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Temporal evolution of hole geometry and influences of energy deposition in ultra-short pulse helical drilling

Chao He[a,*], Claudia Hartmann[b], Christian Fornaroli[a], Frank Zibner[a], Arnold Gillner[a]

[a]*Fraunhofer Institute for Laser Technology ILT, Steinbachstraße 15, Aachen, 52074, Germany*
[b]*Chair for Laser Technology, RWTH Aachen University, Steinbachstraße 15, Aachen, 52074, Germany*

Abstract

This paper presents a static investigation on temporal evolution of hole geometry and influence of laser energy deposition on hole quality in helical drilling process. By using a rotating dove prism a circular oscillation of the laser spots is performed and holes are drilled at intervals in 1 mm thick stainless steel (1.4301) by ultra-short laser pulses of 7 ps at 515 nm. The formation of hole and the behavior of energy deposition differ from other drilling strategies due to the helical revolution. The temporal evolution of the hole shape is analyzed by means of SEM techniques from which three drilling phases can be distinguished. The first phase is characterized by a highest drilling rate and the formation of a sharp-edged circular groove with a pin inside the workpiece. In the following phase, the molten and vaporized material is ejected out from the hole and a funnel-like borehole with a slim tip deepens to the backside of workpiece, growth of hole depth slows down in this period. The exit is broadened to the final shape in the final phase. Laser scanning microscope (LSM) measurements of structure details on the hole wall demonstrate that the quality of the helical-drilled hole is determined by a correlation between the pulse energy applied and the overlapping rate of laser pulses, which is described mainly by helical path and the rotation speed of laser beam.

Key words: Helical drilling; ultra-short pulses; temporal evolution; energy deposition

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1. Introduction

Ultra-short laser pulses in the regime of picosecond and femtosecond pulse duration have been applying widely in micro-scale material processing. For instance, laser fine cutting, micro drilling and high resolution surface structuring have been introduced under industrial conditions [1-3]. Due to their extreme peak intensity and short laser material interaction timescale, ultra-short pulsed lasers provide the possibility to

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[*] Corresponding author. Tel.: +49 241 8906-611; fax: +49 241 8906-121.
E-mail address: chao.he@ilt.fraunhofer.de.

achieve high precision and quality by realization of a vaporization-dominated processing. In recent years, ultrashort pulsed lasers have been developing in aspects of output power and beam quality. As well-established applications, the use of ultra-short laser pulses in laser micro drilling has been demonstrated great advantages of negligible heat-affect-zone (HAZ) and minimized recast layer on material compared with long laser pulses from microsecond to millisecond. However, high performance laser source is not sufficient to meet industrial requirements for drilling of high precision holes with respect to diameter, circularity and conicity.

The helical drilling technology, which is characterized by a high speed self-rotation of laser beam and a relative movement between laser spot and workpiece (See figure 1) enables the best drilling quality in a wide spectrum of materials including metals and dielectrics. During drilling the ablation front of laser spot moves downwards into the material in a helical path and the material volume ablated with each pulse is much smaller compared to trepanning. Thus, the accuracy of hole geometry can be increased and moreover thermal load in the workpiece can be decreased [4].

