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Femtosecond laser drilling of alumina ceramic substrates

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Abstract In the paper, the result on femtosecond laser drilling of alumina ceramic substrate was reported. The effects of various laser parameters such as different focus position, traverse speed, drilling pattern, pausing time, etc. on the drilled hole quality in terms of surface finish, heat affected zone (HAZ), hole circularity, debris, microcracks were studied. The quality of laser-drilled holes on alumina ceramic substrates was evaluated with optical microscope, SEM/EDX, and X-ray μ-CT analysis. The optimum drilling conditions were identified. High-quality laser-drilled holes on alumina ceramic substrates were demonstrated. The developed process has potential application in manufacturing of alumina substrate based electronic devices.

1 Introduction

Ceramics are widely used in many industrial areas such as automobile engine, heat exchanger, electronic substrates for microwave devices and so on. Alumina ceramic is one of most widely used ceramic substrates in the manufacture of high power radio frequency electronic circuits and the fabrication of multichip modules, mainly due to its high electrical resistance (volume resistivity $> 10^{14}\ \Omega\,\mathrm{cm}$), high thermal conductivity ($\sim 28\ \mathrm{W\,m^{-1}/K}$), high dielectric strength ($\sim 10\ \mathrm{kV/mm}$), and excellent thermal stability and so on [1]. The demand for miniaturized devices requires fabrication technologies for denser circuit patterns, smaller via holes and shorter separations. For small via hole drilling of below 100–200 μm, conventional techniques such as mechanical punching, drilling and cutting encounters some severe problems such as tool wear and easy breaking of the tool and workpiece since the alumina ceramic is very hard and brittle. With ever increasing density of integrated circuitry per unit area, conventional drilling processes cannot meet the stringent quality requirements with respect to dimensional tolerance and cleaner, crack-free, via holes.

Laser drilling process is a preferred method in drilling alumina ceramic due to its unique properties such as its non-contact process, no mechanical cutting force, no tool wear, flexibility, high machining rate, and so on. Actually laser micromachining has been successful in drilling via holes and cutting alumina ceramic substrates for electronic packaging applications since ceramic material have a strong absorption in the far infrared (IR) and ultraviolet (UV) wavelength spectrum [2, 3]. However, due to the strong thermal nature of laser beam-material interaction especially for long wavelength CO_2 laser, there are still some challenging issues on how to minimize thermal damage, eliminate microcracks, achieve high precision hole geometry and good surface quality, control hole taper, minimize and even eliminate spatter, dross and recast layer. Ultrashort pulsed lasers have opened up new opportunities for the processing of hard materials such as ceramics [4–6]. For the past decade, the use of ultrashort laser pulses for the structuring and drilling of various materials has been actively investigated [7–10]. The key benefits of ultrashort laser pulses lie in their ability to produce a very high peak power intensity and deliver energy into a material before thermal diffusion occurs. During ultrashort pulsed laser processing, the material is ablated mainly

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by vaporization. Also, the amount of molten material and the zone affected by residual heat are significantly reduced due to short pulse duration.

In this paper, fs laser drilling of alumina ceramic substrates was reported. The effects of various laser conditions on the laser-drilled hole quality were studied. The work aimed to achieve high-quality laser drilling of alumina ceramic substrate in terms of minimal heat affected zone, clean surface finish, no debris, no recast layer, no cracks, and no delamination for Au coated alumina substrates.

2 Experiments

The alumina ceramic substrates used in the experiments were Superstrate® 996 substrates from CoorsTek with 3 different thicknesses of 250/381/625 μm. The sample is composed of 99.6% alumina (Al_2O_3). The fs laser system used in the drilling process is based on a regenerative Ti:sapphire amplifier using chirped pulse amplification technique (Clark-MXR, CPA 2001) which provides high-intensity fs laser pulses for the drilling processes. The pulse duration of the output beam from amplifier is 150 fs with nominal wavelength at 775 nm. The repetition rate is 1000 Hz and the beam profile emitted from the regenerative amplifier is approximately Gaussian shape. The average output power can reach 800 mW at repetition rate of 1000 Hz. The laser beam is redirected with a 45° high reflectivity dielectric mirror through an aperture placed in front of a plano-convex lens with a focal length of 25 mm. The aperture is used to provide a round beam at the workpiece and improve the drilled hole quality. The focused spot was measured to be around 30 μm on the sample surface. A precision translation XYZ-stage were employed to drill via holes with a trepanning method under normal air atmosphere. During the drilling process, the laser beam is fixed whereas the sample moved along a pre-determined circular pattern for either one round or multiple rounds until the substrate is drilled through.

