

Development of Laser Remanufacturing Technology and Application

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Abstract: Laser remanufacturing technology, as the frontier of manufacturing technology innovation, has profoundly changed the design and operation of high-end equipment and is a critical support technology for green remanufacturing and an important force promoting the sustainable development of the manufacturing industry. In this study, the macro-demands of laser remanufacturing technology were analyzed. The development and application status of the laser remanufacturing technology are introduced in detail. The challenges in the development of laser remanufacturing technologies and industries are summarized. The development goals for 2025, 2035, and 2050 are then proposed. Regarding the current challenges of laser remanufacturing technology in China on special materials, core components, remanufacturing concepts, and standard systems, development suggestions are proposed, i.e., strengthening the active guidance at the strategic level, constructing a genome system for laser additive remanufacturing materials, improving the standardization system and the high-level applied talent training system, increasing the application promotion and guiding industry integration, establishing cooperation platforms to accelerate the innovation development of common key technologies, and providing support for laser remanufacturing technology and its industrial development.

Keywords: laser remanufacturing; multi-energy field; on-site remanufacturing; life cycle

1 Introduction

Key components of high-end equipment, such as hot-end components of aero engines, ultra-supercritical steam turbine rotors and blades, railway tracks, and metallurgical equipment, are prone to structural and surface damage owing to harsh service environments, leading to a shut down or scrapping of high-end equipment. If the idea of full lifecycle manufacturing is used, the service wear time of the parts can be prolonged through rapid remanufacturing or on-site remanufacturing. Resources can be reused, and sustainable development can be promoted. As pointed out in *Made in China 2025* [1], green manufacturing can be carried out in an all-round way, vigorously developing the remanufacturing industry; implementing high-end remanufacturing, intelligent remanufacturing, and in-service remanufacturing; and promoting product certification and the sustainable and healthy development of the remanufacturing industry.

Laser remanufacturing technology uses high-power laser beams as the heat source and uses non-contact optical processing to provide new solutions for part repair and remanufacturing. This is an important support technology for green remanufacturing. This technology can quickly restore the products or parts and reach or exceed the performance of new products. It has the advantages of a high repair accuracy, less damage to the workpiece, high

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bonding strength in the repair area, and high material utilization. To meet the repair needs of key parts in various fields, domestic and foreign scholars have carried out theoretical and experimental research on laser cladding of Fe-based [2,3], Ti-based [4,5], Co-based [6,7], and Ni-based [8,9] alloys. They also carried out basic research on the application of laser remanufacturing technology in the fields of aero-engine blades [10], steam turbine rotors [11], metallurgical equipment [12], coal mining machinery [13], and high-pressure oil pump camshafts [14]. However, laser remanufacturing technology has only achieved industrial applications in a few fields, and there are still certain technical and market bottlenecks for large-scale applications.

Aiming at the laser remanufacturing technology and industry, the current technical problems and application challenges were sorted in this study based on the analysis of the development status. The development trend was judged, and countermeasures and suggestions were proposed to promote the development of laser remanufacturing technology and industry in China.

2 Analysis of macroscopic demand for laser remanufacturing technology

2.1 Laser remanufacturing technology is at the frontier of manufacturing technology innovation

Laser remanufacturing technology can be used in the pre-processing, shaping repair, and post-processing links of laser remanufacturing. The specific classifications are shown in Fig. 1. The core link of this technology is the laser-forming repair technology, such as the use of a laser cladding formation, rapid laser prototyping, and laser welding processes for repairing defective parts. In addition, laser cutting and laser cleaning technologies can be used in the disassembly and pre-processing of parts, and laser shock strengthening and laser polishing can be used in the post-processing of repaired parts.

Laser additive remanufacturing technology, based on laser cladding and laser rapid prototyping, has the advantages of forming a metallurgical bond through a stable molten pool, an interface bonding strength much higher than those of coating and spraying, and less heat input than arc surfacing. Therefore, it can meet the remanufacturing demand of high-strength parts and is an important frontier development direction for advanced manufacturing technology. Given the severe repair requirements of some large-scale equipment and key components, special repair and multi-energy field laser remanufacturing technologies have become the current research hotspots.

