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Development of Laser Cutting and Joining Processing

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Abstract: Laser cutting and joining technology is an indispensable advanced manufacturing technology owing to its comprehensive advantages of flexibility, high efficiency, and high quality, and it has had a profound impact on the manufacturing industry. With the intelligentization of advanced manufacturing, laser cutting and joining technology is set to be augmented by the integration of laser and digital manufacturing technology. This study selects and analyzes the four specific technologies that are most widely used in industry to assess the application status of laser joining and cutting technology, namely, laser welding, laser cutting, laser drilling, and laser marking. The problems faced in the development of laser joining and cutting technology are discussed. The study indicates that the development of laser cutting and joining technology should focus on the integration of fundamental processes and equipment to improve key technologies in laser processing units, laser materials processing, and intelligent integration. Moreover, the research platforms for fundamental processes should be strengthened, with a focus on the multi-dimensional combination of technological innovation and talent training. This will promote the coordinated development of laser cutting and joining technology from application development to equipment market guarantee.
Keywords: laser material processing; laser welding; laser cutting; laser drilling; laser marking

1 Introduction

More than 60 years have passed since the ruby laser was first invented in 1960. The CO_2 laser and fiber-delivered yttrium aluminum garnet (YAG) laser have been utilized in various industries for more than 40 years. Over the past decade, disk, fiber, and diode lasers have been rapidly developed and are receiving considerable attention for industrial applications. Laser technology is constantly driving the development of advanced manufacturing technologies. Lasers are important material processing tools and play a meaningful role in lightweight structure manufacturing, green manufacturing, etc. Laser cutting and joining processing is the most extensive and active example of laser material processing technology. It includes laser cutting, laser welding, laser drilling, and laser marking, which have been widely used in aviation, aerospace, vehicles, ships, construction machinery, and other industrial fields [1–3]. Based on data analysis of global laser processing technology patents from 1996 to 2016 [4], the key aspects of innovation and development in laser processing technology focus on laser welding, laser cutting, and laser drilling. This also reflects the future market demand for laser cutting and joining.

Lasers can be controlled in the energy, time, frequency, and space domains, which is beneficial for improving manufacturing efficiency, precision, and quality, and plays a promoting role in the innovation of product design and manufacturing concepts. This shows that laser processing technology can reflect the inherent advantages of high-quality manufacturing when integrated with computer-control, sensing, digital, and intelligent technology. Advanced

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countries and regions have included laser processing in their key development plans for advanced manufacturing technology. China has also established laser processing technology as an important development direction to enhance the national manufacturing capacity. Intelligent and smart manufacturing has become the main direction of global manufacturing transformation [5]. Laser cutting and joining technology is an important aspect of laser material processing technology. The integration of laser processing technology with digital and intelligent technology is an urgent problem to be solved for the future development of laser manufacturing by 2035. Moreover, it is also the key to promoting the transformation and upgrading of the country's manufacturing industry and improving the manufacturing technology level.

This paper discusses the technical meanings of laser cutting and joining technology and its development status and existing problems, as well as the key technology that needs to be developed. Finally, some suggestions and solutions are proposed on how to promote the development of laser removal and connection technology to support future laser manufacturing application requirements.

2 Laser cutting and joining processing

The principle of laser cutting and joining technology is that the laser acts on materials to produce marking, etching, removal, solidification, or melting via the thermo-mechanical coupling effect between the laser beam and material, and subsequently, laser processing technologies such as laser welding, laser cutting, laser drilling, and laser marking can be realized. In other words, the specific process of laser cutting and joining depends on the matching relationship between the laser power density and laser action time, as shown in Fig. 1.