The morphology and quality of the laser-drilled holes were analyzed using optical microscope, Extended Pressure Scanning Electron microscopy (EP-SEM), Energy Dispersive X-ray Spectrometer (EDX) and X-ray μ-CT.

3 Experimental results and discussion

It is known that focus position affects beam spot size on the sample surface, then affect the surface power density, which will affect the cutting kerf width, hole taper and drilling efficiency. The drilling process for the focus position optimization was conducted at the laser power of 700 mW, traverse speed of 0.2 mm/s for 20 rounds Fig. 1 shows the hole diameter and hole taper as a function of focus position for drilling 381 μm-thick alumina substrate. Here, "0" is defined to correspond to the sample surface, positive value (+) is for above the surface, and negative value (−) is for below the surface. It can be clearly seen that with the focus position moving from positive position to negative position, the hole entrance diameter was reduced gradually to a minimum value and then increased again and for the hole exit, the diameter was increased to a certain value and then decrease with further moving focus below −0.4 mm. Also it was observed that there existed a minimum taper value in the focus position of about −0.35 mm. As shown in Fig. 1, an optimum focus position of about −0.35 mm was identified at which the hole taper was reduced to minimum value of approximately 2.5 degree.

In order to find the effects of traverse speeds on the drilling quality and efficiency, the drilling process was

