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Comparative Research on Laser Percussion and Trepanning Drilling for Superalloy GH4033

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Abstract: Laser micro-hole machining is one of the earliest laser processing technologies applied in industrial production and has relatively mature techniques. It features a high degree of freedom in material selection, fast drilling speed, high precision, no tool wear, and good economic benefits. Based on the theory of laser micro-hole machining, this paper uses millisecond pulsed lasers to drill high-temperature alloy GH4033 in both percussion and trepanning methods. A comparative study of millisecond laser drilling is carried out from aspects such as experimental research and process analysis. The experimental results show that the optimal parameter combination for laser percussion drilling is as follows: the pulse energy is 3.8 J, the pulse width is 1.0 ms, the repetition frequency is 30 Hz, the auxiliary gas pressure is 0.35 MPa, the defocus amount is 0 mm, and the beam expansion ratio is 4. For laser trepanning drilling, the optimal parameter combination is: the pulse energy is 3.6 J, the pulse width is 2.0 ms, the repetition frequency is 20 Hz, the beam expansion ratio is 4, the number of trepanning circles is 5, and the trepanning speed is 90 mm/min. The pulse energy, beam expansion ratio, and defocus amount have the most significant percussions on the quality of micro-hole machining.

1. Introduction

In 1960, American physicist T.H. Maiman successfully developed the world's first practical ruby laser, marking the birth of laser technology [1,2]. The advancement of laser technology has significantly facilitated the expansion of the laser industry globally, establishing it as an indispensable key technology across various fields. Laser technology has been recognized as one of the eight frontier technologies for national scientific and technological development. In the fields of industrial manufacturing and mechanical processing, laser processing technology holds a leading position, with its equipment being widely applied. The application of laser technology has been rapidly growing worldwide, as reflected in initiatives such as China’s "Made in China 2025" and Germany’s "Industry 4.0."

The unique characteristics and advantages of laser micro-hole processing technology have driven its expanding application and promising development prospects in industrial manufacturing, especially in critical areas such as aerospace and transportation manufacturing. Both aerospace and laser technologies are regarded as essential among the eight frontier technologies for national scientific and technological development. Related industries, such as aerospace and laser processing, hold strategic importance for major countries globally. In particular, the production of hot-end components in aero-engines, such as turbine blades, combustion chambers, and exhaust nozzles, increasingly relies on the application of laser micro-hole processing technology. This technology directly percussions the economic efficiency, practicality, and combat performance of aircraft. Consequently, the level of engine manufacturing serves as a crucial indicator of a country's manufacturing capabilities, and laser micro-hole processing technology plays a pivotal role in ensuring the manufacturing quality and performance of critical engine components.

This study, based on the theory of laser micro-hole processing, conducts laser micro-hole processing experiments using the superalloy GH4033. Considering that the micro-holes processed in the experiment are through-holes and that the number of laser pulses required to just penetrate the hole is critical, an improved single-factor threshold drilling experimental scheme was first implemented. Laser percussion drilling and trepanning methods were performed separately to investigate the effects of various laser process parameters on the surface morphology, hole diameter, taper, hole roundness, recast layer, microcracks, and heat-affected zone of the micro-holes. A comparative analysis of the two drilling methods was conducted based on these quality indicators. On this basis, the study further considers the mutual interactions among multiple process parameters and designs orthogonal experimental schemes for both percussion and trepanning methods. Comparative analyses of the differences in micro-holes produced by the two laser drilling methods were performed. The optimal laser process parameter combinations for both percussion and trepanning methods were determined, and the influence of laser processing parameters on micro-hole quality was investigated.

2. Materials and Experiment

2.1. Materials and Samples

Superalloys are structural materials capable of long-term operation under high-temperature and stress conditions. GH4033 is a Ni-Cr-based alloy with aluminum and titanium additions, forming a γ' phase for dispersion strengthening. It exhibits excellent cold and hot workability and is primarily used in turbine blades and turbine discs of aero-engines. Considering the significant application value of GH4033 in the aerospace manufacturing field, it was selected as the experimental material in this study.

The GH4033 superalloy used in the experiment was prepared as workpieces with dimensions of $\Phi 40 \times 5$ mm. The chemical composition and corresponding percentage content of GH4033 are shown in Table 1.

Table 1: Chemical composition and component proportion of GH4033[3]

Alloy Grade	Chemical Composition and Content /%											
	C	Cr	Al	Ti	Ni	Fe	B	Ce	Mn	Si	P	S
					≤							
GH4033	0.03 ~ 0.08	19.0 ~ 22.0	0.60 ~ 1.00	2.40 ~ 2.80	margin	4.0	0. 01	0.01	0.35	0.65	0.015	0.007

2.2. Material Preparation

The experimental material, GH4033 superalloy, was prepared with a specification of Φ40 × 5 mm. The preparation process is as follows:

The GH4033 superalloy rod material with a diameter of Φ40 mm was wire-cut into sample pieces with dimensions of Φ40 × 5.2 mm.

Using a metallographic sample grinding machine, several Φ40 × 5.2 mm samples were polished from coarse to fine using metallographic sandpapers (#0 to #6) to ensure the surface quality meets the precision requirements for laser micro-hole processing. The final dimensions of the samples after polishing were Φ40 × 5 mm.

The polished samples were ultrasonically cleaned using a CNC ultrasonic cleaner, immersing them in acetone and anhydrous ethanol for 25 minutes each to remove any surface-adsorbed impurities.

