INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 15, No. 10, pp. 2085-2092

DOI: 10.1007/s12541-014-0567-7

Multi-Stage Forming using Optimized Preform in the Line Array Roll Set Process and Its Industrial Application

Do-Sik Shim[1,#] and **Dong-Yol Yang**[2]

1 Green Manufacturing Process Technology Center, Korean Institute of Industrial Technology, Wolchul-dong, Gwangju, South Korea, 500-460
2 Department of Mechanical Engineering, KAIST, Science Town, Daejeon, South Korea, 305-701
Corresponding Author / E-mail: imagineer@kitech.re.kr, TEL: +82-62-600-6200, FAX: +82-62-600-6099

KEYWORDS: Multi-stage forming, Preform design, Curvature, Genetic Algorithm (GA)

The line array roll set (LARS) process was developed to manufacture doubly curved plates for industrial applications. LARS process deforms a flat plate into a doubly curved plate in a step-wise manner. Forming three-dimensional plates with various curvatures is very challenging, and to obtain highly precise final products, it is necessary to design and appropriately allocate forming increments at each step. In some material processes, formability can be improved by performing multi-stage forming using a preform prior to fabrication of the final shape. In this work, we employed an intermediate shape as a preform for multi-stage forming in the LARS process in order to fabricate the desired plate with optimal quality. The intermediate shape used in the LARS process is defined by a surface with homogeneous curvature in both the longitudinal and the transverse directions, and therefore, fabrication can be achieved without complicated controls of the forming tool. We also developed an approximation method based on a genetic algorithm for designing an intermediate shape of a curved plate. We demonstrated the effectiveness of the proposed method and multi-stage forming methodology through the application of approximated preforms to the manufacture of ship hull plates.

Manuscript received: March 3, 2014 / Revised: May 8, 2014 / Accepted: May 28, 2014

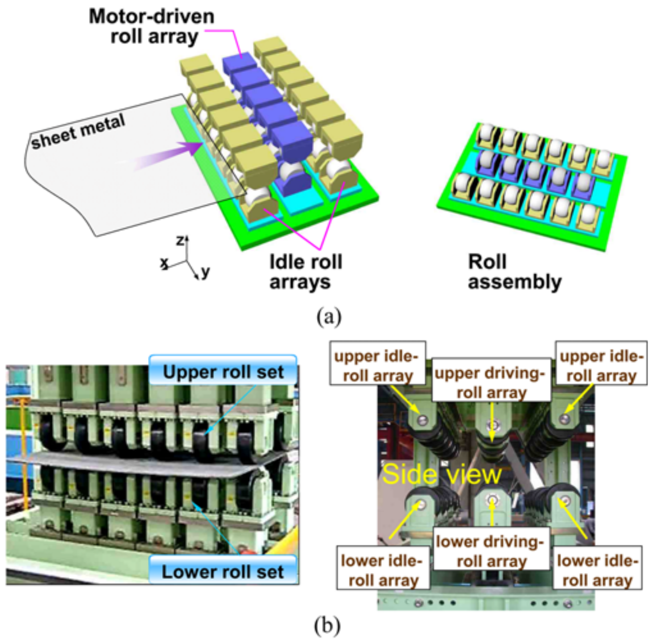
1. Introduction

Bodies of automobiles, ships, and airplanes are composed of doubly curved sheet metal. Although various processes are available for manufacturing doubly curved sheet metal, such as stamping, stretch-bending, and roll forming, the high cost and time requirements for set-up make them unsuitable for manufacturing small batches of doubly curved sheet metal parts. The inefficiency of the conventional techniques used to form doubly curved plates has resulted in research on and development of various new metal forming methods.

Some flexible forming processes that have attracted renewed attention do not require expensive conventional equipment and time-consuming set-up, making them more suitable and efficient for the small-volume production of doubly curved sheet metal. For example, Rady[1] proposed a dieless method with two rollers, in which a curved plate could be formed with repeated passes of narrow-width rollers using the asymmetry of the roller shapes and the angular velocity of the upper and lower rolls. Further, Yoon and Yang[2] proposed a flexible sheet metal forming process that combines the advantages of incremental forming and the roll forming process. Additionally, Shim and Yang[3] proposed a new method termed the line array roll set (LARS) process for the fabrication of doubly curved plates. More recently, Li et al.[4] proposed a continuous forming method based on the flexible roll-bending process for the fabrication of three-dimensional sheet metal parts.

In the LARS process, a flat plate is incrementally deformed into a doubly curved plate as the deformation proceeds simultaneously in the longitudinal and transverse directions in a stepwise manner. To manufacture specific target shapes, the forming schedules must be designed carefully. Because the final shapes for industrial applications have complicated curvature distributions, it is challenging to determine the forming path and process parameters that have a critical influence on the quality of the final product. In the previous study, Shim and Yang[5] investigated the forming sequences in the LARS process and found that it is more effective to form a doubly curved plate from a singly curved shape thereby improving the quality of the formed plate.

