DOI 10.15302/J-SSCAE-2022.04.018

Development of Additive Manufacturing Technology and Industry in China

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Abstract: Additive manufacturing (AM), or three-dimensional printing, is a rapidly developing and emerging technology in the advanced manufacturing field, owing to the continuous expansion of its applications. The development of the AM industry provides a valuable opportunity for modern manufacturing, and the transformation and upgrading of traditional manufacturing. In this paper, the developmental trends of AM technology are explored and the AM industry in China and internationally is systematically summarized. Challenges faced by China's AM industry are also analyzed, including inadequate research and development capabilities regarding common technologies and basic devices, lack of an effective patent structure for the international market, and insufficient development of industrial scale and clusters. Focusing on the future potential of the AM industry, key development directions are proposed, including AM for biomedicine and medical devices, large-scale complex components, space, structural innovation, and new materials. Suggestions for the future of AM include a collaborative innovation mechanism to support enterprise application innovation, implementation of AM process reform of research plans to satisfy the demand for highly technical equipment, and the construction of regional AM industrial clusters.
Keywords: additive manufacturing; 3D printing; advanced manufacturing; high-end manufacturing equipment industry; complex components; structural innovation

1 Introduction

Exciting new manufacturing technologies, such as additive manufacturing (AM), also known as three-dimensional (3D) printing, are developing rapidly in basic research, key technologies, and industrial incubation. AM technology has changed the design and manufacturing process of products and is regarded as an "accelerator" for technological innovation in many fields, as well as a key basic technology supporting the innovation and development of manufacturing. It is changing the production mode of products and driving the development of customization, personalization, and distributed manufacturing. Cloud-based manufacturing, combined with big data technology, is accelerating the upgrading of traditional manufacturing industry, moving it toward personalization, intelligence, and socialization of manufacturing. AM technology has played a considerable role in promoting subversive changes in the manufacturing industry and is promoting the breakthrough and leapfrog development of core manufacturing technologies in the fields of aviation, aerospace, energy, national defense, automobiles, biomedicine, among others.[1].

Technology and industry research on AM is a popular topic, both domestically and internationally. Prominent global management consulting firm McKinsey & Company believes that AM is one of the 12 disruptive technologies that will determine economic development in 2025. The company's article entitled *The Mainstreaming of Additive*

Received date: March 29, 2022; **revised date:** May 05, 2022
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Funding program: CAE Advisory Project "Research on Major Issues of Innovative Development of Strategic Emerging industries Facing Future Demand" (2021-HYZD-06); 173 Project
Chinese version: Strategic Study of CAE 2022, 24 (4): 202-211
Cited item: Wang Lei, Lu Bingheng. Development of Additive Manufacturing Technology and Industry in China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2022.04.018

Manufacturing discusses the 40-year development history of AM and proclaims that AM will become the mainstream manufacturing technology in the future. In recent years, the Strategic Emerging Industries Project Group of the Chinese Academy of Engineering has continued to watch closely the development trends in the AM industry and discussed the roadmap of AM industry for the 14th Five-Year Plan period and the medium and long terms [2]. Some studies have pointed out that AM technology, as a material-oriented manufacturing technology, still has the contradiction of printing accuracy, scale, and speed in polymers, metals, ceramics, glass, and composite materials [3]. On the basis of a comparative analysis of the development overview, macro strategies, and typical applications of the AM industry both domestic and international, the researchers reviewed the standards system, talent cultivation, industry trends, and others [4]. The World Economic Forum and other institutions jointly issued *An Additive Manufacturing Breakthrough: A How-to Guide for Scaling and Overcoming Key Challenges*, which states that AM industrial components will be used in large-scale manufacturing in the next 10 years, and expounds the relevance between epidemic prevention and control of the coronavirus disease 2019（COVID-19）and the application of AM technology.

China’s manufacturing industry faces a complex myriad of international cooperation and fierce industrial competition. The development of the high-end equipment manufacturing industry is inevitably disturbed, and the independent development of cutting-edge technology and engineering face potential challenges. In the process of high-quality development and transformation, China needs to implement a strategy to become a strong manufacturing country [5]. It should be noted that although China’s manufacturing industry has a high degree of enthusiasm for the promotion and application of new manufacturing technologies represented by AM, there is still a gap between AM technology and the industry when compared globally.

The majority of Chinese manufacturing enterprises are still in the initial stages of contact and exploration, and have not reached their goal of fully mastering large-scale applications and creating incremental value. In addition, the research results on AM planning and industrial development based on national conditions are insufficient. Based on this this gap, this study will comprehensively review the progress of AM technology and the industry through an analysis of the existing issues in development. The study highlights the key development steps of AM technology and industries in the future, including biomedical and medical devices, large-scale high-performance complex components, spatial AM, structural innovation, and new material invention. This study is expected to provide a meaningful reference for researchers on addressing technology, upgrading industry, and macro strategies of the AM field in China.