The cleaned samples were further washed and placed in an electric thermostatic air-blast drying oven for low-temperature drying.

After drying, the thickness of several samples was measured, and those with a thickness of 5 mm were selected as experimental materials for laser micro-hole processing. The samples were then placed into labeled sample bags, ready for the micro-hole processing experiments.

2.3. Experimental Method

This study focuses on the micro-hole processing of superalloys. Determining the number of laser pulses required to completely penetrate the material (i.e., the pulse number threshold) is critical when setting the parameters for laser micro-hole processing, as shown in Figure 1. In the case of the laser trepanning method, although the pulse number does not need to be explicitly set in the processing program, it is essentially determined by factors such as trepanning speed, number of trepanning circles, and pulse width[4]. The single-factor experimental method is commonly used to analyze the effect of a single factor on experimental results, while the orthogonal experimental method is typically employed to study the interactions among multiple factors, providing an approach for analyzing multi-factor problems.

Considering this, the study first applies an improved single-factor threshold experimental method. Laser percussion drilling and trepanning experiments are conducted separately to investigate the effects of relevant laser process parameters on surface morphology, hole diameter, taper, hole roundness, recast layer, microcracks, and the heat-affected zone of micro-holes. These quality indicators are then used to compare and analyze the two drilling methods. Subsequently, an orthogonal experimental scheme is developed to account for the mutual interactions of multiple parameters in laser micro-hole processing experiments. A comparative analysis of the similarities and differences between percussion and trepanning methods is conducted. Based on the single-factor experimental results, the processing technique is further optimized to determine the optimal laser processing parameters.

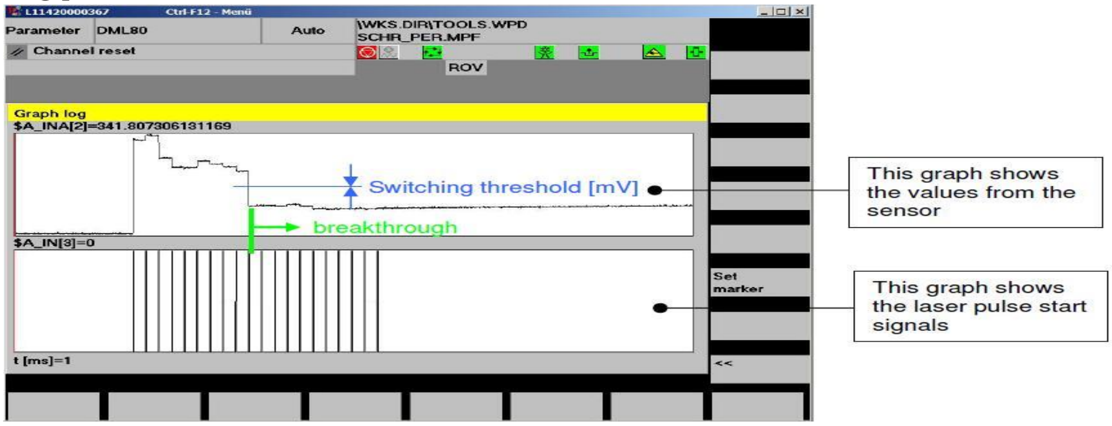

Figure 1: Schematic diagram of breakthrough detection result

3. Results and Discussion

3.1. Percussion of Single-Factor Experiments for Percussion Drilling

3.1.1. Effect of Pulse Energy on Micro-Hole Quality

Extremely high energy density is the key to realizing laser drilling, and the pulse energy of the laser directly determines whether the material can be removed[5]. Therefore, pulse energy is a crucial parameter influencing the quality of the drilled holes. The relationship among pulse energy, frequency, and average power is expressed as Equation (1):

$$E = \frac{P_{avg}}{f} \tag{1}$$

Where:

P_{avg} represents the average power of the laser (W),

E is the pulse energy (J),

f is the pulse frequency (Hz).

In order to study the effect of pulse energy on the quality of laser percussion drilling, an improved single-factor threshold experimental method was employed. The other process parameters were set as follows:

Pulse Width (ms)	Repetition Frequency (Hz)	Beam Expander Ratio (times)	Defocus Amount (mm)	Auxiliary Gas Pressure (MPa)	Auxiliary Gas Type
1.0	30	4	0	0.4	O_2

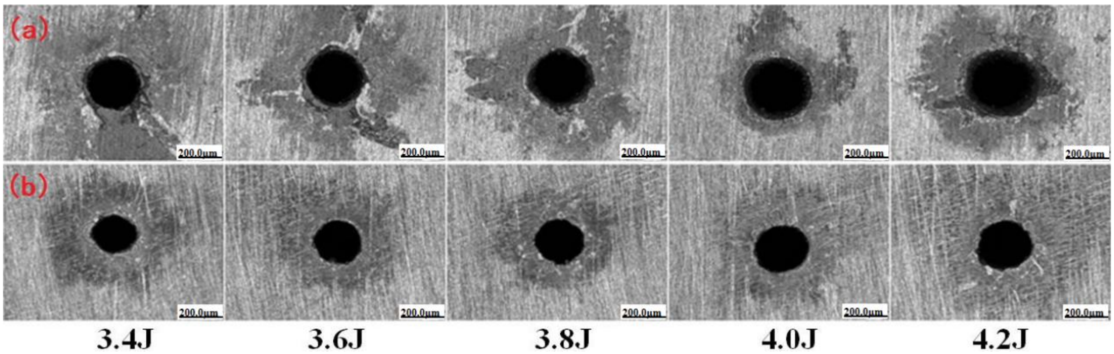

Figure 2: Images of the entrance end and the exit end of the drilled holes under different pulse energy: (a) entrance end (b) exit end