In the present study, we propose a multi-stage forming process wherein an intermediate shape is used as a preform. In this multi-stage forming, the forming path is as follows: first, the flat plate is fabricated into an intermediate shape that is closest to the desired shape, and then, the intermediate shape is deformed into the final shape. The formability and accuracy of the final product are strongly dependent on the



(a)

(b)

Fig. 1 (a) Schematic diagram and (b) pilot machine of the LARS process

intermediate shape; therefore, determination of the intermediate shape is an important step in the design of the multi-stage forming process.

In this paper, we propose a new method for the approximation of a given surface into an intermediate shape. For the optimized preform design, the approximation method employs a genetic algorithm (GA) as a global optimization method and applies it to many kinds of surfaces, including a compound surface, for evaluation. Finally, we demonstrate the effectiveness of the multi-stage forming process by applying the approximated preform to the manufacture of ship hull plates.

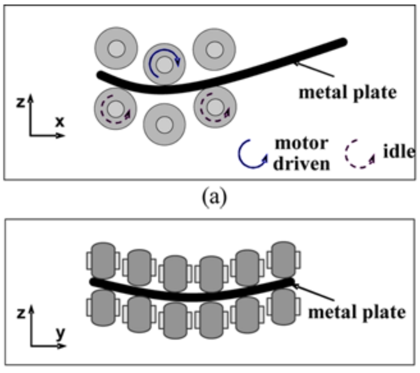
2. LARS Process

2.1 Roll set

The schematic diagram and pilot machine of the LARS process are shown in Fig. 1. The LARS process equipment comprises a pair of symmetrical upper and lower roll sets with three rows of rolls in each set, which are categorized as driving rolls and idle rolls, as explained next. The rolls in the central lines of the upper and lower roll sets are motor-driven, and so, they can simultaneously deform and move the metal plate using the friction between the rolls and the plate. The remaining rolls are idle rolls that generate the bending deformation in cooperative conjunction with the driving rolls.

2.2 Principles of LARS

The LARS process was designed to generate curvatures simultaneously in the longitudinal and transverse directions throughout the entire plate via several movements of the plate. The principle of deformation in the LARS process is illustrated in Fig. 2. For generating a curvature in the longitudinal direction, once the metal plate is pressed by the central driving-roll array, it is bent downward or upward and transferred in a direction tangential to the rotation direction of the driving rolls. For generating a curvature in the transverse direction, the metal plate is bent after suitably configuring the upper and lower roll sets by adjusting the relative position of each roll. Through this process, as the metal plate is transferred in the longitudinal direction, deformation proceeds incrementally until the desired shape is achieved and the manufacture of the doubly curved metal plate is completed.



(a)

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Fig. 2 Principle of deformation in (a) longitudinal direction and (b) transverse direction

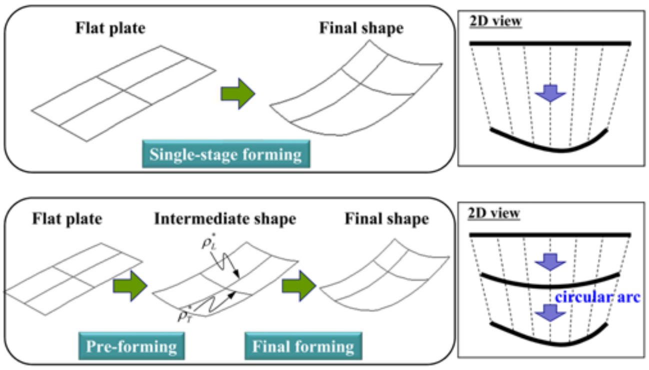


Fig. 3 Single-stage forming (top) and multi-stage forming (bottom)

3. Definition of Intermediate Shape

Fig. 3 shows the forming procedure for fabricating a desired compound shape with a complicated distribution of curvatures. Because most of the desired shapes for industrial applications are compound shapes with complex curvatures, real-time control of the roll heights is necessary during the fabrication of the final shape. However, real-time control of all the rolls in the roll sets requires specialized techniques, which can induce shape error during fabrication of the desired shape. In the multi-stage forming process, prior to forming of the final shape, a flat plate is deformed into an intermediate shape from which the final shape can be fabricated. The main purpose of defining an intermediate shape as a guide for the final shape is to simplify the control of the process parameters, such as adjustment of the roll height. In the case that an intermediate shape has a homogeneous curvature, it can be fabricated without complicated controls of the forming tool, as shown in Fig. 4. Because the intermediate shape has a constant radius of

