Available online at www.sciencedirect.com

ScienceDirect

Manufacturing Letters 7 (2016) 1–5

www.elsevier.com/locate/mfglet

Research Letters

Modeling of picosecond laser-induced plasma amplification inside a microhole and an implied novel technology to drill microholes with varying diameters with depth

Navid Dabir-Moghaddam [a], Sha Tao [b], Benxin Wu [a,c,*], Yung C. Shin [c]

[a] Illinois Institute of Technology, Chicago, IL, United States
[b] Advanced Optowave Corp., Ronkonkoma, NY, United States
[c] Purdue University, West Lafayette, IN, United States

Received 31 July 2015; accepted 1 November 2015
Available online 17 November 2015

Abstract

Microholes with varying diameters at different depths are very desirable in various important applications. However, it is very challenging to produce microholes with varying diameters when the variation is in a complicated way and/or when the hole diameter is very small. This paper presents physics-based modeling work on the interactions among a picosecond (ps) laser pulse, a pre-existing plasma plume inside a microhole, and the hole sidewall. The modeling work implies the potential feasibility of a novel dual-pulse laser ablation and plasma amplification (LAPA) process for drilling microholes with varying diameters at different depths.

Keywords: Laser drilling; Laser micromachining

1. Introduction

Many important industrial applications may need holes with microscale diameters, and some specific examples include the small orifices needed in fuel injectors for diesel engines [1] and the holes for the cooling purpose in aerospace engines [2,3]. Microholes with diameters that vary with the hole depth in certain ways may be very desirable in some applications. For example, microholes with *small* diameters that *vary* with the hole depth (such as a reverse tapered hole where the hole diameter increases with the hole depth, or a dumbbell-shaped hole where the hole diameter first decreases and then increases with the hole depth), if applied in diesel fuel injectors, may enhance the fuel atomization and result in a more complete combustion [1]. However, drilling microholes that have diameters varying with the hole depth is very challenging when the diameter variation with the depth is complicated (such as a dumbbell-shaped hole) and/or when the hole diameter is very small.

To study the potential feasibility of a new technology for drilling microholes that have small diameters varying with the hole depth, in this paper modeling work has been performed on the interactions among a picosecond (ps) laser pulse, a pre-existing plasma plume inside a microhole, and the microhole sidewall. In the model, two-dimensional (2D) axi-symmetric gas dynamic equations are solved for the gaseous phase inside the microhole (including the plasma and the ambient gas), while a 2D axi-symmetric heat transfer equation is solved for the hole sidewall region.

* Corresponding author at: Associate Professor, School of Mechanical Engineering, Purdue University, 585 Purdue Mall, West Lafayette, IN 47907, United States; Adjunct Associate Professor, Department of Mechanical, Materials and Aerospace Engineering, Illinois Institute of Technology, Chicago, IL 60616, United States.

E-mail addresses: wu65@purdue.edu, bwu11@iit.edu (B. Wu).

http://dx.doi.org/10.1016/j.mfglet.2015.11.004
2213-8463/

The gas dynamic equations and the heat transfer equation are coupled through the heat flux from the gaseous phase to the sidewall surface. It has been found that the ps laser pulse can amplify the pre-existing plasma (that is, increase the plasma temperature), and hence increase the heat flux from the gaseous phase to the sidewall surface, which may cause spatially selective material removal from the sidewall. This implies the potential feasibility of drilling microholes with varying diameters at different depths through a novel technology, called dual-pulse laser ablation and plasma amplification (LAPA), which will be introduced later in this paper.

2. Model

Fig. 1 shows the setup of the model. It is assumed that at $t = 0$ an aluminum plasma plume pre-exists inside a microhole whose side and bottom walls are made of solid aluminum. The hole has a diameter of 50 μm, and the hole bottom is located at $z = 0$, and the hole sidewall surface is located at $r = 25$ μm. The pre-existing plasma has an initial height of 150 μm, an initial diameter of 40 μm, and an initial temperature of 100,000 K (which is close to the early-stage temperature reported in [4] for plasma induced by nanosecond laser ablation of aluminum). The plasma region is surrounded by ambient argon gas at an initial temperature of 300 K and an initial pressure of 1 atmosphere. At $t = 0$, it is assumed that a 1064-nm laser beam with a 100-ps full-width-at-half-maximum (FWHM) pulse duration propagates downwards and starts interacting with the plasma. The laser beam intensity has a top-flat spatial distribution and the beam diameter is 40 μm. The model calculation starts at $t = 0$. The evolution of the gaseous phase inside the microhole (including the aluminum plasma and the ambient argon) is simulated by solving the 2D axi-symmetric gas dynamic equations [5–9]:

