International Journal of Mechanical and Electrical Engineering

ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 5, Number 2, Year 2025
DOI: https://doi.org/10.62051/ijmee.v5n2.02
Journal homepage: https://wepub.org/index.php/IJMEE/index

Experimental Study of Water-Assisted Nanosecond Laser Processing of Microvias in IN718 High-Temperature Alloy

Gongliang Chen [1, 2], Shufeng Sun [1, 2, *], Tao Wei [1, 2], Xuri Li [1, 2], Junbao Li [1, 2]

[1] Discipline innovation and Wisdom Introduction Base of High-end Laser Intelligent Manufacturing Technology and Equipment (No. D21017), Qingdao University of Technology, Qingdao 266525, China

[2] School of Qingdao Technological University, Qingdao 266520, China

* Corresponding Author: Shufeng Sun (Email: sunshufeng@qut.edu.cn)

ABSTRACT

In this paper, the optimal parameters of the laser concentric circle (from outside to inside) scanning processing method are investigated by infrared nanosecond laser perforation of nickel-based high-temperature alloy (IN718) in air. Based on the optimal parameters, the effects of the backwater assisted and different graded scanning optimization on the morphology of microvias are investigated, and the advantages of the optimized scanning method are summarized. The results show that the laser energy distribution on the material surface can be adjusted by scanning path graded optimization in air to eliminate the negative effect of excessive heat accumulation in the center of the scanning path to improve the taper of the microporous holes, and the combined effect of water-assisted water evaporation and boiling scouring, water buoyancy, and impact force generated by the collapse of bubbles can reduce the scope of the heat-affected zone and reduce the melt buildup and spraying of the microporous holes at the inlet and outlet of the microporous holes. The combined effect of water buoyancy and the impact force generated when the bubble collapses can reduce the scope of the heat-affected zone and minimize the accumulation of melt and spatter at the inlet and outlet of the microvia. It provides a reference for water-assisted infrared nanosecond laser processing and its optimization process.

KEYWORDS

Nanosecond Laser; Microporous; Water-assisted; Graded Optimization; IN718 High-temperature Alloy.

1. INTRODUCTION

In recent years, laser processing has become an effective microporous manufacturing method by virtue of its unique advantages such as high precision, high efficiency, non-pollution, and wide range of applied materials [1]. And nickel-based high-temperature alloy has become the main material for manufacturing turbine blades due to its creep resistance, strength, fatigue resistance, wear and corrosion resistance at high temperature [2]. A lot of research has been done on laser drilling on nickel-based high-temperature alloys by previous researchers, and pulsed lasers used for microporous processing of nickel-based high-temperature alloys are broadly categorized into millisecond, nanosecond, picosecond, and femtosecond lasers according to the pulse width. Nanosecond lasers have high peak power and small spot size, which are suitable for smaller size and high precision microvia processing, and have the advantages of low cost, high efficiency and good flexibility [3], which are more suitable for industrial production. However, nanosecond laser processing produces defects such as thermal damage [4] and recast layer [5], in order to reduce these defects and improve the processing quality, many scholars use a variety of processing methods such as water-assisted, magnetic field-assisted, ultrasonic-assisted, chemical-liquid-assisted, and multi-physical field coupling, especially water-assisted, which is widely used by people because of its affordable characteristics, and the water-assisted laser drilling helps to improve the quality of the microvia, Ren [6] et al. investigated water film and water-based assisted femtosecond laser for microporous processing on nickel-based high temperature alloys, and the results showed that both methods can improve the quality of microporous holes, and the taper and inner wall roughness can be reduced by 18.04% and 85.43%, respectively. In this paper, nanosecond laser processing of IN718 high-temperature alloy micropores using concentric circle scanning (from outside to inside) perforation in air and water-assisted with graded scanning strategy was investigated, the surface morphology and taper of the micropores processed in the two conditions were comparatively investigated, and the mechanism of optimization of micropores by water-assisted and graded scanning strategy was analyzed, and the microporous morphology and quality of the processed micropores were verified through the comparative analysis of water-assisted and The characteristics and advantages of water-assisted and graded scanning strategies were verified through the comparative analysis of the microporous morphology and quality.

