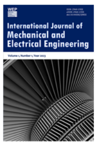
WEP Warwick Evans Publishing

International Journal of Mechanical and Electrical Engineering
ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 8, Number 2, Year 2026
DOI: https://doi.org/10.62051/ijmee.v8n2.05
Journal homepage: https://wepub.org/index.php/IJMEE/index



Research Progress and Development Trends of Water-Mediated Laser Machining Technology: A Review

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ABSTRACT

With the ever-growing demand for miniaturized and high-precision device manufacturing in fields such as electronics, semiconductors, new energy, and medical equipment, traditional machining methods are confronted with bottlenecks like limited precision and severe thermal damage in microscale structure fabrication. Laser machining has emerged as a preferred technique for processing fine structures (e.g., micro-grooves) due to its high energy density, excellent focusing performance, and controllability. However, the thermal damage issue associated with conventional dry laser machining restricts its application expansion. Water-mediated laser machining technology effectively overcomes this limitation by leveraging the dual functions of water (cooling and slag removal), and it has evolved into three mainstream technical routes: water-guided laser machining, water-jet assisted laser machining, and underwater laser machining. This paper systematically reviews the research status and limitations of traditional laser machining, focuses on elaborating the principles, research progress, and application bottlenecks of the three water-mediated laser machining technologies, deeply analyzes the regulation mechanisms and forming laws of liquid layer parameters in underwater laser machining, and finally prospects the future development directions of this field. It aims to provide a reference for the research and engineering application of high-quality, low-damage micromachining technologies.

KEYWORDS

Laser Machining; Micro-groove; Thermal Damage; Underwater Laser Machining.

1. INTRODUCTION

In the field of modern advanced manufacturing, the development trends of miniaturization of electronic devices, high precision of semiconductor chips, high efficiency of new energy components, and precision of medical equipment have imposed stringent requirements on microscale structure processing technologies[1]. Traditional methods such as mechanical machining and chemical etching have been unable to meet the demands of high-end manufacturing due to issues like insufficient processing precision, wide heat-affected zones, or environmental pollution. Laser machining technology, with its unique advantages including concentrated energy, high processing precision, and non-contact processing, has shown broad application prospects in micro/nano structure fabrication, and its applications have covered multiple key fields such as electronics, semiconductors, new energy, and medical care.

However, during the pulsed laser micromachining process, the instantaneous and high concentration of energy tends to cause material melting, vaporization, and rapid solidification, resulting in prominent thermal damage issues under the traditional dry machining mode. For materials with high thermal conductivity or microscale structures, heat is prone to diffuse to the surrounding areas, leading to the expansion of the heat-affected zone (HAZ) and the deterioration of microstructural and mechanical properties. Meanwhile, the thermal stress induced by the temperature gradient can give rise to defects such as residual stress, microcracks, recast layers, and spatter burrs, which severely affect the machining precision and surface integrity[2]. To address this core challenge, researchers have been dedicated to developing novel hybrid machining technologies, and water-mediated laser machining technology has emerged as a promising solution.

Water-mediated laser machining ingeniously leverages the high specific heat capacity, high thermal conductivity, and fluidity of water to achieve rapid cooling of the machining area and efficient removal of molten slag, thereby significantly suppressing thermal damage while improving machining precision. Currently, this technology has developed into three major technical branches: water-guided laser machining, water-jet assisted laser machining, and underwater laser machining. Each branch possesses distinct characteristics in terms of principles, advantages, and application scenarios, but they also face common challenges such as laser energy transmission attenuation and complex parameter regulation. Based on relevant domestic and international research achievements, this paper systematically summarizes the research status of water-mediated laser machining technology, focuses on analyzing the advantages and limitations of various technologies, explores the regulation mechanism of liquid layer parameters, and provides theoretical reference and technical support for the further development of this field.

2. RESEARCH STATUS AND LIMITATIONS OF TRADITIONAL LASER MACHINING TECHNOLOGY

2.1. Applications and Removal Mechanisms of Traditional Laser Machining Technology

Laser machining is an advanced manufacturing technology that utilizes the high energy density characteristic of laser beams to achieve material removal, joining, modification, or forming through thermal effects, photochemical effects, or mechanical effects. It has been widely applied in fields such as cutting, welding, drilling, surface modification, and additive manufacturing, playing a crucial role in industries including machinery manufacturing, electronic information, aerospace, and medical devices[3]. Its core material removal mechanism lies in the interaction between laser and materials, inducing material melting, vaporization, or plasma shock-induced removal to fulfill the preset machining objectives.

