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Review

Research Progress of Water–Laser Compound Machining Technology

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Abstract: As an emerging industry, laser processing technology has developed rapidly and has gradually become a key technology in transforming traditional manufacturing. It has been widely used in various fields such as industrial production, communication technology, information processing, health care, military, and scientific research. The application and development of laser processing technology is restricted by thermal damage and the processing residues existing in traditional laser processing. However, water laser compound machining can better solve the above-mentioned problems. In water laser compound machining , heat and byproducts can be absorbed and taken away by water to improve processing quality. This paper expounds and analyzes the principles and research of three popular water laser compound machining methods (water-guided laser processing, underwater laser processing and water-jet-assisted laser processing). Furthermore, this paper analyzes the technical difficulties in water laser compound machining and looks forward to the future development trends of this technology.

Keywords: laser processing; water laser compound machining; thermal damage; processing quality

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1. Introduction

A laser is a kind of coherent electromagnetic radiation with a wavelength below 1 mm, which has good monochromaticity, coherence, and directivity [1,2]. As a new type of processing method, laser processing has been widely used in cutting-edge technology fields such as medicine, machinery, military, and aerospace [3]. The laser beam with high-energy density irradiates the material surface to reach the material ablation threshold, thereby completing various processing techniques in laser processing. Laser processing is mainly used for laser cutting, laser etching, laser drilling, laser welding, and laser cladding.

Although traditional laser processing has a high-processing efficiency, it is easy to cause a large heat-affected zone on the surface of the material or even severe ablation if the energy is high. At the same time, defects such as microcracks may occur due to uneven thermal stress during laser processing. Therefore, it is necessary to perform secondary processing on the laser-processed material [4]. In order to avoid or reduce the defects of traditional laser processing, many methods have been implemented by many scholars, such as recoagulated layers, ablation, and microcracks. Among these methods, water laser compound machining has been extensively studied. In water laser compound machining, water is used to absorb the heat generated in the laser processing or wash away the slag to improve the processing quality. water laser compound machining technology can be divided into three main types, water-guided laser processing, underwater laser processing, and water-jet-assisted laser processing.

The principles and research of three currently popular water laser compound machining are explained and analyzed in this paper. Meanwhile, the factors restricting its development were analyzed and its future development trend is forecasted.

2. Water Laser Compound Machining Interaction Mechanism

2.1. Laser–Material Interaction Mechanism

Laser machining irradiates the surface of a material using a laser with high-energy density. When the laser power density reaches a certain value, the temperature of the material exceeds the phase-transition temperature of the material, and it undergoes a structural (or phase) change. As the laser power density continues to increase, the surface temperature of the material increases further and eventually reaches the melting point. During this time, the surface material begins to melt, and the heat-affected zone diffuses into the interior of the material, thus melting the internal material. At a sufficiently high-laser power density, the temperature of the material in the laser action region rises to a boiling point and some materials begin to vaporize. Increasing the laser power density beyond this point raises the material temperature to above the ionization temperature, generating plasma on the material surface. As the laser power density continues to increase, the temperature of the portion of the region in contact with the laser increases, thereby melting and vaporizing the material and generating plasma [5]. The different states of the material under the laser are shown in Figure 1.

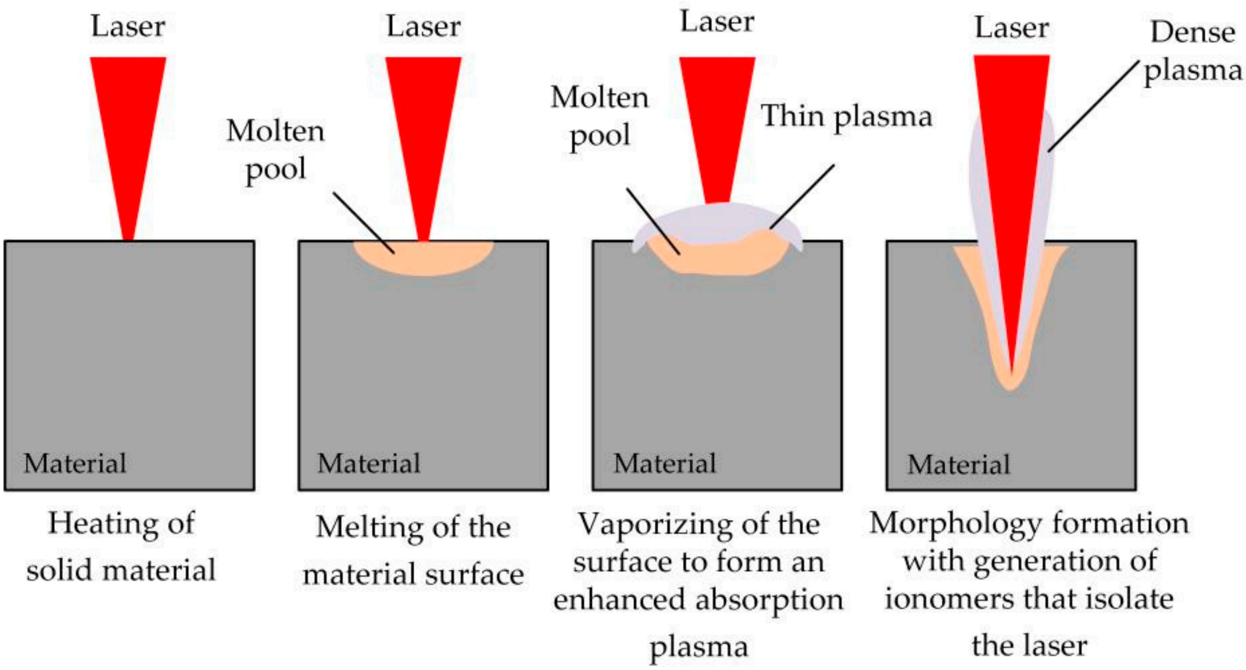

Figure 1. Schematic of the laser–material interactions.