2. EXPERIMENTAL DESIGN AND SETUP

2.1. Experimental Equipment

Nanosecond laser processing equipment is composed of nanosecond laser, scanning galvanometer module, computer control system, dust collection system, worktable, water cooler, nanosecond pulsed laser processing system schematic diagram shown in Figure 1.

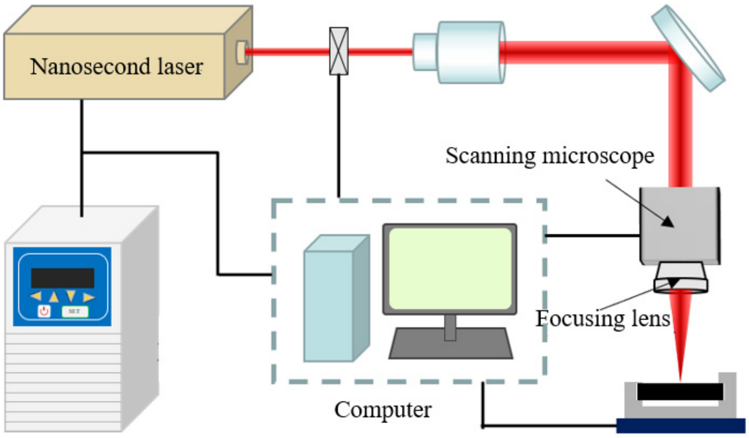

Fig 1. Schematic diagram of nanosecond laser processing system

2.2. Characterization Method

The microporous morphology, microporous exit roundness, microporous taper and surface morphology were characterized. Where the microporous taper (TA) was calculated as.

$$TA = arctan\frac{D_i - D_o}{2T} \tag{1}$$

Where TA denotes the microporous taper angle, denotes the diameter of the microporous inlet, denotes the diameter of the microporous outlet, and T denotes the sample thickness.

Hole circularity (HC) is calculated on the long and short axes, and when HC=100% it means that the orifice is circular. The pore roundness is calculated as:

$$HC = \frac{D_{min}}{D_{max}} \times 100\% \tag{2}$$

where HC denotes microporous hole circularity, indicates the minimum pore size, and indicates the maximum pore size.

3. DISCUSSION AND ANALYSIS OF EXPERIMENTAL RESULTS

3.1. Effect of Machining Parameters on Microporous Morphology

In this section, the infrared nanosecond laser is used to punch IN718 in air by concentric circle scanning (from the outside to the inside) filling method for the test, and the process parameters of infrared nanosecond laser processing of IN718 are optimized by adjusting the laser processing parameters and analyzing the influence of laser processing parameters on the micro-hole morphology and dimensions.

3.1.1. Effect of Laser Power on Microporous Morphology

Laser power is an important factor affecting the processing effect, the degree of material removal and the shape and size of the processed microporous directly affected by it, according to the study of laser ablation intensity on the shape of the ablation pit, under the premise of considering the processing efficiency, the laser power is set to the value of the interval in the range of 120 W-200 W, a group of tests at intervals of 20 W, and each group of tests is processed three times by using the same parameters, and take the average value, laser The laser frequency is set at 100 kHz, the scanning speed is set at 40 mm/s, and the number of scans is set at 100 times.Microporous size characteristics as shown in Figure 2, with the increase in laser power, the microporous inlet and microporous outlet diameter presents a gently rising trend, but are greater than the maximum diameter of the circle set, which is compared with the group's previous research on low-power laser processing of microporous, presented by the microporous inlet and microporous outlet diameter of the upward trend of the obvious slowdown in the analysis of nickel-based high-temperature alloys have a high-temperature performance, when the laser acts on the material surface, the material absorbs laser energy temperature rise, through heat conduction in space to the surrounding heat transfer, when the heat accumulation reaches the melting temperature of the surrounding material, molten material is recoil pressure away to achieve the removal, with the increase in laser power, after reaching a certain value, the through-hole in the processing of the early formation of the majority of the subsequent laser energy is directly through the material or reflected out of the processing range, can not participate in the Material removal, so in a short period of time the material transfer heat is limited, so only a gentle upward trend, of course, the increase in laser power to intensify the reaction of the laser interaction with the material, the rapid removal of large amounts of molten material also take away part of the heat. In addition, it can be found that the taper of the micro-hole with the increase in laser power first decreases rapidly in more than 140 W tends to flatten out, it is analyzed that with the removal of the material, the surface of the laser interaction with the material is gradually away from the focal plane, the laser beam dispersal energy density decreases resulting in an increase in the taper of the micro-hole, and then the increase of the laser power narrows down the effect, resulting in an increase in micro-hole exit diameter, and the rapid formation of a high-laser-power through-hole, the laser interacts more significantly with the material in the lower part of the micro-hole, leading to an increase in the micro-hole exit diameter tends to be greater than the micro-hole inlet, and subsequently the micro-hole taper decreases. As shown in Fig. 3, at the same processing moment high laser power removes a larger volume of material, the melt pool is deeper, the laser beam is more dispersed, and the material exists and is removed in a more molten state, resulting in more melt buildup at the microvia opening. Therefore, choosing 140 W is more beneficial to the dimensional accuracy and morphological characteristics of the microvia.