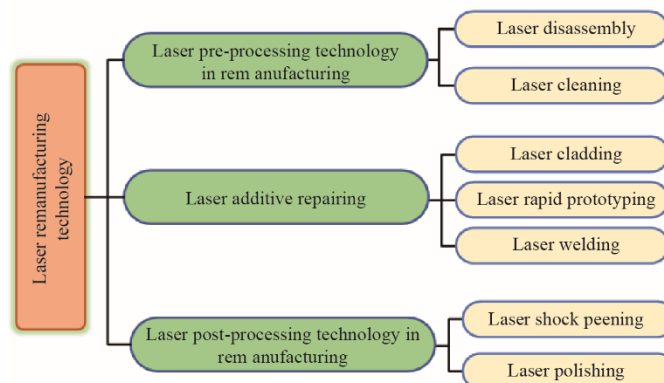


Fig. 1. Classification of laser remanufacturing technology.

2.2 Laser remanufacturing industry is an emerging industry promoting the transformation and upgrading of the manufacturing industry

Laser remanufacturing technology is advantageous in high-end equipment remanufacturing and is considered to be a next-generation strategic support technology for the transformation and upgrade of manufacturing techniques. The laser remanufacturing industry, formed through the development of laser remanufacturing technology, provides an impetus for the transformation and upgrade of the manufacturing industry.

The laser remanufacturing industry has become an industry with significant economic and social benefits in developed countries and in regions such as Europe and the United States and has greatly promoted the transformation and upgrading of the manufacturing industry. To promote the development of the laser remanufacturing industry, major countries and regions in the world have successively formulated a series of strategic recommendations and policy support (Table 1). China has become a major manufacturing nation;

however, the degree of refinement of manufacturing technology still needs to be improved compared to developed countries or regions. In addition, with the development requirements of energy saving and emission reduction, China has gradually focused on the laser remanufacturing industry. A series of strategies and policies to support this development have been launched. In recent years, laser repair and remanufacturing technologies have been applied in aviation, aerospace, mining machinery, turbine equipment, metallurgical equipment, and other industries in China, and have been widely used in the remanufacturing of power equipment such as hydraulic support in coal mines, metallurgical rolls, and steam turbine rotors. The laser remanufacturing industry has become an emerging industry promoting the transformation and upgrading of the manufacturing industry.

Table 1. Strategies and policies related to laser remanufacturing technology and industry in major countries or regions globally.

Country or region	Year	Related strategies and policies
The United States	2012	The National Science and Technology Commission issued the “National Strategic Plan for Advanced Manufacturing,” which clarified the basic but important role of advanced manufacturing, for the United States to ensure economic advantages and national security; the National Additive Manufacturing Innovation Institute was established as the first innovation research institute of the National Network for Manufacturing Innovation; and the United States International Trade Commission released “Remanufactured Goods: An Overview of The U.S. and Global Industries, Markets, and Trade,” which carried out a panoramic study of US remanufacturing
	2016	Release of “Roadmap for Next Generation of Additive Manufacturing Materials” (funded by the National Institute of Standards and Technology)
The United Kingdom	2011	The government established the High Value Manufacturing Technology Innovation Centre (Catapult); near net shape and additive manufacturing are important research directions
	2013	The government released “Future of Manufacturing: A New Era of Opportunity and Challenge for the UK,” proposing directions and policy measures for the long-term development of the UK manufacturing industry, covering remanufacturing and additive manufacturing
European Union	2007	The EU launched the seventh research framework plan, which involves high-performance lasers and laser cladding, among other applications
	2008	Established the European Technology Platform for Micro- and Nano-Manufacturing
	2013	Released “Towards 2020–Photonics Driving Economic Growth in Europe Multiannual Strategic Roadmap 2014–2020,” promoting the development and application of new processes such as laser additive manufacturing and laser cleaning
	2014	Started the implementation of the “Horizon 2020” plan promoting research and development in fields such as advanced manufacturing. Additive manufacturing is one of the key enabling technologies
China	2015	Released the “Made in China 2025 Key Fields Technology Roadmap.” Additive manufacturing equipment and 3D printing materials were listed as key development directions and specific strategic development priorities were proposed
	2016	Issued the “National Thirteenth Five-year Plan on Science, Technology and Innovation,” built a relatively complete additive manufacturing technology innovation and R&D system, carried out theoretical research on ultra-fast pulse and ultra-high power laser manufacturing, made breakthroughs in the key technologies of laser manufacturing, and developed advanced laser manufacturing application technology and equipment
	2017	Formulated the “High-end Smart Manufacturing Action Plan (2018–2020),” accelerating the development of the high-end intelligent remanufacturing industry and forming a green development method
	2020	Issued the “Strengthen ‘From 0 to 1’ Basic Research Work Plan,” the key support directions of which include additive and laser manufacturing, key basic materials, manufacturing technology, and key devices.

