"IHIMU- α " A Fully Automated Steel Plate Bending System for Shipbuilding

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For more than half a century, line heating has been used in shipbuilding as a method of forming curved shell plate. This technique relies completely on the experience, instincts and know-how of the worker involved. In 1997, in order to automate this technique, "IHI- α " was developed, the world's first automatic processing system for bending steel plate. Since then, the IHI- α system has been used for actual ships under construction while being continuously improved. A new version of the system has now been successfully developed that can automatically handle the entire process, including the additional heating used for finishing the plates. This paper details the latest IHIMU- α system.

1. Introduction

Line heating is a steel plate bending technique for making desired non-developable surfaces. The technique combines plastic deformations caused by local thermal stresses during the heating of steel plates. **Figure 1** shows conventional line heating work using gas burners and water hoses as the main tools.

Line heating is a multi-purpose processing technique in shipbuilding, because it can create any curvature by using simple tools. This technique is used for various kinds of objects and requires a wide-range of processes. As such, it relies completely on the experience and technical knowledge of workers, who work without the use of any written instructions. For this reason, the control of costs and delivery time is difficult. There is an urgent need to ensure the passing on of skills and to secure processing capabilities to address the recent lack of suitable replacements for retiring skilled workers.

There have been many reports⁽¹⁾⁻⁽³⁾ on activities towards the automation of this skill, for example, the automatic creation of plate bending plans (for cold pressing or line heating) that make full use of computers, finite element analyses, and other simulation techniques. However, none of these activities has successfully established techniques that can replace or support the skill of line heating.

In 1990, the authors started working toward the establishment of mechanized processes that could replace this skill. In 1997, they developed the first automatic bending system, "IHI- α "⁽⁴⁾⁻⁽⁷⁾ (**Fig. 2**) and then applied it to the forming of curved shell plates for the main products of IHI Marine United Inc. (IHIMU), namely bulk carriers, Very Large Crude Carriers (VLCC), and container ships.

Since then the authors have continued joint research with the Corporate Research & Development of IHI Corporation (IHI) and Osaka University. In fiscal 2007 and 2008, the



(a) Line heating work 1



(b) Line heating work 2

Fig. 1 Conventional line heating work



(b) Automatic heating





Fig. 2 View of the first IHI- α system

authors promoted research into the full automation of line heating with the support of a practical application development project of the New Energy and Industrial Technology Development Organization (NEDO).

This paper introduces "IHIMU- α ," a leading-edge fullyautomatic bending system (**Fig. 3**), which was developed by combining the technical capabilities of IHI Corporate Research & Development, IHI Scube Co., Ltd., and other IHI group companies and by reflecting in the system the results of forming curved plates used for actual ships and research results obtained to date.

2. Outline of the α system

To make a desired shape, it is necessary to describe numerically how much heat needs to be applied to what parts of a steel plate in what direction and in what order, and to describe in what way the plate is to be supported. This is called a heating plan.

The α system consists of a heating-deformation database that systematically organizes the relationship between heating conditions and the amount of deformation, a heating plan creation program that automatically calculates heating plans by referring to this database, and hardware that implements the heating plans.

2.1 Mechanism of deformation caused by local heating Figure 4 shows the mechanism of steel plate deformation

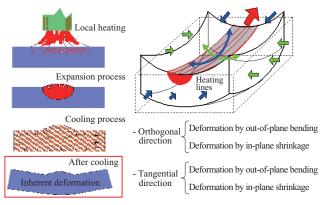


Fig. 4 Mechanism of deformation caused by local heating

caused by local heating. In line heating, out-of-plane bending and in-plane shrinkage occur in the orthogonal direction and the tangential direction, respectively, to heating lines. Workers need to be aware of these four deformation components and arrange heating lines in appropriate positions on a steel plate to make a desired curve. All of these four deformation components were put into the α system's database.

2.2 Heating plans

2.2.1 Heating plan calculation flow

The authors developed a heating plan creation program that calculates heating plans to a degree of accuracy and



(b) Automatic heating



Fig. 3 View of the latest IHIMU- α system

within a calculation time frame that makes it suitable for practical application. The program calculates heating plans by using unique analysis techniques and optimization with a focus on elastic analyses using the Finite Element Method (FEM), which is based on the inherent strain theory. **Figure 5** shows the process for heating plan calculations performed by the α system.

A FEM model of a target shape generated from CAD data and the thickness and material of the plate are input into the system, which then outputs information including: (1) locations to which heat is to be applied, (2) the order in which the locations are to be heated, (3) the speeds at which heating is to be performed, (4) the hight arrangement of supporting position, and (5) the timing at which the plate is to be turned over.

2.2.2 Example implementation of heating plan

Figure 6 shows an example target shape to be formed by bending. It is a shell plate for an engine room of a container ship. This is a complicated shape which is S-shaped in the transverse direction and twisted in the longitudinal direction.

