Development Report:

Basic Study on Laser Forming CAM System for Sheet Material Forming Without Dies or Molds

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Dies and molds are generally used for press forming and injection molding. However, they are expensive and their production is time consuming, so they are not suitable for prototyping or low-volume production. Laser forming is an effective tool for prototyping and low-volume production because it enables one to form sheet material without dies or molds. Laser forming is the deformation process caused by the thermal stress generated in the sheet by laser irradiation. In this paper, a Laser Forming System is proposed for determining laser irradiation conditions for forming a required shape.

Keywords: laser forming, CAD, laser, die, mold

1. Preface

In general, steel sheets are formed on presses with dies or molds. Presswork, though very much suited to the production of large numbers of a small variety of products, is not suitable for prototyping or low-volume production since dies or molds take considerable time and money to manufacture. For prototyping or low-volume production, therefore, there is a growing need for the development of technologies for the forming of sheet materials without the use of dies or molds [1].

The shipbuilding industry has adopted heating methods for bending steel plates for the fabrication of bow sections or propeller screws that have complex curvatures: steel plates are heated by gas burners and then rapidly cooled with water to create thermal stresses and produce plastic deformations. Although such heating methods do not require the use of any dies or molds, workers engaged in such work need to have sophisticated skills. This has hindered automated or high-speed work operations [2].

High expectations have been placed on laser-forming methods as an alternative to the above-mentioned heating method for the following reasons:

(a) No use of expensive dies or molds enables rapid prototyping and also keeps production costs low, even in low-volume production.

(b) Production lines can be adapted to mixed productions of a wide variety of products, and yields may be improved by sequential corrections of defective work [1].

(c) The inflow heat of lasers is easy to control, and the work is cooled by self-cooling actions due to thermal conduction. This means that automation of work can be duly expected [2].

Numerous studies have been conducted [1–16] to put the above-mentioned features into practice and have led to phenomenal clarification and increased understanding.

In this research, which is aimed at the practical application of a laser-forming system, we have developed a basic laser-forming system to automatically form sheet materials to required shapes. In this paper, we have formed sheet materials under typical laser-forming conditions, based on which we propose a basic system to derive laser-irradiation conditions (laser-irradiation positions, laser-irradiation times, and laser-scanning rates) for forming required shapes. We have verified the effectiveness of the proposed laser-forming system through verification experiments. We have also studied through finite-element analyses whether laser-forming can successfully be applied to the formation of curved surfaces.

2. Outline of Basic Laser-Forming System

The proposed basic laser-forming system is designed to acquire CAD data for shapes to be formed and to output laser-irradiation conditions (laser-irradiation positions, laser-irradiation times, laser-scanning rates, and laser power) for forming the required shapes. The prototyped basic system has the following functions:

(a) To acquire CAD data for shapes to be formed and derive bending angles and bending directions at different positions in the sheet material, based on analyses of the acquired CAD data.

(b) To determine laser-irradiation conditions (laser-irradiation positions, laser-irradiation times, laser-

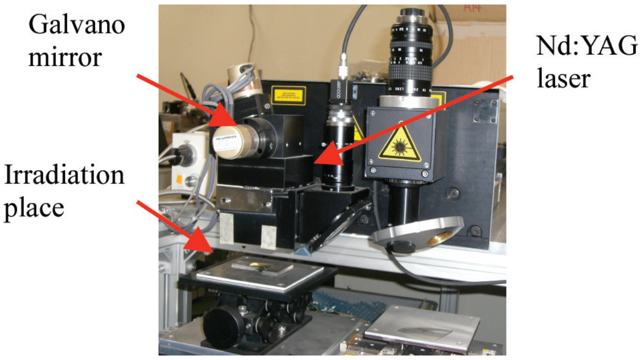


Fig. 1. Experimental apparatus.