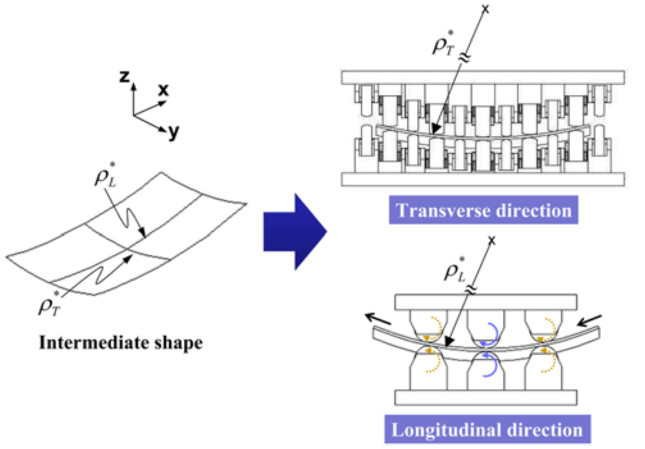


Fig. 4 Fabrication of intermediate surface (ρ_T* and ρ_L* : radii of curvature in the transverse and longitudinal directions, respectively)

curvature in both the longitudinal and the transverse directions, real-time control is not required at this stage. The intermediate shape obtained in the first stage is then formed into the final shape by exercising real-time control. Thus, the errors associated with real-time control can be minimized provided that the intermediate shape is closest to the final shape.

For the same reason, Yun et al.[6] attempted to determine approximated cylindrical surfaces of doubly curved plates for least line heating in a hull forming process in shipyards, and Randrup[7] proposed a method for the approximation of a given surface by a cylinder using the weighted Gaussian image of the surface. However, unlike previous research on optimizing the design of a cylindrical shape that approximates a compound shape, the intermediate shape defined in this study is a type of doubly curved plate with curvatures in both the longitudinal and the transverse directions.

4. Approximation of Intermediate Shape

The optimal design problem is formulated to search for an intermediate shape that is closest to the final product, and the problem is solved using a GA. The following section describes the objective functions and constraint conditions for the design variables, as well as the GA, which is widely used for optimization.

4.1 Design variables

To determine the intermediate surface closest to the final shape, the approximation is formulated by an optimization problem. The intermediate surface can be represented by an explicit function by using the radii of curvature in the longitudinal and transverse directions. The explicit function is expressed as

$$z = \rho_T \cdot \left[1 - \cos\left(\sin^{-1}\left(\frac{y}{\rho_T^*}\right)\right)\right] + \rho_L \cdot \left[1 - \cos\left(\sin^{-1}\left(\frac{x}{\rho_L^*}\right)\right)\right] \qquad (1)$$

where ρ_T* and ρ_L* are the radii of curvature in the transverse and longitudinal directions, respectively.

The goal of optimization here is to determine ρ_T* and ρ_L* of the intermediate shape that approximates the final shape; thus, ρ_T* and ρ_L* are the design variables for the optimization.

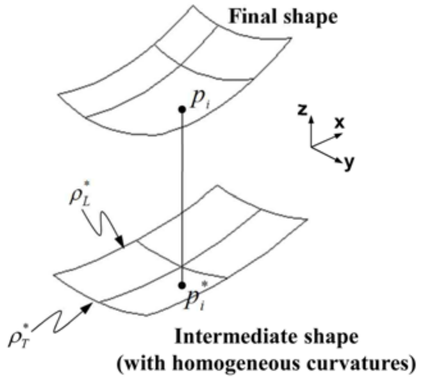


Fig. 5 Distance between final shape and intermediate shape

4.2 Objective function

Fig. 5 shows an example of a final shape and the intermediate shape that approximates it. Point $p_i(x_i, y_i, z_i)$ is on the final surface, and point $p_i^*(x_i^*, y_i^*, z_i^*)$ on the intermediate surface corresponds to point p_i, where x_i=x_i*, and y_i=y_i*. The intermediate shape is approximated by minimizing the distances between the points p_i and p_i* on the final and intermediate shapes, respectively, where the distance between p_i and p_i* is defined by the difference in their z-coordinates. Therefore, the objective function can be expressed as follows:

$$\text{min.} \quad F = \Sigma_{i=1}^{n} \varepsilon_i^2 = \Sigma_{i=1}^{n} |p_i - p_i^*|^2 \qquad (2)$$

where n is the number of points on the surfaces.

For this optimization, the sum of squares of the z-coordinate differences for all the points on the final shape is computed iteratively until the optimized design values ρ_T* and ρ_L* are satisfied.

4.3 Constraint conditions

As stated earlier, a flat plate is deformed into the final shape via an intermediate shape, so the curvature at each point p_i* on the intermediate shape is less than that at each p_i on the final shape. The constraint conditions for the design variables are as follows:

$$\kappa_T^* < \kappa_{T,\,max} \quad and \quad \kappa_L^* < \kappa_{L,\,max} \qquad (3)$$

where $\kappa_{T,\,max}$ and $\kappa_{L,\,max}$ are the maximum curvatures in the transverse and longitudinal directions, respectively, of the final shape.

Prior to computation of the optimization problem, the curvature at each point on the final shape must be calculated using a geometrical approach to find $\kappa_{T,\,max}$ and $\kappa_{L,\,max}$.

4.4 Genetic algorithm (GA)

A GA is a search technique that is commonly used in computing to determine exact or approximate solutions of optimization and search problems and GAs are categorized as global search heuristics. They are a particular class of evolutionary algorithms (also known as evolutionary computation) that use techniques inspired by evolutionary biology, such as inheritance, mutation, selection, and crossover (also called recombination).

