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Optimization of Microhole Morphology in Electrolytic Abrasive Jet Machining

Jiale Cheng[1,2]. Shufeng Sun[1,2*]. Jin Wang[1,2]. Fengyun Zhang[1,2]. Yaofei Ma[1,2]. Tao Wei[1,2]. Junbao Li[1,2] and Pingping Wang[1,2]
[1]Discipline Innovation and Wisdom Introduction Base of High-end Laser Intelligent Manufacturing Technology and Equipment, school of Mechanical and Automotive Engineering, Qingdao University of Technology, Qingdao 266520, China
[2]Key Laboratory of High-end Laser Manufacturing Technology and Equipment of Shandong Province, school of Mechanical and Auto-motive Engineering, Qingdao University of Technology, Qingdao 266520, China
Email: sunshufeng@qut.edu.cn

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Abstract

To address issues such as thick recast layers, high pore wall roughness, and dif-ficult-to-control geometric accuracy during micro-hole machining of nick-el-based high-temperature alloy 718, a laser-electrochemical hybrid processing method assisted by abrasive jet is proposed. By establishing a synergistic "electrolyte abrasive jet-nanosecond laser" processing system, combined with multiphysics coupling simulation and experimentation, this study system-atically investigates the influence mechanisms of parameters such as jet veloci-ty, jet angle, abrasive particle size, and voltage on microhole roundness, taper, wall roughness, surface morphology, and recast layer formation. Results indi-cate that moderate jet and electrical parameters significantly enhance orifice morphology and wall quality while effectively suppressing microcracks and re-cast layers. Orthogonal experiments optimized the following optimal process parameters: jet velocity 8 m/s, jet angle 60°, abrasive particle size 15 μm, voltage 15 V, and current 3 A. Under these parameters, the micro-hole round-ness, surface morphology, and taper achieved optimal values, while hole wall roughness was significantly reduced and surface quality markedly improved.

Keywords

Nanosecond laser; Laser drilling; Nickel-based alloy; Abrasive jet; Inconel 718

1. Introduction

In cutting-edge equipment manufacturing sectors such as aerospace and energy power generation[1],the 718 nickel-based high-temperature alloy has become the material of choice for core components like turbine blade air film cooling holes and combustion chamber fuel injection micro-holes due to its exceptional high-temperature strength[2],outstanding oxidation resistance[3],and thermal fa-tigue properties[4].Take aircraft engine turbine blades as an example:the densely packed micrometer-scale air film holes on their surfaces are crucial for achieving efficient cooling[5].By introducing cold air to form an air film barrier[6], these holes can reduce blade operating temperatures by 150-300° C[7], directly impacting engine thrust-to-weight ratio enhancement and fuel efficiency optimization.However[8],the material's high hardness (45-50 HRC) and complex microstructure containing strengthening phases like Nb and Mo pose severe challenges for micro-hole machining[9]. Traditional mechanical processing is inefficient and struggles to achieve the required hole wall roughness[10],failing to meet aerospace demands for dimensional accuracy and surface quality[11].

In recent years,laser-electrochemical hybrid processing technology has demonstrated potential in enhancing machining efficiency and surface quality through the synergistic effects of laser thermal ablation and electrochemical dissolution[12].However, laser thermal effects readily form recast layers, while pure electrochemical dissolution has limited capability to remove high-hardness strengthening phases,making it difficult to balance efficiency and quality[13].The introduction of jet-assisted technology offers a novel approach to overcoming this challenge:a high-speed electrolyte jet can promptly flush debris and molten material from the laser-affected zone, reducing recast layer formation, while its conductive properties establish an electrochemical circuit,enhancing dissolution and refinement of the hole wall[14].Additionally, the electric field can regulate cavitation pulsation through dielectrophoresis, optimizing energy transfer efficiency,while the cooling effect of the liquid minimizes the heat-affected zone.This paper summarizes the process of microhole processing in Inconel 718 using nanosecond laser-assisted electrolyte abrasive jet technology[15].

2. Experimental Details

The experimental material used in this study is the nickel-based high-temperature alloy Inconel 718.To meet experimental requirements,the material was cut into 1mm-thick sheet specimens using precision wire-cutting technology.Prior to testing, the material surfaces were ground and polished using a metallographic grinding machine,then cleaned in an ultrasonic cleaner to remove surface oxides and impurities,ensuring experimental accuracy.