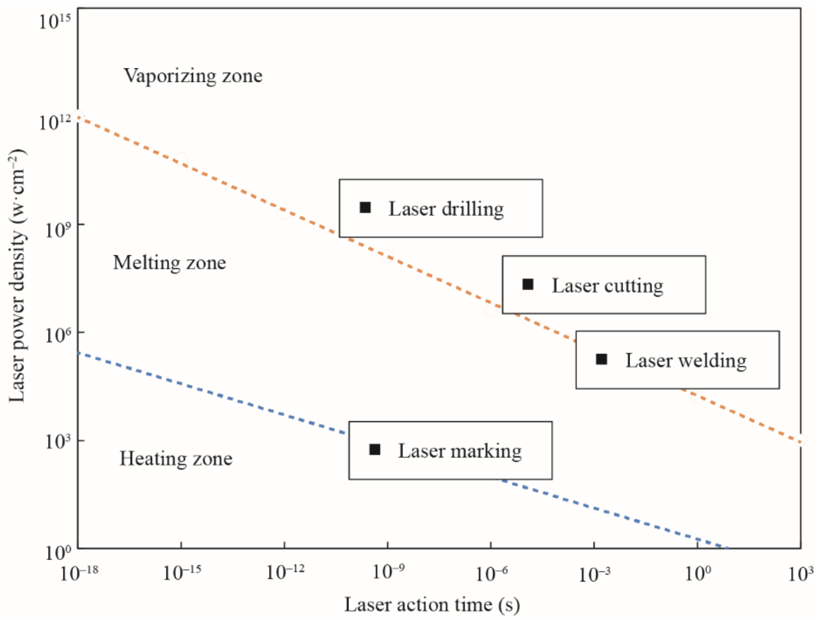

Fig. 1. Influence of laser power density and laser action time on thermal effect.

A variety of processing techniques have been derived from laser cutting and joining technology, as shown in Fig. 2, which are related to the mechanism of thermal action resulting from the laser employed. Laser cutting and joining technology can use different laser wavelengths. At present, the principal lasers used for cutting and joining include CO_2, YAG, fiber, and semiconductor lasers. These lasers can also be used for continuous power output by pulse power output for laser cutting and joining. Several types of pulse laser can be used for material processing, such as millisecond, microsecond, nanosecond, picosecond, or femtosecond ultrafast lasers. When the laser characteristics are different, the control method for the laser beam output can be different and can result in different working mechanisms. Therefore, this method can be adapted to the processing of different materials and structures.

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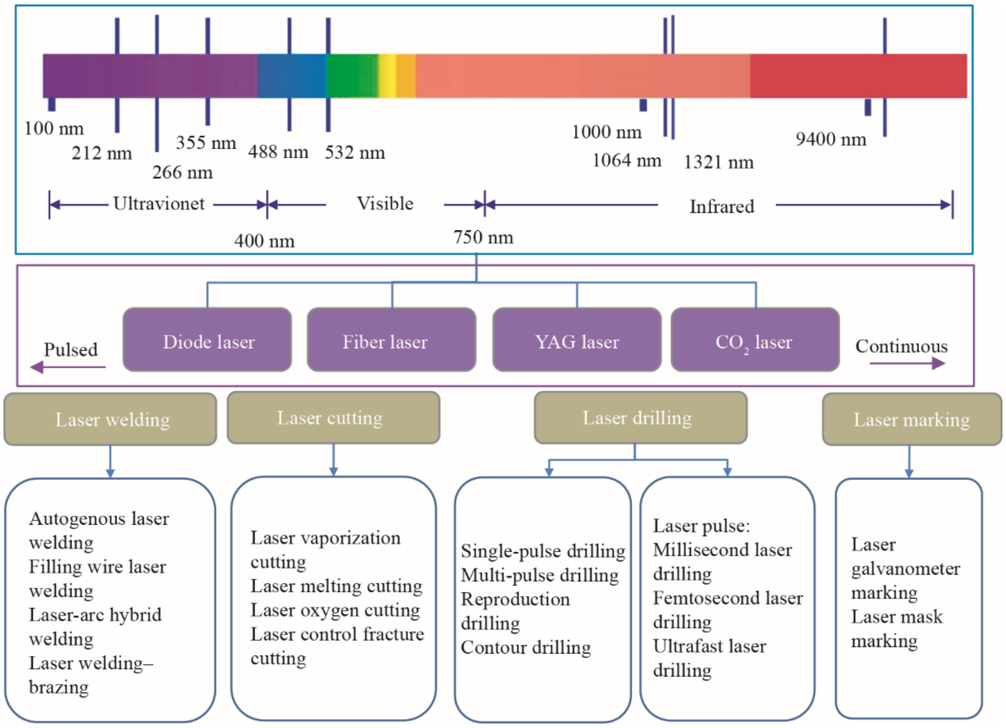

Fig. 2. Classification of laser cutting and joining technology.