2 Technical and industrial development of international additive manufacturing (AM)

2.1 International AM technology trends

Exciting new processes, principles, materials, and applications related to AM are emerging worldwide every day. These new technologies include 4D printing [6], spatial 3D printing [1,7], electronic 3D printing, cell 3D printing [8], and micro–nano 3D printing [9], all emerging one after another. AM technologies for engineering plastics, ceramics, and resin-based fiber-reinforced composites have gradually matured, and the range of materials and engineering applications of AM techniques is constantly expanding. Among them, the mechanical properties of typical metal AM structures tend to be stable, and some of the mechanical properties even exceed the forging properties (Table 1). The research progress of innovative and crossover technologies, such as composition design, material genome design, multi-material functional gradient structure, metamaterial structure, bionic materials and their structures, composite material structures with electromagnetic shielding functions, integrated design of material structures and functions, 3D printing nanostructures [9], axial stereolithography [10], 4D printing intelligent materials, living cell printing, and AM application in extreme environments have made obvious progress in research. Breakthroughs have also been made in some advanced forming processes, such as unsupported metal forming technology, regional selective melting metal (or sintered nylon) forming technology using dense arrays of high-energy beams, metal friction deposition manufacturing technology, hybrid manufacturing technology [11], and large-scale structure AM by multi-robot collaboration. In addition, cutting-edge basic research has achieved rich results, including studies on the microstructure evolution law of additive parts in long-term service, the artificial intelligence detection of defects in the forming process, machine learning to improve the material composition and enhance the comprehensive performance, and the heat treatment control process of the structural performance of high-temperature alloy materials [12,13].

DOI 10.15302/J-SSCAE-2022.04.018

Table 1. Comparison of mechanical properties of some metal additive products.

	316L stainless steel		17-4PH stainless steel		GH4169 Superalloy room temperature		GH4169 Superalloy high temperature (630 ℃)		TC4 titanium alloy	
	Deposition	ASTM forging standard	Heat treatment	Forgings standard	Heat treatment	Forgings standard	Heat treatment	Forgings standard	Heat treatment	Forgings standard
Tensile Strength (MPa)	636.7	485.0	1165.1	1070.0	1362.0	1270.0	1091.3	1000.0	968.8	895.0
Yield Strength (MPa)	334.5	170.0	1050.0	1000.0	1210.9	1030.0	962.2	860.0	871.9	825.0
Elongation (%)	47.0	40.0	15.2	12.0	13.8	12.0	18.6	12.0	13.2	10.0

Note: ASTM: American Society of Testing and Materials.

In terms of enterprise applications, AM technology has provided innovative functions, such as multi-part integrated manufacturing, lightweight, efficient heat exchange design, new material application, and multi-material functional gradient structure. It is being integrated into the manufacturing process, and even the supply chain of existing products on a large scale, which is innovating traditional manufacturing methods and reducing manufacturing costs. Some advantageous manufacturing enterprises have established a complete AM process technology system, including the design ability of innovative structures (such as topology optimization, crystal lattice structure, and structural function integration), AM forming process control, post-processing, quality inspection, and evaluation. Several research institutions, represented by the Fraunhofer Applied Research Promotion Association of Germany, continue to deepen the industrial production and intelligent technology research of AM.

In terms of standards construction, developed countries with traditional manufacturing industries have made rapid progress in AM technology, and more government departments, universities, scientific research institutions, enterprises, and standardization institutions have formed standardization alliances. The alliances are guided by the application requirements of national defense equipment and engineering scenarios, and focus on the development mode of standards basic research. Relevant countries have promoted the construction of AM standards by issuing roadmaps, such as *The Roadmap for Additive Manufacturing Standardization* (United States (U.S.)) and *The Additive Manufacturing Standards Pilot Action Plan (2020–2022)* (China) [14]. The U.S. has also released *The Additive Manufacturing Standardization Roadmap Gap Progress Report* in 2021 to promote the implementation of AM standardization. As of March 2022, more than 200 standards had been published, compiled, and proposed worldwide. The published standards involve the terminology and definition of AM technology, data format, design, materials, forming processes, part inspection, equipment products, personnel operation, safety, evaluation, repair, and industry applications. Standards research and formulation has also been conducted in the fields of aviation, aerospace, automotive, welding, marine, metrology, testing, printed circuit boards, consumer 3D printing, medical treatment, and safety [15]. It is worth noting that the standards construction of AM is still in its infancy, which lags behind the development of the technology itself and the needs of industrial promotion.

In terms of technology roadmaps, traditional manufacturing stakeholders in developed countries are actively researching and releasing their own roadmaps. The U.S. Department of Defense released the *DoD Additive Manufacturing Strategy* (2016), which is divided into four aspects: design, material, process, and value chain. It is oriented toward three application areas: maintenance and support, deployment and expedition, and new component or system procurement, and provides a basic framework for cooperation and coordination of investment. With the support of the European Union, the Additive Manufacturing Industry Skills Strategic Alliance released the *European Additive Manufacturing Skills Roadmap* (2021), which defined the application needs and technical challenges faced prior to the year 2030, and proposed goals and measures from the perspective of eliminating the AM technology gap. In 2019, China released the research results of the AM roadmap for 2035 [16,17], which identified the medium- and long-term development directions regarding China's AM technology strategy. Recently, Chinese scholars have reviewed the design methods, materials, processes and equipment, intelligent structures, biological structures, and extreme environmental application progress of AM. They believed that the current AM technology could not fully meet the standardized and large-scale production needs of the traditional manufacturing industry, and elaborated the research roadmap of AM technology in the next 10 years [18].