Figures 2(a) and 2(b) show the surface morphology of the micro-hole inlet and outlet under varying pulse energy conditions, respectively. As the pulse energy increases, the amount of spatter and molten material on the micro-hole inlet surface increases, the heat-affected zone around the hole expands, and the material ablation phenomenon becomes more severe. Irregular slag appears on the surface, and the size of the accumulated particles gradually increases with the pulse energy. On the micro-hole outlet surface, there is less spatter and molten material compared to the inlet, but the molten material particles accumulated at the hole opening are larger and gradually decrease as the pulse energy increases. The accumulation of molten material at the hole opening is mainly due to the high energy density of the laser beam, which causes the material removed during the micro-hole processing to be expelled in liquid and gaseous forms[6]. As the pulse continues, the pressure inside the micro-hole gradually increases. Under this increased pressure, the molten metal is instantly ejected, and the high-pressure auxiliary gas strongly percussions the molten metal spatter, causing it to melt or even vaporize, thereby refining the spatter particles.

When the number of pulses reaches the threshold, the micro-hole is penetrated. Under the combined effects of gravity and the auxiliary gas jet, residual liquid metal inside the micro-hole forms molten deposits around the micro-hole outlet. As the pulse energy increases, less molten material accumulates around the micro-hole outlet, and the surface flatness of the hole improves.

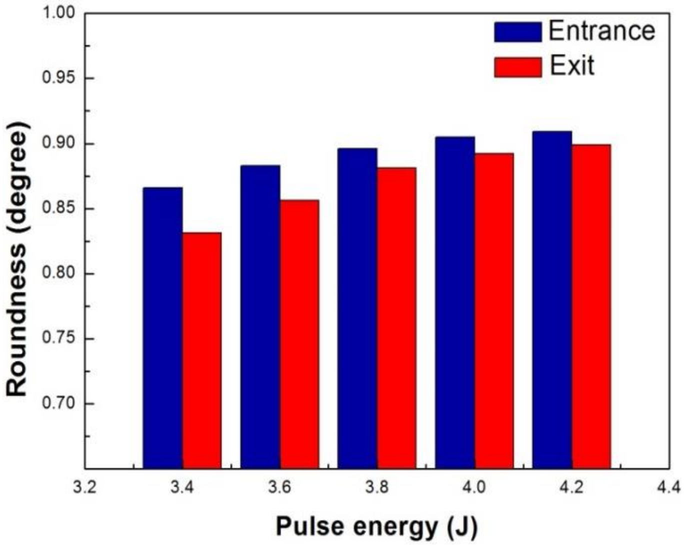

Figure 3: The trend of the Entrance and Exit holes roundness

Figure 3 shows the bar chart of the roundness of the micro-hole inlet and outlet as a function of pulse energy. As pulse energy increases, both the inlet and outlet roundness of the micro-holes gradually improve, with the inlet roundness being better than the outlet roundness. The main reason for this characteristic is that the material removal rate is closely related to the pulse energy. As pulse energy increases, the energy density also rises, leading to an increase in the number of photons absorbed by the material. This results in higher vapor pressure, causing more molten liquid metal inside the hole to be carried and ejected by high-pressure steam[7]. This enhances the laser's ability to remove material, improving the roundness of the micro-hole produced by laser micro-hole processing. In the experiment, the thickness of the material being processed is relatively large, causing uneven heat transfer when the laser acts on the material surface. The heat at the inlet is absorbed and scattered through the hole wall, which then transfers to the outlet, resulting in uneven material removal. As energy continues to increase, the roundness of the micro-hole outlet gradually improves.

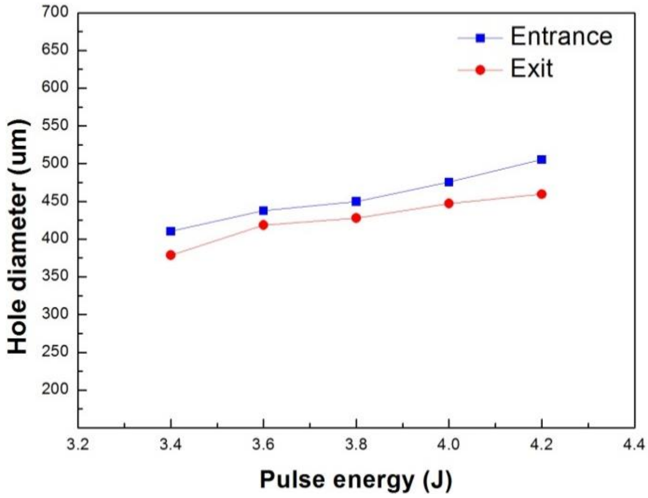

Figure 4: The trend of the Entrance and Exit holes diameter under different pulse energy

Figure 4 shows the curves of the micro-hole inlet and outlet diameters as a function of pulse energy. Both the inlet and outlet diameters of the micro-holes gradually increase as pulse energy increases. This is related to the characteristics of laser energy distribution. The intensity distribution of the laser beam follows a Gaussian distribution, and the high-energy laser beam causes molten metal to be ejected at high speed from the bottom of the micro-hole, leading to an increase in the amount of molten liquid metal[8]. As pulse energy continues to increase, the trend of diameter enlargement gradually slows down. This may be due to the high-temperature plasma cloud formed by the higher pulse energy, which separates the workpiece from the laser beam, resulting in a slower material removal rate and thus a deceleration in the increase of hole diameter.