Figure 7 shows a heating plan calculated for this shape.

Heating lines are divided into line elements with a length of 100 to 200 mm. The heating speed changes gradually for individual line elements.

Figure 8 shows the results of automatic bending carried out by the first "IHI- α " system according to this heating plan. Graphs in **Figs. 8-(a)** and **-(b)** show the target shapes and the planned shapes after heating as solid lines and dots, respectively. Graphs in **Figs. 8-(c)** and **-(d)** show the planned shapes after heating and the measured shapes after heating as solid lines and dots, respectively. Each graph shows the configuration for each cross section shown in **Fig. 6**.

These results on the whole very closely match with

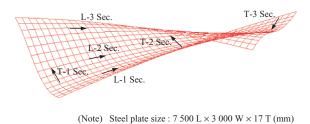
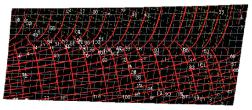


Fig. 6 Target shape for bending

(a) Arrangement of heating lines on the front surface of steel plate



(b) Arrangement of heating lines on the rear surface of steel plate



Fig. 7 Heating plan

the target, though some deviation from the target shape occurred due to a partial breakage during the forming process caused by the steel plate supports being at improper heights.

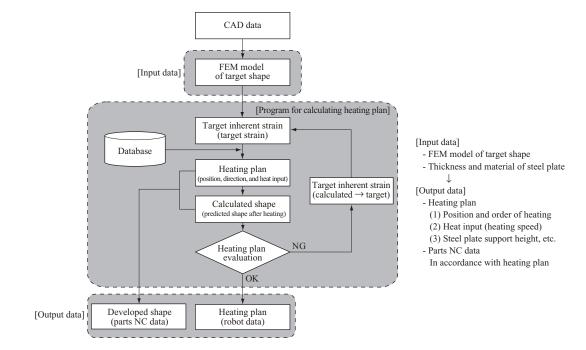


Fig. 5 Calculation process for heating plan

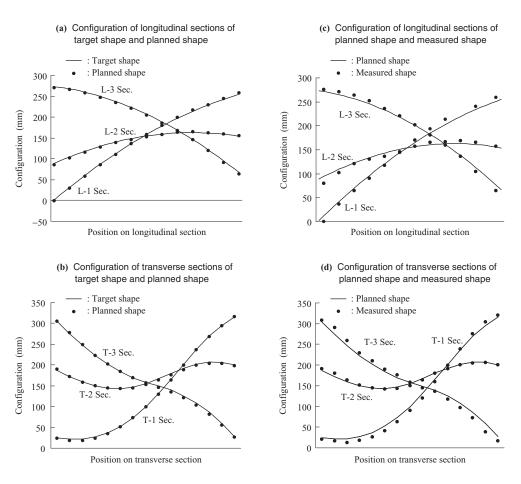


Fig. 8 Results of automatic forming

3. Outline of latest "IHIMU- α " system

3.1 Development goal of "IHIMU- α " system

Heating plans provided by the α system enable the forming of popular curved shell with slight or medium curvature within acceptable accuracy limits, except for in the case of thick plates (i.e. with a thickness of 25 to 50 mm) used for stern construction and of sharp curvature (with a curvature radius of 5 m or less) for a bulbous bow.

However, it requires considerable time and a wide range of processing steps to form a plate. It is not advantageous to have workers intervene during the operation of the advanced, complicated, and automated system, and allowing such intervention prevents the establishment of a forming process that does not depend on workers' skills. In development of the "IHIMU- α " system, therefore, we are aiming to maximize the full capacity of the present α system, which has proved to be effective for the making of slight and medium curvature.

The main targets for the achievement of this goal are as follows:

- (1) Automated evaluation and judgment as a replacement for wood templates
- (2) Automation of correction heating to deal with unavoidable variations in physical property values of materials and in residual stress

- (3) Automation of work to turn plates over that occurs as needed to form plates naturally into target curves
- (4) Heat-source handling device for accurate implementation of heating plans

3.2 **Process of automatic processing**

Figure 9 shows the process of automatic processing for the latest "IHIMU- α " system.

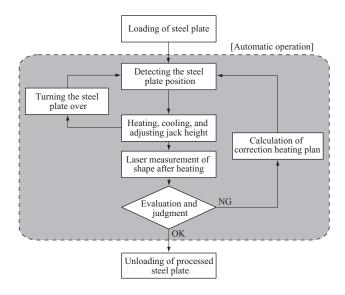


Fig. 9 Process of IHIMU- α 's automatic processing

A machine operator loads a steel plate on a plate support system and pushes a start button on the machine operating panel installed outside a door in a safety barrier. The automatic operation then starts, repeating the following steps: the position of the steel plate is detected; the heights of jacks are adjusted; the heating and the lower-surface cooling are performed; the steel plate is turned over; the new position of the steel plate is detected; the heights of jacks are readjusted; the heating and the lower-surface cooling are performed; the shape is measured; the results are evaluated; a correction heating plan is calculated; correction heating is executed; the new shape is measured, and so on. The above process is repeated until the system judges that the target shape has been achieved.

