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REVIEW ARTICLE

Progress of laser cleaning technology from the perspective of Chinese patents

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ABSTRACT Laser cleaning technology has emerged as a rapidly developing high-tech surface engineering technology in recent years. It is considered the most promising green cleaning technology in the 21st century, and related patent applications exhibit an explosive growth trend. This study summarizes the overall trend of patent applications in laser cleaning in China, with a focus on systematically analyzing patents related to cleaning different substrates and coatings, cleaning equipment, and processes over the past 6 years. The main characteristics of the growth trend, institutional attributes, regional distribution, and type proportion of laser cleaning patent applications in China are clarified. The patent application characteristics of laser cleaning for different substrate materials and coatings are identified. The progress in research and development of laser cleaning equipment, cleaning terminals, and monitoring devices is outlined, while potential for maintaining substrate surface integrity and achieving surface functionalization through laser cleaning is explored. Areas for improvement in laser cleaning are determined to support the innovative development of laser cleaning technology.

KEYWORDS laser cleaning, patent analysis, equipment development, trend analysis, surface functionalization

1 Introduction

Traditional cleaning methods, such as mechanical polishing, easily cause irreversible damage to the workpiece, while chemical cleaning leads to serious pollution. Ultrasonic cleaning, high-pressure water jet cleaning, sandblasting cleaning, and other methods are time-consuming, consumable, cumbersome, and environmentally unfriendly. They also have difficulty meeting the current requirements of high-quality, efficient, and green industrial cleaning. Laser cleaning technology is gaining increasing attention from researchers because of its numerous advantages: it does not damage the substrate, causes no pollution, is safe and intelligent, and offers high cleaning efficiency and quality. The principle involves using a laser to irradiate the surface of pollutants, which causes them to detach from the surface of the workpiece under the combined effects of vibration [1], ablation, and photochemical actions. Moreover, improving the laser power can induce plasma shock waves that penetrate the air medium and act on the surface of the workpiece to remove pollutants [2]. Laser cleaning technology can also strengthen the substrate surface [3], improve corrosion resistance [4], and enhance hydrophobicity [5] while cleaning. In recent years, laser cleaning technology has been widely used in various fields, such as cultural relics protection [6], rubber molds [7], road transport [8], aerospace [9], ocean-going operations [10], and semiconductor workpieces [11].

Although laser cleaning technology has obvious advantages, it still encounters challenges in practical application. For example, the improvement in laser cleaning efficiency, the in-depth understanding of cleaning mechanism, the development of online monitoring technology, and the research and development of intelligent equipment need further research and innovation. Zhu et al. [8] employed dry and wet nanosecond laser cleaning techniques to remove road markings in various colors. They investigated the best cleaning protocols by adjusting the laser energy density

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and the overlap ratio of the laser spots. However, although the cost of laser cleaning technology for actual road cleaning is low, the efficiency is still an important factor limiting its replacement of traditional road cleaning technology. Zhang et al. [12] discussed the mechanism of removing blue and red polyurethane paint from aluminum alloy surfaces by nanosecond pulse laser cleaning. Their study provided parameter information and a theoretical basis for selecting appropriate laser cleaning technology for different colors and types of paint. Li et al. [13] and Zhu et al. [14] summarized the research progress of monitoring technology of laser cleaning technology. They noted that the monitoring technology is vulnerable to environmental interference in practical application and encounters problems such as reliance on light source illumination and poor real-time performance. Ouyang et al. [15] optimized the energy consumption and performance of laser cleaning for coating removal. Hou et al. [16] reviewed the thermal effect and substrate damage control in laser cleaning. The review showed that the diversification of cleaning methods, the selection of laser parameters, and the technology of real-time monitoring are the keys to achieve efficient cleaning and maintain the integrity of the substrate. Selecting appropriate laser parameters, optimizing the cleaning process, and realizing real-time monitoring and intelligent control based on different cleaning objects are the focal and difficult areas in current research. These aspects are also critical for knowledge capitalization, technology transfer, and commercialization.

All valuable technologies usually seek strong authority for exclusive protection, with patents covering nearly all of the most advanced technology research and development. Patents also often reflect whether the applicant and the inventor fully anticipate the potential of the technology and indicate the development direction of the application in related fields. The China National Intellectual Property Administration is an institution directly under the State Council, which is responsible for collecting and managing patents. This study utilizes the "patent retrieval" function provided by the China National Intellectual Property Administration to analyze relevant patents in the past 6 years (from January 1, 2018 to December 31, 2023) for exploring the research status and development trend in laser cleaning in China.

2 Overall overview of laser cleaning patents

On January 24, 2024, data on China's utility model and invention patents related to laser cleaning were inquired. As of December 31, 2023, 3507 entries were available. These data were added to the China National Intellectual Property Administration web analytics library to understand the overall situation of laser cleaning patents in China. Despite the comprehensive collection, the analysis of the overall development trend of laser cleaning remains unaffected. This study focuses on the development trend of related patents, the proportion of classification, the distribution of institutional attributes, and the number of patent applications across provinces.

2.1 Basic trend of laser cleaning patents

Figure 1 shows the development process of laser cleaning before 2013. In 1994, Cauldron Co., Ltd. [17] proposed to selectively remove substances by irradiation, which can remove impurities such as grease, paint, and oxide on the surface of the substrate without affecting its physical characteristics. This patent is the first in China to remove pollutants by laser irradiation. Initially, attention on laser cleaning technology was low in China. As shown in Fig. 2, the first patent related to laser cleaning technology appeared only until 1999 [18]. In 2004, the Institute of Engineering Thermophysics of the Chinese Academy of Sciences [19] developed a device for laser cleaning of micro and nanoparticles. This patent was the first in China to achieve nanoscale particle removal and was named after laser cleaning. In 2008, Tsinghua University [20] disclosed an all-solid ultraviolet laser washer and laser cleaning method. For the cleaned AlN plate silver, the adhesion of the silver layer increased by 120% compared with the plate without laser cleaning. This

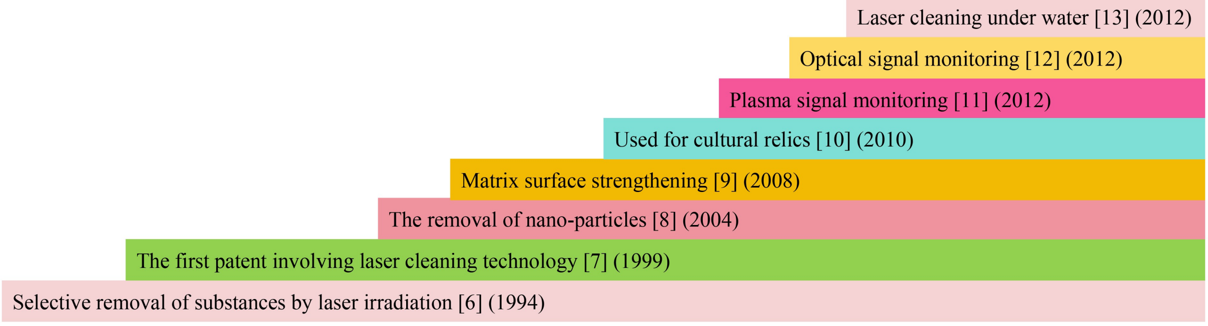

Fig. 1 Development process of laser cleaning before 2013.

patent was the first in China for laser cleaning aimed at matrix surface reinforcement.

In 2010, the Laser Fusion Research Center of China Academy of Engineering Physics [21] proposed a portable laser cleaning machine for stone cultural relics, which was the first laser equipment in China dedicated to cultural relics cleaning. In 2012, Jiangsu University [22,23] suggested the method of automatically judging the laser cleaning effect and testing the laser cleaning threshold. They monitored the cleaning situation through optical and plasma signals to prevent incomplete cleaning and excessive damage to the matrix. In the same year, Jiangsu University [24] also invented an underwater laser cleaning method. High-energy laser action generated a large number of cavitation bubbles in water, and the contaminated layer on the surface of underwater workpiece was cleaned by the shock wave generated by the cavitation effect.

As laser cleaning technology matures, its application fields are becoming extensive. The development trend of laser cleaning patents in China (Fig. 2) shows that, since 2013, the number of patent applications for laser cleaning has increased considerably, and the technology is now in a high-speed development stage. The ranking of the number of keywords from 2018 to the present is analyzed. As shown in Fig. 2(b), the higher prominence of a keyword indicates a more significant advantage in the field of patents. Patents related to laser cleaning mainly focuses on the research and development of laser cleaning equipment suitable for different types of workpieces, with a significant number of patents applied to tire mold cleaning. Given the vast automobile industry market, laser cleaning technology for tire molds has promising development prospects.

In general, laser cleaning not only ensures the surface integrity of the substrate but also conforms to the global environmental protection strategy to achieve green and efficient surface cleaning, which has long-term development prospects.

2.2 Classification and proportion of laser cleaning patents

According to the International Patent Classification System (IPCS), more than 80 categories of laser cleaning patents have been identified, with the main classification information shown in Table 1. Given that a patent may be divided into multiple classification numbers, the number searched is more than the actual number. This study analyzes only the classification proportion of laser cleaning patents. As shown in Fig. 3, B08 (cleaning) accounts for approximately 52%, which indicates that the current focus of laser cleaning patent is on effectively removing pollutants. The disruptive improvement in laser cleaning efficiency depends on the research and development of high-power lasers, but relevant hardware patents only account for 12%, as shown in B23 (machine

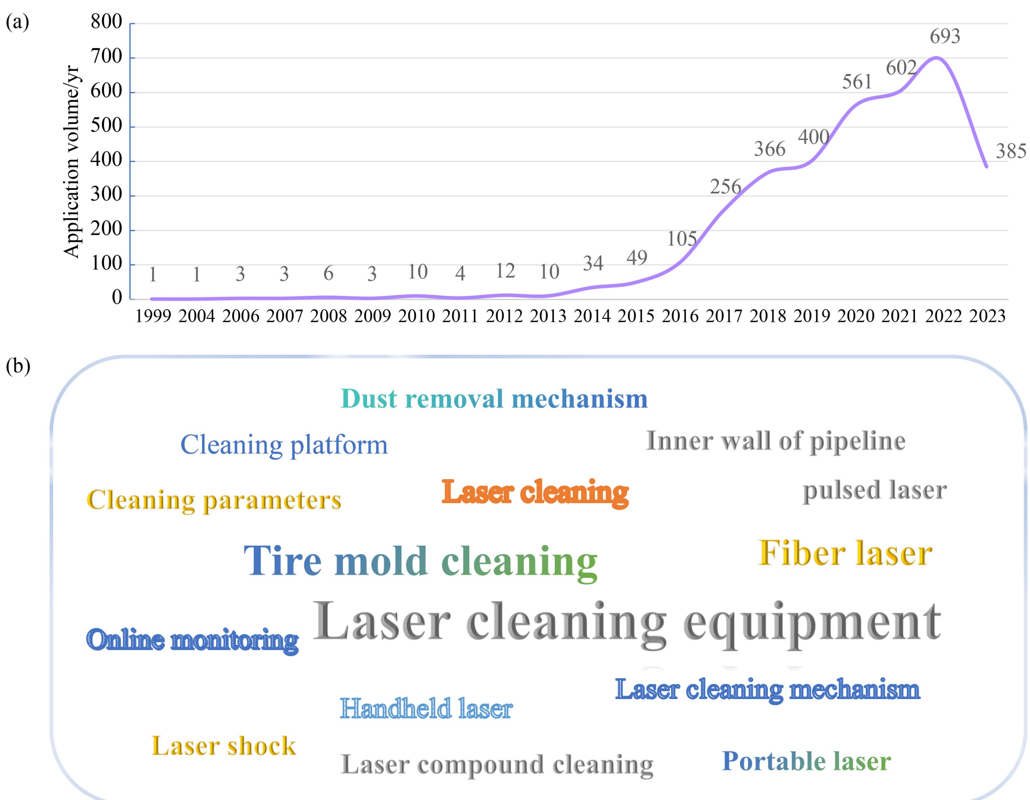

Fig. 2 (a) Trend of laser cleaning patent applications. (b) Ranking chart of the number of keywords.

Table 1 Main classification of patents related to laser cleaning

IPC class number	Description of class number	Application volume	Percentage/%
B08	Cleaning	2548	55
B23	Machine tools; metalworking not included in other categories	578	12
H01	Basic electrical components	256	5
G01	Measurement; test	131	3
B29	Processing of plastics; processing of substances in plastic state	107	2
G02	Optics	101	2
	Other	1198	24

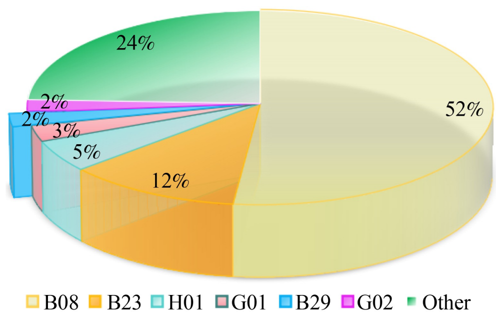

Fig. 3 Classification proportion of laser cleaning patents.

tools; metalworking not included in other categories). This situation is mainly due to the challenges in equipment development, long cycles, and high costs, which hinder the engineering application of laser cleaning.

