International Journal of Heat and Mass Transfer 106 (2017) 989–996

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Characterization of laser-induced local heating in a substrate

Peng Yu [a,*], Yan Zeng [b]

[a] Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology, 1088 Xueyuan Boulevard, Nanshan, Shenzhen, Guangdong 518055, China
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

*Article history:*
Received 10 July 2016
Received in revised form 14 October 2016
Accepted 20 October 2016
Available online 3 November 2016

*Keywords:*
Laser heating
Heat assisted magnetic recording
Optical absorption
Head-disk interface
Absorption coefficient

ABSTRACT

The laser-induced heating in a substrate is investigated in the present study. The non-dimensional form of the governing equation on energy conservation for the unsteady laser heating process indicates that the heating process can be characterized only by two dimensionless parameters, i.e. the dimensionless scanning velocity of the laser spot $U$ and the dimensionless absorption depth $\Lambda$. A criterion, $U \ll 1$, is derived to scale down the heat transfer process from three dimensions to two dimensions, which is verified by the present numerical simulation. Another criterion, $\Lambda > 100$, is also given to correlate the heat flux model and the heat absorption model by comparing the numerical results obtained by these two models. The numerical simulation reveals an interesting phenomenon, the lag between the times for laser center reaching a point and the corresponding point reaching the maximum temperature. The present study provides insight into the unsteady heat transfer process induced by laser heating.


## 1. Introduction

Laser impinging on the surface of a material can be found in many applications. One important application is laser heating of materials for testing their material properties at high temperature. For example, laser heating has been applied to investigate the thermal instability of diamond-like carbon (DLC) [1,2]. Laser heating of material surface is also extensively used for material treatment such as welding, drilling, cutting, alloying, heat treatment [3]. Moreover, laser heating is widely applied in the data storage industry, for example, the conventional optical data storage [4] and the novel heat-assisted magnetic recording (HAMR) [5]. In this kind of applications, the laser beam is introduced to heat a small region of the disk structure to read and/or write information on the disk.

The basic mechanism of energy transfer from laser to the material is via photon-electron interaction. The optical energy is locally absorbed by the material and the attenuation of the laser intensity decays exponentially with the depth (from the surface). This local heating causes non-uniform temperature distribution in the material. Heat is thus conducted away due to the temperature gradient. In many situations, the highly non-uniform temperature may cause severe thermal stress, which may be harmful to the material. For example, in HAMR application, enhanced evaporation and thermocapillary stress due to non-uniform temperature field confer a tough environment for the lubricant attached to the disk surface and lead to severe lubricant loss [6–8], which is not expected in hard disk drive systems. Therefore, it is of importance to investigate unsteady heat transfer induced by laser heating [8–10].

Tagawa et al. [9] developed a novel experimental method to evaluate the local temperature increase under steady-state condition on surfaces of hard disk drives due to laser heating in HAMR system. In their method, the surface temperature increase is determined by linking the relationship between the temperature and the changes in the optical characteristics which were measured using a normal ellipsometry measurement technique. Their experimental results agreed well with the numerical simulation results. Wu [8] and Wu and Talke [11] applied a numerical approach to simulate the unsteady heat transfer process in a hard disk drive in HAMR system. In their model, the laser heating is simplified as a heat flux imposed on the disk surface and the absorptivity of the disk surface has to be determined empirically. Zeng et al. [12] and Zhou et al. [13] also adopted this heat flux model in their simulations. More recently, Yu et al. [10] applied an optical absorption model to quantify the local laser heating. In this optical absorption model, the laser is regarded as an electromagnetic wave. The absorption rate of optical energy by the disk medium is derived from Maxwell equations and incorporated into the energy equation by a source term [14]. The advantage of the optical absorption model is that the absorption rate can be determined form the properties of materials and the energy equation can then be solved numerically without any empirical parameters. Yu et al. [15] compared the simulation results obtained by the heat flux model and the optical absorption model. They concluded that by

* Corresponding author.
*E-mail address:* yup6@sustc.edu.cn (P. Yu).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.10.068
0017-9310/

adjusting empirical absorptivity, the heat flux model can produce the same heat transfer results as those predicted by the optical absorption model only when the absorption coefficient $\beta \geqslant 10^8\ \mathrm{m}^{-1}$.

In HAMR system, the laser heating may cause severe lubricant depletion. Most of previous studies (e.g. [13,16]) mainly focused on the effects of the lubricant properties but not the temperature field on the lubricant depletion. However, previous studies [15,17] indicated that strong couplings exist between temperature field and lubricant depletion. This motivates the present study to characterize the unsteady heat transfer process induced by laser heating. We consider a continuous laser radiation imposed on the material. The laser beam may parallelly move on the material surface. After a certain period, a quasi-steady state (or nearly quasi-steady state) may be achieved, which is characterized by a constant (or nearly constant) temperature distribution related to the reference frame fixed to the laser beam. For this continuous laser radiation (in the order of tens of nanoseconds), the traditional energy equation based on Fourier's law is thus applicable. For ultrashort laser pulse (femtosecond), the nonequilibrium energy transfer [18–21] needs to be considered, which is beyond the scope of the present study.

In particular, we derives the non-dimensional form of the governing equation on energy conservation for the unsteady laser heating process, which indicates that the heating process can be characterized only by two dimensionless parameters. A systematic numerical study is performed over the wide range of parameters to characterize the heat transfer process. Meanwhile, a simple analysis is also carried out to provide insight into the heat transfer process. The organization of the rest of the paper is as follows. Section 2 describes the derivation of non-dimensional governing equations. Section 3 provides simple analyses to interlink the optical absorption model and the heat flux model and evaluate the effect of the laser scanning velocity. The simulation results are presented in Section 4, which includes the detailed heat transfer features as well as a verification of the simple analysis by using the numerical data. And finally, Section 5 draws conclusions.

