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Research progress on the application of high-power laser cutting, welding, and drilling

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High-power laser technology has become an important tool in the field of modern machining due to its high energy density, non-contact processing characteristics and high-precision control ability to make it show significant advantages in cutting and welding. With the continuous development of laser technology, the application of high power laser (such as fiber laser, CO₂ laser) in the industrial field is also expanding. This paper combs through the technical advantages, application research, challenges and future trends of high power lasers in cutting, welding and drilling. In recent years, the increase of laser power and the optimization of processing have promoted the wide application of high-power lasers in aerospace, automotive manufacturing and electronic devices. In this paper, we will discuss laser cutting, welding and drilling, and discuss their future development directions in light of recent research progress.

KEYWORDS

high power laser technology, machining applications, laser cutting and welding, laser drilling, future development trends

1 Introduction

High-power laser technology has gone through an evolutionary process from basic theoretical research to wide application. With the continuous progress of science and technology, lasers have been widely used, such as fiber lasers and carbon dioxide lasers play an increasingly important role in industrial processing. Fiber lasers have the advantages of high electro-optical conversion efficiency, good beam quality, good heat dissipation, high stability, low cost, etc. [1, 2], and their power range is usually in the range of a few kilowatts to tens of thousands of kilowatts, which is suitable for the processing of metal or part of the non-metallic materials. Carbon dioxide lasers have the advantages of high output power, good beam quality, and narrow heat-affected zone, etc. Paper and non-metallic materials are suitable for cutting with carbon dioxide lasers [3, 4], and these materials have a high absorption rate of the wavelength of carbon dioxide lasers [5]. The advantages of high-power lasers lie in their high energy density, non-contact processing characteristics, and adaptability to complex shapes, making them an indispensable processing tool in modern manufacturing. Laser processing technologies such as laser welding and laser cutting have been widely used in aerospace, automotive, electronic equipment

and many other fields, significantly improving productivity and product quality [6, 7].

2 High-power laser cutting technology

2.1 Cutting carbon fiber reinforced composites (CFRP)

High-power laser cutting is an advanced material processing technology that irradiates the material with a high energy density laser beam to melt or vaporize it to achieve separation. It has significant advantages over traditional cutting methods, capable of cutting with high precision and speed, with a small heat-affected zone and high cutting quality [5]. The performance of high-power laser cutting is also affected by the laser parameters, the higher the power, the smaller the focused spot, which can improve the laser absorption rate and energy density, so that the powder melting is better [8], while too high a laser power will reduce the quality of the cut. Laser wavelength, spot size and divergence angle also affect the cutting performance, and optimizing these parameters can improve the cutting quality and efficiency. In addition, laser cutting is one of the most widely used non-contact material cutting methods based on the process of generating thermal energy [9], and can be used to cut engineering materials such as titanium, stainless steel, aluminum and aluminum alloys, as well as non-metallic materials such as wood, glass, plastics, ceramics, and composites, which are widely used in various manufacturing industries [10]. Fiber lasers are mainly used for processing metals, but are emerging in some non-metallic areas, and CO₂ lasers are particularly suitable for cutting non-metallic materials.

Carbon fiber reinforced composites (CFRP), which are made by embedding carbon fibers in a polymer matrix, are widely used in aerospace, automotive manufacturing, and renewable energy due to their high strength, light weight, durability [11, 12]. In recent years, significant progress has been made in fiber laser cutting of CFRP. When laser cutting CFRP, the laser power and cutting speed need to be precisely controlled to avoid excessive thermal damage and delamination of the material. Li M et al. conducted a feasibility study on high-power fiber laser cutting of thick CFRP sheets, and the results showed that 10.0 mm thick CFRP sheets could be successfully cut using a high-power fiber laser and a one-pass cutting strategy [13]. Figure 1a summarizes the cross-sectional morphology of the processed samples at different laser powers in the study. Based on their study, it can be concluded that high cutting efficiency, high cutting surface quality and high material removal rate can be achieved by using fiber laser for cutting CFRP. Fiber laser cutting of CFRP is prone to thermal damage and formation of heat affected zone (HAZ), which leads to degradation of material properties. The laser parameters need to be strictly controlled, too high energy will seriously damage the material, and insufficient power will not cut thoroughly. Due to its high energy density, it is suitable for cutting CFRP sheets with moderate thickness, high efficiency requirements and less stringent requirements on HAZ, or it can be prioritized in scenarios that are sensitive to cutting speed and cost.

