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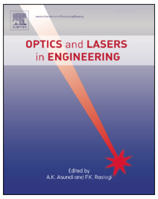

Fast femtosecond laser ablation for efficient cutting of sintered alumina substrates

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ABSTRACT

Fast, accurate cutting of technical ceramics is a significant technological challenge because of these materials' typical high mechanical strength and thermal resistance. Femtosecond pulsed lasers offer significant promise for meeting this challenge. Femtosecond pulses can machine nearly any material with small kerf and little to no collateral damage to the surrounding material. The main drawback to femtosecond laser machining of ceramics is slow processing speed. In this work we report on the improvement of femtosecond laser cutting of sintered alumina substrates through optimisation of laser processing parameters. The femtosecond laser ablation thresholds for sintered alumina were measured using the diagonal scan method. Incubation effects were found to fit a defect accumulation model, with $F_{th,1}=6.0\ \mathrm{J/cm^2}$ (± 0.3) and $F_{th,\infty}=2.5\ \mathrm{J/cm^2}$ (± 0.2). The focal length and depth, laser power, number of passes, and material translation speed were optimised for ablation speed and high quality. Optimal conditions of 500 mW power, 100 mm focal length, 2000 μm/s material translation speed, with 14 passes, produced complete cutting of the alumina substrate at an overall processing speed of 143 μm/s – more than 4 times faster than the maximum reported overall processing speed previously achieved by Wang et al. [1]. This process significantly increases processing speeds of alumina substrates, thereby reducing costs, making femtosecond laser machining a more viable option for industrial users.

1. Introduction

Technical ceramics have a wide range of applications, from bio-implants, chemical resistant parts, thermal barriers, wear resistant coatings, and electronics. The success of these materials in such applications lies in their favourable properties, including high dielectric strength (8 kV/mm), excellent thermal stability (T_m =2032 °C) and high thermal conductivity (25 W/m K) [2,3]. Alumina-based technical ceramics in particular are widely used in devices as diverse as wear-resistant mechanical parts, electrical insulators, and high power, radio frequency circuits [1,3].

Production of devices from manufactured alumina substrates necessarily involves cutting the material. Several methods currently exist for this process, including diamond saw cutting and both CO_2 and excimer (nanosecond) laser machining, however these have a number of drawbacks. Mechanical cutting using a diamond saw has well known disadvantages: wear of expensive tools, linear only geometries, and frequent breakage of the brittle alumina workpiece. CO_2 laser machining is currently the preferred method; it is highly flexible and gives high throughput. Unfortunately, the thermal nature of the machining process leads to significant heat affected zones (HAZ) around the cut, with common cracking and spattering destructive effects [1,3–5]. Excimer (nanosecond) laser machining also has been attempted. The resultant cuts were of quite poor quality, with debris and cracking seen in the surrounding HAZ [6].

Ultrafast laser micromachining (using femtosecond laser pulses) is an emerging technology with the potential to provide a solution to many of these issues. Ultrashort pulse durations deliver extremely high peak power, resulting in multiphoton absorption and avalanche ionisation processes [7–12]. This mechanism opens up new possibilities for machining of materials that is not

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dependent on the single photon absorption properties of the material. The main benefit of ultrafast laser machining lies in the strongly non-thermal nature of the ultrafast machining process. The pulse durations are smaller than the thermal diffusion time (electron–phonon coupling timescale). Hence femtosecond laser micromachining can generate extremely clean, precise and complex cut features with minimal HAZ [7–12].

The main drawback to ultrafast laser machining is the slow processing speed – speeds of up to 33 μm/s have been reported for cutting through alumina substrates [1], whereas speeds up to 152 mm/s have been achieved using CO_2 lasers [13]. Therefore, increasing the efficiency and processing speed of ultrafast laser micromachining is the single most important advance that will increase the uptake of this powerful technique in industry.

In this work we examined the impact of a variety of optical variables upon overall processing speed and quality. We tuned the focal length, focal depth, power, linear translation rate and number of passes, in order to determine an optimal set of conditions for cutting of alumina substrates. Priority was given to maximum overall processing speed while maintaining acceptable cut quality.

This study is part of a larger project that aims to understand the complex interactions between femtosecond laser pulses and dielectric materials, and then to exploit that knowledge to improve femtosecond laser micromachining.