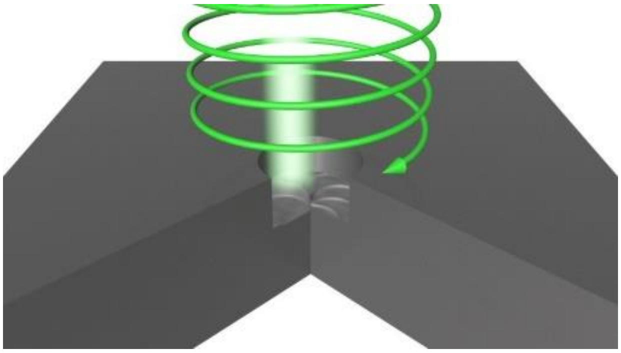

Fig. 1. Schematic for revolution of laser pulse in helical drilling process

Approaches to realize such a helical revolution have been interpreted in several literatures [5-8]. In addition, the influence of laser pulse energy and optical parameter on hole geometry has been investigated [9]. However, the previous studies, in most cases, were limited in the hole geometrical features and also in optical parameters such as incident angle and polarization of laser beam. For high quality drilling, laser parameters such as pulse duration, single pulse energy and pulse repetition rate can lead to significant changes in the hole quality and ablative behavior in drilling progress [10]. The detailed analysis of the temporal evolution of hole shape and size has been utilized to investigate the influence of laser energy deposition on hole geometry [11-13]. S. Döring, et al, has investigated the ablation process material by using in-situ shadowgraphy imaging in silicon [11, 14, 15]. M. Chen proposed a glass-metal-glass sandwich structure setup to observe and clarify keyhole dynamics in metal drilling [14]. Due to the opacity of metals to NIR as well as for green laser radiation and the deviation of dynamic drilling progress by using the sandwich model, an in-situ optical observation of evolution of longitudinal section in helical drilling is not feasible at the moment.

In our experiments, we used static analysis on hole profiles, which were successively drilled at fine temporal intervals and polished to cross section. Compared with an in-situ photographing, the capture and analysis of topography and evolution of holes is possible by using this static method. The influence of laser energy deposition on hole shape and quality are investigated in this paper.

2. Experimental setup

The experimental setup for helical drilling is shown in Fig. 1 and can be divided into three parts. A 515 nm wavelength ultra-short pulsed laser with a pulse duration of 7 picoseconds and a maximum single-pulse-energy of 150 µJ is applied as the laser source. Drilling experiments are carried out by utilizing a helical drilling optics based on a Dove prism as an image rotator. Altering of hole diameter and taper can be exactly realized by setting up the positions of wedge plate and lineal stage in front of hollow shaft motor and the image rotator via computer controller. The laser beam is focused on the workpiece with a 60 mm focusing lens. For real-time observation and positioning of the process, a coaxial monitoring system including CMOS camera and LED lighting is installed.

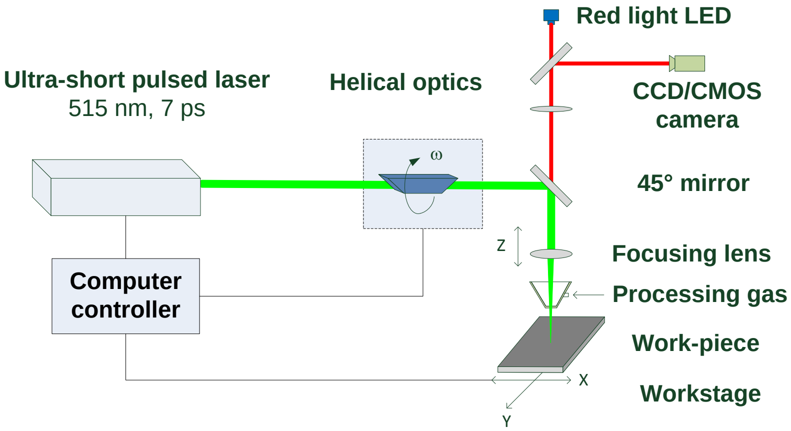

Fig. 2. Schematic for revolution of laser pulse in helical drilling process

The process parameter for drilling experiments on 1 mm thick stainless steel (1.4301) is summarized in table 1. To investigate the evolution of hole geometry, an interval Δt of drilling time were selected in two sections separately, namely 0.1s and 0.5 s. Geometry and morphology of processed specimens were investigated under a high resolution optical microscope and surface topography by confocal laser scanning microscope (LSM) and SEM.