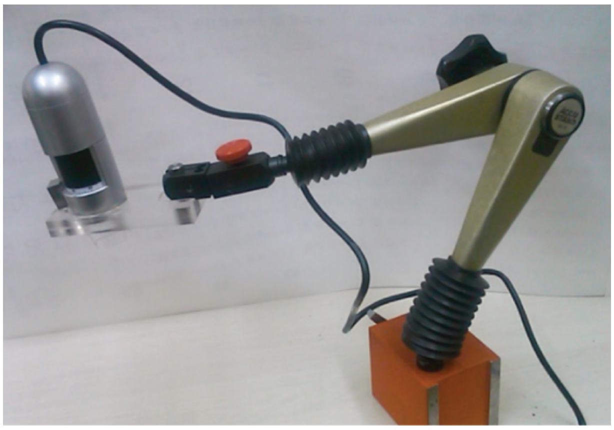


Fig. 2. USB digital microscope.

scanning rates, laser powers) for forming sheet materials with such bending angles and bending directions as obtained in (a) above.

(c) To irradiate sheet materials based on the determined laser-irradiation conditions in order to achieve required shape-formations.

3. Forming a Database

Forming a database will provide data on which to determine laser-irradiation times, laser-scanning rates, and the laser power required to bend sheet materials to the designated angles at any points in the materials. Such a database will be formed through the following process:

3.1. Acquisition of Forming Data

Figure 1 shows the experimental apparatus (Nd: YAG Laser Forming System, 808TQ, Lee Laser, Inc.). In the basic experiments to architect a database, we have used SUS304 sheet materials 0.03 mm thick, 10 mm wide, and 18 mm long. We have set the laser power to 3.0 W, and we have carried out forming tasks at different laser-irradiation times and laser-scanning rates to measure angles under their respective conditions. In measuring the bends in the workpieces, we have used a USB digital microscopic camera (Dino-Lite Plus, AnMo Electronics Corp.) shown in **Fig. 2**. Sectional images of the bends in the formed sheet material are scanned by computer, and the bending angles are calculated and analyzed. In the actual formation of the material, as shown in **Fig. 3**, one end of the sheet material is inserted into the fixture, and the other end is left unconstrained. In this condition, the sheet material surface is irradiated from a point 6 mm away and vertical to the unconstrained end (or at the center of the sheet material) at laser-scanning rates V for designated irradiation times. The fixture is attached to the table. The laser is scanned through a galvano-mirror for irradiation. Laser-scanning rates V are set at 25 mm/s, 30 mm/s, 35 mm/s, 40 mm/s, 45 mm/s, and 50 mm/s.

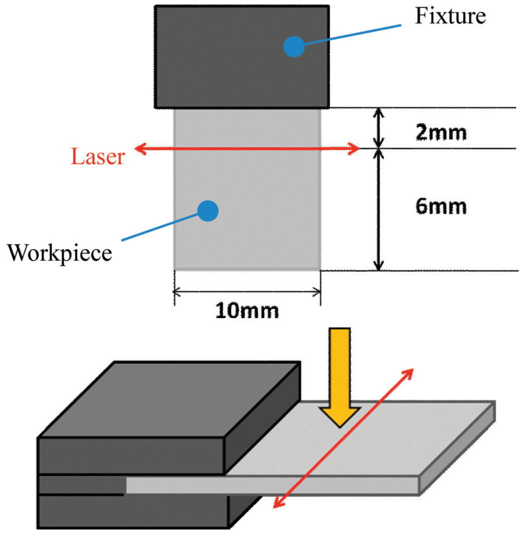


Fig. 3. Irradiation method.

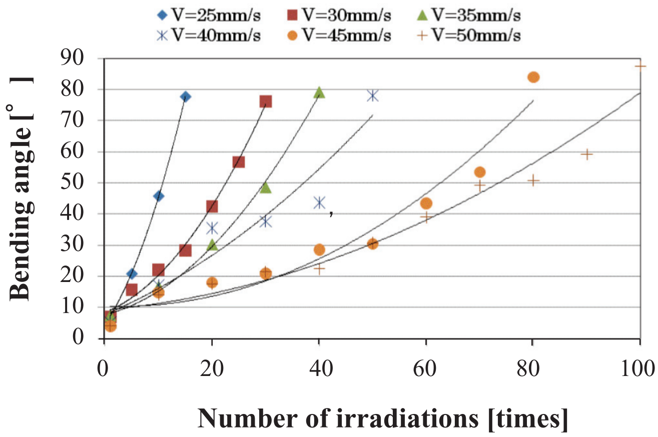


Fig. 4. Relation between angle of bend and number of irradiations.

