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NUMERICAL SIMULATION AND EXPERIMENTAL INVESTIGATION OF LASER BENDING OF STEEL PLATE

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ABSTRACT

Numerical simulation and experimental investigation of the laser bending process of steel plate are discussed. A three-dimensional FEM simulation has been carried out, which includes a non-linear transient coupled thermal-structural analysis accounting for the temperature dependency of the thermal and mechanical properties of the material. The time-dependent temperature, stress, strain and bending angle have been obtained from the simulation. An experimental study was performed for laser parameters and plates of different thickness. The measurement of real-time temperature and bending angle was carried out. The simulation results are in agreement with the experimental results.

Keywords: Numerical simulation; Laser bending; Steel plate; Finite element method

1. INTRODUCTION

Laser forming is one of the new applications of the laser. The forming process utilizes the thermal stresses induced by a localized laser generated temperature gradient between the irradiated surface and the neighboring material. This temperature distribution forces the material to expand non-uniformly, which in turn leads to non-uniform thermal stresses. Where the thermal stresses exceed the yield point of the material, the latter deforms plastically. Laser forming is a much more controllable technique that offers numerous unique application possibilities. In recent years, laser forming has attracted considerable attention [1-11].

Laser forming technology began in the 1980s, and in that time, the development of laser forming technology was more concentrated on experimental studies [1,2]. In the 1990s, the mechanisms in laser forming were investigated [3,4]. In more recent times, the technique has been advanced through the development of a number of analytical [5,6] and finite element method (FEM) [7-11] mathematical models for various aspects of the laser forming process.

In this paper, numerical simulation and experimental investigation of the shipbuilding steel plate bending into a V-shape by the laser beam scanning have been performed. Plates in shipbuilding industry are thick plates so simulation of the laser bending process is complex and difficult. A three-dimensional FEM simulation is proposed for simulating the laser bending process, which includes a non-linear transient coupled thermal-structural analysis accounting for the temperature dependency of the thermal and mechanical properties of the material. The laser bending has also been investigated experimentally with a CO_2 laser.

2. FINITE-ELEMENT SIMULATION OF THE LASER FORMING PROCESS

Numerical simulation of the process was performed by means of a transient coupled thermal-structural analysis. For the analysis, the finite element code 'MSC.Marc' was used.
The thermal equilibrium equation for analysis of heat transfer can be written as

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda \frac{\partial T}{\partial z}) + q \quad (1)$$

Where ρ and C_p are density and specific of the material, respectively, λ is the heat conductivity and q is the rate of heat generation. Here, q is considered as the heat source generated by laser beam scanning.

To get the solution from the thermal equilibrium equation, boundary conditions and initial conditions are needed. The laser beam heating is applied as the surface heat source absorbed by the plate, so the boundary conditions of the top surface irradiated by the laser beam are considered as a moving surface thermal flux. The thermal load is given in the form of the thermal flux density as follows:

$$-\lambda \left.\frac{\partial T}{\partial n}\right|_{\Gamma_2} = \frac{AP}{d^2} \quad (2)$$

Where A is the absorption coefficient on the surface, P is the laser power, and d is the beam diameter.

The boundary conditions can be written as

$$\lambda \left.\frac{\partial T}{\partial n}\right|_{\Gamma_1} = h\ (T - T_a) \quad (3)$$

Where the radiation boundary condition is neglected, h is the natural convection exchange coefficient.

The initial condition for simulation is as follows:

$$T\big|_{t=0} = T_0 \quad (4)$$

Where T_0 is the room temperature.

The basic FEM equations for the thermal problem can be derived from the thermal equilibrium equation

$$[k_T]\{T\}+[n]\{\dot{T}\}=\{P\} \tag{5}$$

Where $[K_T]$ is the heat conduction matrix, $[n]$ is the heat capacity matrix, $\{T\}$ and $\{\dot{T}\}$ are nodal temperature vector and nodal temperature rate vector, respectively, and $\{P\}$ is the heat flux vector.

