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# An Experimental Investigation of the Effects of Femtosecond Laser Helical Drilling: Influence of Process Parameters

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**Abstract.** Femtosecond laser pulses used in micro-drilling, which allows precise and thermal-damage-free removal of material, has progressed remarkably in recent years to become an essential tool for microhole drilling. Helical drilling is the most common method for processing high-precision microholes. Compared to multi-pulse drilling or circular scanning drilling, it is more convenient to process the requested radius and needed depth hole. The mechanism of interaction between the ultra-fast laser and materials is very complex. Exploring the influence of processing parameters on the drilling process not only helps to guide the actual processing, but also helps our understanding of the mechanism. In this study, laser processing parameters for drilling microholes in three materials are investigated. The influence of processing parameters on hole drilling is analysed, and the relationship between the overlapping rate influence on drilling depth and ablation threshold is explored.

## 1. Introduction

Laser manufacturing has been adopted as an effective technology for producing micro-features in various materials, such as metal, silicon, and ceramic[1]. The great demand for precision holes has promoted the rapid development of laser drilling in many fields[2].For example, laser drilling has been applied in the aerospace industry, manufacturing shaped film holes in turbine blades. These film holes vary significantly in morphology and inclination angle, forming a protective cooling layer between the hot gases and external surfaces of the turbine blade[3].

Due to the complexity of the interaction regime between the femtosecond laser beam and material, there is not yet a complete theory which can describe the film cooling hole drilling process based on femtosecond laser. For the work presented in this paper, a helical drilling optic with a femtosecond-pulsed laser source is used for the drilling of microholes in stainless steel, aluminum alloy, and nickel-based alloy, respectively. The objective of the paper is to investigate the main influencing factors on quality and productivity, such as laser energy, repetition rate, and rotation speed.

## 2. Experiment set-up

In our case, an ultra-fast laser machine tool (KH7040A-1) from China KeHan Laser is used. The structure diagram of the machine is shown in Figure 1. The laser beam first passes through a quarter-wave plate to ensure circular polarization of the beam when reaching the workpiece, and then through a beam expander, before it is reflected by the mirror. Next, the beam passes through a beam rotation apparatus consisting of four optical wedges, which makes the beam rotate in the set helical path. The schematic diagram of the helical path can be easily observed through the SEM images of a 5s femtosecond laser pulse helical drilled hole, shown in Figure 2.

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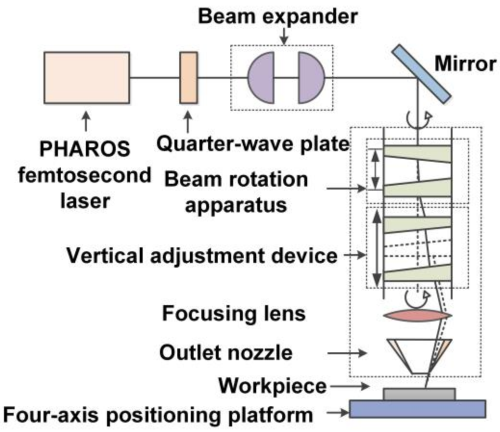


**Figure 1.** Schematic diagram of the femtosecond laser drilling system.

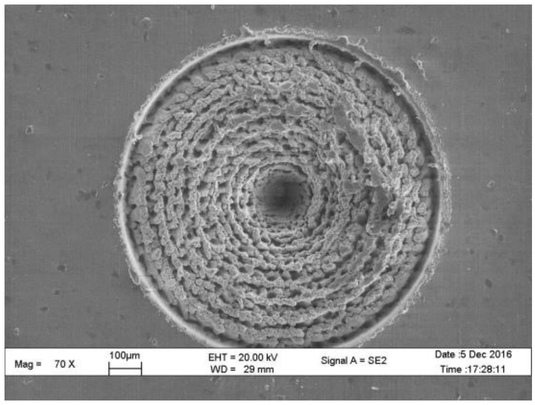


**Figure 2.** SEM images of a five second femtosecond laser pulse helical drilled hole.

For the experiment set-up, we chose three processing parameters: the laser repetition rate, rotation speed, and average laser power, as the variables for drilling microholes in four different materials. We measured the depth of the drilled holes by cutting the holes from the center of each using a scanning electron microscope (SEM). Furthermore, we aimed to explore the influence of the processing parameters on the processing efficiency. We set the processing parameters according to the actual hole processing situation, and set the parameter range near the common value shown in Table 1. The experiment parameters are summarized in Table 2. Based on the technician's suggestion, according to the material properties, the average power is set to 12.5W for processing on aluminum alloy and the others are set to 10W.