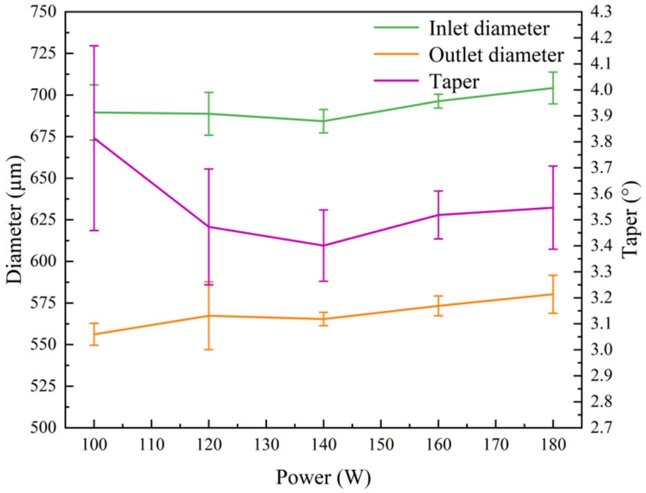

Fig 2. Influence of laser power on the diameter and taper of the micro-hole

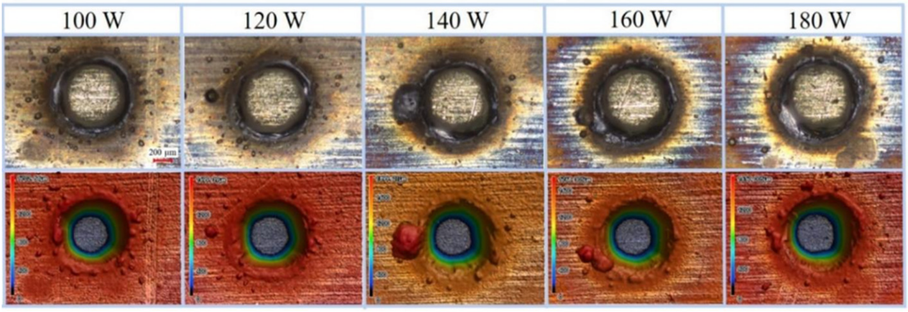

Fig 3. Influence of laser power on micropore inlet morphology

3.1.2. Effect of the Number of Machining Times on the Morphology of Micropores

The good heat resistance of nickel-based high-temperature alloys makes the infrared nanosecond laser not able to obtain the expected microvia after a single processing, and the above parameterized tests at high scanning times, the material ablation is serious, the heat-affected zone is larger, and it is easy to cause energy waste, so the appropriate scanning times are important factors to obtain high-quality microvia under consideration of efficiency. In this subsection, the test is set with laser power of 140 W, laser pulse repetition frequency of 100 kHz, scanning speed of 40 mm/s, the number of processing times is set as 10 times-50 times, and every interval of 10 times is a group of tests, and each group of tests is carried out for 3 times, and the average value is taken.

