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Nanosecond pulsed laser irradiation of sapphire for developing microstructures with deep V-shaped grooves

Nozomi Takayama[a], Shouhei Asaka[b], Jiwang Yan[a,*]

[a] Department of Mechanical Engineering, Keio University, Hiyoshi 3-14-1 Kohoku, Yokohama, Kanagawa 223-8522, Japan
[b] Shinkosha Co., Ltd., 2-4-1 Kosugaya Sakaeku, Yokohama, Kanagawa 247-0007, Japan

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ABSTRACT

A nanosecond pulsed Nd:YAG laser was used to irradiate a sapphire substrate to produce 3-dimensional microstructures with sharp V-shaped grooves. In initial experiments, where single grooves were machined, a maximum taper angle of ~79° was obtained. At constant laser parameters, the taper angle remained constant. As the taper angle increases from a flat surface, the irradiated area increases while incident fluence decreases; once the incident fluence approaches the ablation threshold, the taper angle becomes constant. The taper angle could be controlled by the laser fluence, scanning speed and incident angle of the laser beam. Using these results, a kind of surface microstructure, comprised of micropyramids with steep walls, was successfully machined for optical measurement applications. The surface roughness, transmittance and crystallinity of the microstructure surface could be controlled by the laser scanning speed. By applying the taper formation mechanism proposed in this study, the micromachining of sharp microstructures with steep walls on various hard brittle materials becomes possible.

1. Introduction

Sapphire is a useful material in a wide range of applications, due to its high hardness, strength, wide band-width transparency and chemical inertness. In recent years, sapphire is increasingly used in many optical devices, optic fibers and LED substrates [1–3]. Due to its superior properties such as greater resistance to scratches and abrasion, it is expected to replace glass materials as a display screen material. Moreover, to meet the growing demand for sapphire as LED substrates, technologies for the crystal growth and surface processing of synthetic sapphire have been extensively developed, resulting in the reduction of production costs. This has also stimulated the use of sapphire in new applications. Despite having great potential as a highly functional material, sapphire is very difficult to machine due to its high hardness and brittleness [4]. It is difficult to process microstructures such as holes and grooves, with sub-millimeter feature sizes by conventional mechanical means. For example, if the ultrasonic drilling of sapphire is attempted, there is a possibility of tool breakage by chips filling the drill hole [5]. In addition, mechanical machining of sapphire causes high levels of tool wear, making it incredibly difficult to achieve high shape repeatability.

Therefore, many researchers have turned to non-conventional methods in order to machine sapphire microstructures at a high level of precision. To avoid the problems of tool breakage and wear present in mechanical methods, the primary focus has been on non-contact methods. The etching of sapphire is often performed to process wafer substrates but it is known to be time-consuming and requires a masking process. Sapphire is commonly etched by a $3H_2SO_4$:$1H_3PO_4$ mixture solution at 300–400 °C. Some studies have reported that it takes 10 h to machine a square area of 0.5 × 0.5 mm to a depth of 0.09 mm [6,7]. Therefore, etching is unsuitable for the machining of deep structures.

Laser machining can be applied as a more rapid method, with the additional advantage of high geometrical freedom. It is easy to create complex shapes by controlling and scanning the laser beam. Ultra-short pulsed laser machining has been successfully applied for the ablation of sapphire [8]. However, it must be taken into account that not only is the equipment for this method very expensive, the material removal rate is low. Thus it is unsuitable for the machining of large areas. In order to achieve a higher material removal rate at a lower cost, the use of a nanosecond pulse may be more suitable. Previous studies have shown that a nanosecond pulse can be used to machine small holes into sapphire with high precision [2]. A longer pulse, such as one of a microsecond order, however, would result in a large heat affected zone. As sapphire is both brittle and a poor thermal conductor, many cracks may form after long-pulse laser irradiation.

The laser machining of sapphire is not without its problems. One of

* Corresponding author.
E-mail address: yan@mech.keio.ac.jp (J. Yan).

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the greatest and least understood problems is the formation of a taper, especially when machining deep structures. A taper results when the entrance diameter or groove width is greater than the exit diameter or width. This is a pressing problem as many applications of sapphire require a high aspect ratio without a taper or, conversely with a specific taper angle. Taper formation due to laser machining is not uncommon; it is thought to occur primarily due to inherent focusing properties of the laser; laser power is reduced by beam propagation [9–11]. Thus it was found that focal plane position has a significant effect on taper formation. Some researchers have found that other parameters, specifically laser fluence and pulse number, also affect the taper angle [12]. However, much of the preceding research is focused on the laser machining of metal materials. Sapphire, as a transparent and brittle material, is expected to have a different response. Additionally, it is agreed that the taper formation is difficult to understand due to complex and interacting phenomena; melting/vaporization, plasma formation, heat and mass transfer. Therefore, it is necessary not only to identify the contributing factors of taper formation but to understand how the taper develops and to apply this understanding to control the taper angle.

Much research has been devoted to removing the laser-induced taper [13–15]. However, this study aims to apply it to three-dimensional machining. By understanding the mechanism behind taper formation, it becomes possible to machine three-dimensional structures with feature sizes of sub-millimeter order. For example, a pyramidal structure can be machined by combining tapered grooves. Such structures have resulted in a low reflectivity in the millimeter wave band [16]. Moreover, due to the sloped walls, the structure's surface retains this low reflectivity over a wide band width [17]. This property is essential for optical elements involved in the measurement of cosmic microwave background radiation (CMB). By applying the taper formation mechanism in laser micromachining, it becomes possible to machine sharp structures. Such structures have not been achieved in previous studies, even with the use of a femtosecond pulsed laser, which is generally used to create highly defined structures.