2.3 Laser remanufacturing industry is an important force to promote sustainable development

“Made in China 2025” regards green manufacturing as one of the five major projects, and clearly points out that it is necessary to reform traditional manufacturing through the implementation of energy efficiency improvements, clean production, water-saving, pollution control, and recycling, among other factors. The laser remanufacturing industry is highly compatible with the concept of green manufacturing, providing important support for the sustainable development of traditional manufacturing.

Laser remanufacturing technology has the characteristics of concentrated heat input, small damage to the workpiece, and a fast processing speed, and is an emerging green remanufacturing technology. Laser remanufacturing technology can achieve a rapid repair of key components and reduce a waste of resources, reduce

energy and economic losses caused by a downtime, and promote sustainable development. In addition, the laser remanufacturing industry has fewer “three waste” emissions and controllable pollution sources during the manufacturing process, and is highly compatible with construction of a circular economy and conducive to the implementation of energy-saving and emission-reduction strategies in China.

2.4 Laser remanufacturing technology profoundly changes the design and operation of high-end equipment

The green, low energy consumption, and high-quality development of the high-end equipment manufacturing industry has become a top priority, and the full lifecycle management of the key components has become an important trend in the development of high-end equipment. The emergence and use of laser remanufacturing technology have improved the connotation of the lifecycle management of key components. Specifically, the possibility of repairing key components should be considered in the design stage, and information feedback, such as the service life, should be considered in the service stage. In addition, scrapping methods, such as non-destructive decomposition, should be considered during the scrapping stage. Meanwhile, by strengthening the exploration of product failure analysis and remaining life change rules, the design and preparation of high-performance surface coatings for failed parts and the processing and quality control of weak parts can be realized.

The full lifecycle manufacturing model effectively controls manufacturing pollution from the source, compensates for the losses caused by equipment operation stalls, and subverts the traditional manufacturing model. Laser repair and remanufacturing technology, as a key part, has profoundly changed the design and operation mode of manufacturing equipment.

3 Development status of laser remanufacturing technology

3.1 Laser remanufacturing has been applied in the repair of parts in various industrial fields

With the continuous development of high-power lasers and their support equipment, an increasing number of countries have strengthened their theoretical and technical studies on laser remanufacturing technology in the manufacturing and repair of mechanical parts. As shown in Fig. 2, the current laser remanufacturing technology has been practically applied in industries such as aviation, aerospace, defense, mining machinery, energy and power, and metallurgical equipment. The application of laser remanufacturing technology abroad is mainly concentrated in the defense industry and aviation and aerospace fields, such as applying laser remanufacturing in the repair of failed aero-engine parts.

In the military field in China, laser remanufacturing technology is mainly used to build a core technology system for the remanufacturing of key components of military aircraft engines. In the civil industry, laser remanufacturing technology has been applied in the repair of coal-mine hydraulic support, steam turbine rotors and blades, metallurgical rollers, mandrels, rolling mill archways, and other large equipment in the fields of mining machinery, energy and power, and metallurgical equipment. Among them, the laser remanufacturing technology of coal-mine hydraulic support has realized a batch application.

3.2 Energy field-assisted laser remanufacturing has become an important approach of high-quality remanufacturing

To meet the requirements of high-quality repair and on-site repair of key parts of high-end equipment, laser metal deposition through a single energy beam is prone to defects such as pores, residual stress, and microcracks, which affect the performance and stability of the repaired parts. It is therefore difficult to meet the remanufacturing requirements of high-end equipment in terms of accuracy, complexity, and high performance solely by changing the laser processes.

