Experimental Investigation on the Spatial-temporal Evolution of the hole formation during Laser Helical Drilling

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Abstract: In order to study the influence of process parameters of femtosecond laser helical machining on the formation of micro-holes, we selected main parameters of the femtosecond laser helical drilling process, used 304 stainless steel as the target material, designed a 5-factor and 5-level orthogonal experiment based on the $L_{25}(5^5)$ orthogonal table, and analyzed the significance levels of the impacts of single pulse energy, repetition rate, rotation rate, rate of focus downward movement, and air-blowing pressure on the ablation depth. Based on back propagation (BP) neural network, we established the relationship model between five factors and the material ablation depth, and trained the network with orthogonal experiment data. We used the data of the additional drilling experiments to test the generalization ability of the established network, and the results show that the prediction error of the model is within 3%. We designed a single-factor experiment for the characteristic parameter of the helical drilling--the rate of focus downward movement--and obtained the effect of the rate of focus downward movement on the formation of the micro-holes during the process of femtosecond laser helical drilling.

1. Introduction
Since the birth of the ultrashort pulsed laser processing technology, owing to its advantages of processing excellencies such as materials ablation without producing molten phases [1], low heat-affected zones, minimization of the recast layer, and miniaturization of micro-cracks [2], it has been widely used in the micro and small hole manufacturing process [3]. In the current femtosecond laser drilling process, there are four major processing methods: single pulse processing, percussion processing, trepanning, and helical trepanning processing [4]. Kamlage et al. [5] studied the influence of laser pulse repetition frequency on the access aperture in different environments by using percussion processing methods. Wang et al. [6] used ring-cutting method to drill holes in alumina ceramic substrates, and established the influence rules of parameters such as different focus positions and different circling paths on the exit and entrance aperture and heat-affected zone. Lee et al. [7] conducted a helical drilling experiment on an aluminosilicate glass substrate using a bottom-up femtosecond laser, and obtained through holes with a circularity of less than 20 μm. Helical drilling technology is the best way to achieve machining of holes with high depth-to-diameter ratio [8]. However, the relationship between the geometric evolution of the formation of drilled holes and the main processing parameters is not yet clear in the helical drilling process. The determination of the parameters in the actual production process is still mainly based on empirical trial and error, resulting in processing defects such as back wall damage.
or blind holes in the process. Thus, the life time of the workpiece is affected. Also, the production demands become difficult to meet due to the low efficiency in the processing of the drilled holes. In order to further explore the mapping relation between the laser parameters and the process quality, several researchers optimized the laser processing parameters based on the Backpropagation (BP) neural network. Zhang et al. [9] established the relation between welding appearance and the characteristics of the molten-pool-shadows by using the BP neural network improved by genetic algorithm (GABP). Guo et al [10] investigated the mechanism of laser coloring by using BP neural network, the influence of laser parameters on the coloring effects such as defocusing distance, pulse energy, scanning interval was studied. Based on the BP artificial neural network, Ding et al. [11] established the relationship between the laser parameters (laser power, pulse frequency, defocusing amount) and the microporous surface roughness. It can be seen that BP neural network can be regarded as a powerful tool to establish the nonlinear mapping relations between processing parameters and process quality.

Therefore, in this paper, we selected the main parameters in the femtosecond laser helical drilling process, studied the effects of single pulse energy, repetition rate, rotation rate, rate of focus downward movement, and air-blowing pressure on the ablation depth based on the orthogonal experiment, and established the back propagation (BP) neural network model with the above parameters as input and the ablation depth as output. The neural network model was trained with the acquired experimental data as the training sample. Finally, the generalization ability of the neural network was tested by the experimental data obtained from additional drilling experiments. We conducted a single factor experimental study on the characteristic parameter of the rate of focus downward movement in the process of femtosecond laser helical drilling. Rows of small holes were produced with different processing time by setting different rates of focus downward movement. Under different rates of focus downward movement, the evolution of the small hole was established through measuring the depth of each hole. Thus, we obtained the evolution of the formation of the drilled holes in the femtosecond laser helical drilling process.