**Table 1.** Helical drilling parameters.

| Repetition (kHz) | Pulse width (fs) | Spot diameter (μm) | Wavelength (nm) | Pulse average power (W) | Rotation speed (r/min) |
|---|---|---|---|---|---|
| 100 | 250 | 10-15 | 1064 | 10, 12.5 | 2400 |

**Table 2.** Three-factors experimental parameters.

| Number | Independent variable | Range | Interval | Drilling time |
|---|---|---|---|---|
| 1 | Repetition rate | 60-600kHz | 90 | 10s |
| 2 | Rotation speed | 600-2400r/min | 600 | 10s |
| 3 | Average power | 3-15W | 3 | 5s |

## 3. Results and discussion

### *3.1 Laser processing parameters*

First, we need to know what occurred inside the material when processing a microhole. The evolutionary process of the hole shape is shown in Figure 3. From the graph, we can divide the process into three phases. In the first phase, the ablation started from the central region and gradually spread out. In the second phase, the processing depth increased and the center point penetrated first approximately 4-6s after starting. In the third phase, the material was ablated as time went on and the hole on the back became bigger. During the processing, the center point was the deepest and quickly reached the back of the material, where the other regions were removed slowly. This is owing to the constant rotation speed and laser output power. The laser energy for each cycle is constant, despite the influence of other factors on the ablation volume. The same laser energy absorbed by the material resulted in a smaller diameter of helical path, the deeper it penetrated in this position.

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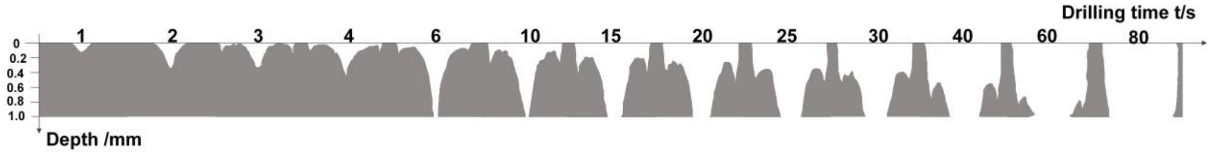



**Figure 3.** Temporal evolution of hole shape from the cutting section.

In order to better process microholes with high quality, it is necessary to know what effect changing the parameters will have on the processing efficiency. As shown in Figure 4, there are experimental results showing the relationship between the depth of the holes and processing parameters for the three different materials. Because the depth of each different radius is not the same, the depth of the center point is taken as the index. As can be seen from Figure 4a, the depth of ablation decreases as the repetition rate increases. This is because the single pulse energy $E_p$ can be calculated by equation (1):

$$E_p = P \cdot f^{-1} \tag{1}$$

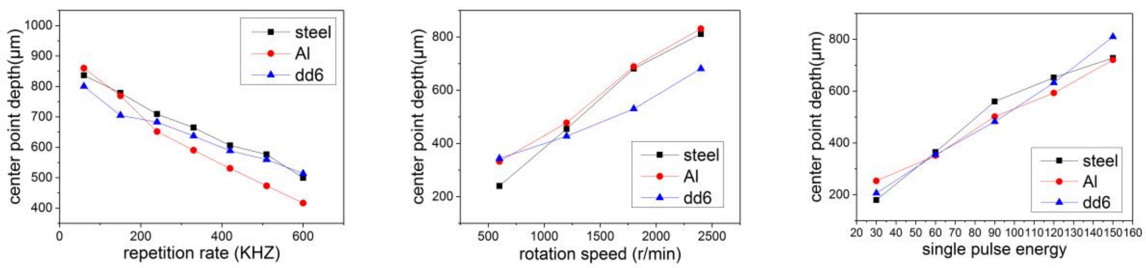
Where $P$ is the average power of laser, and $f$ is the repetition rate of laser. It is clear that an increase in repetition frequency results in a decrease in single pulse energy. From Figure 4c, we learn that the ablation depth decreases with the decrease of the single pulse energy. Thus, the increase of the repetition frequency leads to the lowering of ablation depth, thus affecting the processing efficiency.

With the increase of rotation speed $\omega_m$, the hole depth rises. This is related to the overlapping rate, which will be discussed in the next section.

In order to better understand the influence of laser processing parameters on machining efficiency, assuming a linear relationship between parameters and depth, the linear fitting of experimental data is obtained. Table 3 shows the linear change rate of three kinds of materials. For each of the three materials, the trend is consistent, $S_E > S_f > S_\omega$, which means that the single pulse energy has the greatest influence on the hole depth, followed by the repetition frequency, and finally, the rotation rate, and a, b, and c represents the slope of the repletion rate curve, rotation speed curve, and the single pulse energy curve, respectively.

**Table** 3. Influence of Process Parameters on Drilled Hole Depth of Different Materials.

| Material | $S_f^a$ | $S_\omega^b$ | $S_E^c$ |
|---|---|---|---|
| Steel304 | -0.6030 | 0.3233 | 4.6163 |
| Al5052 | -0.8109 | 0.2846 | 3.9232 |
| dd6 | -0.4940 | 0.1859 | 4.9520 |




**(a)** **(b)** **(c)**

**Figure 4.** Correlation between removal thickness and (a) repetition rate, (b) rotation speed and (c) single pulse energy.