2.2. Thermal Damage Issues in Traditional Laser Machining

Despite the numerous advantages of traditional laser machining, thermal damage is inevitably generated during the machining process, mainly manifested as defects such as recast layers, heat-affected zones (HAZ), spatters, and microcracks. Chen et al[4]. found in their research on femtosecond laser machining of carbon fiber-reinforced polymers (CFRP) that when the laser fluence is 50–60 times the ablation threshold fluence of carbon fibers and the scanning direction is consistent with the polarization angle of the linearly polarized laser, the width of the HAZ can be minimized to approximately 2 μm, which is significantly superior to previous research results. Low[5] indicated that laser machining parameters and defocus amount have a significant impact on the formation of spatters during the machining process. A comparative study on femtosecond and nanosecond ablation of molybdenum conducted by Ning et al[6]. showed that molten layers, holes, and cracks are prone to form in the nanosecond ablation zone, while femtosecond ablation results in much milder thermal damage, with the thickness of the recast layer controllable at the micrometer scale.

2.3. Advantages and Limitations of Ultrashort Pulse Laser Machining

To mitigate thermal damage, researchers have attempted to employ ultrashort pulse lasers (such as femtosecond and picosecond lasers) for machining. Characterized by extremely short pulse durations, this type of laser enables energy to act on the machining area instantaneously before thermal diffusion occurs within the material lattice, significantly reducing thermal effects like melting and recasting, thereby effectively minimizing thermal damage. However, ultrashort pulse laser machining exhibits notable limitations: the high costs associated with equipment R&D and manufacturing, coupled with the expensive core components, result in a procurement cost far exceeding that of traditional nanosecond lasers; simultaneously, its high maintenance costs and operational energy consumption restrict its widespread application in large-scale industrial production. Against this backdrop, researchers have shifted their focus to hybrid machining methods that improve processing quality by introducing auxiliary media while retaining the feasibility of traditional laser systems, making water-mediated laser machining technology a research hotspot.

3. MAIN TYPES AND RESEARCH PROGRESS OF WATER-MEDIATED LASER MACHINING TECHNOLOGY

Leveraging the cooling and flushing effects of water, water-mediated laser machining technology inhibits the expansion of the heat-affected zone (HAZ) and reduces molten slag and thermal cracks. It has evolved into three mainstream technical routes: water-guided laser machining[7], water-jet assisted laser machining[8], and underwater laser machining[9], with each technology exhibiting distinct characteristics in terms of principles, research achievements, and application scenarios.

3.1. Water-Guided Laser Machining Technology: Principles, Advantages and Engineering Challenges

The development of water-guided laser machining technology stems from the phenomenon of light guidance by water jets. Jean-Daniel Colladon first discovered that light can propagate curvilinearly along a high-velocity water jet in 1870, and on this basis, Bernold Richerzhagen conducted in-depth research and first proposed the water-guided laser machining technology in 1993. As shown in Fig. 1, its core principle lies in the efficient coupling of laser and water jet: the laser beam is focused at the nozzle outlet through a pressurized water chamber, and the emitted water jet guides the laser beam in a fiber-like manner, which simultaneously achieves the dual functions of cooling the workpiece and removing molten material[10].

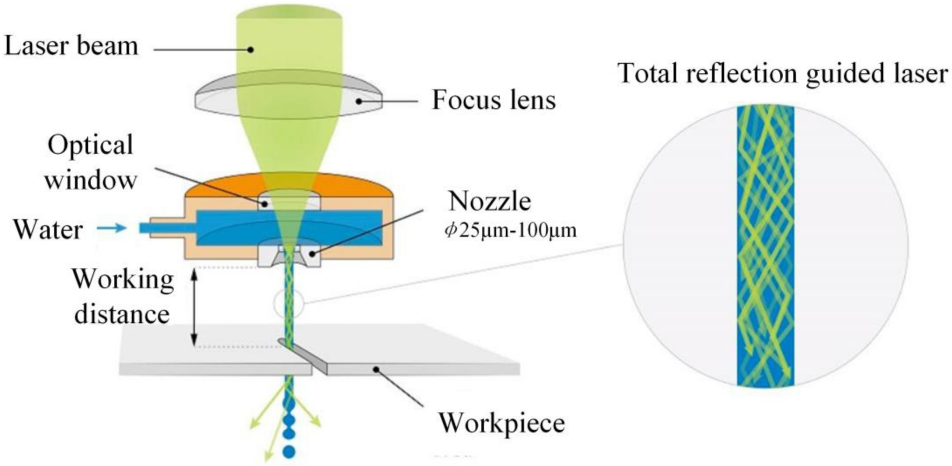

Figure 1. Schematic of Water-Guided Laser Machining[11]