2. Experimental Equipment and Methods

In this paper, we used the KH7040A-1 five-axis ultra-fast laser micro-hole processing machine from Fujian Kehan Laser Company to carry out the micro-hole processing experiments. The main parameters of the laser and machine tools are shown in table 1. The structure of the machining system is shown in figure 1. In order to realize the helical trajectory motion of the laser beam, we used the four optical wedge rotating system E to deflect the laser beam to achieve the planar helical movement. Rotary cutting and machining module H, composed of focusing lens F and laser head G, could be moved in the direction perpendicular to the material surface. By controlling the lifting and lowering of the rotary cutting and machining module H, the rate of the laser focus downward movement was controlled. Combined with the planar helical motion, helical drilling was achieved.

| Parameter           | Unit | Range    |
|---------------------|------|----------|
| Pulse Width         | fs   | 250      |
| Wavelength          | nm   | 1064     |
| Repetition rate     | kHz  | 60-600   |
| Average power       | W    | 0-15     |
| Rotation rate       | r/min| 600-2400 |
| Blowing pressure    | MPA  | 0-0.5    |
| Spot radius         | μm   | 15-25    |
Figure 1. Schematic diagram of femtosecond laser machining system. For this experiment, we chose the 304 stainless steel specimen with thickness of 1 mm and all side lengths of 50 mm. This experiment was to machine the micro-hole with the aperture of 1 mm. Due to the low average power of the femtosecond laser, the drilling time would be too long if the ring cutting method was used for drilling. Therefore, according to the helical processing method adopted in literature [12] and practical machining experience, the laser helical scan path was set to 50 circles, and distance from the outermost circle to the center was 0.5 mm. The scan path is shown in figure 2.

Figure 2. Schematic diagram of laser helical scanning path.

To investigate the formation of the micro-holes, we needed to observe the shape and the depth of the micro-holes. However, most of the micro-holes processed in the experiment were not through holes and had small apertures, so the depth of the holes could not be directly measured. If the measurement was made by opening the hole along the diameter using wire electrical discharge machining (WEDM), it would not be easy to ensure that the metal wire was equally divided along the hole diameter, and the thermal effect generated from the WEDM process could damage the hole morphology. Therefore, we adopted the method of directly drilling holes on the splicing aperture of the specimen. We first used the medium wire to cut the 1 mm thick stainless steel blank into 50×50 mm stainless steel sheets. Then the four sides of the steel sheet were treated by chemical corrosion to make the surface roughness less than Ra3.2. We spliced two stainless steel specimens together by clamping the two specimens using the self-designed fixture, as shown in figure 3, to ensure the aperture closely fitted under the clamping force. Finally, on the laser processing machine, the center of the laser focus (the center of the black cross in
figure 4) was positioned at the splicing aperture for drilling. The splicing aperture of the specimens and the laser focus positioning method are shown in figure 4.

After the drilling was completed, the specimen was removed from the fixture and washed for 15 minutes with 95% ethanol solution in an ultrasonic cleaner. Then it was removed and air-dried. We used a VHX-1000 ultra-depth-of-field 3D microscope and SUPRA 55 field emission and scanning electron microscope (SEM) to observe the hole wall and recorded the depth and the access aperture of each hole.

2.1. The Impact of Multiple Parameters on the Ablation Depth

In order to explore the impact of the main parameters of the femtosecond laser drilling process on the ablation depth of materials, we chose five levels for each selected processing parameter. The factor levels are shown in table 2. Taking the depth of the ablation hole as the investigation index, 25 experiments were carried out using the $L_{25}(5^4)$ orthogonal table. The processing time of the micro-hole in each experiment was 15 s. In order to reduce the experimental random error, each experiment was repeated 3 times. At the end of the experiment, we used the VHX-1000 ultra-depth-of-field 3D microscope to observe hole walls on both sides of the micro-hole, measured the depth of the hole, and recorded the data.

| Factor | Process parameters | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|--------|--------------------|---------|---------|---------|---------|---------|
| A      | Single pulse energy/μJ | 20      | 22      | 24      | 26      | 28      |
| B      | Repetition rate/kHz  | 100     | 200     | 300     | 400     | 500     |
| C      | Blowing pressure/MPa | 0.1     | 0.2     | 0.3     | 0.4     | 0.5     |
| D      | Rotation rate/(r/min) | 600     | 1050    | 1500    | 1950    | 2400    |
| E      | Rate of focus down/(mm/s) | 0       | 0.005   | 0.01    | 0.015   | 0.02    |

