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Laser bending of metal sheet and thermal stress analysis

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ABSTRACT

Laser bending of a steel sheet is examined. Temperature and stress fields are predicted using the finite element code in line with the experimental conditions. The predictions of surface temperature, bending angle, and residual stress formed at the laser scanned surface are validated with the experimental data. Morphological and metallurgical changes in the laser treated region are investigated by incorporating the optical and electron scanning microscopes, energy dispersive spectroscopy, and X-ray diffraction. It is found that predictions of surface temperature, bending angle, and residual stress agree well with the experimental data. The self-annealing effect of the recently formed laser scanning tracks influences stress fields and displacement in the workpiece. Although high pressure nitrogen assisting gas is used in the experiments, the formation of few scattered cavities is observed along the laser scanning tracks at the surface because of the evaporation.

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1. Introduction

Laser forming finds applications in sheet metal industry due to precision of operation and local treatment. The bending process differs slightly from the laser welding such that laser forming requires shallow depth of phase change at the surface while laser welding requires deep penetration of the laser beam into the substrate material. From the heating point of view, the irradiated surface undergoes solid heating and melting following the solidification for the forming process. Since the laser heating and phase change process is almost rapid, the high cooling rates are resulted during the solidification of the melted regions. This causes attainment of high temperature gradients across the irradiated zone while increasing the thermal strain in this region. Depending on the magnitude and the nature of the residual stress generated, compressive or tensile, bending of irradiated substrate takes place towards or opposite to the irradiated surface of the workpiece. Since the laser heating and cooling processes are rapid, the size of the heat affected zone becomes narrow, which in turn provides advantages of the local treatment by a laser beam. In some cases, the formation of high residual stress results in crack formations in the bended region while limiting the practical use of the bended parts. Consequently, investigation of the laser bending and thermal stress levels in the bended region becomes essential.

Considerable research studies have been carried out to examine the laser induced bending process. The effect of laser beam geometries on laser bending of sheet metal was examined by Jamil and Sheikh [1]. They showed that temperature-dependent yield stress played more dominant role in the deformation of the plate than the spread of the beam intensity in the transverse direction. Simulation of laser bending angle of sheet metals due to different laser parameters was carried out by Peng and Hongwei [2]. They indicated that dimensional analysis was an effective method in simulating the complex laser bending process, and the control model, which came from non-dimension group datum, had high accuracy in predictive analysis of bending angle. The transient analysis for laser induced bending was presented by Chen et al. [3]. They showed that the temperature gradient computed from the non-Fourier heat transfer equation was slightly larger than that computed from the classic Fourier heat transfer equation. This, in turn, resulted in different bending angles. Finite element modeling of laser bending of pre-loaded sheet metals was carried out by Yanjin et al. [4]. Their findings revealed that the bending angle of the sheet metal increased remarkably with the increase of the pre-loading and both were almost in exponential relationship. Laser bending of sheet metals was examined by Shichun and Jinsong [5]. They demonstrated that there was a significant influence of the sheet thickness on the bending angle; however, this influence became less important with increasing sheet thickness. Deformation behavior of laser bending of circular sheet metal was investigated by Nadeem and Na [6]. They introduced the possible ways to achieve the geometrical transition from rectangular to circle and ring shapes through laser heating. The residual stresses development in laser bending of stainless steel sheet metal was studied by Gheorghies et al. [7]. They indicated that the effect of multiple scans was difficult to simulate due to the complications involved when incorporating

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the material annealing during forming. The sheet metal bending using a pulsed Nd:YAG laser was examined by Gollola et al. [8]. They identified the effects of process parameters such as laser power, beam diameter, scanning speed and pulse duration, on the bending angle. Sheet metal bending with medium-power diode laser was investigated by Chen et al. [9]. They showed that the maximum bend angle depended mainly on the material thickness and the laser power intensity distribution across the bend line. Numerical and experimental study on laser forming process was carried out by Yongxiang et al. [10]. Their findings revealed that a continuous decrease in bending angle from concave to convex took place with increasing specimen thickness. Femtosecond laser forming of sheet metal was examined by Sagisaka et al. [11]. They indicated that, using the femtosecond lasers, small changes in the processing parameters and scanning paths resulted in forming of various shapes.

Although laser induced bending was investigated previously [12,13], the work presented was limited to experimental investigations including the corrosion response of the bend sections and the model study describing the physical processes did not incorporate the self-annealing effect of the laser scanning tracks. Therefore, the present study is carried out to examine the laser bending of steel plate incorporating the self-annealing effect on temperature and stress fields. The predictions of bend angles are compared with its counterparts obtained from the experiment. The metallurgical and morphological changes in the bend section are examined using the analytical tools.

2. Heating and stress analysis

Laser heating situation is involved with a moving volumetric heat source scanning the workpiece surface as depicted in Fig. 1.

