Precision Engineering 47 (2017) 33–45

Contents lists available at ScienceDirect

Precision Engineering

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

An analytical model for the prediction of temperature distribution and evolution in hybrid laser-waterjet micro-machining

Shaochuan Feng[a], Chuanzhen Huang[a,*], Jun Wang[b], Hongtao Zhu[a], Peng Yao[a], Zhanqiang Liu[a]

[a] Center for Advanced Jet Engineering Technologies (CaJET), Key Laboratory of High-Efficiency and Clean Mechanical Manufacture (Ministry of Education), School of Mechanical Engineering, Shandong University, Jinan 250061, China
[b] School of Mechanical and Manufacturing, The University of New South Wales (UNSW), Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 21 February 2016
Received in revised form 10 June 2016
Accepted 11 July 2016
Available online 12 July 2016

Keywords:
Analytical model
Temperature field
Hybrid process
Micro-machining
Laser
Waterjet

ABSTRACT

A hybrid laser-waterjet micro-machining technology was developed for near damage-free micro-ablation recently. It uses a new material removal concept where the laser-softened material is expelled by a pressurised waterjet. The temperature field in this hybrid machining process is an essential quantity for understanding the underlying material removal mechanism and optimizing the process conditions. This study presents a three-dimensional (3-D) analytical model for the temperature field in this hybrid laser-waterjet micro-machining process. The interaction among the laser, waterjet, and workpiece is considered in the model. The absorption of laser by water, the formation of laser-induced plasma in water, the bubble formation and the laser refraction at the air-water interface are discussed. DuHamel's principle is used to determine a closed-form temperature equation and a solution in a variable separation form is obtained. A calculation for silicon carbide is conducted. The results are illustrated by a group of 3-D temperature profiles intuitively and visually. It is shown that the temperatures are below the melting point during the process due to the cooling action of waterjet. The almost damage-free micro-machining can be achieved. Besides, the maximum temperature increases with the increased average laser power and waterjet offset distance and decreased nozzle exit diameter where the average laser power takes a major action.

1. Introduction

Lasers have been used in a variety of material processing applications especially for the hard and brittle materials that are difficult to machine. However, heat-affected zone (HAZ) is considered as a major drawback of the process. Attempts to reduce HAZ have been carried out by many researchers. For this purpose, liquid-assisted laser ablation processes have been developed in the processing of engineering materials such as silicon, silicon carbide and other thermal-sensitive materials. Some typical liquid-assisted laser ablation processes are under-water laser machining [1], waterjet-guided laser machining [2], and low-pressure waterjet assisted laser machining [3,4]. Nevertheless, the earlier developed water assisted laser machining processes remove material at its liquid status by locally heat and increase the material temperature.

Tangwarodomnukun et al. [5] has proposed a novel hybrid laser-waterjet machining technology which used a new material removal concept where a waterjet is applied off-axially to expel the "softened" elemental material by laser radiation and cool the material for near damage-free micromachining. It combines the advantages of laser processing with those of waterjet cutting. The near damage-free micro-ablation of silicon [5], germanium [6] and silicon carbide [7] are achievable by using this technology. However, further investigations are essential to provide a deeper understanding of the process and optimize the process.

As the thermal effect is utilized in the hybrid laser-waterjet micro-machining, the temperature distribution is a crucial intermediate result that would determine the characteristics of grooves and final surfaces machined. Thus establishing a model for the temperature field is considerable and necessary. Several comprehensive models of temperature field in laser dry ablation have been proposed. Three-dimensional (3-D) numerical models for steady temperature distributions [8,9] and for dynamic temperature distributions [10,11] in laser ablation process have been developed respectively using the finite element method (FEM). Marek Polák

* Corresponding author.
E-mail address: chuanzhenh@sdu.edu.cn (C. Huang).