2.2. Impact of the Rate of Focus Downward Movement on the Formation of the Micro-Hole

In laser helical drilling, the feed along the laser transmission direction, i.e., the rate of the laser focus downward movement, is the most important feature of this method. Currently, there is little literature about the relationship between this parameter and the formation of the micro-holes. Therefore, by changing the rate of the laser focus downward movement, we studied the formation of the micro-hole at different rates of focus downward movement. According to the actual processing experience, we selected laser pulse repetition frequency of 100 kHz, spot rotation rate of 2400 r/min, average power of 10 W, and air-blowing pressure of 0.5 MPa. With these processing parameters, we carried out the drilling test and found that the drilling of the micro-hole was completed after 100 s. At this time, the appearance
of the micro-hole could be regarded as the end of the evolution process. Therefore, the longest drilling time was taken as 100 s. The defocus amount refers to the distance between the laser focus and the surface of the worked material. When the laser focus is above the workpiece, it is positive defocusing; otherwise, it is negative defocusing. Since the thickness of the selected experimental specimen was 1 mm, to ensure both positive defocusing and negative defocusing occurred in the experiment, the rate of focus downward movement was chosen as 0 mm/s, 0.005 mm/s, 0.01 mm/s, 0.015 mm/s, and 0.02 mm/s, so five experiments were designed. At the same time, in order to observe the formation of the micro-holes, 15 holes were made on the splicing aperture of the materials with different processing time in each experiment. The arrangement of the experiments is shown in table 3. In order to reduce the experimental random error, each experiment was repeated 3 times. At the end of the experiment, we used a VHX-1000 ultra-depth-of-field 3D microscope and SUPRA 55 field emission and scanning electron microscope (SEM) to observe the wall on both sides of the micro-hole, measured the depth and the access aperture of each hole, and recorded the data.

| Rate of focus down (mm/s) | Hole 1 | Hole 2 | Hole 3 | Hole 4 | Hole 5 | Hole 6 | Hole 7 | Hole 8 | Hole 9 | Hole 10 | Hole 11 | Hole 12 | Hole 13 | Hole 14 | Hole 15 |
|--------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|---------|---------|
| 0                        | 1      | 2      | 3      | 6      | 10     | 15     | 20     | 30     | 40     | 50      | 60      | 70      | 80      | 90      | 100     |
| 0.005                    | 1      | 2      | 3      | 6      | 10     | 15     | 20     | 30     | 40     | 50      | 60      | 70      | 80      | 90      | 100     |
| 0.01                     | 1      | 2      | 3      | 6      | 10     | 15     | 20     | 30     | 40     | 50      | 60      | 70      | 80      | 90      | 100     |
| 0.015                    | 1      | 2      | 3      | 6      | 10     | 15     | 20     | 30     | 40     | 50      | 60      | 70      | 80      | 90      | 100     |
| 0.02                     | 1      | 2      | 3      | 6      | 10     | 15     | 20     | 30     | 40     | 50      | 60      | 70      | 80      | 90      | 100     |

3. Experimental Results and Analysis

3.1. Orthogonal Test

3.1.1. Range and Variance Analysis. Femtosecond laser helical drilling is a nonlinear process with multi-parameter coupling. Under the coupling effect, studying the influence of the parameters on the ablation depth and mapping the relations between the processing parameters and the ablation depth is the key to establishing the evolitional model of femtosecond laser helical drilling. In this paper, we first conducted the range analysis and variance analysis of the orthogonal experimental results.