2.3 Distribution of mechanism attributes of laser cleaning patents

Regarding the institutional attribute distribution of laser cleaning patent applications, as of 2013 (Fig. 4(a)), most patents were applied by universities, enterprises, and scientific research institutions, with few individual applications. From 2013 to 2023, the number of patents related to laser cleaning applied for by enterprises accounted for the majority of nearly 80%, as shown in Fig. 4(b). The comparison of Figs. 4(a) and 4(b) shows that, with the increase in market demand for this technology, more enterprises have shown interest, and an in-depth understanding of its potential and application value has promoted its sustainable development. As shown in Fig. 5, among the top 10 core applicants in the number of applications, only one is a university, which indicates that enterprises have gradually become the main force of patent applications for laser cleaning. This technology has shown a good momentum of development toward commercialization.

2.4 Distribution of patent application areas

The distribution of patent applications by province (Fig. 6) shows that the main subjects of patent applications in the field of laser cleaning in China are mainly concentrated in the southern provinces, particularly Jiangsu and Guangdong provinces. These provinces guide the investment direction of Chinese enterprises and higher education institutions in laser cleaning research and development, which provides a strong momentum for the development of laser cleaning technology.

In relatively developed cities (regions), the support of local governments and the close cooperation between enterprises and scientific research institutions have driven innovation and progress in laser cleaning technology. For example, Jiangsu University in Jiangsu Province, Wuhan Ruike Fiber Laser Technology Co., Ltd. in Hubei Province, and Shenzhen Hydrolaser Technology Co., Ltd. in Guangdong Province boost excellent laser cleaning

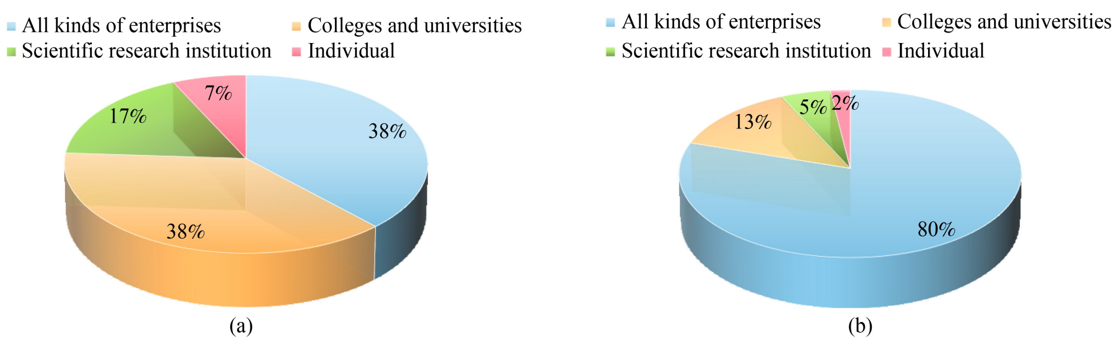

Fig. 4 (a) Distribution of mechanism attributes of laser cleaning patents up to 2013. (b) Distribution of institutional properties for laser cleaning patents from 2013 to 2023.

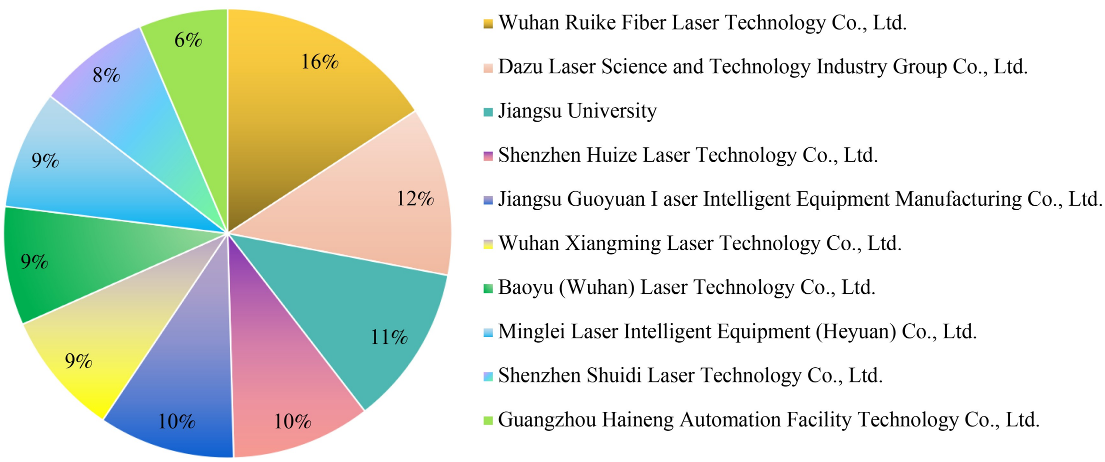

Fig. 5 Top 10 applications of core applicants from 2013 to 2023.

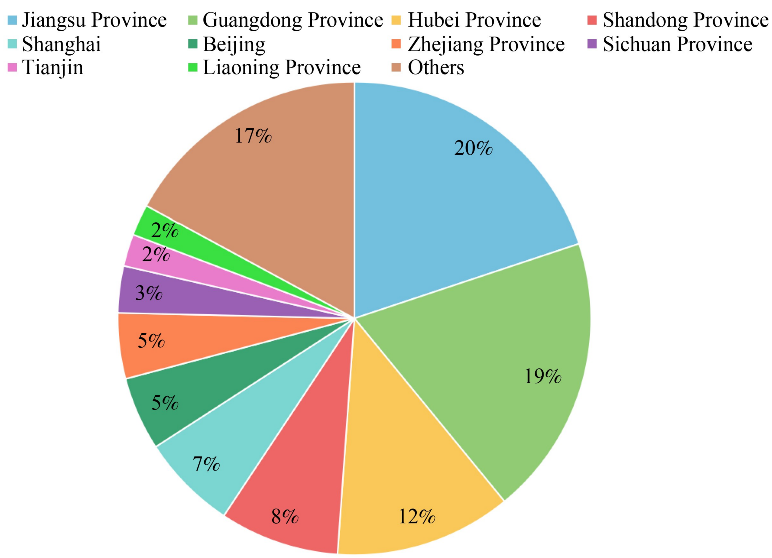

Fig. 6 Distribution of patent applications for laser cleaning in different provinces.

research teams. Their research results not only promote the development of related enterprise technology but also introduce new breakthrough points for the entire industry. An in-depth analysis of the laser cleaning patent application data in Chinese provinces (Fig. 6) reveals that southern China excels in this field, which indicates significant development potential. With the continued participation of more outstanding enterprises and scientific research forces, China's laser cleaning technology will keep growing and secure its place globally.

3 Patent analysis of laser cleaning of different matrix materials

The different shapes of workpieces, surface film layers, and processing environments require various laser cleaning process methods and devices to deal with surface pollutants of different matrix materials. These factors present great challenges to laser cleaning technology. Many enterprises and universities have conducted targeted research to address with these concerns.

3.1 Patent analysis of laser cleaning of iron matrices

Iron-based materials with high strength and hardness are widely used in various sectors, such as ships, railway traffic, and automobile manufacturing. They constitute the important basic materials for China's advanced manufacturing technology.

Corrosion of railway parts affects their performance and service life, as well as railway traffic safety. Thus, regular inspection and cleaning maintenance are required. At present, shot blasting equipment is often used to remove rust from brake beams and other railway parts. However, it has certain issues, such as loud noise, low efficiency, and serious environmental pollution. Laser cleaning can effectively avoid these problems.

Henan Sancheng Mechanical and Electrical Equipment Co., Ltd. [25] developed a laser derusting device for railway tracks. It fully utilizes the high efficiency of laser cleaning by moving the cleaning head between two railway tracks with a horizontal moving mechanism, which realizes the function of cleaning two railway tracks simultaneously by a single laser derusting device. Harbin Wick Rail Transit Technology Development Co., Ltd. [26] created a laser rust removal device for brake beams of railway vehicles. This device incorporates a high-pressure dust removal system to purify dust generated during the cleaning process, which ensures a clean working environment. Hebei University of Technology [27] designed a three-axis support and two-axis scanning vibration laser cleaning track machine. This device, which carries a laser and is equipped with an intelligent measurement and control system, enables accurate fixed-point operations. Real-time camera monitoring of the cleaning surface guarantees precise and efficient comprehensive cleaning. This innovation effectively solves the problem of rail surface rust and pollution, improves the efficiency of railway transport, and ensures the safety of transportation.

Contamination of tire molds reduces the quality of the tire and shorten service life. Therefore, tire molds need to be cleaned regularly to ensure manufacturing quality. However, traditional tire mold cleaning needs stoppage and disassembly, is time consuming and laborious, and reduces production efficiency. Thus, Shenyang University of Technology [28] disclosed a laser equipment that can clean tire molds online. This device uses a six-axis robot to realize multi-angle cleaning of molds on the production line, which enables continuous operation and greatly improves production efficiency. Hangzhou Innovation Research Institute of Beihang University [29] developed a laser cleaning device and method based on 3D point cloud. By combining point cloud data of the inner wall of the tire mold with a 3D spatial coordinate system, they established a 3D column model to determine the cleaning path, which greatly improves cleaning quality and reduces the wear of the tire mold in the cleaning process.

Ductile cast iron pipes are often used in urban water and gas supply, but they are prone to corrosion and erosion caused by external factors such as sediment and water. Zinc spraying can solve the abovementioned problems and improve the appearance and gloss of the pipeline. Laser cleaning the outer wall of the pipeline before spraying zinc effectively enhances the adhesion of the zinc layer. However, the high surface temperature of the substrate after cleaning requires cooling, which easily leads to secondary oxidation. To solve this concern, Hubei Zhengxin Pipe Fitting Co., Ltd. [30] added a cooling system to the laser cleaning equipment for rapid cooling of the substrate surface after laser cleaning, which allows direct zinc spraying without cooling. Xinxing Cast Pipe Co., Ltd. [31] introduced a pretreatment device for inner wall spraying, which cleans and roughens the inner wall of ductile cast iron pipes simultaneously. This approach improves the adhesion of the paint after cleaning.

Compared with traditional cleaning methods, laser cleaning technology has high efficiency, precision, and environmental protection, which considerably improve cleaning efficiency and quality. This technology shows great promise, especially for iron-based alloys that are sensitive to laser irradiation, which makes it a valuable area for further exploration.

3.2 Patent analysis of laser cleaning of aluminum alloy substrates

Anodizing and coating paint can enhance the wear and corrosion resistance of aluminum alloy surfaces. However, over time, the oxide film or paint on the aluminum alloy surface can become damaged and peel off. Thus, it needs to be cleaned and replaced in time, which creates high requirements for the process control of aluminum alloy surface cleaning. Sichuan University [32] proposed a selection method of laser parameters based on the thermal stress and ablation removal threshold of paint layer. The appropriate laser process parameters are selected for cleaning, which provides a process choice for nondestructive cleaning on the surface of aluminum alloy matrices. Wuhan WISCO Huagong Laser Large Equipment Co., Ltd. [33] established a laser cleaning device for the composite layer of aluminum alloy anodic oxide film and paint film. This device uses a nanosecond pulse laser to clean the damaged paint and anodic oxide film layers through ablation and gasification, which eventually peel off the surface of the substrate.

The two patents only clarify the process and parameter selection methods of paint removal on aluminum alloy anodic oxide films, including traditional mechanical grinding and chemical cleaning. They do not address the problem of retaining the anodized oxide film on the aluminum alloy surface after paint removal. For example, in the removal of coatings from aviation equipment skins, completely retaining the oxide film is the basic index requirement. The Armored Force Academy of the Chinese People’s Liberation Army [34] proposed a method to protect the anodic oxide film on the surface of the aluminum alloy substrate during laser cleaning. First, a fiber laser with high cleaning efficiency was used to remove the thick paint layer, followed by a CO_2 gas laser for quantitatively removing the remaining paint in layers. This patent protects the anodic oxide film on the surface of the aluminum alloy to the greatest extent while completely removing the paint layer, which pioneers a new direction in laser cleaning with intact oxide films.