GAs are implemented as a computer simulation in which a population of abstract representations (called chromosomes or the genotype of the genome) of candidate solutions (called individuals, creatures, or phenotypes) of an optimization problem evolves toward better solutions. The evolution typically starts with a population of randomly generated individuals and advances in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population based on their fitness level, and the individuals are modified (recombined and possibly randomly mutated) to form a new population. The new population is then used in the next iteration of the algorithm. The algorithm terminates either when the maximum number of generations has been produced or when a satisfactory fitness level of the population has been achieved. If the algorithm has terminated for the former reason, a satisfactory solution may or may not have been reached.[8]

4.5 Algorithm implementation

A typical GA requires two items to be defined: (1) a genetic representation of the solution domain and (2) a fitness function to evaluate the solution domain. A standard representation of the solution is an array of bits. The fitness function is defined for the genetic representation and measures the quality of the represented solution. The fitness function is always problem dependent. In this work, the solution set is composed of curvatures of the intermediate surface that satisfy the constraint conditions; these curvatures are represented by binary coding.

In this problem, the objective is stated as the minimization of function *F*, rather than the maximization of a profit function. As a result, it is necessary to associate the objective function with a fitness function through mapping. Typically, to transform a minimization problem to a maximization problem, the cost function is simply multiplied by *-1*. With GAs, this operation is insufficient because the measure obtained is not guaranteed to be non-negative. Therefore, the cost function *F*, as defined in Eq. (2), is transformed into a profit function as follows:

$$G = C_{max} - F \quad \text{when} \quad F < C_{max}, \quad \text{otherwise} \quad G = 0 \qquad (4)$$

where C_{max} is an input coefficient that is sufficiently larger than the largest values of *F* and is empirically defined by test computations.

The searching algorithm to determine satisfactory values of the design variables, objective function, and constraints is summarized by the flow chart in Fig. 6. The main control parameters used in the GA were set via test computations and are listed in Table 1. Visual C++ was used for implementation of the optimization algorithm.

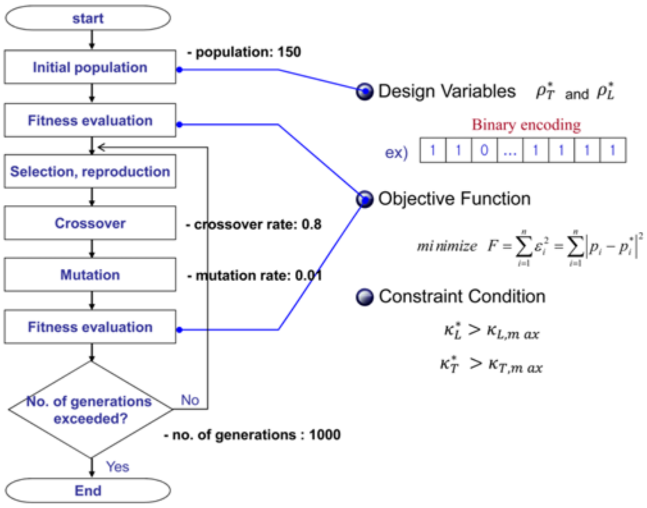


Fig. 6 GA for optimization of intermediate shape

Table 1 Parameters for GA

Parameter	Value
Crossover rate	0.8 (one-point crossover)
Mutation rate	0.01
Number in population	100
Maximum number of generations	1000
Selection	roulette wheel selection

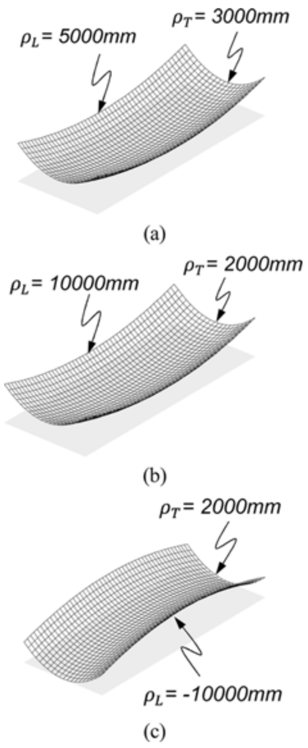
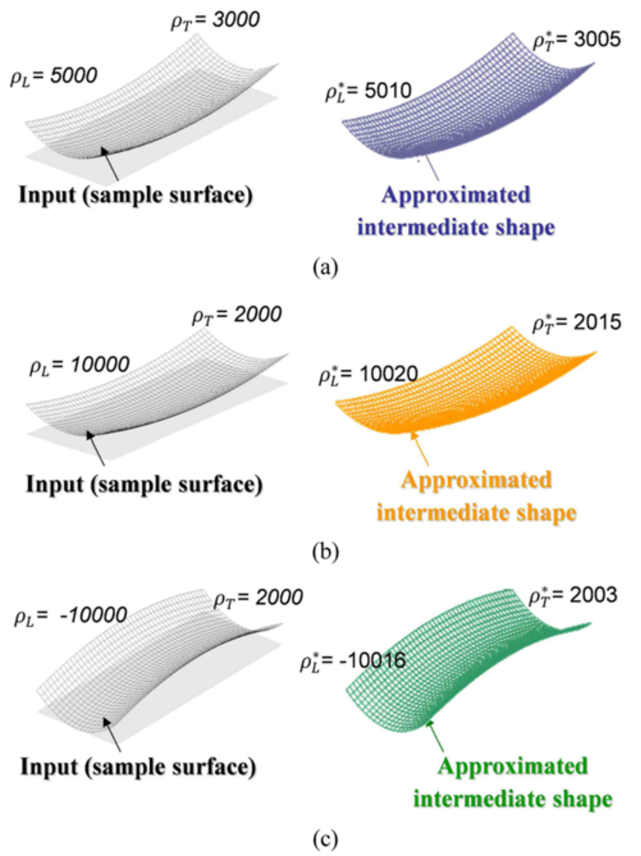