2.2. Water–Material Interaction Mechanism

In water laser compound machining , water plays the role of impact and transport. When the water hits the workpiece, kinetic energy is generated, which can flush the material softened by the laser to the outside of the processing area in time, reduce the accumulation of slag in the processing area and improve the processing quality [6,7]. The schematic diagram of the water impact workpiece is shown in Figure 2.

The kinetic energy E_{water} of the water–workpiece is [8,9]:

$$E_{water} = \frac{1}{2}\rho Q v^2 \tag{1}$$

Here, Q is the water flow; ρ is the density of water; v is the water velocity.

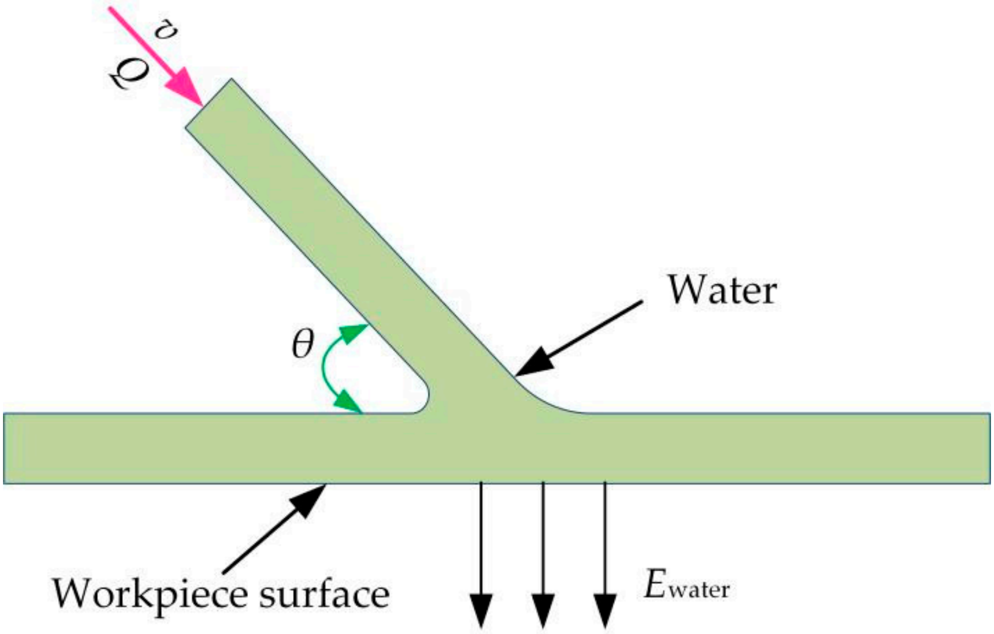

Figure 2. Schematic diagram of water impact workpiece.

2.3. Water–Laser Interaction Mechanism

In water laser compound machining , although the introduction of water will cause laser-energy loss, water can not only cool the area heated by the laser, but also reduce the thermal effect on the material when the laser irradiates the material and reduces the generation of microcracks. In general, the Nusselt number ($N\mu$) can measure the strength of convection heat transfer. The smaller the Nusselt number, the weaker the convective heat transfer; the larger the Nusselt number, the stronger the convective heat transfer. The heat transfer coefficient can better represent the cooling effect of the water jet. The larger the heat transfer coefficient is, the more heat the water jet carries away, and the better the cooling effect is, and vice versa.

The formula for calculating the Nusselt number is [10–12]:

$$h_f = N_\mu \times \lambda \times l^{-1} \tag{2}$$

$$N\mu = \begin{cases} 0.715Re^{1/2} \times Pr^{0.4} & 0.15 \leq Pr \leq 3 \\ 0.797Re^{1/2} \times Pr^{1/3} & Pr > 3 \end{cases} \tag{3}$$

where h is the surface heat transfer coefficient; λ is the coefficient of thermal conductivity, and l is the length of the plate in the direction of the flow velocity; $N\mu$ is Nusser number; λ is thermal conductivity; l is water flow direction plate length, Pr is Prandtl number.

2.4. Water–Laser–Material Interaction Mechanism

In water laser compound machining , the energy acting on the workpiece mainly includes laser–workpiece (E_1), water–workpiece (E_2), and laser–water (E_3). The interaction of these three energies finally realizes the workpiece machining [13]. The combined energy E is as follows.

$$E = E_1 + E_2 - E_3 \tag{4}$$

According to the variation rules of E_1, E_2 and E_3, a schematic diagram of comprehensive energy change of water–laser–workpiece is shown in Figure 3.