Dry laser cleaning is generally used to ensure the cleaning efficiency of aluminum alloy. However, this process produces a large amount of residue and dust, which deteriorate the working environment. To address this problem, Dongguan Ruiyong Hardware Products Co., Ltd. [35] developed laser dry cleaning equipment for anodic oxide films of aluminum alloy, which is equipped with dust removal and residue collection devices to reduce the labor burden of users. Hunan Vocational College of Railway Technology [36] created a laser cleaning process and device for aluminum alloy car bodies. It is equipped with smoke removal equipment. The smoke is introduced into the purification device through a fan for treatment, which prevents air pollution caused by the untreated spilled smoke and ensures the health of the staff.

After welding aluminum alloy workpieces, a nondestructive flaw detection liquid is usually used for penetrant inspection. After inspection, the nondestructive flaw detection liquid will remain on the surface of the workpiece, which will affect the subsequent processes if not promptly cleaned.

CRRC Nanjing Puzhen Co., Ltd. [37] proposed a device and method for dry laser cleaning of nondestructive flaw detection liquid on aluminum alloy surfaces. By adjusting laser cleaning parameters according to the thickness of the flaw detection liquid layers, the liquid can be evaporated instantly without damaging the substrate to achieve the cleaning purpose.

Integrating laser cleaning technology with other processing (maintenance) technologies can maximize its advantages. As shown in Table 2, many patents combine laser cleaning technology with laser welding technology to realize real-time cleaning of oxide film on aluminum alloy surface before welding. This approach effectively avoids reoxidation during processing and provides convenience for subsequent material processing.

From this point of view, laser cleaning technology can efficiently and quickly remove paint layers, oxide films, and other pollutants from aluminum alloy surfaces. Patent analysis reveals that the key to distinguishing laser cleaning technology from other traditional cleaning methods is its ability to ensure the integrity of the anodic oxide layer on aluminum alloy surfaces while removing the paint layer. It demonstrates important application value in welding pretreatment and purification of the working environment.

3.3 Patent analysis of laser cleaning of titanium alloy substrates

Titanium alloy is a new structural material with high strength and lightweight, and its alloy powder is commonly used in additive manufacturing (AM; 3D printing). However, titanium alloy powder easily oxidizes upon exposure to moisture and air, which forms an oxide film. The oxide film prevents the powder from contacting with the next material layers, which decreases the compactness of the printed workpiece and seriously affects the quality of 3D printing. The China Aviation Manufacturing Technology Research Institute [43] introduced a laser cleaning device for titanium alloy powder. This device removes the oxide film on the surface of titanium alloy powder using a laser beam under a protective atmosphere. After the powder is cleaned, the workpieces printed using this device has low porosity and high compactness.

Titanium alloy is mostly used in workpieces with complex structures. However, a dense oxide film forms on the surface of titanium alloy workpieces during high temperature thermoforming, which negatively affects the bonding strength of the workpiece coating. Shenyang Heshitai General Titanium Industry Co., Ltd. [44] proposed a laser cleaning device that efficiently removes the oxide layer on the surface of titanium alloy bars after heat treatment.

The China Aviation Manufacturing Technology Research Institute [45] developed a laser cleaning device and method for titanium alloy welding wire. Different from the traditional method of pickling titanium alloy before welding, this method realizes real-time cleaning of welding, which eliminates the need for wire winding

Table 2 Patent of laser cleaning-assisted laser welding of aluminum alloy matrices

Title of invention	Invention content	Beneficial effect		Applicant
Welding pretreatment method of aluminum alloy spiral welded pipe based on laser cleaning technology	Laser cleaning pretreatment of aluminum alloy before welding	Reduce welding pore rate and improve welding quality	Laser cleaning technology to clean and preheat the workpiece	Laser Institute of Shandong Academy of Sciences [38]
Equipment for laser pretreatment of oxidation film before longitudinal seam welding of aluminum alloy material			Laser cleaning to remove oxide film the aluminum alloy surface	Wuhan Xiangming Laser Technology Co., Ltd. [39]
Laser grinding equipment for aluminum alloy car body profile before and after welding			Removing oxide film is synchronous with welding	Wuhan Xiangming Laser Technology Co., Ltd. [40]
Welding method and device for aluminum alloy shell of high-voltage switch based on laser cleaning				Laser Institute of Shandong Academy of Sciences [41]
Welding device and method of 6-series aluminum alloy profile based on laser cleaning			Additional dust removal system	CRRC Nanjing Puzhen Co., Ltd. [42]

equipment. Wuhan Xiangming Laser Technology Co., Ltd. [46] suggested a laser cleaning method to remove the oxide layer on the surface of titanium alloy. They categorized the oxide layer into three different thickness ranges: 1–20 μm, 20–30 μm, and 30 μm. As a result, suitable laser parameter ranges were selected for each range to achieve better cleaning effect. Chengdu Mairuijie Laser Technology Co., Ltd. [47] established an automatic laser cleaning device for titanium alloy tube sheet welds, which effectively removes the oxide layer. Wuhan Tianyu Intelligent Manufacturing Co., Ltd. [48] created a device that realizes titanium alloy welding under the double guarantee of inert atmosphere and laser cleaning, which ensures no oxidation welding in each pass and improves welding quality. Beijing Xinghang Electromechanical Equipment Co., Ltd. [49] proposed an electron beam welding method for titanium alloy based on laser cleaning treatment. It incorporates laser cleaning to remove the oxide layer, greasy dirt, and non-metallic impurities, which significantly enhances welding quality.

The production cost of titanium alloy is relatively high, which requires considerable investment in processing, production, and other links. Therefore, using laser cleaning technology to clean titanium alloy matrix materials and realize the recycling of workpieces can help reduce the production costs of enterprises and improve efficiency to a certain extent. The advantages of applying laser cleaning technology to titanium alloy materials cleaning are increasingly recognized across various industries.

3.4 Patent analysis of laser cleaning of composite matrices

Composite materials have excellent properties such as light weight, high strength, good toughness, corrosion resistance, and wear resistance. They are widely used in industrial fields. However, traditional cleaning methods for composite surface coatings, such as chemical cleaning and mechanical polishing, tend to damage the matrix and have low cleaning efficiency.

To address this issue, Hunan Xinao Photoelectric Technology Co., Ltd. [50] introduced a laser cleaning method for removing the paint layer on the surface of composite materials. The laser cleaning parameters were adjusted according to the thickness of the paint layer to achieve effective removal. Minglei Laser Intelligent Equipment (Heyuan) Co., Ltd. [51] disclosed a system for cleaning the surface coating of composite materials and an ultraviolet laser cleaning machine. This system uses an ultraviolet laser with a scanning speed of 1800 mm/s, a frequency of 20 kHz, and a pulse width of 1 ns to clean the surface coatings of glass fiber and carbon fiber composite materials. It not only avoids damaging the substrate but also achieves high cleaning efficiency. The patent also compared the mechanical properties of the composite materials before and after laser cleaning, which showed no changes in the mechanical properties of the substrate materials. Nanchang Hangkong University [52] proposed a surface modification method for carbon fiber surface functionalization. This method uses dopamine as a surface modifier to increase the specific surface area and roughness of carbon fiber, which improves its compatibility with resin matrices. Experimental results show that this method obviously improves the mechanical properties of carbon fiber resin matrix composites.

The abovementioned technologies focus mainly on either cleaning or improving surface performance of carbon fiber composites. Jiangsu University [53] developed a device and method for the composite processing of laser cleaning and surface modification of carbon fiber composite materials. This innovation not only cleans surface pollutants but also creates a concave–convex morphology on the carbon fiber surface, which increases surface roughness and adhesion. This approach demonstrates that laser cleaning can effectively clean and modify the surface simultaneously, which simplifies the workflow and saves costs. This patent provides a new idea for laser cleaning and modified composite processing.

Spraying metal powder on the surface of aircraft skin to form a conductive layer helps prevent lightning strike. The method of spraying paint on the conductive layer of aircraft skin is generally used to improve impact and corrosion resistance for withstanding harsh service environments. However, over time, the paint layer can become damaged and ineffective, which necessitate regular removal and reapplication. As shown in Fig. 7, removing the paint layer can easily damage the conductive layer. To solve this problem, Nanjing University of Aeronautics and Astronautics [54] suggested a method for removing paint from the surface of carbon fiber reinforced resin-based composites containing conductive layers. This multi-layered removal method first uses high-power, low-frequency, and wide-pulse laser parameters to remove part of the paint layer. Then, it uses low-power, high-frequency, and narrow-pulse laser parameters to remove the remaining paint layer. This approach removes the paint layer without damaging the conductive layer, which also strengthens the conductive layer and further improve its conductivity. This method effectively promotes the transformation of laser cleaning technology for modern aviation material applications. Jiangsu University [55] disclosed a device and method for laser cleaning of aircraft composite radar topcoats. The device is equipped with a double guide rail system, which realizes multi-directional and comprehensive cleaning of the workpiece. The cleaning position and temperature are monitored in real time through a charge-coupled device imaging system and infrared temperature sensor, which ensures nondestructive cleaning of the composite radar mask.

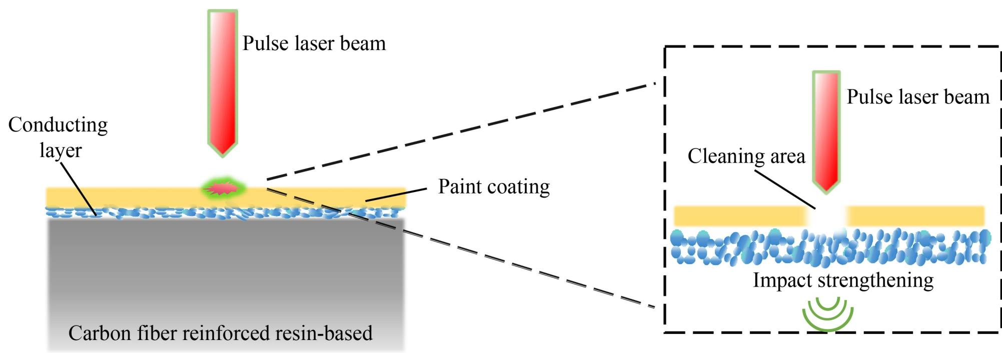

Fig. 7 Structural diagram of carbon fiber reinforced resin-based composites containing conductive layers.

To address the difficulty in predicting temperature field changes in materials during laser cleaning, the Shenyang Institute of Automation, Chinese Academy of Sciences [56] proposed a simulation method for the temperature field of release agents on the surface of carbon fiber material based on laser cleaning. Using COMSOL Multiphysics simulation software, they monitored the temperature changes in the release agent and carbon fiber material in real time during cleaning. They explored the effects of different laser power, energy density, and scanning speed on cleaning depth, which provides a theoretical basis for laser cleaning process parameters of carbon fiber composite materials.

Laser cleaning can efficiently and quickly remove pollutants and damaged paint layers on the surface of composite materials. It can also modify the material during the cleaning process to improve density and surface strength. Therefore, laser cleaning is expected to become an indispensable technology for composite material cleaning in the modern manufacturing industry.

4 Patent analysis of laser cleaning of different coatings

During the manufacturing, processing, and usage of workpieces, surfaces are often covered with various coatings, such as rust, paint, and oxide film. These differing properties of the cladding cause difficulty in controlling the laser cleaning process parameters, which leads to damage to the surface of the workpiece. Thus, comprehensively considering the properties of the covering and the requirements of the workpiece is important to select the appropriate laser cleaning parameters.

4.1 Patent analysis of laser cleaning of rust layers

Compared with traditional rust removal methods, laser cleaning technology has high precision, efficiency, and minimal damage the matrix. Using lasers to clean the rust layer of metal parts is a crucial direction in engineering applications. Choosing appropriate process parameters for laser cleaning of different workpiece materials not only can completely remove rust but also can improve the hardness of the matrix surface, corrosion resistance, and wear resistance, which maximizes the potential of laser cleaning technology [57–60].

The first patent for laser cleaning applied to rust removal in China was the narrow pulse width laser decontamination machine developed by Nankai University [61] in 2007. The equipment uses narrow pulse width lasers to clean various pollutants simultaneously, such as rust layer and paint layer. Instruments and devices monitor and analyze the ultrasonic waves formed by vibrations during cleaning to ensure the integrity of the medium surface and realize the automation of the cleaning process, which demonstrate the advantages of high efficiency and automation of laser cleaning technology in removing rust. After 2017, the number of patent applications for laser cleaning technology for rust removal began to increase.

At present, laser cleaning mostly adopts line scanning, which may be unsatisfactory for seriously corroded surfaces. Jiangsu University [62] developed a method where an energetic coating composed of acrylic epoxy resin, hydrogen peroxide, and nano carbon powder particles is applied to the corrosion layer (Fig. 8(a)). During laser cleaning, this coating explodes under the instantaneous heat of the laser beam and produces a shock wave, which destroys the rust layer and drives it off (Fig. 8(b)). With the help of the special function of the auxiliary coating, this technology efficiently and quickly removes thick rust layer, paint layer, and other coatings on the surface, which greatly improves the efficiency of laser cleaning and provides a new idea and direction for the development of laser cleaning field.

