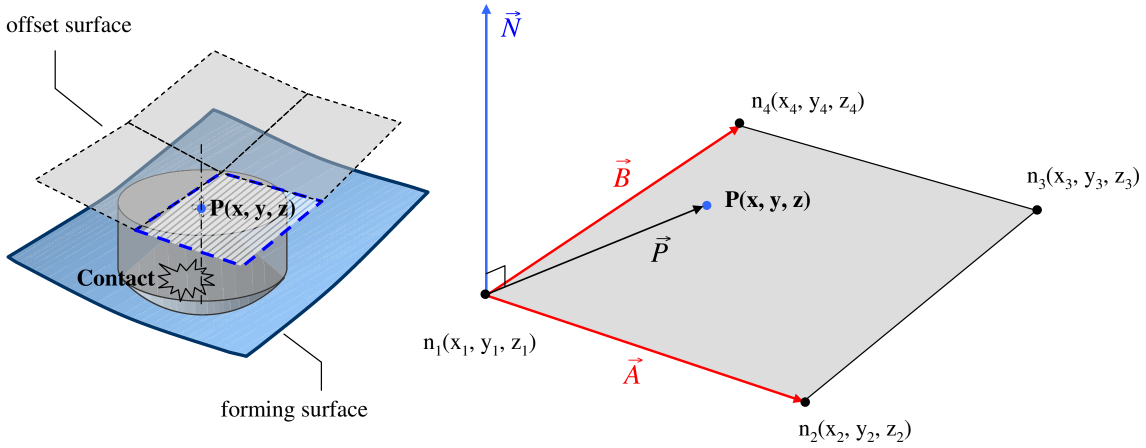


Fig. 17 Calculation scheme for punch height determination using offset surface

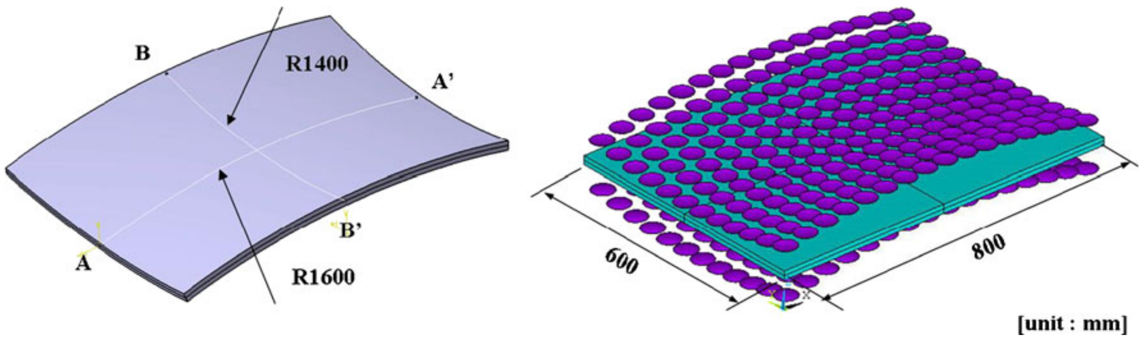
size can be calculated, and thus Z direction coordinate is only unknown in this case. Center point of a punch, $P(x, y, z)$, is to be existed on a specified offset patch as shown in Fig. 17. By using coordinates of three nodes, $n_i(x_i, y_i, z_i)$ on the patch, spatial planar equation for the patch can be obtained and then punch center point can be calculated by the constraint condition, $\vec{N} \cdot \vec{P} = 0$, derived from property of cross product as follows. Where, $\vec{N}$ and $\vec{P}$ denote unit normal vector to a patch that includes center point of a punch and arbitrary direction vector lying on the patch.

$$F(x - x_1) + G(y - y_1) + H(z - z_1) = 0 \quad \text{or} \qquad z = \frac{-F(x-x_1) - G(y-y_1) + Hz_1}{H} \tag{2}$$