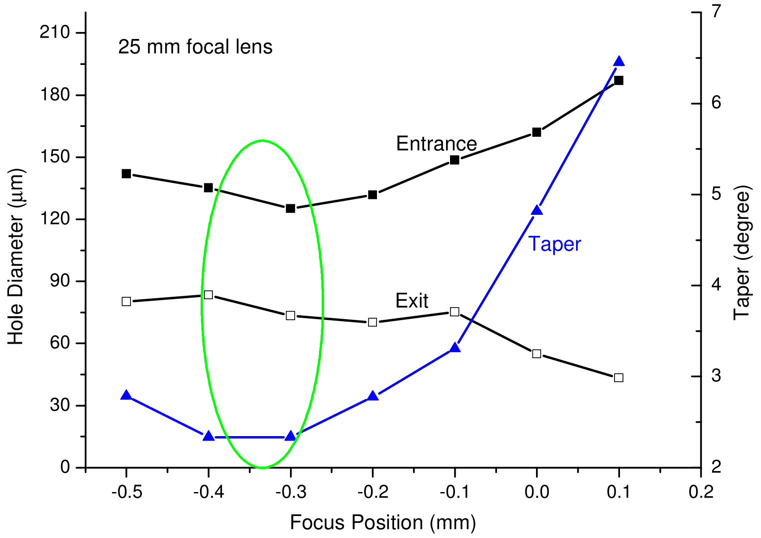

Fig. 1 Hole diameter and taper as a function of focus position

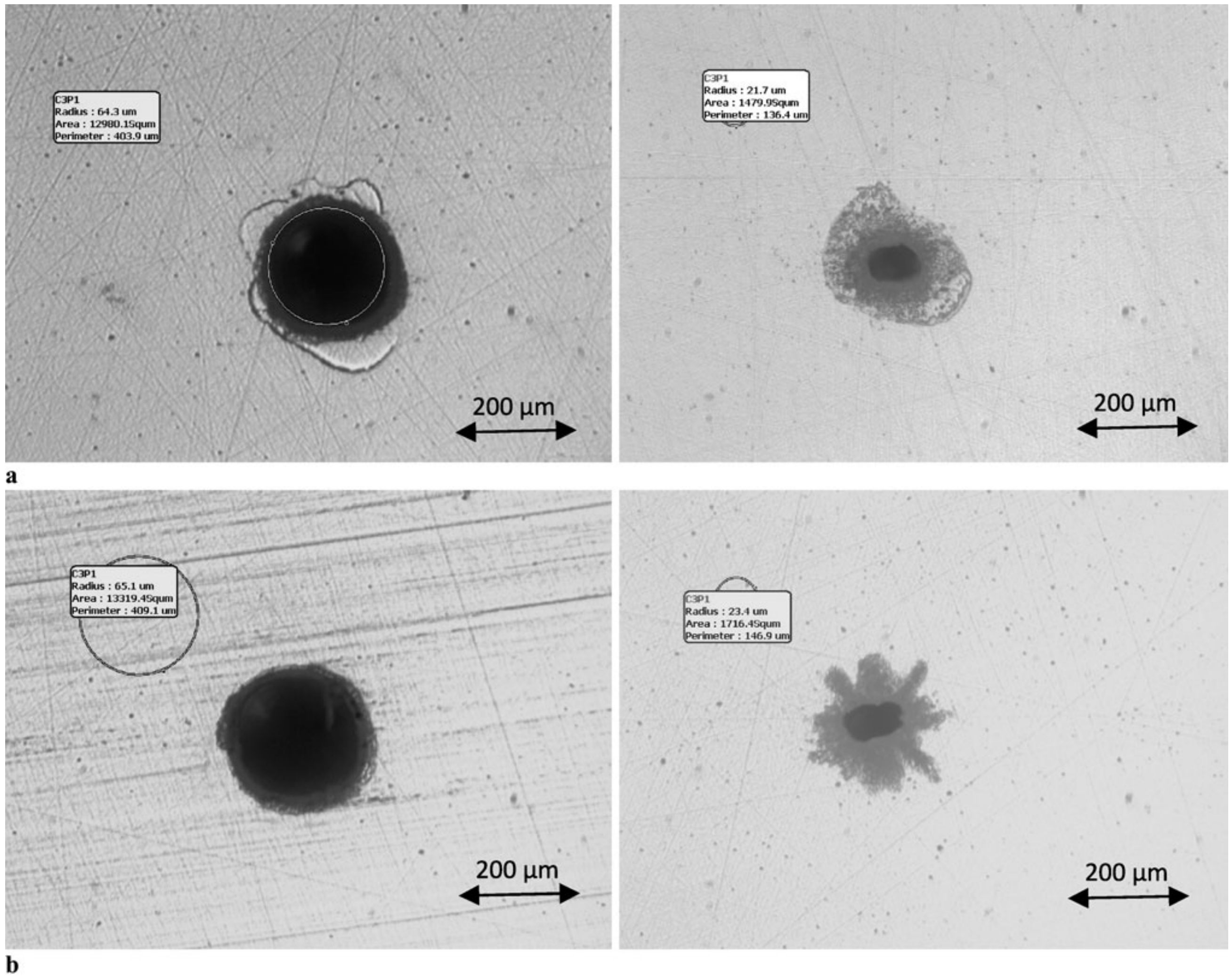

Fig. 2 Holes drilled on 625 μm thick alumina substrate at **a** 0.2 mm/s for 140 rounds, **b** 1 mm for 700 rounds; hole entrance (*left*), hole exit (*right*)

conducted on 625 μm-thick alumina substrate at several different speeds of 0.05 mm/s for 7 rounds, 0.2 mm/s for 140 rounds, 0.5 mm/s for 350 rounds, 1 mm/s for 700 rounds and 1.5 mm/s for 1050 rounds. The laser power was set at 700 mW and the focus position was set 0.35 mm below the sample surface. The effective cutting speed for all cases is the same to be 1.5 μm/s. It was observed that at slower traverse speeds less than 0.5 mm/s, some cracks were induced around the entrance whereas at higher traverse speeds of 1 and 1.5 mm/s, there were no cracks at the entrance as show in Fig. 2, which only showed the samples drilled at 0.2 mm/s for 140 rounds and 1 mm/s for 700 rounds for comparison. The reason may be due to the too much heat accumulation at a slower speed. It is known that high-speed multi-pass cutting has the potential to minimize thermal input to the substrate by spatially separating each pulse on the surface [11]. It can also improve energy coupling by displacing each pulse to avoid impinging on 'defocussing-plasma' generated by the previous pulses. As a result, the lateral heat conduction is minimized for the high-speed multi-pulse cutting so that the HAZ is reduced with increasing traverse speed. However, at high traverse speed, the hole exit became more elliptical. It was also observed that at slower speed of below 0.2 mm/s, the hole exit shape was a little more circular. In order to eliminate the cracks at the entrance and at the same time achieve more circular shape hole exit, the drilling was conduced for 100 rounds at 1 mm/s followed another 20 rounds at 0.05 mm/s. As shown in Fig. 3, there are no cracks on the entrance and the hole exit is more circular compared with hole drilled at only one speed of 1 mm/s as shown in Fig. 2b.

