DOI 10.15302/J-SSCAE-2020.02.005

Research on the Development of Machine Tool Industry in China

Wang Lei [1, 2], **Lu Bingheng** [1, 2]

1. Collaborative Innovation Center of High-End Manufacturing Equipment, Xi'an Jiaotong University, Xi' an 710054, China
2. National Institute Corporation of Additive Manufacturing, Xi'an 710300, China

Abstract: This study focuses on the development of the high-end manufacturing equipment industry in China, represented by machine tools. The machine tools referred to herein includes not only those in a traditional definition, such as lathes, milling machines, planers, drilling machines, boring machines, grinders, and gear making machines, but also additive manufacturing equipment and additive-subtractive hybrid manufacturing equipment. This study analyzes the development trends of the machine tool industry in China and around the globe, and then studies the problems that exist in China's machine tool industry. Compared with advanced manufacturing industries, China's machine tool industry still has weaknesses in some areas: (1) basic research and key technologies for ultra-precision machine tools; (2) the machining accuracy and efficiency of large-scale machine tools; (3) the reliability and accuracy retention of machines; (4) the research and development of common technologies for advanced additive manufacturing and hybrid manufacturing equipment; and (5) the level of intelligence of high-end machine tools. Furthermore, we propose the key direction of China's machine tool industry during the 14th Five-Year Plan and the following 5 to 10 years, and propose some policy measures for the development of the machine tool industry in China, including coordinating national science and technology plans with national policy supporting and evaluation systems, and establishing and strengthening the common technology collaborative innovation system for the high-end manufacturing equipment represented by machine tools.

Keywords: machine tool; industrial development; key direction; high-end manufacturing; numerical control equipment

1 Introduction

Intelligent manufacturing is an integral component of China's bid to become a manufacturing power. Machine tools are fundamental to intelligent manufacturing. Machine tools represented by high-end computer numerical control (CNC) machine tools are of fundamental and strategic importance to national economies owing to their wide applications in industries such as the aerospace, shipping, high-precision instrument, automobile, and medical equipment industries. Moreover, they are a key link in the value chain and industrial chain of the manufacturing industry. This study focuses not only on conventional machine tools for turning, milling, planning, drilling, boring, grinding, and gear hobbing, as well as various types of machining centers, but also equipment for additive manufacturing (3D printing) and additive–subtractive hybrid manufacturing. The deep integration of information and manufacturing technologies has driven the development and innovation of machine tools. Intelligent manufacturing equipment, with machine tools at the core, integrates emerging technologies such as new-generation

Received date: December 25, 2019**; Revised date:** February 17, 2020

Corresponding author: Wang Lei, researcher of Collaborative Innovation Center of High-End Manufacturing Equipment of Xi'an Jiaotong University. Major research field is Numerical control equipment and intelligent manufacturing. E-mail: wlei292@xjtu.edu.cn

Funding program: CAE Advisory Project "Research on the Development Strategy of Emerging Industries" (2018-ZD-12)

Chinese version: Strategic Study of CAE 2020, 22 (1): 029–037

Cited item: Wang Lei et al. Research on the Development of Machine Tool Industry in China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2020.02.005

artificial intelligence (AI), industrial Internet, and big data. Moreover, it is considered a priority for the world's industrial powers for rebuilding their manufacturing advantages and gaining competitive advantages.

Driven by factors such as the increasing application of intelligent manufacturing technologies, evolving trade disputes, and the volatility in overall manufacturing cost, the global manufacturing industry has shown a trend of large-scale migration combined with local adjustments. The underlying momentum of this trend is causing changes to the industry chain, supply chain, and value chain. In developed industrial countries and regions such as the US, Japan, and the European Union, owing to the dividend derived from technological innovations, multinational companies are moving their manufacturing facilities back to developed countries at an accelerating pace. While focusing on controlling the high-end links of the industry chain, these companies are moving low-end manufacturing activities to regions with lower overall cost, such as Southeast Asia, South Asia, and Africa. Emerging economies such as Russia, Brazil, India, and South Africa are taking rapid action to orchestrate the development of new technologies and emerging industries; these countries also actively participate in the redivision of labor in global industries, receive industry and capital migrations, and explore the international market. China's manufacturing industry is now at a competitive disadvantage, as it is experiencing "a blocking force on one side and a pressing force on the other" caused by the current state of development of its manufacturing supply chain. In particular, there is an urgent need for China's manufacturing industry, which is currently quantity-oriented, to become quality-oriented and more advanced through technological innovation.