The range method is a commonly used data analysis method when dealing with orthogonal experimental data. It is simple, intuitive, and has a small amount of calculation. It can visually compare the order of major and minor effects of various factors in orthogonal experiments, and can find the optimal combination of experimental parameters through simple comparison. The result of the range analysis is shown in table 4. Among them, the corresponding value of $\bar{T}$ to $\bar{\bar{T}}$ is the average of the corresponding index under the corresponding factors and the corresponding level. $\bar{R}$ is the factor range. The greater this value, the greater the impact of the factor on the index. By comparing the range of the various factors in the table, we could determine the impact of various factors on the ablation depth as follows: laser pulse repetition frequency > single pulse energy > air-blowing pressure > rotation rate > rate of focus downward movement.

| Level | Column number (Factor) |
|-------|------------------------|
|       | 1 (A) | 2 (B) | 3 (C) | 4 (D) | 5 (E) | 6       |
| $\bar{T}$ | 207.056 | 195.378 | 204.742 | 206.422 | 230.002 | 226.208 |
| $\bar{\bar{T}}$ | 197.594 | 204.326 | 205.804 | 222.628 | 225.840 | 223.050 |
| $\bar{\bar{\bar{T}}}$ | 225.480 | 207.150 | 225.068 | 212.850 | 222.076 | 224.577 |
| $\bar{R}$ | 236.082 | 236.838 | 233.638 | 234.718 | 215.496 | 209.452 |
| $\bar{\bar{R}}$ | 241.576 | 264.096 | 238.536 | 231.170 | 214.374 | 224.196 |
| $\bar{\bar{R}}$ | 43.982 | 68.718 | 33.794 | 28.296 | 15.628 | 16.756 |
Because range analysis cannot consider accidental error and conditional error separately, and variance analysis can overcome this shortcoming, we further performed variance analysis on the experimental data [13,14]. Thus, we could compare the result with range analysis result to determine the order of influence of processing parameters on the ablation depth. The established variance analysis is shown in table 5.

In the F-test of the variance analysis, the following three cases were considered [15]:
1) \( F > F_{0.01}(f_r,f_e) \), then the impact of the factor on the results is highly significant, recorded as: **.
2) \( F_{0.01}(f_r,f_e) \geq F > F_{0.05}(f_r,f_e) \), then the impact of the factor on the results is significant, recorded as: *.
3) \( F \leq F_{0.05}(f_r,f_e) \), then the impact of the factor on the results is not significant.

Where \( f_r \) is the degree of freedom of the factor, and \( f_e \) is the degree of freedom of the error.

Table 5. Variance analysis of orthogonal experiment data.

| Source of variation      | Sum of squares | Freedom | Variance     | F-value | Critical value of F-test | Significance |
|--------------------------|----------------|---------|--------------|---------|--------------------------|--------------|
| Single pulse energy      | 7058.151       | 4       | 1764.538     | 7.515   | F_{0.05(4,4)} = 6.39    | *            |
| Repetition rate          | 16164.423      | 4       | 4041.106     | 17.210  | F_{0.01(4,4)} = 15.98   | **           |
| Blowing pressure         | 4887.327       | 4       | 1221.832     | 5.203   | F_{0.05(4,4)} = 6.39    | *            |
| Rotation rate            | 2858.244       | 4       | 714.561      | 3.043   | F_{0.05(4,4)} = 6.39    | *            |
| Rate of focus downward   | 891.313        | 4       | 222.828      | 0.949   |                         |              |
| error                    | 939.260        | 4       | 234.815      |         |                         |              |
| Total                    | 32798.718      | 24      | 1366.613     |         |                         |              |

According to the above criteria, it can be seen from table 5 that the effect of repetition rate on ablation depth was highly significant, and the effect of single pulse energy on ablation depth was significant, followed by air-blowing pressure, rotation rate, and rate of focus downward movement. The results were consistent with the range analysis, indicating that the experimental results are reliable.

By analyzing the above results, it can be seen that in the same processing time, the higher the repetition rate, the greater the number of pulses acting on the material. That is, when the single pulse energy is constant, the total energy acted on the material by the laser with high repetition rate is high. Therefore, the effect of repetition rate on ablation depth is very significant. The single pulse energy directly affects the total laser energy absorbed by the material, and also has a significant effect on ablation depth.

During the drilling process, the material being eroded formed a cloud of particles consisting of vapor particles and plasma above the small hole, which refracted and absorbed the laser light, hindered the laser from reaching the surface of the material to be processed, and formed a plasma shielding phenomenon. During laser drilling, the injection of compressed gas through the gas nozzle to the processing area helped blow away plasma clouds and slag deposited in the holes. The greater the air-blowing pressure, the better the removal effect on particle clouds and slag, and the more favorable it is for the absorption of the laser by the material. Therefore, the air-blowing pressure also has a certain influence on the ablation depth.