When the relative larger diameter holes of more than 250 μm diameter were drilled on 625 μm-thick alumina substrate, it was found that trepanning drilling with single circle pattern as shown in the left of Fig. 4a was not able to drill through the substrate no matter how many rounds were

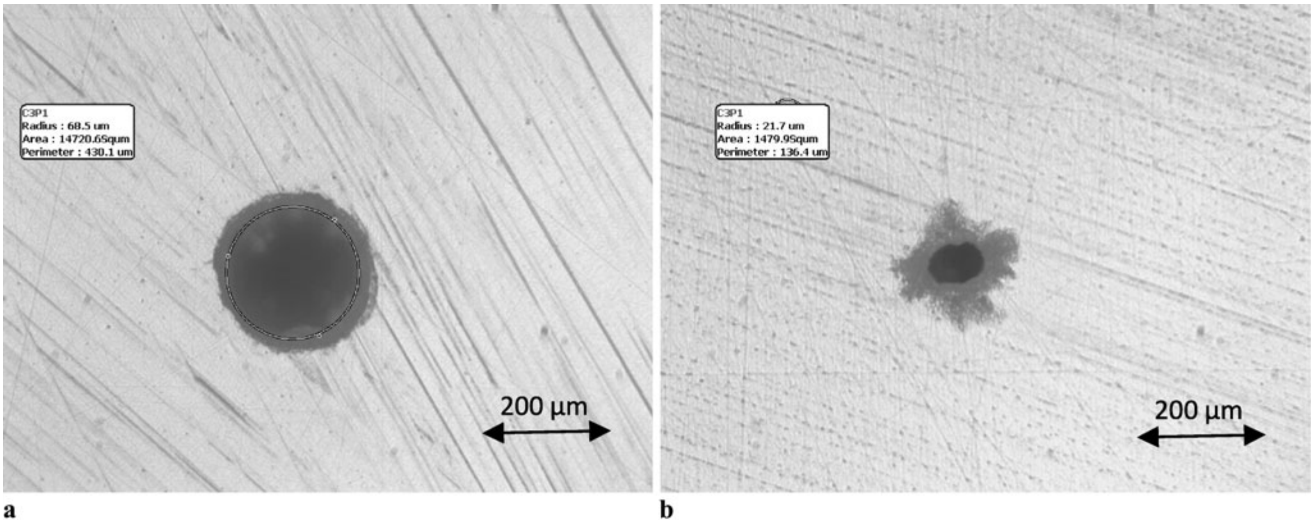

Fig. 3 Laser-drilled 125 µm diameter holes on 625 µm thick alumina substrate at 1 mm/s for 100 rounds plus 0.05 mm/s for 20 rounds. **a** Entrance. **b** Exit

drilled as shown in Fig. 4b. It is because that as the trepanning drilling progresses, it may happen that the laser beam cannot reach the bottom of the narrow kerf produced along the circular irradiation path, which in some cases hinders the drilling process. Especially, for thick substrate it can be a problem and deteriorate the drilling results. To avoid this situation, laser trepanning drilling with multiple circular filling pattern was needed. As shown in Fig. 4c, trepan drilling with 3 circle partial filling pattern (as shown in the right of Fig. 4a) was demonstrated to be able to drill through the sample. However, for multiple circle filling trepan drilling, some cracks were produced at the entrance as shown in Fig. 4c. The crack formation is believed due to much heat accumulation and the heat has no time to dissipate when the hole is drilled on the thick alumina substrates.

In order to dissipate the heat more efficiently and eliminate the cracks, an intermitted drilling was tried, which means drilling was conduced for a certain number of rounds (defined as unit number), then pause for some certain time, then do drilling again for another unit number of rounds, repeat this process until the substrate is drilled through. Figure 5 showed laser-drilled holes at 1 mm/s for 2 rounds trepanning, then pause 30 s and repeat 28 times. In this case, no cracks were observed, the hole exit was circular and the hole quality was very good as shown in Fig. 5. If the trepan drilling was conducted in non-stop continuous mode, the excessive heat can't be dissipated away effectively and the heat effect of subsequent scanning is overlapped with previous scanning. As a result, these accumulated excessive heat effects cause the sample temperature to increase and then induce thermal cracks as shown in Fig. 4c. When the trepan drilling was conducted in an intermittent way where the drilling was carried out at 1 mm/s for some rounds with a 30-second pause between certain round number scanning, the excessive heat could be dissipated away during the pause time before next round number scanning. Consequently, the HAZ and thermal cracks were reduced significantly as shown in Fig. 5 comparing with Fig. 4c. The results show that there is a certain amount of heat generated during laser trepan drilling of alumina substrate so that a certain amount of cooling time is needed before subsequent laser passes is scanned during multi-pass laser trepan drilling process.