Accordingly, scholars have proposed the use of electromagnetic fields [15,16], induced thermal fields [17], ultrasonic vibrations [18–20], and other external energy fields to couple to the laser remanufacturing process (Fig. 3). Specifically, an electromagnetic field is applied to adjust the molten pool flow and suppress pores for the repair of narrow-deep defects and strict requirements for the absence of pores. An ultrasonic energy field is applied to regulate the microstructure morphology of components that have strict requirements for microstructures. A thermal field is applied to reduce the temperature gradient and residual stress of fragile materials or parts. Energy field-assisted laser remanufacturing technology has recently become a research hotspot; however, the related technology is still at the stage of laboratory research and prototype development. To meet the needs of industrial

applications, there is an urgent requirement for the continuing development of hybrid manufacturing processes and energy field integration equipment to meet the high-quality and high-efficiency repair requirements of high-end equipment in the future.

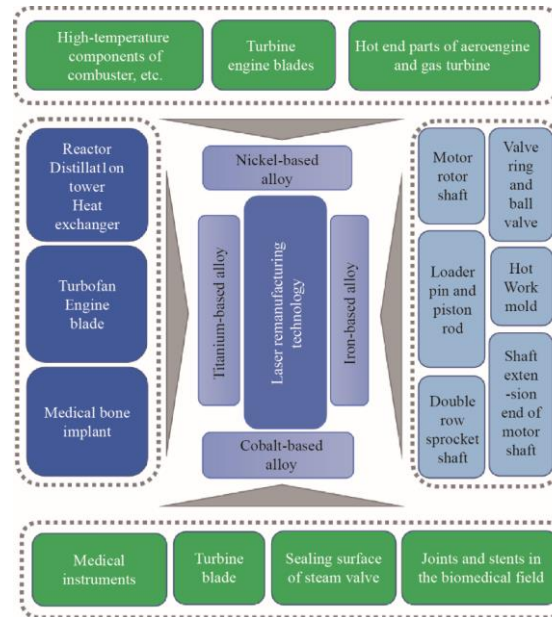


Fig. 2. Laser remanufacturing technology for different industrial fields.

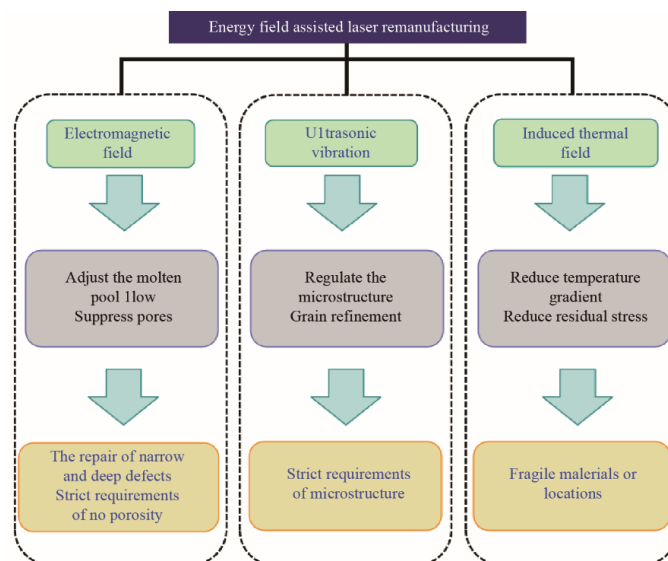


Fig. 3. Mechanisms of external energy field in laser remanufacturing.

3.3 On-site remanufacturing is an important development direction of laser remanufacturing

To meet the needs of repairing large equipment or large parts that are difficult to transport, on-site laser remanufacturing has the outstanding advantage of a quick recovery of damaged equipment. To facilitate on-site remanufacturing, laser equipment needs to be miniaturized, integrated, and easily transported to adapt to complex on-site environments and maintain a high stability.

