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Entropy generation rate during laser pulse heating: Effect of laser pulse parameters on entropy generation rate

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Abstract

Laser pulse heating of solid surface and entropy generation during the heating process are considered. Time exponentially decaying pulse is accommodated in the analysis and the laser pulse parameter (β_1/β_2) resulting in minimum entropy generation rate is computed. Analytical solutions for temperature rise are presented and volumetric entropy generation rate is formulated. Two laser pulses resulting in low volumetric entropy generation rate are examined in detail and volumetric entropy generation rate is associated with the laser pulse parameter (β_1/β_2). It is found that volumetric entropy generation rate attains high values in the early heating period due to large ($1/T^2$). Moreover, the laser pulse with high-peak intensity results in lower volumetric entropy generation rate than that corresponding to the low-intensity laser pulse with the same energy content.

Keywords: Laser; Pulse; Temperature; Entropy generation rate

1. Introduction

Laser pulse heating of solid surfaces finds application in metal industry due to rapid processing, precision of operation, and local treatment. In this case, the depth of annealed surface as shallow as a few μm to a fraction of μm can be achieved. Analytical modeling of the heating process provides closed form solution for temperature rise in the irradiated region. This, in turn, enables one to optimize the process parameters to reduce the experimental time and cost. The thermodynamic irreversibility in the thermal system lowers the second law efficiency and gives insight into the thermal quality of the process. Moreover, thermodynamic irreversibility can be quantified through entropy generation rate. Minimum entropy generation rate can be considered to be a key issue for the efficient thermal processing. Consequently, entropy generation rate can be minimized and laser pulse parameters resulting in minimum entropy generation rate can be identified for the efficient heating process. Therefore, investigation into entropy generation rate and identifying the laser pulse parameters minimizing entropy generation rate during the laser heating process becomes essential.

Considerable research studies were carried out to examine analytically the laser heating process. Ready [1] introduced analytical solution for a constant intensity laser pulse heating process. The closed form solution was limited with the constant intensity pulse applications. Yilbas [2] obtained a closed form solution for temperature rise during the laser heating process using the Laplace transformation method. His solution was also limited with the constant intensity pulse applications. Blackwell [3] provided analytical solution for the laser heating process. The closed form solution assumed exponentially decaying pulse and pulse variation including intensity change was neglected. Time exponentially varying pulse was considered by Yilbas [4] and the exact solution was obtained using the Laplace transformation method. However, the pulse optimization for efficient processing was left obscure in the study. Analytical model for laser pulse heating of embedded biological targets was presented by Mirkov et al. [5]. They developed a mathematical model for the laser-induced heating and cooling processes.

Laser pulse heating and entropy generation was investigated by Yilbas [6]. He formulated entropy generation

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Nomenclature

C_P	specific heat (J/kg K)
I_0	laser peak power intensity (W/m^2)
k	thermal conductivity (W/m K)
Q	heat flux (W/m^2)
r_f	reflection coefficient
t	time (s)
T	temperature (K)
T_1	temperature for first laser pulse parameter (β_1) (K)
T_2	temperature for first laser pulse parameter (β_2) (K)
$\dot{S}_{gen}$	volumetric entropy generation rate (W/m^{3}K)
$\dot{S}^*_{gen}$	dimensionless volumetric entropy generation rate
U	internal energy (J/kg)
x	spatial location (m)
α	thermal diffusivity (m^2/s)
β	laser pulse parameter (1/s)
δ	absorption coefficient (1/m)
ρ	density (kg/m^3)

rate and computed numerically during the heating and cooling phases of the laser pulse. Entropy generation rate during laser short-pulse heating was also examined by Yilbas [7]. He introduced entropy production rate due to thermal coupling of electron and lattice sub-systems. The irreversible thermodynamic analysis for thermal conduction was carried out by Jou and Casas-Vazquez [8]. They indicated that the irreversibility analysis provided useful information when the perturbation of the system were fast enough so that their frequency become comparable to the inverse of the relaxation times of the fluxes. However, in the analysis optimization of heating was not included.

In the present study, laser pulse heating of solid surface and entropy generation rate are considered. Time exponentially varying pulse is accommodated in the analysis to resemble the actual laser pulse and closed form solution for temperature rise is presented. Laser pulse parameter (β_1/β_2) resulting in minimum entropy generation rate is investigated.

2. Mathematical analysis

Mathematical analysis is composed of two parts, namely heating analysis and entropy analysis. Each analysis will be given under the appropriate subheadings.

2.1. Heating analysis

The schematic view of the laser heating process is shown in Fig. 1. Since the spot size is small (<1 mm) and the heat transfer in the radial direction is considerably smaller than its counterpart that takes place in the axial direction, one-dimensional heating model can be considered [9]. Laser heating pulse can be constructed from twotime exponentially decaying pulses ($\exp(-\beta_1 t) - \exp(-\beta_2 t)$), where β_1 and β_2 are the laser exponential pulse parameters. The solution of conduction equation (the Fourier equation) can be obtained for only one exponential term ($\exp(-\beta_1 t)$) of the laser heating pulse; then, the solution for the second exponential term can be added to the solution of the first exponential term according to the superposition role. Consequently, temperature variation for the complete laser heating pulse can be obtained. In this case, the Fourier heat transfer equation due to time exponentially decaying laser pulse for the first term β (β is used for the general purpose and it will be replaced with β_1 and β_2 later in the mathematical analysis) can be written as

$$\frac{\partial^2 T}{\partial x^2} + \frac{I_1 \delta}{k}(e^{-\beta t})e^{-\delta x} = \frac{1}{\alpha}\frac{\partial T}{\partial t}, \tag{1}$$

where

$$I_1 = (1 - r_f)I_0.$$

In the analysis, no heat convection is considered from the free surface of the substrate material. It should be noted that the convective heat loss from the surface is negligibly small during the laser heating pulse [10]. The depth well below the surface ($x \cong \infty$), temperature remains the same. Therefore, the corresponding boundary conditions are

at the surface:

$$\text{At } x = 0 \Rightarrow \left.\frac{\partial T}{\partial x}\right\|_{x=0} = 0.$$

at depth infinity:

$$\text{At } x = \infty \Rightarrow T(\infty, t) = 0.$$

Initially, substrate material is considered at uniform temperature. Hence, the initial condition is

$$\text{Initially: At } t = 0 \Rightarrow T(x, 0) = 0.$$

The Laplace Transformation of Eq. (1) with respect to t, results

$$\frac{\partial^2 \bar{T}}{\partial x^2} + \frac{I_1 \delta}{k}\frac{e^{-\delta x}}{(s+\beta)} = \frac{1}{\alpha}\left[s\bar{T}(x,s) - T(x,0)\right]. \tag{2}$$

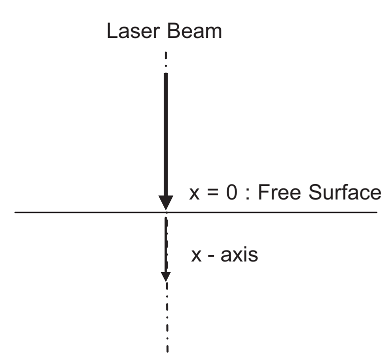

Fig. 1. Schematic view of laser heating and x-axis location.