For fs laser drilling on alumina ceramic substrates, the critical factor is to control the laser energy deposition on the sample surface so as to control the heat dissipation and then eliminate the detrimental effects such as microcracks. For the fs laser machining system used in this work, the laser beam energy deposited per unit area per second (average power density, W cm^{-2}) on the material surface during the focused spot trepanning is given approximately by [12]:

$$\langle I \rangle = \nu E_{\mathrm{p}} / \left[(\varphi s t) + \pi \varphi^2 / 4 \right] \tag{1}$$

Where $t = 1$ s, ν is repetition rate (Hz), E_{p} is the pulse energy (J), φ is the spot diameter and s is the traverse speed. From (1), it can be clearly seen that with fixed laser pulse energy and repetition rate, the focus position (affecting focus spot size at the sample surface) and traverse speed have a significant effect on the laser energy density deposited on the sample surface and overlap of the irradiated laser pulses, which then affects the drilling process and heat dissipation. Also, the sample thickness affects the drilling process. Usually, the thicker the substrate, the more difficult the drilling can be. This is because more material needs to be ablated away from the cutting kerf (more of round number

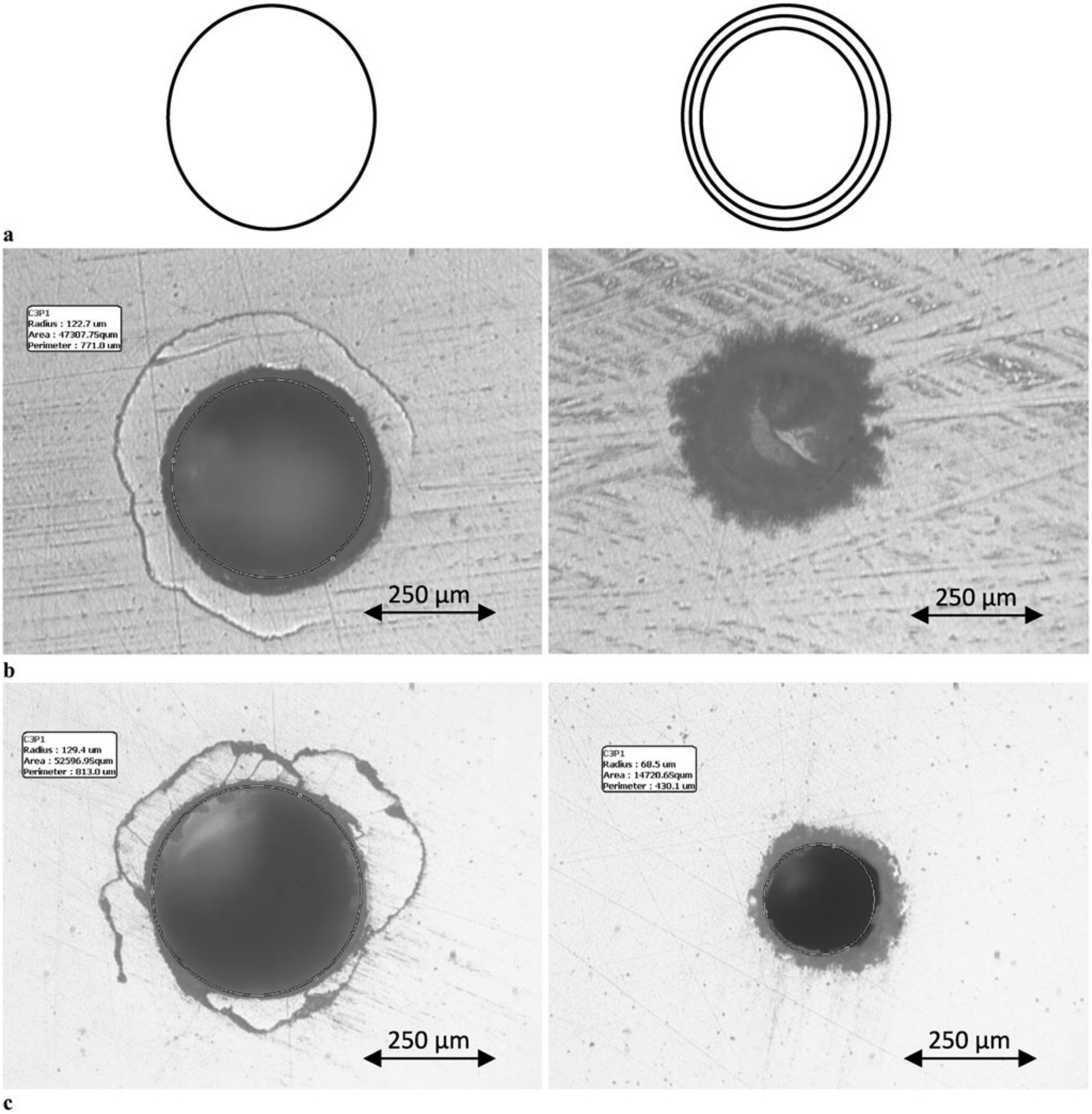