In terms of scientific papers and patents, the number of articles related to AM has rapidly increased in recent years. China, the U.S., Germany, South Korea, and Japan are the most active countries conducting AM technology research [19]. Fig. 1 shows the global AM patent applications according to inventor country and priority country. It can be seen that the U.S. maintains an important position in the original patent output of AM, which corresponds to their strong innovation ability in the core technology of AM.

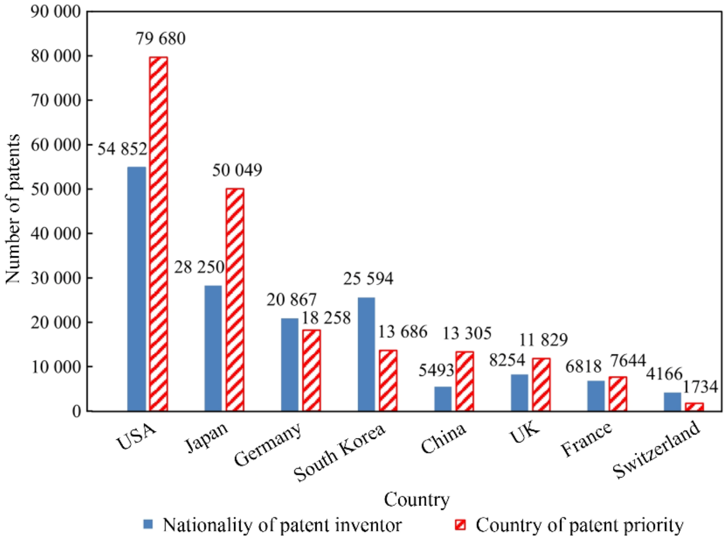

Fig.1. Global ranking of AM patent inventor and priority countries.

2.2 International AM industry trends

In preparation for future industrial development, developed manufacturing countries have implemented active AM industrial policies. For example, the U.S. focuses on continuously enhancing the innovation capability and competitiveness of the manufacturing industry, leading to the development of the AM industry through top-level design and strategic planning [20]. The country has established a national AM innovation institution (America Makes) and released the *DoD Additive Manufacturing Strategy*, *Additive Manufacturing Standardization Roadmap*, and the *Department of Defense Additive Manufacturing Strategy*. The AM promotion plan known as "AM Forward" was launched to coordinate and promote the demonstration application of AM technology in national defense equipment and advanced manufacturing industry, as well as promote the formation of an industrial ecology.

Internationally, the AM industry has shifted from the initial, infancy stage to the growth stage. With the improvement of technological maturity, the reduction of unit cost, and the enhancement of industrial supporting capabilities, AM technology has gradually become the mainstream manufacturing method in the industrial field as it promotes the development of downstream applications with comprehensive benefits (such as cost, cycle, and lightweight). Leading companies in the industry have planned a variety of AM technology development routes by increasing capital investment, setting up research and development (R&D) centers, actively deploying AM software and hardware capabilities, and innovative network platforms to rapidly promote commercial applications. Meanwhile, in response to potential competition in AM-related industries, these companies have advanced their layout in terms of patents and standards, and strive to grasp the commanding heights of new manufacturing technologies. Furthermore, these leaders in the field of AM are promoting the innovative development of AM technology in the manufacture of civil aircraft, engines, medical equipment, and other equipment.

Internationally, the AM industry chain is continuously expanding. Enterprises and service manufacturers in the fields of aviation, aerospace, navigation, energy and power, automobile and rail transportation, electronics industry, mold manufacturing, medical health, digital creativity, and construction are joining this emerging market. AM technology is widely used in aviation/aerospace engine manufacturing, such as fuel nozzles, sensor housings, low-pressure turbine blades, and other parts of aircraft engines that have passed airworthiness certification, and are applied to commercial aircraft engines in batches. Turbine AM parts have batch production capacity, and the cost of metal additive parts is close to casting. In the automotive industry, the application of AM technology covers the scope of prototyping, mold-making, and batch printing of parts. In the computer numerical control (CNC) machine tool industry, CNC machine tools and robotic products equipped with 3D printing heads have been developed. The combination of additive functional modules and subtractive equipment (machine tools) and other material equipment

DOI 10.15302/J-SSCAE-2022.04.018

(casting, forging, welding, and heat treatment) promotes the formation of composite equipment for various manufacturing functions. Relevant policies incorporate AM equipment into the industrial chain of industrial mother machines to promote the development of the entire industry.

