International Journal of Heat and Mass Transfer 111 (2017) 367–373

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

A semi-analytical solution for 2-D axisymmetric modeling of repetitive pulse laser heating with body absorption

Guibo Chen, Juan Bi *

School of Science, Changchun University of Science and Technology, Changchun 130022, PR China

ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form 4 February 2017
Accepted 5 April 2017

Keywords:
Body absorption
Repetitive pulse
Semi-analytical solution
Laser heating

ABSTRACT

In the forthcoming paper (Chen et al., 2017), we presented an analytical solution for two-dimensional (2-D) modeling of repetitive pulse laser heating with surface absorption using the method of separation of variables combining with Laplace transform. But in practice, it often confronts the body absorption for the laser heating. Unfortunately, the above method due to the surface absorption is no longer suitable to the body absorption. In this paper, a semi-analytical solution for 2-D axisymmetric modeling of repetitive pulse laser heating with body absorption is obtained using the integral transform method. The method is validated by comparing with the results of existing finite element method. Temperature distributions for different repetitive pulses heating Silicon are modeled, and some physical mechanisms of repetitive pulses heating are analyzed. Results show that: repetitive pulse laser heating has obvious temperature intermittent cumulation effect; in the thin layer of material surface vicinity, temperature rises due to absorption of irradiated energy dominates over the conduction energy transport from surface to vicinity, and as the depth increases, the absorption decreases, whereas the conduction enhances; the shape of radial distribution of temperature is similar to that of the radial distribution of laser intensity for both Gaussian and flat top laser.

1. Introduction

Repetitive pulse laser heating material is widely used in laser processing or laser damage [2]. When the surface of material is irradiated by a repetitive pulse laser, the absorption of material to the incident laser is presented in an intermittent cumulation mode, so it has the energy accumulation effect and can provide sufficient energy deposited onto the material, but the single pulse or continuous wave (CW) laser does not have it [3].

The theoretical modeling of laser heating is of great significance for revealing the laser heating mechanism or the other laser applications, because it can reduce the cost of experimental research, as well as more conditions can be simulated than the experimental research [4–6]. Moreover, analytical modeling can provide more useful information because it can establish a direct relationship between variables and physical parameters, so it has received wide attention both in the single pulse and the repetitive pulse laser heating [7].

In recent years, there are some studies on the analytical modeling of repetitive pulse laser heating materials. Khenner et al. [8] obtained an analytical solution of the classical heat conduction problem for a solid film with a surface that is simply deformed and irradiated by repetitive laser pulses using the method of separation of variables. In their studies, convective heat losses from the surface and the film-substrate interface are taken into account. Kalyon and Yilbas [3] 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. Nath et al. [9,10] presented 1-D analytical solutions for the temperature profiles of heating and cooling cycles in repetitive pulse laser irradiation, and effects of various process parameters such as laser power, beam diameter, scan speed, pulse duration, repetitive frequency and duty cycle on the laser surface hardening were studied.

Chen et al. [1] presented an analytical solution for 2-D modeling of the repetitive pulse laser heating using the method of separation of variables combining with Laplace transformation, and temperature distributions for different radial locations, axial locations, duty cycles and repetitive frequencies are calculated. Unfortunately, this method is only suitable to the surface absorption, and cannot be used to solve the body absorption problem. But in practice, it often

* Corresponding author.
E-mail address: custcb@126.com (J. Bi).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.04.014
0017-9310/

Nomenclature

I_0	laser peak power intensity (W/m^2)
$g(t)$	temporal distribution function of the laser intensity
$P(t)$	pulse function
r_0	waist radius of the Gaussian pulse laser (m)
t	time (s)
Δt	duration time for heating (s)
T	temperature (K)
δ	absorption coefficient (/m)
ρ	density (kg/m^3)
c	specific heat (J/kg K)
k	thermal conductivity (W/m K)
T_0	initial temperature (K)
α	Thermal diffusivity (m^2/s)
r_f	reflection coefficient
R	radius of material plate (m)
H	thickness of material plate (m)
b_0	spot radius of flat top laser (m)
J_0, J_1	Bessel functions

confronts the body absorption for the laser heating. In addition, it is assumed that the laser intensity distribution is flat top in [1], but Gaussian pulse laser is also more often used in applications.

In this paper, we develop a semi-analytical solution for 2-D axisymmetric modeling of repetitive Gaussian pulse laser heating with body absorption. To the best of our knowledge, a detailed analytical study of the 2-D heat transfer with body absorption induced by a repetitive pulse laser is not in the existing literature.

