

Ultrashort-laser-pulse machining characteristics of aluminum nitride and aluminum oxide

B.C. Chen^{a,1}, C.Y. Ho^{b,*}, M.Y. Wen^c, C.S. Chen^b, C. Ma^b, Y.H. Tsai^b

^aDepartment of Chinese Medicine, Buddhist Dalin Tzu Chi General Hospital, Chiayi 622, Taiwan, ROC

^bDepartment of Mechanical Engineering, Hwa Hsia University of Technology, Taipei 235, Taiwan, ROC

^cDepartment of Mechanical Engineering, Cheng Shiu University, Kaohsiung 833, Taiwan, ROC

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Abstract

This paper analytically investigates the ablation characteristics of aluminum nitride and aluminum oxide irradiated by an ultrashort pulse laser. Aluminum oxide or aluminum nitride has been one of the main ceramic packaging materials used for microelectronics packaging. However, a more extensive use of these ceramics has been limited due to their high inherent hardness and brittleness. An ultrashort pulsed laser micromachining could be a viable technology for these ceramics. The hyperbolic thermal model instead of heat transfer equation based on Fourier's law is employed to study the ablation rate of an ultrashort laser pulse machining for aluminum nitride and aluminum oxide. The ablation depth per pulse predicted by this study agrees with the available experimental data. The delay of temperature rise is presented for the case of laser pulse duration shorter than thermal diffusion relaxation time. This study also demonstrates the reasons why high temperature is obtained for an ultrashort laser pulse machining of materials. The distinctions of properties such as thermal diffusivity, optical penetration depth, thermal expansion coefficient and reflectivity result in the differences of the ablated depth per pulse between aluminum nitride and aluminum oxide.

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1. Introduction

Aluminum nitride is an important ceramic material because of its excellent properties [1]. Aluminum nitride has attracted increasing interest because of its low compressibility, good thermal stability, chemical and radiation inertness, and applications such as short-wavelength light-emitting diodes, optical detectors, high-pressure, high-temperature, and high-frequency optoelectronic devices [2]. Aluminum oxide ceramic material has been one of the main ceramic packaging materials used for microelectronics packaging due to its low cost and good electrical and mechanical properties [3]. However, the development of

these materials has been hindered by difficulties in fabrication, especially in shaping them for end use of applications due to their high inherent hardness and brittleness, causing machining difficulties and high processing costs. As a means of overcoming these problems, it is thought that an ultrashort pulsed laser micromachining could be a viable option because the intense laser light from an ultrashort pulse laser can induce nonlinear processes such as multiphoton absorption. This implies that the fine micromachining of high band-gap materials like ceramics can be readily achieved with minimum thermal and mechanical defects on the substrate. Accordingly, the use of ultrashort laser pulses in the structuring and drilling of ceramics has been actively researched in recent years.

Laser processing of aluminum nitride and aluminum oxide is widely used in the microelectronics industry for scribing and via hole drilling. Some theoretical and experimental studies were performed [4,5]. Laser processing involves light and heat. Therefore optical and thermal properties of aluminum nitride and

*Corresponding author.

Tel.: +886 2 89415059 (office)/+886 961107053 (Mobile);
fax: +886 2 89415059.

E-mail address: hcy2182@yahoo.com.tw (C.Y. Ho).

¹These authors contributed equally.

aluminum oxide play important role on laser processing of these ceramics. This paper investigates the effects of optical and thermal properties of aluminum nitride and aluminum oxide on the ablated depth per pulse by an ultrashort-pulse laser.

2. Analysis

2.1. Optical and thermal properties

The chemical composition and preparation techniques can significantly affect the optical properties of Al_2O_3 and AlN [6,7]. The variations of refractive index and extinction coefficient with wavelength were shown in Ref. [6] for Al_2O_3 and in Ref. [8] for AlN ceramics. According to the Fresnel's formula, the reflectivity R follows

$$R_{\lambda//} = \frac{(p - n_1 \sin \theta_1 \tan \theta_1)^2 + q^2}{(p + n_1 \sin \theta_1 \tan \theta_1)^2 + q^2} \times \frac{(n_1 \cos \theta_1 - p)^2 + q^2}{(n_1 \cos \theta_1 + p)^2 + q^2} \quad \text{for } p - \text{polarization} \quad (1)$$

$$R_{\lambda\perp} = \frac{(n_1 \cos \theta_1 - p)^2 + q^2}{(n_1 \cos \theta_1 + p)^2 + q^2} \quad \text{for } s - \text{polarization} \quad (2)$$

$$R_{\lambda c} = \frac{1}{2}(R_{//\lambda} + R_{\perp\lambda}) \quad \text{for } c - \text{polarization} \quad (3)$$

where n_1 is the refractive index of air and θ_1 is the angle of incidence. p and q yield

$$p^2 = \frac{1}{2} \left[\sqrt{(n_\lambda^2 - k_\lambda^2 - n_1^2 \sin^2 \theta_1)^2 + 4n_\lambda^2 k_\lambda^2} + (n_\lambda^2 - k_\lambda^2 - n_1^2 \sin^2 \theta_1) \right] \quad (4)$$

$$q^2 = \frac{1}{2} \left[\sqrt{(n_\lambda^2 - k_\lambda^2 - n_1^2 \sin^2 \theta_1)^2 + 4n_\lambda^2 k_\lambda^2} - (n_\lambda^2 - k_\lambda^2 - n_1^2 \sin^2 \theta_1) \right] \quad (5)$$