Table 1. Process parameter in helical drilling

Wavelength (nm)	515	Gas pressure(bar)	3
Pulse duration (ps)	7	Rotation speed (rps)	60
Spot diameter (µm)	15	Drilling time (s)	0.1~1 ($\Delta t1=0.1$)
Pulse energy (µJ)	120	time interval Δt (s)	1~10 ($\Delta t2=0.5$)
Pulse repetition rate (kHz)	50	Focus position (mm)	0.2 in material

3. Results and discussion

3.1. *Helical path and overlapping rate of laser pulse in helical drilling*

As results of Dove prism and half-lambda plate rotation a superposed motion of self-rotation and circular movement of laser pulses is performed with a helical radius. Due to high repetition rate of laser pulses, a large number of pulses are deposited in one revolution and by changing rotational speed a certain overlapping ratio can be set (shaded area in figure 3a). Overlapping rate as a key parameter in helical drilling process describes the energy deposition directly and plays an important role in the drilling of high quality holes. With the assistance of numerical simulation software Matlab, a map of laser intensity distribution in one complete revolution is presented in Fig. 3b.

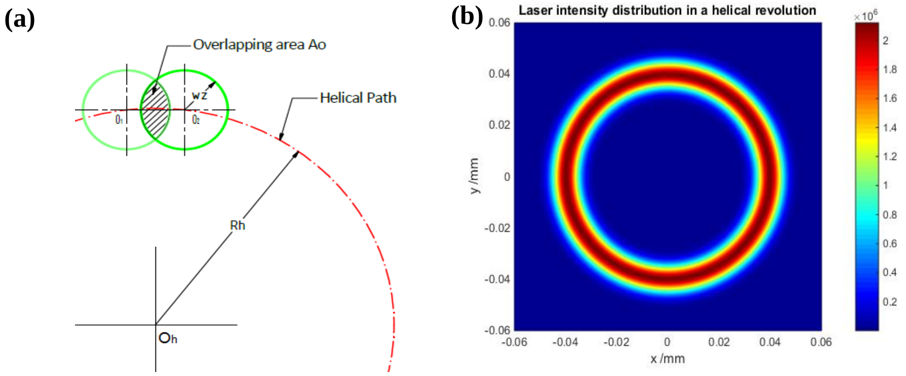

Fig. 3. Calculation of overlapping rate (a) and 2D laser intensity distribution (b) in one helical revolution simulated using Matlab

The calculation expression of overlapping rate η_{or} of the laser spot in helical drilling is given as following [16]:

$$\eta_{or} = 1 - \frac{r_h(z) \cdot \sin(2\pi \cdot \omega_m / f)}{\omega(z) + \pi \cdot \omega_m \cdot r_h(z) \cdot \tau_p} \qquad (1)$$

Here, $\omega(z)$ is radius of laser spot in z position and z=0 means at focal plane of laser beam, $r_h(z)$is helical radius of circular movement at z position, ω_m is rotation speed number of hollow shaft motor, f repetition rate of laser pulses, τ_p is single pulse duration.

Since the single pulse duration τ_p is 7 ps, and $f \gg \omega_m$, the phrases $\pi \cdot \omega_m \cdot r_h(z) \cdot \tau_p \to 0$ and $sin(2\pi \cdot \omega_m/f) \to 2\pi \cdot \omega_m/f$. Thus the expression of overlapping rate in a helical revolution can be simplified as:

$$\eta_{or} = 1 - \frac{2\pi \cdot r_h(z) \cdot \omega_m}{\omega(z) \cdot f} \qquad (2)$$

Helical radius, rotation speed and repetition rate are, first of all, the three factors, that determine the overlapping rate during helical drilling. Figure 4(a) and (b) show the map of relationship between two factors and overlapping rate respectively. With the increase of rotation speed and helical radius, the overlapping rate decreases linearly and sharply. Whereas it stays relative stable at higher repetition rate (>100 kHz) but drops dramatically if the laser pulse number per second is reduced below 50 kHz. Normally, higher overlapping rate is preferred to achieve higher efficiency. For high precision drilling with minimized heat-affect-zone, however, relative low repetition rate of laser pulses is reasonable. A trade-off between efficiency and accuracy should be taken into consideration.