A large number of studies on water-guided laser machining technology have been conducted by scholars at home and abroad. Cheng et al[12]. established a heat transfer model of water-guided laser machining for silicon carbide ceramics and their composites, and found that the water jet exerts a significant cooling effect on the ablated area, with the temperature of the final ablated area presenting an annular distribution with a high center and low sides. Chao et al[13]. compared the surface quality of ultra-thin kerfs machined on Ti-6Al-4V alloy by gas-assisted laser machining and water-guided laser machining. The results showed that the groove machined by water-guided laser machining has a lower surface roughness without obvious cavities and microcracks formed by the spalling of remelted debris, which benefits from the scouring effect of the water jet on molten slag and its promoting effect on groove formation. Wagner et al[14]. compared the water-guided laser cutting effects of a traditional Nd:YAG laser and a Q-switched laser, and found that under the same parameters, water-guided laser machining can produce burr-free and slightly tapered kerfs without an obvious heat-affected zone. Richerzhagen[15] realized the coupling of laser and water jet, and proved that water-guided laser machining exhibits excellent performance in the high-precision machining of heat-sensitive materials such as diamond, silicon carbide and semiconductors.

Despite its remarkable advantages, water-guided laser machining technology is confronted with numerous engineering challenges: the water jet diameter directly affects the beam width and machining precision-smaller diameters yield higher precision but lower jet stability; to ensure high jet stability, the nozzle is required to have a small thickness, high hydraulic impact resistance stiffness, low surface roughness, and high installation precision; the stability of the conversion from a high-pressure low-velocity water jet to a low-pressure high-velocity water beam is difficult to control; the optical path of the laser beam in water is relatively long, and stimulated Raman scattering results in significant energy loss. These issues lead to a substantial increase in system and maintenance costs, which restricts the scope of its engineering applications.

3.2. Water-Jet Assisted Laser Machining Technology: Types, Efficacy and Application Bottlenecks

Water-jet assisted laser machining technology introduces a fine water jet or water film into the laser machining area through a nozzle, achieving heat and fume/slag removal, plasma suppression, and edge quality improvement. According to the relative position of the jet axis and the laser axis, it can be divided into two types: coaxial water jet and paraxial water jet (Fig. 2); paraxial water-jet assisted laser machining can be further classified into low-pressure and high-pressure types based on the material removal mechanism.

