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Induction of low-stress and crack-free laser micro holes in sapphire: optimization of the process parameters under different ambient conditions

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Abstract

Objective: Generation of high-precision micro holes in thin substrates made of sapphire with the aim of avoiding residual stress while maintaining high edge strength and processing quality.
Materials and methods: Micro holes of 1000 µm and 500 µm in diameter were drilled in 1mm and 0.5mm thick sapphire samples using an UV nanosecond laser (355 nm, 7 ns). The tests were carried out both under normal pressure and under reduced ambient pressure of 10mbar generated by a specially designed vacuum chamber. Chipping was assessed and measured by means of optical microscopy. Furthermore a polarization microscope was used to quantify tensions, which were induced throughout the drilling process.
Results: Holes drilled in sapphire with pulse durations of about 10ns show significantly smaller chipping compared to drills in other transparent materials (e.g. borosilicate glass). Due to the faster removal of erosion products from the drill channel, higher ablation rates were reached under reduced pressure. Moreover, a 20% reduction of the laser power caused a considerable decrease of stress in the material.
Conclusion: From the literature and own preliminary investigations it is known that sapphire can be hardly processed from the reverse direction since very high mechanical tensions occur immediately which can destroy the entire sample. This effect was also confirmed in the present experiments where front-side laser irradiation proved to be more efficient than rear-side irradiation. Overall, higher laser powers and slower feed rates are necessary in order to achieve an ablation in sapphire.

Keywords: micro processing; drilling; processing of transparent materials; sapphire

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1. Introduction (Objective)

Sapphire (Al_2O_3) is a material with high potential for the use in a variety of applications. Due to its hardness and brittleness the processing with mechanical methods of drilling is difficult and the needed tools are expensive. The induction of high-precision micro holes in such a brittle and very hard material implies a variety of difficulties which have to be considered throughout the drilling process. Mechanical methods thereby often fail due to the hardness of the substrate. For this reason there's a great interest in developing new processes with laser systems. Optical transparent materials can for example serve as insulating layers between electrical or optical devices for packaging in micro electronics where clearance holes are needed. In order to improve the hole quality and reduce chipping as well as tensions in the material the investigations are also performed with different ambient pressures.

2. Materials and methods

2.1. Material properties

Characteristic properties of the material are its high optical transmission (87%) in a spectral range from near infrared to ultraviolet wavelengths. Furthermore sapphire is an insulation material, which could be used as insulating or carrying material in semiconductor technology. It has a relatively high thermal conductivity compared to other insulators. These properties are on the one side positive for the use of sapphire in a large number of application fields. On the other side these properties (especially the hardness) complicate the processing of sapphire.

Compared with other transparent materials Sapphire has a relatively high transmission in a great range of wavelength. However that makes the crystalline substrate a fitting choice for many applications, it also makes its processing difficult. Reason therefore is the absorption, which is responsible for the ablation. It's very low for wavelength from UV to near IR. That's why longer processing durations are necessary than for other materials.

2.2. Processing methods

The first approach was trying to drill the micro holes from the reverse direction, i.e. with rare-side laser irradiation. Therefore the material has to be transparent for the laser wavelength. This condition is fulfilled for the used sapphire samples. For receiving a clearance hole you have to move the laser focus along the z-axis, what allows a further ablation of material. Rare side processing has a few advantages compared to the already in industry established front side laser induction. You can reach cylindrical holes without bending the laser beam additional. Further the removal of the erosion products is supported by gravitation what enables a movement of the beam without blocking of the laser energy for the following ablation.

Laser micro processing from the front side is an already established method and is widely used in industry. In general therefore no movement of the laser beam along the z-axis is necessary but due to the crystalline structure and the enormous hardness of sapphire it is needed to achieve an adequate ablation. A disadvantage of this method is the generation of taper-shaped holes what reduces the hole quality.

The holes were drilled with a trepanning method with an additional wobble function. The resulting distribution of the pulses on the sample surface is shown in fig. 1.

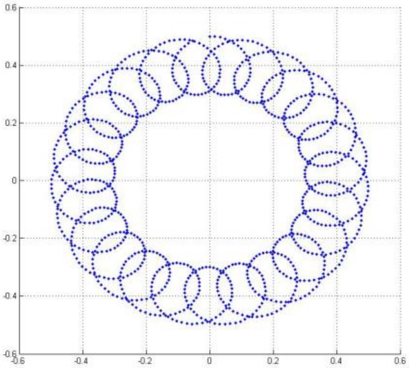

Fig. 1. Mat Lab simulation of the pulse distribution

2.3. Evaluation criteria and measuring

For the valuation and analysis of the processing quality we used different criteria. We regard the visual impression of the holes. There are cracks and chipping around the hole as well as tensions in the material. For all holes were drilled with the same starting conditions, the different settings of the process parameters are decisive for the quality of the results. Regarding the holes drilled with different attitudes we can see the connection between the set parameters and the resulting quality. During the drilling process chipping and cracks can occur. Their magnitude is connected with the value of the different process parameters. The chipping on the edges of the hole was analyzed with a digital microscope (KEYENCE VHX5000) and was measured as the maximal distance from the edge in [µm].