3.1.2. Effect of Pulse duration on Micro-Hole Quality

The relationship between pulse width and pulse energy is given by Equation (2):

$$E = P \times D \tag{2}$$

Where:
E is the pulse energy (J),
P is the peak power (W),
D is the pulse width (s).

In order to study the effect of pulse width on the quality of laser percussion drilling, an improved single-factor threshold experimental method was employed. The other process parameters were set as follows:

Pulse Width (ms)	Repetition Frequency (Hz)	Beam Expander Ratio (times)	Defocus Amount (mm)	Auxiliary Gas Pressure (MPa)	Auxiliary Gas Type
4.0	30	4	0	0.4	O_2

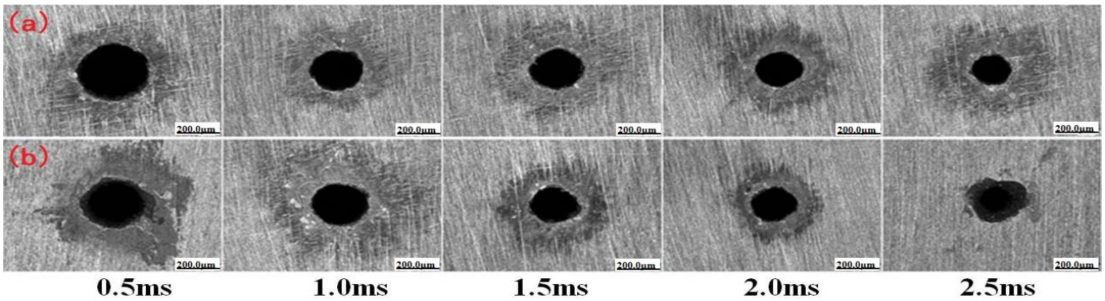

Figure 5: Images of the entrance end and the exit end of the drilled holes under different pulse duration: (a) entrance end (b) exit end

Figures 5(a) and Figure 5(b) show the surface morphology of the micro-hole inlet and outlet under varying pulse width conditions. As the pulse width increases, the accumulation at the micro-hole inlet gradually increases, while the heat-affected zone at the outlet gradually decreases. When the pulse width is 2.5ms, the inlet surface has more accumulation, and the heat-affected zone at the outlet is very small. According to Equation (2), since the pulse energy is kept constant in this experiment, as the pulse width increases, the peak power of the laser gradually decreases, leading to a reduction in energy density. Lower energy density means that melting plays a dominant role in the micro-hole processing process, which reduces the metal vapor pressure. The increased amount of liquid-phase material generated on the workpiece surface and inside the small hole reduces the oxidation and ablation of the material. Additionally, the vaporization ratio of the laser material removal decreases, which causes a reduction in the vapor pressure inside the micro-hole. The amount of molten metal ejected from the hole opening decreases, and under the action of the auxiliary gas, it adheres to the base material surface. The remaining molten liquid inside the micro-hole is ejected from the hole exit when the laser penetrates the material[9]. Therefore, as the pulse width increases, the heat-affected zone on the micro-hole outlet surface gradually decreases.

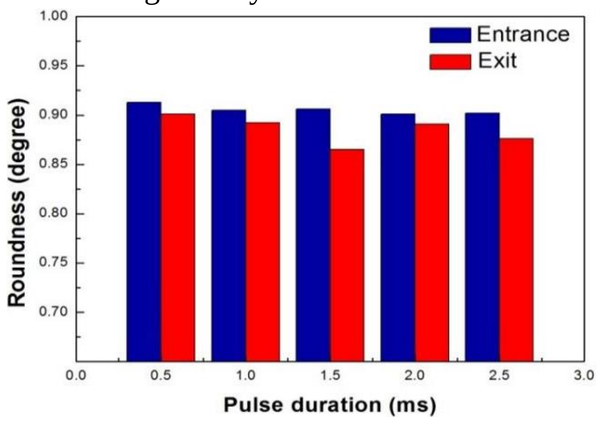

Figure 6: The trend of the Entrance and Exit holes roundness under different pulse duration

Figure 6 shows the bar chart of the micro-hole inlet and outlet roundness as a function of pulse width. As the pulse width increases, the roundness of both the inlet and outlet of the micro-hole generally shows a slow decreasing trend, though the change is not very significant. Additionally, the inlet roundness is better than the outlet roundness. This can be attributed to the fact that as the pulse width increases, the peak power of the laser decreases, leading to a reduction in energy density and a lower material removal rate. This results in uneven material removal at both the inlet and outlet, causing a decrease in the roundness of the hole opening.

