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Heating and material removal process in hybrid laser-waterjet ablation of silicon substrates

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ABSTRACT

A hybrid laser-waterjet micromachining technology has recently been developed for near damage-free micro-ablation. It uses a laser to heat and soften the target material and a waterjet to expel the laser-softened elemental material to decrease thermal damages and increase the material removal. A computational model for the hybrid laser-waterjet micro-grooving process for single crystalline silicon is presented in this paper using an enthalpy-based finite difference method. Laser heating and waterjet cooling and expelling with the temperature-dependent silicon properties are considered in the model to predict the temperature profiles of silicon and groove characteristics under different machining conditions. The simulation results show that the introduction of a high pressure waterjet enables to remove material at its soft-solid status much below its melting temperature, while the waterjet cooling effect can reduce the workpiece temperature during the laser non-pulse period and eliminate the effect of heat accumulation, so that the thermal damage induced by laser heating is minimized. The temperature field model is also used to predict the groove depth and profile, and it is found that the model can reasonably represent the machined groove characteristics when comparing to the experimental data.

1. Introduction

Lasers have been used in a variety of material processing applications since it was invented. A laser with a sufficient energy density can provide the ability to remove material and form a relatively narrow kerf. However, heat-affected zone (HAZ) is considered as a major drawback of the process, particularly for the fabrication of thermal-sensitive materials as well as micro part structures where HAZ can significantly affect the reliability and functionality of the micro parts. In fact, HAZ can be reduced or even eliminated by using the ultrashort pulsed (such as femtosecond) lasers [1,2]. However, at this stage of development, the low ablation rate from the low power and high photon cost of the ultrashort-pulsed lasers limit their potentiality for some fine-scale applications with low removal rates only.

Liquid-assisted laser ablation processes have been used to reduce HAZ in the processing of engineering materials such as silicon and other thermal-sensitive materials [3,4]. There are several ways to apply a liquid, like water, to the laser machining process, such as underwater laser [5,6], waterjet-guided laser [7] and waterjet-assisted laser [8,9]. Among these methods, the hybrid laser-waterjet ablation technique developed by Tangwarodomnukun et al. [10] has been found to be an effective approach to reducing thermal damage and HAZ, and increasing material removal rate in the micromachining of silicon. In this technology, a laser is used to heat and soften the work material and a waterjet is used to expel the laser-softened material in an element by element (or layer by layer) manner and take a cooling action. The effect of the major process parameters on the cut characteristics of silicon has been studied through an experimental work [10]. It has been shown that near damage-free micro-ablation of silicon is achievable by using this technology. However, further investigations are essential to provide a deeper understanding of the process (i.e. the interaction among the laser, waterjet and material and the material ablation process) and optimize the process.

Considerable studies [11–14] have been carried out to describe laser-material interactions in laser machining by using heat transfer models. In general, the heat transfer investigations include the use of an analytical approach [15–18], where a closed-form equation is formulated and solved under the boundary conditions given for a specific machining condition. However, this approach has been found to be difficult for handling highly nonlinear boundary-value problems. Numerical modeling has thus