The experiments employed direct current (DC) for testing.A nozzle with a diameter of 0.6 mm was positioned 10 mm above the workpiece,with the jet angle set at 60° relative to the workpiece surface. The selected abrasive was aluminum oxide (Al_2O_3).The electrolyte consisted of disodium ethylenediaminetetraacetate (EDTA)+sodium citrate+tartaric acid (with nitric acid to adjust pH)+water.The experimental setup for electrolyte jet-assisted nanosecond laser microhole processing is shown in Figure 1,primarily comprising a nanosecond laser, water tank, water pump, copper nozzle, return flow pipe, and DC power supply.

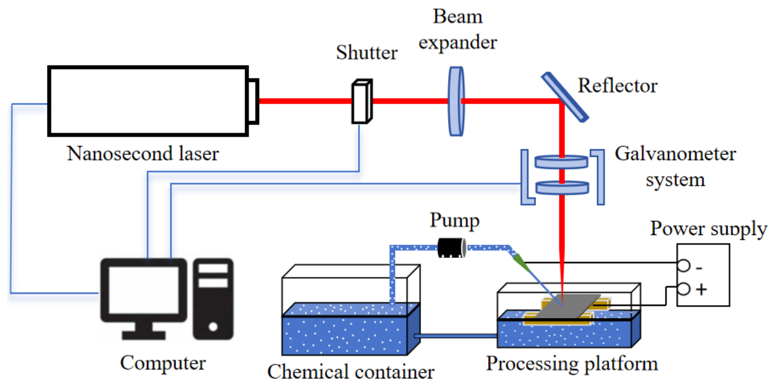

Fig 1. Shows the experimental process diagram

At room temperature, a passivation film of NiO and Cr_2O_3 forms on the Inconel 718 surface, acting as a barrier to further reactions. However, H^+ ions (provided by the ionization of nitric acid) in the acidic electrolyte undergo a double displacement reaction with NiO and Cr_2O_3, breaking down the passivation film and releasing Ni^{2+} and Cr^{3+} ions. The reaction equations are:

$$NiO + 2H^+ \rightarrow Ni^{2+} + H_2O \quad (1)$$

$$Cr_2O_3+6H^+\rightarrow 2Cr^{3+}+3H_2O \quad (2)$$

During laser processing, the high-temperature environment combined with acidic electrolytes reacts with the base metal elements, triggering various chemical reactions that produce substances such as nitrogen monoxide gas and water. The specific chemical reaction equations are as follows:

$$3Ni+2NO_3^-+8H^+3Ni^{2+}+2NO\uparrow+4H_2O \quad (3)$$

$$3Cr2++NO_3^-+4H^+3Cr^{3+}+NO\uparrow+2H_2O \quad (4)$$

$$Fe+NO_3^-+4H^+Fe^{3+}+NO\uparrow+2H_2O \quad (5)$$

$$Cr_2O_3+6H^++2Cit^{3-}2[CrCit]^-+3H_2O \quad (6)$$

After microporous processing, wear safety gloves to rinse residual acidic chemicals from the material surface with clean water. Then place the sample in an alcohol beaker and clean it in an ultrasonic cleaner for 5 minutes. After drying with a hair dryer, perform microporous morphology measurements under a confocal microscope.

3. Experimental Principle and Results

The material removal process in microhole laser processing assisted by electrolyte abrasive jets can be divided into three stages. The first stage involves laser preheating and initial jet interaction (Figure 2a). The laser beam penetrates the jet to preheat the workpiece surface, forming a thin molten pool with minimal thermal material removal. Simultaneously, the electrolyte jet impacts the processing zone: the electrolyte solution cools the molten pool to stabilize temperature; while inducing mild anodic dissolution within the electrolytic circuit. Abrasive particles lightly cut the softened layer, aiding product removal. This synergistic action achieves low-loss removal, laying the foundation for subsequent processing.

The second stage involves energy escalation and multi-effect coupling (Figure 2b). As laser energy accumulates, material rapidly melts and partially vaporizes, with plasma breaching the liquid film to form a cavitation channel. Laser thermal effects dominate melting and evaporation; electrolytic reactions intensify, accelerating dissolution; abrasive particles violently impact the channel walls, hastening product ejection. The plasma within the cavitation channel maintains high temperature and pressure, exerting thermomechanical coupling on the underlying material to promote material breakdown.