The reflectivities of aluminum oxide and aluminum nitride are approximately 0.065 and 0.142, respectively, for wavelength 790 nm at zero angle degree of incidence. According to the manufacturer's data sheets used in the available measured data [4,9], the densities of these ceramics are similar: 3.75 and 3.26 g cm⁻³ for aluminum oxide and aluminum nitride, respectively. However, their thermal conductivities and thermal expansion coefficients are significantly different. The thermal conductivity and thermal expansion coefficient of aluminum oxide are 24 W m⁻¹ K⁻¹ and 7.7 × 10⁻⁶ K⁻¹, respectively. On the other hand, the thermal conductivity and thermal expansion coefficient of aluminum nitride are, respectively, 170–240 W m⁻¹ K⁻¹ and 4.2 × 10⁻⁶ K⁻¹.

2.2. Mathematical model

For the ultrashort-laser-pulse heating of materials, the Fourier's parabolic heat transfer model breaks down due to the unrealistic assumption of infinite speed for heat propagation [10]. To improve the unrealistic hypothesis, a hyperbolic thermal transport model

with thermal relaxation time is proposed by Cattaneo [11] and Vernotte [12]. The one-dimensional hyperbolic thermal model of ultrashort-laser-pulse machining for materials may be written as

$$c \left(\frac{\partial T}{\partial t} + \tau_q \frac{\partial^2 T}{\partial t^2} \right) = k \frac{\partial^2 T}{\partial z^2} + \frac{3P}{\pi \delta \sigma^2} (1-R) e^{-(t/\tau_0)^2 - (z/\delta)} \left[1 - \frac{2\tau_q t}{\tau_0^2} \right] \quad (6)$$

where T is the temperature in the workpiece. k represents thermal conductivity. c denotes volume heat capacity. z signifies spatial coordinate. The symbol t stands for time. A 185 fs pulse laser with a wavelength 790 nm is used to conduct this laser ablation of ceramics, which mode is TEM₀₀ with the profile of Gaussian distribution. The symbols P , R , δ , σ and τ_q correspondingly represent the laser power, reflectivity, optical penetration depth, energy-distribution radius and heat flux phase lag time. 3 in Eq. (6) are taken to assure 90 percent of laser energy included within the energy-distribution radius. τ_0 symbolizes the pulse duration at FWHM.

The initial condition and boundary conditions are set as

$$T(z, t) = T_\infty, \quad \frac{dT(z, t)}{dt} = 0 \quad \text{at } t = 0 \quad (7)$$

$$T(L, t) = T_\infty \quad \text{for workpiece thickness } L \gg \delta \quad (8)$$

$$k \frac{\partial T(z, t)}{\partial z} + h[T(z, t) - T_\infty] = 0 \quad \text{at } z = 0 \quad (9)$$

where h is convection heat transfer coefficient and L is the thickness of workpiece. If the vaporization is assumed to be the ablation mechanism of the materials, the energy balance at the solid–vapor interface is employed. Due to the short time in the process of ablation, it is very quick that solid is melted into liquid and then liquid is evaporated into vapor. Therefore, the time for liquid occurrence is very short. Consequently the phase change between solid and vapor is considered in this study [13].

$$T = T_e \quad \text{at solid–vapor interface} \quad (10)$$

$$-k \frac{\partial T}{\partial z} = \rho \gamma \frac{df}{dt} \quad \text{at solid–vapor interface} \quad (11)$$

where γ is the latent heat of evaporation and T_e is the evaporation temperature. f is the solid–vapor interface. ρ symbolizes mass density.

The nondimensional parameters are defined as

$$\begin{aligned} \theta &= \frac{T - T_\infty}{T_e - T_\infty}; \quad \tau = \frac{t}{\tau_0}; \quad \xi = \frac{z}{L}; \quad \tau_{0L} = \frac{\tau_0}{cL^2/k} = \frac{\tau_0}{\tau_D}; \\ H &= \frac{hL}{k}; \quad G = \frac{f}{L}; \quad \Omega = \frac{\rho \gamma L^2}{k \times \tau_0 \times (T_e - T_\infty)}; \\ Q &= \frac{F_0}{c\delta(T_e - T_\infty)}(1-R); \quad \tau_{0q} = \frac{\tau_0}{\tau_q} \end{aligned} \quad (12)$$

Therefore, the nondimensional forms of hyperbolic thermal model, initial condition, boundary conditions and energy balance equation at solid–vapor interface yield

$$\frac{\partial \theta}{\partial \tau} + \frac{\partial^2 \theta}{\partial \tau^2} = \tau_{0L} \frac{\partial^2 \theta}{\partial \xi^2} + Q e^{-\tau^2 - (L\xi/\delta)} \left(1 - \frac{2 \times \tau}{\tau_{0q}} \right) \quad (13)$$

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