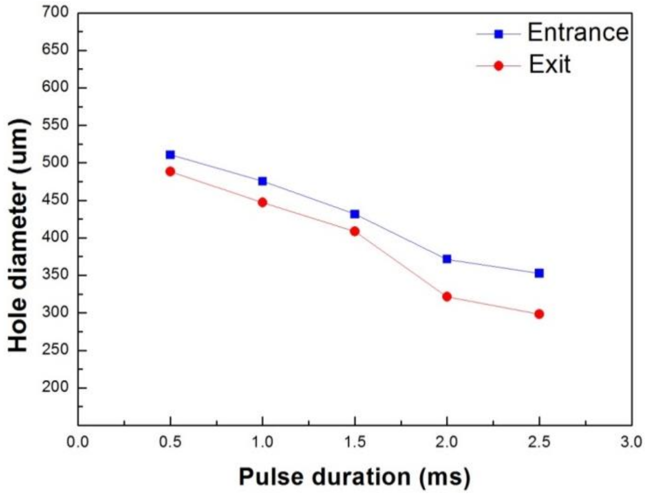

Figure 7: The trend of the Entrance and Exit holes diameter under different pulse duration

Figure 7 shows the curve of the micro-hole inlet and outlet diameters as a function of pulse width. Both the inlet and outlet diameters of the micro-hole gradually decrease with the increase in pulse width. According to the functional relationship between pulse width and peak power, it can be observed that a narrow pulse width corresponds to a higher peak power and spot energy density. The higher vapor pressure inside the micro-hole causes the molten metal to evaporate outside the hole, resulting in effective material removal, which leads to larger inlet and outlet diameters. As the pulse width increases, the energy density decreases, which causes the inlet and outlet diameters of the micro-hole to decrease.

3.2. Percussion of Single-Factor Experiments for Trepanning Drilling

When setting the processing parameters, although the number of pulses is not directly reflected in the machining program for laser trepanning drilling, it is influenced by three processing parameters: pulse width, number of trepanning passes, and trepanning speed[10]. To enable a more scientific and reasonable comparison between the percussion drilling and trepanning drilling methods, the processing parameters for laser trepanning drilling were set based on the parameters used in laser percussion drilling. Experiments were conducted on 5 mm-thick GH4033 material, with the micro-hole machining diameter set to 0.5 mm, to study the intrinsic effects and patterns of pulse energy, pulse width, repetition frequency, beam expansion ratio, number of trepanning passes, and trepanning speed on the quality of trepanning drilling. A schematic diagram of the trepanning trajectory for laser micro-hole processing is shown in Figure 8.

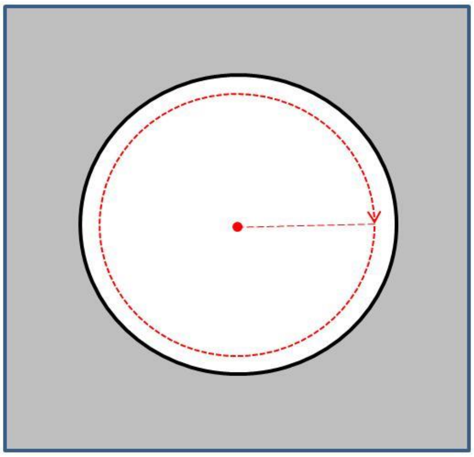

Figure 8: The schematic diagram of path of laser trepanning drilling

3.2.1. Effect of Pulse Energy on Micro-Hole Quality

To investigate the effect of pulse energy on the quality of laser trepanning drilling, the single-factor threshold-improved experimental method was employed. The other processing parameters were set as follows:

Pulse Width (ms)	Repetition Frequency (Hz)	Beam Expander Ratio (times)	Defocus Amount (mm)	Auxiliary Gas Pressure (MPa)	Auxiliary Gas Type
1.0	30	4	5	100	O_2

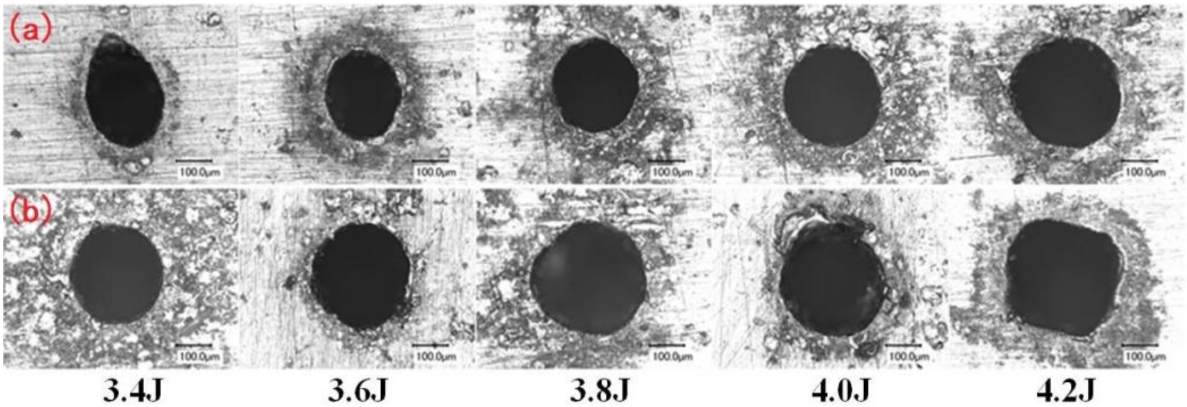

Figure 9: Images of the entrance end and the exit end of the drilled holes under different pulse energy: (a) entrance end (b) exit end

Figure 9(a) and Figure 9(b) show the surface morphology of the micro-hole's entrance and exit under varying pulse energy conditions. As the pulse energy increases, the accumulation of material at the entrance grows, and the exit exhibits more deposits with a larger heat-affected zone. This is primarily because laser trepanning drilling is essentially a specialized form of laser cutting, where the laser beam follows a circular trajectory to remove material layer by layer. The high-pressure assist gas expels molten liquid metal from the micro-hole exit, resulting in more deposits and a larger heat-affected zone at the exit surface[11]. With increasing pulse energy, oxidation and ablation at the material's upper surface become more pronounced, leading to a gradual increase in splatter and molten material around the micro-hole entrance.