The third stage involves channel contraction and fine-tuning modification (Fig. 2c). The jet exhibits bidirectional flow: one stream erodes outward, clearing spatter from the hole opening; another stream infiltrates the hole, generating bubbles under residual heat. These bubbles implode against the hole wall, stripping the recast layer. The electrolyte also reacts chemically with the hole wall, producing easily detachable products. Residual abrasive particles perform secondary grinding, refining the hole wall to ultimately achieve a microhole with high surface quality and minimal recast layer.

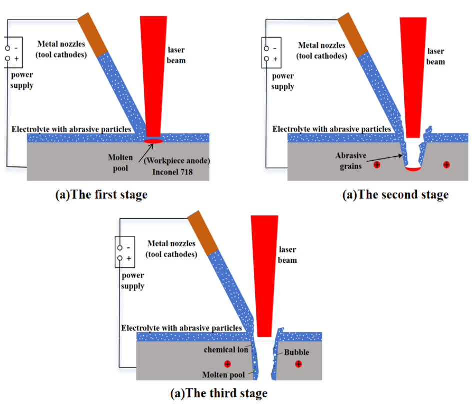

Figure 2. Process of Microhole Treatment Using Electrolyte Abrasive Jet

3.1. Effect of Abrasive Particle Size on Micro-Pore Morphology and Pore Wall Roughness

Abrasive particle size is one of the key parameters affecting microhole machining quality. This study investigates the influence of particle size on microhole characteristics. Experimental parameters were set as follows: processing size 500 μm, micron-grade aluminum oxide powder with particle sizes of 5 μm, 10 μm, 15 μm, and 20 μm, and laser parameters: 160 W power, 50 kHz repetition rate, scanning speed of 150 mm/s, 10 ms pulse delay, and 150 processing cycles.

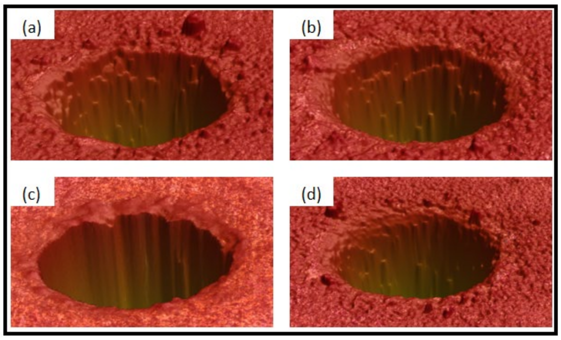

Figure 3. Three-dimensional microporous morphology of different abrasive particle sizes: (a) 5 μm, (b) 10 μm, (c) 15 μm, (d) 20 μm

As shown in Figure 3, the surface morphology of the micro-pores exhibits significant improvement with the addition of abrasive particles. The 15-micron particles demonstrate the most effective optimization of the recast layer, indicating a clear relationship between inlet morphology and particle size. Smaller abrasive particles possess relatively lower mass and inertia. When propelled by the jet stream, they exert weaker impact forces on the workpiece material, resulting in insufficient cutting and grinding action. This leads to relatively lower material removal rates. Although the laser can melt and vaporize the material, the absence of adequate abrasive assistance for removal prevents timely and effective clearance of molten material from the processing zone. Consequently, portions of the molten material may re-solidify on the pore walls and pore mouth. As abrasive particle size increases, their mass and inertia grow. Under jet impact, they can exert greater impact and cutting forces on the workpiece material, more effectively removing the material melted and vaporized by the laser. These particles can more rapidly clear molten material from the processing area, reducing re-solidification. This allows material at the microhole inlet to be more thoroughly removed, thereby promoting an increase in both the inlet and outlet diameters of the microhole.