3.2. Formulation of Forming Data

Figure 4 shows the relations between the laser-irradiation times and bending angles at the parts irradiated. One round of irradiations is counted as one irradiation. The spots marked with ♦, ■, ▲, ∗, •, and + in the Figure represent experimental results at laser-irradiation rates of 25 mm/s, 30 mm/s, 35 mm/s, 40 mm/s, 45 mm/s, and 50 mm/s, respectively. Formation data have been architected by formulating the relationships between laser-irradiation times and bending angles by quadratic polynomial approximate curves, based on the experimental results, as shown by solid lines in the Figure.

4. Basic System

In this research, we have developed the basic system the Visual Basic (VB), using the Application Program Interface (API) of Solid Works. The basic system is designed to acquire the shape-data architected by the three-dimensional CAD system Solid Works as data for required forming shapes and to derive forming conditions through the following processes:

4.1. Analysis of Forming Shapes

The basic system is to acquire three-dimensional CAD data (data from Solid Works), to recognize planes constituting these data, and to extract boundary lines and normal lines of such recognized planes. The basic system at the current stage of development can only analyze shapes as a group of planes.

4.2. Derivation of Irradiation Positions and Required Forming-Angles

We have obtained, through analyses of shapes formed, such information as the boundary lines of planes constituting required shapes and normal lines of such planes. The basic system is to derive, as irradiation positions, straight lines connecting starting points and ending points of the planes. The basic system is also to derive, from normal lines of the planes with such boundary lines, required forming angles, based on Eq. (1):

$$\cos\theta = \frac{\vec{a}\cdot\vec{b}}{|\vec{a}|\left|\vec{b}\right|} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

4.3. How to Derive Laser-Irradiation Conditions

The basic system is to derive the smallest laser-scanning rates V_1 and shortest laser-irradiation times N_1 possible that will still allow angled formations within required forming angles in as few irradiation times as possible with the fixed laser power of 3.0 W. In order to make up for deficiencies in the angles formed by laser-scanning rates V_1 and laser-irradiation times N_1, the basic system is then to derive the smallest laser-scanning rates V_2 and shortest laser-irradiation times N_2 possible that will still complete formations at required angles. In case there are still some deficiencies in the angles formed, the same process can be repeated to derive laser-scanning rates V_n and laser-irradiation times N_n.

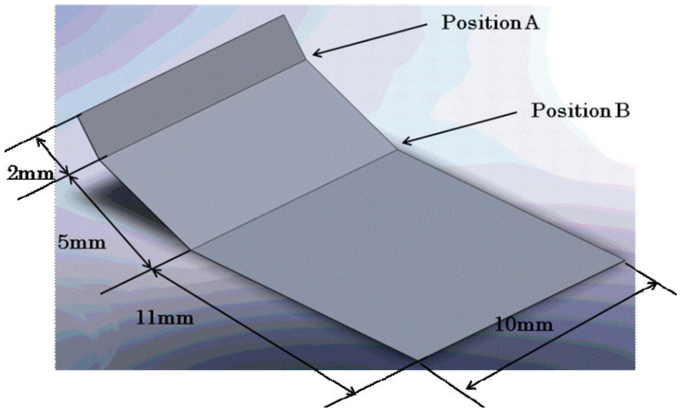


Fig. 5. Demand shape.

Table 1. Angle of bend of each model.

	Bending angle [°]	
	Position A	Position B
Model 1	60	20
Model 2	40	50
Model 3	30	70

5. Verification Experiments

5.1. Experimental Method

We have verified the effectiveness of the basic system developed. Forming attempts have been made with Models 1, 2 and 3 for required forming shapes (shown in **Fig. 5**) with angles (given in **Table 1**) at Positions A and B. We have used the same sheet material used to architect the forming database.