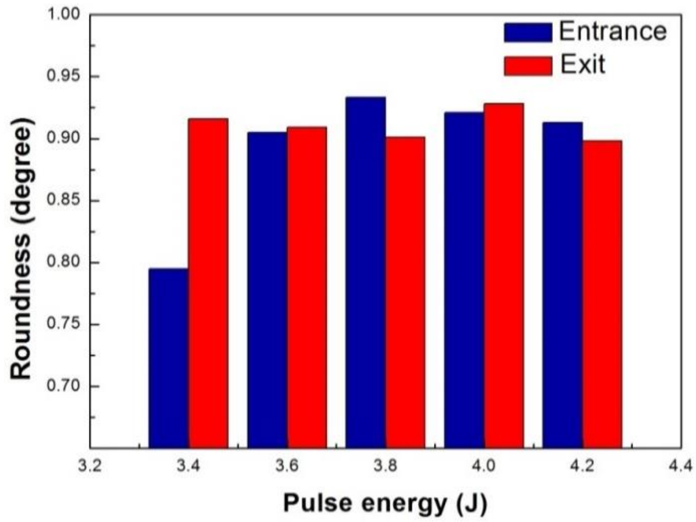

Figure 10: The trend of the Entrance and Exit holes roundness under different pulse energy

Figure 10 shows the circularity of the micro-hole's entrance and exit under varying pulse energy conditions. As pulse energy increases, both entrance and exit circularity show a general upward trend, with exit circularity generally surpassing entrance circularity. This improvement is primarily due to the increase in energy density with higher pulse energy, which enhances the absorption of photon energy by the material. Consequently, the higher vapor pressure generated carries more molten liquid metal out of the hole, improving the material removal capability of the laser and thus enhancing the circularity of the micro-holes. At a pulse energy of 3.8 J, the entrance circularity reaches its best, while the exit circularity is optimized at 4.0 J. Compared to percussion drilling, trepanning drilling achieves better overall circularity at both the entrance and exit of the micro-holes, with the exit circularity consistently outperforming the entrance circularity.

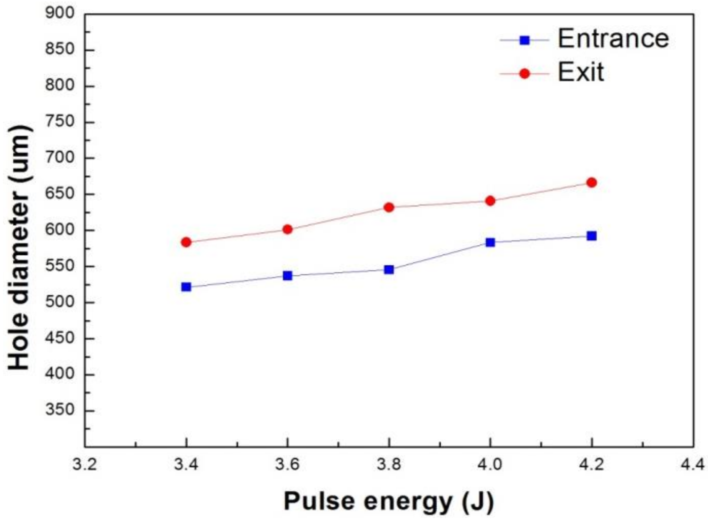

Figure 11: The trend of the Entrance and Exit holes diameter under different pulse energy

Figure 11 shows the variation in entrance and exit diameters of micro-holes as a function of pulse energy. Both the entrance and exit diameters of the micro-holes increase progressively with the rise in pulse energy, which aligns with the trend observed in percussion drilling. This phenomenon is primarily attributed to the Gaussian distribution of laser energy, where the laser beam's intensity is highest at the center, causing molten metal to eject at high speeds from the bottom of the micro-hole[12]. As pulse energy increases, the laser beam follows the designated circular trepanning trajectory, and the edges of the micro-hole along this trajectory absorb the laser energy, converting it into heat and increasing the material removal rate. This explains why the actual hole diameter in trepanning drilling is larger than the pre-set diameter. Compared to percussion drilling, trepanning drilling produces micro-holes where the entrance diameter is smaller than the exit diameter, in contrast to percussion drilling, where the opposite trend is observed.