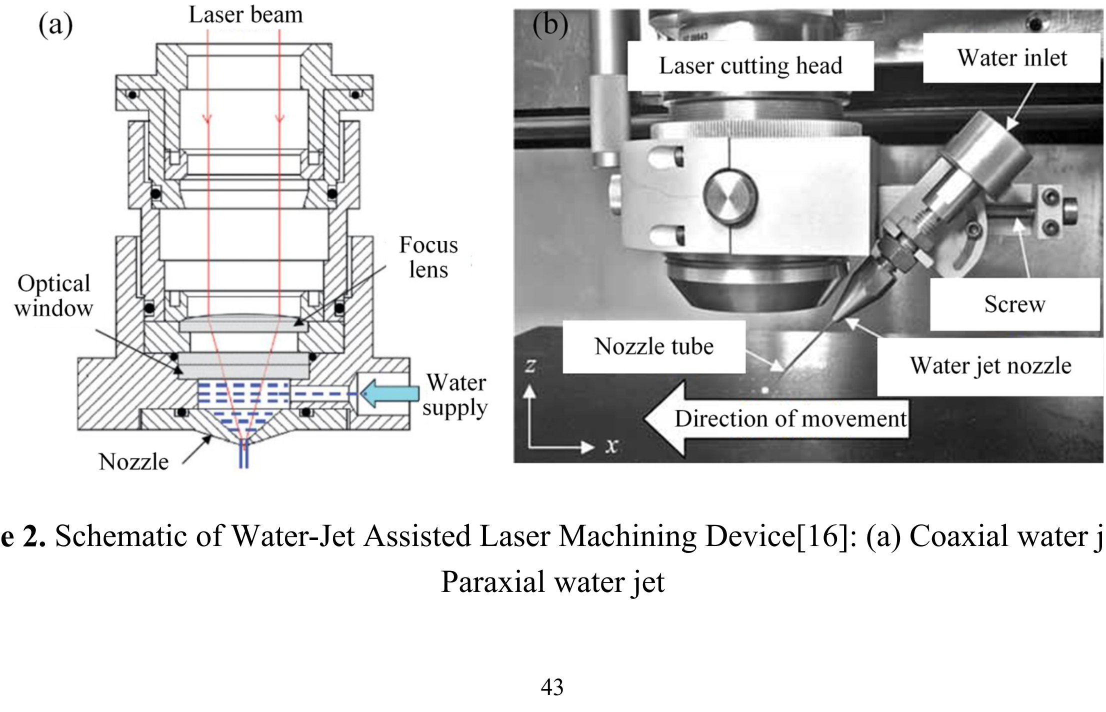

Figure 2. Schematic of Water-Jet Assisted Laser Machining Device[16]: (a) Coaxial water jet; (b) Paraxial water jet

The working principle of low-pressure water-jet assisted laser machining is that the laser rapidly melts and vaporizes the material, and the low-pressure water jet synchronously flushes away the unsolidified molten slag. Chryssolouris et al[17]. adopted the paraxial water-jet technology for cutting fiber materials, which increased the kerf depth and reduced the heat-affected zone by 70%, with the cutting efficiency higher than that of gas-assisted cutting within a certain range. Mullick et al[18]. established a laser energy loss model for water-jet assisted underwater laser machining, and experimental verification showed that the energy lost due to water vaporization accounts for 40%–50% of the total loss, which is the primary energy loss pathway. Suvradip et al[19]. analyzed the influence of various factors on the kerf width in coaxial water-jet assisted underwater laser machining and found that the increase in laser energy leads to a slow increase in kerf width, while the increase in cutting speed results in a gradual decrease in kerf width.

The core of high-pressure water-jet assisted laser machining is that the laser heats and softens the material, and the instantaneous shearing force of the high-pressure water jet is used to peel off and remove the softened material. Since the material is removed without melting, thermal damage in the machining area is greatly reduced and no recast layer is formed[20]. Tangwarodomnukun et al[21]. introduced a high-pressure water jet into laser machining, and the results showed that compared with traditional dry micromachining, this technology can achieve machining with an almost non-existent heat-affected zone and a higher material removal rate. Zhu et al[22]. established a numerical model of heat transfer and ablation for the micro-grooving process of monocrystalline germanium (Ge) by hybrid laser-water jet, and found that an increase in laser pulse energy leads to deeper grooves, while an increase in water pressure reduces the threshold temperature for material removal.

Water-jet assisted laser machining technology has demonstrated remarkable advantages in the machining of difficult-to-machine materials such as fiber materials and silicon carbide. It can greatly reduce the heat-affected zone, inhibit the formation of resolidified layers and the accumulation of molten slag, and improve edge quality and machining efficiency. However, this technology still faces multiple engineering challenges: the matching window for jet pressure, flow rate and nozzle-workpiece distance is narrow, and jet oscillation, breakage or excessive washing are prone to introduce trajectory deviation and quality fluctuation, resulting in great difficulty in fluid stability control; the structural design of nozzles, water quality management (filtration/deaeration) and high-precision alignment with the laser optical path impose stringent requirements on equipment precision and maintenance costs, leading to a high complexity of the device. These factors restrict its large-scale application in high-precision and high-efficiency scenarios.

