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Laser forming of plates using rotating and dithering beams

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ABSTRACT

Laser forming is a useful process for flexible forming, during which a laser beam causes deformation of a plate. In this work we introduce a new method for laser forming of plates that is laser forming with rotating and dithering beam. In laser heat treatment of steel some method is used to produce a wider and nearly uniform average irradiance profile. It may be achieved by rotating the beam optically, thereby producing an overlapping spiral track or by dithering the beam (rocking the lens or mirror) perpendicular to the track, thus producing a zigzag pattern. In this study an analytical solution and a numerical solution is developed for a transient heat conduction equation in which a plane slab is heated by a rotating or dithering laser beam over the upper surface. The temperature distribution was then input as a body load for the three-dimensional nonlinear structural analysis to determine the bending angle and distortions. The result of structural analysis show that the bending angel of laser forming using rotating and dithering beam in similar condition are several times more than the bending angel of laser forming using a beam which move along a straight line with uniform velocity.

1. Introduction

Laser forming is a novel technique, during that a laser beam causes thermal expansion locally, and deformation is achieved by scanning the laser beam across one side of the material. The temperature gradients that are developed through the material induce distortion because the temperature changes with thickness that causes different expansion of adjoining layers. Laser forming is currently used because of its technical benefits of it do not require external forces and thus reduces cost and increases flexibility. In past years, considerable attention has been paid to the comprehending the laser forming mechanisms and in investigating the effects of laser forming parameters on the deformed shape and mechanical properties of the formed parts [1–3]. In the recently years, in particular, considerable research has been done on computer modeling of the laser forming process of plates [3–7].

Yongjun Shi [3] conducted one of the comprehensive research on the mechanisms of laser forming for the metal plate. Based on the study of thermal transfer and elastic–plastic deformation, he explained the mechanisms of laser forming further. In addition, he proposed a new mechanism, coupling mechanism. Zhenqiang Yao [4] pioneered the study of laser forming with pre-load. He carried out a numerical investigation on the effects of various pre-loads on the bent angle of laser forming process. He found that pure compression and pure bending toward the laser beam can increase the bent angle, while the pure tension and pure bending away from the laser beam will decrease the bent angle. Hong Shen [5] used a three-dimensional nonlinear, indirectly coupled thermal–structural model to investigate the laser forming with two laser beams which scanning simultaneously along two parallel lines. He made this numerical investigations to research the difference in temperatures and plastic deformations between the two simultaneously laser scans and the single sequential scan along the same lines. He found that the plastic deformation of simultaneously laser scans is larger if the distance between the two scanning lines is smaller than the size of plastic zone of single laser scan. Liu [6] conducted one of the first investigations on the laser forming of a composite material. He investigated the deformation mechanism of an aluminum matrix composite during laser forming with different volume fractions of particle reinforcement. He carried on this investigation by using a microstructure-integrated finite element method. He found that the bending angle of the composite increased with an increase in volume fraction of particles.

For laser heat treatment there are three approaches to use a wider and more uniform heat intensity distribution:

The first one is achieved by rotating the beam optically, thereby producing an overlapping spiral track or by dithering the beam (rocking the lens or mirror) perpendicular to the track, thus producing a zigzag pattern. Fig. 1 is an illustration of these techniques. The second one is achieved by the use of a bimodal (TEM_{11}) shaped laser beam. Unfortunately it is difficult to maintain a high-quality, high-order mode over a long period of time; also the beam may not be symmetrical which complicates matters if contour tracks are required. The third one is achieved by the use of not-so-sharp focused high-peak power, low order (TEM_{00}) mode Gaussian laser beam [7].

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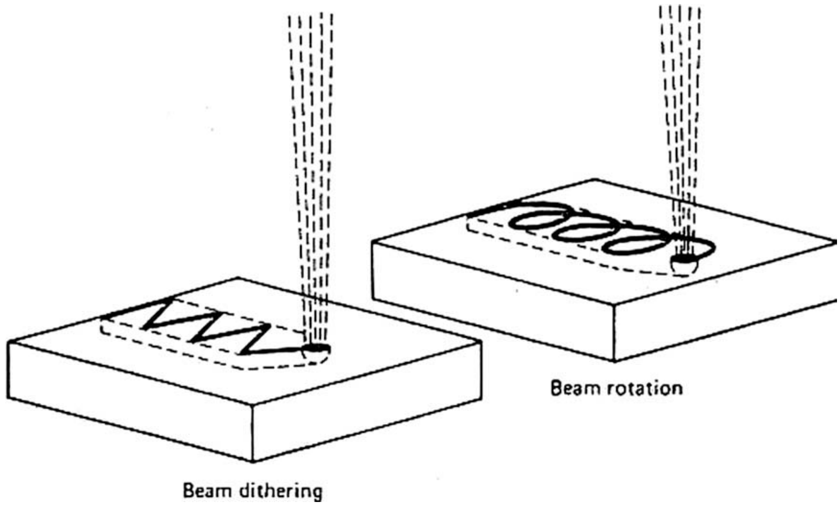

Fig. 1. Active methods for spreading out a laser beam for laser heat treatment applications [7].

