Optik 135 (2017) 389–394

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Modeling of annular long pulsed laser heating solid material using closed-form solutions

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ARTICLE INFO

Article history:
Received 5 November 2016
Accepted 28 January 2017

Keywords:
Annular laser
Long pulsed laser
Laser heating
Closed-form

ABSTRACT

In this paper, modeling of annular long pulsed laser heating solid material was presented using closed-form solutions. Heat conduction model of annular long pulsed laser heating was established and analytical solutions for temperature were obtained by integral transform method. Annular long pulsed laser heating silicon material was modeled for different parameters. Modeling results show that, when the silicon material is irradiated by an annular long pulsed laser, the temperature rise in the region of laser irradiation is higher than that in the region of no laser irradiation. On the silicon surface, the temperature rise is the largest. And as the depth increases, the temperature rise decreases gradually. When the inside radius of the annular laser is fixed, the greater the outside radius, the larger region of the higher temperature rise. But the difference of temperature rise is not obvious for different laser irradiation areas. When the width between inside radius and outside radius of the annular laser is fixed, with the irradiation center location toward the edge of the material, the region of higher temperature rise is also close to the edge of the material, and the maximum of the temperature rise is located in the irradiation center. With the increase of pulse width of the annular long pulsed laser, the maximum value of the temperature rise is also gradually increased.

1. Introduction

Analysis of thermal effects of material can be used in many fields such as laser damage and laser processing. Numerical simulation of such physical problems not only can replace expensive experiments, but also can indicate the influence of various parameters on the results and deepen the understanding of interaction process of laser with matter. Moreover, analytical solution is an important method to model laser heating due to its closed-form representation of the physical quantity. Comparing with the pure numerical methods such as the finite element method or the finite difference method, the closed-form analytical method is not only able to obtain the exact results rapidly, but also investigate the internal relations of physical problems in the solving process. These advantages have important significance in the study on the interaction mechanism of laser with matter and the multi-parameters inversion or optimization of laser heating [1–10].

Considerable research studies were carried out to solve the laser heating using closed-form modeling. Yilbas obtained a closed-form solution for a step input laser heating pulse. In their studies, in order to validate the closed-form solution, an experiment is conducted to measure the surface temperature and evaporating front velocity during the Nd–YAG laser heating process [11]. The closed-form solution for the temperature rise due to the time exponentially varying pulse is obtained using

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http://dx.doi.org/10.1016/j.ijleo.2017.01.101

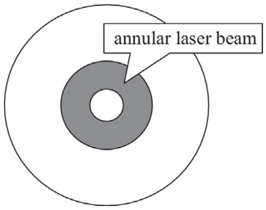

Fig. 1. Schematic diagram of annular laser irradiation.

Laplace transformation method by Kalyon and Yilbas [12], and the effects of the boundary condition at the surface and pulse parameters on the temperature profiles are examined in detail. Kalyon derived a closed-form solution of the dimensionless temperature rise including the cooling cycle for repetitive pulse laser heating using Laplace transformation method. It is found that the magnitude of the maximum surface temperature is influenced by the cooling period of two successive pulses. The rapid response of material to heating pulses is more pronounced in the region just below the surface [13]. Laser step input pulse heating of a two-layer assembly is considered and the closed-form solution for temperature distribution in the assembly is obtained by Yilbas and Ali [14]. In their studies, Laplace transformation method is introduced to solve the governing equation of heat conduction, and the practical example for temperature formulation is presented for a two-layer assembly consisting of steel and nickel.

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

2. Mathematical modeling

The classical Fourier heat transfer equation for an annular long pulsed laser heating with a 2-D axisymmetric form can be written as [15]:

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

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 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:

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

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 laser intensity and its expression is:

$$f(r) = \begin{cases} 1, & r_1 \le r \le_2 \\ 0, & r < r_1 \quad \text{or} \quad r > r_2 \end{cases} \tag{3}$$

where r_1 and r_2 are the inside and outside radius of annular laser. In Eq. (2), $g(t)$ is the temporal distribution function of the laser intensity, for the single pulsed laser, $g(t)$ yields:

$$g(t) = \begin{cases} 1, & 0 \le t \le t_p \\ 0, & t > t_p \end{cases} \tag{4}$$

where t_p is the pulse width of the incident laser beam.

It is assumed that the boundary conditions of Eq. (1) are adiabatic as:

$$-k\frac{\partial T(r,z,t)}{\partial r}\bigg|_{r=R} = 0 \tag{5}$$

$$-k\frac{\partial T(r,z,t)}{\partial z}\bigg|_{z=0} = -k\frac{\partial T(r,z,t)}{\partial z}\bigg|_{z=H} = 0 \tag{6}$$