Forming work has been carried out on these models under the respective irradiation conditions as derived by the developed basic system. For Model 1 (Position A), irradiation has been conducted 11 times at the scanning rate of 25 mm/s, 2 times at 40 mm/s and once at 45 mm/s. For Model 1 (Position B), irradiation has been conducted 4 times at 25 mm/s, once at 40 mm/s, and 2 times at 45 mm/s. For Model 2 (Position A), irradiation has been conducted 7 times at 25 mm/s, 2 times at 35 mm/s, and 2 times at 45 mm/s. For Model 2 (Position B), irradiation has been conducted 10 times at 25 mm/s, once at 30 mm/s, and once at 45 mm/s. For Model 3 (Position A), irradiation has been conducted 6 times at 25 mm/s, once at 40 mm/s, and 3 times at 45 mm/s. For Model 3 (Position B), irradiation has been conducted 12 times at 25 mm/s and 4 times at 45 mm/s. With laser power set at 3.0 W, three forming attempts in each of the irradiation conditions have been conducted to check forming accuracies.

5.2. Experimental Results and Consideration

Figure 6 shows target forming angles at Positions A and B for Models 1, 2, and 3 and the actually formed angles (average values of three attempts ±SD). **Fig. 7** shows actually formed shapes of Models 1, 2, and 3. **Fig. 6** con-

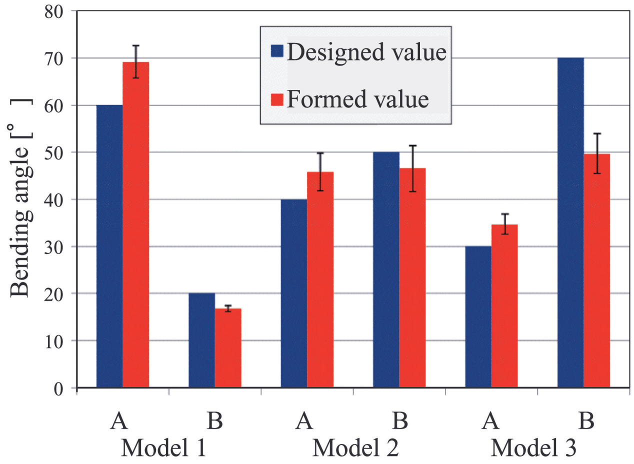


Fig. 6. Experimental results of angle of bend.

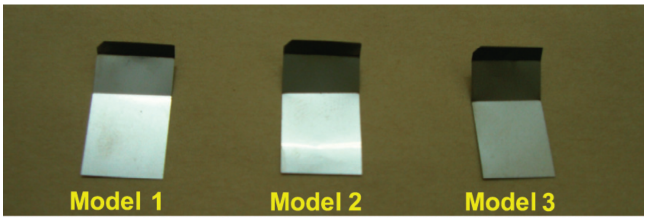


Fig. 7. Formed results.

trasts the forming errors with the required angles. Even miniscule variations may have great effects on bending formation since materials only 0.03 mm in thickness were used, but these errors may be attributable to the following factors:

- Sheet thickness
- Laser power
- Irradiation position
- Metal-cutting direction on workpiece
- Absorption rates of laser beam

6. Possibility of Forming Curved Surfaces

To check the possibility of forming curved surfaces, we have vertically irradiated the center of the sheet material once at the scanning rate of 50 mm/s, and then have horizontally shifted irradiation positions sequentially by 0.1 mm for a total of 30 line irradiations as shown in **Fig. 8**. As a result, we have succeeded in forming the semi-cylindrical shape shown in **Fig. 9**. This proves that it is possible with the developed basic system to form curved shapes as well.

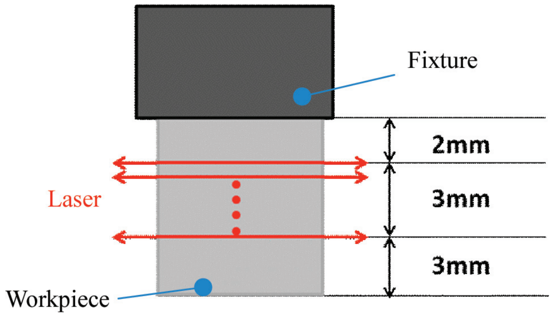


Fig. 8. Irradiation method.

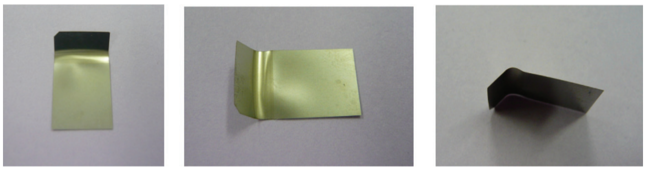


Fig. 9. Half-round sample.