The rotation rate only changes the number of spiral circles of the spot scanning per unit time, and does not change the number of pulses and the pulse energy acting on the material. Therefore, rotation rate has no significant influence on the ablation depth.

The rate of focus downward movement is directly related to the defocus amount in the process, and some scholars have found that the defocus amount has a certain influence on the efficiency of percussion processing [16]. However, since the helical drilling method was used, and the maximum depth of ablation was used as the evaluation indicator for the depth of the hole. The laser focus did not always act at one point. During the processing, the inside of the hole exhibited the characteristic of being deep in the center and being shallow in the rest of the area. Therefore, the defocus amount in the process had time-varying fluctuation characteristics. Therefore, with different rates of focus downward movement,
the change in the defocus amount at a certain point at the bottom of the hole is not as significant as during the percussion process. Thus, the result shows that the rate of focus downward movement has minimal effect on the depth of ablation.

3.1.2. BP Neural Network Modelling. Femtosecond laser helical drilling is a complex nonlinear process. It is difficult to establish a rigorous mathematical model and use mathematical expressions to describe the mapping relations between processing parameters and ablation depth. Back propagation (BP) neural network, as one of the most widely used neural network models, can realize the mapping of any nonlinear function. Therefore, we characterized the mapping between processing parameters and ablation depth based on BP neural network in this paper.

For a BP network with three or more layers, the network can approximate a nonlinear function with arbitrary precision as long as there are enough hidden neurons. We used a three-layer neural network structure in this paper, namely, an input layer, a hidden layer, and an output layer. According to the orthogonal experiment, the processing parameters were single-pulse energy, repetition rate, air-blowing pressure, rotation rate, and the rate of focus downward movement. Therefore, the number of nodes in the input layer was 5. The ablation depth was taken as the index of investigation, so the node in the output layer was 1. At present, there are no unified theoretical standards for determining the number of hidden layer nodes, so the number of hidden layer nodes is often determined based on empirical formulas combined with the trial-and-error method. According to the experience [17] of “number of input layer nodes ≤ number of hidden layer nodes ≤ number of learning samples - 1,” we set the maximum number of hidden nodes to 24 and the minimum number of hidden nodes to 5. The tangent S-type transfer function was chosen as the transfer function from input layer to hidden layer, and the linear transfer function was chosen as the transfer function from hidden layer to output layer. The Levenberg-Marquardt optimization algorithm was chosen as the network training function, and the momentum gradient descent algorithm was chosen as the network learning function, with the initial learning rate of 0.01. In order to improve the generalization ability of the network, 25 groups of data in the orthogonal experiment were normalized [18]. After transforming into numbers in the range from 0 to 1, 20 networks with the number of hidden nodes from 5 to 24 were trained. The final number of nodes selected for the network hidden layer was 19, and the network topology was obtained as 5-19-1.

For a trained network, its prediction capability needs to be tested to ensure that the network can accurately characterize the mapping between processing parameters and ablation depth. In this paper, an additional 5 drilling experiments were carried out, and the processing parameters of the 5 experiments were input into the trained network for simulation. The simulation results were compared with the experimental results. As shown in table 6, the absolute value of the relative error of the predicted ablation depth by the neural network was less than 3%, which shows that the established neural network model has good generalization ability. This neural network can effectively model the mapping between the main processing parameters and the ablation depth of the material in the femtosecond laser drilling process.

| Serial number | Single pulse energy/μJ | Repetition rate/kHz | Air-blowing pressure/MPa | Rotation rate/(r/min) | Rate of focus down/(mm/s) | Ablation depth/μm | Relative error |
|---------------|------------------------|--------------------|--------------------------|-----------------------|--------------------------|------------------|----------------|
| 1             | 20                     | 500                | 0.3                      | 1050                  | 0.01                     | 240.91           | 235.48         | -2.25%         |
| 2             | 22                     | 400                | 0.2                      | 2400                  | 0.015                    | 278.19           | 276.51         | -0.61%         |
| 3             | 24                     | 500                | 0.1                      | 2400                  | 0.02                     | 248.38           | 250.22         | 0.74%          |
| 4             | 26                     | 400                | 0.3                      | 1050                  | 0.015                    | 248.64           | 245.32         | -1.34%         |
| 5             | 28                     | 200                | 0.4                      | 600                   | 0.01                     | 182.18           | 184.35         | 1.19%          |