Thus, in this study, we will investigate the development of the taper angle of deep grooves in sapphire. Various laser parameters will be considered to understand their respective influences on taper development. The results and findings obtained from this study will be extended to developing an efficient method for the machining of typical three-dimensional structures, namely a pyramidal structure for optical elements used in CMB measurement. The understanding of the taper formation phenomena is expected to contribute not only to the laser drilling and cutting of sapphire, but also to the laser machining of other brittle and transparent materials, such as diamond and glass.

2. Experimental method

The laser used in the following experiments was LR-SHG, a Nd:YAG laser pumped by a laser diode, from MegaOpto Co., Ltd. It has a maximum power output of 1W, a wavelength of 532 nm and a spot diameter of 85 μm. The laser output energy has a Gaussian distribution. The laser beam scanning was controlled in two dimensions using a galvanometer scanner system. The laser beam was focused onto a stage using an fθ lens. The sapphire used is a single-crystal cube with a length of 10 mm, produced by Shinkosha Company. It was annealed to remove all internal residual stress and to prevent this from affecting the irradiation results. The plane parallel to the optical axis of the crystal (c-axis) was irradiated. The sample surface was prepared by grinding and the surface roughness of the irradiated plane was 1.02 μmRa.

A specific laser irradiation scheme was used, as presented in Fig. 1. Fig. 1a shows the scheme for groove machining. A single line was irradiated, then the laser beam was moved a pitch of 42.5 μm (half of the beam diameter) across and a second line irradiated. 7 lines was irradiated to form a single groove. Fig. 1b shows the scheme for pyramid irradiation. A thick line represents a single groove as machined by the scheme of Fig. 1a. The vertical grooves are irradiated first, then followed by the horizontal grooves. The combination of the irradiation of the 2 groove sets are counted as 2 irradiation times. In this way, a 3 × 3 pyramidal structure was machined. The parameters used are shown in Table 1.

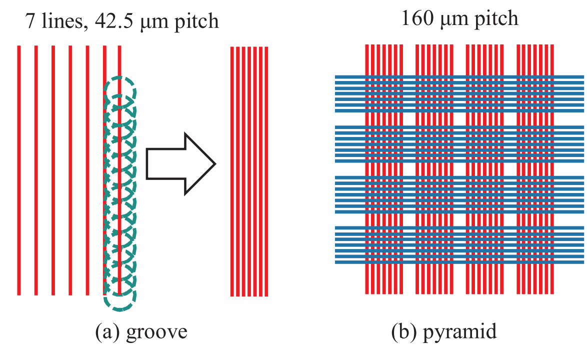

Fig. 1. The laser irradiation scheme used for the machining of (a) a groove and (b) a pyramid structure.

Table 1
Experimental laser parameters.

Laser parameters	Value
Wavelength (nm)	532
Pulse width (ns)	15.4
Repetition frequency (kHz)	1
Fluence (J/cm^2)	7.4, 10.6, 12.5, 15.7
Scanning speed (mm/s)	0.5, 5
Irradiation times	1, 5, 10, 15 (for 0.5 mm/s) 1, 10, 50, 150 (for 5 mm/s)

After irradiation, the samples were observed using the Inspect S50 Scanning Electron Microscope (SEM) made by FEI Company for confirming the surface structure. A MP-3 laser probe profilometer made by Mitaka Kohki Co., Ltd. was used to measure groove profile and depth. A laser microscope VK-9700 made by Keyence Corporation was used to measure the surface roughness. In addition, sound generation during machining was measured and analyzed by a High Function Sound Level Meter LA-3560 made by Ono Sokki Co., Ltd.

3. Simulations of temperature

A simulation was performed to investigate the temperature after irradiation by a pulsed laser. COMSOL Multiphysics software was used in the following simulations. A geometry, similar to that of the actual sapphire samples used in the experiments, was employed, where the z-axis was directed into the material, with the origin at the surface. The maximum temperature of the sapphire during laser irradiation was calculated. Heat transfer during a nanosecond pulsed irradiation occurs through thermal conduction; a conduction model was applied using the following equations.

$$\mathrm{d_z \rho c_p}\left(\frac{\partial \mathrm{T}}{\partial \mathrm{t}}\right) + \nabla\cdot \mathrm{q} = \mathrm{q_0} \tag{1}$$

$$q = -\mathrm{d_z} k \nabla T \tag{2}$$

where T is the temperature, q is the heat intensity, ρ is the density, c_p is the specific heat capacity and k is the thermal conductivity of the material. As the laser spot size and the heated region are small compared to the thickness of the sapphire sample, the temperature of the bottom surface of the sample is thought to be maintained at ambient temperature. The heat input Q_{in} to the material delivered by a single pulse of the laser is given by

$$\mathrm{Q_{in}}(r, t) = A^* I_0(t)^* \alpha^* \exp(-\alpha z)^* \exp\left(\frac{-2r^2}{R^2}\right)^* \mathrm{f}_{\mathrm{tri}(t)} \tag{3}$$