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Function estimation of laser-induced heat generation in a gas-saturated powder layer heated by a short-pulsed laser

Yu-Ching Yang [a,*], Haw-Long Lee [a], Win-Jin Chang [a], Wen-Lih Chen [b]

[a] Clean Energy Center, Department of Mechanical Engineering, Kun Shan University, No. 195, Kun-Da Rd., Yung-Kang Dist., Tainan 710-03, Taiwan, ROC
[b] Department of Aeronautics and Astronautics, National Cheng Kung University, No. 1, University Rd., Tainan 701, Taiwan, ROC

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ABSTRACT

In this study, an inverse algorithm based on the conjugate gradient method and the discrepancy principle is applied to solve the inverse heat conduction problem with a dual-phase-lag equation for estimating the unknown space- and time-dependent laser-induced heat generation in a gas-saturated porous medium exposed to short-pulse laser heating from the temperature measurements taken within the medium. Subsequently, the powder particle temperature distributions in the porous medium can be determined as well. The temperature data obtained from the direct problem are used to simulate the temperature measurements. The effect of measurement errors on the estimation accuracy is also investigated. The inverse solutions are justified based on the numerical experiments in which two different forms of heat generation are estimated. Results show that the unknown laser-induced heat generation can be predicted precisely by using the present approach for the test cases considered in this study.

1. Introduction

Selective area laser deposition vapor infiltration (SALDVI) is a developing solid freeform fabrication (SFF) technique in which a 3D component can be fabricated by depositing solid material from gas precursors into the porous layer of loose powders and repeating this layer-by-layer infiltration procedure until the shape is formed [1]. A moving laser source is commonly used to produce the desired chemical vapor infiltration (CVI) into the powder layer in a spatially controlled manner. Because the CVI process can deposit a variety of desirable materials in pure form, SALDVI is capable of building ceramic and composite bodies and shapes with functionally graded compositions such as embedded devices in a single machine [2,3]. In addition, SALDVI has a great potential due to several inherent features like to produce fully dense shapes without post processing, can make wide materials selection, and can overcome the dimensional constraints that are present in traditional chemical vapor infiltration techniques [4].

In SALDVI, the laser-induced temperature distributions are found to affect the shape and densification rate of the infiltrated region as well as the final mechanical properties. In addition, among other parameters, the size and geometry of the densified part depend in large part on the distribution of the laser-induced processing temperature. Therefore, an understanding of the temperature distribution in the SALDVI process is very important to achieve insight into the effect of various process parameters on the shape of the SALDVI workpiece. Many numerical modeling efforts have been carried out to investigate the effect of various processing parameters on the SALDVI process [5–7].

In the past several decades, inverse analysis has been widely applied to solve engineering problems. In the heat transfer area, external inverse problems include estimation of temperature, heat flux, or heat transfer coefficient [8,9], and internal inverse problems include determination of heat generation and thermophysical properties, such as thermal conductivity and heat capacity [10,11].

The focus of the present study is to solve the inverse heat conduction problem with a dual-phase-lag equation, for estimating the unknown space- and time-dependent laser-induced heat generation in a gas-saturated porous medium exposed to short-pulse laser heating, from the knowledge of temperature measurements taken within the medium. Subsequently, the powder particle temperature distributions in the porous medium can be determined as well. To the best of the authors' knowledge, this study is the first in the literature that estimates the unknown quantities in a gas-saturated porous medium exposed to short-pulse laser heating through an inverse method. Here, we present the conjugate gradient method (CGM) [12–14] and the discrepancy principle [15] to estimate the unknown space- and time-dependent laser-induced heat generation by using the simulated temperature measurements. The CGM derives from the perturbation principles and transforms the inverse problem to the solution of three problems, namely, the direct, the sensitivity, and the adjoint problem, which will be discussed in detail in the following sections.

* Corresponding author.
E-mail address: ycyang@mail.ksu.edu.tw (Y.-C. Yang).

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Nomenclature

c	specific heat (J kg^{-1} K^{-1})
d	optical penetration depth (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
I_0	laser fluence (J m^{-2})
J	functional
J'	gradient of functional
k	thermal conductivity (W m^{-1} K^{-1})
L	thickness of powder layer (m)
M	total number of thermocouples
P	direction of descent
R	reflectivity
S	laser-induced heat generation (W m^{-3})
t	time coordinate (s)
t_p	full-width at half maximum pulse width (s)
T	temperature (K)
T_∞	ambient temperature (K)
x	space coordinate (m)
x_i	temperature measurement position (m)
Y	measured temperature (K)
Greek symbols	
Δ	small variation quality
α	thermal diffusivity (m^2 s^{-1})
β	step size
γ	conjugate coefficient
ε	very small value
η	coupling factor (W m^{-3} K^{-1})
θ	new dependent variable, $\theta_s = T_s - T_\infty$ (K)
λ	variable used in the adjoint problem
ξ	transformed time coordinate (s)
ρ	density (kg m^{-3})
σ	standard deviation
τ_q	phase lag of heat flux (s)
τ_T	phase lag of temperature gradient (s)
φ	porosity
ϕ	new measured temperature, $\phi_s = Y_s - T_\infty$ (K)
ϖ	random variable
Superscripts/subscripts	
g	gas
K	iterative number
s	solid phase (particle)