The development of the Chinese machine tool industry has always been an interest in the Chinese industrial research community. *The Blue Book on the Development of China's Machine Tool Industry (2018)* analyzed the development status of the machine tool industry in China and abroad, the development trends in the industry and the relevant technologies, the needs of users from major areas of application, and major national policies regulating the industry. Shen et al. [1] published several reviews on the development strategies for new-generation intelligent manufacturing focusing on analyzing the limitations of China's CNC machine tools and systems and recommending solutions. Chen [2] conducted an objective, comprehensive analysis of the history of the Chinese machine tool industry in the last four decades, its current limitations, and gaps to be filled.

The world economy is currently in a period of sluggish growth. For example, the Chinese automobile industry has experienced negative annual growth for the first time. This has brought uncertainties to the market for machine tools, particularly CNC machine tools, and has directly impacted the investment and operations of manufacturing equipment enterprises. As the main "battlefield" of intelligent manufacturing, which is technology-, capital-, and talent-intensive, the machine tool equipment industry needs a profound transformation [3]. Therefore, this paper mainly investigates the macro development of the machine tool industry, represented by high-end CNC machine tools, to analyze the developmental status of this industry in China and abroad, diagnose the problems of this industry's development, and propose a staged direction plan for industrial development in China.

2 Developmental status of the global machine tool industry

2.1 Competitive trends in the global industry chain

The evolution and restructuring of international relations has been influencing the landscape of the global manufacturing industry, resulting in new trends in the industry chain. The world's industrial powers are formulating and implementing aggressive developmental strategies for the industry. In November 2019, Germany released the *Made in Germany: Industrial Strategy 2030* with the aim of maintaining the leading position of its industrial sector in the European and global markets. At the beginning of 2019, the US released *America Will Dominate the Industries of the Future*. In the document, AI, advanced manufacturing, quantum information, and 5G communication were proposed as the four key areas of high-end industries. The US industry chain value standards emphasize that the US must control and lead the global industries and, particularly, maintain a position of absolute advantage in the technology-intensive, high-end equipment manufacturing industry.

The major players in the global machine tool industry include the US, China, Japan, and the European Union (as represented by Germany), with China, Japan, and Germany as the major producers of machine tools. In 2019, Japan was the world's largest producer of CNC machine tools, its output accounting for approximately 32.1% of the global total. China's output of CNC machine tools is slightly smaller than Japan's, accounting for approximately 31.5% of the global total, while Germany's output of CNC machine tools accounts for approximately 17.2% of the global total. However, the world's leading companies of high-end CNC machine tools mainly come from Germany, Japan, and

DOI 10.15302/J-SSCAE-2020.02.005

the US (Table 1), the industry leaders being Yamazaki Mazak (Japan), TRUMPF (Germany), and DMG MORI (a Japanese-German joint venture).

Table 1. Top 10 CNC machine tool manufacturing enterprises in the world in 2019.

Number	Enterprise name	Country	Scale (US $100 million)
1	Yamazaki Mazak	Japan	52.8
2	TRUMPF	Germany	42.4
3	DMG MORI	Germany	38.2
4	MAG	US	32.6
5	AMADA	Japan	31.1
6	OKUMA	Japan	19.4
7	MAKINO	Japan	18.8
8	GROB	Germany	16.8
9	HAAS	US	14.8
10	EMAG	Germany	8.7

Note: The data was provided by CCID consultants.

Japan focuses on the development of CNC systems; critical components such as precision bearings and guide rails; high-end CNC machine tools; critical electromechanical, hydraulic, pneumatic, and optical components; and advanced cutting tools and measurement tools, boasting a globally competitive complete industry chain. European builders of machine tools have competitive advantages in special-purpose machines, high technologies, and customized solutions. In particular, Germany and Switzerland focus on the sophistication and practicality of CNC machines, critical components, and high-end accessories, ranking first in the world in terms of the quality and performance of complete machines and components. The US has maintained a capability for continuous innovation in the high-end application of machine tools in the aerospace, military, and other downstream industries, allowing it to remain a world leader in this regard. China is the world's largest maker, consumer, and importer of machine tools. Owing to the impact of national policies, the competition landscape of the global high-end equipment manufacturing industry is undergoing major adjustments. In particular, major multinational equipment builders are attempting to improve their core competitiveness through various efforts such as mergers and acquisitions, and providing value-addition services

The major players in the global additive manufacturing industry include the US, Germany, China, Japan, and the UK, with China, Japan, and Germany as the major machine producers. In 2019, the global 3D printing industry grew at an annual rate of 29.9% to 11.956 billion USD. The US is the world's largest supplier of 3D printing equipment, taking a 40.4% share of the global 3D printing industry. Germany is the second-largest supplier, with an approximately 22.5% share, followed by China, with an approximately 18.6% share. The market shares of Japan and the UK are 8.2% and 6.3% share, respectively.