In the numerical solution, the user subroutine DFLUX in ABAQUS [14] is used to introduce the volume flux described by Eq. (1). The subroutine first calculates the position of the laser beam according to the scanning time, t, and then computes the heat flux, Q, at each integration point. The Gauss parameter "a" is taken as 0.0003 m and a velocity of 10 cm/s is used in line with the experimental conditions.

In the thermal analysis, the solid body heat conduction and phase change with temperature-dependent conductivity, internal energy (including latent heat effects), and convection and radiation boundary conditions are considered. The Fourier heat transfer equation for the laser heating process can be written as

$$\rho \frac{DE}{Dt} = (\nabla(k \nabla T)) \tag{1}$$

where E is the energy gain of the substrate material, ρ is the material's density, and k is the thermal conductivity. In the case of a moving heat source along x-axis of the sheet with a constant velocity U, energy gain of the substrate material yields

$$\rho \frac{DE}{Dt} = \rho \frac{\partial E}{\partial t} + \rho U \frac{\partial E}{\partial x} \tag{2}$$

or

$$\rho \frac{DE}{Dt} = \rho \frac{\partial (C_p T)}{\partial t} + \rho U \frac{\partial (C_p T)}{\partial x} \tag{3}$$

Combining Eqs. (1) and (3) yields

$$\rho \frac{\partial (C_p T)}{\partial t} = (\nabla(k \nabla T)) + \rho U \frac{\partial (C_p T)}{\partial x} \tag{4}$$

where C_p is the specific heat. To analyze the phase change problem, the enthalpy method is used [14]. The specific heat is associated with the internal energy gain of the substrate material. However, the internal energy gain during the phase change is associated with the latent heat of fusion, which is given separately in terms of solidus and liquidus temperatures (Table 1) and the total internal energy associated with the phase change, called the latent heat. Since the primary interest is the stress field developed in the cutting section, the flow field generated in the liquid phase at the kerf surface during the laser cutting process is omitted.

The convective and radiation boundary conditions are considered at the free surface of the workpiece. Therefore, the corresponding boundary conditions are

At the irradiated surface

$$\frac{\partial T}{\partial z} = -\frac{I_{max}}{k}(1 - r_f) e^{(-(x^2+y^2)/a^2)} + \frac{h_f}{k}(T_s - T_{amb}) + \frac{\varepsilon \sigma}{k}(T_s^4 - T_{amb}^4) \tag{5}$$

where I_{max} is the laser power peak density, a is the Gaussian parameter, r_f is the surface reflectivity, x, y and z are the axes, and h_f=3000 W/m^2 K [15] is the forced convection heat transfer coefficient due to the assisting gas.

At the rear side of the surface

$$\frac{\partial T}{\partial y} = \frac{h}{k}(T_s - T_{amb}) + \frac{\varepsilon \sigma}{k}(T_s^4 - T_{amb}^4) \;\&\; \frac{\partial T}{\partial z} = \frac{h}{k}(T_s - T_{amb}) + \frac{\varepsilon \sigma}{k}(T_s^4 - T_{amb}^4) \tag{6}$$

where h=20 W/m^2 is the heat transfer coefficient due to natural convection, and T_s and T_{amb} are the surface and ambient temperatures, respectively, ε is the emissivity (ε=0.9 is considered), σ is the Stefan–Boltzmann constant (σ=5.67 × 10^{-8} W/m^2 K^4). Initially (prior to laser heating), the substrate material is assumed to be

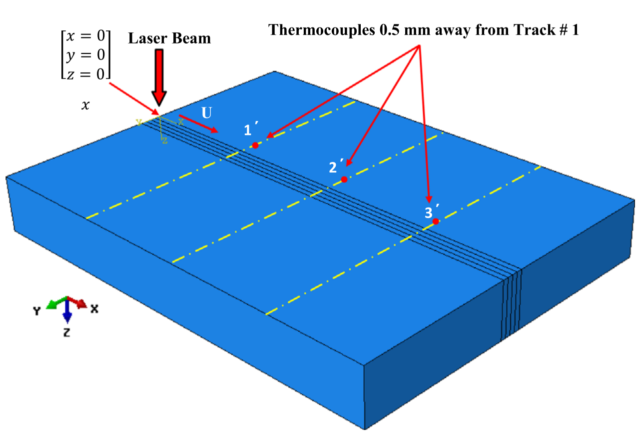

Fig. 1. Schematic view of laser heating situation and the coordinate system.

Table 1
Properties used in the simulations [24–27]. Density=8030 kg/m^3, latent heat=300,000 J/kg, solidus temperature=1673 K, liquidus temperature=1728 K, Poisson's ratio=0.3, strength coefficient=1.4 GPa and n=0.44.

Temperature (K)	Thermal conductivity (W/m K)	Specific heat (J/kg K)	Modulus of elasticity, $E \times 10^{11}$ Pa	Expansion coefficient $\times 10^{-5}$ 1/K
300	14	456	1.95	1.6
473	15	532	1.83	1.67
673	17.5	557	1.71	1.76
873	21	599	1.52	1.83
1073	25	620	1.33	2.0
1273	28	645	1.24	2.1

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