3.3. Underwater Laser Machining Technology: Classification, Characteristics and Application Potential

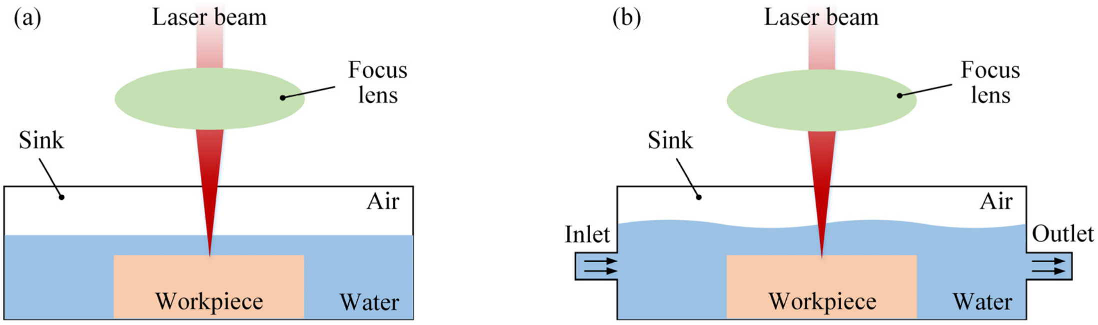

Figure 3. Schematic of Underwater Laser Machining: (a) Laser machining in static water; (b) Laser machining in flowing water

Underwater laser machining technology is a hybrid machining method that places the entire laser machining area in a water environment. Its principle is that the workpiece is positioned beneath a water layer, and the laser beam penetrates the water layer and is focused for machining. It achieves material removal by virtue of the high energy density of the laser, while the water layer exerts multiple effects including rapid cooling, plasma suppression, molten material confinement and debris removal. As shown in Fig. 3, it can be divided into two categories according to the state of water: laser machining in static water and laser machining in flowing water.

Compared with laser machining in an air environment, both laser machining in static water and flowing water offer the advantages of a small heat-affected zone and minimal recast layers. Charee et al[23]. investigated the process of underwater laser ablation of silicon by controlling the flow velocity and direction of water in a closed water chamber, and found that a flowing water layer can minimize the interference of bubbles, water waves and debris on the laser beam, resulting in better ablation performance than that in a static water environment. Kruusing et al[24]. confirmed through research on underwater laser micromachining of magnetic materials and silicon that this technology can achieve a cleaner ablated surface, reduce kerf width, and significantly optimize machining precision and surface quality. Wee et al[25]. conducted ablation experiments in air and flowing water environments using a 355 nm wavelength laser, and found that laser pulse frequency, power, scanning speed and focal plane position all have effects on spatter deposition, irradiated area and hole taper; when the focal plane is located inside the workpiece surface, spatter deposition, irradiated area and taper are all smaller. Krstulovic et al[26]. compared pulsed laser ablation of aluminum blocks in water and air environments, and found that drilling under water confinement is more efficient, and the drilling efficiency can be optimized by adjusting the water layer thickness.

The introduction of gas-assisted technology has further improved the ablation efficiency and quality of underwater laser machining. By introducing a high-pressure gas stream (e.g., argon, nitrogen, oxygen) into the laser action area, bubbles and plasma clouds can be effectively dispersed, the laser beam shielding effect is reduced, and energy is ensured to act directly on the workpiece surface. Chida et al[27]. developed a gas-assisted underwater laser cutting process, using a 4 kW Nd: YAG laser to cut 14 mm thick steel plates for the nuclear industry, achieving minimal molten slag. Jain et al[28]. successfully cut 4.2 mm thick zirconium alloy pressure pipes and 6 mm thick steel plates using a fiber-coupled pulsed Nd:YAG laser with an average power of 250 W. Kruusing[29] presented a detailed review of gas-assisted and water-assisted underwater laser cutting processes, describing the application of high-power CO_2 and Nd:YAG lasers in the underwater cutting of nuclear fuel rods. Black et al[30]. used argon, nitrogen, oxygen and air to assist CO_2 laser underwater cutting of ceramics, and found that the auxiliary gas can promote the rapid solidification of molten ceramics and reduce the combustion area, with oxygen not causing cracks in ceramic tiles; continuous lasers can achieve a higher cutting speed, while the pulsed mode can obtain a smoother cutting surface with fewer cracks.

Overall, underwater laser machining technology has the advantages of simple equipment structure, low cost and easy operation, and has become one of the most widely used water-mediated laser machining methods at present. Among them, laser machining in flowing water can more effectively eliminate bubbles and debris, reduce laser beam interference, further improve machining quality and stability, and show greater potential in specific application scenarios.

