# Ultrafast Laser Helical Drilling of Three-Dimensional Shaped Holes using Synchronized Adaption of Energy Deposition

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We present a three-dimensional (3D) drilling strategy for symmetrically shaped microholes using helical drilling optics and ultrashort pulsed laser radiation. In the helical drilling process, the helical movement of laser beam is performed by using a rotating Dove prism, bore diameter and taper are controlled by a motorized wedge prism and a linear table separately. More precisely, the helical diameter of focused laser beam is determined by the tilt angle of wedge prism, which alters the incident angle of the incoming raw laser beam in front of focusing lens, while the linear table regulates a defined lateral offset, which determines the incident angle of focused laser beam on workpiece. A helical path of laser beam in the borehole is primarily determined by the positions of wedge prism and linear table. Distinguished from a classic helical drilling process with a fixed helical path, a 3D helical process is characterized by a dynamic helical path generated by altering the position of wedge prism or linear table and hole taper during helical process. To fabricate a 3D shaped microhole using helical optics, both classic and dynamic helical drilling process are essential. In this work, a micro-funnel with an opening angle of 90 degree and a straight slant as a drilling example is fabricated in a 0.5 mm thick stainless steel with an ultrashort pulsed laser having a 7 ps pulse duration. A cylindrical stem hole can be drilled by a classic helical process, the hole entrance is shaped by the 3D helical drilling. During this process the deposited laser energy in the volume can be dynamically adapted by synchronizing the helical diameter and laser pulse energy. The results demonstrate the feasibility of extending the drilling conicity and high precision of shaped hole. Moreover, neither micro cracks nor recast layer is detected on the hole wall by using ultrashort laser pulses.

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**Keywords:** ultrashort laser pulse, helical drilling optics, micro shaped hole, helical path, three-dimensional drilling, energy deposition.

## 1. Introduction

Laser-beam drilling as one of the well-established laser technologies for material processing has been developed and employed for industrial applications such as micro filters for electronic products and injection nozzles for automotive parts, as well as air-cooling holes for aerospace components[1-3]. Compared with Electrical Discharge Machining (EDM), one of the mostly used conventional microdrilling technology, laser drilling is characterized by a non-selectivity of materials[4]. Owing to the rapid development of innovative laser source, laser drilling enables high precision holes with diameters ranging from less than one micrometer to several millimeters while maintaining the same drilling depths in a variety of materials. The research focus of laser drilling today is on the combination of enhancing productivity with the increasing demand on high quality with respect to geometrical tolerances and reduced processing side effects mainly thermal effects[5]. Such thermal effects include change of metallurgy and generation of recast, cracks and burr etc. which lead to a dramatic reduction of performance, reliability and lifetime of components[6]. The requirements on decreasing thermal effect is therefore extreme crucial in the case of fabrication of cooling air holes in turbomachinery components[7]. By taking advantage of short laser pulses especially ultrashort laser pulses with pulse duration less than 10 picosecond, the mechanism of material ablation process is dominated by material vaporization. Owing to that, an extraordinary geometrical precision of drilling with minimized thermal effect can be achieved in a variety of materials[7,8].

One of the most fascinating application of three-dimensional shaped holes is cooling air holes in a turbine blade[9,10]. As the state-of-the-art technology, a two-step drilling process is employed to fabricate such shaped holes in turbomachinery components with optimized three-dimensional(3D) geometries[11]. As the first step, a cylindrical through hole is drilled by a trepanning optic using a QCW laser with ms pulse duration. Following that, hole exit is shaped by means of a short-pulsed laser ablation and scanning optics. The employment of ms QCW laser contributes to a high productivity but, in turn, redundant thermal load could be introduced in materials and leads to spalling between thermal barrier coating (TBC) layer and base alloys and reduction of life span of the turbomachinery components[12]. Furthermore, the complexity is increased by using a two-step drilling strategy with two optics and laser beam sources. Recent research work on fabrication of shaped holes using high power ultrafast lasers combined with galvanometer scanner has demonstrated the advantages of the ultrashort pulse duration in regard to metallurgic characteristics (e. g. heat effect zone, recast layer, etc.) and high precision. The product yield and cost-efficiency, however, need to be increased to meet the industrial requirement.