2. Analysis

2.1. Direct problem

The physical model of the problem under consideration is shown in Fig. 1. A powder layer with a thickness L and an initial temperature T_∞ is subjected to a short-pulse laser heating. Due to the porous nature of the powder layer, the laser heat source can penetrate the powder layer and the laser energy is absorbed within the powder layer, not just only at the surface of the powder layer. It is assumed that heat transfer is one-dimensional along the thickness of the powder layer because the size of the laser beam is much larger than the thickness of the powder layer. The effect of chemical reaction heat on heat transfer along the thickness of the powder layer is negligible [5]. The porosity of the powder layer during irradiation of a single pulse is assumed to be constant due to the small amount of deposition in the duration of one short pulse. The convection effect in the gas phase is neglected since the pulse duration is very short. Under these assumptions, the problem becomes a simple heat conduction problem in a gas-saturated porous medium with an internal heat source.

Since the precursors and the particles are not in thermal equilibrium, a two-temperature model is employed to describe the heat transfer in the precursors and particles. The energy equations for the powder particles and the precursors can be respectively expressed as [4]:

$$(1-\varphi)(\rho c)_s \frac{\partial T_s(x,t)}{\partial t} = \frac{\partial}{\partial x}\left[k_{se}\frac{\partial T_s(x,t)}{\partial x}\right] + S(x,t) - \eta\left[T_s(x,t) - T_g(x,t)\right], \tag{1}$$

$$\varphi(\rho c)_g \frac{\partial T_g(x,t)}{\partial t} = \eta\left[T_s(x,t) - T_g(x,t)\right], \tag{2}$$

where φ is the porosity, k_{se} is the effective thermal conductivity of the powder layer, and η is the coupling factor between powder particles and precursors, respectively. The effective thermal conductivity of the powder layer is $k_{se} = (1-\varphi)k_s$. In arrival to Eq. (2), heat conduction in the gas phase has been neglected because the conductivity of the gas is several orders of magnitude lower than that of the powder material. In addition, light intensity of the laser beam appears as the volumetric heat source term $S(x,t)$.

Combining Eqs. (1) and (2), the following energy equation can be obtained:

$$\frac{\partial^2}{\partial x^2}\left[\theta_s(x,t) + \tau_T\frac{\partial \theta_s(x,t)}{\partial t}\right] + \frac{1}{k_{se}}\left[S(x,t) + \tau_q\frac{\partial S(x,t)}{\partial t}\right] = \frac{1}{\alpha}\frac{\partial}{\partial t}\left[\theta_s(x,t) + \tau_q\frac{\partial \theta_s(x,t)}{\partial t}\right], \tag{3}$$

where α is the effective thermal diffusivity. The elevation temperature $\theta_s(x,t)$ is defined as $\theta_s(x,t) = T_s(x,t) - T_\infty$, and the phase lag times of the heat flux and temperature gradient are:

$$\tau_q = C_s C_g/\eta(C_s + C_g), \quad \tau_T = C_g/\eta, \tag{4}$$

and

$$C_s = (1-\varphi)(\rho c)_s, \quad C_g = \varphi(\rho c)_g, \tag{5}$$

where C_s and C_g are effective heat capacities of the solid and gas phases, respectively. The effective thermal diffusivity is:

$$\alpha = k_{se}/(C_s + C_g). \tag{6}$$

Eq. (3) describes the temperature response with lagging accommodating the first-order effect of τ_T and τ_q. It captures several representative models in heat transfer as special cases. This equation reduces to the diffusion equation in the absence of the two phase lags, $\tau_T = \tau_q = 0$. In the absence of the phase lag of the temperature gradient, $\tau_T = 0$, it reduces to the hyperbolic thermal wave model.

The initial and boundary conditions for the temperature of powder particle are assumed given below [4]:

$$\theta_s(x,t) = 0, \quad \text{for } t = 0, \tag{7}$$

$$\frac{\partial \theta_s(x,t)}{\partial t} = 0, \quad \text{for } t = 0, \tag{8}$$

$$-k_{se}\frac{\partial \theta_s(x,t)}{\partial x} = h\theta_s(x,t), \quad \text{at } x = 0, \tag{9}$$

$$\frac{\partial \theta_s(x,t)}{\partial x} = 0, \quad x = L. \tag{10}$$

It is evident from Eq. (3) that the dual-phase-lag process depends on the phase lag times and thermal diffusivity. The phase lag times, in turn,