Over time, environmental factors and the natural aging of oil pipelines can lead to corrosion. The surface of the pipeline is generally coated with a protective layer to prevent corrosion for ensuring safe and stable operation. Baoyu (Wuhan) Laser Technology Co., Ltd. [63] developed laser cleaning equipment for derusting oil pipelines. This equipment not only offers good cleaning

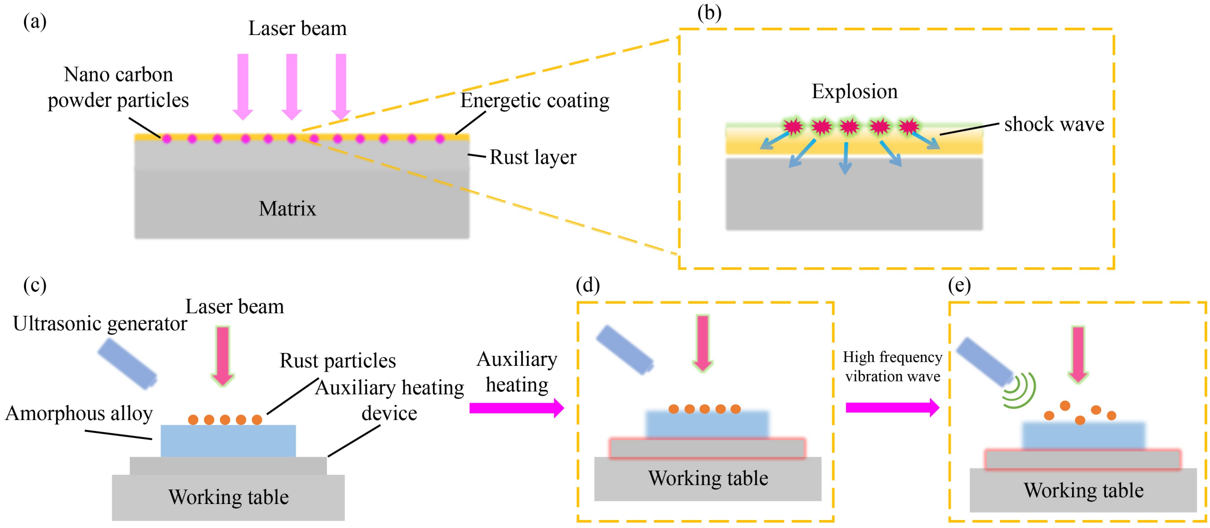

Fig. 8 (a) Schematic of laser cleaning of energetic coating for rust layer removal. (b) The shock wave drives the rust layer to fall off. (c) Structural diagram of integrated laser cleaning equipment with heating and ultrasound. (d) Auxiliary heating reduces the strength and hardness of amorphous alloy. (e) Ultrasonic wave loosens corroded particles.

effect but also produces uniform anchor lines during derusting, which ensures good adhesion for repainting and a close combination of subsequent anti-corrosion coatings and pipeline surfaces.

In atmospheric environments, aircraft skin and certain key parts can corrode, which is a problem for damage-free removal. To solve this issue, Qingdao Campus of Naval Aeronautical University [64] proposed a nanosecond pulse laser cleaning method for the surface corrosion of 7B04 aluminum alloy. They conducted in-depth analysis of the corrosion mechanism and optimized the process parameters through testing. This method eliminates the uncontrollable factors of mechanical grinding to remove the rust layer and significantly improves cleaning efficiency. This achievement has important application value in the maintenance of military equipment.

Low-power lasers are used to protect alloy substrate surfaces from damage during cleaning, but this method reduces efficiency. For this reason, Dongguan Eontec Co., Ltd. [65] added an auxiliary heating device and an ultrasonic generator to the low-power laser cleaning equipment (Fig. 8(c)). First, the amorphous alloy sample is heated to reduce its strength and hardness (Fig. 8(d)). Then, the ultrasonic generator emits high-frequency vibration waves to loosen the corrosion particles embedded in the surface (Fig. 8(e)), which reduces cleaning difficulty while ensuring high efficiency and avoiding matrix damage. Shenhua Group Zhungeer Energy Sources Co., Ltd. [66] coupled the laser beam into a deionized water jet to create a deionized water environment in the cleaning area. This approach prevents thermal damage even with high-power laser cleaning, and the water jet washes away corroded particles to prevent secondary pollution. With rising environmental protection awareness and sustainable development, recycling through laser cleaning is increasingly recognized by researchers all over the world. This method removes the rust layer on the surface of the workpiece without replacing the entire workpiece, which reduces environmental pressure and energy consumption [67].

4.2 Patent analysis of laser cleaning of paint layers

Paint layers are mostly used to protect the workpiece from the external environment but can become damaged over time, which necessitates regular removal and reapplication [9]. The complexity of paint layer composition and the difficulty in controlling laser cleaning parameters, such as laser power and pulse width, can risk substrate damage [68]. At present, chemical cleaning and sand blasting are common methods for paint layer removal, but they can cause stress damage to the substrate and environmental pollution. Laser cleaning uses a high-energy laser beam to move paint layers without contacting with the surface of the substrate. Thus, it avoids secondary pollution from chemical reagents and mechanical polishing damage. Minglei Laser Intelligent Equipment (Heyuan) Co., Ltd. [69] disclosed a method and system for laser paint removal. It generates a laser beam according to the thickness of the paint layer on the surface of the workpiece, which effectively removes the paint layer and realizes rapid removal and intact and accurate cleaning of the substrate.

The application of laser cleaning technology in the marine field is becoming increasingly common. When necessary, laser cleaning operations need to be conducted in water. The cleaning process should consider not only the physical properties of paint layer and substrate but also the acoustic impedance of the water layer. Sichuan

University [70] proposed a method and device for removing paint in water. By analyzing the impact strength of the pulsed laser on the paint layer in water, as well as the reflection and transmission coefficients at the interface between water and the paint layer and between the paint layer and substrate, the optimal energy density range is determined. This way ensures that the original substrate structure remains intact while efficiently cleaning the paint layer, which expands new directions for laser underwater cleaning.

For materials such as stainless steel, which are highly reflective of light and sensitive to heat input, Shanghai Ruirong Laser Welding Technology Co., Ltd. [71] introduced a laser cleaning device for the paint layer of aero-engine stainless steel parts. This device uses the thermal effect of the laser and the difference in thermal expansion coefficient between the paint layer and the substrate to crack and peel off the paint layer through laser plasma impact, which removes it completely without damaging the surface of the substrate. Durr Coating System Engineering (Shanghai) Co., Ltd. [72] invented a laser paint removal device for automobile manufacturing. By irradiating the high-energy pulsed laser emitted by the laser on the surface of the workpiece, this device rapidly gasifies and separates the paint layer from the surface of the automobile body, which ensures the stability and sustainability of the automobile production process.

China Hi-Tech Co., Ltd. [73] developed an aircraft skin cleaning system to address the high cost, toxicity, and environmental pollution in the process of using paint remover on aircraft skin. This system uses high-energy laser pulses to vaporize the paint layer and impurities on the skin surface, as well as high-intensity shock waves to remove the paint layer. The cleaning cost is low, and it can clean complex-shaped workpieces. However, a large amount of solid powder is produced during laser cleaning, which if not treated in time, can lead to inhalation by workers and affect their health. Sichuan Minghang Lander Technology Co., Ltd. [74] equipped their laser cleaning system for aircraft skin with special dust removal equipment. This system uses a combination of a dust cover and a vacuum cleaner to promptly remove dust generated in the cleaning process, which highlights the environmental friendliness of laser cleaning.

Aircraft skin has aerodynamic characteristics, which can be divided into single curvature, double curvature, and complex shapes. In view of the complexity of these shapes and the difference in the head and tail curvature, maintaining the consistency of the laser and aircraft skin spacing during cleaning is challenging. This complexity also causes difficulty in planning the cleaning path and regulating process parameters.

Hebei University of Technology [75] combined the laser cleaning device with a cross-frame moving device, which ensures that the cleaning process is close to the surface of the aircraft with a high safety factor. This approach allows the paint layer to be removed in layers without damaging the substrate. Nanchang Hangkong University [76] planned the running path of the robot arm by establishing the aircraft skin model. This system allows the laser to clean the paint layer on aircraft skin with different curvatures and large irregular areas. They found that the optimal cleaning effect for the surface paint layer is achieved when the power is 50 W, the frequency is 200 kHz, the scanning speed is 2000 mm/s, the robot arm speed is 2 mm/s, and the cleaning time is six passes. Hebei Hanguang Heavy Industry Co., Ltd. [77] developed a laser cleaning device for curved objects. This device uses a laser ranging module to measure the distance between the cleaning head and the cleaning target, which allows it to automatically focus and fit the curved surface. The operation is simple, and the surface cleanliness after cleaning is high. These technologies effectively prevent uneven cleaning caused by varying laser energy density, which solves the cleaning problem of large, curved, and irregular surfaces. This innovation provides a strong technical foundation for the large-scale application of laser cleaning technology to aircraft skin cleaning. It is expected to replace traditional cleaning methods with cost-effective and efficient green cleaning solutions.

As shown in Table 3, various patents of laser cleaning devices and methods applied to paint removal from specific workpieces or objects are listed. Compared with traditional cleaning methods, laser cleaning technology offers efficient cleaning of the surface of workpieces without producing chemical substances, which makes it environmentally friendly. The miniaturization, portability, and lightweight nature of laser cleaning devices bring this technology closer to daily life and work, which expands its application prospects.

4.3 Patent analysis of laser cleaning of composite coatings

Composite coating is composed of two or more materials with comprehensive properties, in which the composite coating made of metal or ceramic powder has high performance, superior durability, and easy maintenance. The Laser Institute of Shandong Academy of Sciences [85] disclosed a device and method for laser cleaning of composite coatings. This method, which is tailored to the specific requirements of aircraft skin paint stripping, allows for the selective removal of single-layer coatings in composite coatings on aircraft surfaces. This approach solves the problems of poor uniformity and accuracy associated with traditional sandblasting and chemical paint stripping.

In aircraft assembly, ensuring anti-electric shock and anti-interference lap joints on designated parts requires cleaning the nonconductive coating on this part to maintain good conductivity. Current methods such as manual sandpaper or grinder grinding cannot accurately

Table 3 Patent of laser cleaning of paint layers of different workpieces

Title of invention	Purpose of invention	Beneficial effect	Applicant
Laser cleaning device for brake regulator of railway vehicle	Cleaning the paint layer on the surface of railway vehicle brake regulator	No contact, no damage, and no pollution	Harbin Wick Rail Transit Technology Development Co., Ltd. [78]
Laser cleaning device for small advertisements	City cleaning	Portable	Yingtan Zhihui Internet of Things Application Research Institute Co., Ltd. [79]
Self-propelled wire laser cleaning device and method	Wire cleaning	360° laser cleaning	Shandong Zhongshi Yitong Group Co., Ltd. [80]
Device for laser cleaning of the inner wall of a pipeline	Cleaning the inner wall of the pipeline	Efficiently cleans the inner wall of pipes	Jiangsu University [81]
Automatic device for removing paint coating from flat wire of motor by laser	Laser paint removal for flat wire of motor	Automatic completion of paint removal for flat wire	Suzhou Jinghai Laser Intelligent Technology Co., Ltd. [82]
Automatic laser cleaning paint equipment	Laser cleaning paint	Suitable for laser cleaning of pipes with different sizes	Hunan Xinao Photoelectric Technology Co., Ltd. [83]
Laser cleaning device for inner wall paint of flat tail big shaft	Laser cleaning paint layer on the inner wall of flat tail big shaft	Real-time observation of cleaning effect and laser light-emitting condition	State-owned Wuhu Machinery Factory [84]

control the grinding shape and depth. Wuhan Jindun Laser Technology Co., Ltd. [86] proposed an *in situ* laser cleaning method for aircraft nonconductive composite coatings. The laser process parameters are adjusted based on the material type and processing requirements of the area to be cleaned. This way ensures that the energy density of the laser beam is between the cleaning and damage thresholds of the substrate. Protective tape is covered around the area to be cleaned to avoid additional damage to the internal structure. This method allows for the efficient, accurate, and nondestructive cleaning of the composite coating.

Micro-arc oxidation coating is a composite ceramic coating with high temperature and corrosion resistance. It is produced through micro-arc discharge under electrolyte and corresponding electrical parameters, which results in instantaneous high temperature and pressure on the surface of valve metals and their alloys. When a micro-arc oxidation coating is damaged locally, the damaged area needs to be removed and a new coating generated in situ. Zhejiang University of Technology [87] established a device and method for locally repairing micro-arc oxidation coatings on titanium alloy (Fig. 9(a)). The residual thickness of the damaged film layer is measured using an eddy current thickness gauge. Under appropriate laser cleaning parameters, the workpiece should be completely immersed in electrolyte. In addition, the residue after cleaning can be washed away with flowing electrolyte.