In our previous works, a helical drilling optics system based on a rotating Dove prism for a classic helical drilling process and the drilling results on cylindrical and tapered holes were published[12-14]. The helical optics enables drilling of cylindrical as well as positive and negative conical holes with a typical achievable diameter in range from 5 µm to 1.5 mm depending on the thickness of material and focusing optics. In this paper, we present a dynamic helical drilling process to implement a circular symmetric three-dimensional shaped hole in steel using the helical optics and an ultrashort pulsed laser. The influence of spatial helical path and laser parameters on hole geometry and precision are investigated. Furthermore, examples of drilling of three-dimensional shaped holes are included with discussions on their potential applications.

## 2. Experimental setup

The helical drilling system for three-dimensional shaped holes consists of an ultrashort pulse laser source, helical drilling optics and CNC linear motor stages, as schematically shown in Figure 1. The ultrashort pulse laser source delivers a second harmonic generation of 515 nm wavelength using a LBO crystal leading to a maximum average output power of 60 W at the maximal repetition rate 400 kHz. The pulse duration $\tau_p$ is 7 ps. Passing through the spinning Dove prism with a maximum rotation frequency 160 Hz, the linear polarized laser beam rotates with doubled speed along an optical axis and is focused on the surface of sample to a spot diameter of 15 µm by an objective having a 60 mm focal length. The output power and duration of laser pulse is programmable and thus a laser energy deposition can be adapted for drilling geometry during helical process. In helical drilling optics, the helical radius is determined by the declination angle of wedge prism $\Delta\alpha$ on a step motor. Its position and rotation speed can be precisely preset before drilling start or simultaneously set during drilling process by a CNC program.

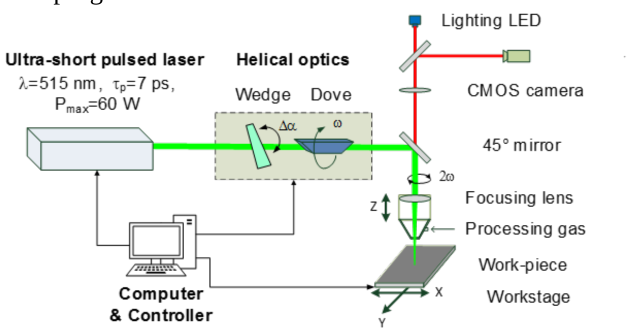


**Fig. 1** Helical drilling system for three-dimensional shaped holes

In the work, micro funnel-shaped holes were drilled in a thin-wall stainless steel (X5CrNi18-10) of 0.5 mm thickness. Foremost a cylindrical stem-hole can be drilled through with a classic helical drilling process. Following that, a wide positive conical entrance was fabricated by a three-dimensional helical drilling process, where helical diameter was enlarged dynamically during drilling. The parameters applied for the 3D drilling are listed in Table 1.

**Tab. 1** Parameters applied for the experiment

| Process | Classic helical drilling | 3D helical drilling |
|---|---|---|
| **Single pulse energy** | 22.5 µJ | 3 - 60 µJ |
| **Laser Frequency** | 50 kHz | 40 kHz |
| **Helical diameter (angle of wedge prism)** | 0 (0°) | 0 - 370µm (0 - 13.5°) |
| **Rotation speed of wedge prism** | 0 (fixed) | 0.5 - 4°/s |
| **Rotation frequency of dove prism** | 60 Hz | 60 Hz |

## 3. Results and discussion

### 3.1 Two and three-dimensional helical path

In the helical drilling, a two-dimensional (2D) helical path can be described as the coordinate of the laser pulses in one revolution locations of rotational movement. Branding marks with an interval in Figure 2 shows a 2D helical path with a diameter $d_h$ on the focal plane. Furthermore, by plotting the positions of laser pulses sequentially deposited, the spatial path of laser pulses in the whole drilling channel can be represented approximately as a 3D helix curve - the 3D helical path.

