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Estimating the absorptivity in laser processing by inverse methodology

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Abstract

In the present study, a conjugate gradient method is applied to estimate the unknown time-dependent laser absorptivity during a laser processing, based on available temperature measurements. It is assumed that no prior information is available for the functional form of the unknown absorptivity. But depending on the temperature history at a measuring position, the unknown time-dependent absorptivity can be estimated by an inverse analysis. The accuracy of the current method is examined by using the simulated exact and inexact temperature measurements. Results show that excellent agreement on the absorptivity can be obtained for all the test cases considered in this study. Subsequently, accurate melting depth and temperature distributions can also be returned. The methodology presented here can also be applied to other various applications, such as calculating the cutting forces in nanomachining by atomic force microscopy (AFM), and estimating the heat sources in a X-ray lithographic process.

Keywords: Inverse problem; Laser processing; Absorptivity; Conjugate gradient method

1. Introduction

Laser has been widely used in microelectronics, aerospace, and other higher-precision applications [1,2]. The use of laser technology provides flexible, precise, and efficient processing for thermal machining. The laser does not come into contact with workpiece during operation and is suitable for use on brittle and hard materials, which are difficult to cut by mechanical force. When laser is irradiated on a material surface, a portion of laser energy is absorbed and conducted into the interior of the material. If the absorbed energy is high enough, material surface will melt and the melting front will propagate into the workpiece.

The analysis of the transient heat transfer problem for laser processing is especially complicated, since it involves not only phase changes but also the movement of the melting front, which is an interface between the solid and liquid phases. It is well known that, to simplify the analysis, most of the literature usually assumed the laser absorptivity of the material to be constant. However, this contradicts to the reality that

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the absorptivity is a time-dependent quantity. Furthermore, this quantity is also difficult to measure, which makes the prediction of laser processing problem a challenging task.

In this paper, the laser machining is treated as an inverse heat transfer problem with the unknown time-dependent laser absorptivity to be determined. A direct heat transfer problem is concerned with the determination of melting depth and temperature at the interior of a region when initial and boundary conditions and thermophysical properties are specified. In contrast, an inverse heat transfer problem considered in this study involves the determination of the unknown time-dependent absorptivity in laser machining from the knowledge of the temperature measurements taken within the body. The technique of conjugate gradient method (CGM) [3,4] is applied to estimate the time-dependent absorptivity by using the simulated temperature measurements. Subsequently, the melting depth and temperature distributions of the material can also be calculated. One of the advantages of the conjugate gradient method is that an iterative regularization is implicitly built into the computational procedure. In addition, it does not require prior information for the functional form of the unknown quantities to perform the inverse calculation. Therefore it is a very powerful analysis tool and has been widely used in various applications [5–8] to solve function-estimation problems. The conjugate gradient method includes the following problems: the direct problem, the sensitivity problem, and the adjoint problem, which are discussed in the following section.

2. Analysis

To illustrate the methodology for developing expressions for use in determining the unknown time-dependent laser absorptivity $A(t)$ in laser machining, we consider the following transient heat conduction problem. As shown in Fig. 1, a uniform laser heat flux $A(t)I$ is irradiated on a semi-infinite slab, where I is the power density of laser beam. In here, the absorptivity $A(t)$ is time-dependent. As the surface temperature of the slab becomes greater than the slab material's melting temperature, a solid–liquid interface is formed, which would move deeper into the slab as time advances. Let $X(t)$, called the melting depth, refer to the solid–liquid interface measured from the surface $x = 0$ at any time t. Because the absorptivity $A(t)$ is unknown, an inverse heat conduction problem has to be solved.

2.1. Direct problem

Neglecting the surface heat loss and assuming constant thermophysical properties, the one-dimensional heat conduction problem in a semi-infinite slab during laser processing can be expressed as [9]

$$k_1 \frac{\partial^2 T_1(x,t)}{\partial x^2} - \rho_1 c_1 \frac{\partial T_1(x,t)}{\partial t} = 0, \quad 0 \leqslant x \leqslant X(t), \tag{1a}$$

$$k_s \frac{\partial^2 T_s(x,t)}{\partial x^2} - \rho_s c_s \frac{\partial T_s(x,t)}{\partial t} = 0, \quad X(t) \leqslant x \leqslant \infty, \tag{1b}$$

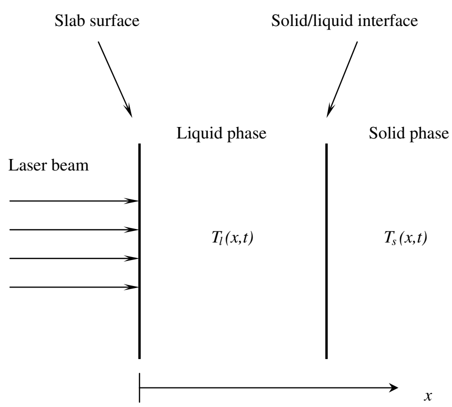

Fig. 1. Laser process on a semi-infinite slab.