Thermal barrier coatings have excellent oxidation and high temperature resistance. However, excessive internal pores in the manufacturing process can lead to crack propagation, which necessitates the removal of unqualified coatings for reapplication. As shown in Fig. 9(b), Nanchang Hangkong University [88] proposed a method for cleaning thermal barrier coatings of Yttria-stabilized zirconia (YSZ). This method uses ultrasonic vibration to weaken particle sputtering in the laser cleaning process. The synergistic effect of ultrasonic cleaning and laser cleaning reduces the molten pool generated by overheating of the surface interface, which blocks the splashing and enrichment of molten pool particles due to plasma shock wave and ensures the cleanliness of the substrate surface. As the service temperature of a new generation of engine turbine blades greatly increases, YSZ thermal barrier coatings may encounter phase transformation and sintering problems when the temperature is higher than 1200 °C. Deposits on engine turbine blades (e.g., CaO, MgO, Al_2O_3, and SiO_2, which are abbreviated as CMAS) can transform into molten state and penetrate into the coating at high temperatures, which leads to the degradation of coating performance. Tianjin University [89] proposed a method of laser cleaning to remove deposits from the surface of thermal barrier coatings of aero-engine. Using a pulsed laser with a power of 50–200 W, the CMAS layer is removed in several stages. The initial stage removes 1/2–3/4 of the total thickness, with subsequent stages removing less than 5 μm each. After the CMAS layer is completely removed, an additional thermal barrier coating of 5–30 μm is removed to ensure that at least 2/3 of the original thickness remains. This process ensures that the engine blade retains its original function and meets daily service requirements.

Laser cleaning technology can accurately remove single layers in composite coatings by adjusting the energy density. This innovation provides a new process for micro-area repair of micro-arc oxidation coatings, which guarantees effective maintenance and use of thermal barrier coatings. It holds important practical application value.

4.4 Patent analysis of laser cleaning of other coatings

Laser cleaning is an efficient cleaning technology that can clean rust, paint, and composite coatings, as well as remove carbon deposits in engines, tiny particles of optical devices, greasy dirt, metal oxides, and other

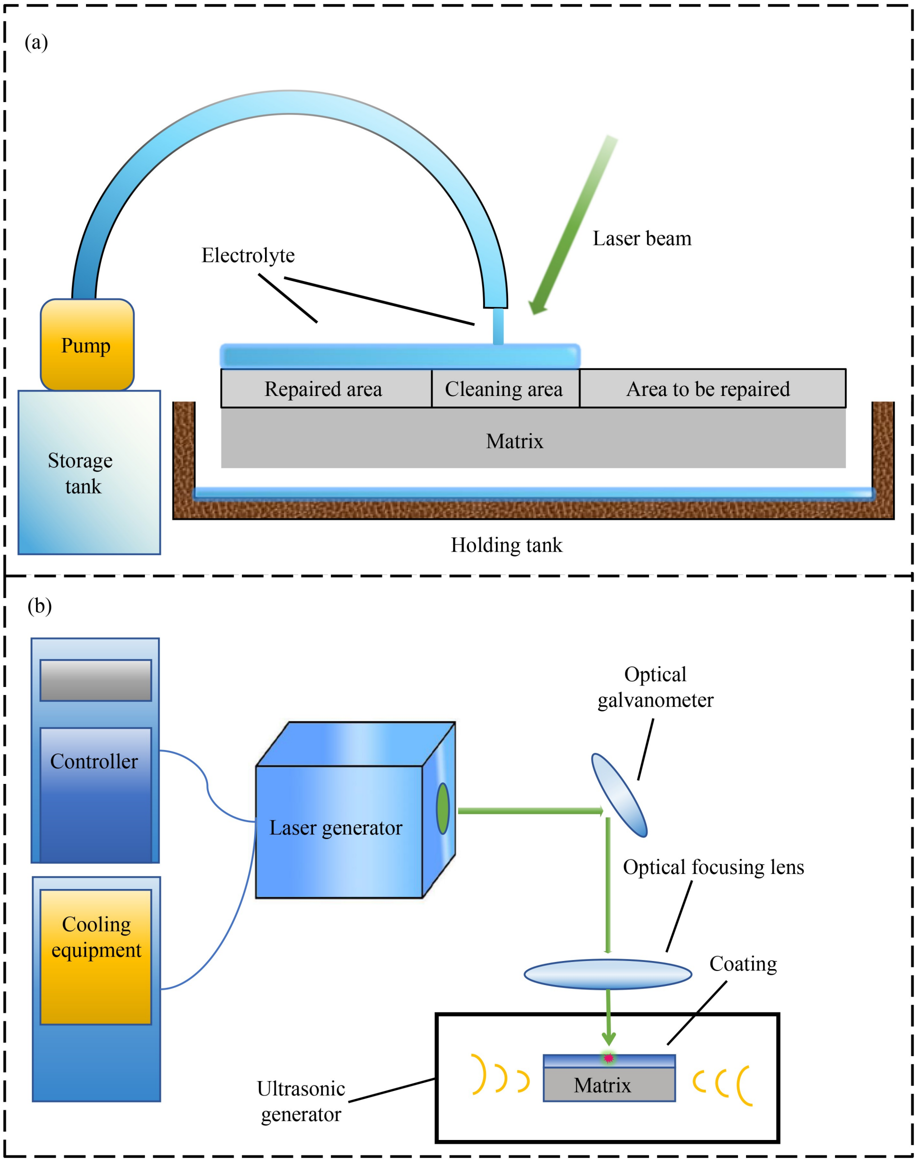

Fig. 9 (a) Device and method for locally repairing micro-arc oxidation coatings of titanium alloy. (b) Schematic of laser cleaning of zirconia thermal barrier coatings.

contaminants (Fig. 10). This capability is achieved by accurately locating the surface of the workpiece to be cleaned with a laser beam of high energy density, which instantly heats the pollutant surface. The pollutants are then removed under the synergistic effect of ablation, vibration, plasma impact, and other mechanisms.

4.4.1 Particles

Ductile iron exhibits high strength, toughness, and wear resistance. It can also maintain stable performance in harsh environments such as high temperature and pressure. However, the embedded spherical graphite particles affect its welding performance. Current methods such as pickling and alkali washing cannot effectively remove graphite particles. The Laser Fusion Research Center of China Academy of Engineering Physics [90] developed a technique to effectively remove graphite particles from the surface of nodular cast iron by adjusting laser pulse frequency, pulse width, average power, and spot size. This technology allows for selectively removal of graphite particles without damaging the nodular cast iron matrix.

When using a 3D printer to print layer by layer, impurities and metal particles usually appear on the surface of semi-finished metal prints. These impurities lead to gaps between the layers of the finished printed parts, which reduce their binding force and affect their quality. Shandong CharmRay Laser Technology Co., Ltd. [91] introduced a laser cleaning device for metal 3D printing layer by layer. This device uses the non-contact, accuracy, and high efficiency of laser cleaning to quickly

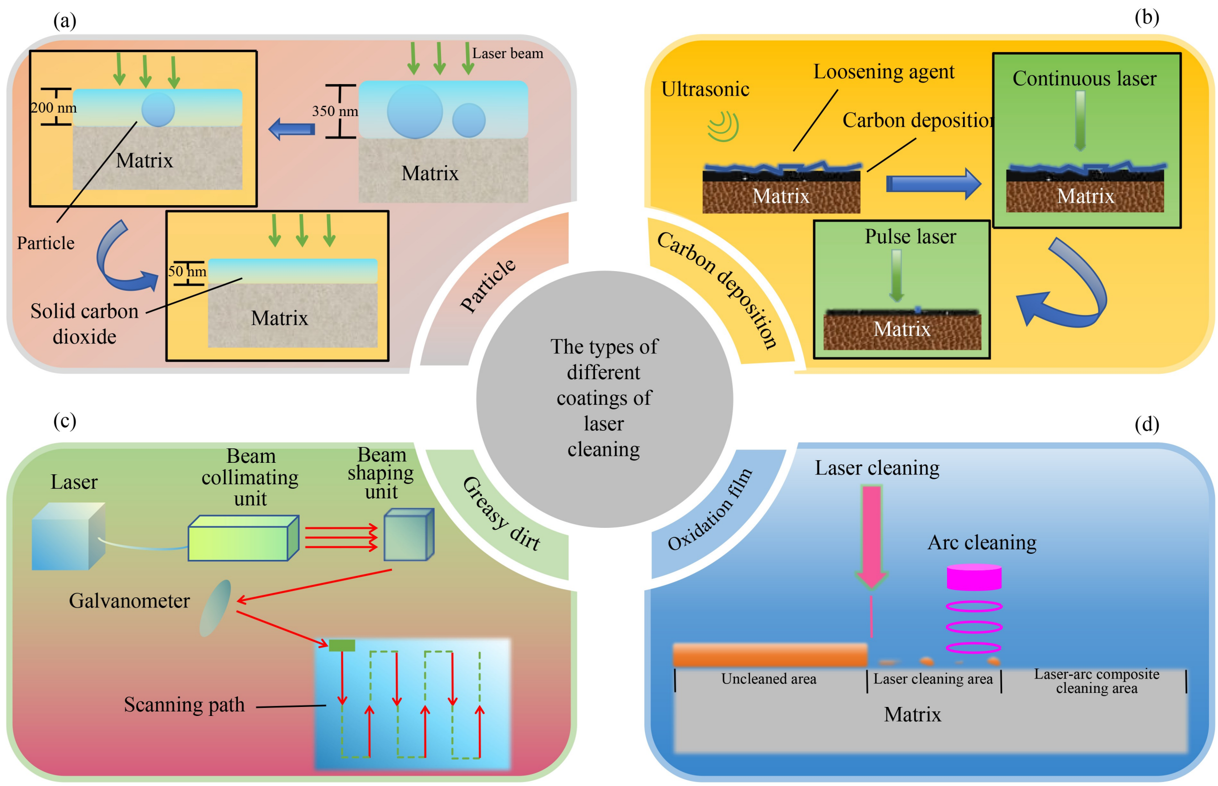

Fig. 10 Schematic of laser cleaning of carbon deposits, particles, greasy dirt, and oxidation films. (a) Method for laser cleaning of semiconductor surface particles using solid carbon dioxide as a buffer medium [74]. (b) Method for laser cleaning of surface carbon deposits of titanium alloy using a loosening agent [77]. (c) Method and system for laser cleaning of oil stains on metal plate surfaces using a rectangular spot [79]. (d) Laser-arc compound cleaning of oxide film on aluminum alloy surface [81].

remove impurities on the surface of each printed layer.

In processing optical devices and semiconductors, dust and other pollutant particles are generated on the surface of components, which lead to the failure of semiconductors and affect the reflection and transmission of laser beams in optical devices. SOL Electronic Technology Co., Ltd. [92] proposed a laser cleaning method to remove nanoparticles from semiconductors. Solid carbon dioxide is used as a buffer medium to clean particles of different sizes on the surface of silicon wafers. The solid film is progressively thinned, and the thickness of the film is reduced by 150 nm at a time to 50 nm. Particles of different sizes are removed using solid films with different thicknesses.

Notably, the laser cleaning process results in thermal ablation, plasma radiation, and other phenomena, which require detection of optical components after cleaning. Dongguan Feichuang Laser Intelligent Equipment Co., Ltd. [93] developed a method to detect the effect of laser cleaning on surface impurities of optical components. By analyzing the changes in substrate elements before and after cleaning using EDS energy spectrum, observing the laser cleaning effect, and assessing the damage condition, the cleaning parameters are constantly adjusted to realize nondestructive cleaning.

4.4.2 Carbon deposit

Over time, the aero-engine generates a layer of carbon deposits on the inner wall, which continues to accumulate and block the nozzle, air inlet, piston ring, or other components. This phenomenon leads to the decline in engine performance. Although carbon deposits are a product of high temperature, they can still combust and potentially explode when ignited, which causes serious accidents. Xi’an Lanxiang New Materials Technology Co., Ltd. [94] proposed a laser cleaning device designed for carbon deposits on aero-engine blades. This device presets the corresponding cleaning parameters according to the carbon deposit status on the surface of aero-blades. The carbon deposits are burned and vaporized using high-energy laser beams. The Armored Force Academy of the Chinese People’s Liberation Army [95] established a method using ultrasonic waves to disperse and coat a loosening agent on the carbon deposit layer of titanium alloy. This process weakens the force between carbon deposit molecules. Pulsed laser cleaning then reduces the thickness of the carbon deposit layer, followed by low-energy density continuous laser to clean the remaining carbon deposits. The cleaning temperature is monitored in real time to avoid damage to the titanium alloy matrix. This patent shows the advantages of the combined use of chemical and laser cleaning methods, which greatly improves cleaning efficiency.