2.1 Laser welding

Laser welding is a fusion welding process in which laser beam radiant energy with adjustable focus control is used to produce the heat required to melt and vaporize the materials, and form a molten pool on the materials. The molten pool then solidifies and crystallizes to form a metallurgical joint when the laser beam moves forward. Compared with the traditional welding method, laser welding has the advantages of concentrated heating and low welding deformation, which can improve the utilization rate of the structural materials and reduce the structural weight and cost. There are two modes of laser welding: conductive laser welding, which is mainly used for precision welding of microstructures such as instruments and electronic components; and deep penetration laser welding, which is considered an important welding method for large-scale structures in automobiles, ships, aviation, aerospace, nuclear power, and other fields. However, laser welding requires high precision for parts assembly before welding as a result of its very small beam size, and it is difficult to weld highly reflective materials with lasers. To solve these problems and avoid weld defects due to fusion welding, a variety of processes have been derived from laser welding, such as laser welding with filling wire, laser arc hybrid welding and laser welding–brazing, multi-beam laser welding, and beam-oscillating laser welding.

2.2 Laser cutting

Laser cutting is a slitting or removal process during which an intense light beam quickly heats up and melts the material, and a high-velocity auxiliary gas is applied to remove the molten metal from the cut kerf simultaneously. The advantages of laser cutting are contactless cutting, repeatability, high quality, high precision, and a small heat-affected zone. All materials commonly used in industrial processing, including metals and non-metal materials such as, glass, wood, and leatherwear, can be cut safely and with high quality using the laser. There are four cutting processes. Laser vaporization cutting is mostly used for metal and non-metallic thinner sheets, which require a high-power-density laser. Laser melting cutting is mainly used for stainless steel, titanium alloys, and aluminum alloys. Laser oxygen cutting is generally used for steel and other easily oxidized metals in which laser and oxygen oxidation reaction heat is used as energy, and can produce a higher cutting speed than laser vaporization cutting or melting cutting. Laser-controlled fracture cutting is only used for cutting brittle materials that can be quickly and neatly severed by guiding a crack with a fine spot heated by a laser, because these materials are vulnerable to thermal fracture. Moreover, it is noted that research on and development of the cutting process and equipment should be related to the cutting parameters, including laser power, cutting speed, focus position, and auxiliary gas [6].

2.3 Laser drilling

Laser drilling is a method that uses a high-energy pulsed laser to produce holes on components that have little effect on the hardness, rigidity, strength, and brittleness of materials, and can realize high-speed and efficient drilling. The process of laser drilling requires the cooperation of optical, mechanical, and electrical integration technology to obtain micro, inclined, irregular, or closely spaced holes, which are always designed for aeroengine blades [7]. Beam rotation is usually used during laser drilling because it can produce fast holes with high inner surface quality and can easily build group hole processing. The laser drill also uses direct beam drilling, which is suitable for microholes with apertures of 0.05–0.6 mm. The laser beam can be moved by tracing the hole machining line to the cut hole, which is suitable for large-scale holes with apertures of 0.05–3 mm.

2.4 Laser marking

When the laser irradiates the material, vaporization etching or chemical reaction occurs on the surface to form a permanent and clear mark without damage to the material, which is defined as laser marking processing. Laser marking can be employed for all types of materials, including integrated electronic modules, automotive glass, medical devices, rubber products, and mobile phone panels, and is also suitable for functional treatment of polymer surfaces [8]. Laser marking can be realized by laser mask scanning or by multiple laser-emitting pulse arrays, and beam scanning can be mechanically or galvanometer driven.