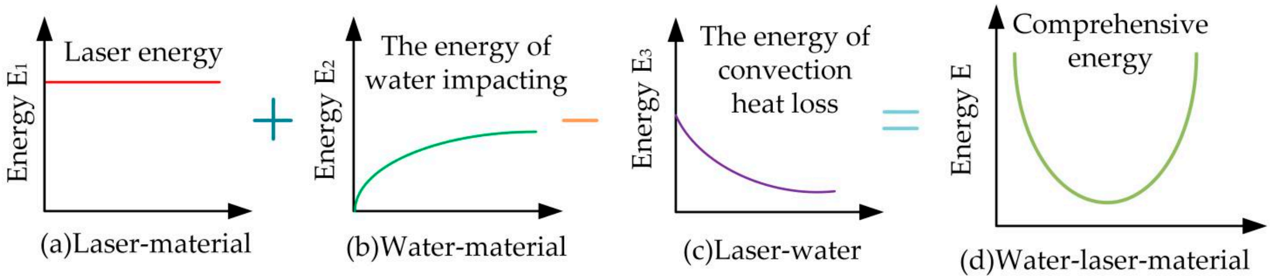

Figure 3. Schematic diagram of the comprehensive energy change during water laser compound machining.

3. Water-Guided Laser Processing

Water-guided laser cutting technology is a new cutting method that uses a water beam to guide the laser to the machined surface. The processing principle is shown in Figure 4 [14–16]. It has attracted extensive attention from many researchers due to its small heat-affected zone, high precision, and lack of pollution. In addition, water and laser simultaneously act on the processing area, so it can cool the processing area well and wash away the molten material, which can almost eliminate the heat-affected zone and the recast layer [17–21].

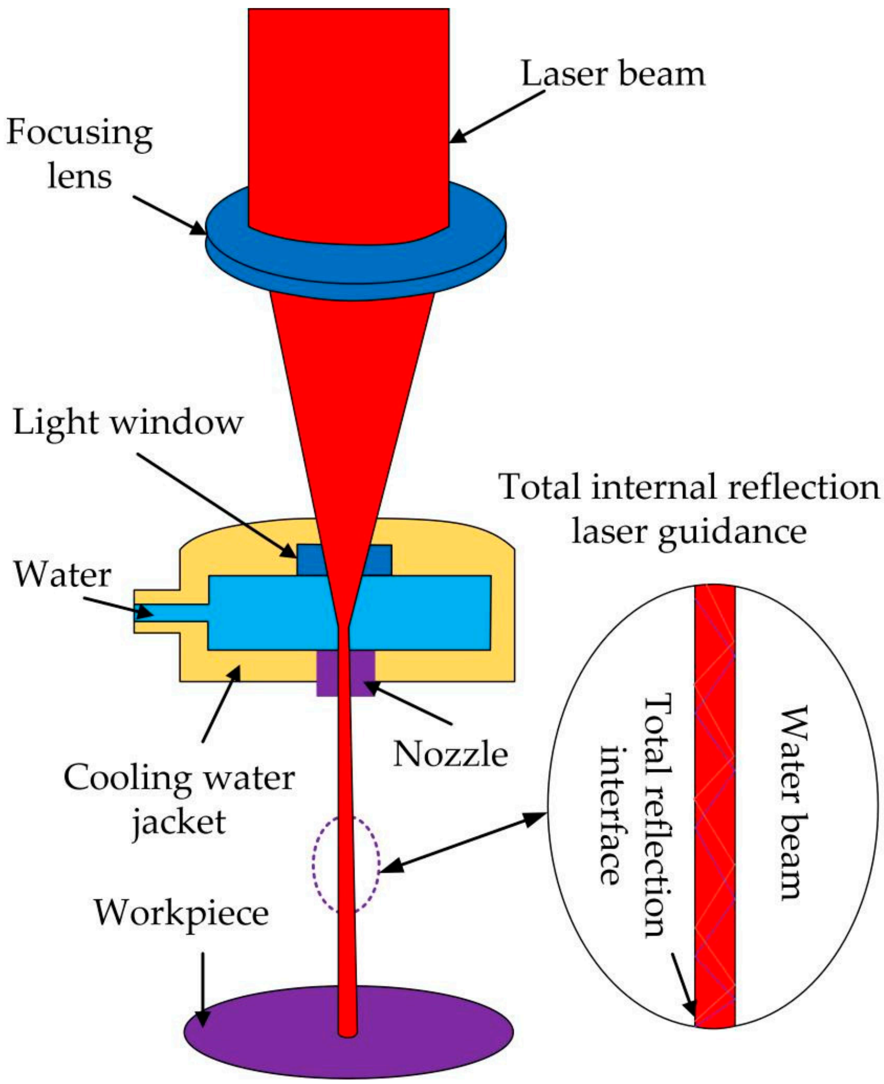

Figure 4. Principles of water-guided laser processing.

Li et al. [22,23] proposed a simulation model of water-guided laser drilling silicon to simulate the temperature field distribution and phase change removal process during laser irradiation. The correctness of the model was verified by experiments to improve the understanding of the laser–water–workpiece interaction.