Aiming to gain a first-mover advantage over their global competition, the world's industrial powers are formulating aggressive strategies to upgrade their advanced manufacturing industries. In particular, countries and regions are introducing policies to support and prioritize their high-end equipment manufacturing industries. The European Committee for the Cooperation of the Machine Tool Industries suggested that the basis on which the European machine tool industries will sustain their competitiveness is advanced manufacturing technologies, continuous investments in research and development (R&D), a shortened innovation cycle, and a high-skill workforce. The US Department of Defense has defined "advanced machines and CNC systems" as a potential area for technological development and is driving research into next-generation high-end machine tools. The US National Science and Technology Council has updated the *Strategy for American Leadership in Advanced Manufacturing*. In the policy statement, the following strategic goals were established: 1) develop and transition new manufacturing technologies; 2) educate, train, and connect the manufacturing workforce; and 3) expand the capabilities of the domestic manufacturing supply chain. In addition, the policy statement further detailed the following three objectives for technological development: 1) research and develop world-leading materials and processing technologies; 2) encourage the ecosystems of manufacturing innovation; and 3) strengthen the base of the defense manufacturing base.

2.2 Development trends of the global high-end CNC machine tool

Extreme manufacturing, “green” manufacturing, internet-assisted manufacturing, and intelligent manufacturing are being used to develop next-generation high-end CNC machine technology with attributes such as high speed, high precision, high reliability, and functional hybridity. The major players in the global machine tool industry have unanimously chosen to develop intelligent CNC machines and increase the level of smartization of CNC machine equipment. Based on their cumulative advantages in technology, the US, Germany, and Japan are focusing their efforts on increasing the level of equipment smartization to strengthen their competitive advantage. Owing to the weakening competitiveness of their machine tool manufacturing industries, Sweden, Switzerland, Italy, Spain, and France are transforming their medium-sized and small machine tool enterprises (which account for 80% of the European machine tool industry) by improving their level of digitization and exploring intelligent solutions.

The major trends of technological innovation and development in the industrial technology field include intelligent machine tools that integrate CNC machine tools and new-generation AI, intelligent manufacturing units with intelligent machine tools at the core, intelligent production lines integrating robots with control software and hardware, intelligent manufacturing workshops, intelligent manufacturing factories, and intelligent manufacturing ecosystems. In addition, hybrid machines with integrated subtractive manufacturing, additive manufacturing, and laser processing functions have profoundly changed the evolution of the machine tool industry, representing a major direction of development of the global machine tool industry.

The automobile industry is a major downstream industry of the machine tool industry and is one of the major consumers of middle- and high-end metal-cutting machines. Countries are accelerating their efforts to popularize and increase the production capacity for new-energy vehicles. Powertrains manufactured using CNC systems may have a game-changing effect, directly influencing the direction of evolution of the machine tool industry. The global aerospace manufacturing industry is a high consumer of metal-cutting machine tools, but many companies resort to subcontracting when they fall short of production capacity. This trend will indirectly influence the landscape of the machine tool industry.

2.3 Developmental trends of the global additive manufacturing

With the increasing demand for additive manufacturing and equipment from the aerospace, marine, new energy, new-energy vehicle, intelligent product, and high-end medical device industries, additive manufacturing has become a mainstream manufacturing method. Moreover, it has entered the stage of mass application, causing the global additive manufacturing equipment industry to enter a stage of rapid development. The global additive manufacturing industry is expected to grow to 15.8 billion USD, 23.9 billion USD, and 35.6 billion USD in 2020, 2022, and 2024, respectively [4] (Data source: Wohlers Report 2019). McKinsey & Company has predicted that the global additive manufacturing industry will create an economic benefit of 200–500 billion USD in 2025 [5].