AM technology has been widely used in the production of personalized medical devices. For example, new 3D printed medical device products are becoming increasingly diversified, and the application range has expanded from the manufacture of bio-prostheses to the printing of cells, tissues, and organs, and can also be used for manufacturing medical robots [21]. AM technology has been widely used in the production of personalized medical devices, including new 3D printed medical device products that are becoming increasingly diversified. The application range has expanded from the manufacture of bioprostheses to the printing of cells, tissues, and organs, and can also be used for manufacturing medical robots [21]. Industry-leading enterprises have introduced AM equipment, high-end machine tools, and intelligent industrial robots into production lines, and some enterprises have integrated this equipment into the same production line for production, thereby improving market competitiveness in terms of production efficiency, quality control, and flexible production.

The growth of the international AM industry shows a positive trend, with a compound annual growth rate of over 20%, including equipment, materials, and services, and a compounded annual growth rate of metal AM of over 30%. In 2021, the market scale was 15.2 billion USD (year-over-year growth of 19.5%), of which the material industry scale was 2.6 billion USD (year-over-year growth of 23.4%) [22]. At present, the market competition pattern of AM is relatively concentrated, with the U.S. and China occupying the primary market space (the former accounting for 34.4% and the latter accounting for 10.8%). This study predicts that the AM equipment market will continue to grow rapidly in the future.

There are a number of challenges faced by the AM industry as well. Affected by international situations such as the COVID-19 pandemic and policy orientations of various countries, the competitive landscape of the high-end equipment manufacturing industry among major countries is undergoing adjustments. Large-scale equipment enterprises tend to use mergers and acquisitions, value-added services, and other methods to enhance their core competitiveness, promoting the formation of a new industrial chain pattern of AM. Multinational enterprises are leading the way with adjustments in the supply chain, with the gradual shortening of the supply chain becoming a new trend. Another consideration are the active measures taken by countries to reduce carbon emissions in response to climate change, which will also promote the acceleration of the global industrial chain. The regional industrial chain tends to be complete and the supply chain diversified. It is predicted that over the next 15 years, the original supply chain system in various manufacturing fields will be interrupted and reorganized. AM is expected to change the value structure of the global manufacturing industry chain, considering the unit cost-effectiveness brought about by the maturity of the technology, and more cost-effective locally printed parts. Based on all of this, the scale of the AM industry is expected to expand in the future.

3 Current status and challenges of AM technology and industrial development in China

3.1 Progress of AM technologies in China

China has initially established a full-chain AM technology innovation system covering 3D printing materials, processes, equipment, and major engineering applications. Related technical research involves a complete link from the prototype manufacturing of ultra-violet (UV)-cured materials (product development) to the hybrid manufacturing of large-scale metal materials with additive and subtractive material processing (equipment application). This includes AM equipment for various processes, AM data processing software, path planning software for various AM processes, simulation software for simulating physical and chemical changes in the AM process, digital twin modeling, and spatial in situ AM. AM engineering application technology has been extended to product equipment innovation, the remanufacturing and repair of high-value components, and the *in situ* repair and manufacturing of major equipment. In the medical field, biomedical 3D printing has become a cutting-edge technology in precision medicine and rehabilitation healthcare research [21]. The corresponding products are represented by customized solutions for patients, AM rehabilitation devices, surgical navigation, and medical implants, all of which have great application prospects.

During China's Thirteenth Five-Year Plan period, the AM industry completed technical research and independent production of more than 10 types of key components, such as ultra-high-speed laser cladding heads, electron guns, and droplet jet print heads. Domestic core components have shown positive progress in development. Among them, more than 20 types of laser cladding nozzles have been developed, which are suitable for 1−20 kW laser direct energy deposition and have been applied in the additive repair of power components such as motor rotors and fan rotors. Laser-heated cathode electron guns, large-scale digital dynamic focus scanning systems, and online detection systems have overcome the technical barriers of foreign companies. Moreover, the cathode life of the domestic 3 kW lanthanum hexaboride single-crystal cathode electron gun was increased to 800 h. In addition, related electron guns and dynamic focus scanning systems have been deployed in domestic large-format array electron beam-selective melting equipment and are being introduced to the market.

Through the continuous efforts of the industry, research on AM technology in China has also made significant progress, including in process and equipment stability, precision control, and component deformation and stress regulation. Among them, a series of products, including rotary powder bed AM equipment for large-scale components and hybrid manufacturing equipment for the new generation of high-performance difficult-to-machine alloy large-scale components, have been successfully developed and inserted into market applications. Currently, China’s AM technology has been widely recognized in the manufacturing of high-end equipment in the fields of aviation, aerospace, power, and energy. As an example, laser cladding deposition technology has been used to manufacture aircraft engine load-bearing frames and landing gears with projected areas of 16 m^2. This solves the overall manufacturing problems of complex structures and function integration that are difficult to deal with using traditional methods. Multi-wire arc fuse addition and subtraction hybrid manufacturing equipment has been used to manufacture 10 m size high-strength aluminum alloy connecting ring samples, and an innovative process integrating “melting, casting, forging, and welding” has been developed. Fused deposition molding of industrial-grade pellets, stereo lithography apparatus for resin and ceramic slurries, laser AM technology for metals [23], plasma beam/arc fuse molding, large-format laser selective melting molding, additive and subtractive hybrid manufacturing technology, and other equipment have achieved a wide range of industrial applications. In addition, metal binder jet 3D printing technology is improving its structural and mechanical properties and is expected to move toward low-cost, batch applications.