Rashed et al. [24] used electrical discharge machining (EDM) and a water-guided laser to process the microholes of fuel injector nozzles and compare the processed surfaces. The experimental results show that the microholes processed by the water-guided laser had high repeatability and good surface quality, which could better realize the atomization of the fuel jet.

Huang et al. [25] proposed a deflected water beam-guided laser method based on a nonuniform electric field for the water-optic coupling process. In the coupling of the laser and the water beam, the problem of the laser easily burning the nozzle and deviating from the set ablation area was effectively solved.

Shi et al. [26] used water-guided laser technology to process microtextures on metal surfaces to achieve super-hydrophobicity. The effects of grid spacing, laser power, and water flow diameter on super-hydrophobicity was analyzed. The experimental results show that water-guided laser processing had almost no heat-affected zone and could achieve super-hydrophobicity of metal.

Adelmann et al. [27] found that water-guided laser technology could obtain larger aspect ratios and form rectangular cuts when cutting thick aluminum, titanium, and steel materials. The laser power and repetition frequency could be adjusted to obtain a structure with a larger aspect ratio. The maximum cutting depth was 8 mm for aluminum alloy, 4.7 mm for titanium alloy, and 1.5 mm for steel; aspect ratios were 66.7, 39.2 and 12.5, respectively.

Qiao et al. [28] investigated the relationship between the processing parameters and surface topography changes in water-guided laser processing. The experimental results showed that the water-guided laser micromachining technology had excellent performance in the cutting of single crystal silicon. At the same time, Qiao [29] also successfully processed a hydrophobic surface microtexture on the surface of the stainless steel. The experimental results show that the microtexture was uniform and neat, and the squares were clear. Although the groove depth of the microtexture increased as the grid spacing L decreased, the groove width did not change with the grid spacing L.

Cao et al. [30] investigated the influence of laser power, laser repetition frequency, and feed speed on the shape of 6061 aluminum grooves in water-guided laser processing. They found that higher laser power and lower laser repetition frequency were beneficial to the formation of trenches with vertical sidewalls; higher laser power, lower laser repetition frequency, lower feed speed, and multiple processing were conducive to the formation of grooves with a large aspect ratio.

Zhang et al. [31] simulated the process of water-guided laser processing of carbon fiber-reinforced plastics. It was found that the duty cycle significantly affected the shape and temperature distribution of the composite after drilling. Water-guided laser processing can achieve better processing results than traditional laser processing.

To solve the difficulty of traditional laser drilling in metal-matrix composite materials, Marimuthu et al. [32] used water-guided laser technology to drill holes in aluminum metal-matrix composite materials, as shown in Figures 5 and 6. It was found that regardless of laser power and speed, water-guided laser drilling produced holes with excellent roundness and no recast and oxide layers were observed in the holes. However, due to the lack of energy in the water-guided laser drilling process, the hole has a certain taper.

In summary, because the water can cool the material in the laser-pulse gap, the thermal deformation and thermal damage of the material are greatly reduced and the material maintains its original structure, which prevents thermal damage in water-guided laser processing. Moreover, the water jet can take away the molten material in time, reducing the contaminants in the water-guided laser processing. The processing accuracy is higher than that of traditional laser processing, and it is especially suitable for high-precision processing of thin-walled parts and structures with large aspect ratios. However, the coupling device of the water jet and the laser beam is more complicated, and the pulsation of the water jet will affect the transmission of the laser beam, which reduces the processing quality and efficiency. In addition, a laser beam that is not perfectly coupled to the water jet can cause the nozzle to burn out during processing and increase the cost.

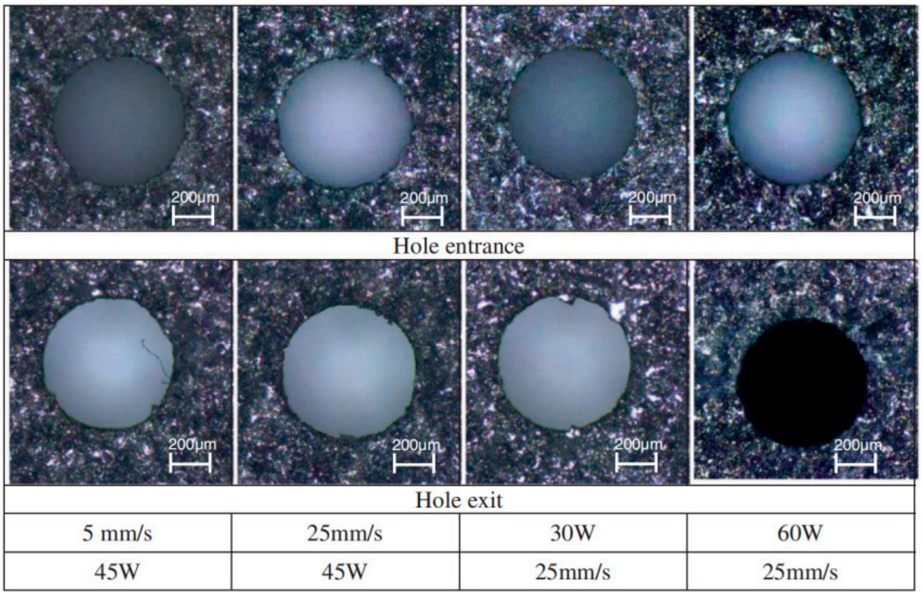

Figure 5. Optical microscopic image showing the hole entrance and exit for various trepanning speeds and power during water-guided laser drilling. Reprinted from [23], with permission from SAGE.