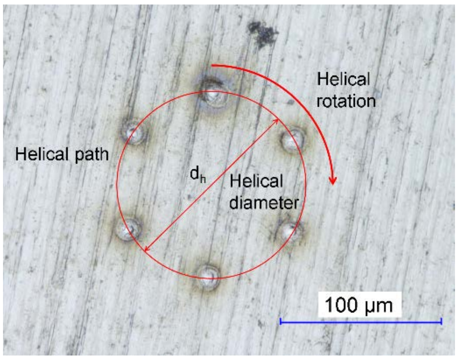


**Fig. 2** Illustration of 2D helical path with branding marks on stainless steel at a low output laser power

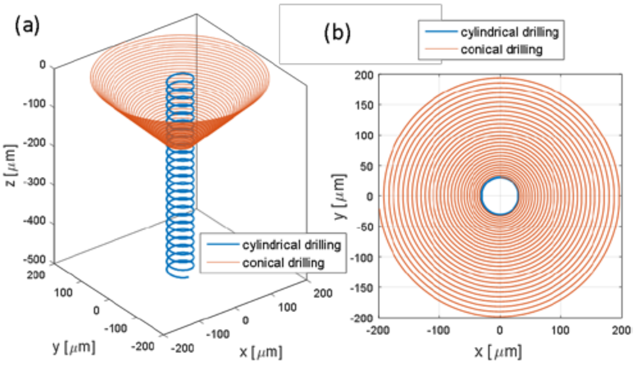


**Fig. 3** Combined helical path for funnel-shaped holes (a) 3D helical path, (b) top view of 3D helical path

In the classic helical drilling process, a cylindrical or positive/negative conical helical path and a helical diameter depending on the desired hole profiles are predefined by setting proper optical parameters fixed. By means of that, a 2D or 2.5D borehole is producible. Whereas an adapted 3D helical path plays a significant role in helical drilling of 3D shaped holes such as a microfunnel, the helical path is plotted in a Cartesian coordinate system and shown in Figure 3.

### 3.2 Influence of laser intensity distribution on ablation behavior in helical drilling of shaped holes

As aforementioned, a 3D helical drilling with dynamic increase of helical diameters was employed in the fabrication of a wide conical entrance (frustum) of the funnel-shaped 3D hole. Since the local superposed laser intensity determinates the area and depth of the ablated volume [15], the hole profile can be predicted by investigation on laser energy deposition in the 3D helical path. To quantify the laser energy deposition and pulse density in 3D helical drilling, an overlap degree of laser pulses and the number of laser pulses per unit length are introduced. Both parameter indicate the density of laser pulses deposited on helical path. Considering that, a 7-ps ultrashort pulsed laser is applied, the overlap degree of laser pulses $\eta_{or}$ in a single revolution can be given by:

$$\eta_{or} = 1 - \frac{\pi \cdot d_h(z) \cdot \omega_m}{\omega(z) \cdot f} \quad (1)$$

And the number of laser pulses per unit length on helical path $N_{ppl}$:

$$N_{ppl} = \frac{f/2\omega_m}{\pi d_h(z)} = \frac{f}{2\omega_m \pi d_h(z)} \quad (2)$$

Here, $\omega(z)$ is the beam intensity $1/e^2$ radius of laser spot in $z$ position and $z = 0$ corresponds focal plane of laser beam, $d_h(z)$ is helical diameter at $z$ position, $\omega_m$ is rotation frequency of dove prism, $f$ refers to repetition rate of laser pulses.