In China, the industry–university–research consortium, voluntarily composed of scientific research institutes, equipment manufacturing enterprises, and users, is cooperating to develop an AM process and equipment, testing technology, and standards of large-scale metal AM parts. Equipment enterprises actively promote the integration of AM technology into the existing manufacturing system in structural optimization design, materials, equipment, processes, testing, and evaluation to improve the support ability of new product manufacturing. In addition, the development and mass production of complex special-shaped components have driven the iterative upgrade of mature aerospace power products. Here, AM of rocket engine components is used as an example. Domestic enterprises have mastered the application characteristics of 16 grades of AM parts: titanium alloys, superalloys, stainless steel, aluminum alloys, and copper alloys. After heat treatment, the five types of mechanical performance indicators were equivalent to forgings of the same composition. The types of AM materials studied cover more than 70% of the commonly used casting/forging difficult-to-machine materials. In addition, AM creates more than 200 types of products, including more than 90 types of components that have passed the test run, and more than 30 types of components that have been delivered in batches.

3.2 Progress of AM industry in China

China is forming an innovation network and industrial ecosystem consisting of AM innovation centers of national, provincial, and major industry companies. All aspects of the AM industry chain, including raw materials, key components, equipment development, general technology R&D institutions, application service providers, and various application fields, are developing rapidly. Among them, the scale of China’s consumer-grade AM industry is a world class leader. In terms of high-performance metal AM raw materials and production equipment, domestic production has occupied the primary domestic market, with a competitive advantage of mass supply and lower cost. The localization process is accelerating for core components and parts, and large-scale support is being realized in domestic low- and mid-end equipment. The bottleneck of large-scale industrialization has essentially been broken in terms of high-performance metal AM equipment, and 5-axis additive and subtractive hybrid manufacturing equipment has been commercialized. AM of sand molds has become a breakthrough for the transformation and upgrading of the foundry industry, and domestic enterprises have built 3D printing manufacturing factories with a 10 000-ton-level foundry. During the development of the new aircraft, AM of structural parts accounted for more than 3%, and an intelligent production workshop for rocket engine components was built. In addition, the State Drug Administration has established a technical focal point for the standardization of medical AM technology and medical devices, focusing on AM medical device software, equipment, raw materials, process control, and so on, to formulate standards and specifications to ensure industrial development. Relevant institutions have obtained medical device

DOI 10.15302/J-SSCAE-2022.04.018

registration certificates for several AM products, and the number of clinical application cases of medical AM products exceeds 1×10^4. In addition, a batch of medical AM products, such as 3D printed degradable stents, has entered the stage of animal experiments and individual clinical trials.

The scale of the AM industry in China has grown steadily in recent years. Data from the China AM Industry Alliance show that in 2021, the scale of China's AM industry was 26.5 billion CNY, and the growth rate of 30% exceeded the world average by about 10 percentage points. In China's AM industry chain, the pattern of integrated development of large, medium, and small enterprises has emerged. Domestic AM equipment suppliers have shifted from following the state, to independent innovation and development, with leading AM enterprises having the technical ability to participate in international market competition. At present, the regional spatial pattern of the development of China's AM industry has essentially taken shape, with the Beijing–Tianjin–Hebei region, the Yangtze River Delta region, and the Pearl River Delta region as the core, and the central and western regions as the link. In these regions, the advantages of AM industry chain agglomeration are gradually reflected.

To cope with the changes in the international market and technological exchanges, and promote the healthy development of the AM industry chain, the industry actively promotes an industry–university–research–application coordinated development mode, complements the weak links of the industry chain, and develops key technologies.

The upstream, midstream, and downstream institutions and enterprises of the AM industry chain work together closely. Downstream users benefit from solving the appropriate technology sources based on their needs; upstream AM raw material producers and midstream AM equipment products have clarified the technology development priorities and market directions. For example, users in the fields of aviation, aerospace, nuclear power, and medical care have formed a technical alliance with relevant domestic enterprises and institutions to carry out experimental verification and certification of additive parts to realize the large-scale application of domestic materials, processes, and equipment with lower prices in various fields.

In the future, positive economic development and the large-scale domestic demand market will be the fundamental driving force for the development of China's strategic emerging industries, including the AM industry. "3D printing +" is developing in depths in the subdivision of manufacturing industries, including automobiles, molds, precision medicine, new energy, and remanufacturing, and in many aspects of social life [2]. With the continuous improvement in the maturity of AM technology and decline in material and production costs, the application scope and industrial scale of AM technology are expected to be further expanded. AM, subtractive manufacturing, and equal material manufacturing are expected to develop simultaneously in the manufacturing value chain.