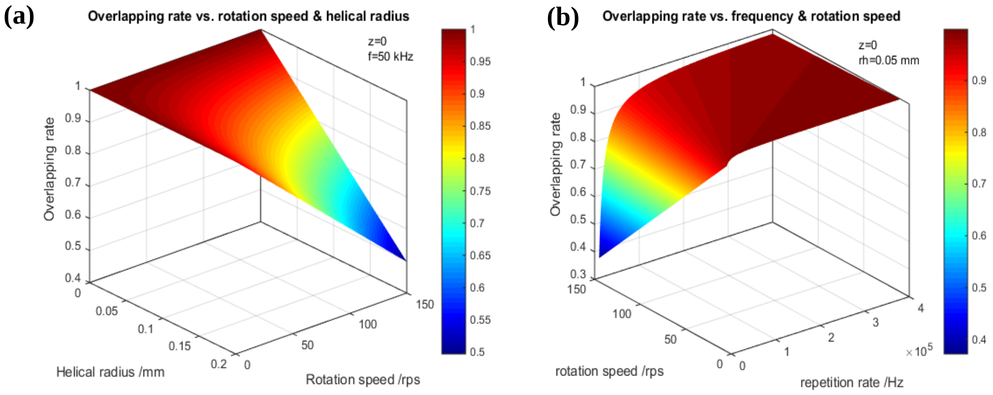

Fig. 4. Correlation between overlapping rate and rotation speed, repetition rate and helical radius at focal plane

3.2. Evolution of hole shape and temporal analysis

In order to investigate the evolution of hole geometry, the holes' silhouettes are extracted from high resolution optical image by means of professional photo processing software. Only steps with a significant change in the shape of helical-drilled hole are presented in Fig. 5 to illustrate the temporal geometric evolution.

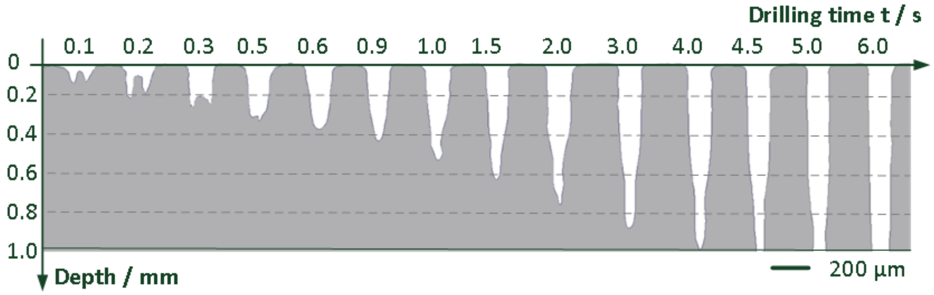

Fig. 5. Evolution of longitudinal sections of holes produced by helical drilling process

Three drilling phases can be distinguished according to the features of hole capillary and ablation behavior. In the first phase (t=0~0.9 seconds), a hole with an island-like pin in the middle is excavated at shallow surface of material. The groove has an ideal longitudinal section with respect to the overlapped laser intensity distribution shown in Fig. 3 (b). By the following laser pulses revolutions, the depth of groove increases and the height of pin firstly grows up to maximum but the pin melts and disappears rapidly due to the local heat accumulation and energy deposition. At this time a capillary hole with a dome-like bottom is observable. From t=0.6 s, the capillary hole deepens and the ablation front moves forward longitudinally. The second phase (t=0.9~4.0 s) is characterized by the funnel-like borehole with a slim tip. As a result of change of laser ablative behavior, the bottom of capillary is sharped and finally forms a slim tip at the bottom. Noteworthy is the small change in direction of capillary bottom at t=1.0 second to right side of the image. This can be attributed to reflections of laser beam at the internal hole walls. Once the tip is formed, its length and funnel-like profile stay quasi constant until it reaches the rear side of the sample. The final phase begins at the time when hole is drilled through. It functions as broadening of hole exit to the final geometry and finishing the hole to designed profile. For the drilling hole investigated here, about 100 revolutions of laser pulses are performed to enlarge diameters of exit and form a cylindrical hole profile. The number of revolution depends on the setting of hole diameter and laser parameters applied.

