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RESEARCH ARTICLE

Drilling high aspect ratio holes by femtosecond laser filament with aberrations

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Abstract A near-infrared femtosecond laser is focused by a 100 mm-focal-length plano-convex lens to form a laser filament, which is employed to drill holes on copper targets. By shifting or rotating the focusing lens, additional aberration is imposed on the focused laser beam, and significant influence is produced on the aspect ratio and cross-sectional shape of the micro-holes. Experimental results show that when proper aberration is introduced, the copper plate with a thickness of 3 mm can be drilled through with an aspect ratio of 30, while no through-holes can be drilled on 3-mm-thickness copper plates by femtosecond laser with minimized aberration. In addition, when femtosecond laser filament with large astigmatism is used, micro-holes that had a length to width ratio up to 3.3 on the cross-section are obtained. Therefore, the method proposed here can be used to fabricate long oval holes with high aspect ratios.

Keywords femtosecond laser, aberration, drilling, high aspect ratio

1 Introduction

Micro-holes with high aspect ratios fabricated on metallic targets are highly demanded in engine manufacturing, biomedical applications, and other practical fields. Electrical discharge machining [1], electrochemical machining [2], and laser machining [3] are major prevailing methods for metal hole drilling. Among these methods, femtosecond laser drilling has its unique advantages. The femtosecond laser can accomplish energy deposition before the establishment of the electron-phonon thermodynamic equilibrium and therefore achieve fewer thermal defects, smaller heat-affected zone, and higher fabrication precision [4,5] than long-pulse laser fabrication. Accompanied with magnetic field, femtosecond laser could also fabricate some high aspect-ratio micro-structures for dynamic modulation of optical and mechanical properties of textured surfaces [6,7]. Moreover, femtosecond laser with peak power larger than the critical power P_{cr} for self-focusing may undergo the subtle balancing among the Kerr effect induced self-focusing, the plasma-induced defocusing and the propagation induced diffraction, forming a plasma channel called laser filament [8]. Laser filament is a plasma channel with a high optical intensity of ~10^{13} W/cm^2 [9,10], sustaining orders of magnitude longer than the Rayleigh length, which suggests that a filament is a competent tool for high aspect ratio hole drilling [11,12]. Bessel and Bessel-like beam with long focal range generated by the axicon and axilens are potent tools used for deep hole drilling [13–15], while the processing target needs to be transparent at the laser's wavelength so that the sidelobes can penetrate through the target to form a long focal-length beam. Contrastingly, the femtosecond filament sustained by the dynamic balance among the Kerr effect induced self-focusing, the plasma's defocusing, and the beam diffraction in the paraxial region would be an effective method for deep hole drilling in opaque materials.

A major problem when using femtosecond laser filament to drill high aspect ratio holes is the large taper, induced by the decrease of laser energy coupling efficiency as the increase of hole depth [16,17]. Trepanning drilling can, in principle, eliminate the hole taper. Nevertheless, in practice, trepanning drilling expands hole diameter and thus decreases the aspect ratio and increases processing time. Several studies have demonstrated that aberration introduced before laser focusing can modify the diameter, length, and spatial distribution of laser filaments [18–21], i.e., modify the drill tool's 3D shape. However, so far, there have been few discussions about the effects of aberration on laser filament drilling.

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This study is intended to investigate the effects of aberration on laser filament drilling. Here, the aberration effect, which is commonly a hope-to-diminished factor in the laser drilling process, was quantitatively introduced into the femtosecond laser beam by shifting or rotating the focusing lens [22]. Experimental results show that the aberration-modified laser filament can not only drill almost zero tapered holes but also drill holes with different shapes, such as round and oval holes. This research serves as a basis for future studies and enhances our understanding of the role of aberrated laser filamentation in high aspect ratio hole drilling.