The results are shown in Fig. 4 and Fig. 5, when the number of scans is 10 times, a large amount of recast layer is attached to the inner wall of the micro-hole, the material at the exit of the micro-hole has not been completely removed, and the shape profile of the exit of the micro-hole is uneven, and with the increase of the number of scans, the exit of the micro-hole has been improved, and the diameters of the inlet of the micro-hole and the exit of the micro-hole have been gradually increased, but the increase is small. In the scanning number of 10 times and 50 times, the microporous inlet appeared larger melt accumulation, analysis that in the scanning number of 10 times, the laser on the lower part of the microporous processing time is shorter, the material continues to absorb the laser energy after the melt vaporization to produce recoil pressure process is shorter, resulting in the melt discharge difficulties, insufficient power, in the microporous inlet produced by the accumulation of molten material. When the number of scans is 50 times, the melt pool volume increases under the influence of heat accumulation, and a large amount of molten material adheres to the inlet of the microporous hole under the combined effect of recoil pressure and its own gravity and viscous force, forming the accumulation of molten material. In addition, when the number of scans is 30 times when the microporous taper is minimized, so the choice of the number of scans is 30 times when the microporous can be obtained with better quality.

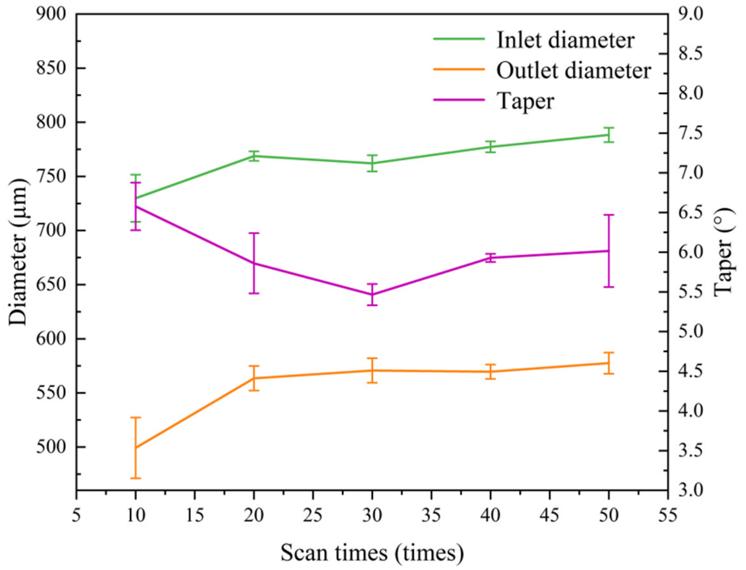

Fig 4. Influence of scanning times on diameter and taper of micropore orifices

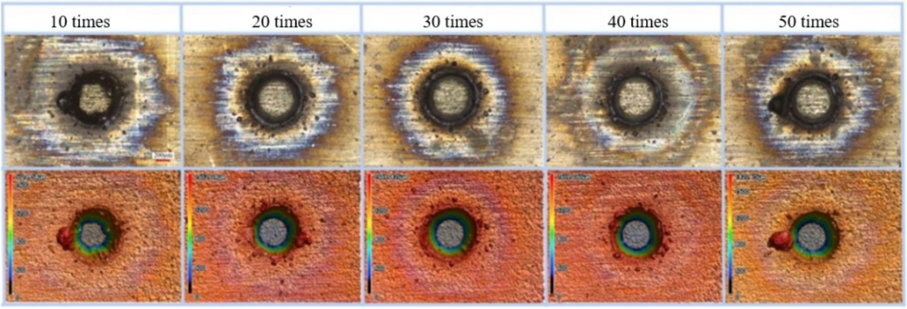

Fig 5. Influence of scanning times on micropore inlet morphology

3.2. Effect of Water-assisted Laser Hierarchical Scanning Optimization Strategy on Microporous Morphology

Infrared nanosecond laser processing IN718 high-temperature alloy, through the optimization of parameters cannot be further achieved by high-quality microporous processing, through the above study found that the scanning process is often easy to accumulate a large amount of heat inside the scanning path resulting in the removal of the "bowl" shape phenomenon, and