3.2. The Experiment of the Rate of Focus Downward Movement
The evolution of the formation of micro-holes was observed by placing the workpiece with a row of drilled holes under the VHX-1000 ultra-depth-of-field 3D microscope. As shown in figure 5, the number means the hole number as shown in table 3. During the helical drilling process, the ablation rate of the
material at the center of the hole was the fastest, and the ablation rate of the material at the edge of the hole was second fastest, resulting in a ring structure on both sides. Thus, the evolution of micro-holes was: after the laser acted on the surface of the material, the material in the center of the hole ablated fastest, and the center point of the hole was opened up first. As the processing continued, the ring depth on the edge of the hole also increased. When the ring depth on both sides reached the thickness of the material, the material that had not been machined in the hole fell off due to gravity, and a hole with a large taper was formed at this time. The laser continued the helical scan and ablated the excess material on the wall of the hole. The tapering of the hole gradually reduced, and finally the through hole in line with the design requirements was formed.

Figure 5. Hole evolution at the focus downward movement rate of 0 mm/s.

In the above process, a part of the material was not directly ablated by laser; instead the material to be processed was peeled off from the parent material in a manner similar to laser rotary drilling, such as the evolution from holes 13 to 14 in figure 5. The reason for this phenomenon is the cumulative effect. The laser spot rotated clockwise outward along the helical path from the center of the hole. When it reached the outermost circle, it continued to rotate clockwise inwardly until it reached the center of the circle. This process was considered as one cycle of the helical scan. Then the spot started to rotate outward again, cycling until the hole was completed.

Within one cycle, the material located at the edge of the hole was laser irradiated twice within a short time interval. Therefore, there was a cumulative effect. The following relationship existed between the ablation threshold $F_{th}(N)$ at the $N$th pulse ablation and the ablation threshold $F_{th}(1)$ at the single pulse ablation [19]:

$$F_{th}(N) = F_{th}(1)N^{S-1}$$

Where: $F_{th}(1)$ is the ablation threshold at single pulse ablation, $N$ is the number of pulses, and $S$ is the cumulative coefficient characterizing the multipulse effect.

From equation (1), it can be determined that the material at the edge of the hole has a more obvious cumulative effect, resulting in lower ablation threshold and larger ablation rate, and forming a deeper ring ablation zone. Due to the small radius of the helical trajectory near the center point, more pulses act near the center point. The laser energy absorbed by the material is higher than other regions, resulting in faster ablation of the material at the center point. From the end of the pre-cycle to the beginning of the post-cycle, the spot ablated the center point twice in a short time interval. The cumulative effect was obvious, resulting in the maximum depth of ablation at the center point.

Therefore, the depth of the ring ablation zone on both sides of the hole was taken as the ablation depth of the hole in this paper. We used it as the evaluation index to observe the evolving process of the ablation depth of the hole under different rates of focus downward movement, as shown in figure 6.
Figure 6. Time-dependent change of hole depth at different focus downward movement rates.

Since the ring ablation area of Hole 14 and Hole 15 was already opened, the ring depths on both sides of the first 13 holes were analyzed. As can be seen from figure 6, the ring depths on both sides increased with the increase of processing time. During the whole process, the ablation rate was the slowest when the focus did not move down and when the rate of focus downward movement was 0.02 mm/s.

Figure 7. Comparison of the ablation depth curve with and without the focus moving down at a high speed.

Figure 8. Comparison of the ablation depth curve with focus moving down at three different medium rates.

The rate of focus downward movement was divided into three levels--motionless, medium rate, and high rate, as shown in figure 7 and figure 8. It can be seen from figure 7 that the ablation depth curves basically coincided with each other when the focus did not move down and when the focus moved down at high rate. The two curves were relatively smooth, and the slope of the ablation depth decreased with time. In figure 8, the three curves were interlaced with each other, and there were obvious fluctuations in all of them. However, there was no obvious difference in ablation rates under the three different rates of focus downward movement. As can also be seen from the state of the five curves in figure 6, the effect of the rate of focus downward movement on the ablation depth of micro-holes was small, which is consistent with the result of the orthogonal experiment.