3 Development status of laser cutting and joining

Laser cutting and joining technology has found widely customized applications in industry. Developed countries and regions, especially in Europe and the USA, have built up an industrial ecological chain ranging from laser sources to processing equipment, which supports effective laser cutting and joining technology integrated into various industrial manufacturing fields. Laser applications in this technology field have matured considerably in China over the last decade. The Chinese laser industry chain for laser cutting and joining technology is also well established. However, there is still a gap compared with the international level for high-end laser manufacturing equipment. With the advent of the Internet era, higher demands have been put forward for the intelligentization of laser equipment and product manufacturing in industrial fields.

3.1 Laser welding

Laser-welding applications have received attention in Europe and the USA since the mid-1980s. The first laser tailor-welded blanks were reported to have been applied to the Audi 100 body in 1985. Airbus published that laser-welding aluminum alloy panel structures were used in the fuselage of the Airbus 380 in 2005, which has become a symbol of progress in aviation manufacturing technology [3]. With the evolution of society, energy conservation, environmental protection, and other green manufacturing technologies have become a global focus. This is driving an increase in laser-welding applications in all industries. More demands are emerging to support the development of laser-welding applications to improve their technical stability, equipment reliability, and quality assurance [9]. In recent years, great progress has been made in the application of laser-welding technology in China, and it has been applied to aircraft panels, rail cars, and other applications [3,10]. Over the last decade, fiber lasers have been the focus of laser-welding applications. In the future, low-cost, high-power semiconductor lasers could find wide applications for welding. Research on and development of laser welding will focus on how advanced lasers can be combined with advanced numerical control and robot technology.

3.2 Laser cutting

Laser cutting is the earliest form of laser material processing and the one that has been applied the most extensively worldwide. Laser cutting is also developing rapidly in China. Chinese laser-cutting equipment has also entered the international market and has supported the expansion of application of laser cutting from steel structures to non-ferrous metal structures. Currently, the tendency of laser-cutting technology and equipment is moving toward high-level research and development abroad, where more attention is paid to the development of high-power, intelligent laser-cutting equipment in conjunction with research on laser beam control optimization and cutting process simulation, as well as extended applications in special environments [6]. At present, the application potential of laser-cutting technology in China’s traditional industrial upgrading and transformation processes is increasing. It is urgently required

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to match laser-cutting technology with existing technology, promote laser-cutting technology in more production fields, and improve the intelligence level of high-power laser cutting equipment.

3.3 Laser drilling

Laser drilling is the development direction of drilling technology in industrial fields. The efficiency of laser drilling is 12–15 times that of EDM and 200 times that of mechanical drilling. The laser beam makes it possible to drill holes with poor machinability as a resulting of the advantage of laser action. Femtosecond laser-drilling technology has received more attention in recent years because it is a good tool for producing film-cooling holes on engine blades. Compared with nanosecond laser drilling, femtosecond laser drilling produces a cold working effect, which can avoid the recast layer and microcracks during processing. Moreover, the intelligent control system helps the laser-drilling equipment to realize beam adaptive adjustment in conjunction with workpiece high-speed automatic positioning, thereby ensuring the precision machining of the film-cooling holes [11].

3.4 Laser marking

The application of laser-marking technology is basically consistent with the development of a laser-marking control system, which has gone through three stages during 1995 and 2003. These stages generally refer to the control of beam line movement for a large-scale surface, by mirror rotation, and using a galvanometer. Laser marking control systems have gone through a development process from direct control to upper and lower computer control, and then to real-time processing and time-sharing multiplexing control. At present, with the application of semiconductor, fiber, and ultraviolet lasers in laser marking, new requirements have been proposed for the process control of laser marking.

4 Issues with laser cutting and joining technology

With the development of industrial lasers and intelligent technology, laser cutting and joining technology is evolving from "laser manufacturing" to "laser intelligent manufacturing." Laser cutting and joining technology urgently needs to be upgraded to adapt to the strategic transformation of traditional industries, and to develop key technology integrated deeply with information technology and intelligent technology. Recently, great progress has been made in the integration and intelligent development of laser cutting and joining equipment, and the market scale has gradually expanded. However, to promote the key technology of laser cutting and joining, and integrate it with advanced laser technology, high-end equipment technology, and digitalization, as shown in Fig. 3, there are unsolved problems that need to be addressed and innovated.