2 Material and methods

Figure 1 depicts the top view of the experimental setup for femtosecond laser drilling. A Ti:sapphire femtosecond laser amplifier system (Legend Elite, Coherent Inc.) is employed to generate an 800 nm, 35 fs, 1 kHz laser pulse train. Laser average power is modulated in the range of 0.14–1.1 W by inserting different neutral density filters, while the shortest pulse duration near the laser focus is maintained by adjusting the pulse compressor of the femtosecond laser amplifier system. The diameter of the laser beam incident on the focusing lens is 10 mm. The laser beam is focused by a plano-convex lens with a focal length of 100 mm and a central thickness of 3.6 mm to form an optical filament. The laser filament is an air plasma channel along Z-axis. To introduce the aberration to the laser filament, the focusing lens is mounted on a one-dimensional translation stage and a rotation stage to achieve lens shifting along X-axis and lens rotating about Y-axis. Lens offset along X-axis and rotation angle φ about Y-axis are used to quantify the lens movement relative to the principal axis of the optical setup. The workpiece, i.e., the copper plate, is placed at different positions along Z-axis during the hole drilling process. Finally, hole features are investigated by an optical microscope (Olympus, BX51). Copper plates used in experiments are 20 mm × 20 mm in size, 0.5 and 3 mm in thickness, mounted on a three-dimensional translation stage. Copper has high electrical and thermal conductivity, thus widely used in industrial for precision manufacturing.

In experiments, high aspect ratio holes are drilled respectively by the focused laser beam with minimized aberration (see the dash-line frame in Fig. 1) or modulated external aberration (see the dot-dash-line frame in Fig. 1).

3 Results and discussion

3.1 Characteristics of holes drilled by laser filament with minimized aberration

In this subsection and the following parts of this paper, D_x and D_y are respectively used to evaluate the hole diameters along X and Y axis, which is schematically shown in Fig. 2(a). Defocusing amount (DA) indicates the distance between the top surface of the target and the geometrical plane of the focusing lens. DA is positive when the top target surface is closer to the focusing lens than the geometrical focal plane. Figure 2(a) presents the optical microscopic images of the top surface after drilling. It is seen from Figs. 2(b) and 2(c) that D_x and D_y both reach the minimum at DA = 0 when laser filament with minimized aberration is used. The diameters of holes are nearly independent of the laser power in the range of 0.2–0.9 W. As shown in Fig. 2(d), holes at the top surface of the target have good symmetry (D_x/D_y). Other parameters of holes fabricated by femtosecond laser with additional artificial aberrations are presented in the following sections.

3.2 Characteristics of holes drilled by laser filament with lens shifting induced aberration

As mentioned above, lens shifting was quantified by the lens offset along X-axis. It is seen from Figs. 3(a) and 3(b) that D_x and D_y have individual dependences on the lens offset. As the offset value increases from 0 to 5 mm, the

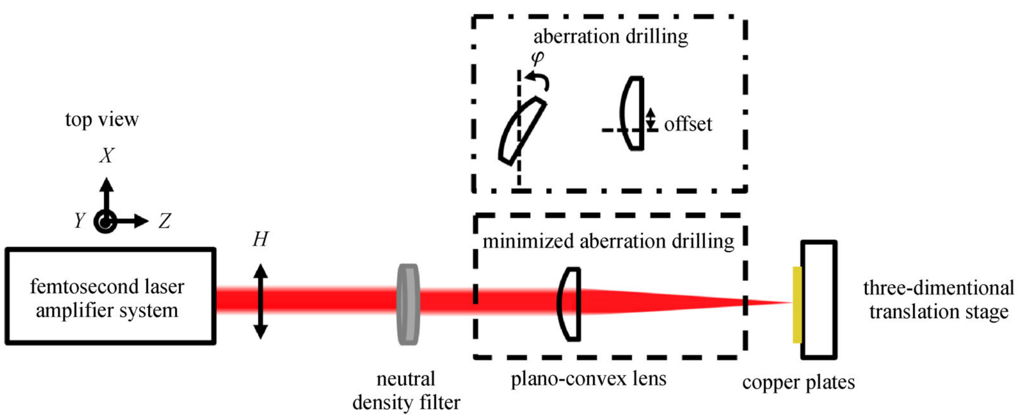

Fig. 1 Top view of experimental setup for femtosecond laser drilling copper plates