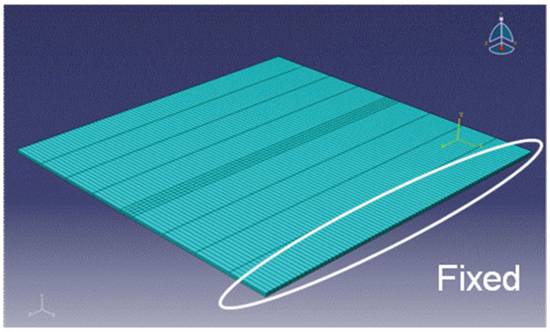


Fig. 10. Analytical model.

7. Possibility of FEM-Assistance in Architecting Forming Database and Possibility of Forming Curved Surfaces

7.1. Validation of Analytic Models and Analytic Methods

Actual data alone from forming experiments are not always sufficient for the architecture of a forming database. FEM-based analytic results are considered useful for complementing the forming database. We have conducted FEM-analyses on laser-forming work for validation purposes. Such validation is based on comparison with the experimental results in prior research [3, 4].

Analyses have been conducted with the nonlinear structural analysis system Abaqus. We have used as analytic models stainless steel SUS304 100 mm in width, 100 mm in length, and 1 mm in thickness, as shown in **Fig. 10**. Hexahedron quadratic elements with 20 contacts have been used as analytic elements. In setting material properties such as Young's modulus, Poisson's ratio, yield stress, thermal conductivity, specific heat and thermal expansion coefficients, we have taken into account their temperature dependences [3, 4]. We have established heat transfer to

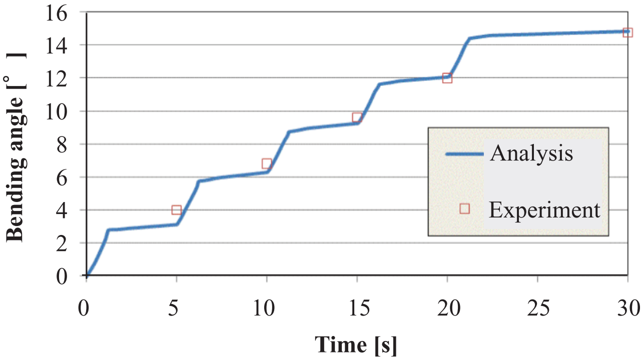
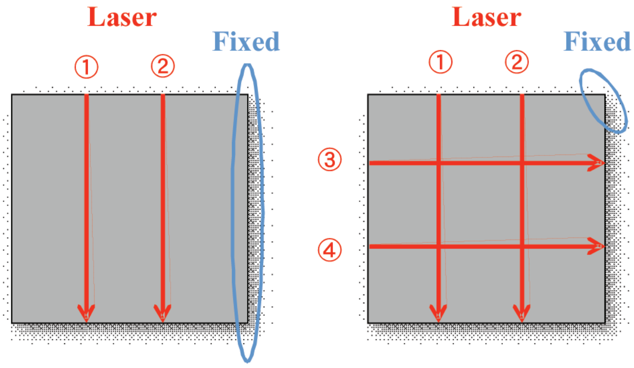


Fig. 11. Validity of the analysis.



(a) Pattern 1 (b) Pattern 2

Fig. 12. Irradiation procedure.

ambient conditions as boundary conditions. In conducting analyses, with one end of the test piece constrained against displacements, heat flows q of a carbon-dioxide gas laser have been applied to square regions of 5 mm × 5 mm on test piece surfaces on the assumption that carbon-dioxide gas-laser-irradiation points will have a diameter D of 5 mm. Heat flow q has been set as Gaussian distributions in Eq. (2), where sheet materials are assumed to have a laser-heat-flow absorption rate of 60%; W represents 60% of laser outputs; x and y denote distances from the laser center.