4.4.3 Greasy dirt

Lubricating oil is added to the workpiece in the processing and production to reduce friction, which causes difficulty in avoiding greasy contamination. To address the problem of greasy dirt, Shengtong Intelligent Machinery Equipment (Shanghai) Co., Ltd. [96] specially designed a laser cleaning equipment for greasy dirt cleaning on metal surfaces. However, traditional circular spot lasers have a Gaussian distribution with high center energy and low edge energy, which leads to low laser cleaning efficiency. Beijing University of Technology [97] shaped the circular laser beam into a rectangular beam, which effectively increases the efficiency and area of cleaning greasy dirt on the metal plate surface. Many other similar patents for laser cleaning of greasy dirt are available. However, they will not be elaborated here due to the already mentioned innovations.

4.4.4 Oxidation film

In the 3D printing of aluminum alloy parts, oxides often appear with each additional layer, which decreases the bonding force between layers. Wuhan Xiangming Laser Technology Co., Ltd. [98] disclosed a device and method for laser cleaning-assisted arc AM. This method uses laser cleaning technology to remove surface oxides generated during machining. Traditional AM processes generally use either single laser cleaning or arc cathode cleaning to remove the oxide film on the surface of the substrate. However, single cleaning methods are prone to incomplete cleaning and secondary oxidation. Beijing University of Technology [99] introduced a laser-arc compound cleaning method for aluminum alloy oxide film, which removes the oxide film to a fixed depth by using the ability of the laser to remove the oxide film at the same depth. This way provides preconditions for fixed-point cleaning of the oxide film with an arc cathode. Under a protective atmosphere, the cathode spots with extremely high current density in the arc automatically find and locate the residual oxide film, which realizes high-quality cleaning, effectively prevents the oxide film from regenerating, and obviously improves working efficiency. This combination of laser cleaning and arc cathode cleaning addresses the deficiency of single cleaning methods and provides ideas for the future integration of multiple cleaning techniques.

Mirrors made by magnetorheological polishing are widely used in aviation infrared optical systems, but a black oxide film can form on the mirror surface during magnetorheological polishing, which affects the mirror performance. National University of Defense Technology [100] disclosed a method and device for ultra-fast laser cleaning of aluminum alloy mirror surfaces. They conducted photothermal absorption experiments on aluminum alloy mirrors and their surface oxide films. By selecting the wavelength range where the photothermal absorption rate of the aluminum alloy oxide film is greater than that of the aluminum alloy matrix, they used femtosecond lasers to clean the oxide film. This method removes surface impurities and pollutants without damaging the substrate, which greatly improves the reflectivity of the aluminum mirror. This achievement can be applied to the production and maintenance of optical components, which enhances their accuracy and performance to meet the needs of modern optical mirrors.

Laser cleaning as an efficient and environmentally friendly cleaning technology is highly effective in metal processing, such as AM and welding. Konfoong Materials International Co., Ltd. [101] proposed a welding method for aluminum target assembly that promotes the diffusion between atoms and enhances the bonding effect by creating a brazing metal infiltrating layer on the surface of the material. However, aluminum is prone to oxidation during the production of the infiltration layer. To avoid this situation, laser cleaning is the most convenient and effective way before welding. Aifaco Electronic Materials (Suzhou) Co., Ltd. [102] introduced a new welding method that quickly removes oxides and other pollutants on the aluminum surface using laser cleaning parameters with a power of 100–400 W, a wavelength of 1064 nm, a spot diameter of 60 um, and a scanning speed of 1.2–3.0 m/min. Shanghai Chip Electronic Technology Co., Ltd. [103] developed a laser cleaning mechanism for aluminum alloy oxide film before welding. This mechanism relies on a device table to clean the inner wall of aluminum alloy parts and is equipped with a dust suction head to remove debris generated after cleaning. This way ensures the oxide film is cleaned before welding and improves the working environment.

Laser cleaning technology complements other laser technologies, particularly as a surface pretreatment before laser welding, which makes it an excellent cleaning process. As shown in Table 4, many patents combine laser cleaning technology with laser welding technology, which integrates the laser cleaning head into the robotic arm for automatic welding. This integration ensures that the entire cleaning process is accurate, efficient, and highly automated. It has high practical value and industrial application prospect.

5 Patent analysis of equipment and monitoring devices for laser cleaning

Equipment and supporting monitoring devices for laser cleaning are the basic guarantee to obtaining high-quality,

Table 4 Patents of laser cleaning of oxide films

Title of invention	Invention content	Beneficial effect		Applicant
Welding gun integrating laser cleaning and welding	Laser cleaning removes impurities and pollutants such as oxide film on the surface before and after welding	Avoids welding defects	Improves welding quality	Borunte Robot Co., Ltd. [104]
Welding method for automatically cleaning welding seams before and after welding				Sichuan Aerospace Changzheng Equipment Manufacturing Co., Ltd. [105]
Continuous narrow gap gas shielded welding method with online cleaning		Realizes no oxidation before welding		Dongfang Electric Group Dongfang Steam Turbine Co., Ltd. [106]
Underwater welding device and method	Removal of water film by thermal effect of laser cleaning	Realizes oxygen-free and hydrogen-free before welding		Huazhong University of Science and Technology [107]
Integrated equipment and method for laser cleaning and welding combined processing	Device and method capable of performing laser welding immediately after laser cleaning	Realizes no oxidation before welding		Shenyang University of Technology [108]

efficient, green, and intelligent cleaning results. In recent years, research and development of laser cleaning-related hardware have accelerated, with the number of related patent applications increasing exponentially. This situation has effectively promoted the rapid development of laser cleaning technology.

5.1 Laser cleaning equipment

5.1.1 Functionalization of laser equipment

In general, a high-power laser needs a high-power vibrating mirror, and the power of the vibrating mirror is proportional to the volume. Thus, the corresponding high-power laser cleaning head becomes bulky, which presents a great burden for handheld operation. Shenzhen Hydrolaser Technology Co., Ltd. [109] combined low-power continuous lasers and pulsed lasers. This combination needs only a vibrating mirror and a bracket with extremely small volume and weight. This way reduces the weight of the laser cleaning head, which makes it convenient to hold. However, handheld laser cleaning is still dangerous. Baoyu (Wuhan) Laser Technology Co., Ltd. [110] disclosed a portable handheld intelligent laser cleaning device that uses a gyroscope to monitor the handheld state. This innovation solves the problem of instability, which can easily cause uneven cleaning or the device falling off from the hand and injuring the staff. This method fully guarantees the safety of the workers.

The abovementioned invention optimizes the volume and weight of the laser cleaning head, addresses the problem of handheld instability, and provides convenience for manual operation. However, it does not include a dust-blowing function. Dust particles can attach to the surface of the laser lens after cleaning, which absorbs part of the laser energy and affects the cleaning result. Jiangsu Guoyuan Laser Intelligent Equipment Manufacturing Co., Ltd. [111] proposed a handheld composite laser cleaning gun equipped with a ventilation system. This system blows gas from air channels on both sides of the gun not only for blowing away dust particles but also for air cooling. Nanjing University of Aeronautics and Astronautics [112] established a pollution monitoring method and device for a protective mirror of a laser cleaning head, which are internally provided with detecting light. The pollution degree is determined by changes in light refraction and reflection caused by pollutants. When the pollution degree reaches a preset value, it automatically stops working to avoid damage to the protective glasses from the absorption of energy by pollutants. Baoyu (Wuhan) Laser Technology Co., Ltd. [113] introduced an annular laser cleaning head, which is different from existing annular laser heads in the market. It has high transmission precision and can rotate 360° to realize cleaning without dead angles in the pipe.

5.1.2 Continuous laser equipment

Continuous lasers have high cleaning efficiency because of their durable and high energy characteristics. However, their concentrated and continuous energy easily cause thermal damage to the material matrix, especially in the cleaning process of precision devices. Therefore, continuous laser cleaning technology is usually suitable for application scenarios where surface quality is not very critical. Wuxiang County Hong Chen Wan Ju Environmental Protection Technology Co., Ltd. [114] used continuous lasers to treat the surface of concrete imitation bricks or slabs, which causes the solid surface to expand by heating and realizes the crushing and peeling of cement attached to the top layer of surface sand. China Energy Longyuan Environmental Protection Co., Ltd. [115] utilized the characteristics of continuous lasers, such as high energy density, controllable direction, and strong convergence ability, to remove organic substances from waste salt. Notably, the laser energy should not be too high; otherwise, the waste salt particles melt and agglomerate. South China University of Technology [116] proposed a laser remelting technology, which involves using continuous laser technology to clean and repair the surface of damaged waste steel. This method avoids the need of using a pulsed laser for initial cleaning and then switching to a continuous laser for remelting repair. Thus, it simplifies the processing flow and improves processing efficiency. The integrated treatment with continuous laser reduces the process steps, avoids interruptions and inconsistencies that may arise from frequent switching of laser modes, and ensures consistency in the processing process and the quality of steel repairs.

5.1.3 Pulsed laser equipment

For cleaning tasks that require high precision and surface integrity, gentler technologies such as pulsed laser should be considered. Shanghai Yingfeng Electronic Technology Co., Ltd. [117] adopted laser cleaning instead of traditional methods to process the evaporated metal film of thin-film capacitors, given that the laser action time is below the nanosecond level. Nanosecond pulse laser cleaning is a cold working technology that does not affect the film substrate. Similarly, Kunming Sachuang Photoelectricity Technology Co., Ltd. [118] employed a pulsed laser with a high peak power of 200 kW and an ultra-short pulse width of 4 ns to clean the mask plate. This approach controls the thermal damage to the target in a small range and avoids deformation caused by thermal influence.

Although pulse lasers have lower thermal effect than continuous lasers in the cleaning process, they can still cause different degrees of damage to high-precision surfaces. China Yangtze Power Co., Ltd. [119] controlled the laser to form a sine wave shape in the X–Y direction using a galvanometer system and applied Fourier transform technology to form any complex sine wave shape in a specific plane size. This innovative scanning mode and focal length compensation mechanism effectively avoid the problems of uneven cleaning and surface damage in traditional methods.

Judging from the current development trends, laser cleaning equipment is improving in the direction of miniaturization, portability, and intelligence. These improvements not only enhance the efficiency and convenience of the equipment but also make laser cleaning technology easier to popularize and more universal. Continuous wave laser cleaning technology, with continuous high energy input, is mainly used in engineering fields with relatively low surface accuracy requirements and high efficiency demands. However, pulsed laser cleaning technology is more suitable for application scenarios with high requirements on surface cleanliness and accuracy because of its high peak energy and short pulse characteristics.

5.2 Terminal device

In addition to improving the performance of laser cleaning equipment, the intelligent upgrade of terminal equipment is also an important way to improve the cleaning efficiency [14]. With the gradual improvement in the intelligent level of terminal equipment, its influence effect has been widely recognized by researchers in various fields.

China Construction Third Division First Construction Engineering Co., Ltd. [120] provided a control method for a laser cleaning robot based on machine vision. By collecting image information such as workpiece position and surface impurity state, the corresponding model of the laser cleaning robot is selected. This method eliminates the need for workers to operate on-site, which not only improves work efficiency but also ensures worker safety. Fanachi Laser Technology (Shandong) Co., Ltd. [121] suggested an efficient and intelligent laser cleaning machine. This machine reasonably plans the placement position of the equipment and provides a special protective box for the laser cleaning gun, which improves the convenience and safety of the equipment. China Aviation Xi'an Aircraft Industry Group Co., Ltd. [122] introduced an intelligent laser cleaning system and method based on robotics. This system uses an intelligent module on the laser cleaning head instead of manual operation to realize adaptive and intelligent tracking cleaning. It addresses the issue of desktop equipment being cumbersome and difficult to use for large-scale surface treatment.

Similarly, Suzhou Xiangming Laser Technology Co., Ltd. [123] designed laser cleaning equipment for aluminum alloy surface paint. This equipment uses a longitudinal transfer module and a positioning bracket to fix the position of the workpiece, which ensures stability of the workpiece in the cleaning process. It is equipped with components such as a transverse transfer module and a cleaning bracket to realize multi-angle and all-round cleaning. Shandong Zotye Construction Technology Co., Ltd. [124] invented a laser cleaning device for aluminum alloy template processing. This device combines a cleaning mechanism and a clamping component, which allow both sides of the aluminum alloy template to be cleaned without flipping. On this basis, Guangdong Longyue Construction Engineering Co., Ltd. [125] equipped the laser cleaning equipment with a sweeping device to remove surface debris residue after cleaning. This innovation completely addresses the environmental pollution problem caused by laser cleaning, which makes the green characteristics of laser cleaning technology more evident.