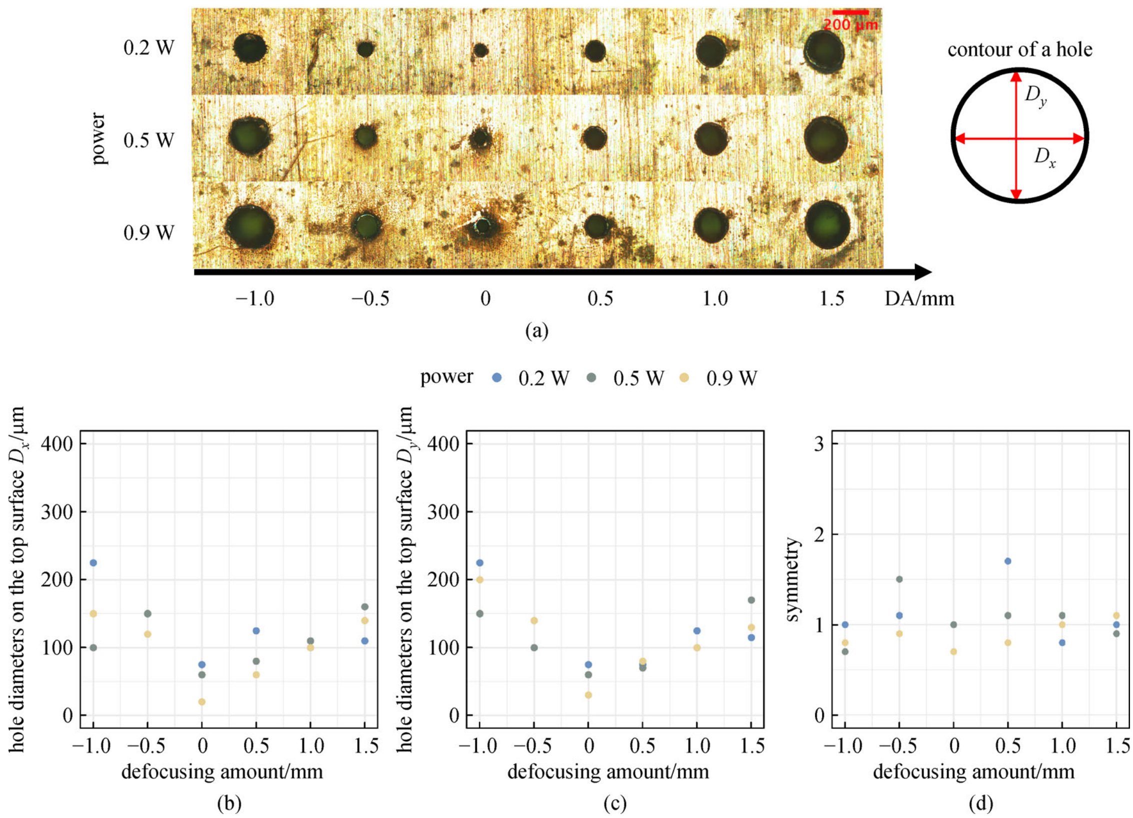

Fig. 2 (a) Optical microscopic images of the drilled top surface of copper plates. Dependences of the top surface hole diameters D_x (b), D_y (c), and hole symmetry (d) on the target defocusing amount. The copper plate has a thickness of 0.5 mm