When laser cladding remanufacturing technology is used to repair large equipment or parts, particularly the laser repair of non-horizontal base surface damage, the shape of the molten pool is prone to changes under the action of gravity, which puts forward higher requirements for multi-angle laser remanufacturing. For this reason, Shihong et al. adopted laser cladding technology with optical powder feeding and controlled the laser cladding head to be perpendicular to the base surface at different inclination angles to achieve full-angle laser cladding [21].

In addition, Yao et al. studied the influence of the working airflow and cladding angle on the quality of the laser-repaired rotor shaft and realized laser repair at various angles [22].

4 Challenges in the development of laser remanufacturing technology

The equipment repair and remanufacturing industry represented by laser remanufacturing is a derivative industry of equipment manufacturing. Although China's laser remanufacturing technology has been applied in the fields of mining machinery, energy and power, and metallurgical equipment, new requirements for laser remanufacturing technology and industry have been proposed with the development of the high-end equipment industry, such as the laser remanufacturing of high-end equipment represented by aviation engines and gas turbines. At present, the industrial scale of China's laser remanufacturing industry does not match with that of the manufacturing industry, and there are problems in industrial development including "small, scattered, and weak" characteristics, few application fields, and a lack of international leading enterprises with a large scale and high technological strength. The application and development of laser remanufacturing technologies in China face the following challenges.

4.1 Backward development of special materials for laser remanufacturing

The special materials required for laser remanufacturing are a significant bottleneck in China. For example, the development of new special materials, such as laser remanufacturing powder and wire materials, is lagging, and the selection of proprietary materials is limited. Problems have occurred such as a few varieties, few suppliers, and a lack of high-performance repair materials. The reliability and stability of the proprietary materials are generally low and lack verification. At present, foreign companies have developed a series of materials for laser additive manufacturing technology. For example, SLM Solutions (Germany) developed aluminum-, nickel-, titanium-, cobalt-, iron-, and copper-based lasers. Additive manufacturing materials have established a stable process system using self-produced equipment. For imports, foreign equipment manufacturers usually adopt an "equipment + powder" bonding sales policy, making the import of special materials into China expensive, which increases the production costs and reduces its competitiveness in the field of laser additive remanufacturing.

4.2 Dependence on imports of core equipment and components

China already has R&D capabilities for equipment used in the field of laser remanufacturing; however, it is still focused on the integrated development of equipment for industrial applications. Its core components, such as high-quality beam lasers and beam shaping systems, high-quality electron guns and high-speed scanning systems, precision components such as power laser scanning galvanometers, dynamic focus mirrors, and array-type high-precision nozzles/printers still rely heavily on imports. Domestic laser manufacturing equipment still has a large gap with imported brands in terms of the process stability and environmental temperature control. China currently has several internationally influential equipment manufacturers, such as Han's Laser Technology Industry Group Co., Ltd. and Wuhan HGLaser Engineering Co., Ltd.; however, the high-end laser equipment market is still dominated by advanced foreign companies, such as Trumpf and APA Odd Company (IPG), Coherent, and Laserline.

4.3 Insufficient understanding and knowledge of laser remanufacturing by enterprises

Laser remanufacturing technologies provide new solutions for high-end equipment repair and remanufacturing; however, this technology has not been widely accepted or recognized by the equipment industry. As the specific reasons for this, some traditional equipment companies are less sensitive to new technologies and need to strengthen their promotion and awareness; however, rigorous scientific analysis and completeness are required when laser remanufacturing technology is introduced in a certain equipment field. Process verification and the blind introduction of new technologies will increase the equipment operation risks. In addition, the product and material design needs to consider the maintenance and remanufacturing of parts during the product lifecycle management, whereas traditional equipment parts are not considered to be repaired by laser remanufacturing during the design. Therefore, it is difficult to apply laser remanufacturing technology to several equipment parts affected by restrictions in the structural form or material selection.

4.4 Incomplete industry standards system

In the field of laser repair and remanufacturing, national standards including *Laser Repair Technical Terms and Definitions* [23], *Laser Repair General Technical Specifications* [24], and several machinery industry and corporate standards have already been established in China. However, a complete set of standards systems for laser remanufacturing technology has yet to be established, which restricts the accumulation, curing, promotion, and application of related technological achievements. Because of a lack of a unified industry-standard system, some companies have insufficient scientific consideration of material selection and technology in the laser repair process, resulting in a failure of repair parts, property losses, and even safety accidents, which in turn have a negative impact on the promotion of laser remanufacturing technology in the industry.