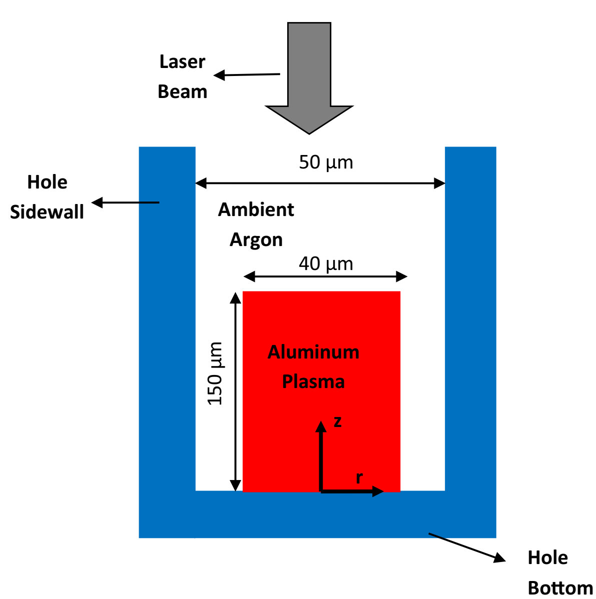

Fig. 1. Schematic diagram of the model setup in this work (which also shows the initial plasma plume geometry at $t = 0$; the figure is not drawn to scale).

$$\frac{\partial \rho_1}{\partial t} + \frac{1}{r}\frac{\partial (r\rho_1 v_r)}{\partial r} + \frac{\partial (\rho_1 v_z)}{\partial z} = 0 \quad (1)$$

$$\frac{\partial \rho_2}{\partial t} + \frac{1}{r}\frac{\partial (r\rho_2 v_r)}{\partial r} + \frac{\partial (\rho_2 v_z)}{\partial z} = 0 \quad (2)$$

$$\frac{\partial((\rho_1+\rho_2)v_r)}{\partial t} + \frac{1}{r}\frac{\partial(r(\rho_1+\rho_2)v_r v_r)}{\partial r} + \frac{\partial((\rho_1+\rho_2)v_r v_z)}{\partial z} = -\frac{\partial P}{\partial r} \quad (3)$$

$$\frac{\partial((\rho_1+\rho_2)v_z)}{\partial t} + \frac{1}{r}\frac{\partial(r(\rho_1+\rho_2)v_r v_z)}{\partial r} + \frac{\partial((\rho_1+\rho_2)v_z v_z)}{\partial z} = -\frac{\partial P}{\partial z} \quad (4)$$

$$\frac{\partial(E_k+E_{in})}{\partial t} + \frac{1}{r}\frac{\partial(r(E_k+E_{in}+P)v_r)}{\partial r} + \frac{\partial((E_k+E_{in}+P)v_z)}{\partial z} = \nabla\cdot(k_e\nabla T) + \alpha_{IB} I \quad (5)$$

where t denotes time, r and z are spatial coordinates, ρ_1 and ρ_2 represent the density of aluminum plasma and argon, respectively, P represents pressure, v_r and v_z are the velocity components in r and z directions, respectively, E_k and E_{in} denote the kinetic energy and the internal energy, respectively, T is temperature, k_e represents electron thermal conductivity [10–11] (for ambient argon at temperatures close to its initial temperature of 300 K, the argon conductivity at 300 K is applied), α_{IB} is the inverse bremsstrahlung optical absorption coefficient [10–12], and I denotes the laser beam intensity.

To solve the gas dynamics equations, related equation of state (EOS) data is needed, which is developed based on the electron number density obtained by solving the Saha equation [13–14].

Due to the heat transfer between the gaseous phase in the microhole and the hole sidewall surface, the sidewall temperature may change. The spatial distribution and temporal evolution of the temperature in the sidewall is obtained by solving the 2D axi-symmetric heat transfer equation in the sidewall [5,9,15–18]. When the sidewall surface is melted and the surface temperature is sufficiently high, surface vaporization may become significant. The surface vaporization flux can be calculated using the Hertz–Knudsen equation [18–19] based on the sidewall surface temperature. The surface vaporization flux, divided by the density of the vaporizing sidewall surface and integrated with time, can yield the accumulated vaporization depth.

The gas dynamic equations are solved numerically using a finite difference essentially non-oscillatory (ENO) scheme [20], and the heat transfer equation in the sidewall is solved using the explicit finite volume method [7,16]. At each numerical time step, by solving the gas dynamic equations, the gaseous phase velocity, density, and temperature