at the same time the phenomenon for the next beam of the laser will produce Uneven distribution of energy and reflection, the process becomes complex and uncontrollable, resulting in melt spattering and microporous taper, so this subsection through the scanning path optimization to adjust the distribution of laser energy to the surface of the material, in order to eliminate the negative impact of the scanning path in the center part of the corresponding excessive heat accumulation, at the same time, through the backwater method to further reduce the nanosecond laser processing of the thermal defects generated. The experimental parameters refer to the settings of parameter optimization, and the laser power is set to

140 W, the laser pulse repetition frequency is set to 100 kHz, the scanning speed is 40 mm/s, and the number of scans is 30 times. The path optimization method is shown in Fig. 10, and the scanning paths are set to be graded, each level corresponds to a different color, and the maximum diameter of the circle is 600 µm, Fig. 6 (a) shows that five adjacent scanning paths in the outermost circle are set to be the first level, with an interval of 30 µm, and the rest of the scanning paths in the inner circle are set to be the first level, with an interval of 40 µm; Fig. 6 (b) shows that five adjacent scanning paths in the outermost circle are set to be the first level, with an interval of 20 µm, and the rest of the inner circle are set to be the first level, with an interval of 20 µm. m, and the remaining inner circle adjacent scanning paths are one level with 40 µm spacing; Fig. 6 (c) shows setting the outermost circle 5 adjacent scanning paths as one level with 20 µm spacing, and the remaining inner circle adjacent scanning paths as one level with 30 µm spacing; Fig. 6 (d) shows setting the outermost circle 3 adjacent scanning paths as one level with 20 µm spacing, the middle layer 4 adjacent scanning paths as one level with 30 µm spacing , and the remaining inner layer with one level of adjacent scanning paths spaced at 40 µm. The following descriptions in the text represent the path optimization approach as shown in Fig. 6 (a), (b), (c), and (d) with (a), (b), (c), and (d), respectively.

