Procedia Manufacturing
Volume 5, 2016, Pages 724–733
44th Proceedings of the North American Manufacturing Research Institution of SME http://www.sme.org/namrc

Amplification of Plasma at Different Initial Temperatures inside a Microhole by a Short Laser Pulse and the Effect on the Hole Sidewall

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Abstract
Microholes with diameters varying with the hole depth have promising applications in important applications, but their manufacturing is difficult when the diameter of the hole is very small and/or varies complicatedly with the depth. In the authors' previous work (Dabir-Moghaddam et al., 2016), physics-based modeling study has been carried out on the interaction of a short laser pulse with a plasma plume that pre-exists in a microhole and the resulted effect on the sidewall of the hole. The model calculations have implied that a novel dual-pulse laser ablation and plasma amplification (LAPA) technique is potentially feasible for drilling microholes with diameters that are different at different hole depths. In this paper, further model calculations have been performed to study the effect of different initial plasma temperatures. Under the studied conditions, it has been found that laser amplification of a plasma plume with a higher initial temperature can lead to a larger heat flux to the hole sidewall surface and a larger surface vaporization depth in the sidewall, which indicates that more significant material removal will be expected. On the other hand, a lower initial plasma temperature can lead to more non-uniform vaporization depths at different sidewall locations, indicating that a spatially more selective material removal will be expected.

Keywords: laser machining, laser drilling, laser ablation

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 Selection and peer-review under responsibility of the Scientific Programme Committee of NAMRI/SME

doi:10.1016/j.promfg.2016.08.059

Nomenclature

r, z	Spatial coordinates
t	Time
V_r	r-direction velocity component
V_z	z-direction velocity component
ρ_1	Aluminum plasma density
ρ_2	Argon density
T	Temperature
P	Pressure
k_e	Electron thermal conductivity
E_{in}	Internal energy
α_{IB}	Optical absorption coefficient due to the inverse bremsstrahlung effect
I	Intensity of the laser beam

1 Introduction

Small holes with micro-scale diameters that are different at different hole depths (for example, a hole that is dumbbell-shaped, or a hole that is reverse tapered with larger diameters at larger depths) have important promising applications, such as in diesel fuel injectors for higher fuel efficiency (Clarke and Profeta, 2004). However, the manufacturing of such holes is obviously very difficult when the hole has very small diameters and/or the diameter variation with the hole depth is complicated (for example, a dumbbell-shaped hole).

In the authors' previous work (Dabir-Moghaddam et al., 2016), physics-based modeling has been carried out on the interaction of a short laser pulse with a plasma that is assumed to pre-exist in a microhole and the resulted effect on the sidewall of the hole. Under the model-calculated conditions, it has been discovered that the short laser pulse can amplify the plasma (i.e., drive up the plasma temperature), which can lead to enhanced and spatially non-uniform heat flux to the hole sidewall. As a result, material vaporization has occurred from the sidewall surface, and the vaporization depth is spatially non-uniform, indicating that selective material removal has occurred from the sidewall (which can yield different hole diameters at different hole depths). The simulation results have implied that a new dual-pulse laser ablation and plasma amplification (LAPA) technique is potentially feasible for drilling microholes with diameters that are different at different depths (Dabir-Moghaddam et al., 2016). In the LAPA process, a first short laser pulse is delivered to the hole bottom wall to perform ablation to increase the depth of the hole and also lead to a high-temperature plasma. After that, a second laser pulse (or even additional pulses) is fired to amplify the generated plasma and enhance the heat flux to the sidewall of the hole to selectively remove materials from the sidewall to change the hole diameters. By appropriately selecting and controlling the parameters and relative timing of the first and second (or additional) laser pulses and repeat the process, potentially LAPA can produce a microhole that has different diameters at different depths.

In the authors' previous work (Dabir-Moghaddam et al., 2016), it is assumed that the pre-existing plasma in the microhole has an initial temperature of 100000 K. In this paper, further model calculations will be performed to study the effects of the initial temperatures of the pre-existing plasma on the induced heat flux to, and the vaporization and melting depths in, the hole sidewall.