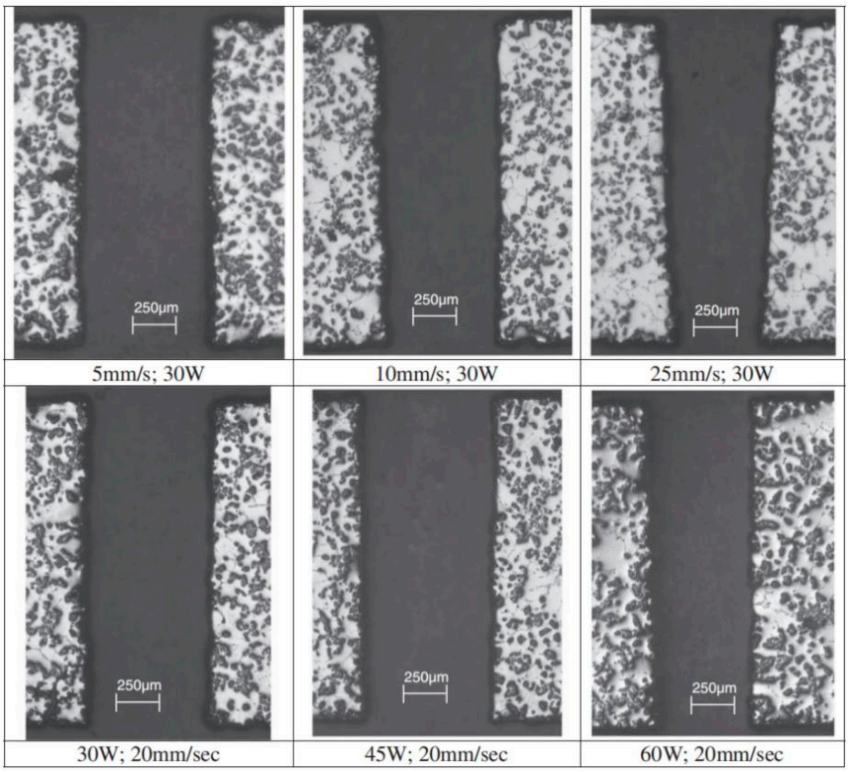

Figure 6. Microscopic image showing the hole cross-sections for various trepanning speeds and laser powers during water-guided laser drilling. Reprinted from [23], with permission from SAGE.

4. Underwater Laser Processing

Underwater laser processing is a simple water laser compound machining technology with good applicability. The principle of underwater laser processing is shown in Figure 7. Firstly, the workpiece is immersed in water; then the laser beam irradiates the workpiece surface through a water layer with a certain thickness; and finally, the workpiece is processed [33]. Underwater laser processing can reduce the heat-affected zone and recast layers more effectively than conventional laser processing [34–37]. Due to the confinement of the water layer, the shock wave formed in underwater laser processing can reach a higher level, which is beneficial to the removal of materials. Moreover, static underwater laser processing will also produce a unique phenomenon of cavitation, and the shock wave formed by the collapse of cavitation bubbles will also promote the material removal process [38].

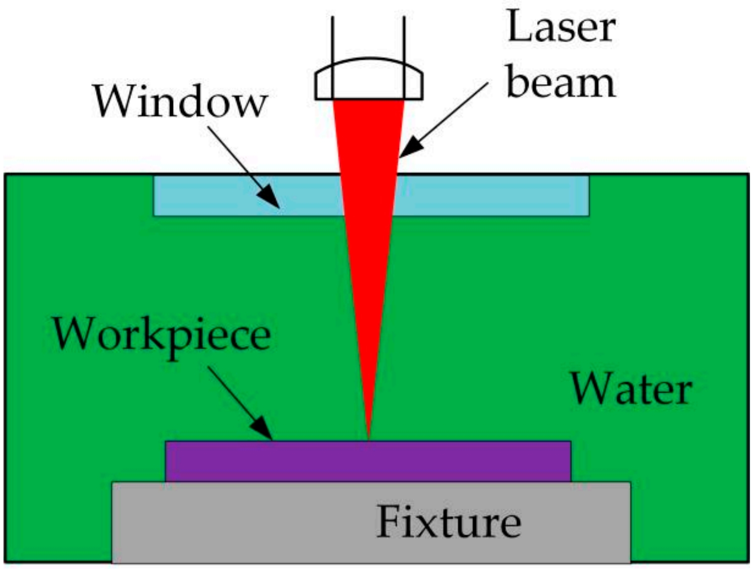

Figure 7. Principle of underwater laser processing.

Long et al. [39] studied the influence mechanism of the thickness of the water layer on the etching quality of the workpiece. The results demonstrated that the formation of cavitation bubbles was not affected by the immersion depth, which provides theoretical support for the choice of the water-layer thickness in underwater laser processing.

Tangwarodomnukun [40] and Das [41] found that the surface quality of underwater laser ablation was significantly improved, the heat-affected zone was significantly reduced, and the sputtering of molten material was also significantly reduced compared to that of the laser in the air. It is more conducive to the removal of melt because the confinement effect of the water layer on the plasma increases the intensity of the shock wave. It was found that the redeposit of underwater laser processing was significantly less and the heat-affected zone was smaller.