While laser cleaning technology focuses on improving cleaning efficiency, the safety of operators also needs to be considered. The intelligence of terminal equipment improves the production efficiency of enterprises, which makes it a crucial focus in the modernization construction. At the same time, implementing robust protective facilities is essential to ensure the safety and health of workers [126].

5.3 Monitoring device

Traditional monitoring technology usually monitors the cleaning quality and effect offline after laser cleaning. This approach often lacks timeliness and accuracy and cannot improve the efficiency and quality of laser cleaning. Given the complex components of pollutants, controlling the cleaning parameters is difficult. Real-time monitoring of the cleaning state during the cleaning process is necessary to timely control the laser power, scanning path, and other parameters, which achieves the requirements of complete cleaning without damaging the substrate [127].

Numerous sound and light signals are generated during laser cleaning. Researchers analyze these signals and express them as sound waves, images, and spectra for monitoring. Hebei University of Science and Technology [128] developed a real-time monitoring method and system for laser cleaning, which realizes real-time monitoring by collecting acoustic, optical, and video stream signals during laser cleaning. Dongguan Feichuang Laser Intelligent Equipment Co., Ltd. [129] identified the cleaning state of aircraft skin in real time through the differences in acoustic signals generated by laser cleaning the top coat, primer, and substrate. Nanjing University of Aeronautics and Astronautics [130] disclosed a real-time monitoring system and method for laser cleaning based on visual and tactile perception. This system uses the electric signal transmitted by the friction between the sensor block and the workpiece surface to realize online monitoring of the cleaning process. CRRC Nanjing Puzhen Co., Ltd. [114,131] proposed a method and device for visual inspection feedback control in the laser cleaning process of train exterior wall paint. By using a visual inspection device, different paint layers can be intelligently identified, which allows for the selection of the optimal cleaning parameters.

Laser-induced breakdown spectroscopy (LIBS) involves irradiating a high-energy laser beam on the surface of the sample to excite plasma. The changes in the characteristic peaks of each element in the cleaning process are then detected by laser plasma spectroscopy. This method allows for accurate and real-time monitoring of the cleaning situation and is favored by researchers [132]. Civil Aviation Flight University of China [133] suggested a laser cleaning control method and system based on online monitoring of LIBS technology. This system uses laser-induced plasma spectrum to quickly detect and analyze sample components and accurately control cleaning quality. Dongguan Feichuang Laser Intelligent Equipment Co., Ltd. [134] disclosed a real-time monitoring device and method for laser cleaning of aircraft skin using a spectral monitoring method. The cleaning process is divided into four stages: single-pulse laser to remove the top coat, multi-pulse laser to remove the primer, substrate exposure, and complete removal of the paint layer. According to the EDS test results (Fig. 11(a)), Ba is selected as the main characteristic element of the top coat, Ti is selected as the main characteristic elements of the primer, Cr is selected as the main characteristic element of the chemical conversion coating, and Al is selected as the main characteristic element of the matrix. As shown in Fig. 11(b), from the 16th pulse, the characteristic peak intensity of Ti began to weaken, while that of Al gradually increased. The results showed that the paint layer was nearly cleaned at the 16th pulse, but the substrate was not damaged. After the 16th pulse, the primer was completely removed, and the damage degree of the substrate gradually increased with the rise in pulse number. Element calibration of the corresponding

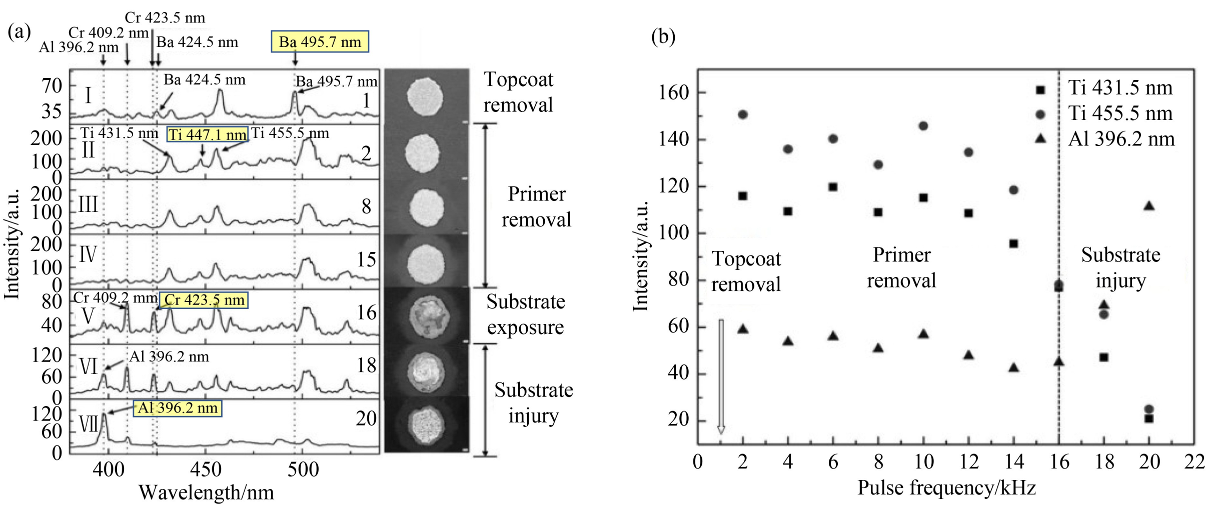

Fig. 11 Plasma spectra at different pulse numbers [134]. (a) Plasma spectra under different pulse numbers: I. 1 pulse; II. 2 pulses; III. 8 pulses; IV. 15 pulses; V. 16 pulses; VI. 18 pulses; VII. 20 pulses. (b) Relationship between the characteristic peak intensity and the number of pulses.

characteristic peaks at different stages in the LIBS spectrogram can monitor the removal process of different paint layers under different pulse numbers in real time. When a specific signal appears in the plasma spectrogram, it indicates that the cleaning task of the previous stage has been completed, which makes the monitoring process real time and accurate.

The existing LIBS technology mostly uses a dual laser beam mode, with a high frequency laser beam for cleaning and a low-frequency laser beam used for stimulating plasma. However, the dual beam method has high energy, which increases the risk of matrix damage. The strong continuous background radiation caused by the laser paint removal process masks the characteristic spectra of atoms and ions, which causes difficulty in collecting the plasma spectrum. Therefore, using only a single laser for cleaning and plasma excitation is challenging. Civil Aviation Flight University of China [135] disclosed a system and method for detecting the effect of high-frequency laser paint removal. By adjusting the process parameters of high-frequency laser paint removal in an industrial personal computer, the laser cleaning threshold and the peak power density excited by plasma are balanced. This approach resolves the problem of mutual interference between thermal radiation and plasma during cleaning. It promotes the application and development of high-frequency lasers in the field of paint removal detection based on LIBS.

Beijing University of Technology [136] invented a method and system for monitoring the quality of laser cleaning of thermoplastic resin based on the plume angle. This system monitors and analyzes the plume angle of spatter in the cleaning process, promptly removes spatter pollutants, and effectively ensures the sustainability of cleaning. Shanghai Hangyi High-tech Development Research Institute Co., Ltd. [137] proposed an online monitoring method of laser cleaning effect based on visual inspection. By converting the RGB image on the surface of the cleaned workpiece to grayscale, the grayscale image is divided into multiple sub-images and compared with a preset gray standard value to identify untreated areas and plan for re-cleaning.

The diversification of monitoring methods enables researchers to control the state of laser cleaning more accurately. Combining multiple monitoring methods can mitigate the accuracy doubts caused by a single monitoring method to some extent. This approach is indispensable for the intelligent judgment of laser cleaning and the independent adjustment of process parameters. It will be a major trend in the development of laser cleaning monitoring technology in the future [13].

In summary, the laser cleaning equipment is constantly updated and upgraded, which develops toward a more convenient and lightweight direction. This subsequent development may not be limited to enterprises and factories but will extend to all aspects of daily life. The terminal equipment and the cleaning equipment are linked and controlled through robots to achieve intelligent automatic cleaning. This approach helps reduce manpower and time costs, improve production efficiency and quality, and decrease the production costs and risks for enterprises. At the same time, the laser cleaning equipment is equipped with advanced sensors and data processing systems. The real-time monitoring and data analysis of the cleaning process can be realized through acoustic and optical sensors, which significantly improves the controllability of the cleaning process. Analysis of Chinese patents reveals that laser cleaning equipment not only enhances cleaning efficiency and quality but also makes great progress in cleaning speed, stability, energy saving, and environmental protection.

6 Patent analysis of laser cleaning process

The control of the laser cleaning process is fundamental for improving cleaning efficiency, avoiding substrate damage, and obtaining the best surface quality. In recent years, the protection of related intellectual property rights has attracted the attention of technical researchers. Analysis of related patents reveals that precise regulation of the laser cleaning process has great potential for functional modification of the cleaned substrate surface, which is worth exploring. However, the process requirements for cleaning efficiency, matrix surface integrity, and functional collaborative control are very demanding. Notably, laser cleaning methods using laser composites, liquid assistance, and surface microtexture preparation have shown significant effectiveness (Fig. 12), as confirmed by the rapid increase in relevant patent applications.

6.1 Surface integrity control of laser cleaning

The common laser beam intensity follows a Gaussian distribution, with high intensity at the center of the spot and weaker intensity at the periphery. This distribution results in problems such as irregular edges of the spot and uneven energy distribution, which cause difficulty in removing the coating evenly while ensuring the surface integrity of the substrate. China Aviation Manufacturing Technology Research Institute [138] disclosed a device and method for accurately and uniformly cleaning aircraft composite coatings by laser. The issue of poor roundness of light spot is resolved by laser spinning. In addition, combining the common spinning and scanning mode increases the effective cleaning range and improves the accuracy and uniformity of laser cleaning.

The quality of repainting after laser cleaning is related to the thickness of the molten layer produced on the cleaned surface. To solve this problem, the Armored Force Academy of the Chinese People’s Liberation Army

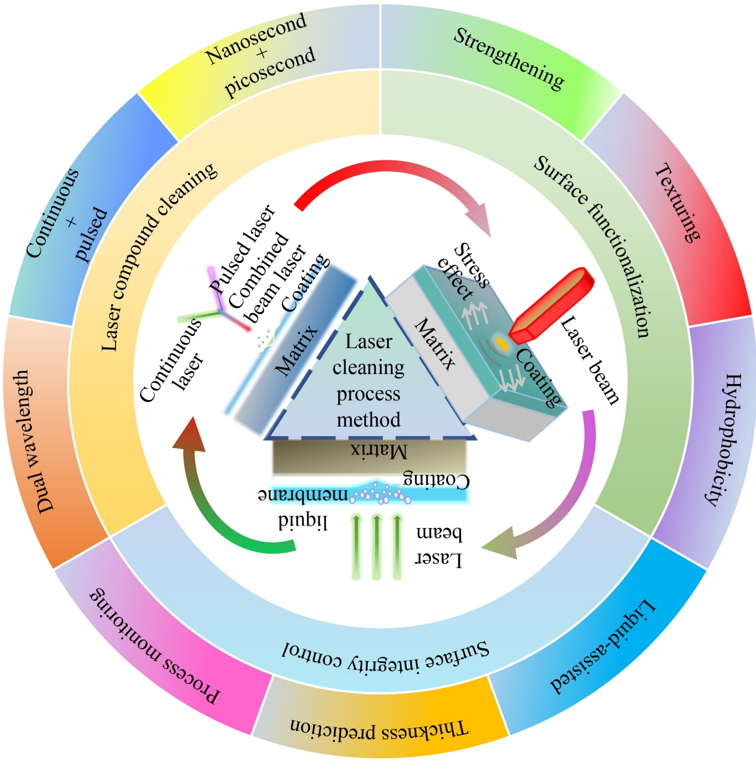

Fig. 12 Schematic of the laser cleaning process: liquid-assisted laser cleaning, laser cleaning for surface modification, and composite laser cleaning.

[139] proposed a control method that effectively controls the thickness of the molten layer of the paint layer on the surface of the substrate after cleaning. First, the thickness of paint layer is predicted. Then, the laser parameters are adjusted accordingly. Finally, the thickness of the surface melting layer after cleaning is effectively controlled without affecting the mechanical properties of matrix materials. Qilu University of Technology [140] established a PSO–SVR prediction model for laser paint removal thickness to predict the relationship between paint removal thickness and cleaning parameters. This model accurately controls the paint removal thickness and protects the substrate from damage.