The elastic-plastic FEM equations is as follows:

$$[k]\Delta\{\delta\}=\Delta\{Q\} \tag{6}$$

Where $[k]$ is the tangential stiffness matrix, $\Delta\{\delta\}$ is the displacement incremental at the element nodes, $\Delta\{Q\}$ is the force vector, including applied nodal force and the force caused by thermal strain.

The basic equation for thermal-structural coupled calculation is as follows:

$$\begin{bmatrix}[0] & [0]\\ [0] & [n]\end{bmatrix}\begin{Bmatrix}\{\dot{u}\}\\ \{\dot{T}\}\end{Bmatrix}+\begin{bmatrix}[k] & [0]\\ [0] & [k_T]\end{bmatrix}\begin{Bmatrix}\Delta\{\delta\}\\ \{T\}\end{Bmatrix}=\begin{Bmatrix}\Delta\{Q\}\\ \{P\}\end{Bmatrix} \tag{7}$$

3. EXPERIMENTS

The experimental set-up for the laser bending process is shown in Fig.1. The CO_2 laser is controlled by a computer control system. The laser beam is 12 mm in diameter. With respect to the stationary laser beam, the plate moves during the scanning.

The temperature variation was measured on-line by thermocouples measuring system. Plates were heated along the centerline of the top surface, and temperature was measured at points on the bottom surface, which are 0, 6 and 12 mm from the centerline respectively. For the measurement of the bending angle of the plate during the laser bending process, a device comprising a displacement transducer was used.

The material used in this study was the shipbuilding steel. The material was received in plate form of 9, 11,and 13 mm thickness, the experiments being performed on 300×150 mm plates.

4. RESULTS AND DISCUSSION

The computed time-dependent temperature, stress, strain and bending angle are given for the case of a 300×150 mm plate of 9 mm thickness. The values that were selected for the laser parameters were 1300 W for the power, 2 mm/s for the velocity and 12mm for the beam diameter. All results refer to the central point of the plate in the scanning line.

As can be seen in Fig.2, radiation of the top surface by the laser beam yields to a rapid temperature increase at the irradiated surface, which leads to high temperature gradients between the top and the bottom plate surfaces.

Fig.3 shows the distribution of stress σ_x during the process. The stress is tensile from the top surface to the bottom surface in the heated zone at the beginning of the heating period and then changes rapidly. The stresses at the points are dropped to a maximum compressive stress. The maximum compressive stress also corresponds to the maximum achieved temperature. Then the stresses at the points of the top and bottom surface are increased rapidly to tensile stress, and the stress at the point of the middle surface is increased smoothly to a relatively smaller compressive stress. The obtained residual stresses cause tension at the top and bottom surface of the plate and compression in the middle surface of the plate.

Fig.4 shows the distribution of plastic strain ε_x during the scanning. It can be observed that at the points considered, when it starts to be heated, a tensile plastic strain appears. The compressive plastic deformation at the points of the top and middle surface has initiated when the maximum temperature is achieved. While at the bottom surface, the tensile plastic strain is increased to a maximum tensile plastic strain and then drops to a relatively smaller tensile plastic strain during the scanning. The distribution of this plastic strain is responsible for the achieved bending angle (Fig.9). The bending action is caused by the thermal stress in the plate upon the plastic deformation due to the extremely rapid heating and cooling process during the laser irradiation. The bending is in the direction away from the laser beam firstly with a minus bending angle and then toward the laser beam during the bending process. The residual strain is negative at the top surface and is positive at the bottom surface, which explains the formation of the bending angle towards the laser beam.

For evaluating the influence of the laser parameters and the thickness of the plates, a parametric experimental investigation was performed. Fig.5 shows the relationship between laser power and bending angle. It is obviously that the bending angle increases as the laser power increases. Fig.6 shows the effect of laser beam scanning speed on the bending angle. The bending angle is decreased with the increase of the scanning speed. Fig.7 shows the relation between the number of scanning passes and the bending angle for each different plate thickness. The bending angle is increased with the number of scanning passes. The relatively thin plate is more easily bent. The bending angle decreases with an increase in thickness in relation to the laser power and the scanning speed.