Parmar et al. [42] comparatively investigated the laser processing quality of PZT ceramic materials in air and liquid media, and Figure 8 shows the processing results under different conditions. It can be seen that the laser machining in the air produces large diameter and large cavities. Furthermore, the laser machined surface in the air shows the redeposition and scorching of the material due to the presence of temperature gradients and thermally induced stress. The presence of the liquid medium helps to control the heat-affected zone and taper the angle of the drilling cavity, thereby improving the machining quality. Krstulović et al. [43,44] studied the influence of the water-layer thickness on pores. The study found that underwater laser processing could obtain holes with better processing quality.

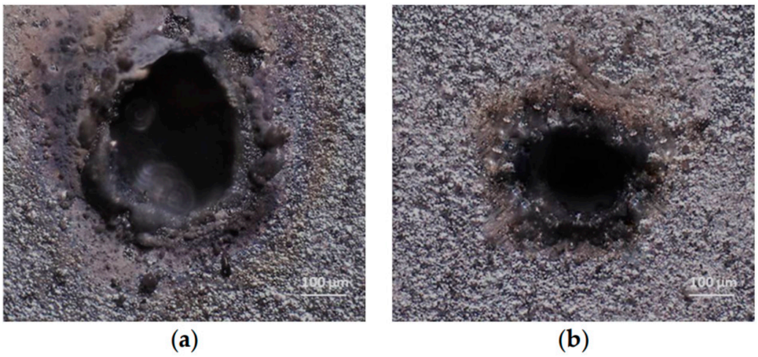

Figure 8. Micromachined cavities in smart ceramic materials using (**a**) in air and (**b**) underwater. Reprinted from [42], with permission from MDPI journals.

Zhu et al. [44] compared the groove width, cracks, and cut quality of the laser processing ceramics in air and water. It was found that underwater laser processing could obtain smoother grooves and fewer cracks and narrower grooves could be obtained when the water layer was thicker. Choubey et al. [45] implemented pulsed fiber laser processing of stainless-steel plates in the air and underwater and found that underwater laser processing could obtain a better cutting quality than in the air.

Muhammad et al. [46] used underwater microsecond lasers to process thin nickel-titanium alloy tubes for medical coronary stents. The results show that underwater laser processing can achieve good surface quality and no debris accumulation and redeposition.

Lv et al. [47] used nanosecond pulsed lasers to drill Inconel 718 samples in air and water. The experimental results show that the edges of the holes processed in the air have obvious melt recasting and redeposition, while the edges of the holes processed underwater are significantly smoother, and there is almost no recasting and redeposition.

Although static underwater laser processing significantly improves the processing quality compared to traditional laser processing, the formed shock wave makes the surface of the water layer fluctuate, which not only interferes with the transmission of laser energy, but also affects the processing efficiency and quality. Therefore, scholars from various countries have also carried out research on mobile underwater laser processing technology.

In order to reduce the impact of debris and bubbles generated in static underwater laser processing on the processing quality, Charee et al. [48] performed underwater laser processing to study the laser-pulse energy, scanning speed, and water flow on the heat-affected zone and roughness. The research results demonstrated that when the laser energy and scanning speed increased, the roughness of the cut surface decreased and when the water-flow speed increased, while the roughness and the range of the heat-affected zone also decreased. Figure 9 shows the heat-affected zone of the cut surface under different water-flow-speed conditions.

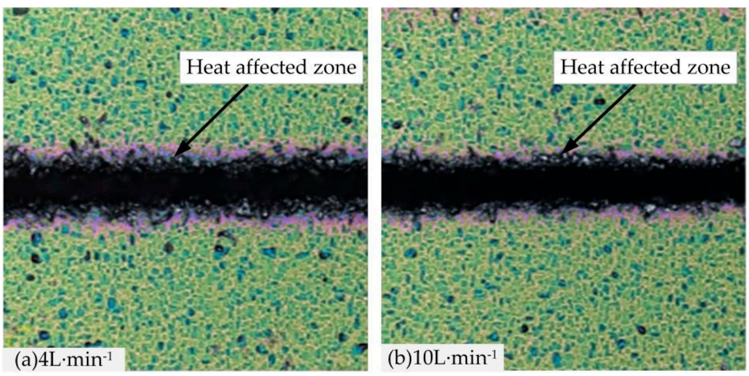

Figure 9. Heat-affected zone of cutting surface with different water velocities. Reprinted from [39], with permission from Trans Tech Publications.

Wee et al. [49] used a pulsed laser to perform laser drilling tests on SiC workpieces in air, water, and methanol. It was found that flowing water could better take away excess heat, debris, and bubbles and obtain better processing results than in air and stagnant water. Higher hole quality could be achieved by laser machining holes in methanol instead of in air or water. The analysis indicated that methanol evaporates faster under the action of the laser, which could take away the silicon carbide particles faster (compared to air and underwater). As a result, the accumulation and oxidation of processed products are reduced.