To clarify the relationship between the helical diameter and the overlap degree, the laser repetition rate and rotation frequency of dove prism were kept as constant during the 3D helical drilling. Since the total number of laser pulses in a single revolution is determined by laser repetition rate and rotation frequency of dove prism, it stays the same at varied helical diameters. According to Eq. 1 and 2, the overlap degree and the number of laser pulses per unit length drop with the increase of helical diameter, therein the overlap degree declines with a linear behavior. As a result, the local superposed laser intensity distribution, which describes the total pulse energy irradiated on one site, decreases correspondingly. The correlation between superposed laser intensity and single pulse energy as well as rotating speed of wedge prism are simulated and visualized by a numeric methodology in Figure 4.

The curves in Figure 4(a) and (b) are characterized by two evident zones: middle part with a sharp-edged donut top and flank part with a gentle slope. This two zones correspond to the stem hole and the positive conical entrance of the funnel-shaped hole. Due to a higher pulse density, the superposed laser intensity in the central area of helical diameter within 0.05 mm is significantly higher than that of areas with greater diameters, where the superposed laser intensity drops much more gently. In addition, a linear relationship between the applied laser pulse energy and the superposed laser intensity exists in the range of helical diameter greater than 0.05 mm as shown in Figure 4a. The rotation speed of wedge prism determines the duration of process and spiral trace offset in radial direction. More precisely, the higher the rotation speed is, the shorter is the process duration and the broader the trace offset. As a result, the local superposed laser intensity declines sharply after the start of 3D helical drilling as shown in Figure 4b. A 3D diagram of superposed laser intensity distribution is shown in Figure 4c, which shows a circular symmetric 3D profile of the energy deposition in the dynamic helical drilling.

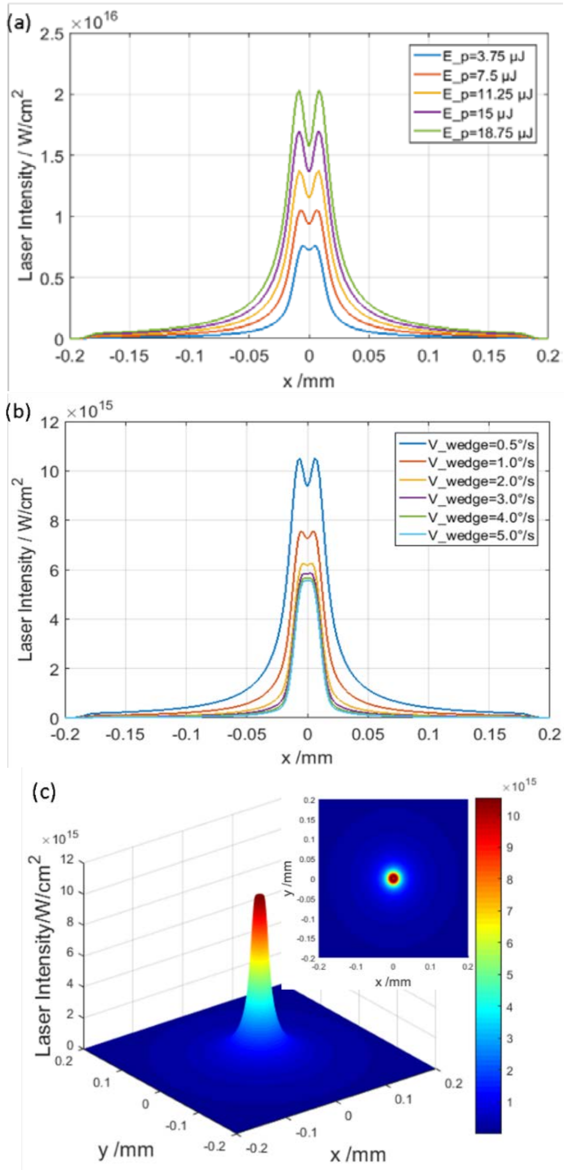


**Fig. 4** Simulation of superposed laser intensity in the 3D helical drilling of a funnel-shaped hole with (a) varied laser pulse energy at $V_{wedge}$ = 1.5 °/s and (b) rotation speed of wedge prism at $E_p$ = 7.5 μJ. (c) 3D diagram of adapted superposed laser intensity distribution at $V_{wedge}$ = 1.5 °/s and $E_p$ = 7.5 μJ