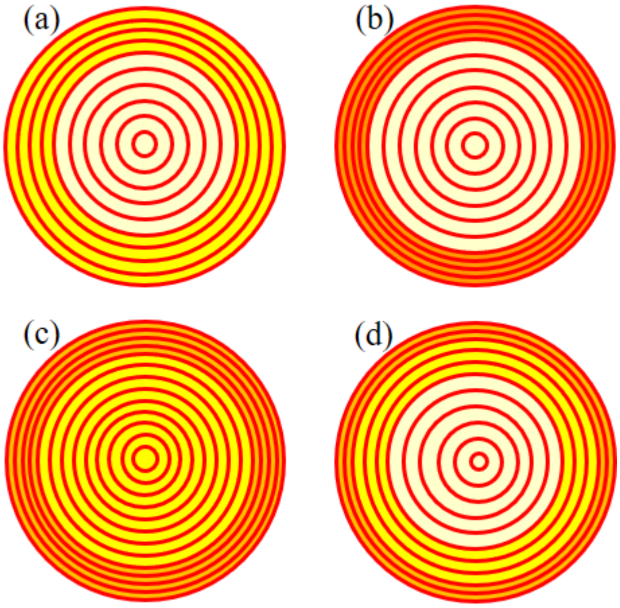

Fig 6. Hierarchical scan optimization strategy

The results are shown in Fig. 7 and Table 1. When processing in air, the scanning path graded optimization modes (a), (b), (c), and (d) have spatter generation at the microhole inlet, but there is no obvious accumulation of large amounts of molten material, and at the microhole outlet, the scanning path graded optimization modes (a) and (d) do not see obvious spatter generation, and the scanning path graded optimization modes (b) and (c) show a small amount of molten material spatter at the microhole outlet, which is analyzed to be unable to enhance the average laser intensity of the edge processing, at this time, it is still not possible to enhance the average laser intensity of the scanning path graded optimization modes (b) and (c). A small amount of molten material spattering occurs at the exit of the micro-hole, and the analysis suggests that the scanning path classification optimization methods (b) and (c) have enhanced the average laser intensity of the edge processing of the micro-hole, and at this time, it is still impossible to avoid the ablation of the “bowl” shape, and the laser reflection to the bottom accelerates the formation of the through-hole during the processing of the edge of the micro-hole, and the exit of the micro-hole has just opened up with a small hole, and the molten material on the sidewall is not visible. When the exit of the micro-hole is just opened, the opening is small, and there is more molten material on the side wall, and a large amount of molten material is sprayed out and adheres to the surface, whereas the scanning path hierarchical optimization modes (a) and (d) have a smaller average laser intensity during the processing of the micro-hole, and there is less heat accumulation in the inner layer, which avoids a large-volume spattering of the molten material. The heat-affected zones at the microhole inlet and microhole outlet are improved when processing by the backwash method, especially the spattering and heat-affected zones at the microhole outlet are significantly improved, whereas the spattering of molten material at the microhole outlet still exists, which is due to the fact that the water is not involved in the processing of microholes when the microholes are not formed into a through-hole when assisted by the backwash method, and the spattering of the molten material at the microhole inlet before the microholes are formed into a through-hole, and at the time of the formation of the through-hole, the Molten material in the backwash pressure, water evaporation boiling scouring effect, water buoyancy and bubble collapse under the combined effect of the impact generated by the microporous outlet. However, the backwater method to assist the micro-hole exit relative to the air processing becomes irregular, analysis suggests that the phenomenon is attributable to two aspects, one is the role of water laser energy attenuation and beam changes, relative to the ultraviolet and visible laser, water on the infrared laser absorption is the highest, the formation of the through-hole, the water rushes into the interior of the micro-hole, absorbing the laser energy vaporization and evaporation, taking away some of the laser energy and micro-hole inner wall heat In addition, material removal produced by the smile vapor particles and water influx, under the action of buoyancy produced by the larger particles of molten material particles distributed in the aqueous solution to continue to absorb the laser energy caused by the loss of laser energy, resulting in the reduction of laser energy for material removal at the exit of the micro-aperture, compared to the removal of air is not enough, in addition, the water and the distribution of particle clusters in the water leads to refraction and reflection of laser light, which increases the irregularity of material removal. In addition, water and particle clusters distributed in the water cause refraction and reflection of the laser light, which aggravates the irregularity of material removal. The second is the scouring of the vacuole collapse and the disturbance of the fluid when the water boils. The high-pressure jet generated by the collapse of the vacuole under the action of the laser and the scouring force of the water when it boils violently also increase the irregularity of the microporous exit when assisted by the backwater method. In addition, as shown in the table, the scanning path hierarchical optimization method (c) minimizes the taper of the micropores processed in air, whereas when processed by the backwater method, the taper of the micropores obtained increases compared to that in air due to the decrease in the diameter of the micropores' exit.