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

3.2 Numerical simulation of flexible forming process

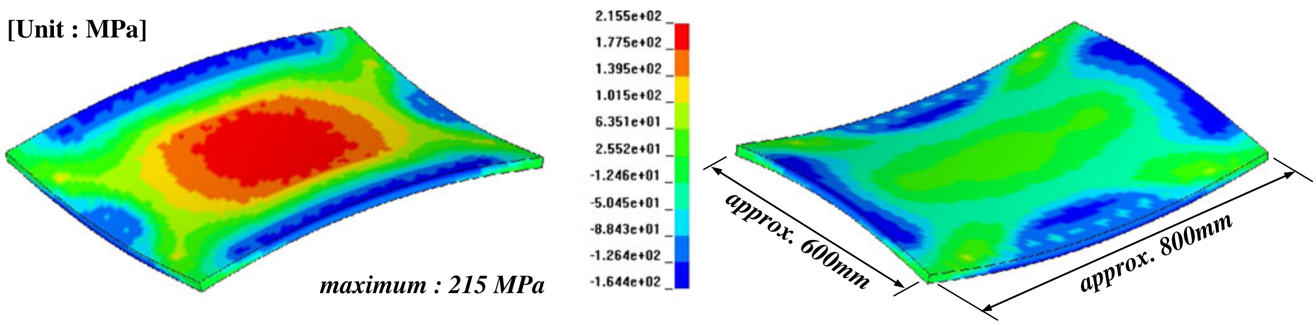
In this study, a saddle-type plate which is one kind of frequently used plate types in hull structure is selected as an analysis model. As shown in Fig. 18a, objective surface has doubly curved curvatures, R1600(mm) and R1400(mm), along length and breadth directions, respectively. Blank size is 800×600 mm^2, the same area of the forming area of forming machine, and its thickness is 20.0 mm. AH-32 steel material is selected and its mechanical behavior is assumed as elasto-plastic material in the simulation. Elastic modulus, E, and Poisson's ratio, ν, are 210 GPa and 0.29, respectively, and the relationship of the exponential work-hardening plastic material, $\overline{\sigma} = K\overline{\varepsilon}^n$, is used with plastic strength coefficient (K) of 790.5 MPa and work-hardening exponential (n) of 0.168, obtained from uni-axial tensile test results. Blank plate is made up of four layers of solid-type element along the thickness direction. The blank model includes 24,705 nodes and 19,200 elements and the reduced integrated brick element type is used for the elements. Punches are accounted to be rigid, so only tips of the punches that contact with blank are considered using shell elements as shown in Fig. 18b and total stroke calculated as 68.6 mm. During the forming simulation, only displacement load is imposed to prevent onset of dimples on the blank because excessive force loading condition may cause the defects on the blank surface. Both dimensions of



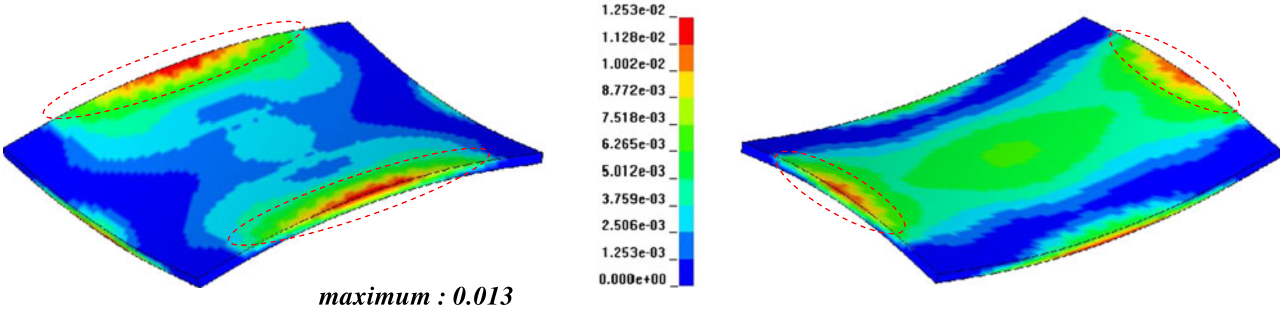
(a) saddle type curved plate model

(b) flexible forming analysis model

Fig. 18 Configuration of saddle-type plate model and simulation model for flexible forming analysis



(a) pressure distribution on upper and lower surface



(b) strain distribution on upper and lower surface

Fig. 19 Numerical simulation results for flexible forming process (original plate: 800 mm × 600 mm × 20 mm)

punch width, w_p, and punch tip radius, r_p, are set as 50.0 mm. In total, $384(16 \times 12 \times 2)$ punches are modeled for both upper and lower dies. In the modeling procedure, punch height data obtained by using the developed scheme are imported using ANSYS parametric design language. Friction coefficient between blank material and punches is assumed as 0.05, considering the point contact conditions and application of elastic cushions in the flexible forming process. Explicit-to-implicit sequential simulations are carried out by using LS-DYNA solver based on explicit code for plate-forming analysis, and ANSYS solver based on implicit code for spring-back analysis.