The local superposed laser intensity increases linearly with applied single pulse energy, according to the result of simulation described in Figure 4a. Nevertheless, the development of ablation depth at the same helical radius in dynamic helical drilling shows a non-linear behavior with increased laser pulse energy, as the diagram in Figure 5 shown. The higher pulse energy, on one hand, contributes to a deeper ablation of the material especially in the middle area of slant (helical radius around 120 μm), forming a straighter profile. As depicted in Figure 6 the curvature of slant profiles become smaller with higher laser pulse energy. On the other hand, the depth of frustum bottom extends when higher single pulse energy is applied and thus the opening angle of the taper declines with a same entrance diameter.

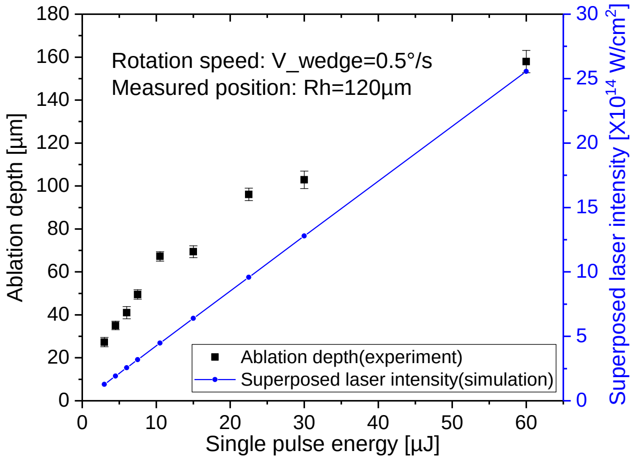


**Fig. 5** Ablation depth for various applied single pulse energy at rotation speed of wedge prism 0.5°/s. Measured position was 120 µm from center line(Helical radius 120 µm)

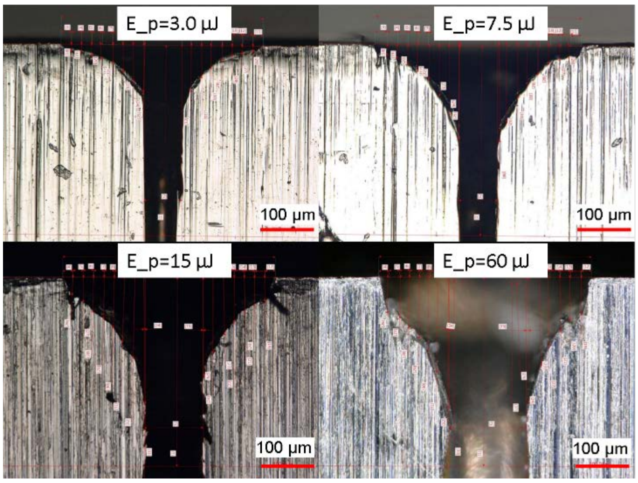


**Fig. 6** Longitudinal sections of funnel-shaped holes drilled with varied single pulse energy of 3.0, 7.5, 15 and 60 µJ at a rotation speed of wedge prism 0.5 °/s

The rotation of wedge prism play an important role in 3D helical drilling. It regulates the helical radius and further the pulse overlap within a single helical revolution. The speed of the rotation determines the varying rate of helical radius as well as the path overlap between neighbored helical revolutions. By means of that, the energy deposition of laser pulses can be spatially modulated during the dynamic helical drilling. As depicted in Figure 7, the ablation depth decreases with the increase of rotation speed of wedge prism. Similar to the ablation behavior depicted in Figure 5, the tendency of ablation depth at the position of helical radius 120 µm is in a good agreement with the curve of the simulated superposed laser intensity, as can be seen in Figure 7. The longitudinal sections in Figure 8 show the drilling results with varied rotation speed of wedge prism under the same applied single pulse energy. The images in Figure 7 and 8 demonstrate that the profile of a 3D hole has a dependency not only on the local laser pulse energy applied but also on the speed of helical diameter increasing.