Fig. 7 Sample surfaces for validation of proposed algorithm: (a) concave 1, (b) concave 2, and (c) saddle

5. Evaluation and Discussion

5.1 Algorithm validation I (simple surfaces)

The proposed searching algorithm based on the GA was applied to several types of surfaces to evaluate its feasibility. Simple double curvature surfaces, which have homogeneous curvatures, were first examined before the proposed algorithm was applied to compound surfaces. Fig. 7 shows sample surfaces chosen for validation. These



(a)

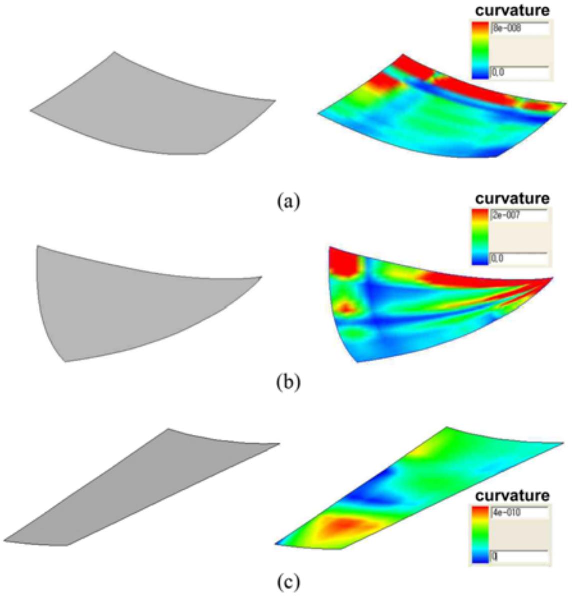
(b)

(c)

Fig. 8 Input surface and approximated intermediate surface (unit: mm): (a) concave 1, (b) concave 2, and (c) saddle

Table 2 Results of test approximation

Sample ($\rho_T - \rho_L$)	Approximated shape ($\rho_T{}^* - \rho_L{}^*$)	CPU time	Error
Concave 1 (3000 - 5000)	Concave 1 (3005 - 5010)	10~15 s	Less than 1%
Concave 2 (2000 - 10000)	Concave 2 (2015 - 10020)		
Saddle (2000 - (-)10000)	Saddle (2003 - (-)10016)		



(a)

(b)

(c)

Fig. 9 Sample surfaces and their Gaussian curvature distributions: (a) Sample surface 1, (b) sample surface 2, and (c) sample surface 3

surfaces include two types of concave surfaces (Figs. 7(a) and (b)) and a saddle surface (Fig. 7(c)). According to the definition of Gaussian curvature,[9] the ρ_T and ρ_L values of a concave surface have the same signs whereas those of the saddle surface have opposite signs. Because all of the sample surfaces selected for the validation have homogeneous curvatures, the outputs (intermediate shapes) that are approximated by the algorithm should be identical to the input (sample surfaces). The surfaces were exactly and automatically subdivided into quadrilateral meshes, and their nodal points were used as input point data for the approximation. The computing system used was a Pentium IV (CPU 2.8 G) machine with 2 GB memory.

After the computation, the longitudinal and transverse curvatures of the sample surfaces were compared with those of the approximated surfaces, as shown in Fig. 8. It was found that the curvatures of the approximated surfaces resulting from the optimization were identical to those of the input surfaces. The intermediate surfaces can be well approximated by global optimization with constraints as defined in section 4.3. From the validation results, it can be concluded that the optimization problem including the design variables, the objective function, and the constraint conditions defined in the previous section is well established and that its performance is reliable enough for its application to surfaces that are more complicated. Furthermore, the computation time for the approximation as summarized in Table 2 is reasonable in spite of the use of the GA-based global searching algorithm. Thus, the GA-based searching algorithm for optimal solutions is competitive and practically applicable. The feasibility of the proposed algorithm for shapes that are more complicated is discussed in the following sections.