### *3.2 Overlapping rate*

In the machining process using ultra-short laser in the helical path, we need to determine what actually changed in the laser beam by changing these processing parameters. Owing to a high repetition rate, a large number of pulses are deposited in one revolution, which results in the overlap of the pulses. According to many literatures, the overlapping rate, as a key parameter in the helical drilling process for directly describing the energy deposition, plays an important role in the drilling of high quality holes. The calculation of the overlapping rate $\eta_{or}$ of the laser spot in the helical drilling is given as shown in equation (2):

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

In the formula, $r_h(z)$ is the helical radius of the circle when the laser spot is at z position, $\omega_m$ represents the rotation speed of the laser beam, $\omega(z)$ is the radius of the laser spot in z position, and $\tau_p$ is the duration of a single pulse.

To simplify the above equation to make the following calculations easier, because $\tau_p$ is 250fs, and $f >> \omega_m$, thus, it can be considered that $\pi \cdot \omega_m \cdot r_h(z) \cdot \tau_p \to 0$ and $\sin(2\pi \cdot \omega_m / f) \to 2\pi \cdot \omega_m / f$ . Then, we can obtain the following formula as[4]:

$$\eta_{or} = 1 - \frac{2\pi \cdot \omega_m \cdot r_h(z)}{\omega(z) \cdot f} \tag{3}$$

Now, we have the repetition rate $f$ and rotation speed $\omega_m$, the maximum radius of the hole, 1mm, as the helical radius $r_h(z)$, and the radius of the spot $\omega(z)$ is 10μm. Thus, the overlapping rate can be calculated. Figure 5 depicts the depth of the center point with the overlapping rate. As shown in the figure, the depth of the microhole is inversely proportional to the overlapping rate. The slope of the curves denotes the sensitivity of the ablation depth to the overlap rate. Obviously, it is easy to conclude when discussing the influence of the overlapping rate, that it is related to the material properties. Moreover, from our experiment, the order of influence is Steel304>dd6.

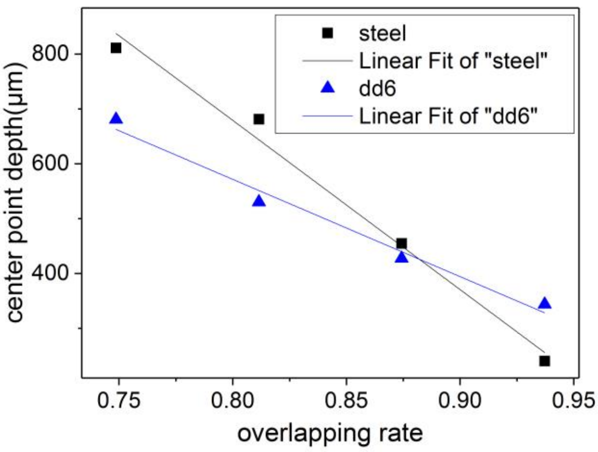



**Figure 5.** Correlation between overlapping rate and the depth of drilling hole.

What resulted in this phenomenon? We need to think from the source. Why can the overlapping rate affect the depth of the holes? One popular explanation is because of the energy shielding due to adsorption by vaporized particles and plasma created with ultrashort pulse laser ablation[5,6]. We assume that the greater influence of the overlapping rate is because of the energy shielding making it more difficult to reach the ablation threshold of the material, which means that the threshold is bigger, and the influence of the overlapping rate is more obvious.

As for now, the general method to get the ablation threshold of a material is using the following equation with single pulse drilling experimental data:

$$D^2 = 2\omega_0^2 \ln(-\frac{E_p}{E_{th}}) \tag{4}$$

In the formula, $\omega_0$ is the waist radius after laser focusing.

Within the femtosecond pulse width, the material has a fixed ablation threshold[7]. There are few studies on femtosecond laser ablation thresholds, as the picosecond laser processing and femtosecond laser processing mechanisms are similar, we can learn through the investigation of the picosecond laser drilling experiment. An experimental study is presented of microhole drilling on the surface of stainless steel using a 10ps Q-switched Nd:VAN pulsed laser at two wavelengths 532 and 1064nm. From the measured data, the calculated thresholds are 0.276 $J/cm^3$ and 2.537 $J/cm^3$ [8]. Experimental results demonstrate that the ablation threshold of dd6 in the picosecond laser is 0.11 $J/cm^3$ [9]. Thus, we can probably draw the conclusion that the ablation threshold of stainless steel 304 is indeed bigger than the nickel-based single crystal alloys dd6s, which fits our guess.

## 4. Conclusion

Through the laser processing parameters in helical drilling experiment, the influence of parameters on the depth of the hole is obtained: with the increase of rotation speed, decrease of laser repetition frequency, and increase of the single pulse energy, the depth of the hole is increasing, which denotes that the drilling efficiency is higher, within the range of values taken in the paper. From the shape evolution of the hole inner shape, which can be obtained by cutting holes from the center, the drilling process can be divided into three phases. The depth decreases with the larger radius, and the center point will penetrate first. The overlapping rate has a great impact on the drilling process because of the energy absorption by vaporized particles and plasma. The influence of the overlapping rate on the drilling process is related to the material, and likely to have a relationship with the material ablation threshold. The more difficult to ablate, the bigger the threshold, and the impact of overlapping is more obvious.

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