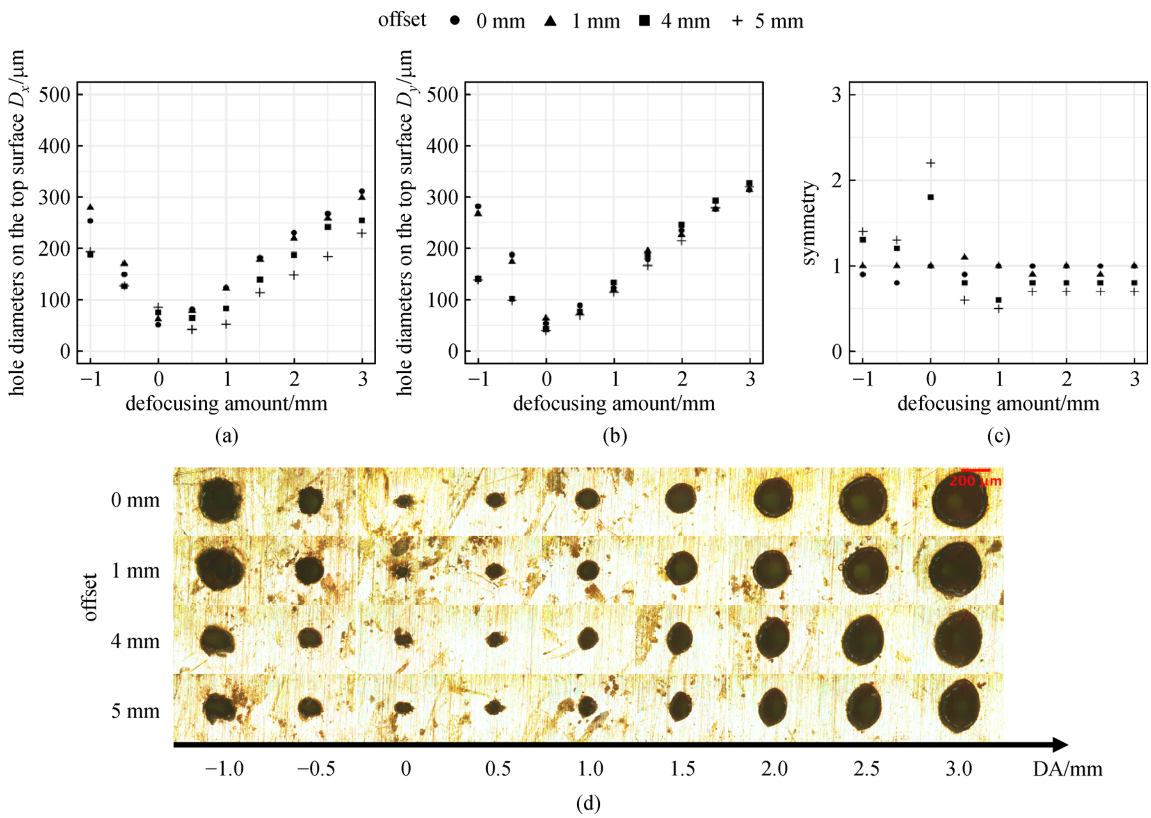

Fig. 3 Dependences of top surface D_x (a), D_y (b), and symmetry (c) on the lens offset and target defocusing amount. (d) Optical microscopic images of holes on the top surface. The copper plate has a thickness of 0.5 mm. These through-holes are drilled by femtosecond laser with an average power of 0.5 W

position of minimal D_x moves from the geometrical focal plane to the position at DA = 0.5 mm. However, no such movement exists for D_y, and D_y seems independent on the aberration introduced by lens shifting along X-axis for DA > 0. In Fig. 3(c), it is seen that asymmetric holes are fabricated when different offset value is introduced, and the major axis of the hole alters when the sign of the defocusing amount changes. Figure 3(d) shows the optical microscopic images of holes on the top target surface drilled by femtosecond laser with lens shifting in varying degrees.

The aspect ratio and taper are two key parameters to evaluate hole quality, shown in Fig. 4. Since the hole diameter on the top surface is always larger than that on the bottom surface, the aspect ratio is defined as the ratio of the hole depth to the hole average diameter D_{top} on the top surface and D_{top} can be calculated by

$$D_{\mathrm{top}} = \frac{D_x + D_y}{2}. \tag{1}$$

Taper in degree is calculated by

$$\theta = \arctan\frac{D_{\mathrm{top}} - D_{\mathrm{btm}}}{2L}, \tag{2}$$

where D_{btm} is the average hole diameter on the bottom surface, L is the hole depth. Data points in Figs. 4(a) and 4(b) respectively show a peak and a valley near DA = 0, indicating that both high aspect ratio and small taper appear at DA = 0. From Figs. 4(a) and 4(b), lens offset-induced aberration cannot increase the aspect ratio but can make the hole taper closer to zero for DA = 0 – 0.5 mm.