3.3 Challenges of AM technology and industrial development in China

3.3.1 Common technology research and basic device capability are insufficient

High-quality development of the AM industry depends on the comprehensive breakthrough of key technologies and the comprehensive improvement in the maturity of the technical system, which is manifested in the expansion of material types, improvement in efficiency, innovation of quality control means, and reduction in comprehensive costs. Although China's AM industry is developing rapidly, its original innovation capability is still weak. This is manifested by the fact that there are objective gaps in basic common technologies, basic device supporting capabilities, industrial frontier technology research, domestic supporting capabilities for industrial software and core devices that are insufficient, and some core key technologies that are controlled by others. The core components used in high-end AM equipment (such as print heads, lasers, long-life electron guns, scanning galvanometers, droplet nozzles, and precision optical devices), key components, and commercial industrial software rely on imports. Some lasers and scanning devices have been independently developed, but the scale of commercialization is small and the quality and reliability need improvement. Domestic high-end metal AM equipment still lags behind the world's advanced level in terms of the development of special processes and accuracy.

The support capacity of common key technologies in the AM industry is insufficient and has become a bottleneck for large-scale applications. AM technology involves many disciplines and has a wide range of applications, which makes its basic theoretical research, applied research, and research in interdisciplinary fields pressing. In particular, in civil aviation, rail transit, nuclear power, medical, and other industries, AM parts face strict product access requirements owing to strict supervision [21,24]. However, for the entire product lifecycle (design, manufacturing, distribution, service, maintenance, recycling/reuse, and disposal), research on the quality assurance and certification of AM parts remains at an early stage, which is not conducive to the promotion and application of AM technology and products. Similar to the overall situation with a lack of basic data and lagging standards construction, the accumulation of basic data, such as high-performance special materials for AM process packages, is relatively small, and the standards and quality evaluation systems are incomplete. In particular, insufficient research on defect detection and quality evaluation technologies for applications in various fields has resulted in less reliable data for additive parts in complex working conditions and environments. These factors restrict large-scale development of the AM industry. Defect inspection and detection, critical failure prediction, and early warning technology of additive parts under extreme conditions, such as high temperature, ultra-high pressure, cryogenic and complex corrosion, systematic engineering risk assessment technology, and structural integrity assessment technology for extended service and long-term operation. All of the aforementioned technologies need to be improved.

3.3.2 The patent structure for the international market is lagging behind

To build international competitiveness in China's AM industry in the future, it is necessary to actively layout international patent applications. Enterprises in the United States, Germany, Japan, and South Korea attach importance to patent applications, and prefer to apply in the international market. For example, 66.2% of the patents applied for by German patent inventors were applied for abroad, and overseas patents in Japan accounted for 48.4%. In contrast, the focus of patent applications of Chinese patent applicants is still limited to domestic applications; domestic applications account for 97.8%, while 2.2% are targeted at overseas market applications [19]. The patent barriers built by developed countries interfere with the investment and research of Chinese enterprises in AM and laser manufacturing. Having a core independent intellectual property system is the basis for breaking foreign technical barriers and the core link for strengthening the domestic AM industry. In the increasingly fierce international market competition for AM technology, the protection of China's AM technology patents is relatively insufficient, and the market-oriented sharing channel of information and technology is not ideal. It is necessary to grasp the international commanding heights of AM technology, promote the application of relevant patents in overseas markets with greater effort, and resolve the development risks of the AM industry in internationalization.

3.3.3 Industrial scale and industrial cluster construction need to be strengthened

China's AM industry initially formed a complete ecological chain and built a coping mechanism for industrial chain and supply chain risks. However, objectively speaking, challenges still remain, such as non-centralized distribution, small-scale enterprises, and weak comprehensive competitiveness. The number of "specialized, special, and new" enterprises is small, the establishment time is short, and R&D intensity and market competitiveness cannot be separated from the support of industrial policies in the short term. The scale of demonstration and promotion in various application fields and commercial applications remains to be developed [25], and internationalization is only at the initial stage. In addition to limiting the application scale, owing to cost control, most enterprises still do not have a deep understanding of AM technology and lack the ability to develop innovative applications; they generally follow the experience of foreign cases or are forced by market competition. They prefer short-term economies of scale, follow market hotspots for repeated investments, and lack continuous investment power for products with great difficulty in technological innovation. The existing AM industry clusters show the scattered, and the industrial chain is too centered midstream (AM equipment). The general technology of the AM industry is also weak, the innovation capability system is not strong, the guarantee of talents and R&D funds is insufficient, and the industry profit is insufficient to support sustainable development.

Due to the imperfect development of inter-departmental and inter-regional communication and coordination mechanisms, the industrial chains of various provinces are weakly complementary in terms of planning. The phenomenon of low-level homogeneous competition is more serious in some AM industrial parks than others. When competing between regions, a challenge exists with local-market barriers, which also hinders high-quality development of the AM industry chain. In an industrial cluster area, the business independence of large enterprises is relatively high. The business scope covers raw materials, equipment, applications, and almost all R&D and production tasks. Small enterprises, especially start-up companies, have difficulty supporting large enterprises. Therefore, this development model must be reformed. State-owned enterprises put too much emphasis on past sales records in equipment procurement, making it difficult to obtain opportunities for application and practice for self-innovated technical and equipment. Therefore, in the AM industry cluster, the challenge regarding unbalanced development level and development quality is more prominent and requires immediate attention.