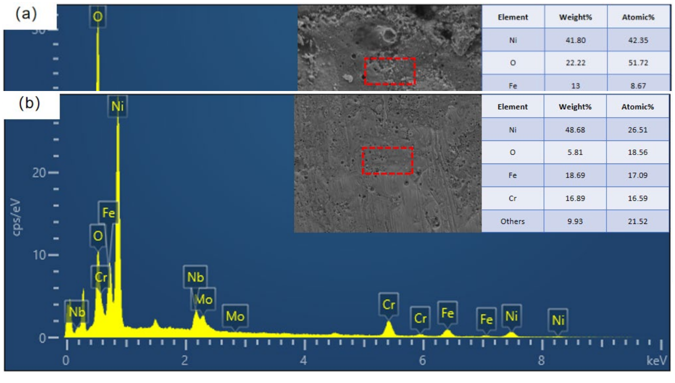

Figure 4. Energy-dispersive X-ray spectroscopy (EDS) patterns of microhole sidewalls processed in air and under electrolytic abrasive jet machining (a) air machining (b) combined machining.

Figure 4 shows the EDS analysis of micro-holes processed under air and electrolyte abrasive jet-assisted machining. Elemental analysis was performed at the same location on the hole wall, revealing significant variations in elemental content, particularly for oxygen. The oxygen content in air-processed samples was approximately 51.72%, indicating that the material readily reacts with atmospheric oxygen to form oxides during air-based processing, resulting in rougher hole walls. In contrast, the oxygen content under electrolyte-assisted abrasive jet machining is approximately 18.56%, indicating that this method reduces opportunities for oxygen to participate in oxidation reactions. The high-velocity abrasive jet promptly flushes away oxidation byproducts generated during processing. Simultaneously, laser-induced photodischarge creates cavitation effects that accelerate abrasive impact and removal, preventing oxide layer accumulation on the bore wall surface and reducing surface roughness. Electrochemical anodic dissolution further diminishes oxygen content on the bore wall. These results demonstrate that the electrolyte-assisted abrasive jet machining process effectively suppresses oxidation reactions in bore wall materials.

3.2. Effect of Electrolytic Machining Voltage on Microhole Taper

Figure 5 shows the micro-hole morphology under air and electrolyte abrasive jet machining. Regarding micro-hole surface morphology optimization, at the level of hole wall roughness optimization, under non-abrasive conditions, laser thermal erosion tends to leave a molten recrystallized layer and heat-affected zone on the hole wall. The introduction of abrasive particles achieves dual-action refinement of the pore walls: First, as the jet-carried particles traverse the pore channel, they perform micro-grinding on the recast layer protrusions and microcrack regions of the pore walls, stripping loose layers and impurities from the surface to reduce surface undulations. Second, the localized micro-vibrations induced by abrasive particle impacts on the hole wall promote contact between the electrolyte and high-temperature regions of the hole wall, enhancing the “selective removal” of microscopic protrusions on the hole wall through electrochemical dissolution. The synergistic effect of these two mechanisms significantly reduces hole wall roughness.

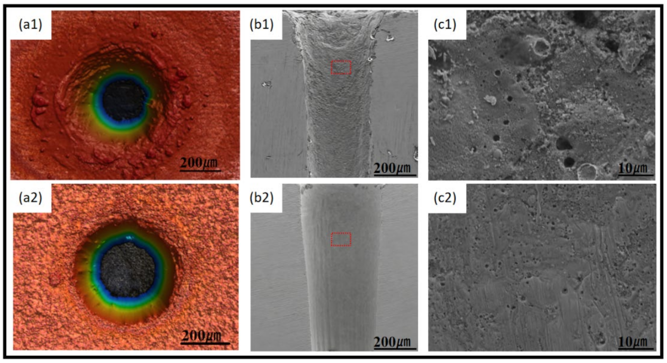

Figure 5. Morphology Comparison Without Abrasive Particles vs. With 15 μ m Abrasive Particles (1) In Air (2) With Composite Aid (a) Orifice Morphology (b) Cross-Section View (c) Localized Magnification of Inner Wall.

At the micro-pore taper regulation level, Figure 7 illustrates the effects of different voltages on the inlet and outlet, while Figure 8 shows the impact of taper angle. At low voltages (0-5V), the pore mouth region experiences concentrated laser energy and stronger abrasive particle impact. Electrochemical dissolution primarily occurs at the pore mouth, resulting in insufficient dissolution efficiency at the pore bottom. This leads to a significant difference between the inlet and outlet diameters. When voltage increases to 5 – 15V, the electric field distribution within the pore becomes more uniform, enhancing electrochemical dissolution rates at the pore bottom. The exit diameter expands to 429 – 472 μ m, reducing the inlet-exit diameter difference and significantly optimizing taper. However, at excessively high voltages (>15V), the greater ion concentration gradient at the hole mouth causes dissolution rates far exceeding those at the bottom. This abnormally enlarges the inlet diameter, compromising micro-hole dimensional accuracy. The medium voltage range (5-15V) enables synchronized, rational expansion of both inlet and outlet diameters while minimizing the diameter difference, thereby achieving optimal taper.