3.2.2. Effect of Pulse duration on Micro-Hole Quality

To investigate the effect of pulse width on the quality of laser trepanning drilling, a single-factor threshold-improved experimental method was adopted. The other processing parameters were set as follows:

Pulse Width (ms)	Repetition Frequency (Hz)	Beam Expander Ratio (times)	Defocus Amount (mm)	Auxiliary Gas Pressure (MPa)	Auxiliary Gas Type
4.0	30	4	5	100	O_2

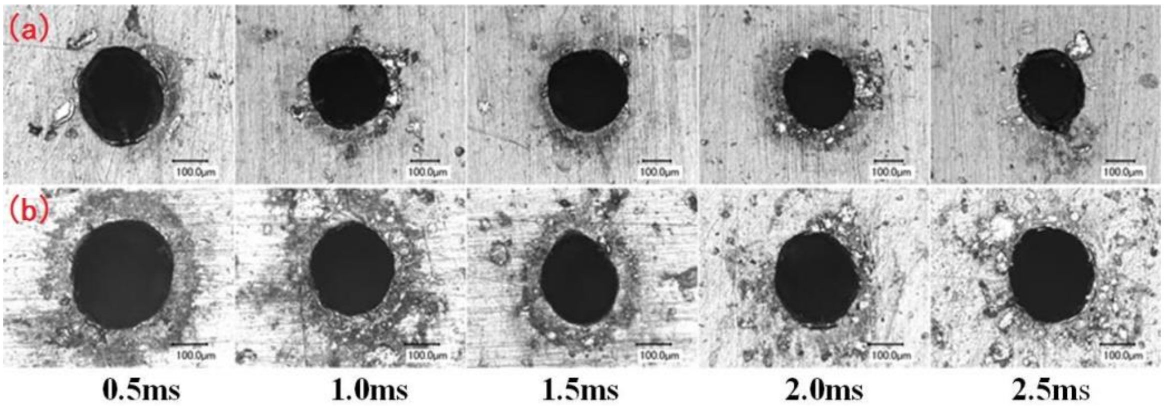

Figure 12: Images of the entrance end and the exit end of the drilled holes under different pulse duration: (a) entrance end (b) exit end

Figure 12(a) and Figure 12(b) show the surface morphology of the micro-hole entrance and exit under varying pulse width conditions. As the pulse width increases, the peak laser power gradually decreases, which leads to a reduction in the energy density of the laser spot on the material surface[13]. This results in a decrease in the oxidation and ablation of the material, reducing the vaporization of the material. Consequently, the amount of molten metal expelled from the hole with the steam also decreases. More material starts to accumulate on the hole entrance surface. Additionally, the heat transfer at the micro-hole exit decreases, leading to faster cooling. As a result, the heat-affected zone at the exit surface decreases with the increase in pulse width.

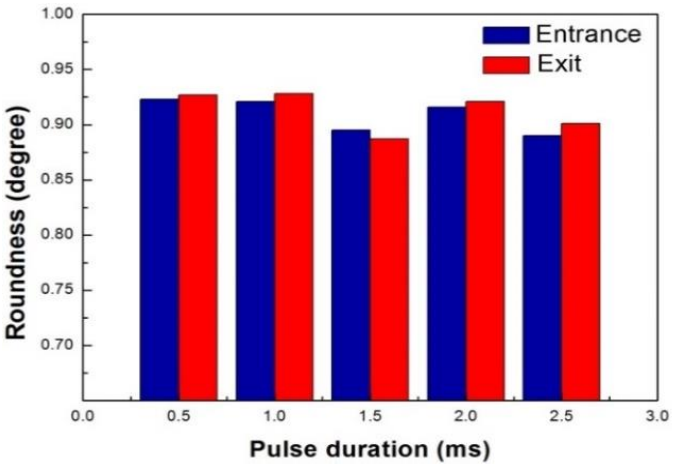

Figure 13: The trend of the Entrance and Exit holes roundness under different pulse duration

Figure 13 shows a bar chart of the entrance and exit roundness of the micro-hole as a function of pulse width. As the pulse width increases, both the entrance and exit roundness of the micro-hole gradually decrease, but the change is not very significant. This trend is similar to the pattern observed in percussion drilling. However, the exit roundness is generally better than the entrance roundness. This is primarily because as the pulse width increases, the peak laser power decreases, which lowers the energy density and reduces the material removal rate. This causes an uneven material removal rate at both the entrance and exit, leading to a reduction in hole roundness. Additionally, in the laser circumferential drilling method, the laser beam follows a circular path around the material surface, and the energy generated is converted into heat that is transferred along the hole wall to the bottom of the micro-hole. This results in better roundness at the exit of the micro-hole.

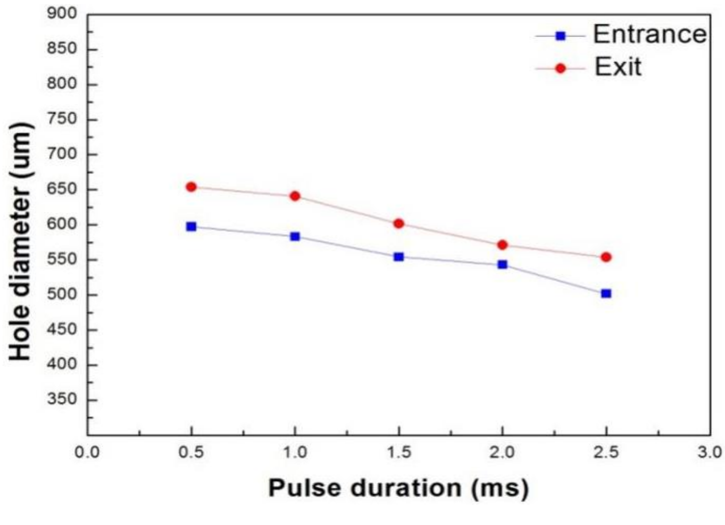

Figure 14: The trend of the Entrance and Exit holes diameter under different pulse duration

Figure 14 shows a curve of the entrance and exit diameters of the micro-hole as a function of pulse width. Both the entrance and exit diameters of the micro-hole gradually decrease as the pulse width increases. This is primarily because when the pulse width is relatively short, the narrow pulse corresponds to higher peak power and spot energy density, leading to a larger material removal at the micro-hole opening[14]. This results in larger entrance and exit diameters. As the pulse width increases, the energy density decreases, and the material undergoes less oxidation and ablation, leading to a reduction in the material removal rate. Consequently, the entrance and exit diameters of the micro-hole gradually decrease.