Later, we used the SUPRA 55 field emission scanning electron microscope to observe the profile of Hole 15 processed at each rate of focus downward movement, and obtained the morphology of the micro-holes as shown in figure 9. As can be seen, after 100 s processing, there were material residues in the micro-hole processed at the rate of focus downward movement of 0 mm/s and 0.02 mm/s. There were no material residues in the micro-hole processed at the rate of focus downward movement of 0.005 mm/s, 0.01 mm/s, or 0.015 mm/s, and basic shape of the hole was almost completed. The taper of the micro-hole processed at the rate of focus downward movement of 0.01 mm/s and 0.015 mm/s was better than that of the hole processed at 0.005 mm/s. The electron microscopy observation of Hole 15 was...
consistent with the result of the ablation depth of the above 13 holes. Therefore, it can be concluded that the ablation rate of the material first increases with the increase of the rate of focus downward movement. When the rate of focus downward movement exceeds a certain threshold, the ablation rate begins to decrease as the rate of focus downward movement increases. In addition, the rate of focus downward movement has a significant impact on the taper of the micro-hole.

Through the analysis of the experimental phenomenon, we determined that when the focus does not move down, the ablation depth of the material increases with the increase of the processing time. The positive defocusing occurs between the light spot and the material, and the defocusing amount continuously increases. The femtosecond laser used in the experiment was the Gaussian beam. According to the transmission characteristics of the Gaussian beam [20], the light spot area in the focal plane is the smallest, and the energy density is the highest. The light spot area far away from the focal plane increases, and the energy density decreases, as shown in figure 10. Therefore, the greater the defocus amount, the smaller the energy density of the laser acting on the material, resulting in reduced ablation rate. When the laser focus moves down at a high rate, the focus is within the material and the negative defocusing occurs because the rate of moving down is greater than the material ablation rate. At this time, the light spot area acting on the material at the bottom of the hole is greater than the focal spot area, and the ablation rate decreases. When the laser focus moves down at a medium rate, the down rate is close to the material ablation rate, and the defocus amount is maintained within a small range. The surface of the material to be processed is irradiated in a small area for a long time, and the energy density is high. Therefore, the ablation rate at this time is higher than the material ablation rate when the focus does not move down and when the focus moves down at high rate.

Figure 9. The SEM images of the machined holes with different focus downward movement rates at a processing time of 100 seconds. Focus downward movement rates: (a) 0 mm/s; (b) 0.005 mm/s; (c) 0.01 mm/s; (d) 0.015 mm/s; (e) 0.02 mm/s.

Figure 10. Transmission characteristics and light intensity distribution of the Gaussian beam.
In addition, because a row of micro-holes is processed in the material splicing aperture, it is difficult to ensure that the aperture at each point of the splicing aperture is equal. When drilling at a large aperture, light leakage can occur, resulting in a large increase in ablation depth, and the experimental data can be affected.

4. Conclusions
Through the femtosecond laser helical drilling experiment, the evolution of the micro-holes in the drilling process can be described as follows: the center point of the micro-hole is opened up first, forming ring structures on both sides. When the ring structures on both sides are opened, the remaining material is peeled off from the parent material to form a through hole with a large taper. The laser spot continues to scan according to the helical track. Finally, the excess material in the hole wall is etched away to form a through hole that meets the geometric design requirements. In this process, the order of the effect of the five main parameters on the ablation rate is: repetition rate > single pulse energy > air-blowing pressure > rotation rate > rate of focus downward movement. As the characteristic parameter of the helical drilling process, the rate of focus downward movement has a significant impact on the taper of the micro-hole, and its impact on the ablation rate is as follows: The ablation rate first increases with the increase of the rate of focus downward movement. After the rate of focus downward movement reaches a certain critical value, the ablation rate decreases as the rate of focus downward movement continues to increase. In addition, the BP neural network can be used to predict the ablation depth in the femtosecond laser helical drilling process. The relative error of the predicted ablation depth is within 3%. Therefore, in practical engineering applications, BP neural network can be used to predict laser drilling efficiency and optimize processing parameters. This paper has an important impact on exploring femtosecond laser helical drilling and improving production efficiency.

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