2.2 CO₂ laser cutting glass sheet

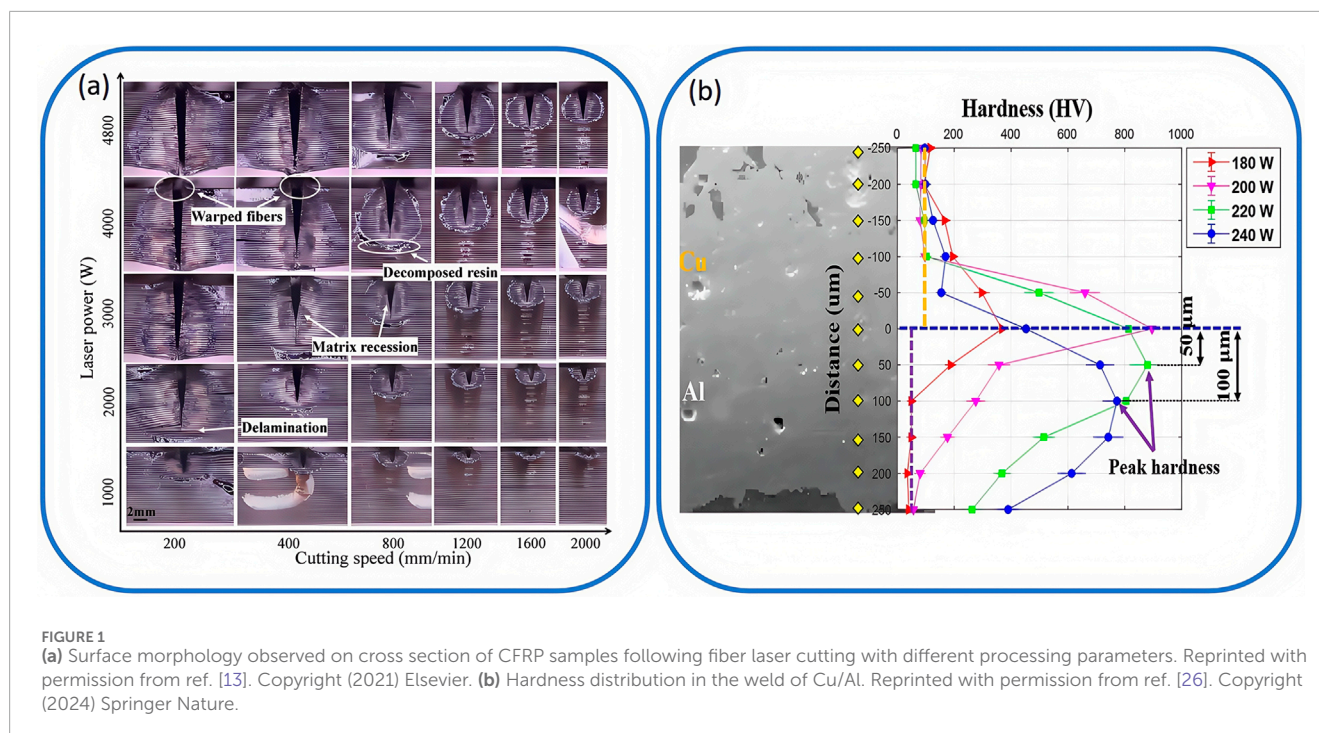
Thin glass sheets are widely used in electronics, microfluidic devices, optical applications and automotive components due to their light weight, high transparency and wear resistance. Due to its brittleness, amorphous nature and low mechanical strength, cutting thin glass sheets has become an important engineering problem. And the traditional mechanical cutting methods suffer from many defects, such as cracks, uncontrollable fracture and fragments at the cutting edge. With the rapid development of CO₂ laser technology in recent years, it is widely used for cutting non-metallic materials, such as cutting thin glass plates, because of its advantages of good processing quality, high processing efficiency [14], cleanliness and environmental protection. However, cutting at open environment can produce a large heat affected zone, which leads to cracks and affects the quality of the cut. Prakash S and Nirala CK did a study of CO₂ laser cutting of glass sheet in different environments [15], which showed that underwater CO₂ laser cutting of glass sheet has significant advantages over open air processing, reducing heat related defects such as crack formation and large damage areas, and the cracks produced during the cutting process are more controllable or crack-free. CO₂ laser cutting of thin glass can be used when high precision and efficiency are required and underwater processing equipment and devices are available.