In short, underwater laser processing can obtain higher surface quality and processing accuracy than traditional laser processing. However, for high-frequency pulsed laser processing, the shock wave formed by static underwater laser processing causes the surface of the water layer to fluctuate, which not only interferes with the transmission of the laser energy but also affects the processing efficiency and quality [50,51]. In addition, laser processing in flowing water can achieve better quality than static water. This is because the flowing water can wash away the laser processing products and carry away excess heat in time. Furthermore, the water-flow speed needs to be strictly controlled to ensure that the water flow and the laser parameters are accurately coupled to obtain good processing results. Therefore, it is necessary to design the coupling device at a high cost.

5. Water-Jet-Assisted Laser Processing

A water jet with a certain angle and speed is introduced into the laser processing to form a water-jet-assisted laser processing technology. The principle of water-jet-assisted laser processing is shown in Figure 10. Water jets have an impingement and cooling effect. They can wash away laser processing products and absorb excess heat, effectively improving the surface quality of difficult-to-machine materials. According to the pressure of the water jet, they can be divided into low-pressure water jets and high-pressure water jets [52–54].

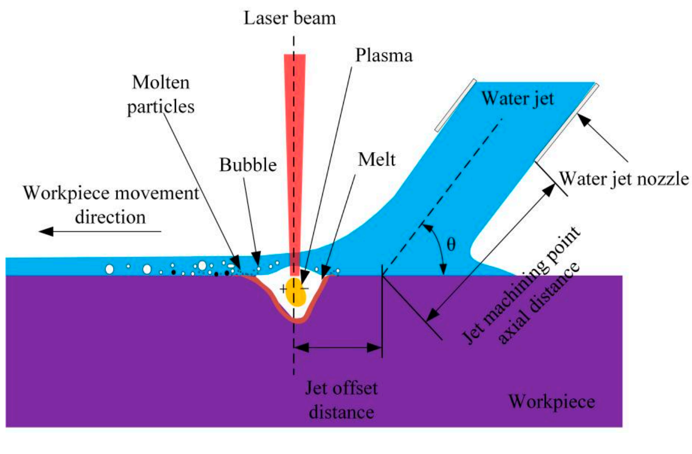

Figure 10. Schematic of water-jet-assisted laser processing.

Wang et al. [55] used water-jet-assisted laser machining silicon nitride to study the effects of laser energy, water-jet pressure, and laser moving speed on groove depth and surface microtopography. It was found that the laser-pulse energy and water-jet pressure dominated the groove depth and microscopic morphology.

Zhu et al. [56] established a numerical model to study the heat transfer and material ablation mechanisms in water-jet-assisted laser processing single crystal germanium. He demonstrated that the shielding effect of laser-induced plasma increased with increasing the laser-pulse energy. The water jet could not only wash away the material softened by the laser but could also effectively remove the heat accumulation in the workpiece to minimize thermal damage. It was found that the groove depth increased with the laser-pulse energy and the pressure of the water jet lowered the threshold workpiece temperature for material removal.

Because the jet velocity and nozzle diameter affected the results of the water-jet-assisted laser processing, Eddie [57] studied and optimized the jet velocity and nozzle diameter from these two aspects.

Zhou et al. [58] analyzed the effects of heat transfer, water jet, and water film on laser ablation during jet-assisted laser processing. They found that the jet velocity and the shape of the water layer would affect the laser ablation efficiency and the quality of the ablation characteristics. Annoni et al. [59] comparatively studied the influence of different parameters on the groove of laser and water-jet-assisted laser processing silicon carbide. It was found that when laser processing silicon carbide, there was more slag on both sides of the groove, and the heat-affected zone was larger. On the contrary, the water-jet-assisted laser processing silicon carbide could obtain better processing quality grooves.

Jiang et al. [60] studied the effects of the defocus amount, laser scanning speed, laser power, water pressure, and water-jet angle on the processing quality of water-jet-assisted laser cutting of Korean pine combined with the orthogonal experiment method, and determined the optimal process parameters.

Guo et al. [61] investigated the effect of different processing parameters on the ablation depth, ablation width, and material removal rate in water-jet-assisted laser machining and successfully processed the microgroove array on the CVD diamond coating tool. Tangwarodomnukun et al. [62] proposed high-pressure water-jet-assisted laser processing technology and studied the mechanism of material removal. Research has found that the laser first heats the material to increase its temperature and reduces the yield strength during the process of material heating. When the material is softened and not yet melted, the impact pressure of the high-pressure water jet is stronger than the shear-yield pressure of the material and the softened material will be washed away by the high-pressure water jet. Because the material is removed before it reaches the melting point, the thermal damage of the processing area is greatly reduced, which leaves the processing surface without a recast layer [63].

Brecher et al. [64] constructed a laser–water-jet heat transfer model and discussed the effects of laser energy and nozzle diameter on laser-energy loss through experiments. Kalyanasundaram et al. [65] designed a laser–water-jet composite device to cut ceramics. They found that the water jet needed to lag 4 mm behind the laser beam to better assist the laser to cut the workpiece and reduce the loss of the laser beam in the water jet. Chryssolouris et al. [66] reduced the heat-affected zone of the workpiece surface by about 70% using high-pressure water-jet-assisted laser machining techniques.