4 Future-oriented AM technology and industry prospective

4.1 Biomedicine and medical devices industry

With the development of the biopharmaceutical industry and new treatment technologies, stricter requirements have been placed on the manufacturing technology for biopharmaceuticals and medical devices. AM technology is

DOI 10.15302/J-SSCAE-2022.04.018

the key technology for realizing personalized diagnosis, treatment planning, and implant manufacturing. Based on the current application of 3D printing in precision medicine, it is necessary to continue to improve the certification standards, regulations, and evaluation systems for medical AM products and innovate and develop new processes, technologies, and equipment for more efficient AM. Based on 3D printing technology, controlled-release pharmaceutical products should be developed, orthopedic implants that meet biocompatibility should be manufactured, and bio-printed products of degradable materials should be developed. The development of growth factor-based 3D printing technology will bring about major technological breakthroughs in human organ reconstruction. It is also necessary to explore *in situ* printing and repair technology at the lesion site in the body, which will provide new technical means for the clinical repair of bone defects and the repair of some functional organs. In view of the increasingly serious phenomenon of social aging in the future, based on AM technology, research on the functional regeneration of human aging organs is conducive to prolonging the healthy lifespan of human beings and improving the quality of human life to achieve major innovations in life sciences. These developments are expected to create large-scale emerging industries.

4.2 Large and high-performance complex components

Focusing on the development needs of major equipment in the fields of aviation, aerospace, ships, and nuclear energy, it is necessary to develop the bottleneck technology that currently exists in the production of large and complex precision components, such as the AM processing of high-performance aluminum alloys, titanium alloys, marine steel, high-temperature refractory alloys, and composite materials; engineering application, testing standards certification, and quality evaluation of serialized complete sets of equipment. In addition, it is necessary to address key technologies, such as organizational performance regulation, online quality inspection, service performance prediction, equipment integration, and reliability in the manufacture of large-scale high-performance complex components. The application of AM technology will promote breakthroughs in the construction of major equipment and key projects and improve the development level of related products and the upgrading capabilities of the industry.

4.3 Space industry

Space AM has important value in forming new space materials, equipment, processes, and applications, improving space activity capabilities, and enhancing the advantages of space development and utilization. To meet the actual needs of future engineering, such as on-orbit manufacturing and maintenance of spacecraft, space stations, and satellites, on-orbit manufacturing and assembly of large space structures (solar cell arrays, antennas, optical systems, etc.), and the construction of bases on other planets, it is necessary to plan and develop advanced space AM technologies. The research design includes AM technology and equipment in the microgravity environment in the cabin, new material forming technology and equipment adapted to the extreme environment outside the cabin, multidirectional AM technology for space megastructures, and on-orbit manufacturing plants. Also, development of metal metallurgy and component *in-situ* repair technology in a vacuum microgravity environment, *in-situ* AM technology for lightweight metals and new alloys, space AM technology for composite materials, space augmentation for multi-material and multi-functional devices, and space AM technology for biological organs, and others should be developed. A development system for on-orbit manufacturing technologies should be built.

In addition, large-scale space development supporting technologies for future development include *in situ* metallurgy and AM of new alloys using extraterrestrial materials, and 3D printing of lunar soil bases. It is necessary to take the basic research of space AM technology as a breakthrough, improve the ability of technology to be applied, and explore commercial application scenarios. In the future, by combining the needs of civil, commercial, and national defense needs, AM will create new manufacturing systems and manufacturing bases for humans to provide strategic support for solving the *in-situ* utilization of space resources and expanding human sustainable survival and activity capabilities.

4.4 Structural innovation and new material invention

Innovative designs for development needs in the energy field based on AM technology will significantly reduce the structural volume of the heat exchanger and support the engineering development of miniaturized, modular, and mobile nuclear power small reactor equipment, which will improve the safety and potential of nuclear power, as the security of the power supply is guaranteed. The R&D projects could include groundbreaking designs of key structures, such as core fuel assemblies, nuclear main pumps, heat exchangers, and thermoelectric conversions; new materials and corresponding AM technologies; exploration of online enhancement and hardening technologies for

AM parts; improving the service performance of additive parts in complex working conditions; and building a forward-looking AM standards and quality evaluation system for the nuclear power industry. For cutting-edge new materials, the role of AM technology as a platform technology in the design of new alloys, materials, and functional composite components from the material genome is introduced. Research can occur in new material synthesis technology based on AM, new material AM process and its application technology, and development of special alloys for high-end equipment, electronic printing materials, biomedical materials, intelligent bionic materials, high-performance fiber composite materials, high-performance ceramic matrix composite materials, new alloy materials, and other technologies. Relying on AM technology, the innovation system of new material invention will improve the R&D ability of materials and competitiveness of the new material industry.