This paper is organized as follows. In Section 2 we introduce the mathematical modeling and semi-analytical solution of the temperature distributions induced by a repetitive pulse laser heating with body absorption. Results of temperature distribution for different repetitive pulses laser are presented in Section 3. Our main conclusions are summarized in Section 4.

2. Mathematical modeling

The Fourier heat transfer equation for a laser heating with a 2-D axisymmetric form can be written as [11]:

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

where k is the thermal conductivity of the material, $\alpha = k/\rho c$ is the thermal diffusivity, ρ is the mass density and c is the heat capacity. The temperature T is defined here as a function of(r,z,t),and variable ranges of the positional arguments r,z are $0 < r \leqslant R$, $0 < z \leqslant H$ respectively (as shown in Fig. 1).

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

$$Q(r,z,t) = I_0(1-r_f)\delta\exp(-\delta z)\exp\left(-\frac{r^2}{r_0^2}\right)g(t) \quad (2)$$

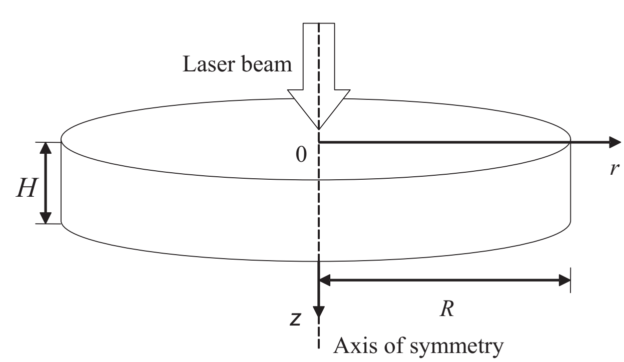

Fig. 1. Schematic diagram of laser irradiation material surface.

where r_f is the reflection coefficient, I_0 is the peak power intensity, r_0 is waist radius of Gaussian beam, δ is absorption coefficient of the material, $g(t)$ is time distribution function of repetitive laser intensity and yields:

$$g(t) = L_1P_1(t) + L_2P_2(t) + \ldots + L_{N_P}P_{N_P}(t) \quad (3)$$

where $L_1, L_2, \ldots, L_{N_P}$ are the amplitudes of pulse, and N_P is the total pulse number. The pulse function $P_1, P_2, \ldots, P_{N_P}$ can be given by:

$$\begin{aligned} P_1 &= u(t-t_1) - u[t-(t_1+\Delta t_1)] \\ P_2 &= u(t-t_2) - u[t-(t_2+\Delta t_2)] \\ &\vdots \\ P_{N_P} &= u(t-t_{N_P}) - u[t-(t_{N_P}+\Delta t_{N_P})] \end{aligned} \quad (4)$$

where $u(*)$ is the unit step function, t_j $(j = 1,2,\ldots,N_P)$ is the time for beginning of the j-th pulse, and Δt_j $(j = 1,2,\ldots,N_P)$ is the duration time for heating of the j-th pulse. The schematic diagram of the repetitive pulse is given in Fig. 2.

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

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

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

and the initial condition yields:

$$T(r,z,t)|_{t=0} = T_0 \quad (7)$$

In order to solve the Eqs. (1)–(7), forward and inverse transforms for $T(r,z,t)$ about r are introduced based on integral transformation method [11] and written as:

$$T(r,z,t) = \sum_{n=1}^{\infty}\frac{J_0(\mu_n r)}{C_1(\mu_n)}\cdot\bar{T}(\mu_n,z,t) \quad (8)$$

$$\bar{T}(\mu_n,z,t) = \int_0^R r' J_0(\mu_n r')T(r',z,t)dr' \quad (9)$$

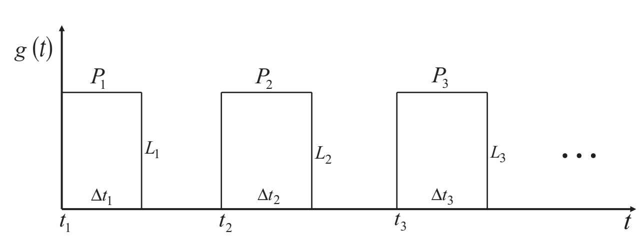

Fig. 2. Schematic diagram of the repetitive pulse.