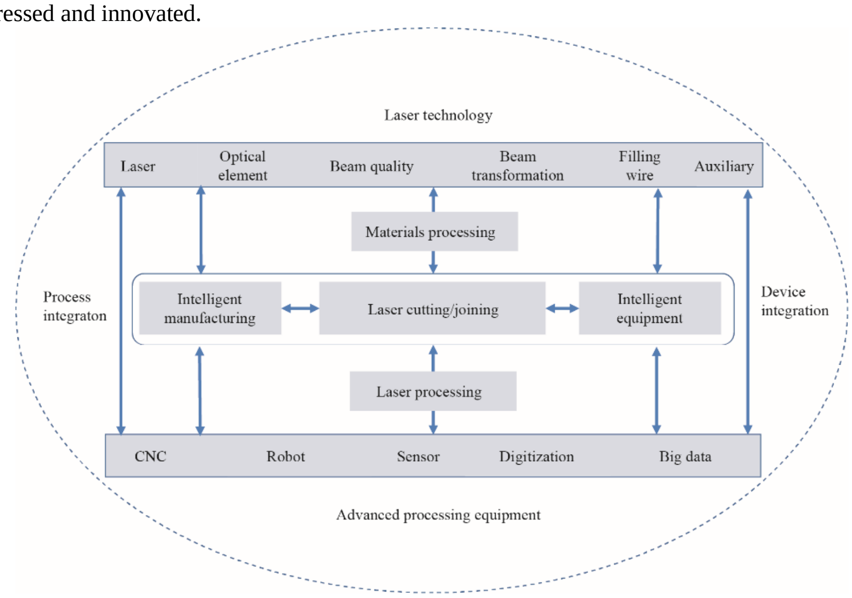

Fig. 3. Process equipment integration for laser cutting and joining.

4.1 Processing recognition and informatization

It should be emphasized that fundamental research is necessary to expand the industrial application of laser cutting and joining technology. In terms of new material applications and structure manufacturing, it is essential to elucidate the mechanism of defect formation and the method of defect prevention by fundamental processing research. With technology innovating oriented laser cutting and joining, it is important to understand how to control and detect defects during processing.

With increasing digital development of processing, the challenge facing laser cutting and joining technology is to establish a fine and precise digital connection between materials, processes, and equipment, and then to build a simulation system of product lifecycle manufacturing that can be used to extract key elements for solving the realization of intelligent manufacturing.

4.2 Laser beam feature and processing ability

Laser cutting and joining technologies are widely used in macro and micro manufacturing. With the increasing requirement of high-speed and efficient laser processing technology, the employed lasers should improve their quality and stability. However, domestic lasers have not been able to cope adequately with the application boom for laser cutting and joining in China, especially high-power and high-brightness lasers. It is urgent to strengthen research-related processing principles and parameters for laser beam feature control.

4.3 Laser working cell and processing ability

To some extent, laser cutting and joining technology can be applied reliably in industry depending on the functionality and controllability of the laser-processing cell. In particular, the precise control of the beam energy is combined with beam movement by means of digital control. Laser processing can realize multi-physical field control in the laser energy, time, frequency, and space domains according to the requirements for cutting and joining. For example, a rotary-scanning processing unit can enable laser welding with molten pool control to simulate high-level manual welding. This suggests that the experimental data should be transplanted to the processing cell to ensure its intelligent and extensive application.

4.4 Understanding of intelligent integration for laser cutting and joining equipment

The goal of intelligent equipment integration is to realize high-efficiency and high-precision manufacturing of laser cutting and joining technology. On the one hand, it has the integrative control of laser beam output, beam moving, and detection system. On the other hand, it has an integrative software tool that has the ability to optimize processing and make independent decisions. It is more important that it includes the transmission and integration of information flow, including process simulation information based on its mechanism research, process experimental data information, and multi-layer control data information. In summary, the theoretical research and soft tool development of the information mentioned above will be important pillars supporting the intelligent development of laser cutting and joining technology in the future.