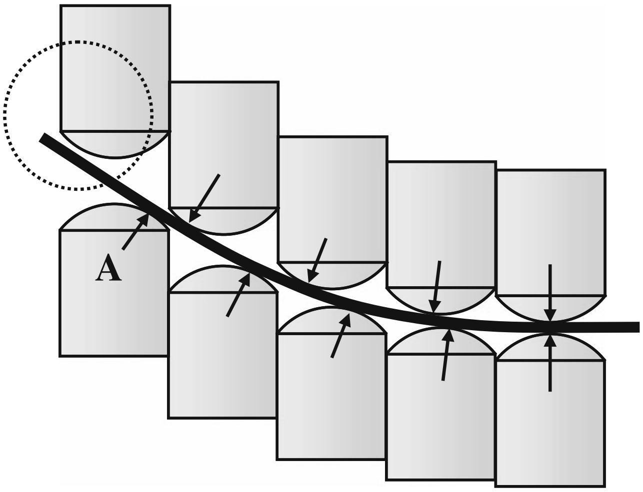


Fig. 20 Forming error caused by 'straight effect' in flexible forming process (the *dotted circle* shows undeformed straight part)

Figure 19a and b depict the results of pressure and strain distribution on the blank from the forming simulation. In the pressure distribution, concentration arises at the center of the plate because the first contact occurs at the region. In contrast to conventional solid die forming process, it is remarkable that the pressure distribution is discrete according to contact points in the flexible forming process. At several points, pressure concentration arises but it is small enough to be neglected. As shown in Fig. 19b, rough strain distribution is also observed at the boundary of the blank caused by the gaps between punches. To confirm the accuracy of the flexible forming process, the curvature radii of the formed plate at the end of the forming simulation are investigated by measuring three points on the curvature

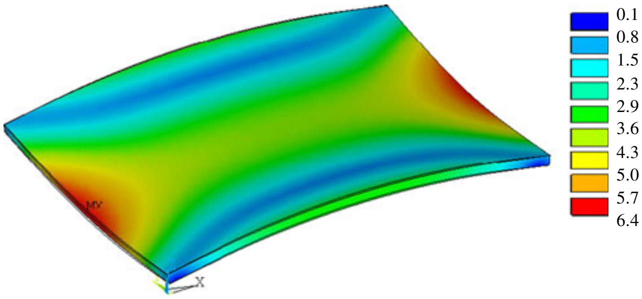


Fig. 21 Spring-back analysis result—spring-back amount [unit: mm] (plate dimension: 800 mm × 600 mm × 20 mm)

Fig. 22 Picture of the flexible forming machine

directions. Curvature radius in the section A–A′ shown in Fig. 18 is measured as 1,640 mm which has a 2.5% error in comparing with target shape, and 1,518 mm in section B–B′ which has 8.4% error in view of the 1,400 mm target radius. The main reason of the error can be understood due to the inevitable characteristic of flexible forming method, which is called as ‘straight effect’. Flexible forming is performed by surface-to-point contact between blank and punches so forming surface at the boundary of the forming region cannot be supported accurately and even it would remain as a straight line as shown in Fig. 20. In the figure, the boundary region of the blank marked with the dotted circular line is remained straight, because the objective curved forming surface shape could not be formed at the left side of the contact point ‘A’ of the boundary punch. Bigger error in the section B–B′ than A–A′ is caused by the bending deformation along the section A–A′ reversely restrains the curvature deformation in the section B–B′. However, curvature radii values are very sensitive to coordinates of measuring points so it was judged that this forming operation is satisfactory. In addition to the forming analysis, spring-back simulation is carried out to obtain the final configuration of the curved plate. Nodes on the curvature lines are constrained in both the longitudinal and width-wise directions respectively. Figure 21 displays the spring-back amount estimated in the simulation, and maximum spring-back was estimated as about 6.5 mm at the edge. From the results, curvature radii were measured as 1,730 mm in the longitudinal direction and 2,010 mm in the width-wise direction, respectively.