3 High-power laser welding technology

3.1 Dissimilar metal welding

High-power laser welding is an advanced welding technology that utilizes a high-energy-density laser beam to locally heat the material to a molten state, thereby achieving a material connection. Laser welding is one of the useful techniques that provides high energy and fewer heat deformation and heat-affected zones (HAZs) [16]. Compared to traditional welding methods, laser beam welding enables high manufacturing precision and locally concentrated thermal input into the material at high processing speeds [17]. Traditional welding methods, such as arc welding and resistance welding, there are often slow welding speed, large heat-affected zone, welding deformation and other problems. In contrast, high-power laser welding is capable of realizing high speed and high quality welding with small heat-affected zone and small welding deformation [18, 19]. Moreover, laser welding can be adapted to different working environments [20]. Another advantage of laser welding is that the welding process can be automated by robots and no additional material is required to achieve the specified wall thickness [21]. By means of an advanced control system, the laser beam could be kept focused over a wide range of welding parameters and full penetration was realized [22]. In addition, laser welding is a non-contact process that improves precision and prevents distortion of the weld material [23].

Dissimilar metal welding is of great significance in industrial applications, but traditional welding methods often face many challenges when welding dissimilar metals, such as poor weldability, low joint strength, and the formation of brittle intermetallic compounds [24]. Laser welding of dissimilar materials is



characterized by a thin heat affected zone (HAZ), high energy density, low distortion, high welding speed and high heat input control [19]. Fiber lasers, have the advantages of good beam quality, high conversion efficiency, excellent heat dissipation performance, and good maintainability [1], and are inherently suitable for intermetallic welding, and are considered to be a desirable choice for dissimilar metal welding [25]. Trinh L and Lee D used a pulsed fiber laser to weld aluminum-copper dissimilar metals, which demonstrated that the pulsed fiber laser welding technique can effectively join the two dissimilar metals, aluminum and copper, and the optimization of welding parameters can significantly improve the performance of welding joints [26]. The hardness of the Al/Cu welds in is shown in Figure 1b. At the same time, the optimization of welding parameters can significantly improve the mechanical properties of the joints and reduce defects. Tao TAO et al. used the sandwich-assisted laser welding technique to study the welding of magnesium alloy with steel, and the study showed that under the process conditions of 1,000 W laser power, 30 mm/s welding speed, 30° laser head deflection, 2 mm defocusing, and 15 L/min argon protection, the welding of magnesium and steel can be achieved by adding a sandwich can realize the metallurgical connection between magnesium and steel, and the weld surface is continuous and smooth, without spatter, and well formed [27]. In addition to fiber laser, CO₂ laser also has unique advantages in welding of dissimilar metals, which has the advantages of precise heat input control, high speed welding, high quality weld seam, etc., which is suitable for high quality welding of thick materials, such as dissimilar metal welding in power equipment. Prabakaran M P and his team did CO₂ laser welding of dissimilar metals of mild steel (AISI 1018) and austenitic stainless steel (AISI 316) dissimilar metals to influence dissimilar metal process optimization [28], which showed that the optimum process parameters for CO₂ laser welding of mild steel (AISI 1018) and austenitic stainless steel (AISI 316) can be

determined by Response Surface Methodology (RSM) and Centered Composite Design (CCD) to obtain the maximum weld strength. Therefore, fiber lasers and CO₂ lasers have their own advantages in dissimilar metal welding. Fiber laser welding of dissimilar metals such as aluminum, copper, magnesium and steel is highly efficient and of high quality, while CO₂ laser welding of dissimilar metals in thick materials such as mild steel and stainless steel can be optimized to achieve maximum welding strength.

3.2 Transparent material welding

Laser welding of transparent materials is one of the important research directions of laser technology in recent years. Ultrafast laser welding technology is able to weld a variety of transparent materials, including but not limited to glass, diamond, organic polymers, etc. These materials have important applications in many fields such as aerospace, sensors, microelectronics, optical communications, optical storage, and so on, due to their excellent optical properties, high mechanical strength, chemical stability, and excellent electro-thermal-mechanical properties [29, 30]. Nonlinear absorption and thermal accumulation effects are the core mechanisms of ultrafast laser welding of transparent materials, and efficient energy deposition and thermal accumulation can be realized by precisely controlling the laser parameters. It is found that the welding index will be significantly affected by controlling the number of pulses. Jia X et al. conducted a study on the burst ultrafast laser welding of quartz glass, and found through experiments that the Burst mode with different numbers of sub-pulses had a significant effect on the melting structure and welding strength of quartz glass, indicating that the length of the melting structure increases and the width decreases with the increase of the number of sub-pulses, but the welding strength gradually decreases [31]. Femtosecond laser welding of transparent materials has also made

