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Closed-form solutions for 2-D axisymmetric modeling of thermal-stress in solid material induced by an annular long pulsed laser irradiation

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ABSTRACT

In this paper, 2-D axisymmetric modeling of thermal-stress of solid material induced by an annular long pulsed laser was presented using closed-form solutions. Physical model of annular long pulsed laser irradiation was established and closed-form solutions of thermal-stress were obtained by analytical method based on thermo-elasticity theory. Thermal-stress of silicon material induced by an annular long pulsed laser was simulated. Results show that, when the silicon material is irradiated by an annular long pulsed laser, the thermal-stress on the surface of the material is the largest, and with the increase of the depth, the thermal-stress is gradually reduced. On the silicon surface, when the inside radius of the annular laser is fixed, the greater the outside radius, the larger region of the higher thermal-stress occupies. When the width between inside radius and outside radius of the annular laser is fixed, for the radial component of the thermal-stress, the smaller the irradiation center location, the greater the maximum value of stress; for the hoop and axial components, the difference of the maximum stress for different irradiation center location is not obvious. With the increase of the pulse width of annular long pulsed laser, the maximum value of the thermal-stress is also gradually increased.

1. Introduction

When the solid material is irradiated by a long pulsed laser, the absorption of laser energy will transform into heat and which will diffuse into the inside of material through heat conduction. Then, there exists a non-homogenous temperature field that creates temperature gradient in the material. The temperature gradient and deformation restraint of material lead to the generation of thermal-stress in the material. Under a certain temperature rise and thermal-stress, the characteristics of material will change in different extent. Therefore, study of the temperature rise and thermal-stress induced by laser irradiation is very important to reveal the physical mechanism of laser-matter interaction.

In recent years, there are many studies due to the temperature rise problems of laser irradiation [1–10]. And some scholars researched on the thermal stress problems of laser irradiation. Laser heating of sheet metal is formulated analytically and thermal-stress field is obtained using finite element method by Khan, and it is found that laser scanning speed influences considerably temperature and thermal-stress [11]. D.W. Tang obtained the thermal stress relaxation processes in Al films of 20–50 μm thickness by comparison of the calculated temperature rise and thermal expansion. Their results show that

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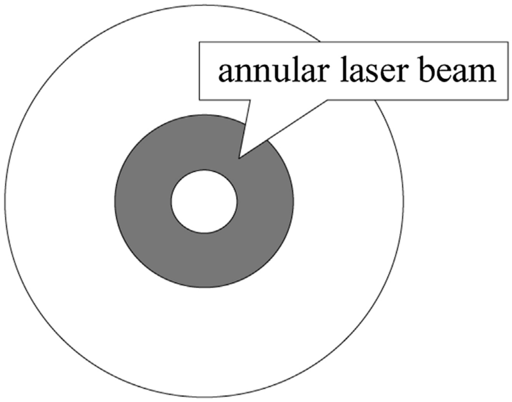

Fig. 1. Schematic diagram of annular laser irradiation.

thermal stress exists even in the case of uniform temperature distribution and free expansion for laser transient heating [12]. Naqavi presented the time exponentially varying pulse laser heating of four and two layer assemblies and stress levels considering the elasto-plastic problem using a numerical control volume approach [13]. A closed-form solution for thermal stress developed in the substrate material due to volumetric pulse heating is presented by Yilbas, and it is found that thermal stress wave is tensile in the surface region and it becomes compressive at some depth below the surface for stress free condition at the surface [14]. Yilbas obtained closed-form solutions for temperature and stress fields due to a laser pulse decaying exponentially in time using Laplace transformation method, and stresses in the surface region and inside the substrate were investigated [15].

In current researches on thermal-stress induced by laser irradiation, most of them are solid lasers, but in practice, more of them use the annular lasers. In this paper, modeling of thermal-stress in solid material induced by annular long pulsed laser irradiation is presented using closed-form solutions. This paper is organized as follows. In Section 2, the physical model of thermal-stress is established based on thermo-elasticity theory, and integral transform method is used to solve the governing thermo-elasticity equations and closed-form solutions of thermal-stress are obtained. Modeling of thermal-stress in silicon material for different parameters is studied in Section 3. Our main conclusions are summarized in Section 4.

2. Mathematical modeling

2.1. Temperature modeling

The temperature gradient is the reason that causes the thermal-stress in the material, so we first study the temperature modeling of the annular long pulsed laser heating. The classical Fourier heat transfer equation for laser heating with a 2-D axisymmetric form can be written as [16]:

$$\frac{\partial^2 T(r,z,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,z,t)}{\partial r} + \frac{\partial^2 T(r,z,t)}{\partial z^2} + \frac{Q(r,z,t)}{k} = \frac{1}{\alpha}\frac{\partial T(r,z,t)}{\partial t} \tag{1}$$

where, k is the thermal conductivity, $\alpha = k/\rho c$ the thermal diffusivity, ρ the mass density and c the heat capacity of the material. The temperature T is defined here as a function of (r, z, t), and variable ranges of the positional arguments r, z are $0 < r \le R, 0 < z \le H$ respectively.

In Eq. (1), $Q(r, z, t)$ represents the source function of the annular laser heating. If we assume that the annular laser intensity distribution is flattened profile as shown in Fig. 1, and the energy gain mechanism of the material to the laser is the body absorption, then $Q(r, z, t)$ can be expressed as:

$$Q(r,z,t) = I_0\left(1 - r_f\right)\delta \exp\left(-\delta z\right) f(r) g(t) \tag{2}$$

where, I_0 is the laser power density, r_f is the reflection coefficient, δ is absorption coefficient of the material, $f(r)$ is the radial distribution function of annular laser intensity and its expression is:

$$f(r) = \begin{cases} 1, & r_1 \le r \le r_2 \\ 0, & r < r_1 \text{ or } r > r_2 \end{cases} \tag{3}$$