3.3 Characteristics of holes drilled by femtosecond laser filament with lens rotation induced aberration

In addition, aberration can also be induced by rotating the focusing lens. In this section, the lens is rotated in the range of 0°–8°, and different aberrations are introduced on the femtosecond laser. In Figs. 5(a) and 5(b), it is seen that the minimal diameter appears at different defocusing amounts for different rotation angles. It should be noted that a large rotation angle may deteriorate the symmetry of holes, as shown in Fig. 5(c). Circular holes or oval holes can be drilled at a certain lens orientation, as shown in Fig. 5(d).

Figure 6 shows the aspect ratio and the averaged taper of holes fabricated in Fig. 5. A remarkable observation is that the data points show a more gentle slope at $\varphi = 5°$ and $\varphi = 8°$ than that at $\varphi = 0°$, which indicates the filament is modified along Z-axis by rotation-induced aberration. Modified filament has a flexible machining range along Z-axis, which is the desired tool in deep hole drilling. Since the shape of holes on the X-Y plane is deformed (see Fig. 5(d)) due to the aberration induced by lens rotation, it is considered that calculating the taper respectively for the X and Y directions can better exhibit the taper reduction effect by the aberration. The calculated results are shown in Figs. 7(a) and 7(b). Tapers on the X and Y directions are calculated by

$$\theta_X = \arctan\frac{D_{\mathrm{top}_X} - D_{\mathrm{btm}_X}}{2L},$$

and

$$\theta_Y = \arctan\frac{D_{\mathrm{top}_Y} - D_{\mathrm{btm}_Y}}{2L}.$$

The obvious distinction in the variation tendency exists for tapers along X and Y directions, caused by the asymmetric external aberration on the X and Y directions. It can be seen from Fig. 7 that setting the rotation angle of the lens to be 5° can lead to a smaller θ_Y compared with those without introducing aberrations. It is also found that rotating the focusing lens can counteract the increasing tendency of θ_X for larger defocusing amount. For the lens rotation angle of 2° and defocusing amount of 0.5 mm, tapers on both the X and Y directions are close to zero, which is much smaller than that without aberrations.

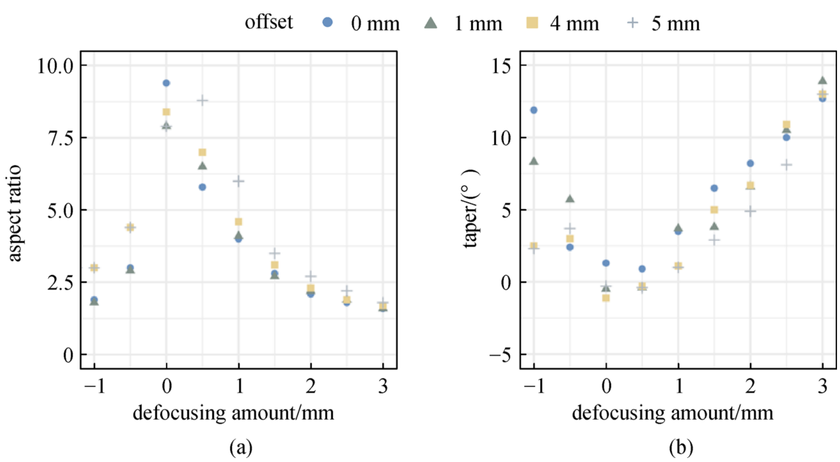

Fig. 4 Characteristics of through holes drilled by femtosecond laser filament with lens shifting. Aspect ratio (a) and taper (b) of holes in 0.5 mm-thickness copper plates are presented. The lens shifting amount ranges from 0 to 5 mm. The average laser power is 0.5 W