The results of the experimental investigation have also been utilized to evaluate the simulation results for the case of a 300×150 mm plate of 9 mm thickness. The values that were selected for the laser parameters were 1300 W for the power, 2 mm/s for the velocity and 12mm for the beam diameter. In fig.8, the computed results of the temperature distribution at the bottom surface during the laser bending process and the respective experimental results are compared. In fig.9, the computed results of the bending angle and the respective experimental results are compared. The available simulated temperature distribution and bending angles are in agreement with the experimental results.

5. CONCLUSIONS

Numerical and experimental investigation of the laser forming process has been performed. The following conclusions have been reached.

1. A 3-D FEM model has been developed which includes coupled transient thermal-structural analysis accounting for the temperature dependency of the thermal and mechanical properties of material. The time-dependent temperature, stress and strain as well as the bending angle can be obtained by computer simulation. The available simulated temperature distribution and bending angle are in agreement with the experimental results.

2. Experimental study was carried out on the influence of the laser parameters and the thickness of the plates. The bending angle is increased with the increase of laser power and the number of laser beam scanning passes, decreased with the increase of the thickness of plates and the laser beam scanning speed in the given experimental conditions.

6. ACKNOWLEDGEMENTS

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FIGURES

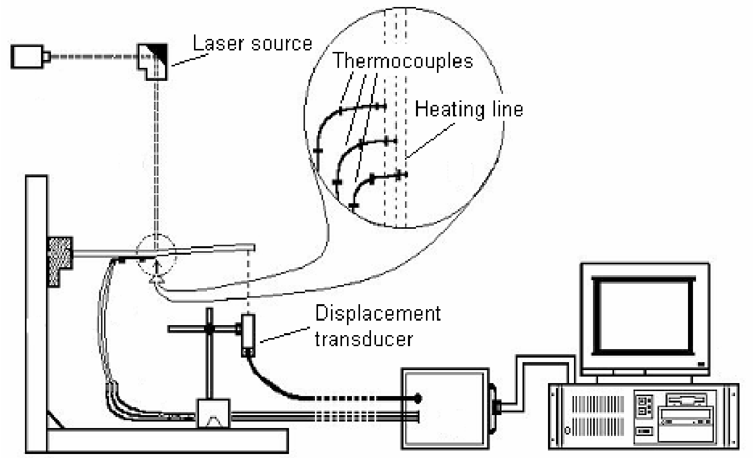

Fig.1 Experimental set-up for the laser bending process

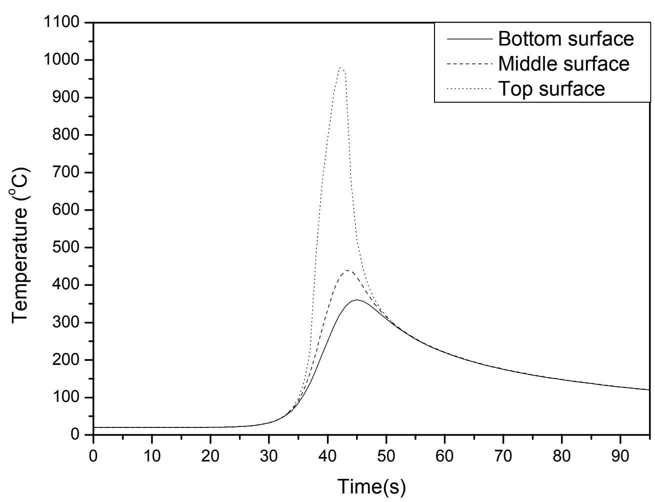

Fig.2. Temperature distribution during laser beam scanning by simulation

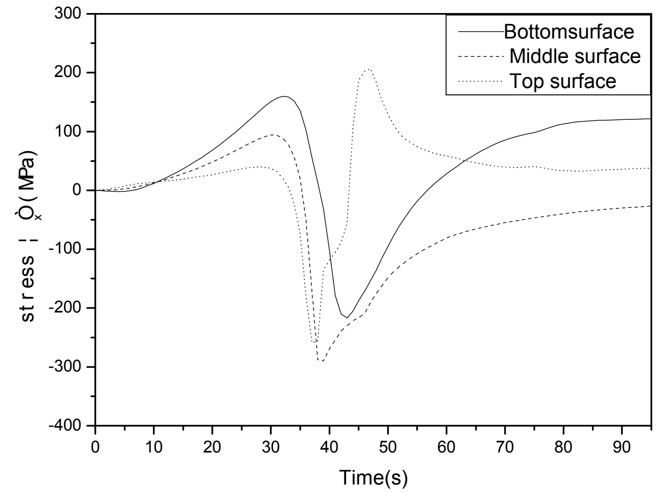

Fig.3. Distribution of stress σ_x during laser beam scanning by simulation

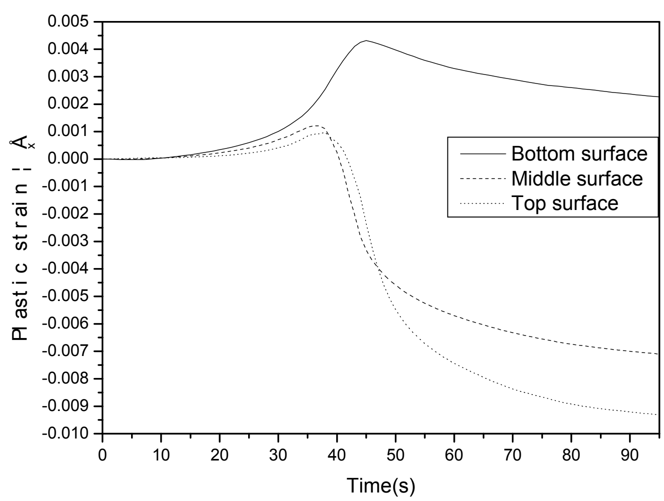

Fig.4. Distribution of plastic strain ε_x during laser beam scanning by simulation