5 Development goal of laser remanufacturing technology

With the continuous development of laser repair and remanufacturing technology in recent years, the laser remanufacturing industry in China has begun to take shape. It has been estimated that the scale of the laser repair and remanufacturing industry in China will reach approximately 2 billion CNY in 2019, and laser remanufacturing technology has shown significant application potential in the field of industrial repair. In the future, with further improvements in repair quality, efficiency, and intelligence, laser remanufacturing technology will be further promoted and applied, which will have a profound impact on the equipment design concepts, industrial structure, and manufacturing services. Considering technological, industry, and conceptual innovations, the future development goals of laser remanufacturing technology are as follows:

5.1 Development goals for 2025

To meet the remanufacturing development strategy proposed by *Made in China 2025*, according to the urgent need for key parts of high-end equipment to improve the repair quality and efficiency, and to solve the current state of the “small, scattered, and weak” characteristics of the laser remanufacturing industry, the development goals of laser remanufacturing technology and industry by 2025 are as follows: comprehensively improving the level of laser remanufacturing equipment, materials, and processes; continuously meeting the needs of high-quality remanufacturing, on-site remanufacturing, and in-service remanufacturing technologies for key components in various industrial fields; improving the comprehensive efficiency of laser remanufacturing and its pre- and post-processing processes to meet the demand for high-efficiency remanufacturing; combining with a “two-machine” localization strategy to solve the need for repairing core parts such as hot-end components; and taking the scale as the development goal, expanding the application fields and industrial scales based on technology development and cost reduction. It is estimated that the overall scale of the laser remanufacturing industry in China will reach 10 billion CNY by 2025.

The key development directions by 2025 are to focus on the development of laser hybrid remanufacturing and its key equipment, high-speed/ultra-high-speed/broadband laser remanufacturing equipment and processes, high-quality laser additive remanufacturing technology for hot-end components with complex shapes, synchronous detection and control in the laser remanufacturing process, laser remanufacturing technology in harsh on-site environments, and the formation of a hybrid laser equipment manufacturing industry, repair service industry, and special powder and wire industry for repairs. Laser remanufacturing technology has been extended to many fields and parts, leading to the formation of a large-scale on-site laser remanufacturing service industry.

5.2 Development goals for 2035

Serving manufacturing has become the main direction of manufacturing transformation and upgrades, and laser remanufacturing technology is an important support technology for recycling and remanufacturing services. To support the distributed laser remanufacturing service system, the development goals of laser remanufacturing technology and industry by 2035 are as follows: As the intelligent laser remanufacturing technology becomes mature, and the laser repair of parts and components realizes an automatic and convenient operation, a standardized system of laser repair and remanufacturing will be formed, and a mature laser remanufacturing industry chain will be developed to meet the needs of different industrial fields for laser intelligent repair technology. It is estimated that the overall scale of the laser remanufacturing industry in China by 2035 will reach 50 billion CNY.

The key development directions by 2035 are focusing on the development of automatic defect identification and

repair process of intelligent specification technologies, laser intelligent repair and remanufacturing, and accurate life prediction for laser-remanufactured parts, forming four major industries, namely, special laser remanufacturing equipment, intelligentization control system and software, special repair materials, and remanufacturing services.

5.3 Development goals for 2050

The harmonious development of humans and nature is the only way to develop human civilization. With the penetration of renewable products and the concept of a circular economy, remanufacturing technology will become popular and domestic. By 2050, the development goals of laser remanufacturing technology and industry are rapid repair equipment using miniaturized lasers and support process technologies, laser remanufacturing with extreme conditions and environments, and widespread manufacturing services with laser remanufacturing as the core technology in the high-end equipment industry.

The key development directions by 2050 are to focus on the development of precise monitoring of micro damage and precise repair at the microstructure level; laser remanufacturing in extreme environments such as deep-sea, space, and bipolar regions; transformation of high-end equipment sales industry into high-end equipment service industry as a mainstream; and laser remanufacturing technology supporting the popularization of recycled products and a circular economy.