Chen et al. [67] investigated the temperature change during water-jet-assisted laser etching of aluminum alloys through simulation and experiment. At the same time, experiments were carried out to study the effects of laser processing and water-jet-assisted laser processing of aluminum alloy groove. Figure 11 shows the surface morphology of aluminum alloy groove processed by laser processing and water-jet-assisted laser processing. Laser processing with high-energy density is a “quick cold and hot” process and the molten metal is not removed in time, which causes the accumulation of recoagulated layer and slag.

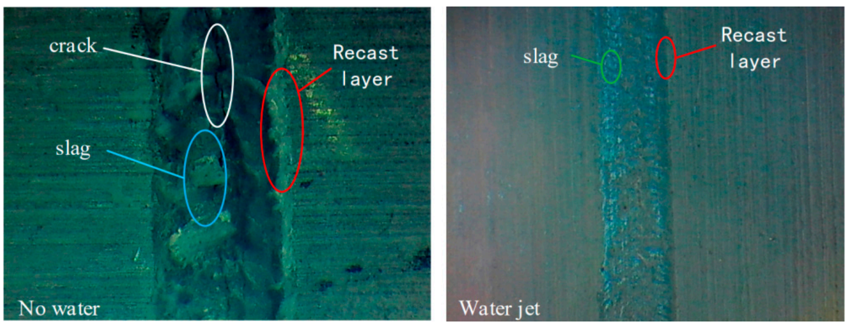

Figure 11. Graph of laser processing results. Reprinted from [67], with permission from MDPI journals.

Feng et al. [68] considered the interaction between laser–water-jet workpieces to establish a three-dimensional analysis model of the temperature field in water-jet-assisted laser micromachining. It was found that in the water-jet-assisted laser processing, the removal temperature of the material is lower than the melting point of the material due to the cooling effect of the water jet. The maximum temperature increased with increasing the laser power and water-jet offset distance, and with decreasing the nozzle-outlet diameter.

Bao et al. [69] used smooth-particle hydrodynamics (SPH) technology to construct a water-jet-fluid dynamic model and performed water-jet-laser cutting silicon materials. The simulation results show that the melt jet disturbs the water and may cause laminar and turbulent flow in the water, and the water jet can take the molten silicon away from the workpiece surface.

Chen et al. [70] investigated the energy efficiency, groove width, depth, and surface microstructure in low-pressure water-jet-assisted laser processing of polysilicon. The study found that the low-pressure water-jet-assisted laser etching technology could reduce the defects existing in traditional laser processing.

Wang et al. [71] performed a water-jet-assisted laser processing microchannel experiment on a stainless-steel surface and used the response surface method to study the influence of various process parameters on the microchannel processing quality and heat-affected zone. The response surface method was used to study the influence of various process parameters on the quality of microchannel processing and the heat-affected zone.

To summarize, the water-jet-assisted laser technology not only avoids the difficult problem of coupling cavity design in water-guided laser processing, but also has the advantages of both water-guided laser and underwater laser processing. The water jet directly acting on the laser processing area can quickly take away the heat and processing products generated by the laser processing, which can prevent any impact on the subsequent processing process.

6. Technical Difficulties and Development Trends of Water Laser Compound Machining

This paper analyzes the principles of water-guided laser processing, underwater laser processing and water-jet-assisted laser processing. The characteristics of the three processing technologies and the current research progress are summarized. This paper analyzes the technical difficulties in water laser compound machining and looks forward to the future development trend of this technology.

(1) Water-guided laser processing mainly realizes the perfect coupling of a water beam and a laser beam to reduce nozzle ablation problems; it improves the jetting stability of the water beam to reduce the laser scattering loss in the water beam; it reduces the coupling of the water-beam pulsation to improve the localization of the processing; and it reduces equipment maintenance costs.

(2) The characteristics of the water layer have a greater impact on laser processing, whether in static or flowing water. Static underwater laser processing products scattered in the water and rising cavitation bubbles will affect the laser transmission. Therefore, the development trend of static underwater laser processing is to reduce the influence of processing products, cavitation bubbles on laser transmission and the disturbance of the water layer caused by bubble collapse. Flowing underwater laser processing needs to control the flow speed of the water layer to ensure that the processed products are taken away smoothly. In addition, the setting of the water inlet and outlet will increase the cost of the equipment and the reasonable thickness of the water layer can meet the processing requirements while reducing the laser loss in the water layer. Therefore, reasonable processing parameters and cost control are the development trend of flowing underwater laser processing.

(3) Water-jet-assisted laser processing is a relatively economical processing technology. It does not require expensive laser–water coupling devices, only the stability of the water jet. The stability of the water jet is a prerequisite for ensuring the quality of water-jet-assisted laser processing. Therefore, an excellent nozzle structure and a

stable and reliable liquid supply system are the prerequisites for ensuring the quality of water-jet-assisted laser processing. Furthermore, reasonable setting of the process parameters is the guarantee of good processing quality.

Water laser compound machining technology has been developed by many scholars since its birth in the last century. In the future, it will develop in a more complete and economical direction and provide impetus for the further development of precision manufacturing.

Author Contributions: K.S. contributed to the experiment, processed the data and wrote the paper. The data analysis was performed and the grammar was modified by X.L. Q.C. discussed the results. Q.Z. and Y.L. proposed the study conception and design. C.W. is responsible for part of the experimental data, data discussion, and grammar revision. All authors have read and agreed to the published version of the manuscript.

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