http://dx.doi.org/10.1016/j.precisioneng.2016.07.002
0141-6359/

Nomenclature

a_b	Absorption coefficient of material (1/m)
A_l	Laser-irradiated area (m^2)
c	Heat capacity at constant pressure of material (J/Kg K)
c_w	Heat capacity at constant pressure of water (J/Kg K)
d_b	Laser beam diameter (m)
d_{f1}	Focused laser diameter without refraction (m)
d_{f2}	Focused laser diameter after refracted (m)
d_w	Nozzle exit diameter (m)
D	Laser beam diameter before focused by a lens (m)
E_p	Laser pulse energy (J)
f	Laser pulse frequency (Hz)
F	Focal length (m)
h_a	The combined heat transfer coefficient of air (W/m^2 K)
h_w	Heat transfer coefficient of water (W/m^2 K)
I	Laser beam intensity (W/m^2)
I_0	Laser beam intensity at center position (W/m^2)
k	Thermal conductivity of material (W/m K)
k_w	Thermal conductivity of water (W/m K)
l_a	Light absorption length in water (m)
l_w	Water layer thickness (m)
L_f	Characteristic length of thin water film region (m)
M_R^2	Laser beam quality factor in water
n_w	Refractive index of water relative to air
Nu_f	Average Nusselt number on the thin water film region
P_i	Hydrostatic pressure at nozzle inlet (Pa)
P_a	Average laser power (W)
ΔP	Pressure drop in nozzle (Pa)
Pr	Prandtl number of water
Q	Heat source (W/m^3)
q_1	Heat flux caused by waterjet impingement (W/m^2)
q_2	Heat flux caused by surface radiation (W/m^2)
R_f	Targeted material reflectivity
R_w	Water reflectivity
Re_f	Average Reynolds number on the thin water film region
t	Time (s)
T	Temperature (K)
T_f	Surrounding temperature (K)
u	Temperature-dependent property
u_c	Temperature-independent property
v	Traverse speed of laser (m/s)
v_0	Waterjet velocity at nozzle exit (m/s)
x, y, z	Cartesian system coordinates
x_w	Waterjet offset distance (m)
z_c	Downward distance of focal position (m)
α	Thermal diffusivity of material (m^2/s)
β	Laser absorptivity of water
γ_1	Divergence angle in air (°)
γ_2	Divergence angle in water (°)
ε	Surface emissivity
θ	Waterjet inclination angle (°)
λ	Laser wavelength (m)
μ	Viscosity of water (Pa s)
ρ	Material density (kg/m^3)
ρ_w	Water density (kg/m^3)
σ	Stefan-Boltzmann's constant (5.67×10^{-8} W/m^2 K^4)
τ_0	Relaxation time of material (s)
τ_p	Laser pulse duration (s)
φ	Laser pulse function in time domain
ψ	Laser pulse function in space domain

et al. used two numerical methods, i.e. FEM and finite difference method (FDM), for the calculation of the temperature field in laser cutting and drilling [12]. The temperature field in laser pulse heating and phase change processes of the substrate material was formulated numerically using the energy method [13]. Chi-Kyung Kim has dealt with a 1-D analytical solution to transient heat conduction in the medium subjected to a moving heat source [14]. An analytical solution of temporary temperature field in half-infinite body caused by moving heat source tilted towards the direction of motion was presented [15]. Based on the two-temperature coupling theory, a numerical model of temperature field of electron and lattice in the heating process of femtosecond laser for metal has also been established by using FEM [16].

For the liquid-assisted laser machining, the processes are more complex than that in laser dry ablation because of the interaction among laser, waterjet and workpiece. The temperature field models for the waterjet guided laser grooving of silicon have been presented by Li et al. using FDM [17] and by Yang et al. using FEM [18]. Both of these models are assumed that the silicon was removed in its liquid status. Tangwarodomnukun et al. [19] has developed a mathematical model to predict the temperature field in the hybrid laser-waterjet micro-grooving process for a single crystalline silicon using an enthalpy-based FDM, without considering the plasma effect.

The present study is to investigate the temperature field in the hybrid laser-waterjet micro-machining process using an analytical approach where the various physical phenomena associated with the process are discussed to give an insight into the process. Firstly, a governing equation and its boundary conditions will be proposed according to the problem under investigation. The coupled effects of laser heating and waterjet cooling associated with the process will then be discussed. The interference between laser and waterjet, including the absorption of laser by water, the formation of laser-induced plasma in water, the bubble formation and the laser refraction at the air-water interface, will be studied. Subsequently, an analytical solution to the temperature field model that was established previously will be carried out and the method of eigenequation and DuHamel's theorem will be applied. In order to represent the results intuitively and visually, a group of 3-D temperature profiles will be plotted via MATLAB. In addition, the relationship between the temperature and process parameters will also be obtained. The calculation for silicon carbide will be implemented as an example.

2. Problem description

The laser beam and the pressurised waterjet beam are applied off-axially travel on the workpiece surface where the waterjet beam is exerted behind the laser beam at a fixed distance, i.e. waterjet offset distance, as shown in Fig. 1. The laser is used to locally heat and soften the material and the waterjet is applied to expel the laser-softened elemental material. Water also takes a cooling action. Hence, there is the complicated interaction between the laser, waterjet and work material under the coupled effect of laser heating and waterjet expelling and cooling.

The mechanical properties of most of the engineering materials, such as strength and hardness, are temperature-dependent. Further, these mechanical properties of the material will decrease obviously with the increase of the temperature [20,21]. Based on