3.3 Experimental confirmation of flexible forming process

Experiment of flexible forming process for the saddle-type plate is carried out to confirm the formability and to assure the feasibility of the process. Figure 22 shows the picture of the flexible forming machine used in the experiment, which has 2,000 kN hydraulic press unit. Punches and flexible die

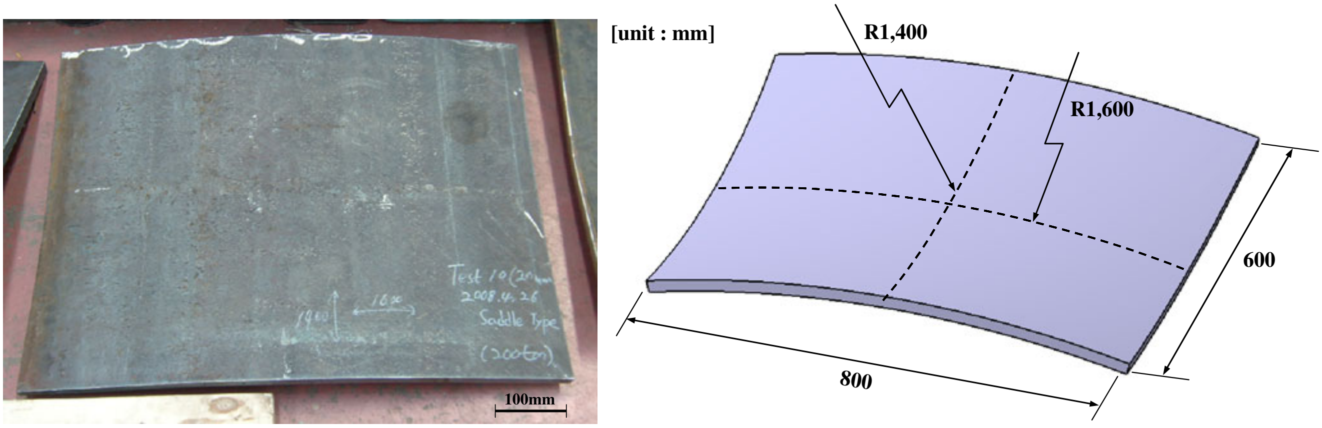


Fig. 23 A saddle-type curved plate formed by the flexible forming machine (800 mm × 600 mm × 20 mm)

sets are fabricated as the shape and dimensions described above. The forming area of the machine is 800×600 mm^2 and it consists of 384 punches. Twelve servomotors are used to control punches and punch modules. Thick AH-32 steel plate materials with 20 mm thickness are prepared and it has also 800×600 mm^2 in surface area. In the experiment, two high-strength polyurethane sheets of 10 mm thickness are inserted between punches and plate to prevent surface defect and scratch on the punches and blank material. In the process design procedure, the thickness of the steel plate and polyurethane materials are considered because the curvature radii on the upper and lower surfaces are quite different when thick materials are used. Figure 23 shows configuration of the saddle-type plate produced by the flexible forming machine. The curvature radius along the longitudinal direction is measured as 1,786 mm which has 3.1% error with regard to that of the spring-back simulation results. From the width-wise direction, the curvature radius is 2,071 mm which has 2.8% error with regard to the final configuration in the simulation. From the results, it is confirmed that the flexible forming process can be applied to manufacturing of slightly curved plates used as a part of a hull structure in shipbuilding. In addition, the flexible forming machine developed here proves its forming capability in manufacturing of thick-curved plates.

4 Concluding remarks

In this study, a 2,000-kN flexible forming machine for forming of thick-curved plate used for shipbuilding industry is designed and fabricated. The related software for process configuration and machine operation with automatic punch control are also developed. In addition, numerical analysis and a series of experiments for manufacturing of curved prototype using steel plate of 20 mm thickness are conducted to figure out the feasibility of the forming machine. For the flexible dies, numbers of punches with partial spherical type punch tips are designed to improve the formability and economic feasibility. An algorithm for determination of the punch heights is implemented in the process design software. Flexible die control mechanism and its control scheme are proposed in view of screw-type punch assembly and the use of linear servomotors. In the punch height control, longitudinal and width-wise controllable motor module is adopted. Due to the geometrical characteristic of the flexible dies with uniform array form, the numerical simulation model is constructed based on automatic modeling scheme using a parametric design language. In the simulation, flexible forming process and spring-back analyses are carried out and the configuration of the results is compared with the prototype with respect to curvature radii. From the simulation results, the straight effect which causes forming error at the edges and is a typical characteristic of the flexible forming method appears to be observed, but the forming error in flexible forming process is in a small amount, enough to be tolerated. As a result of the comparative approach, the same configurations of the saddle-type plate are obtained within the error of 3.1% in curvature radius. It is confirmed that the flexible forming process and its forming machine are appropriately designed, and it shows a technology impact to manufacturing of curved thick plate used in the shipbuilding industry.

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