5.2 Algorithm validation II (compound surfaces)

The proposed algorithm, which was verified by application to three sample surfaces as explained in the previous chapter, was also applied to compound surfaces that have non-homogeneous curvatures (shown in Fig. 9). The sample surfaces in this case were concave surfaces having curvatures that change substantially at each point on the surface, as is clear from the distribution of Gaussian curvatures; thus, the selected sample surfaces are appropriate as examples of compound surfaces. The proposed algorithm was validated using these sample surfaces, which have a variety of curvature distributions, Gaussian curvatures, and sizes.

The results of iterative computations performed for determining intermediate shapes for the selected sample surfaces are presented in Fig. 10; this figure also shows the optimized design values with the Gaussian curvature distributions. The intermediate surfaces have a uniform Gaussian curvature distribution because they have homogenous curvatures in both the longitudinal and the transverse directions. Figs. 11 and 12 show comparisons of the cross-sectional profiles of the final and intermediate shapes for sample surfaces 1 and 2, respectively. On the basis of the computation results, the cross-sectional profiles were approximated by circular arcs with a minimum level of shape errors.

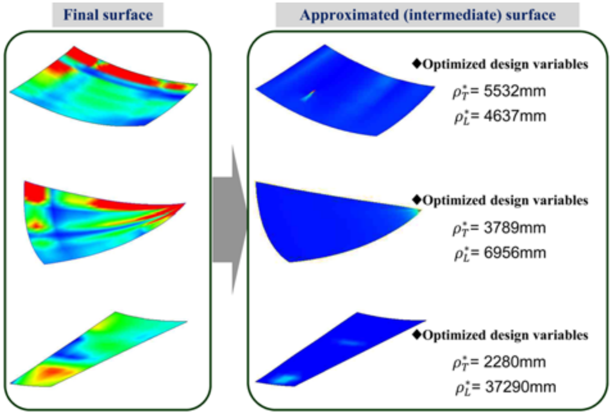
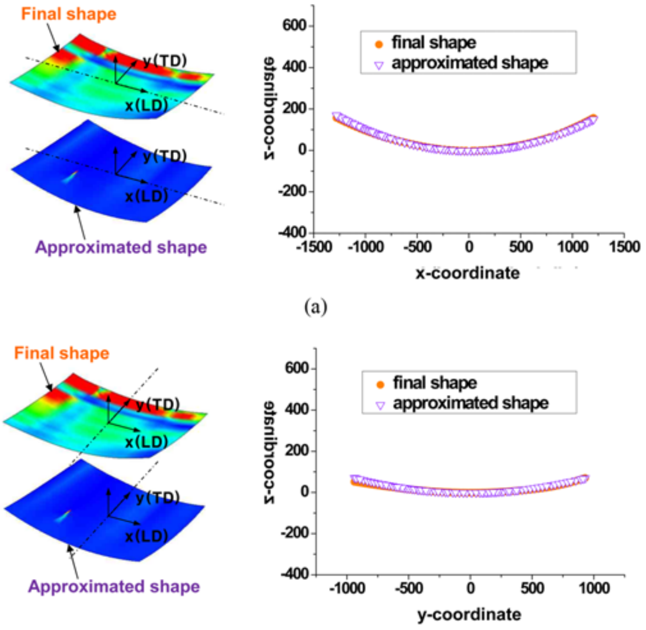


Fig. 10 Approximated intermediate surfaces and their Gaussian curvature distributions

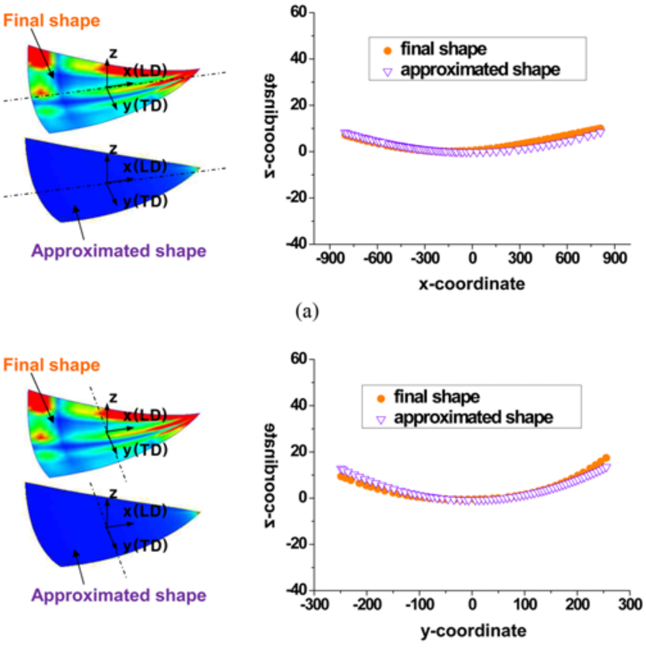


(a)

(b)

Fig. 11 Comparison of cross-sectional profiles of final shapes and their intermediate shapes (sample surface 1) (a) Longitudinal cross-section (b) Transverse cross-section

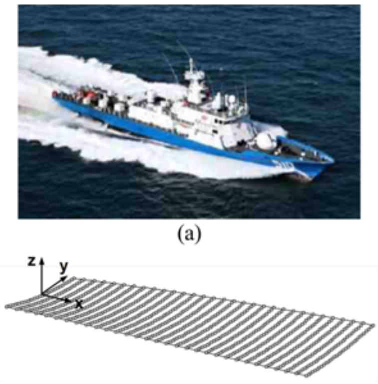
These circular arcs can be easily preformed before the final forming stage; therefore, it is possible to reduce forming errors that may occur in the final stage and also to facilitate hardware control. We thus conclude that the proposed algorithm for approximating an intermediate surface of a given final shape can be effectively used for the design of preforms in multi-stage forming in the LARS process.