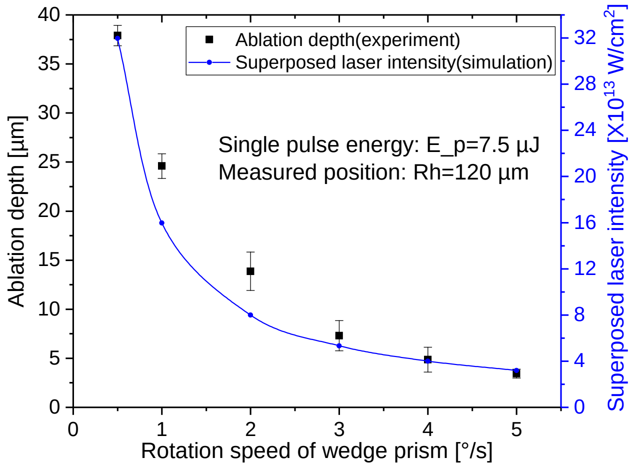


**Fig. 7** Ablation depth for various rotation speed of wedge prism at single pulse energy 7.5 µJ. Measured position was 120 µm from center line(Helical radius 120 µm)

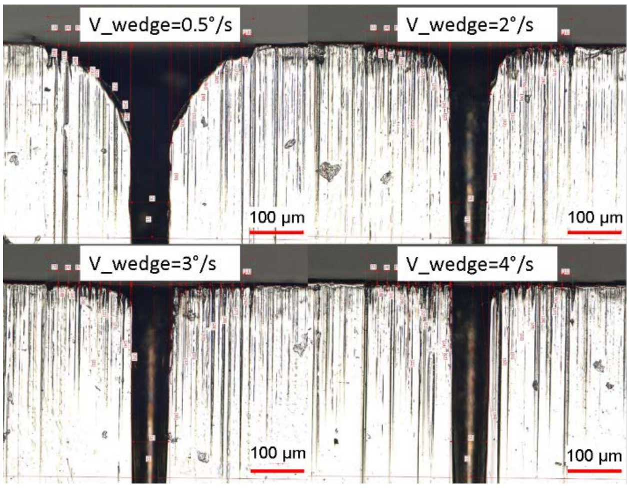


**Fig. 8** Longitudinal sections of funnel-shaped holes drilled with varied rotation speed of wedge prism 0.5, 2, 3 and 4 °/s at a single pulse energy of 7.5 µJ

### 3.3 3D helical drilling with optimized laser energy deposition

The results and discussion in section 3.2 represent the influence of superposed laser intensity, in other words laser energy deposition, on the hole profile of 3D helical drilling. Based on this analytic relationship, applicable parameter windows can be adapted for a designated drilling geometry. For this purpose, the laser pulse energy applied can be synchronized with the increase of helical diameter if the rotation speed of wedge prism is constant during the helical drilling. Similarly, the rotation speed of wedge prism can be adapted with a constant laser pulse energy applied. A microfunnel with a straight slant and a full opening angle of 90 degree in the conical part was fabricated by means of adaption of laser pulse energy in the middle area (helical radius from 100 µm to 140 µm) of slant as shown in Figure 9a. The single pulse energy applied in this area has been increased from 7.5 µJ to 15 µJ, so that more volume of material in this area can be ablated. The diameters of entrance and exit of stem hole are 100 µm and 80 µm respectively. The slight conicity exist due to the process parameter for the stem hole was not optimized for a cylindrical bore. The metallic glossy on the hole wall can be in the cross-section of the stem hole. The morphology of the stem hole is analyzed by a scanning electronic microscope (SEM) and demonstrates a recast-free drilling as laser induced periodic surface structure (LIPSS) can be observed on the hole wall (Figure 9b). Furthermore, the surface roughness $S_q$ on the wall of stem hole is measured less than 0.10 µm, owing to a vaporization dominated ablation process. The top view of hole entrance and exit are shown in Figure 9c and 9d, in which neither recast layer nor heat affect zone can be detected.