The world’s industrial powers are accelerating their efforts to boost their additive manufacturing industries. The US was the first to define the additive manufacturing industry as an industry of strategic importance, as its market size has grown to 4.83 billion USD in 2019. In *Made in Germany: Industrial Strategy 2030*, Germany defined the additive manufacturing industry as one of the nine key industries for future development. According to statistics on global additive manufacturing, patents, and installed capacities, the global additive manufacturing industry is a landscape in which the US, Europe, and other developed countries and regions lead the competition while Asian countries and regions are catching up [5].

The Chinese additive manufacturing equipment industry has been developing rapidly in terms of technological application, with the industry chain having begun to take shape and in-depth integration of additive manufacturing and traditional manufacturing emerging in various industries. In 2019, the Chinese additive manufacturing industry grew to 15.747 billion CNY; the Chinese additive manufacturing equipment industry grew to 7.086 billion CNY, accounting for 45% of the additive manufacturing industry. China is a leader in the number of patents and research papers on additive manufacturing but is still weak in terms of original and major technological innovations.

3 Development status of the Chinese machine tool industry

3.1 High-end CNC machine tool equipment industry chain

Since implementation of the National Science and Technology Major Project (hereafter referred to as “Project 04”) “*High-End Numerical Control Machine Tools and Fundamental Manufacturing Equipment*” a decade ago, the

DOI 10.15302/J-SSCAE-2020.02.005

Chinese machine tool industry has evolved significantly. In particular, the machine tool industry has achieved major transformations—from being dominated by conventional machine tools to being dominated by CNC machine tools and the high-end machine tools have developed from scratch. In addition, a complete supply chain for high-end CNC machine tools has begun to take shape, equipping China with a domestic capability for building high-end CNC machines required for its aerospace, automobile, and other strategic sectors. The S-specimen international standard drafted under the initiative of Chinese enterprises has been officially approved and released by the International Standardization Organization. This is the first international standard for the inspection of high-end CNC machine tools, which China has initiated. However, owing to market volatilities and an insufficiently firm foundation, the structural imbalance in the Chinese machine tool industry has not been completely resolved. Although Project 04 was successfully implemented as planned, the Chinese machine tool industry still lags behind the advanced international machine industries by approximately 15 years.

(1) Since 2012, the cumulative sales volumes of high-end and standard CNC systems developed under the support of Project 04 have exceeded 2000 and 100 000 units, respectively. However, more than 90% of the high-end CNC and servo drive systems needed in the domestic market depend on imports, and high-end basic components (such as precision bearings and high-precision gratings) remain a bottleneck. The Chinese machine tool industry has a limited capacity for the forward design of complete machine tools, manufacturing processes research, and the design of corresponding whole machines and production lines to satisfy specific user requirements. Machine reliability and accuracy retention technologies are still in the application promotion stage; core components such as CNC systems, servo systems, and precision gratings still do not show connectivity. Moreover, industry user recognition is not high.

(2) The development level of key functional components and critical components such as high-performance spindle units, precision swivels, precision swivel stands, gratings and other measurement feedback elements, automatic tool changers, precision rolling guide rails, precision screw units, high-precision bearings, and liquid-gas lubrication devices, has improved considerably. From the perspective of the industrial chain, high-end component development in China still cannot meet the requirements for the advancement of the high-end CNC machine tool industry. For example, more than 90% of key functional units and critical components—particularly motor spindles, linear motors, spindle bearings, and precision gratings—still depend on imports.

(3) At the whole-machine level, more than 30 categories of major products (such as precision horizontal machining centers) produced by Chinese companies have reached the advanced international level, facilitating the sustainable development of the Chinese equipment manufacturing industry. Under the support of Project 04, many domestic-made high-end CNC systems have been applied in the aerospace, weapons, and shipping industries, and demonstration applications have been carried out. The 25 m column-type mobile vertical milling-turning machine has reached the advanced international level in terms of technical parameters and grade, representing the highest level of domestic-made high-end heavy-duty CNC machine tools. However, the machines made in China are considerably below the advanced international level in terms of reliability and accuracy retention.