## 2. Governing equations

In the present study, we concern the heat transfer process in a small region of the rotating disk in a HAMR system subject to laser heating (Fig. 1). For simplicity, we consider a single layer disk structure. A laser beam with wave length $\lambda$ and power $P_W$ is shot onto the rotating disk. The in-plane laser intensity distribution is assumed to be governed by the Gaussian function. The laser center initially located at (0, 0) in the $x-y$ plane. The unsteady energy equation in a rotating Cartesian frame of the hard disk can be written as

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{\dot{Q}}{\rho_a C_p} \tag{1}$$

where $T$ is the temperature, $t$ is time, $\dot{Q}$ is the laser absorption rate, $\alpha$, $\rho_a$, $C_p$ are the thermal diffusivity, density, and the specific heat capacity of the disk medium, and $x$, $y$, $z$ are the spatial coordinates.

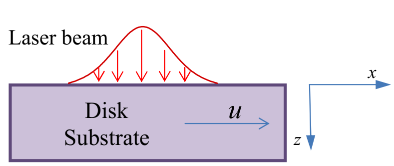


**Fig. 1.** Schematic diagram of disk substrate subject to laser heating.

In the rotating frame, the relative moving speed of the laser beam is $u$. In Eq. (1), the laser absorption rate can then be calculated as [15]:

$$\dot{Q} = \frac{P_W}{\pi r^2}\beta(1-R)e^{-\frac{(x-ut)^2+y^2}{r^2}}e^{-\beta z} \tag{2}$$

where $r$ is $e^{-1}$ radius of the laser beam, $R$ is the reflection coefficient, and $\beta$ is the absorption coefficient. The parameters $R$ and $\beta$ are determined by the optical properties of disk medium [15], respectively. In the present study, we neglect the heat loss from the disk surface by convection because convection loss is not significant [14,15]. Thus, at the disk surface adiabatic condition is imposed. We shall refer to Eqs. (1) and (2) as the optical absorption model. This model indicates that the energy absorption rate decays exponentially in the $z$ direction.

It is worth noting that the laser heating process is considered as a heat flux imposed on the disk surface in the previous studies [8,12]. In this heat flux model, the heat generation rate in Eq. (1) is zero and the laser energy is transferred into the disk by the surface heat flux:

$$-\alpha\rho_a C_p \frac{\partial T}{\partial z} = A_b \frac{P_W}{\pi r^2} e^{-\frac{(x-ut)^2+y^2}{r^2}} \tag{3}$$

where $A_b$ is the absorptivity of the disk surface, which is determined empirically.

For the sake of brevity, we define $H_0 = \frac{(1-R)P_W}{\rho_a C_p \pi r^2}$ for the optical absorption model and $H_0 = \frac{A_b P_W}{\rho_a C_p \pi r^2}$ for the heat flux model, respectively. By suitable scaling, the dimensionless governing equation for the optical absorption model can be rewritten as:

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} + \frac{\partial^2 \theta}{\partial Z^2} + \Lambda e^{-\Lambda Z} e^{-[(X-U\tau)^2+Y^2]} \tag{4}$$

where $X = \frac{x}{r}$, $Y = \frac{y}{r}$, $Z = \frac{z}{r}$, $\tau = \frac{\alpha t}{r^2}$, $\theta = \frac{\alpha(T-T_0)}{H_0 r}$ with $T_0$ a reference temperature, $\Lambda = r\beta$, and $U = \frac{ur}{\alpha}$. The dimensionless governing equations for the heat flux model can be rewritten as:

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2} + \frac{\partial^2 \theta}{\partial Z^2} \tag{5}$$

$$-\frac{\partial \theta}{\partial Z} = e^{-[(X-U\tau)^2+Y^2]} \quad \text{at } Z = 0 \tag{6}$$

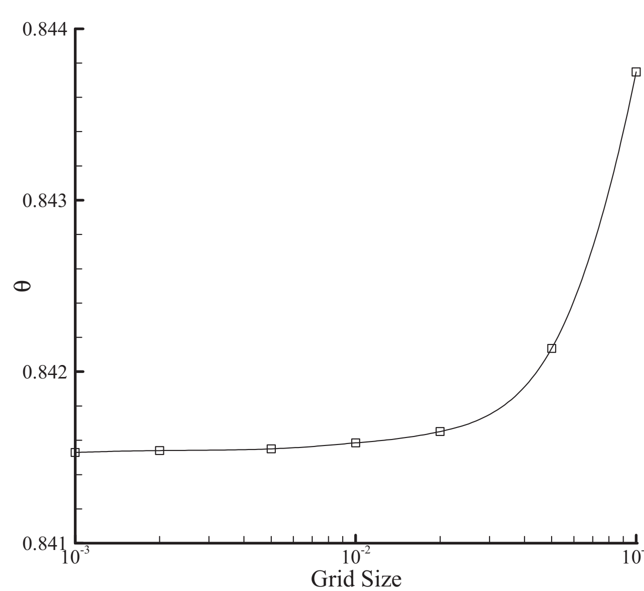


**Fig. 2.** The maximum temperature on the disk at $\tau = 40$ for different grid size. The $x$-axis shows the size of the first grid underneath the surface in the $z$ direction.