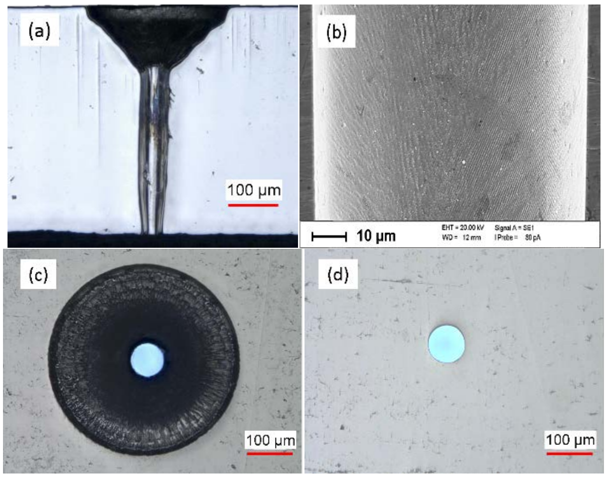


**Fig. 9** Mircofunnel in 0.5 mm stainless steel fabricated by 3D helical drilling with optimized parameter. (a) Longitudinal sections shows the frustum with an opening angle of 90° and a quasi-cylindrical stem hole, (b) SEM image of the stem-hole wall, (c) and (d) top views of hole entrance and exit. Processing time: 40 s, $V_{wedge}$=0.5°/s, $E_p$=7.5 µJ and 15 µJ (15 µJ at helical radius 100 - 140 µm)

The morphologic analysis on the wall in the funnel is conducted by using a confocal laser scanning microscope (LSM), details of the surface quality of the frustum in the funnel are shown in Figure 10. The root mean square roughness $R_q$ of the frustum part amounts 0.39 µm. Due to that most of the molten and vaporized material is driven out from the widely opened frustum to the constricted joint part of frustum and stem, the surface on the bottom of frustum is roughened by the process of material ejection, thus the roughness there was measured to be 1.16 µm.

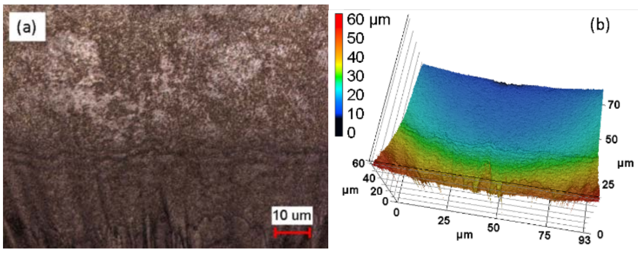


**Fig. 10** Laser scanning microscopy on the surface of frustum part of the microfunnel. (a) Morphology of the surface and (b) 3D display with color bar

## 4. Summary

We have presented a three-dimensional drilling process for fabrication of shaped holes with a dove-prism-based helical optics system and an ultrashort pulsed laser. This method extends the technical limits of classic helical drilling: increased taper and more complex hole profile. A 3D helical path of designated shaped holes can be generated when the helical diameter is regulated dynamically during the drilling process. Due to the fact that, the description of the revolutionary motion of laser pulses in the volume by 3D helical path is insufficient for the prediction of the hole profile drilled. For this purpose, the influence of local superposed laser intensity on hole profile have been investigated by a numeric simulation on the laser pulse energy applied and the speed of helical diameter increasing. The experimental results are in good agreement with that of the simulation and demonstrate the determinative of laser energy deposition on ablation depth and hole profile. The laser energy deposition can be adapted by the synchronization of the laser pulsed energy with the increase of helical diameter.

As a final remark, a microfunnel with a full taper angle of 90 degree and a straight slant profile of frustum can be fabricated by the proposed 3D helical drilling method. A morphological analysis with SEM and LSM on the hole wall show excellent drilling quality without recast layer and heat affect zone by using an ultrashort pulsed laser.

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