The surface of carbon fiber resin matrix composites is susceptible to aging by light. Thus, it needs to be coated with paint to improve its lifespan. In dry laser cleaning, the substrate ablation damage threshold is often higher than that of the surface paint. However, the opposite is observed for resin-based composites. Thus, they are easily damaged when using dry laser to clean the surface paint. Therefore, liquid-assisted laser cleaning can be considered by levering the good corrosion resistance of resin-based composites. As shown in Fig. 12, the existing liquid-assisted laser cleaning method involves placing the material to be cleaned in a suitable liquid layer. This liquid layer protects the substrate to prevent the focusing energy of the laser from directly acting on the substrate and realize nondestructive cleaning. Controlling the thickness of the liquid layer is important for realizing nondestructive laser cleaning, Therefore, Harbin Institute of Technology [141] proposed a wet laser cleaning device and method. In this method, the thickness of the liquid film can be adjusted by controlling a valve, and the liquid film will boil after absorbing laser energy, which causes the pollutants to be stripped away. During the liquid-assisted laser cleaning, the liquid film absorbs much of the laser heat energy, which prevents damage to the substrate but also weakens the laser impact force. As a result, effectively peeling off the surface coating is difficult. Nankai University [142] suggested a laser cleaning method for the surface coating of resin-based composite materials. Based on the characteristic that the decomposition temperature of resin is lower than that of coating, high-pressure liquid flow is used to spray the surface after liquid-assisted laser cleaning, which separates the decomposed resin from the surface coating. However, the abovementioned patents still lack process monitoring for liquid-assisted laser cleaning. Jiangsu University [143] provided a monitoring device and method for laser wet cleaning of carbon fiber resin-based composite materials. The appropriate lens is selected according to the different surface structures to be cleaned, and a water quality sensor is added to monitor the change in impurity content in the water to determine if the cleaning is complete. This method solves the shortage of process monitoring research in wet laser cleaning.

Changzhou Campus of Hohai University [144] introduced a laser cleaning device and method for aluminum alloy. This method uses liquid nitrogen for pre-cooling to avoid changes in the original internal structure caused by excessive heat accumulation in the base material. This cleaning device can reduce the heat accumulation on the surface of aluminum alloy during laser cleaning while ensuring the cleaning effect.

Composite materials are sensitive to laser, which makes the possibility of ablation damage high. Therefore, laser cleaning technology should choose an appropriate cleaning process according to different situations. While improving the cleaning efficiency and quality, the excessive thermal impact and impact stress caused by laser irradiation on the material surface should be accurately controlled to maintain the integrity and stability of the material surface after cleaning.

6.2 Surface functionalization of laser cleaning

Some researchers combine laser cleaning with laser shock reinforcement. By using pulse laser irradiation on the surface of the matrix, surface pollutants undergo ablation, gasification, phase explosion, and other physical processes. This combination achieves the purpose of cleaning while the phase explosion-induced plasma shock wave modifies the surface, which improves its comprehensive performance (Fig. 12). China Aviation Manufacturing Technology Research Institute [145] developed a compound processing method for laser cleaning and strengthening of aluminum alloy materials. By adopting laser cleaning parameters with a short pulse width of 10–20 ns and a power density of 20–100 GW/cm^2, the dual effects of removing the corrosion layer and improving fatigue resistance on the metal surface are realized. Shenzhen Institute of Information Technology [146] disclosed a compound processing equipment and method for laser cleaning and laser shock strengthening. First, lasers with wavelengths of 1064 and 532 nm are used for cleaning. Then, a 355 nm ultraviolet laser with high single photon energy is used to shock strengthen the surface of the workpiece, which enhances properties such as hardness, fatigue resistance, wear, and stress corrosion. Shenyang Institute of Automation Chinese Academy of Sciences [147] proposed a compound method of laser cleaning and strengthening for plate heat exchangers. This method utilizes two laser beams with different wavelengths and pulse widths to first clean the sample surface and then strengthen it. Thus, it integrates cleaning and strengthening and addresses the technical problem of traditional laser methods.

The hydrophobic paint layer cannot be attached effectively because the metal surface is too smooth after cleaning. Harbin Institute of Technology [148] suggested a laser cleaning-texturing compound machining method, which puts forward two schemes: the first one uses a gun head to divide a laser beam into two beams, which are used for laser cleaning and laser texturing, respectively; the second one directly uses two lasers to generate two beams, which clean in front and roughen in the back simultaneously; ultimately, the purpose of simultaneous implementation of cleaning and strengthening is achieved. Compared with painting on metal surface to achieve hydrophobicity, Suzhou Xingbo Laser Technology Co., Ltd. [149] offered a one-step preparation method for femtosecond laser cleaning-superhydrophobic micro-nano surfaces of aluminum alloy. The patent describes using femtosecond laser low power for cleaning, and then increasing the power for etching to prepare the micro-nano texture with ultra-hydrophobicity on a small scale. By controlling the laser power, cleaning and etching are combined, which achieves the hydrophobic effect on the metal surface. The entire process is connected with information speed, which effectively avoids re-oxidation after cleaning.

Armored Force Academy of the Chinese People's Liberation Army [150] recommended a method of cleaning the stainless steel surface with a pulsed laser to form a micro-nano structure layer. In the process of cleaning stainless steel surface paint layer with a pulsed laser, the micro-nano structure layer is formed on the stainless steel surface using the impact and thermal effects of the laser, which improves the deformation resistance of the stainless steel surface and could be expanded as a new functional material. Taiyuan University of Science and Technology [151,152] invented a magnetic pulse welding method for lap joints of Mg/Ti alloy plates and a method for preparing layered wave-interface composite materials made of Mg and Ti based on a rolling method. In both patents, a laser is used to clean the welded joint of Mg alloy plate and Ti alloy plate before welding, and micro-texture is prepared while removing the oxide film on the surface. The patent example demonstrates that the interface between the Mg alloy plate and Ti alloy plate will form a wave-like mechanical interlocking bonding mode after welding, which greatly improves the bonding strength of the welding interface.

By analyzing the abovementioned patents, we find that laser cleaning technology not only effectively cleans but also improves the properties of metal materials through impact strengthening. Preparing the corresponding interface micro-texture during laser cleaning functionalize the substrate surface after cleaning and better meet the requirements of industrial production for multifunctional special surfaces.

6.3 Composite laser cleaning

Existing laser cleaning equipment generally uses a single wavelength continuous laser or pulsed laser, which leverages the difference in difference in absorption rates between the substrate and the coating to decompose or evaporate the pollutant layer from the surface of the substrate [153]. When faced with pollutants with complex components, the cleaning effect of a single type of laser is limited. Therefore, in order to improve the cleaning efficiency some researchers began to consider the combination of multiple lasers and cooperative cleaning (Fig. 12) [154].

Experience shows that the nanosecond pulse laser mainly relies on the thermal expansion vibration effect of contaminant particles and the substrate to achieve cleaning. Thus, it is suitable for cleaning large particle pollutants. Meanwhile, the picosecond pulse laser has high instantaneous energy, and the energy absorbed by pollutant particles is ablated and gasified before being conducted to the substrate by heat conduction. Thus, its removal effect on small particles is the best. Xiamen University of Technology [155] invented an intelligent dual-beam laser cleaning device and its usage method. The light sources of nanosecond and picosecond lasers are overlapped. The advantages of two lasers with different pulse widths are utilized to complement each other. This method can be applied to cleaning pollutant particles with different sizes and improve cleaning efficiency and quality.

Lasers can be divided can be divided into continuous and pulsed lasers according to their working conditions. Continuous laser injection easily causes damage to the matrix due to heat accumulation. By contrast, pulsed lasers have high instantaneous power but low overall heat input. Thus, they usually require multi-point laps for cleaning. However, their cleaning efficiency is worse than that of continuous laser cleaning. Jiangsu University [156] adopted the laser cleaning method to remove paint, which includes fast scanning cleaning with continuous laser and finishing with pulsed laser. This approach avoids damage to the substrate and overcomes the problem of slow cleaning efficiency with pulsed laser. Wuhan Raycus Fiber Laser Technologies Co., Ltd. [157] designed a new type of laser cleaning device that couples the continuous laser beam with the pulsed laser beam through the beam combiner. This device not only significantly improves cleaning efficiency but also has good rust and paint removal effects. China Aviation Manufacturing Technology Research Institute [158] disclosed a dual-light source composite laser cleaning method and device. This device uses the peak power of pulsed layer to destroy the coating at multiple points. Then, continuous laser energy is applied to achieve rapid cleaning. In addition, a multi-mode fiber laser for laser cleaning has been developed [159], which can switch between continuous laser and pulsed laser through a seed light module. Depending on the specific cleaning requirements, the light mode can be adjusted to achieve various cleaning modes, such as continuous laser, full pulse laser, and continuous pulse alternating cleaning modes, which meet different substrate cleaning thresholds and a wide range of applications.

Beijing University of Technology [160] devised a laser cleaning system and method that can synchronously output dual-wavelength lasers to efficiently remove pollutants without damaging the radar cover substrate. It uses the difference in absorption rates of different paint layers to remove them with different wavelengths in layers. Suzhou Usiland Optronics Co., Ltd. [161] proposed a dual-wavelength laser cleaning machine for cultural relics, which is compatible with dual-wavelength outputs of 1064 and 532 nm. Compared with single-wavelength laser cleaning equipment, the cleaning color range is wider. Wenzhou Polytechnic [162] introduced a desktop laser precise cleaning device with dual-wavelength composite energy distribution. This device divides a Gaussian laser beam into a Bessel ring laser beam and a short-wavelength laser beam, which are then coupled to form a dual-wavelength composite beam. This beam improves cleaning accuracy and uniformity. The abovementioned patents combine different wavelengths of laser without needing cooperation between the two types, which makes the laser cleaning process more convenient and efficient.

Efficient and accurate cleaning can be achieved by using lasers with different wavelengths to clean different components in composite materials or by combining pulsed and continuous lasers to complement each other. This approach provides a new idea for the subsequent combination of different lasers.

In summary, current laser cleaning and strengthening composite technology fully utilizes the characteristics of different laser sources. However, the complex structure of the optical system and high processing costs restrict subsequent development. When using lasers with different wavelengths and pulse widths, the laser power density varies considerably, which makes accurate control difficult and potentially causes matrix damage. Therefore, combining liquid-assisted laser cleaning, monitoring devices, and surface modification under real-time monitoring can improve the corrosion and wear resistance of the material surface through laser shock strengthening technology. This approach can avoid the thermal ablation damage of the substrate, which greatly expands the application field and scope of the equipment and is worthy of further study.

7 Conclusions

This study systematically analyzes the patents in the field of laser cleaning in China. At present, the number of laser cleaning patents is increasing rapidly, and the industrial layout is essentially established. However, certain problems are encountered in transforming the intellectual property of laser cleaning into engineering applications, such as imperfect mechanisms and poor universality, which are urgent issues that need to be solved in the field of laser cleaning in China. Therefore, strengthening cooperation between enterprises and universities, incentivizing intellectual property innovation, and providing special policy support are effective measures to promote the high-quality development of laser cleaning in production, research, and application. Laser cleaning technology has been highly concerned by the government, universities (or scientific research institutes), and enterprises, which demonstrates vigorous development.

(1) Laser cleaning can meet the cleaning requirements of different substrates, such as iron, aluminum, titanium, and composite materials. It effectively cleans corrosion layers, paint layers, and carbon deposits. Laser cleaning equipment is developing in a more convenient and lightweight direction, which considerably improves compatibility between terminal and cleaning equipment. Online monitoring methods have become more abundant, and intelligent cleaning has gradually become the mainstream. The precise control of the laser cleaning process and laser compound cleaning method has great potential for maintaining surface integrity and realizing surface functionalization.

(2) Several areas in the field of laser cleaning still require improvement. For example, offline monitoring methods generally lack timeliness, which causes difficulty in adjusting the cleaning scheme according to the cleaning effect in real time. It also complicates the control of the cleaning threshold of pollutants and the damage threshold of the matrix. Thus, developing real-time monitoring equipment and methods is urgently needed. Laser cleaning with high energy density can cause damage to the substrate due to heat accumulation. Adopting liquid-assisted laser cleaning and liquid nitrogen (precooled gas)-assisted laser cleaning can help avoid secondary damage to the substrate. Research and development should focus on pipe fittings, precision instruments, and large components to expand the application scope of laser cleaning.

(3) Reducing costs, increasing efficiency, and improving the quality of laser cleaning are the directions for continuous efforts in the future. Laser compound cleaning, intelligent cleaning, and "washing–repairing" integration are expected to become the research focus in the field of laser cleaning. Moreover, related patent applications are set to become a focal point in the industrial field, which drives the laser cleaning technology to a new phase of rapid development. In addition, laser cleaning as a green cleaning technology will play an increasingly important role in China's "carbon peaking and carbon neutrality" strategy while contributing to global sustainable development.

Nomenclature

AM	Additive manufacturing
CMAS	CaO, MgO, Al_2O_3, and SiO_2
EDS	Energy dispersive spectroscopy
LIBS	Laser-induced breakdown spectroscopy
IPCS	International patent classification system
PSO	Particle swarm optimization
SVR	Support vector regression
YSZ	Yttria-stabilized zirconia

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