(a)

(b)

Fig. 12 Comparison of cross-sectional profiles of final shapes and their intermediate shapes (sample surface 2) (a) Longitudinal cross-section (b) Transverse cross-section



(a)

(b)

Fig. 13 (a) Patrol ship and (b) target hull plate selected as the industrial application

6. Industrial Application of Multi-Stage Forming using Intermediate Shapes

The developed approximation algorithm was applied to the shipbuilding industry. Specifically, an under-construction patrol ship in a shipyard was selected as the industrial application. As shown in Fig. 13(a), the selected patrol ship and its hulls are composed of many curved plates of varying double curvatures and sizes. Considering the specifications of the experimental setup as shown in Fig. 1, the target hull plate shown in Fig. 13(b) was chosen for design testing. The intermediate shape based on the selected target hull plate was calculated by using the developed approximation program; the calculation results are shown in Fig. 14 and summarized in Table 3.

In our previous research,[10] we developed springback compensation logic to determine the bending radii in two orthogonal directions by adopting theoretical and empirical equations, which were derived to predict the inevitable springback phenomenon in cold sheet metal forming processes. In this study, the springback compensation logic was utilized to fabricate the intermediate shape.

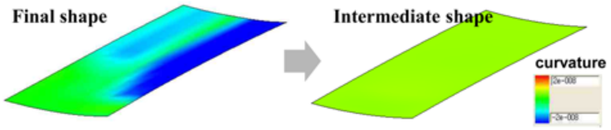
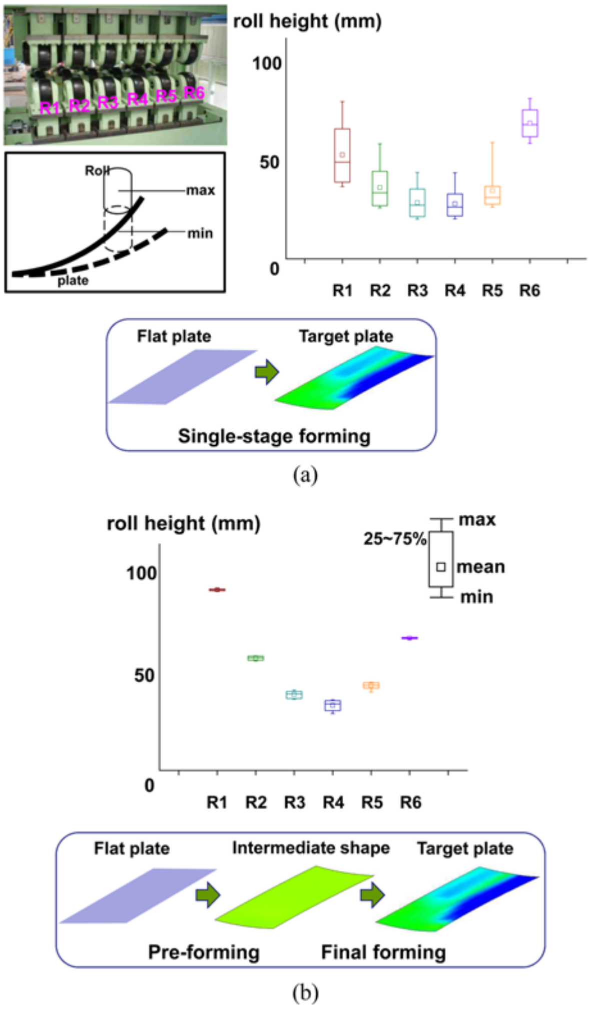


Fig. 14 Final shape and its intermediate shape

Table 3 Input data and calculated forming information

Target plate		Intermediate plate	
Length	2500 mm	ρ_T*	2050 mm
Width	1000 mm	ρ_L*	9920 mm
Thickness	6 mm		
Material (AH32) Yield stress: 467 MPa, Young's modulus: 207 GPa			