5 Recommendations for AM and industrial development in China

5.1 Establishing a collaborative innovation mechanism for AM and supporting enterprises to conduct application innovation

It is suggested to take the overall national development goals and industrial development needs as guidance to coordinate the national scientific forces represented by various innovation centers under planning and construction, and provide continuous policy support in key areas of AM. National management institutions should actively learn from the development experience of advanced international scientific research institutions to build a stable and applicable management mode while considering the stable development and coordination of different scientific research teams.

An industrial chain security early-warning mechanism should be established that is composed of national scientific research institutions, industrial alliances, and third-party institutions. Strategic research on AM technologies and industrial development should be strengthened. Basic industrial capability and key common technology improvement plans, development catalogues, standards formation, and roadmaps should be devised. These measures will provide solid support for the advanced and modernized industrial chain of the equipment manufacturing industry.

Recommendations for the government include: (1) formulation of incentive and subsidy policies to encourage enterprises to apply self-owned technology products; (2) formulation of assessment and management measures for new scientific and technological institutions that conform to the laws of technological innovation; (3) clarification of assessment orientation; (4) increase of the proportion of technological innovation in assessment and assessment of the long-term R&D investment by category; 5) formation of an assessment mechanism that supports, encourages innovation, tolerates failure, and stimulates enterprises' innovation drive. Meanwhile, relevant government departments should guide enterprises in shifting from reliance on excessive resource consumption and low performance/low-cost competition modes to technology and application innovation, and implementing differentiated competition modes to enhance the international competitiveness of China's manufacturing industry.

5.2 Conducting an AM process transformation project for the development of major equipment

Focusing on the major strategic needs of national defense and the needs of international frontier competition, it is recommended to conduct the top-level design of major equipment development, beginning with original innovation, new materials, core devices, industrial software, high-end equipment, innovative applications, among others, to strengthen the AM technology innovation system. It is recommended to create a science and technology project (referred to as "special project") for major equipment development based on AM. The special project will establish a collaborative mechanism led by users and participated in by multiple subjects; it also forms a production–university–research–use consortium. The special project will build a product quality system for the AM industry chain, covering raw material specifications, forming accuracy, production efficiency, special software, manufacturing equipment, post-processing, testing and inspection, standards, and others. This special project will help break up the technological bottleneck in the AM industry chain that is broken, and provide technical support for major equipment manufacturing.

The science and technology special project will focus on supporting the technology diffusion and industrial application of AM in major equipment R&D and production units. It will also promote the application of domestic materials, software, devices, manufacturing equipment, application processes, and other full-chain technologies in the manufacturing of various engineering equipment and key components, such as large aircraft and unmanned aerial vehicles, aviation/aerospace engines, heavy carrier rockets, space vehicles, automobiles, medical devices, and marine equipment. This special project will cultivate and enhance participation in the AM industry chain, while

DOI 10.15302/J-SSCAE-2022.04.018

focusing on guiding the accelerated application and technical iteration of AM technology, and building an application-oriented basic database of the entire process flow of AM to meet the actual needs of technology research, performance verification, and product development. This special project will solve the industrial matching problems of domestic materials, key functional components, and industrial software in a deep-seated manner and will substantially improve the market matching ability and international market competitiveness of domestic AM technology and equipment.

5.3 Promoting the construction of regional AM industry clusters

Based on the innovative development trends and laws of the international equipment manufacturing industry, national conditions, and needs of the equipment manufacturing industry, it is recommended to continue to optimize the top-level design and coordinate the development planning of the regional AM industry. In view of the technology-intensive, capital-intensive, and talent-intensive characteristics of the AM innovation and industrial chains, it is suggested to integrate the superior scientific and technological resources of various regions with the resources of the advanced manufacturing industrial chain to effectively promote the coordinated development of "3D printing +" in various sub-industrial fields. Focusing on the development goal of building world-class industrial clusters, and based on the AM industry advantageous clusters in the Beijing–Tianjin–Hebei region, Yangtze River Delta region, Pearl River Delta region, and central and western regions, it is suggested to promote the deep integration of AM technology with the industrial chain and supply chain of each region's advantages, break down unreasonable regional restrictions and hidden barriers, and further promote the cross-regional coordinated development of industrial chains and supply chains to form China's AM industry chain ecology with international competitive advantages.

It is recommended to establish an AM industry chain with the participation of government departments, innovation platforms, and enterprise users; provide necessary policy support in terms of equipment, key functional components, and application innovation; encourage enterprises to jointly conduct technological research and application demonstration; and realize the coordinated development of the AM industry chain and various industry chains in the region. Reasonable tax incentives should be provided or financial support given to guide small and medium-sized enterprises to grow in the direction of specialization and innovation. Governments should support small and medium-sized enterprises in the in-depth development of basic components, materials, components, sensors, industrial software, special equipment, and other subdivisions to improve the overall industrial chain through differentiated development. Enterprises should be encouraged to conduct comprehensive cooperation with the innovation platform of AM by means of investment, joint investment, among others, to achieve efficient integration of innovation resources and drive the innovative development of the industry. Meanwhile, it is necessary to promote key enterprises in all fields to increase the application of domestic AM equipment and domestic devices, promote the integrated development of military and civilian technology, and promote the development of AM industrial chain clusters through application innovation.

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