6 Development suggestions for the laser remanufacturing technology

6.1 Strengthening active guidance at the strategic level

It is recommended to increase financial support in key areas, such as special materials for laser remanufacturing, core equipment, and components; make full use of funding channels, such as national major special projects and national key R&D programs; and adopt a combination of universities, research institutes, enterprises, and users. Based on the continuous promotion of the development of general equipment and processes, focus will be on supporting the development of special laser remanufacturing equipment, materials, and processes for typical vulnerable parts.

6.2 Establishing a material genome system for laser additive remanufacturing

The continuous development of laser additive remanufacturing technology has led to higher development requirements for special materials. Owing to the non-equilibrium metastable characteristics of special materials, the design and development of special materials are becoming more difficult, with a longer cycle and greater complications than traditional materials. Traditional methods have been unable to meet the current development needs. Therefore, it is recommended that a laser additive remanufacturing material genome system be established as soon as possible. In addition, the non-equilibrium metastable properties of special materials should be improved and a high-throughput calculation basis and theory based on the genome should be established.

6.3 Speeding up the establishment and improvement of a standardized system and a high-level application-oriented talent training system

It is recommended to improve the ability of laser remanufacturing technology and product development, inspection, and certification, strive to promote the close integration of standardization and industry, and establish a complete standard system for the development of the laser remanufacturing industry. In addition, international cooperation should be strengthened, active connections should be made with international organizations for standardization, and related standards should be established, transformed, and improved. At the same time, focus should be given to the lack of professional talent and industry norms in the field of laser remanufacturing in China, and to continuous improvements in the construction of a training system for high-level talent relying on the existing domestic talent training and introduction policies.

6.4 Increasing application promotion and guiding industry integration

It is recommended to combine government support with various industry resources; strengthen the links between the various sub-fields of the laser remanufacturing industry in China; broaden the connection channels between industry and government, between the upstream and downstream areas of the industrial chain, between industries, and between manufacturers and users; and accelerate technology promotion and application. Focus should also be given to the implementation of special hierarchical and field-specific pilot demonstration actions,

and the input of social forces and local governments based on a point-to-surface combination and coordinated advancement should be actively guided and promoted, jointly promoting the in-depth application of laser remanufacturing technology, and promoting the continuous and rapid development of the laser remanufacturing industry in China.

6.5 Strengthening “production, study, research, and application” and accelerating the development of common key technological innovations

The establishment of a national R&D platform in the fields of laser remanufacturing and full lifecycle manufacturing, led by universities, scientific research institutes, and key enterprises, is recommended to open the upstream and downstream areas of the industry chain, and form a complete system of materials, equipment, processes, testing, and applications. Research and innovation of common key technologies facing different industries and fields should be accelerated, with the setting up of unique remanufacturing industry alliances, remanufacturing product evaluation and testing centers, and collaborative innovation centers.