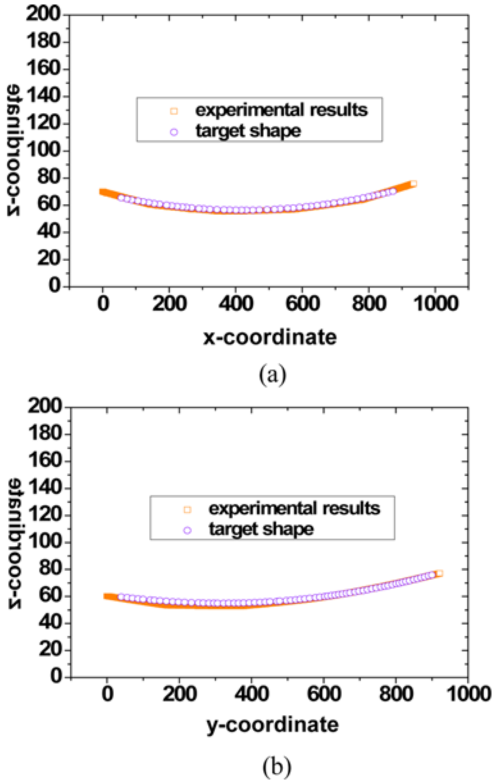


(a)

(b)

Fig. 15 Comparison of roll height changes between (a) single-stage forming and (b) multi-stage forming using an intermediate shape

As discussed earlier, the main objective of adopting an intermediate shape as a preform is to minimize the need for real-time adjustments of roll height during plate transfer, because real-time control of all rolls in the roll sets is a high-level operation requiring specialized techniques, which may induce shape error during fabrication of the desired shape. In Fig. 15, position changes required in the z-direction for all the rolls to fabricate the given target product are compared between single-stage and multi-stage forming. In single-stage forming, the rolls need to move a lot to deform the flat plate into the target shape. Conversely, because multi-stage forming uses an intermediate shape with a constant radius of curvature, there is almost no movement in the preforming stage, and only a small amount of movement is required in final forming.



(a)

(b)

Fig. 16 Comparison between formed (i.e., final) shape and target shape in (a) longitudinal and (b) transverse directions

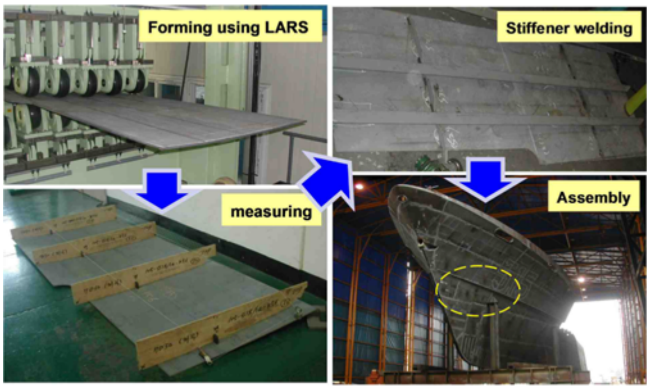


Fig. 17 Fabrication and assembly of target hull plate

Multi-stage forming of the final plate using an intermediate plate was completed successfully, on the other hand, the single stage forming experiment failed. It means that doubly curved plate could not be fabricated by using single stage forming, so that the formed plate could not be compared with the experimental result of the multi-stage forming. Then, to verify the accuracy of the final plate obtained by multi-stage forming, it was measured along the central lines in the longitudinal and transverse directions by using a coordinate-measuring machine (CMM). The measured points are plotted in Fig. 16 for comparison with the target profiles. As seen in the figure, the final product is remarkably consistent with the target plate shape and the difference between them is insignificant. Although the maximum deviation between the final plate and the target plate is about 3 mm (equivalent to 98.5% accuracy), the shape error is acceptable because it is within the allowable range defined by shipyards. The formed product (i.e., plate), after being inspected and subjected to reinforcement welding, was assembled as shown in Fig. 17.

7. Conclusions

Successful and optimal prediction of the intermediate shape in multi-stage forming is a prerequisite for the accurate and efficient fabrication of curved plates. In this paper, we have proposed a simple and efficient method to approximate a preform, i.e., intermediate shape, for a given compound surface for multi-stage forming in the LARS process. Using examples of curved hull plates of a ship, we showed that the proposed approximation method is simple and effective enough to predict an appropriate preform for fabrication of the given design shape. Both the approximation and the optimization including the design variables, objective function, and constraint conditions are well formulated and the performance of the method is reliable enough for its application in industry. Furthermore, the computation time required for the approximation is acceptable in spite of the global searching technique used.

The proposed method can be used for the design of preforms for multi-stage forming in the LARS process. As opposed to single-stage forming, wherein the rolls need to move considerably to deform the flat plate into the target shape, multi-stage forming uses an intermediate shape with a constant radius of curvature, so there is almost no movement in the preforming stage and final forming requires only a small amount of movement. Through the forming of an intermediate shape, it is possible to minimize the shape error that might occur during fabrication of the desired shape. Because this simple method is fast and stable, it can be utilized in industries where many curved plates are fabricated within a short period. In future research, it would be beneficial to estimate additional parameters, such as the number of forming steps and the preferred forming direction, for the fabrication process with the help of the intermediate shape. In addition, it is necessary to accurately predict the amount of springback in final forming stage and compensate it to minimize the production time as well as to enhance the product quality.

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