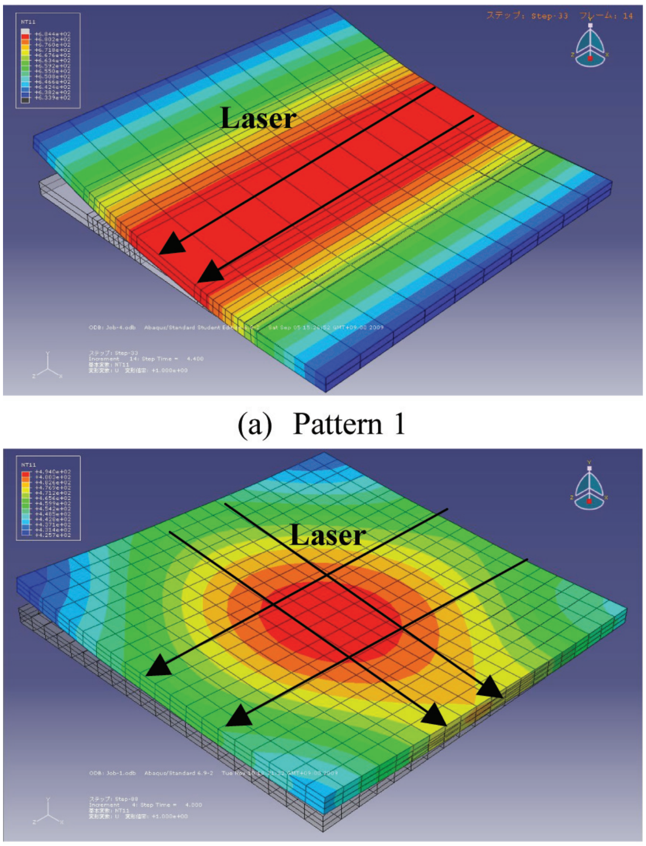
$$q = \frac{8W}{\pi D^2} \exp\left\{-\frac{8(x^2+y^2)}{D^2}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Laser-irradiation positions have been set by discretely shifting the center position of heat flows by $D/4$ each time. Heat-flow irradiation time for each position is determined by dividing shifting-distances ($D/4$) by scanning rates. We have employed heat-stress mixing analyses. In forming operations, laser-scanning with a laser output of 1500 W and a laser-scanning rate of 5 mm/s has been applied five times to the center of the sheet material (shown in **Fig. 10**).

The analytic results are shown in **Fig. 11**, where the solid line represents analytic results and square marks indicate experimental results in prior research [4]. According to the analysis, five laser irradiations achieved a bend of 14.83°, while prior experiments [4] accomplished an angle of 14.75°. This indicates that the analytic results correspond well with the experimental results. Thus, the validity of the analytic method has been confirmed. The architecture of the forming data base including FEM-analytic results has also been recognized as significant.

7.2. Possibility of Forming Curved Shapes

We have also checked the possibility of forming curved surfaces through the above-mentioned analytic method. As shown in **Figs. 12(a)** and **(b)**, laser-irradiation with a laser output of 1300 W and a laser-scanning rate of 150 mm/s has been applied to stainless steel SUS304 sheets 25 mm wide, 25 mm long, and 1 mm thick, at the positions and in the directions indicated by directional lines in the Figures. Analytic results of the aforementioned laser-irradiation attempts are shown in **Fig. 13**, which manifests the possibility of forming curved surfaces by the laser-forming method.



(b) Pattern 2

Fig. 13. Formation of curved surface.

8. Conclusion

In this research, we have developed a basic system for laser-forming sheet materials, and we have verified its effectiveness. We have also conducted laser-forming analyses by FEM and have confirmed the validity of the analyses. In addition, we have checked through experiments and analyses the possibility of forming curved surfaces. The outcomes of this research may be summarized as follows:

(1) Based on the forming results, we have proposed a method of architecting a database for deriving forming conditions and have architected a basic database.

(2) We have acquired required-forming-shapes as CAD data, and we have proposed, based on their analyses, a basic system by which to derive laser-irradiation positions and laser-irradiation conditions with reference to the database to derive forming conditions. We have also verified the effectiveness of this basic system.

(3) We have proposed an FEM-analytic method, have conducted FEM-analyses based on the proposed method, and have confirmed the validity of the proposed method by comparing the analytic results with the prior experimental results.

(4) We have confirmed the possibility of laser-forming curved surfaces through actual forming-experimental results and their analytic results.

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