Fig. 4 **a** Drilling pattern used, *left*: single circle trepanning. *Right*: partial filling trepanning; and laser-drilled holes. **b** Single circle trepanning drilled hole, *left*: entrance, *right*: exit. **c** 3 circle partial filling trepanning drilled hole, *left*: entrance, *right*: exit

is needed), which would lead to more heat accumulation. Consequently, more serious thermal effects and cracks are generated. The crack formation is due to much heat accumulation and the heat is not able to dissipate effectively when the drilling is conducted on the thicker alumina substrates. So, in the case of thick substrate, some certain pause time is needed so as for the generated heat to have sufficient time to dissipate effectively as illustrated in Fig. 5. Laser drilling process is an inter-parametric complex process. However, it is believed that there exist optimum drilling conditions under which high efficient and good quality drilling could be achieved. From the above discussion, it was found that the laser focus position, traverse speed, drilling pattern, and pause time did affect the drilling quality of alumina substrates in terms of surface finish, heat effects, and drilling efficiency and could be optimized.

Figure 6 shows the laser-drilled 381 µm-thick alumina ceramic substrate at optimized drilling conditions. It can be

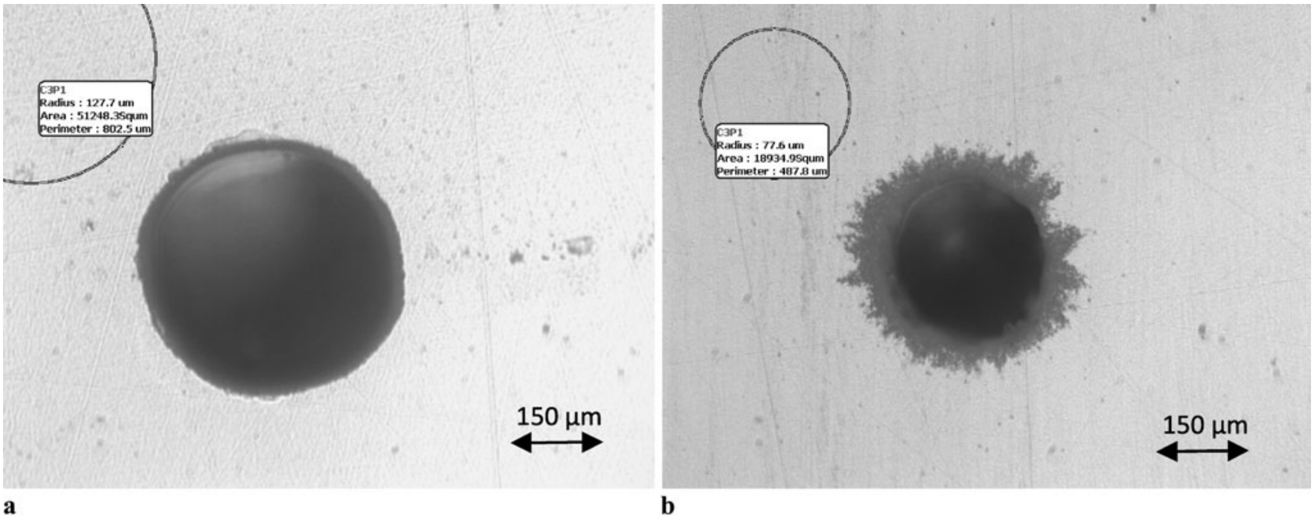

Fig. 5 Laser-drilled holes at 1 mm/s for 2 passes for 28 times; the pause time is 30 s. **a** Entrance. **b** Exit