(4) In terms of downstream application of high-end CNC machine tools, China boasts a large output of CNC machine tools owing to the rapid development of its automobile, aerospace, shipping, electrical equipment, and engineering machinery industries. Because of the leading and driving effects of Project 04, China’s high-end CNC machine tool industry has provided its national major projects (such as nuclear power and large aircraft) and key engineering projects with critical manufacturing equipment, solved the problem of the lack of domestic ability to make the critical equipment required in industries, and made breakthroughs in many key technologies and kinds of equipment. For example, China’s aerospace industry has established several demonstration production lines using domestic-made CNC equipment, showing that domestic-made CNC equipment has passed the stage of serving as a backup option and has entered the stage of large-scale application; production lines for high-efficiency automatic stamping of large vehicle-body cover panels using domestic technologies have reached the advanced international level and have gained a more than 40% share of the global market. However, China’s domestic supply chain for automobile powertrains still lags far behind those of countries with advanced supply chains, as more than 80% of the manufacturing equipment still depends on imports. Domestic-made machine tools for high-speed precision and composite material manufacturing needed in high-end equipment fields such as aeroengine still cannot meet the market demand. China's machine tool enterprises have not yet formed diversified and efficient solutions for the new-energy vehicle and other popular industries.

(5) Localization of foreign enterprises has emerged as a new trend in the Chinese domestic market of CNC machine tools. As more domestic-made CNC machine tool products have replaced imports, and owing to the impact of policies, market, cost, and competition, the proportion of purely imported equipment is diminishing. Facing high

market demand in China, foreign enterprises are resorting to localization as the major means of competing in the Chinese market. Many multinational machine producers have entered China and are accelerating their efforts to localize manufacturing and sales. Some of them have even built their largest factories in China for reverse supply to the global market. For example, with an output of more than 600 units of machines in 2018, the Jintan factory of the German EMAG group now serves as a base for supplying EMAG group customers in China, Europe, the US, and Japan.

3.2 Industry clusters of high-end CNC machine tool equipment producers

Boasting the world's largest market, R&D, manufacturing, and supply systems, China has developed its CNC machine tool industry into a complete industry ecosystem covering the entire supply chain from materials, functional components, and whole machines to modern service systems and applications in various industries. The four major industry clusters of the Pearl River Delta, Bohai Economic Rim, Yangtze River Delta, and Northwest China are now taking shape, covering the following key provinces: Liaoning, Shandong, Beijing, Shanghai, Jiangsu, Guangdong, Zhejiang, and Shaanxi. Given the need for high-quality development of the national economy, the CNC machine tool industry is transitioning from simply focusing on the growth of scale, quantity, and speed to a high-quality-oriented outlook.

China's CNC machine tool industry clusters suffer serious imbalances in development level and quality, a problem that needs to be urgently resolved through adjustment and optimization of the industry. Owing to the impact of international trade disputes, declining automobile sales, and other factors, China's CNC machine tool industry has been experiencing slow growth. One the one hand, domestic machine tool companies are performing unevenly, some experiencing debt crises, operations difficulties, or even insolvent restructuring as a result of blind expansion, while others have focused on technological innovation, market penetration, and seizing market development opportunities owing to market segmentation and are now enjoying rapid growth. On the other hand, some foreign enterprises have been increasing their investment in China, thus greatly impacting the landscape of the industry clusters.

The machine tool producers in China's four machine industry clusters can be classified into three tiers: 1) foreign enterprises with strong technological capabilities; 2) large state-owned enterprises, state-holding enterprises, and a few private enterprises with strong technological capabilities; and 3) small, low-tech private enterprises. Under the current economic slowdown, the second- and third-tier enterprises face the risk of an industry reshuffle, and the concentration degree of the Chinese machine tool industry is speculated to further increase in the future.

3.3 Additive manufacturing equipment

Owing to the implementation of the *Action Plan for the Additive Manufacturing Industry 2017–2020*, China's additive manufacturing equipment industry has been enjoying rapid development. In particular, the industry has made a series of breakthroughs in innovation capabilities, the critical and core technologies of manufacturing technology and equipment, the supply chain of critical components, and industrial applications. The industry has provided China's strategic industries, such as aircraft, carrier rockets, shipping, and nuclear energy, with advanced means of manufacturing. China has established a preliminary technological innovation system covering the entire 3D printing industry chain, from metal materials, components, manufacturing technology, and equipment technology to major engineering applications, with an overall technological level close to the advanced international level. It is worth noting that in some areas, the advanced international level has been reached.

Overall, China is a leader in the global additive manufacturing industry in terms of patent numbers and research output; however, it lags behind the world leaders because of weaknesses in core component and critical technology manufacturing and a lack of original technologies. In particular, China relies heavily on imports for core components such as high-quality lasers, long-life electron guns, high-performance galvanometer scanners, and array-type high-precision micro-nano 3D printing heads. In addition, China does not contribute to the development of additive manufacturing standards, so it has limited power in international discourse. The trade frictions in recent years clearly reveal the weaknesses of the Chinese additive manufacturing industry in original innovation and critical components. In the future, China's additive manufacturing industry should focus on making breakthroughs in critical common technologies, eliminating bottlenecks in the advancement of the industry, and quickly realizing independence and control cover critical and core technologies so that it can gain advantages in innovation and development.