2. Materials and methods

The alumina substrates used in these experiments were commercial sintered alumina tiles (CoorsTek Inc., USA), with a thickness of 250 μm. The laser used was a commercial Ti:Sapphire amplified femtosecond laser (Mantis and Legend Elite, Coherent Inc., USA), with a maximum average power of 3.5 W. This system produces 800 nm wavelength pulses with duration of 110 fs and repetition rate of 1 kHz, with a Gaussian spatial profile. For most studies, the laser repetition rate was 1 kHz. For ablation threshold tests at low pulse overlap values, the laser repetition rate was reduced using a mechanical shutter and Pockels cell pulse picker (Model 5046ER, FastPulse Technology Inc., USA). The beam was directed to a micromachining stage consisting of XYZ translation stages for sample movement. For D-scan ablation tests, a purpose-built micromachining stage consisting of XYZ translation stages (Thorlabs Inc., USA) capable of simultaneous XYZ movement was used. For all other micromachining experiments, a more user-friendly commercial micromachining stage (IX-100C, JP Sercel Associates Inc., USA) was used. The laser beam was focused through plano-convex lenses of varying focal length, from 50–300 mm, and laser power was adjusted using a variable attenuator based on a half waveplate and polarising beam splitter (Watt Pilot, UAB Altechna, Lithuania).

Machined alumina substrates were analysed using a combination of scanning electron microscopy (SEM) (Jeol JCM-6000 Neoscope, Coherent USA), stylus profilometry (Dektak XT, Bruker USA) and optical profilometry (Contour GT-K, Bruker USA).

Ablation threshold measurements (minimum pulse fluence required to cause ablation) were performed using the diagonal scan (or D-scan) technique originally developed by Samad and Vieira [14]. This method involves a sample placed in the beam path of a focused Gaussian laser beam, located above the focal point. The sample is then translated along the y and z axes simultaneously (i.e. the directions perpendicular and parallel to the optical axis) so that it passes through the focal point (Fig. 1). The machined feature has a characteristic “two lobe” shape. By assuming a Gaussian beam profile, the ablation threshold can be calculated from the maximum radius of the ablation feature ρ_{max} using Eq. (1).

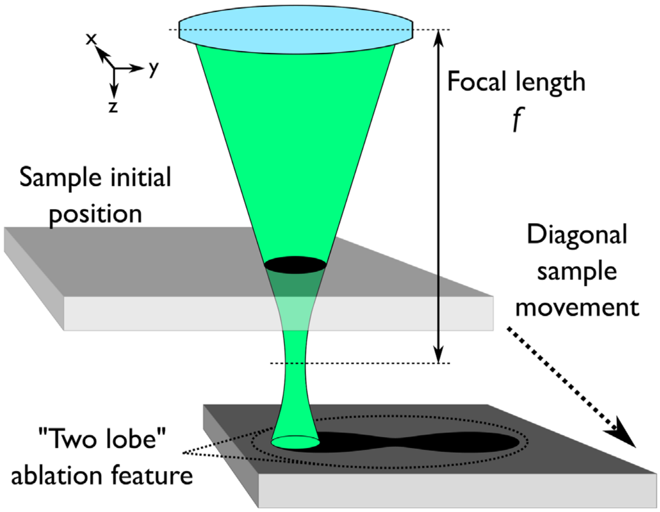

Fig. 1. D-scan method for measurement of femtosecond pulsed laser ablation thresholds, where the sample is translated simultaneously along *y* and *z*, across and through the laser focal point.

$$F_{th} = \frac{E_0}{e\pi\rho_{max}^2} \tag{1}$$

in which F_{th} is the ablation threshold in J/cm^2, E_0 is the pulse energy in J, ρ_{max} is in cm. The method does not require measurement of beam parameters such as beam waist, position, or focal length, making it a faster and easier method than techniques such as diameter regression [15].

Incubation effects, variation in the ablation threshold for different numbers of incident laser pulses striking the sample, also were investigated using this method. The number of overlapping pulses can be calculated from measurement of the ρ_{max} dimension, as well as knowledge of the laser repetition rate f and material translation speed (MTS) v_y in cm/s [16–18].

$$N = \frac{\sqrt{\pi} f \rho_{max}}{v_y} \tag{2}$$

D-scan ablation threshold tests were carried out at a range of different material translation speeds (10–500 μm/s) and two different repetition rates (10 Hz and 1 kHz) to determine the incubation behaviour of the ablation threshold of the material. No difference in the laser-material interaction is expected for the different repetition rates used, because even at the maximum repetition rate used (1 kHz), the pulse separation (1 ms) is sufficient time for any plasma or heat to dissipate – the only lasting effect expected between pulses is permanent or quasi-permanent structural changes. This is confirmed by multiple previous experiments [19–22].

Ablation tests also were carried out to determine the optimal conditions for cutting of alumina wafers. These tests varied the focal length and depth, laser power, number of passes, and MTS. At this point it is useful to clarify the definitions of two different parameters; the MTS is the speed at which the sample is translated under the focal point during a single pass, and the overall processing speed (OPS) is the speed at which a finished, multipass cut is made – i.e. OP = MTS ÷ number of passes.

3. Results and discussion

3.1. Ablation threshold

In Fig. 2 we see example surface plots of ablation profiles machined into the sintered alumina sample; the degree of pulse