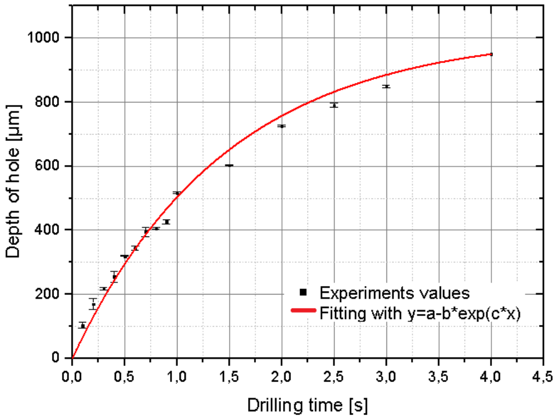

Fig. 6. Laser ablation rate in helical drilling with helical radius 50 µm and repetition rate 50 kHz, single pulse energy applied 120 µJ

The ablative behavior in helical drilling are investigated and the relationship between drilling time and hole depth is plotted and shown in Fig. 6. This diagram further illustrates the three phases in helical drilling process. For the first 1 second in the first phase the borehole is drilled with a high average ablation rate and approximate half of the final depth is reached. The reason for the high ablation rate can be explained as following. The Rayleigh length $z_r$of laser beam applied in this experiment calculates to be 264 µm, and focus is located at 200 µm beneath the material surface. Thus, the most effective ablation range extends longitudinally to 464 µm and nearby the middle of the material. In the second drilling phase, the growth rate of the hole depth is strongly reduced during the following seconds due to the declined laser intensity and internal reflection of laser beam, as well as energy absorption by vaporized particles and plasma [17].

3.3. Hole geometry and surface morphology

Processing parameters in helical drilling are optimized to achieve an effective and high precision drilling process based on the investigation and analysis of the influence of laser energy deposition on drilling geometry. Fig. 7 shows the hole entrance and exit qualified with high circularity and well-defined edge. Optical inspection and statistical analysis of the hole produced with ps-pulses reveal a tolerance of diameter within ±2 µm. Moreover, heat-affected-zone and volume of recast layer at material surface and on hole wall can be minimized. Another advantage by utilizing helical drilling optics is great feasibility to achieve aspect ratio higher than 10: 1.

To evaluate the drilling quality, topography of hole wall is analyzed by means of SEM technique and confocal laser scanning microscope (LSM). A selected SEM segment of hole wall with 1000X magnifications (Fig. 8a) demonstrates a smooth and uniform surface, on which a Laser Induced Periodic Surface Structures (LIPSS) with almost constant periodicity 576 nm in Fig. 8b is present. As reported in[1, 18-20], the mechanism of LIPSS formation is supposed to be an interference of laser and surface Plasmons (surface electromagnetic waves). To investigate the evolution of roughness of hole wall surface in different depths, 7 points at different areas are measured and evaluated by LSM. The average value of root-mean-square (RMS) surface roughness $\mathrm{R_q}$ in the full length on hole wall is $\overline{R_q}$=290 nm. It is competitive to other micro machining techniques such as micro Electrical Discharge Machining (μ-EDM)[18].