China's additive manufacturing industry has formed a spatial development landscape with the Bohai Economic Rim, Yangtze River Delta, and Pearl River Delta as the core, and Central and West China as the bond. Led by

DOI 10.15302/J-SSCAE-2020.02.005

backbone enterprises with market competitiveness, several industry clusters have been fostered: 1) In the Yangtze River Delta, owing to a developed economy, advantageous geographic conditions, and a strong industrial base, an additive manufacturing industry chain covering material preparation, equipment production, software development, application services, and related supporting services has taken preliminary shape; 2) in the Pearl River Delta, with the deepening construction of the Guangdong–Hong Kong–Macao Greater Bay Area, the additive manufacturing industry will further grow; and 3) in Central and West China, Shaanxi, Hubei, and Hunan Provinces play a key role in China's additive manufacturing industry, particularly in terms of technology and industrialization.

4 Challenges of China's machine tool industry

China's machine tool industry has developed a preliminary domestic ability to safeguard its strategic sectors. However, it is being faced with major problems such as low overall competitiveness of CNC machine tools, low economies of scale, low technological innovation capability, and high external dependence of high-end products. China's localization rate of middle-end CNC machine tools is 60%; the market share of domestic-made high-end CNC systems is less than 15%. In downstream application industries, most of the CNC machine tools for precision machining are imported. The overall gap between Chinese machine tools and the advanced international tools has greatly diminished, but there is still a gap between Chinese-made machine tools and advanced international tools in terms of machining tool efficiency, reliability, precision, and service life. Overall, China's machine tool industry is still situated at the middle to low end of the value chain of the global machine tool industry, lacking enterprises and products with international competitiveness.

China's machine tool industry has a relatively weak foundation. In particular, Chinese producers of high-end CNC machine tools are struggling owing to fierce market competition and suffering market mechanism failure. The gap between Chinese-made CNC machine tools and advanced international tools in terms of forward design, basic common technologies, and research on cutting-edge technologies tends to be widening. To meet the manufacturing goals of higher quality, greater reliability, and lower cost, the dependence of China's machine tool industry on imports for the supply of CNC systems and core CNC devices has increased. In particular, China relies on imports for the supply of core components, critical industrial software, CNC systems, functional components, and complete machines, which severely limits the domestic design and manufacturing of high-performance equipment. The overall gap between Chinese-made high-end CNC machining equipment and advanced international tools is approximately 10–15 years. China is basically a follower in additive manufacturing equipment technology. Its nonmetal machining equipment industry is enjoying a healthy growth but is experiencing bottlenecks in core components and special-purpose software. There is a wide gap between "made in China" high-end additive manufacturing equipment (particularly high-performance machines for additive manufacturing of metals) and advanced international equipment, particularly in terms of quality, performance, and stability.

The major developmental problems facing China's machine tool industry can be summarized as follows:

(1) Gaps in basic research and critical technologies of ultraprecision machine tools. At the advanced international level, ultraprecision machine tools have a resolution of 0.1 nm and positioning accuracy of 1 nm; ultraprecision lens manufacturing machine tools can produce optical lenses with only nano-level errors and a high-frequency roughness of approximately 0.1 nm. Some countries have imposed strict export embargos and technological blockades on high-end machine tools. In contrast, most of the machines used for precision processing in China were introduced more than two decades ago and have only a submicrometer-level processing precision, which is lower than that of advanced international technology by 1–2 orders of magnitude. Because of an inability to meet product R&D requirements, the performance of Chinese-made inertial sensors and other core products lags behind that of advanced international technology by a generation, a major constraint to the development of China's high-end equipment industry.

(2) Gaps in the machining precision and efficiency of large machine tools. The most advanced planer-type milling machines outside China measure 20 m in length and have a machining precision of 4 μm, and an efficiency three times that of their traditional counterparts. Chinese-made general-accuracy machines have a utilization rate in the range of 15%–30% and an acceleration smaller than 0.8 g, whereas those made outside China generally have a utilization rate in the range of 60%–90% and a minimum acceleration in the range of 1–1.5 g. Because of this, China has been unable to significantly improve the trajectory precision and processing efficiency of domestic-made multiaxis machines.