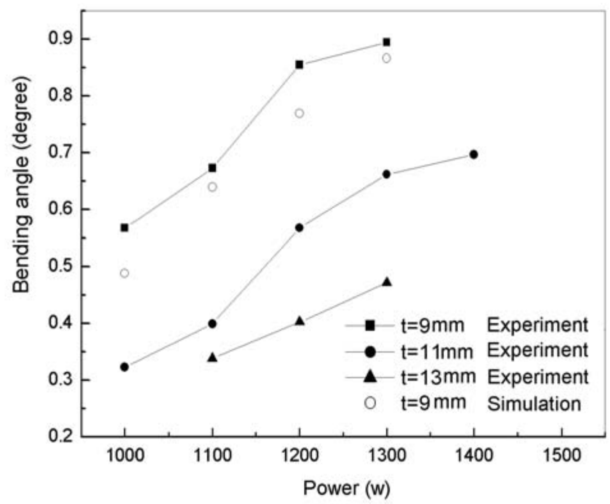

Fig.5. Relationship between laser power and bending angle

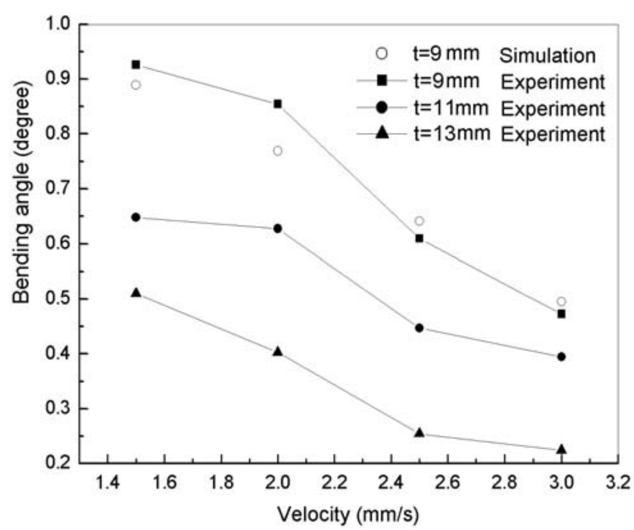

Fig.6. Relationship between scanning speed and bending angle

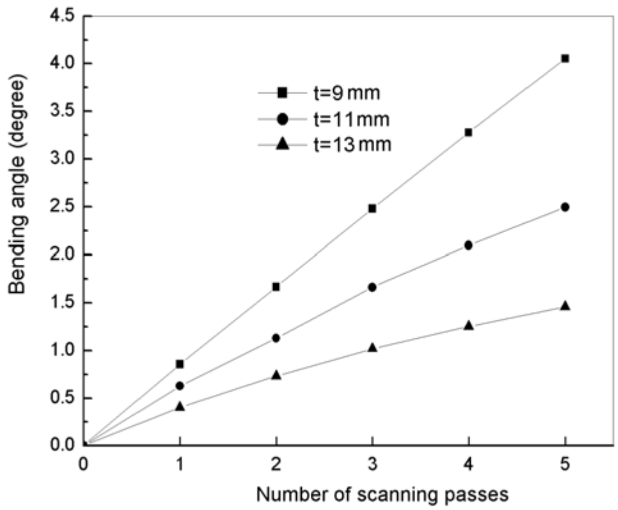

Fig.7. Relationship between scanning pass and bending angle

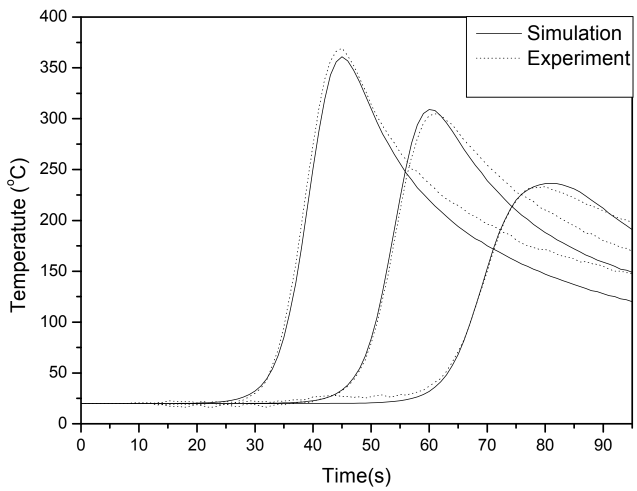

Fig.8. Comparison of temperature between simulation and experimental results

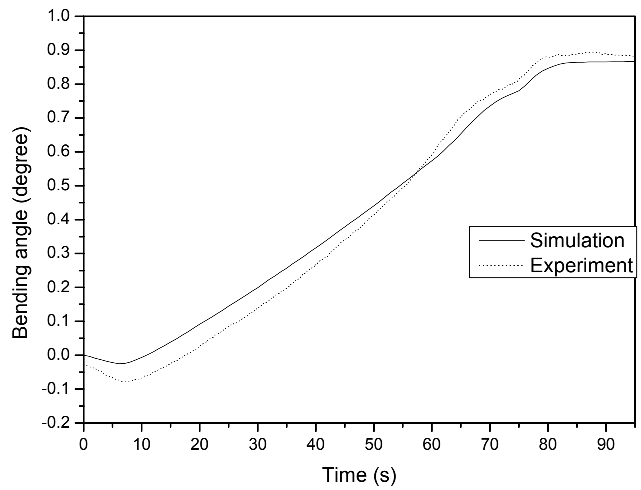

Fig.9. Comparison of bending angle between simulation and experimental results