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Modeling of long pulse laser thermal damage of Silicon using analytical solutions

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ABSTRACT

In this paper, we present the modeling of long pulse laser thermal damage of Silicon using analytical solutions. Firstly, the two-dimensional axisymmetric physical model of the temperature rise problem for long pulse laser heating is established. By using the integral transformation method, analytical solutions of the heat conduction equation are obtained. Then, temperatures in the surface and inside of the Silicon are modeled, and the change characteristics and rules of the radial and axial distributions of temperature are studied. Finally, an analytical expression for the melting damage threshold of Silicon is given, and the threshold of different radial distances is analyzed.

1. Introduction

The long pulse laser has been widely used in many fields such as industry, military and so on, because of its high energy density and good heating effects. The modeling of long pulse laser-matter interaction is an important method to obtain the heating mechanism of long pulse laser, it is able to reduce the experimental cost and minimizes the experimentation time [1,2]. Moreover, modeling studies can provide results of laser heating for sufficient conditions even if in the environment that traditional experiment cannot achieve. The modeling method of laser heating can be divided into numerical modeling and analytical modeling. Analytical modeling establishes a direct functional relationship between the parameters and the laser heating process, which can provide very useful information for revealing mechanism of the irradiation effects and parameters optimization of the laser [3–10]. Considerable research studies were carried out to solve the laser heating using analytical modeling. The absorption mechanism of the material on the laser energy is studied and 1-D analytical solution to the temperature rise problem of the laser heating is given by Ready [11]. El-Adawi studied on the 1-D analytical solutions of heat conduction in homogeneous material and two layered material respectively [12,13]. A closed-form solution for temperature rise inside solid substrate due to time exponentially varying laser pulse was obtained using Laplace transform by Yilbas [14]. Gospavic studied the 2-D axisymmetric analytical solution of the thermal effect problem of laser irradiation [8]. Yilbas introduced analytical simulation methods and the related results of laser heating in the application field systematically [1].

In this paper, the Silicon material is selected as the example bulk. It is organized as follows. In Section 2 we introduce the physical model and analytical solutions of heat transfer problems induced by a long pulse laser heating Silicon bulk with body absorption. Results of temperature distributions for different cases are presented in Section 3. Our main conclusions are summarized in Section 4.

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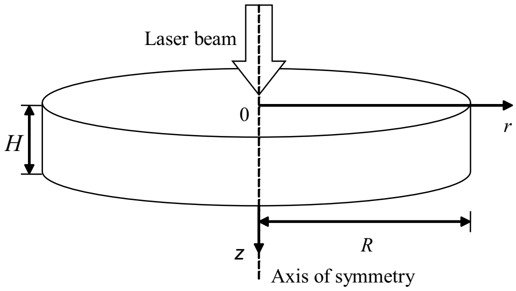

Fig. 1. Schematic diagram of laser irradiation material surface.

2. Physical model

The classical Fourier heat transfer equation for a long pulse 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 $0 < r \leq R$,$0 < z \leq H$ respectively (as shown in Fig. 1).

In Eq. (1), $Q(r, z, t)$ represents 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:

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

where, I_0 is the laser power density,r_f is the reflection coefficient, δ is absorption coefficient of the material, r_0 is the waist radius of laser. $g(t)$ is the temporal distribution function of the laser intensity, for the single millisecond pulse laser, $g(t)$ yields:

$$g(t)=\begin{cases}1, & 0\leq t\leq t_p\\ 0, & t>t_p\end{cases} \tag{3}$$

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:

$$-k\frac{\partial T(r,z,t)}{\partial r}\Big|_{r=R}=0 \tag{4}$$

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

and the initial condition yields:

$$T(r,z,t)|_{t=0}=T_0 \tag{6}$$

In order to solve the Eqs. (1)–(6), forward and inverse transform pairs for $T(r, z, t)$ about r are introduced based on integral transformation method [15] and written as:

$$T(r,z,t)=\sum_{n=1}^{\infty}\frac{J_0(\mu_n r)}{C_1(\mu_n)}\cdot\bar{T}(\mu_n,z,t) \tag{7}$$

$$\bar{T}(\mu_n,z,t)=\int_0^R r'J_0\left(\mu_n r'\right)T\left(r',z,t\right)dr' \tag{8}$$

where, $J_0(\mu_n r)$ is the zero order Bessel function of the first kind, $\mu_n\,(\mu_n \geq 0, n = 1, 2, 3, \cdots)$ is the n-th root of equation $J_1(\mu_n R) = 0$, $C_1(\mu_n)$ is the normalization integral as:

$$C_1(\mu_n)=\int_0^R r'J_0^2\left(\mu_n r'\right)dr'=\begin{cases}R^2/2 & \mu_n=0\\ R^2J_0^2(\mu_n R)/2 & \mu_n\neq 0\end{cases} \tag{9}$$