(3) Gaps in the reliability and accuracy retention of whole machines. Chinese-made machine tools have a short mean time between failure and thus have difficult production scheduling. In addition, the geometric precision,

spindle rotation precision, and motion control precision in the entire machine tool life cycle is difficult to guarantee, and there is no data support. This is the major bottleneck that limits the use of Chinese-made machines in the manufacturing of automobile powertrains and the major problem that restricts the improvement of the competitiveness of China's machine industry.

(4) Gaps in the R&D of common technologies for advanced additive manufacturing and hybrid manufacturing equipment. China lacks original technological innovations in additive manufacturing and is a follower in equipment development. China has a small additive manufacturing industry with an extremely scattered distribution. In addition, the advancement of the industry is constrained by export embargoes imposed by some countries on some large, high-efficiency equipment. For hybrid manufacturing technologies, manufacturing equipment combining turning and milling, boring and milling, additive and subtractive manufacturing, colding and hotting work, as well as equipment powered by multiple energy resources represents the major international trend of technological innovations. However, Chinese-made machines are dominated by single-process designs, and as a result, they significantly lag behind tools that have achieved an advanced international level.

(5) Gaps in the level of smartization of high-end machine tools. New machines developed outside China have been integrated with intelligent functions or have preliminarily realized the intelligent function of the machine tools that can support the networking of multiple units, for example, intelligent setting of processing parameters and mobile-based safety control of the machining process, and heat treatment equipment with completely intelligent control of the quenching and annealing processes. Chinese companies have just started developing intelligent CNC systems, and they have a long way to go before mass production and application can be realized.

(6) Gaps in the innovation capability and ecosystem of machine tools. In China's machine tool industry clusters, there is a lack of high-end CNC machine tool enterprises competing at the upper end of the value chain; there is also a lack of investment in common technologies. Overall, the development of the industry has stagnated at the middle and lower ends of the value chain, owing to a lack of specialized enterprises in the supply chain. The Chinese machine tool industry has not fostered a sound coordination between its upstream and downstream enterprises. This situation does not facilitate overall upgrading of the industry. In addition, the mechanism for equipment sharing between the military and civil sectors needs to be improved. China has not established a system of standards for intelligent manufacturing; it also urgently needs to improve the system for training high-quality R&D professionals and training high-skill workers, and ensuring their stable employment.

5 Major directions of industry development

Intelligent manufacturing is developing rapidly. Furthermore, competition in the global manufacturing industry led by intelligent manufacturing is increasing. Therefore, China needs to focus on the strategic needs of economic and social development and national security, grasp the opportunities provided by the latest technological and industrial revolution, and resolve bottleneck problems in key sectors. To achieve the strategic goal of becoming a manufacturing leader, China must significantly improve the overall competitiveness of its machine tool equipment industry, enter the international development frontier of high-end machine tool equipment, and establish a comparative advantage in industrial competition.

5.1 Development goals

5.1.1 Development goals for the 14th Five-Year Plan period

China should considerably improve the international competitiveness of its machine tool products, particularly high-end CNC machines, resolve the bottleneck problems with the manufacturing of the CNC systems and critical functional parts of high-end CNC machine tools, and develop machine tool equipment urgently needed in its key sectors. China should attach great importance to smartization of the machine tools and production lines used in its industries, implementing large-scale verification systems, and improving the level of smartization of machine tools, thereby facilitating the market exploration and high-speed development of the industry.

By 2025, China should supply most of the core components and materials needed by domestic industries; establish a complete industry development chain for domestic-made high-end CNC machine tools that mostly satisfy the key needs of its aerospace, offshore, national defense, and new-energy vehicle industries; and start developing new-generation information electronics manufacturing equipment. In addition, China should realize engineering applications of additive manufacturing to major domestic-made equipment and increase the capacity of its additive manufacturing industry to manufacture large, complex critical components.

DOI 10.15302/J-SSCAE-2020.02.005

5.1.2 Goals for 2035

By 2035, China should be a leader in the global machine tool equipment industry. To this end, China should develop complete sets of equipment that mainly consist of domestic-made high-end CNC machine tools and have the capacity to support the construction of intelligent factories, produce industry-level solutions, drive the innovation and development of key equipment, and support the upgrading of manufacturing equipment.