3.3 Features of "IHIMU- α "

3.3.1 Employment of articulated robots

The first system had a heating coil that contacted a steel plate surface under its own weight and that slid along a curve. It was difficult for the system in cases of a deep and complicated vessel shape to fit the coil in required posture at the edges of a steel plate. As such, the system had a problem in that its processing accuracy for bowl shapes that require a large shrinkage deformation at their edges was poor. It also caused problematic wavy edges due to improper shrinkage at that location. Due to these problems, heating for edge shrinkage was carried out by hand in the actual application of the system.

To solve these problems, the "IHIMU- α " system employs two 7-axis articulated robots to handle the heating coil. **Figure 10** shows this robotic heating system.

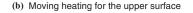
Each robot is suspended from two carriers running on runway girders. Unlike the first system that could not effectively heat steel plate edges, these two robots can effectively shrink edges by holding a steel plate from both sides and heating its edge for a planned period of time (**Fig. 10-(a**)). The two robots can also move in a coordinated way while heating and bending the upper surface of a steel plate (**Fig. 10-(b**)).

3.3.2 Plate support system and lower-surface cooling system

Figure 11 shows the plate support system of the "IHIMU- α "



(a) Stationary heating for the edge



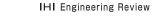




Fig. 11 Plate support system

system. Forty-six motorized jacks are arranged on a platform and their heights are adjusted automatically and sequentially in accordance with the steel plate shape as it varies during heating.

The first system sprayed cooling water around the heating coil; in other words, from above the steel plate to be bent. This caused water to flow in a direction regardless of the heating direction and also caused water holes to be created in steel plates formed into a bowl shape. These problems resulted in the poor reproducibility of cooling.

As a solution to these problems, the "IHIMU- α " system is equipped with water jet nozzles at the tops of motorized jacks arranged in the plate support system to spray water from below the steel plate to cool it.

3.3.3 Turning over bent steel plates

Heating plans provided by the α system required a steel plate to be heated from both sides and to be turned over at least three times before forming was complete. Therefore, the first system always needed human intervention, preventing its unattended operation for a long time or at night.

The "IHIMU- α " system contains a device for turning over a bent steel plate. It can handle a steel plate within the following dimensions: a length of 12 m, a width of 3.5 m, a deflection depth of 600 mm, and a weight of 10 t. **Figure 12** shows the plate reversing system. This has enabled the turning over work during heating to be automated, thereby



Fig. 10 Robotic heating system



Fig. 12 Plate turnover system

realizing fully unattended operation.

3.3.4 Check and evaluation of shapes after bending

The first system also had a shape measurement system, but it had no effective mechanism for the evaluation of measurement results. After the automatic bending, workers checked and evaluated shapes using wood templates.

The "IHIMU- α " system employs a mechanism that automatically measures curved shapes after heating and then evaluates the measurement results. In order to take into consideration differences in required accuracy depending on plate thickness and curve rigidity, the system also employs a mechanism of evaluating shapes based on a new evaluation parameter, strain energy, which is required for the correction of measured shapes into target shapes, in addition to the difference in depth between target shapes and resultant shapes after heating, which is a conventional evaluation parameter.

3.3.5 Final finish heating

Final finishing is the most difficult work for workers, and most of their man-hours are spent on it. The first system had no effective mechanism of calculating correction heating plans and thereby relied on workers to handle operations from shape checking and evaluation to finishing.

The "IHIMU- α " system has a mechanism that calculates plans for the correction of measured shapes into target shapes. It can automatically calculate correction heating plans depending on the evaluation results and proceed to correction heating.

4. Conclusion

We developed the "IHIMU- α " system by drastically improving the first "IHI- α " system, which was developed in 1997 for automatic bending. The latest system can automatically handle all processes, including evaluating curved shapes and judging whether the shapes need to be corrected, replacing the manual work required under the first system, as well as the calculation and implementation of correction heating plans as needed. The latest system employs articulated robots for handling the heating coil used as a heat source, and can be used for bowl shapes, which account for 70% of all curved shell plates that the first system had difficultly forming.

In addition, the latest system can automatically turn

steel plates over to heat their back surfaces, as heating plans provided by the α system require this operation to be carried out. This allows unattended operation for all processes except the loading and unloading of steel plates.

At present, this system can be used with plates with a curvature radius of 5 m or more in the transverse direction and 60 m or more in the longitudinal direction, and with a thickness of 12 to 25 mm (60 to 70% of curved shell plates fall within this range of thickness). The authors intend to expand the application of this system to thick plates (with a thickness of 30 to 50 mm) used for stern construction and to sharp curvature (with a curvature radius of 3 m) used for bow construction, which both require more advanced processing techniques.

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