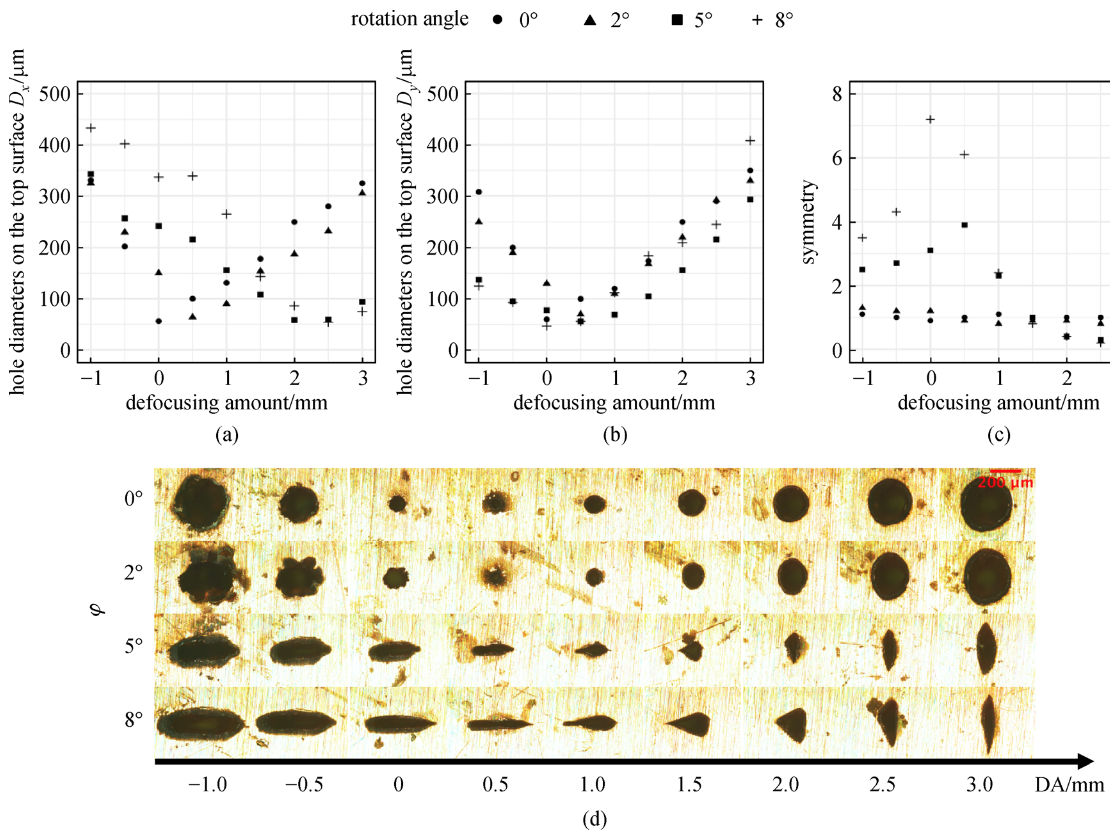

Fig. 5 Dependences of the top-surface hole diameters D_x (a), D_y (b), and symmetry (c) on the lens rotation angle and target defocusing amount. (d) Optical microscopic images of holes on the top target surface. The copper plate has a thickness of 0.5 mm. These through-holes are drilled by femtosecond laser with an average power of 0.5 W

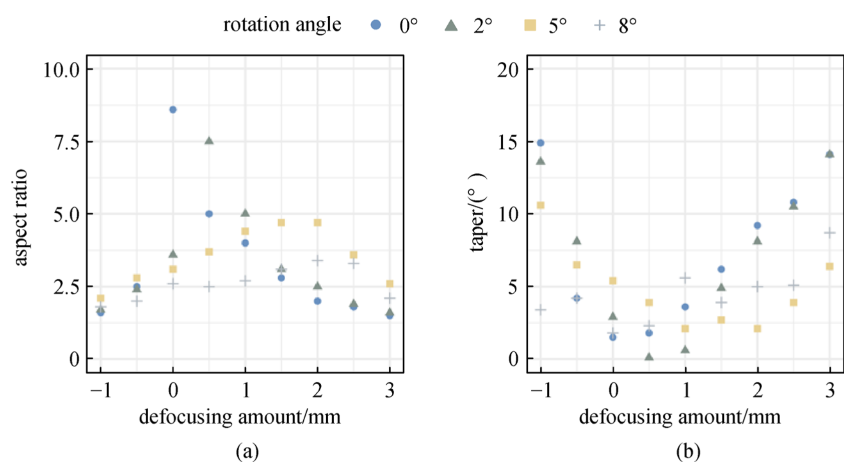

Fig. 6 Characteristics of through holes drilled by femtosecond laser filament with lens rotation. Aspect ratio (a) and taper (b) of holes in 0.5 mm-thickness copper plate are presented. The lens rotation angle ranges from 0° to 8°. The average laser power is 0.5 W