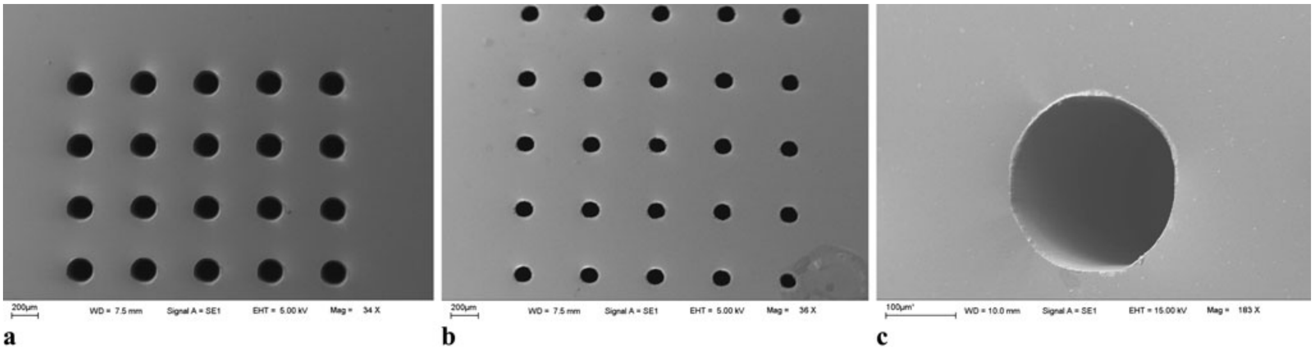

Fig. 6 Fs laser-drilled 150 µm diameter holes on 381 µm thick alumina substrate. **a** Entrance. **b** Exit. **c** Magnified 3D view

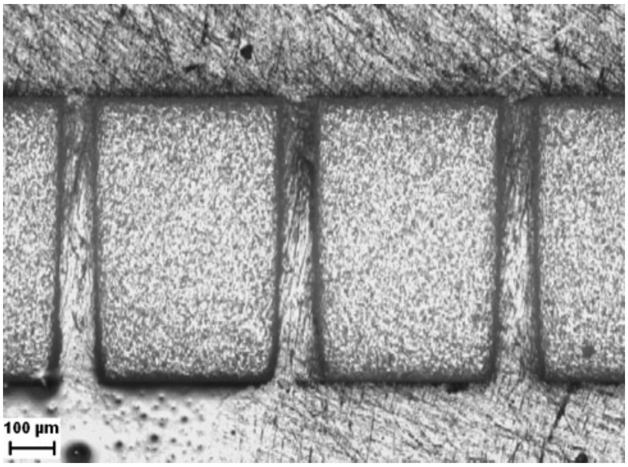

Fig. 7 Cross-sectional optical micrograph of laser-drilled 125 µm diameter holes on 625 µm thick alumina substrate

seen that the drilled hole quality is very good with clean surface finish, no debris, no cracking and no recast layer.

Figure 7 showed the cross-sectional view of the laser-drilled 125 µm diameter holes on 625 µm-thick alumina substrate. It is obvious that the drilled hole is straight and has minimum taper.

Alumina substrate with Ti/Au seeding layer was also drilled at the optimum drilling conditions. As shown in Fig. 8, the drilling quality is very good and no delamination was observed on the Ti/Au seeding layer side.

X-ray µ-CT was conducted to detect whether there existed microcracks in laser-drilled ceramic samples. Figure 9 showed X-ray µ-CT images on laser-drilled ceramic substrates with Ti/Au seeding layer. It can be clearly seen that no cracks were observed at all.

4 Conclusion

In conclusion, a systematic investigation on fs laser drilling of alumina substrates was conducted. The effects of various