significant progress in recent years. Gao Z et al. proposed a method of using a double-pulse femtosecond laser to weld quartz glass under non-optical contact conditions by adjusting the optical paths of the two pulsed lasers to control the time difference between their arrivals at the sample to achieve double-pulse processing, and by optimizing the parameters of the average power, pulse delay, and scanning intervals, we have successfully realized the High-strength welding of quartz glass under non-optical contact conditions, the welding strength reached 57.15 MPa, and the temperature resistance test showed that the welded samples have excellent stability and thermal shock resistance under high temperature conditions [32]. Laser welding of transparent materials technology has shown great potential for application in many fields due to its wide material applicability, high precision, and excellent welding performance. With the continuous innovation and optimization of the technology, its prospect will be even broader.

4 High-power laser drilling technology

4.1 Alumina ceramic drilling

High-power laser drilling technology is a processing method that uses a high-energy density laser beam focused on the surface of the material to remove the material through local melting and vaporization caused by the high-energy laser beam, without the need for traditional drilling tools [33], and to achieve precise removal of the material and the formation of holes. Compared with traditional mechanical drilling, laser drilling laser drilling can produce a large number of holes in a non-contact manner, with non-contact machining, fast speed, high machining accuracy, wide range of applications and other significant advantages, laser beam drilling is widely used in a variety of aerospace fields that require high dimensional accuracy and hole quality [34]. Alumina ceramics are widely used in electronics, machinery, healthcare and other fields due to their excellent hardness and high temperature stability [35]. However, the traditional processing methods have problems such as low efficiency, large heat affected zone, and poor hole wall quality. Compound pulsed laser (CPL), by combining two or more lasers (e.g., millisecond and nanosecond lasers), can significantly improve the drilling performance. Li Z et al. investigated the dynamic process of compound pulsed laser (CPL) drilling in alumina ceramics through theoretical modeling and experimental validation, and demonstrated that the CPL can achieve high efficiency and high quality microporous machining without the aid of high-pressure gases or absorbing coatings, and high-quality microvia processing without the assistance of high-pressure gas or absorption coating [36], which provides important technical support for the miniaturization of ceramic substrates.

4.2 Composite material drilling

Composite materials are widely used due to their excellent properties, CFRP is widely used in aerospace field due to its light

weight and high strength, but its laser drilling process is prone to problems such as accuracy, surface quality and thermal damage, while SiCf/SiC is widely used in many fields due to its excellent high temperature mechanical properties and oxidation resistance, so it is necessary to study its drilling strategy in depth in order to improve the processing quality. Liu X et al. conducted a study on optimizing the laser drilling strategy for CFRP, and used a one-way experimental strategy to investigate the effects of the laser beam moving order (Scheme I and Scheme II), scanning spacing, and the direction of pumping (Pump-Front and Pump-Rear) on the hole quality under the helical scanning path, showing that the laser beam moving order (Scheme I) and the direction of pumping (Scheme III) are the same as those of Scheme I and Scheme IV, respectively, but the laser beam moving order (Scheme I) and Scheme II are the same as those of Scheme III. It is shown that the best micro-hole accuracy, surface morphology, and the smallest thermal damage defects can be achieved when Scheme I moving order, 20 μm scanning spacing, and Pump-Rear pumping direction are adopted, which can effectively improve the quality of CFRP laser drilling, and provide new insights and optimization references for the research in this field, Figure 2a shows the schematic diagram of the laser drilling system [37]. SiCf/SiC composites are difficult to process with the characteristics of high hardness, high brittleness, and low electrical conductivity. SiCf/SiC composites, with high hardness, high brittleness, low electrical conductivity and other characteristics, are difficult to process, and there are many challenges in the processing of their small holes. The femtosecond laser has the advantages of short pulse and small heat-affected zone, and the femtosecond laser rotary drilling technology can realize small-hole machining with high precision and short drilling time, and the femtosecond laser rotary drilling (FLRD) technology also shows great potential for the application of the femtosecond laser rotary drilling technology to the machining of small holes in the difficult-to-machine materials, such as the silicon carbide fiber-reinforced silicone carbide-ceramic matrix composites (SiCf/SiC), Feng Y et al. The application of femtosecond laser rotary drilling (FLRD) technology in the small hole processing of silicon carbide fiber reinforced silicon carbide ceramic matrix composites (SiCf/SiC) was investigated by experimental research, which showed that FLRD technology can effectively improve the quality and efficiency of small hole processing of SiCf/SiC composites, and realize the processing of small holes with no obvious thermal damage, high precision, and short drilling time, which can provide a solution for the precision processing of small holes in difficult-to-machine materials. The FLRD technique can effectively improve the quality and efficiency of small-hole machining of SiCf/SiC composites without obvious thermal damage, realize high-precision and short drilling time, and provide a new method for precision machining of small holes in difficult-to-machine materials, Figure 2b shows the FLRD system including a femtosecond laser, a rotation optical system, a focusing module, and so on [38]. These studies provide valuable theoretical support and practical guidance for the application of high-power laser drilling technology in different difficult-to-machine materials, and promote the further development and application of this technology in aerospace, electronics, machinery and other fields.