4. Conclusions

Based on the quality requirements for laser trepanning drilling on the high-temperature alloy GH4033 using Nd:YAG millisecond pulsed lasers, a comparative analysis of experiments numbered 1 to 25 was conducted. Experiments 6 and 17 most closely meet the micro-hole processing quality criteria. Figures 11 and 12 show the SEM images of the micro-hole entry and exit surfaces under the two experimental conditions. A comparison reveals that the micro-hole processed under condition 17 has a smooth surface with fewer deposits and a smaller heat-affected zone[15]. The micro-hole taper is minimal, and the hole edge roundness is better. Therefore, the micro-hole quality processed under the 17th experimental condition is the best.

The superalloy GH4033 was selected as the experimental material, with pulse energy, pulse width, and other process parameters as the research objects. A single-factor threshold improvement experimental method was used to systematically study the effects of various process parameters on the micro-hole processing quality under both percussion and trepanning laser drilling methods[16]. The study compared and analyzed the influence of laser processing parameters on various quality indicators of the micro-holes. Through the analysis of the experimental results, it was found that three processing parameters—pulse energy, beam expansion ratio, and defocus amount—had a significant percussion on the laser micro-hole quality. The optimal parameter combination for laser percussion drilling was: pulse energy of 3.8J, pulse width of 1.0ms, defocus amount of 0mm, repetition frequency of 30Hz, auxiliary gas pressure of 0.35MPa, and beam expansion ratio of 4. The optimal parameter combination for laser trepanning drilling was: pulse energy of 3.6J, pulse width of 2.0ms, repetition frequency of 20Hz, beam expansion ratio of 4, number of cutting rings of 6, and cutting speed of 90mm/min. Additionally, among the 25 experimental conditions for both percussion and trepanning drilling methods, the micro-holes processed under conditions 7 and 17 were the highest in quality for the laser percussion and trepanning drilling methods, respectively.

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References

[1] T.H. Maiman. Stimulated optical radiation in ruby [J]. Nature, 1960, 187(4736): 493-494.

[2] Yu Gang, Yu Heji. Integrated Laser Intelligent Processing Engineering [M]. Metallurgical Industry Press, 2013.

[3] P. Solana, P. Kapadia, J. Dowden, et al. Time dependent ablation and liquid ejection processes during the laser drilling of metal [J]. Optics Communications, 2001, 191(1): 97-112.

[4] N.F. Ren, L.L. Jiang, D. Liu, et al. Comparison of the simulation and experimental of hole characteristics during nanosecond-pulsed laser drilling of thin titanium sheets [J]. International Journal of Advanced Manufacturing Technology, 2015, 76(5-8): 735-743.

[5] W. Koechner. Solid State Laser Engineering [M]. New York: Springer-Verlag, 2006.
[6] F. Gruber. A combination of laser drilling and laser erosion enhances turbine efficiency [J]. Industrial Laser Solutions, 2007, (6): 10-12.
[7] S. Mishra, V. Yadava. Modeling and optimization of laser beam percussion drilling of thin aluminum sheet [J]. Optics & Laser Technology, 2013, 48: 461-474.
[8] M.M. Hanon, E. Akman, B.G. Oztoprak, et al. Experimental and theoretical investigation of the drilling of alumina ceramic using Nd:YAG pulsed laser [J]. Optics & Laser Technology, 2012, 44: 913-922.
[9] H. Kogelnik, T. Li. Laser beams and resonators [J]. Applied Physics, 1996, 5(10): 1550.
[10] R. Poprawe. Laser Manufacturing Processes [M]. Translated by Zhang Dongyun. Beijing: Tsinghua University Press, 2008.
[11] William M. Steen. Laser Material Processing (3rd Edition) [M]. Translated by Meng Daqiao, Zhang Youshou, He Jianjun, et al. Mechanical Industry Press, 2012.
[12] Shao Dan, Hu Bing, Zheng Qiguang. Advanced Laser Manufacturing Technologies and Equipment Integration [M]. Science Press, 2009.
[13] Yang Qing, Wan Xingzi, Liu Xingxing. Research on the development strategy of the laser industry in "China's Optics Valley" [J]. Science & Technology and Industry, 2015 (8): 24-28.
[14] D. Abidou, N. Yusoff, N. Nazri, et al. Numerical simulation of metal removal in laser drilling using symmetric smoothed particle hydrodynamics [J]. Precision Engineering, 2017, 49: 69-77.
[15] Liu Xunhuan, Sun Shufeng, Zhang Fengyun, et al. Research on the process and quality of laser micro-hole machining [J]. Laser Journal, 2023, 44(07): 9-20.
[16] Zou Mengmeng, Zhang Wei, Li Jinchao, et al. Experimental study on nanosecond laser micro-hole machining assisted by additional electric field [J]. Modern Manufacturing Engineering, 2021 (11): 104-108.