In all the previous work the laser forming by a laser beam which moving with uniform velocity along a straight line was modeled. This paper presents a study on the laser forming of plates using rotating or dithering beam. The results obtained from this study show that the bending angel of laser forming using rotating and dithering beam in similar condition are several times more than the bending angel of laser forming using a beam which move along a straight line with uniform velocity.

2. Laser forming analysis procedure

The heat which produced due to plastic deformation is very small and can be ignored [8]. Thermo-structural problem can then be decoupled and solved sequentially in two steps. A transient thermal analysis was first carried out to determine temperature distribution which was then input as a body load for the structural analysis to determine the residual stresses and distortions.

Ansys/explicit could be used to model both the initial load (thermal load), and to determine the final distortion. Ansys programming language (APDL) was used to model the laser beam motion scheme, and subsequent application of thermal loads in the structural analysis. The convergence toward the final distortion state is extremely slow. A number of techniques have been used to facilitate rapid convergence, but none have been sufficiently applicable and reliable. The thermal results of the FEM model compared with the results of an analytical model to examine the accuracy of FEM result.

3. Thermal modeling

The transient thermal field in laser forming was modeled by employing both three-dimensional analytical model and finite element model. In finite element model the laser beam was considered as a moving plane heat flux to establish the temperature rise distribution in the workpiece. While in analytical model laser beam was considered as an internal heat generation.

3.1. Analytical model

An analytical model, based on the renowned transient heat conduction equation, was used to establish the temperature rise as a function of time and step $T(r, t)$ in the material under the action of a laser beam that move with different moving patterns:

$$\rho c_p \frac{\partial T}{\partial t} + \nabla(-K\nabla T) = f(r,t) \tag{1}$$

where ρ, K and c_p are the density, thermal conductivity and specific heat of the material. The internal heat generation term $f(r, t)$, at the right side of Eq. (1), is identified as the energy distribution of the laser beam.

If ρ, c_p and K are temperature and position independent, Eq. (1) is taken in the form,

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} - \nabla^2 T = \frac{f(r,t)}{K} \tag{2}$$

where $\alpha = K/\rho c_p$ is the thermal diffusivity.

In the case of three-dimensional transient, nonhomogeneous heat conduction problem given by Eq. (2), the solution for $T(r, t)$ is expressed in terms of the three-dimensional Green's function [9],

$$T(r,t) = \frac{\alpha}{K}\int_{\tau=0}^{t} d\tau \int_R G(r,t|r',\tau)f(r',\tau)dv' + \int_R G(r,t|r',\tau)|_{\tau=0}F(r')dv' \tag{3}$$

where $F(r')$ is the initial temperature distribution.

The three-dimensional Green's function can be obtained from the product of the three one-dimensional Green's function as in rectangular coordinates:

$$G(x,y,z,t|x',y',z',\tau) = G1(x,t|x',\tau)\cdot G2(y,t|y',\tau)\cdot G3(z,t|z',\tau) \tag{4}$$

where each of the one-dimensional Green's functions $G1$, $G2$ and $G3$ depends on the extent of the region (i.e., finite, semi-infinite, or infinite) and the boundary conditions.

The one-dimensional infinite medium Green's function (for *x*- and *y-directions)* is obtained as [9]:

$$G1(x,t|x',\tau) = [4\pi\alpha(t-\tau)]^{-1/2}\exp\left(-\frac{(x-x')^2}{4\alpha(t-\tau)}\right) \tag{5a}$$

and for *y-direction*

$$G2(y,t|y',\tau) = [4\pi\alpha(t-\tau)]^{-1/2}\exp\left(-\frac{(y-y')^2}{4\alpha(t-\tau)}\right) \tag{5b}$$

The one-dimensional Green's functions in *Z-direction* is a function of depth. To find the desired Green's function in *Z-direction* the auxiliary problem in *Z-direction* which should be considered is,