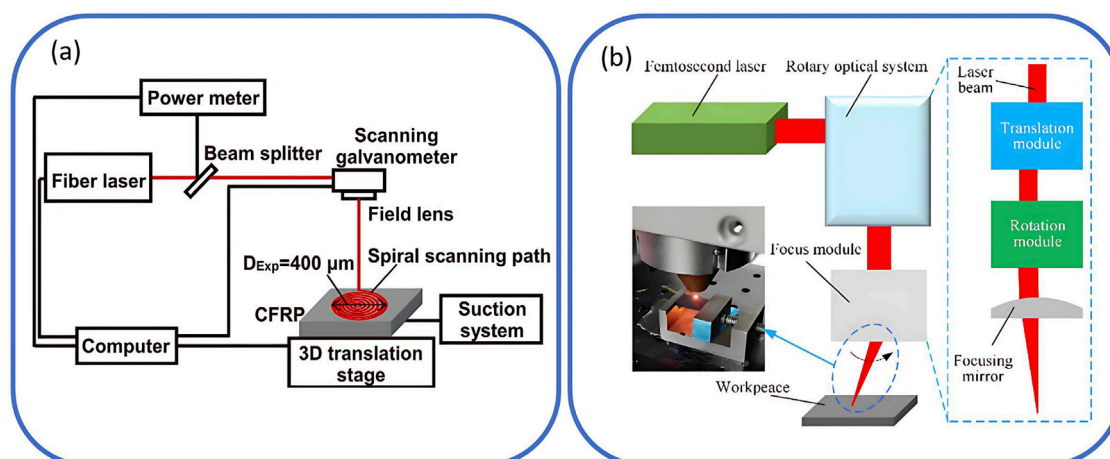


FIGURE 2

(a) Laser drilling experimental system. Reprinted with permission from Ref. [37]. Copyright (2024) Elsevier. (b) Schematic diagram and actual processing of FLRD system. Reprinted with permission from Ref. [38]. Copyright (2025) Elsevier.

5 Conclusion and outlook

In summary, high-power laser cutting and welding technology has many advantages, but still faces some challenges in practical applications, such as when processing highly reflective materials, the reflection of the laser beam may lead to damage of guards or melting of specific areas of other sensitive components [39]; when cutting thick plates, the cutting speed and quality are difficult to be guaranteed; and the laser welding process produces a serious thermal conversion effect, which has high demands on the welding process parameters and the Workpiece fixation precision requirements are very high [40]. When welding thick plates, in addition to ordinary defects, special defects such as root defects, intermediate cracks (longitudinal and transverse), humps, and air holes can occur during the formation of lock holes [41]. Laser drilling faces challenges such as the control of thermal effects in high-precision micro-hole processing and the need for higher energy density and longer processing time when processing thick or hard materials, where processing efficiency has to be optimized. In addition, the high cost and stringent maintenance requirements of high-power laser equipment limit its wide application in certain fields. The continuous progress of ultrafast laser technology will provide new ways for high-precision and low-damage material processing. The integration of laser processing and artificial intelligence will realize real-time monitoring and parameter optimization of the processing process, improving production efficiency and processing quality. At the same time, laser-assisted processing technology innovation, such as laser-assisted additive manufacturing, laser micro-nano-processing, etc., will expand the application areas of laser technology, providing stronger technical support for intelligent manufacturing. In short, the application of high-power laser technology in the field of machining has a broad prospect. By constantly overcoming the limitations of the existing technology

and promoting the development of technological innovation, high-power laser technology will realize breakthroughs in more fields, and provide strong support for the upgrading and innovation of the manufacturing industry.

Author contributions

Y-GW: Investigation, Writing – original draft, Resources. S-PH: Writing – review and editing, Supervision. Q-CL: Writing – review and editing.

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