Fig. 2.(a) shows an exemplary presentation of the used measuring method. There occur deviations from the circular shape of the hole what could be explained by the polarization of the laser radiation. Therefore the diameter was measured horizontally and vertically and for the calculations and the consideration of the results the average of both diameters was used. Additionally the diameters of the holes were measured on both front and rare side to see of which dimensions the slope of the borehole walls is.

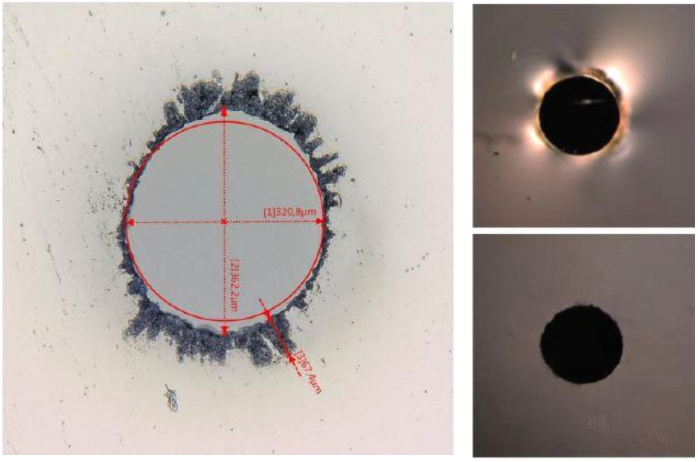

Fig. 2. (a) Measuring method ; (b) changes in brightness for different tensions

The heat input during the process can lead to tensions in the material which could be measured by polarization microscopy (Leica DM 2700P), because the tensions cause an anisotropy in the material which leads to a variation of the refractive index. To quantify these tensions a polarization microscope was used. Due to its crystalline structure, sapphire shows already birefringent properties in raw state. The difference between the refractive indexes of the different directions in sapphire (Δn) is 0.008. According to the following equation (1) this leads to a path difference of about 8µm (with d: substrate thickness and λ: wavelength of the microscope).

$$\Gamma = \frac{d}{\lambda} \cdot \Delta n \tag{1}$$

Unfortunately the compensator of the polarization microscope, which was initially provided for the measuring of tensions in amorphous materials, has only a measuring range of five orders what corresponds to a change in path length of 2µm. Although we could therefore not measure the exact value of the tensions in the sapphire substrate, there could be made a qualitatively description of the tension compared to each other. As shown in fig. 2.(b) the different parameter settings lead to a change of brightness in the images of the holes.

2.4. Experimental setup

A nanosecond laser (Conqueror3Lambda, Compact Laser Solution GmbH) which is operating at a wavelength of 355nm (UV) was used for drilling the holes in sapphire. The pulse duration lays between 7 and 16ns. The laser beam was adjusted by several deflection mirrors and focused by a scanner which includes the focusing lens with a focal length of 100mm.

In order to minimize the chipping and the induction of tensions in the substrate, the drilling was also carried out under reduced ambient pressure. The therefore created vacuum chamber was evacuated by a vacuum pump and the received operating pressure was up to 10mbar.For the drilling under reduced ambient pressure the sample was placed in a vacuum chamber. One reason for the performance of the drilling under reduced ambient pressure are requirements for laser based serial production which come from the special machine construction. They prefer so called "dry" methods without the use of liquids and process gases. With the reduction of the ambient pressure the erosion products should exit the drill channel faster. The vacuum chamber has an UV transparent AR-coated quartz glass where the laser beam enters the chamber. When the beam transits the glass, aberration can occur and worsen the quality of the focus diameter.

3. Results

The processed sapphire substrates had a thickness of 1mm and the drilled holes had diameters of 1000µm and 500µm. Primarily the holes with 500µm diameter were regarded for the evaluation of the results as the ones with 1000µm showed the same behavior for parameter changes.

3.1. variation of the process parameters

We started with one set of parameters known from preliminary investigations (Table 1) which led to acceptable results. Subsequently one of the parameters was changed per series of tests to see the impact on the hole quality.