5 Key technology for laser cutting and joining

Based on the 2030 development strategy of advanced manufacturing technology, laser cutting and joining technology should strengthen technological research on the entire manufacturing cycle. It should be noted that fundamental research on the processing principle is the source of development of laser cutting and joining technology, which needs to deeply integrate information technology to satisfy the increasing industry demand. There is more process information to be unearthed for key technology solutions during the entire manufacturing cycle. Many common and separate problems need to be researched for processing equipment integration and information integration. More attention should be paid to the intelligent connotation of laser cutting and joining technology to make breakthroughs in key technologies. With regard to the application of laser cutting and joining technology, the following key technologies should be considered.

5.1 Process optimization based on big data

The mechanism of laser cutting and joining involves a complex physical phenomenon resulting from the thermal and mechanical action of the laser on the material. The material properties and states vary with changes in the beam energy and beam movement relative to the equipment control. The objective of processing optimization is to study the relationships between parameters, forming quality, microstructure, and properties for special processing, through which

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a correlation model can be established. However, there is currently no proper chain to integrate simulations and experiments for processing research. This can easily cause uncertainty in process optimization and restricts the intelligent development of laser cutting and joining technology. Therefore, it is crucial to solve the optimization and planning of the entire manufacturing cycle, which the simulation research has clarified properly for experimental research. Big data technology is used to transform simulation data that reveal the scientific features of processing into controllable processing data, and to explore the scientific features in experimental data. It is also the key to realizing virtual manufacturing for laser cutting and joining.

5.2 Flexible laser processing unit

It is an important aspect of integrated intelligent equipment for laser cutting and joining that the laser processing unit is made flexible. On one hand, the integration of beam control and auxiliary parameter control can offer a solution to improving laser processing accuracy; for example, parameter control can match movement control for filling wire, exporting gas, and focusing the beam during laser welding. On the other hand, the integration of sensors and data flow of the laser processing unit allows integration of the “eye” of the processing unit and the “brain” of the control system. The future development direction of laser processing cell technology is to integrate the laser beam source control technology into the laser processing cell.

5.3 Intelligent integration technology of laser processing equipment

The industrial application of laser cutting and joining technology strongly depends on the function and reliability of the equipment. Therefore, the development of intelligent integration technology for laser output, beam movement, and process detection sensors is essential for the realization of automatic, digital, and intelligent processing for laser cutting and joining. However, it is not simply assumed that the intelligentization of laser processing will use robots, CNCs, and big data technology. Understanding the interaction of the multi-dimensional energy field that occurs during laser processing requires more in-depth research with the help of cognition and perception technology. It is assumed that the integration of multiple systems and software tools will play a supporting role in intelligent laser cutting and joining based on core control of the beam motion trajectory, which incorporates the controls required for optics, mechanics, electricity, materials, technique, control, and information.

6 Summary

The intelligent development of laser cutting and joining technologies is an important trend for the future. From a technical perspective, we should not only focus on integration with advanced information, digital manufacturing, and laser technology, but also be aware of the importance of developing digital technology related to laser cutting and joining with respect to the entire lifecycle of product manufacturing. Scientific understanding of laser processing is the basis of intelligent development. The merging of processing analysis software with information transmission software and the integration of processing control with equipment control will be the key to supporting the development of laser processing technology.

The development of laser cutting and joining technology depends on multidisciplinary merging as well as government guidance and support. It also requires contributions from enterprises, institutions, universities, etc. First, it should provide a high-level innovation platform to guide and support fundamental research on laser processing and innovative design of processing cells. This platform should create a favorable environment for bringing talents, scientists, and relevant enterprises together to research and innovate new principles and methods with the aim of improving laser cutting and joining technology. This platform should also become a basis for fostering specialized talent and incubating new products related to laser cutting and joining technology. Second, the government and enterprises have collaborated to plan the development roadmap of laser cutting and joining technology, which includes all requirements ranging from laser beam quality to products manufactured by laser, especially lasers satisfactory for material processing, equipment cells supporting material processing, and reliability of the process performed. It should be emphasized that key projects could meet the demands for the entire lifecycle of products manufactured mainly by lasers. An effective method of ecologically guiding the development of laser cutting and joining technology is by enhancing high-end technology development capacity, balancing mid-level technology rebuilding capacity, and regulating low-end technology.

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