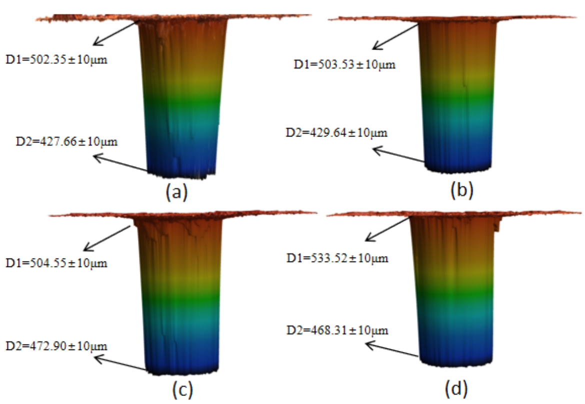

Figure 7. Microporous morphology at different voltages: (a) 5V, (b) 10V, (c) 15V, (d) 20V

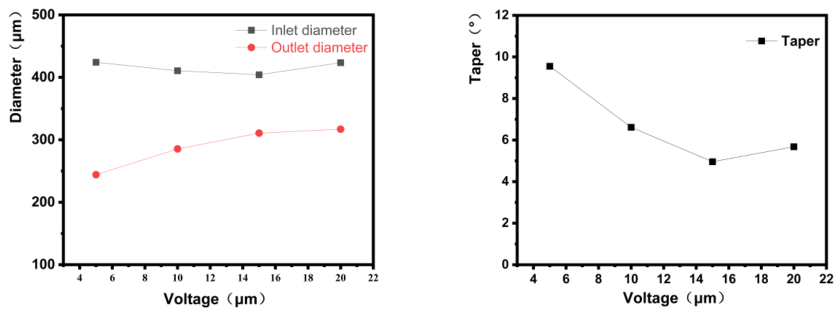

Figure 8. Effect of Different Voltages on Inlet/Outlet (Left) Aperture (Right) Taper

4. Conclusion

This study systematically investigated the effects of key parameters—including jet velocity, jet angle, abrasive particle size, and voltage—on the microhole machining quality of Inconel 718 nickel-based high-temperature alloy using the “electrolyte abrasive jet-assisted laser drilling” process. The optimal combination of process parameters was ultimately determined, significantly enhancing the geometric precision and surface quality of the microholes. Electrolyte-assisted nanosecond laser microhole processing substantially improves surface and wall quality, effectively suppresses recast layer formation on hole walls, and significantly reduces slag accumulation at the hole entrance. During post-processing with laser-assisted electrolytic treatment, the laser's thermal effect greatly enhances electrolysis, further removing residual recast layers and promoting the formation of a denser, periodic structure in the hole wall material. Regarding jet parameters, moderate jet velocity (8 m/s) and angle (60°) ensure liquid film stability and impact effectiveness, enhancing the abrasive's scouring and finishing action on molten material. Regarding electrical parameters, a voltage of 15V effectively promotes electrochemical dissolution behavior, optimizes micro-hole taper, and reduces hole wall roughness. Voltage levels that are too low or too high, however, can lead to over-etching at the hole opening and reduced dimensional accuracy. Regarding abrasive particle size, 15 μm aluminum oxide particles deliver optimal impact and micro-grinding effects while maintaining jet stability. They synergize effectively with laser thermal erosion and electrochemical dissolution to achieve efficient, uniform material removal. Ultimately, optimal microhole processing quality was achieved under the following process conditions: jet velocity of 8 m/s, jet angle of 60°, abrasive particle size of 15 μm, voltage of 15 V, and current of 3 A. This resulted in significantly improved roundness and taper, reduced hole wall roughness Ra to 10.499 μm, and markedly decreased recast layer thickness. The results demonstrate that this method significantly improves the geometric accuracy and surface quality of micro-holes, effectively suppresses the formation of recast layers and micro-cracks, reduces slag accumulation at the hole mouth, and enhances the uniformity and consistency of the hole walls.

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