4. REGULATION OF LIQUID LAYER PARAMETERS AND RESEARCH ON FORMING MECHANISM IN UNDERWATER LASER MACHINING

In underwater laser machining, liquid layer parameters (e.g., water layer thickness and flow velocity) directly affect the laser energy transmission efficiency, heat management in the machining area and the stability of machining quality, which constitute a key scientific issue for advancing the technological level of machining[31]. Rational regulation of liquid layer parameters can effectively suppress the shielding effect of bubbles and plasma clouds, improve surface quality, reduce the heat-affected zone and recast layers, and enhance machining precision and efficiency; inappropriate parameter selection, however, will lead to energy attenuation and fluctuations in machining quality. A large number of studies on the regulation mechanisms of liquid layer flow velocity and thickness have been conducted by scholars at home and abroad.

4.1. Research on the Influence Law of Liquid Layer Flow Velocity

Liquid layer flow velocity exerts a significant effect on machining outcomes by influencing heat diffusion, bubble expulsion, and molten slag removal in the machining area. Wang et al[32]. conducted water-mediated laser grooving experiments on titanium alloy plates with a variable water flow velocity range of 0~0.6 m/s. The results showed that a combination of high laser power, low pulse frequency, and relatively slow water flow velocity leads to a more pronounced heat-affected zone in the machining area and a relatively higher material removal rate. Duangwas et al[33]. first introduced an incoming water flow velocity parameter of 0~0.624 m/s into traditional laser machining, and found that continuous water flow can wash away ablated debris and bubbles in the water, improve the efficiency and stability of laser ablation, and reduce interference with the laser beam. Wang et al[34]. adopted aqueous solution-assisted laser machining technology to address the issues of recast layers and heat-affected zones in air machining, and orthogonal experiments indicated that water flow velocity and pulse frequency are the most significant factors affecting machining efficiency. Tevinpibanphan et al[35]. confirmed in experiments on laser milling of titanium alloy under a flowing water layer that a uniform cavity depth and a smooth milled surface can be obtained when the laser beam moves along the direction of water flow.

4.2. Research on the Regulation Mechanism of Water Layer Thickness

Water layer thickness directly acts on machining quality and efficiency by influencing laser energy attenuation, bubble expulsion and optical path stability. Linden et al[36]. conducted underwater machining of silicon and stainless steel with a picosecond laser under different water layer thicknesses, and after a systematic analysis of the morphological characteristics of ablation craters, revealed the dependence of the geometric characteristics of ablation craters on water layer thickness. They found that when the water layer thickness is less than 1 mm, bubbles cannot be discharged in a timely manner, which block and scatter the laser beam, leading to a significant decrease in material removal rate. Markauskas et al[37].investigated the laser ablation of soda-lime glass plates under air and water-assisted conditions, and found that applying a thin flowing water film on the sample surface can greatly improve the ablation efficiency, with a maximum increase of 12 times.

The above studies indicate that parameters such as liquid layer flow velocity and thickness have a significant impact on laser energy transmission, heat distribution and material removal behavior in underwater laser machining, and their regulation effects are closely related to material properties and laser parameters. Therefore, conducting systematic research on the optimization of liquid layer parameters for specific machining objects and process conditions is the key to achieving high-quality and stable machining.

5. SUMMARY

This paper systematically reviews the research progress of water-mediated laser machining technology and draws the following main conclusions:

(1) Although traditional laser machining technology has advantages in the fabrication of microscale structures, its application is limited by the problem of thermal damage and the high cost of ultrashort pulse laser equipment. By virtue of the cooling and slag removal effects of water, water-mediated laser machining technology provides an effective approach to solving the thermal damage problem.

(2) Three mainstream types of water-mediated laser machining technology have been formed, namely water-guided laser machining, water-jet assisted laser machining and underwater laser machining. Water-guided laser machining features high precision but imposes stringent requirements on system stability and entails high costs; water-jet assisted laser machining exhibits a remarkable effect in thermal damage suppression yet faces great challenges in parameter matching and fluid control; underwater laser machining is the most widely applied due to its simple equipment and convenient operation, among which machining in flowing water and gas-assisted machining have further improved the machining quality and efficiency.

(3) In underwater laser machining, liquid layer flow velocity and water layer thickness are the key regulatory parameters. A reasonable flow velocity can facilitate the discharge of bubbles and molten slag and stabilize the machining process; an appropriate water layer thickness can reduce laser energy attenuation and ensure optical path stability. The optimized combination of the two parameters can effectively improve the machining precision and surface quality.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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