Table 1. Initial set of parameters

mean power $\bar{P}$ [W]	repetition rate f_{rep}	velocity (scanner) v	velocity (z-axis) v_z	wobble frequency f_w	width of the wobble function d_w
5.9	30	20	0.25	666	200

The images show clear that the chipping on the rare side is much bigger than on the front side. This is also one disadvantage of the front side processing which could be avoided by processing from the back side. A reduction of the mean power (Fig. 3.(a)) leads to a smaller chipping on the rare side but simultaneous the diameter of the hole diminishes. A change of the feed rate in z-direction shows an inverse effect on the chipping.

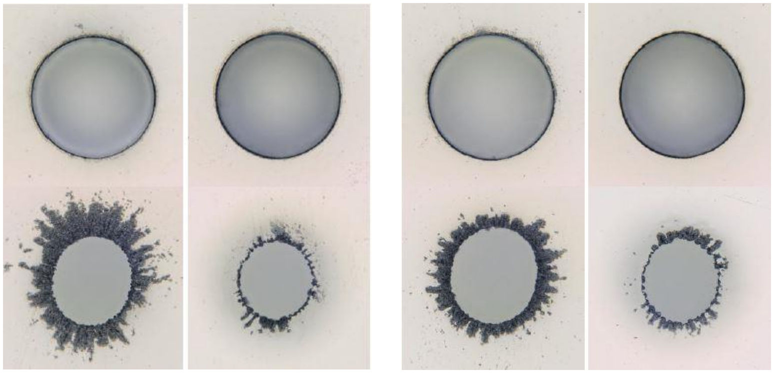

Fig. 3. (a) Reduction of the mean power from 5.9W (l.) to 3.6W (r.) ; (b) enlarged feed rate (z-axis) from 0.1mm/min (l.) to 0.5mm/min (r.)

Fig. 4. shows exemplarily the changes in brightness in the images taken with the polarization microscope and therefore a change of the tensions in the materials. Here you can see that for a lower repetition rate (b) the tensions are higher.

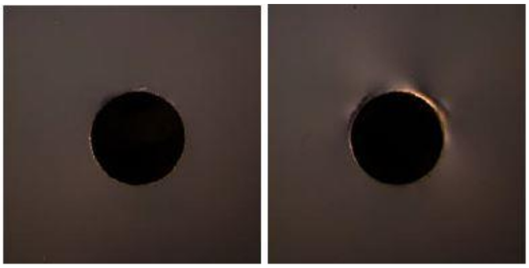

Fig. 4. Different repetition rates (a) 40kHz; (b) 30kHz

3.2. Process under reduced ambient pressure

Fig. 5. shows images of holes drilled under normal pressure (a) and under reduced ambient pressure at about 10mbar (b). The hole drilled in the vacuum chamber has sharper edges. We achieve holes from a mean power of about 2.2W and also drilling without a movement in z-direction was possible where under normal pressure clearance holes are impossible.

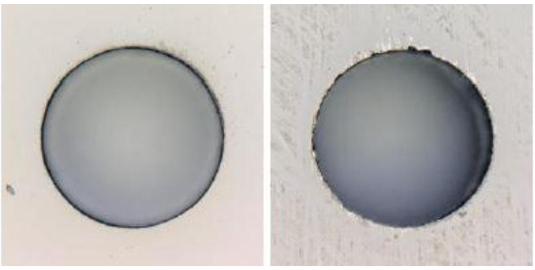

Fig. 5. (a) Normal pressure; (b) reduced ambient pressure

4. Conclusion and Outlook

The mean power used for the process influences the chipping significantly. A change in other parameters can also modify the effective mean power and thereby the energy per area. An important parameter is also the distribution of the laser pulses on the substrate which is especially influenced by the parameters of the wobble function as well as the velocity of the scanner. A lower feed rate in z-direction leads to a higher ablation, because of the smaller distance between two pulses, i.e. higher energy per volume, on the surface of the material. That's an explanation for the greater diameter on the rare side which we achieve for lower feed rates and also for the greater chipping. Due to its crystalline structure sapphire is sensitive to the polarization of the laser radiation and the scan direction. The elliptical shape of the holes which occurs on the rare side could be reduced to the different ablation in x- / z-direction caused by the polarization. This point could be improved by convert the linear polarization to a circular with a wavelength plate. Further the pulse duration could be reduced, because the shorter exposure time and the lower heat input may lead to smaller chipping and less tensions. The setup could be also improved by reducing the diameter of the laser focus (replacing the scanner optic with one with a smaller focal length.

The investigations should be repeated with samples of less thickness, because therefore a processing from the rare side could be possible. Furthermore the measuring of the tensions with the polarization microscope could be improved by adjust the equipment in order to reach the required measuring ranges.

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