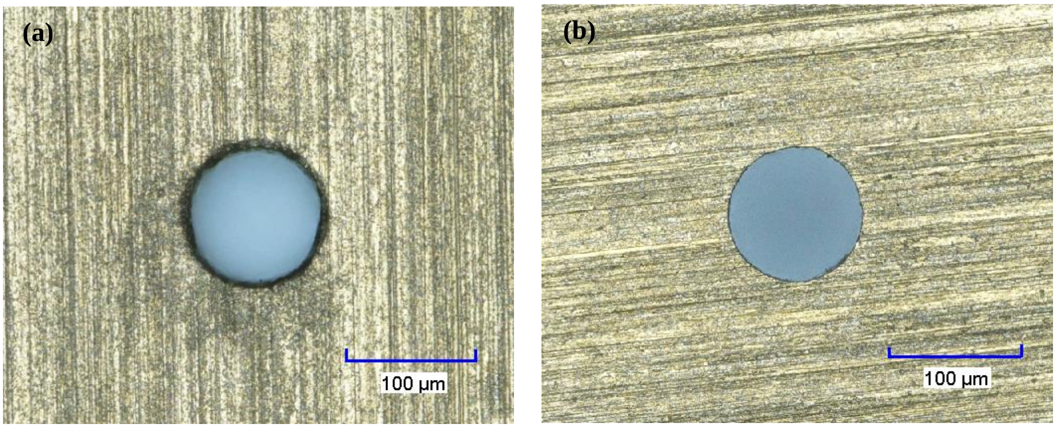

Fig. 7. Entrance (a) and exit (b) geometry of helical drilled hole in 1 mm thick stainless steel (1.4301)

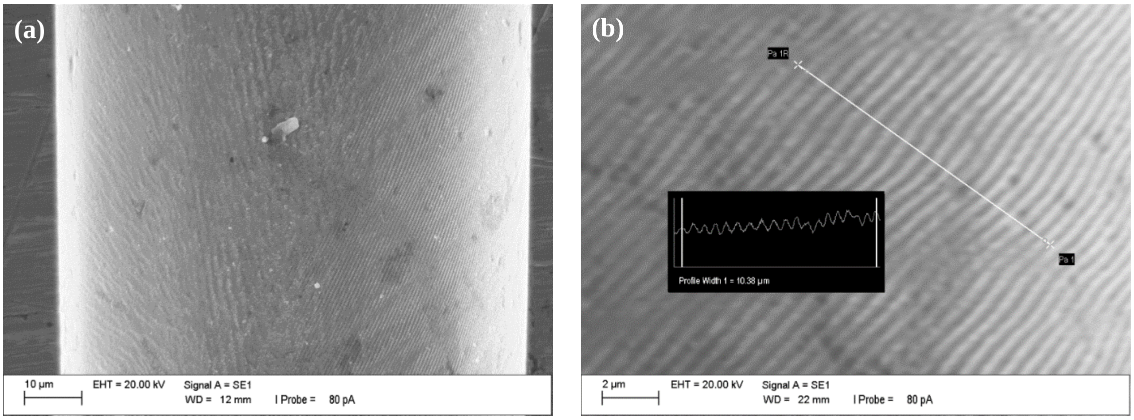

Fig. 8. SEM images of (a) ps laser pulses helical drilled hole wall and (b) relative details of the obtained surfaces with Laser Induced Periodic Surface Structures (LIPSS)

4. Conclusions

By using ultrashort pulses laser helical drilling and static analysis methodology, we have investigated the temporal evolution of hole geometry and influence of laser energy deposition on hole quality. As a result of this investigation, the following can be concluded:

- The ablative behavior in helical drilling is changed by a helix revolution of laser spots. As a result of the circular oscillation the local input laser energy volume per unit time is decreased, thus heat accumulation slows down and HAZ is minimized.
- Overlapping rate as one of the important factors for energy deposition plays a role in high qualitative drilling. The correlation between overlapping rate and energy deposition related parameters (rotation speed of laser beam, pulse repetition rate and helical path radius) is described in a formula and visualized by numerical simulation.

- Through temporal analysis of the evolution of hole shape during helical drilling, three phases can be distinguished. The relationship between drilling time and depth of hole reveals influence of laser focal position and Rayleigh length on ablation rate in different phases. The growth of hole depth slows down at the end of second phase due to the decrease of effective laser pulse intensity. The third phase is characterized by broadening of hole exit to the final geometry.
- To obtain high precision and best quality holes, it is advantageous to use ultrashort pulses. By means of SEM techniques LIPSS with periodicity comparable to laser wavelength is observed on the hole wall surface. Furthermore, the roughness values in the full depth of hole measured with LMS give evidence to the significance of laser energy deposition in helical drilling.

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