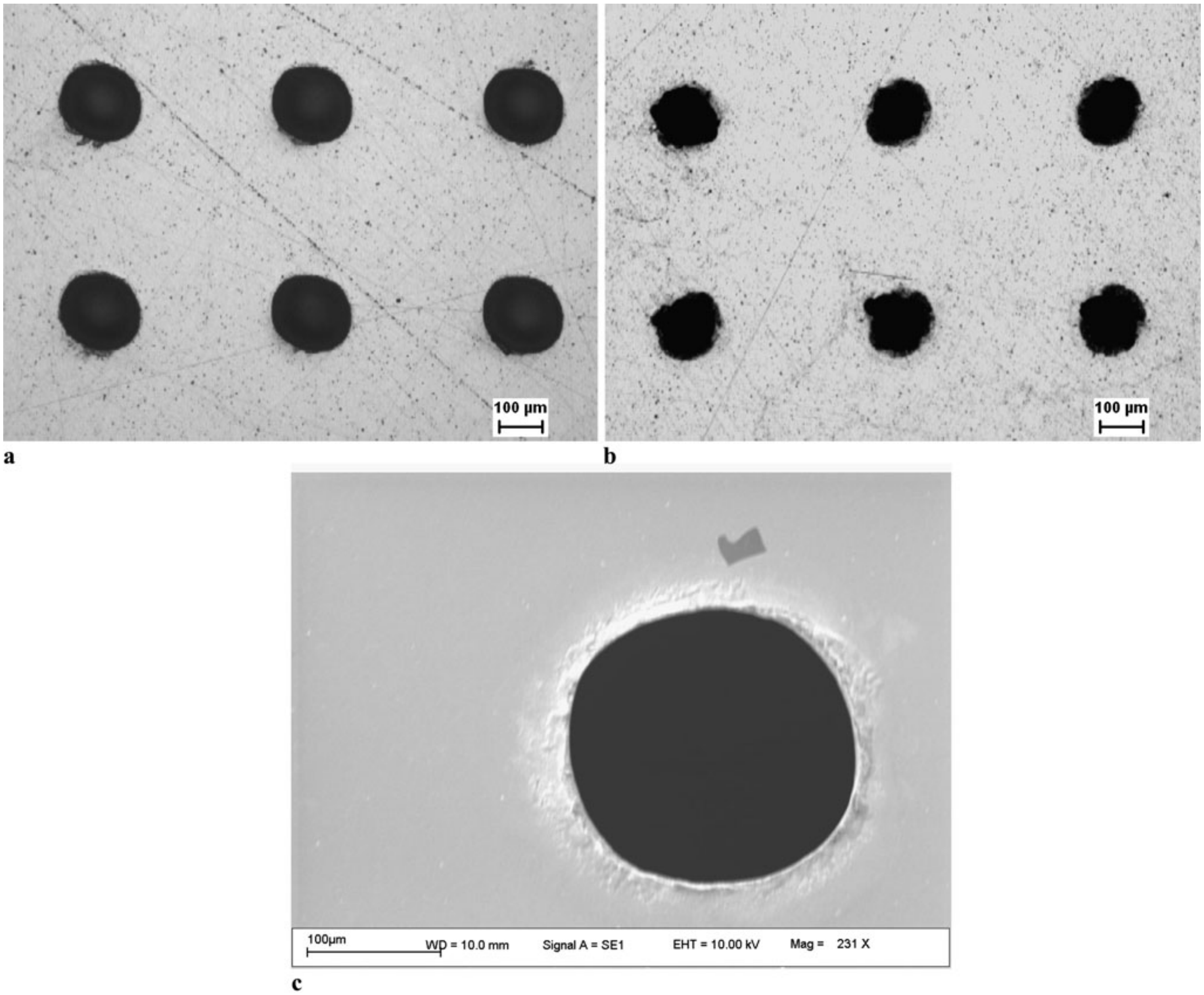

Fig. 8 Fs laser drilling of alumina ceramic substrate with Ti/Au seeding layer, **a** entrance, **b** exit, **c** magnified exit side

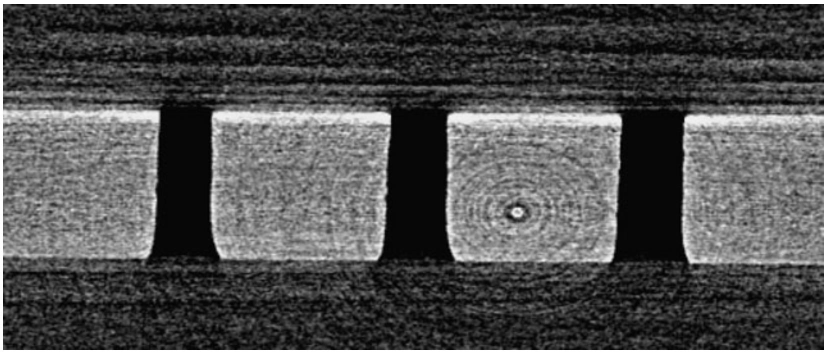

Fig. 9 X-ray μ-CT examined image on fs laser-drilled 125 μm diameter holes on 381 μm thick alumina substrate with Ti/Au seeding layer

laser processing parameters on the drilling quality of alumna substrates in terms of HAZ, surface cleanness, cracks, recast layer, hole circularity and delamination were studied. The optimum laser parameters were identified for drilling alumina ceramic substrates. High-quality laser drilling of alumna substrates with clean surface, no cracks, no recast layer and no delamination was demonstrated. The developed laser ceramic micromachining process has potential application in manufacturing of alumina substrate based electronic devices.

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