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Mathematics and Computers in Simulation 81 (2011) 1541–1552
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original article

A simple model for laser drilling

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Received 23 March 2009; received in revised form 3 June 2010; accepted 13 July 2010
Available online 3 August 2010

Abstract

A simple mathematical model of laser drilling is proposed. Assuming axi-symmetry of the process around the axis of the laser beam, a one-dimensional formulation is obtained after cross-sectional averaging. The novelty of the approach relies on the fact that even after dimension reduction, the shape of the hole can still be described. The model is derived, implemented and validated for drilling using lasers with intensities in the GW/cm^2 range and microsecond pulses.

Keywords: Laser drilling; Phase change; Free boundary; Numerical methods

1. Introduction

Laser drilling is an important industrial process by which laser pulses are used to drill holes in hard materials. It presents several advantages over conventional techniques such as low heat input into the material, accuracy, consistency, ease to automate and ability to drill very small holes of the order of 10 μm in diameter. This technique is used either with single or multiple pulses.

During drilling, material is removed from the workpiece through two mechanisms: vaporization and melt ejection. The relative importance of each mechanism has been the object of several theoretical studies, see for instance [13]. Some authors have also developed more phenomenological criteria [9], see Fig. 1. In the case of thermal ablation (roughly the lower left part of Fig. 1), the interaction of the laser with the material surface creates a molten pool. As some of the material vaporizes, the pressure of the vapor (recoil pressure) is large enough to push the melt radially outward from the center of the beam leading to melt ejection. On the other hand, in so-called non-thermal ablation (roughly the upper right part of Fig. 1), which corresponds to higher melt surface temperature, the main process by which melt is removed is through evaporation instead of convection as the material vaporizes before it can get convected in any significant way.

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1 Partially supported by the National Science Foundation (NSF) through grants DMS-0636590 and DMS-0811150.
2 Partially supported by the National Science Foundation (NSF) through grants CMMI-0738044, DMS-0636590 and DMS-0811150.

0378-4754/$36.00
doi:10.1016/j.matcom.2010.07.010

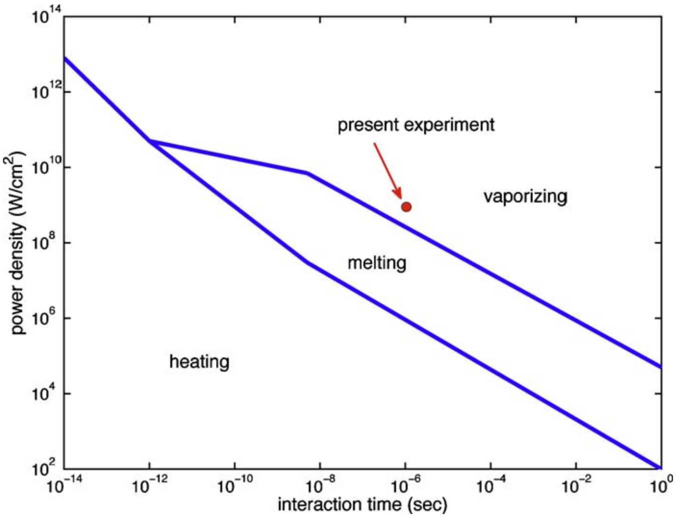

Fig. 1. Approximate range of various regimes for laser ablation.

adapted from [9]

The mechanisms involved in laser drilling have been described by previous authors [1,7,8,11,13,17–21] to cite but a few. In [18–20] a volumetric source term is used to describe the laser intensity, and an exact solution is derived for the temperature profile. The main contribution of the present paper is the construction and implementation of a new simple model to predict penetration depth and hole diameter in a specific regime corresponding to a relatively powerful laser, with power density in the GW/cm^2 range, used in conjunction microsecond pulses, see Section 4 for details, see also [5] for general remarks on this regime. Fig. 1 illustrates where the case(s) considered here stand(s) in relation with other applications; see for instance [4,12] for recent models dealing with TW/cm^2 power densities and pico or femto second pulses.

Many practical questions remain open such as the determination of optimal firing schedules or the mitigation of instabilities leading to poor quality holes. Our approach leads to a model amenable to either optimization or stability studies. The proposed model is based on several simplifying assumptions which are detailed in Section 2. The process is also considered to be fully axi-symmetric along the axis of the laser beam. The model is made pseudo one-dimensional through the use of a cross-sectional averaging. However, in the present model, various polynomial hole shapes can still be considered. The aspect ratio is a model parameter that is determined here based on the available experimental data. Implementation is described in Section 3. Our results are discussed in Section 4 together with comparison with experimental data.

2. Mathematical modeling

2.1. Heat transfer

We assume the workpiece to be homogenous and the laser beam to have a Gaussian intensity distribution. Under these conditions, the entire process can be considered axi-symmetric. Working with a cylindrical coordinate system (r, θ, z) centered on the laser with z pointing down, energy conservation takes the form the classical heat equation:

$$\rho_s c_s \frac{\partial T}{\partial t} = k_s \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right], \qquad r > 0, \quad z > 0, \quad t > 0, \tag{1}$$

where T is the temperature, ρ_s, c_s and k_s are, respectively, the density, heat capacity and thermal conductivity of the solid material and are in first approximation considered constant. If W stands for the intensity or power flux of the laser, we have in the first stages of the process:

$$k_s \frac{\partial T}{\partial z} = -W, \qquad \text{at } z = 0. \tag{2}$$