Figures 4(b) and 6(b) indicate that a smaller taper can be achieved by shifting or rotating the focusing lens, which is more valuable than a high aspect ratio for fabricating deeper holes. For laser drilling, especially drilling through holes on a thick metallic sample, deposited laser energy decreases as the increase of hole depth, which causes the enlargement of the top surface hole diameter or the shrinkage of the bottom surface hole diameter. According to the experiment results in this paper, the taper can be decreased by the lens rotating from 2° to 8°. Lens rotation as a taper reducing method is more economical and simpler than trepanning [23], helical drilling [24], and chemical post-process [25].

Finally, a femtosecond laser beam with 0.9 W average

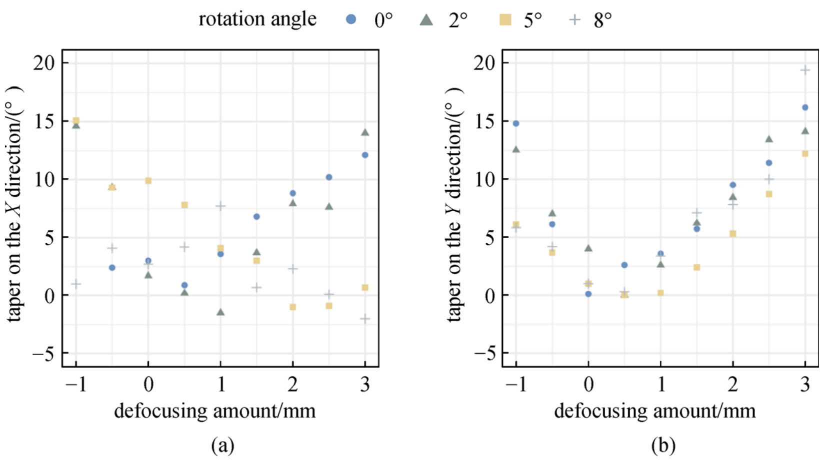

Fig. 7 Hole tapers for the X direction (a) and Y direction (b) on the 0.5-mm-thickness copper plate. The lens rotation angle ranges from 0° to 8°. The average laser power is 0.5 W

Table 1 Characteristics of holes on 3 mm copper plate at DA = 1.5 mm

	aspect ratio	taper	symmetry	drilling result
offset = 0, φ = 0°			1.0	blind holes*
offset = 4 mm, φ = 0°	25.2	0.4°	1.0	through holes
offset = 0, φ = 5°	34.1	0.2°	0.7	through holes

Notes: * For blind holes, aspect ratio and taper have not been computed.

power is employed to drill a 3 mm thick copper plate. Only blind holes can be drilled by femtosecond laser with minimized aberration. However, through-holes can be drilled by focused femtosecond laser when the focusing lens is shifted by a specific amount or rotated by a specific angle. The optimal drilling parameters and drilling results are listed in Table 1.

4 Conclusions

This study investigates the aberration's effect on laser filament drilling. Aberration is artificially introduced to the laser filament by shifting or rotating the focusing lens, and laser filaments with diverse aberrations are used to drill holes on copper targets. The experimental results indicate that laser filament with specified aberration can drill through holes with larger aspect ratio compared with those drilled by laser filament with minimized aberration. A 3-mm-depth through-hole with an aspect ratio larger than 30 can be drilled on the copper plate by laser filament with specified aberration. In addition, hole taper can be reduced by the lens shifting and rotation-induced aberration. These findings suggest that the focusing laser beam with aberration is a promising tool in drilling high aspect ratio holes on metallic targets.

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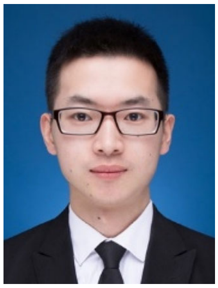

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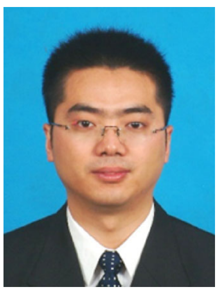

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