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Nomenclature

A_{imp}	waterjet impact area (m^2)
A_j	cross-sectional area of a circular waterjet beam (m^2)
A_l	laser-irradiated area (m^2)
c_p	heat capacity of material (J/kg K)
c_{pw}	heat capacity of water (J/kg K)
d_b	laser beam diameter (m)
d_f	focused laser beam diameter (m)
dt	time step (s)
D_n	waterjet diameter (m)
E_p	laser pulse energy (J)
f^{-1}	pulse period (s)
F_{imp}	impact force (Pa)
fpp	focal plane position (m)
h	heat transfer coefficient (W/m^2 K)
h_0	heat transfer coefficient on the stagnation zone (W/m^2 K)
h_w	water layer thickness (m)
H	specific enthalpy (J/kg)
H_l	laser heat source (W/m^3)
i	time sequence
k	thermal conductivity of material (W/m K)
k_f	thermal conductivity of fluid (W/m K)
k_w	thermal conductivity of water (W/m K)
L_c	characteristic length of water flow (m)
L_m	latent heat of melting (J/kg)
L_v	latent heat of vaporization (J/kg)
p	real term for determining the reflectivity
PO	pulse overlap
P_{wj}	waterjet pressure (Pa)
q	imaginary term for determining the reflectivity
Re	Reynolds number of waterjet
R_f	reflectivity of material
R_{fw}	reflectivity of water
t	time (s)
t_p	timing counter for pulse duration (s)
t_v	timing counter for traverse speed (s)
T	temperature (K)
T_0	initial temperature (K)
T_m	melting temperature (K)
T_{sur}	surrounding temperature (K)
T_v	vaporization temperature (K)
u	unit vector normal to the surface
u_w	waterjet velocity (m/s)
v_t	traverse speed (m/s)
x, y, z	Cartesian system coordinates
x_{wl}	waterjet offset distance (m)
y_p	imaginary plane on y direction
α	thermal diffusivity of material (m^2/s)
α_b	absorption coefficient of material (1/m)
α_{bw}	absorption coefficient of water (1/m)
ε	emissivity
θ_j	waterjet impact angle (deg)
κ	coefficient of Gaussian regression model
λ	laser wavelength (m)
μ_w	dynamic viscosity of water (Pa s)
ν_w	kinematic viscosity of water (m^2/s)
ξ	shear factor
ρ	material density (kg/m^3)
ρ_w	water density (kg/m^3)
σ_{sb}	Stefan–Boltzmann's constant (5.67×10^{-8} W/m^2 K^4)
σ_z	normal stress caused by waterjet impact (Pa)
τ	laser pulse duration (s)
τ_m	material shear strength (Pa)
τ_{max}	maximum shear stress (Pa)
τ_{xz}	shear stress caused by waterjet impact (Pa)
ω	laser pulse function in time domain

become a more practical method to solve the complex boundary-value problems with fewer predefined mathematical functions [19]. Finite difference method (FDM) is normally used for solving heat transfer problems, due to its simplicity and short computing time [20]. Some studies [21–23] applied the enthalpy method with the FDM to facilitate the energy balance and phase change of work material [24,25]. By using the FDM with the enthalpy method, the temperature profile and cut geometries induced by laser heating and ablation can be numerically evaluated [19,26–28].

The modeling of temperature and cut profiles for liquid-assisted laser machining processes may be achieved by adding a forced convection caused by a liquid flow into the domain of the heat transfer models. Such a study has been reported by Li et al. [11,12], where a temperature field model for waterjet-guided laser machining of silicon was developed using an explicit central space FDM with the temperature-dependent material properties. A similar study for the waterjet-guided laser machining of silicon using finite element method (FEM) was reported by Yang et al. [29]. According to these models, silicon was assumed to be removed in its liquid status. This may imply that the mechanical effect of waterjet impingement is essentially neglected or negligible.

Following the development of a hybrid laser-waterjet technology [10], this study attempts to develop a mathematical model to predict the temperature field and groove characteristics in the hybrid laser-waterjet micro-grooving process for a single crystalline silicon. The temperature field model will firstly be formulated using an enthalpy-based FDM and then verified by experiment. A numerical simulation of the heating and cooling process and the material removal mechanisms under the coupled effect of laser heating and waterjet cooling and expelling associated with the hybrid laser-waterjet grooving process for the silicon will then be carried out.

2. Hybrid laser-waterjet technology

The essence of this technology is to remove material at its soft-solid status rather than through melting or vaporization as in the conventional laser machining process, so that the temperature for material removal and the thermal damages induced by the laser are minimized. The process uses a laser beam for heating and softening the material and a waterjet for removing the laser-softened material gradually. In the technology used in this study, the waterjet is off-axially applied to the laser beam to enable the removing action. A pressurized air-driven pump from Haskel with a pressure stabilizer able to yield the water pressure of up to 67 MPa was used to form a waterjet through a nozzle of 570 μm. The waterjet nozzle could be adjusted precisely by a specially designed mechanism to change its inclination angle relative to the laser beam, standoff distance from the impacting work surface and offset distance from the laser incident at the work surface. A Manlight model ML20-PL-R-OEM nanosecond-pulsed fiber laser providing a Gaussian beam with the focal diameter of 17.2 μm at 1080 nm wavelength with a random polarization was employed as the heating unit. The maximum laser pulse energy at 42-ns pulse