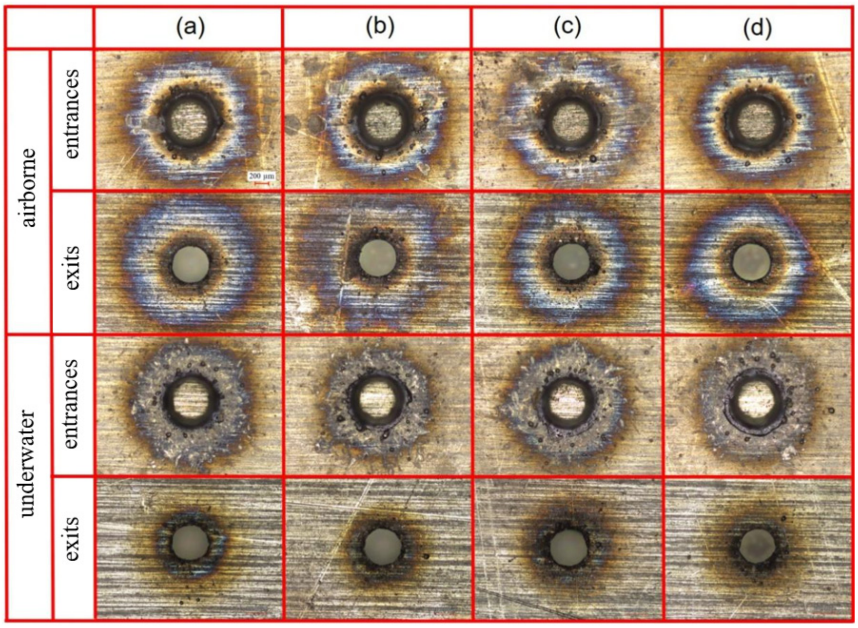

Fig 7. Micropore morphology of the optimization strategy of back-water assisted laser fractional scanning

Table 1. Effects of optimization strategies on micropore size characteristics

Typology		Inlet Diameter (μm)	Outlet Diameter (μm)	Taper (°)
Air	(a)	764.206-789.924	561.438-571.335	5.7891-6.2374
	(b)	803.353-833.875	579.523-582.290	6.3857-7.1697
	(c)	750.007-761.869	572.739-574.053	5.0651-5.3648
	(d)	791.890-830.751	573.134-593.788	6.2421-6.7570
Water	(a)	812.535-825.989	567.041-573.620	6.9979-71918
	(b)	820.535-829.530	557.298-579.863	7.4981-7.8547
	(c)	776.744-790.905	539.806-582.749	5.9418-6.7563
	(d)	809.852-813.305	550.564-554.996	7.3593-7.3869

4. CONCLUSION

In this chapter, the micro-hole processing of nickel-based high-temperature alloy (IN718) by infrared nanosecond laser has been tested, and the laser processing parameters of infrared nanosecond laser perforation of nickel-based high-temperature alloy (IN718) in air have been optimized, and the scanning path hierarchical optimization strategy and the assistance of the backwater method have been used to optimize the micro-hole processing by infrared nanosecond laser. The experimental results show that when the laser is scanning and processing in concentric circles (from the outside to the inside), higher quality microvias can be obtained at a laser repetition frequency of 100 kHz, a scanning speed of 40 mm/s, a laser power of 140 W, and a number of scans of 30 times. Microvias with a smaller taper of 5.0651°-5.3648° can be obtained by the scanning path hierarchical optimization method (c) in air. However, there is still a small amount of melt buildup and spatter present at the microporous inlet and microporous outlet, which can be improved by water-assisted, but the microporous outlet becomes irregular and the taper increases with water-assisted, which is related to the attenuation of the laser energy, reflection and refraction of the laser beam, the washout from the collapse of the vacuole, and the fluid perturbation caused by the boiling of water. In this paper, a strategy of water-assisted and graded scanning optimization is used to improve the quality of microvia processing, which provides a reference for infrared nanosecond laser processing and its optimization process.

REFERENCES

[1] WANG H J, YANG T. A review on laser drilling and cutting of silicon[J]. Journal of the European Ceramic Society, 2021, 41(10), 4997-5015.

[2] HOSSEINI E, POPOVICH V A. A review of mechanical properties of additively manufactured Inconel 718[J]. Additive Manufacturing, 2019, 30, 100877.

[3] ZHANG H, DI J, ZHOU M, et al. A comparison in laser precision drilling of stainless steel 304 with nanosecond and picosecond laser pulses[J]. Chinese Journal of Mechanical Engineering, 2014, 27(5), 972-977.

[4] KEERTHI P P S, SREENIVASA Rao M. Numerical simulation of laser micro drilling of polymethyl Methacrylate[J]. Materials Today: Proceedings, 2022, 67, 1085-1089.

[5] LIU C, ZHANG X, WANG G, et al. New ablation evolution behaviors in micro-hole drilling of 2.5D Cf/SiC composites with millisecond laser[J]. Ceramics International, 2021, 47(21), 29670-29680.

[6] REN N F, YANG H Y. Influence of different water-assisted methods on femtosecond laser layered-ring trepanning in superalloy. Infrared and Laser Engineering. 2022, 51(12), 20220143-1.