References

- [1] The State Council of the People's Republic of China. Made in China 2025 [EB/OL]. (2015-05-19) [2020-02-26]. http://www.gov.cn/zhengce/content/2015-05/19/content_9784.htm. Chinese.
- [2] Li Y J, Dong S Y, He P, et al. Microstructure characteristics and mechanical properties of new-type FeNiCr laser cladding alloy coating on nodular cast iron [J]. *Journal of Materials Processing Technology*, 2019, 269: 163–171.
- [3] Song L J, Zeng G C, Xiao H, et al. Repair of 304 stainless steel by laser cladding with 316L stainless steel powders followed by laser surface alloying with WC powders [J]. *Journal of Manufacturing Processes*, 2016, 24: 116–124.
- [4] Zhang Q, Liang Z L, Cao M, et al. Microstructure and mechanical properties of Ti6Al4V alloy prepared by selective laser melting combined with precision forging [J]. *Transactions of Nonferrous Metals Society of China*, 2017, 27(5): 1036–1042.
- [5] Wang H M, Zhang S Q, Wang X M. Progress and challenges of laser direct manufacturing of large titanium structural components [J]. *Chinese Journal of Lasers*, 2009, 36(12): 3204–3209. Chinese.
- [6] Xu G J, Yang W Q, Hang Z X, et al. Performance of clad layer using mixed powder of Stellite 6 and VC [J]. *Journal of Mechanical Engineering*, 2017, 53(14): 165–170. Chinese.
- [7] Liu H X, Dong T, Zhang X W, et al. Microstructure and cutting performance of WC/Co50/Al cemented carbide coated tools fabricated by laser cladding process [J]. *Chinese Journal of Lasers*, 2017, 44(8): 1–9. Chinese.
- [8] Shin J, Mazumder J. Composition monitoring using plasma diagnostics during direct metal deposition (DMD) process [J]. *Optics & Laser Technology*, 2018, 106: 40–46.
- [9] Li Q G, Lin X, Wang X H, et al. Research on the cracking control of laser additive repaired K465 superalloy [J]. *Rare Metal Materials and Engineering*, 2017, 46(4): 955–960. Chinese.
- [10] Guo S Q, Luo K L, Liu R, et al. Application of 3D printing technology in aeroengine maintainance [J]. *Aeronautical Manufacturing Technology*, 2015, 58(S1): 18–19, 27. Chinese.
- [11] Guo S R, Yao J H. Research on properties of laser remanufacturing coatings based on the surface of steam turbine rotor [J]. *Applied Laser*, 2016, 36(2): 131–135. Chinese.
- [12] Chen Q H, Fu W. Application of laser surface strengthening technologies in steel industry [J]. *Electric Welding Machine*, 2015, 45(1): 81–84. Chinese.
- [13] Tantai F L, Tian H F, Chen F, et al. Discussion on application of high-speed laser cladding on 27SiMn hydraulic support column [J]. *New Technology & New Process*, 2019 (3): 52–54. Chinese.
- [14] Shi Y, Li Y F, Liu J, et al. Research of gradient wear-resisting coating produced by laser additive manufacturing on high-pressure pump camshaft [J]. *Journal of Mechanical Engineering*, 2017, 53(6): 80–87. Chinese.
- [15] Qin L Y, Yang G, Bian H Y, et al. Experimental study on electromagnetic stirring assisted laser deposition forming titanium alloy [J]. *Chinese Journal of Lasers*, 2014, 41(3): 1–5. Chinese.
- [16] Hu Y, Wang L, Yao J H, et al. Effects of electromagnetic compound field on the escape behavior of pores in molten pool during laser cladding [J]. *Surface & Coatings Technology*, 2020, 383: 1–13.
- [17] Liang S D, Zhang A F, Wang T, et al. Elimination of laser direct forming crack on DD4 parts by induction heating [J]. *Chinese Journal of Lasers*, 2017, 44(2): 1–10. Chinese.
- [18] Todaro C J, Easton M A, Qiu D, et al. Grain structure control during metal 3D printing by high-intensity ultrasound [J]. *Nature Communications*, 2020, 11(1): 142.
- [19] Xu J L, Zhou J Z, Tan W S, et al. High-temperature oxidation resistance of co-based alloy coatings by ultrasonic vibration assisted laser cladding [J]. *Chinese Journal of Lasers*, 2019, 46(1): 1–9. Chinese.
- [20] Yao Z H, Yu X W, Nie Y B, et al. Effects of three-dimensional vibration on laser cladding of SS316L alloy [J]. *Journal of Laser Applications*, 2019, 31(3): 1–13.

- [21] Zhu G X, Shi S H, Fu G Y, et al. The influence of the substrate inclined angle on the section size of laser cladding layers based on robot with the inside-beam powder feeding [J]. *The International Journal of Advanced Manufacturing Technology*, 2017, 88(5–8): 2163–2168.
- [22] Ye Z T, Fang Z, Yang G L, et al. Influence of gas flow on oxidation of molten pool during laser remelting under open-air condition [J]. *China Surface Engineering*, 2019, 32(1): 108–116. Chinese.
- [23] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration. Laser repairing technology—Terms and definitions GB/T 29795—2013 [S]. Beijing: China Quality and Standards Publishing & Media Co., Ltd., 2013. Chinese.
- [24] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration. Laser repairing general specification GB/T 29796—2013 [S]. Beijing: China Quality and Standards Publishing & Media Co., Ltd., 2013. Chinese.