5.2 Directions of development

5.2.1 Manufacturing technologies and equipment for the aerospace industry and aeroengines

For the manufacturing equipment required in the aeronautic and deep-space exploration industries, China should establish a domestic capacity for building complete sets of equipment urgently needed for the mass production of new-generation middle and large launch vehicles, make breakthroughs in high-efficiency, precision manufacturing technologies for the mass production of large and complex components of large military and civil aircraft, and establish a domestic capability for manufacturing components of craft for deep-space exploration, particularly complex but lightweight components with integrated structural functions.

China should make breakthroughs in the equipment for manufacturing large military and civil aircraft, particularly breakthroughs in technologies enabling high-speed machining of aircraft structural components made from titanium alloys, carbon-fiber composite materials, and polymerized materials; additive–subtractive hybrid manufacturing; and high-precision interchangeable manufacturing of large components, thereby realizing high-efficiency, low-cost manufacturing of high-performance, high-precision aircraft components.

For aeroengine manufacturing equipment, China should nationalize the equipment for manufacturing typical engine components and eliminate technological bottlenecks in the integrated design and manufacturing, and high-efficiency, high-precision manufacturing of critical engine components made from high-temperature alloys, high-strength alloys, and composite materials, thereby eliminating its dependence on imports.

5.2.2 Technologies and equipment for manufacturing new ships and deep-water exploration devices

China should continue to improve advanced technologies and equipment for manufacturing the cylinder blocks, crankshafts, and gears of large diesel engines, and the blades, turboshafts, and blade discs of marine gas turbines used in the shipping and offshore industries. In addition, China should develop technologies and equipment for manufacturing the critical components of large ships and whole large marine propellers, equipment used for deep-water welding/detection and deep-water workstations, and complete sets of 3D printing equipment for in situ ship repair, thereby building a domestic capability for supplying critical equipment.

5.2.3 Complete equipment sets and production lines for manufacturing mass-transit vehicles, new-energy vehicles, and critical components

China should develop intelligent polishing systems and flexible polishing tools for manufacturing train vehicle bodies of large, complex surfaces and special-purpose, high-efficiency complete equipment sets and production lines for manufacturing critical components of train vehicles such as bogies, gearboxes, and wheelsets. China should particularly focus on the development of high-efficiency complete equipment sets and production lines for the machining and near-net shape forming of new-energy vehicle gearboxes, and for integrated machining, forming, in-process inspection, and assembly.

5.2.4 Ultraprecision manufacturing equipment urgently needed in national key areas

Ultraprecision machining technology is critical to the manufacturing of high-end equipment required in the military and civil sectors; ultraprecision machine tools are fundamental to ultraprecision machining. For new-generation inertial sensor production in multitarget infrared detection and high-precision intelligent steering sectors, China should concentrate on quickly breaking through the technical bottleneck of ultraprecision machine tools and promoting major advancements of basic theory and the development of measurement technology and ultraprecision machine tools, as well as online measurement and intelligent control technologies. China should explore and establish a mode for high-efficiency innovation and development of ultraprecision machining and high-end machine tools.

6 Policy recommendations

To realize the strategic goal of becoming a science and technology leader by 2035, China should strengthen its high-end equipment industry as represented by machine tools by leveraging the advantage of its socialist market

economy, in which nationwide resources can be mobilized to achieve breakthroughs in critical technologies. In this way, China can build a domestic capacity for supplying machine tools that are urgently needed by its strategic and emerging industries, and lay a solid foundation for realizing the strategic initiative of becoming a global manufacturing leader. In the future evolution of the machine tool industry, China should effectively break industry barriers; give full play to market competition; reinforce the foundation for a large-scale national industry; focus on the development of product supply chain capability, value chains, and innovation chains; and reconstruct the industry system to enable integrated development of military and civil equipment, thereby realizing socialized, coordinated development.

6.1 Effective consistency between various national scientific projects

China should adopt effective consistency in managing its national scientific projects and improve the mechanisms that support the research of basic, strategic, and cutting-edge science, and the development of common technologies according to the characteristics of the machine tool industry. Full play should be given to the role of the National Natural Science Foundation of China in guiding and supporting basic, original, and innovative research. In particular, interdisciplinary research in advanced manufacturing technologies and original, innovative research on machine tool equipment should be encouraged. The deployment of relevant original innovation research should continue with key R & D plans and major science and technology projects. The findings of basic research should be implemented, spread, and integrated in combination with the key tasks of relevant projects. The achievements of key R&D programs (such as prototypes and manufacturing processes) should be continuously verified and promoted through application and demonstration in related major projects.

It is suggested that a new program to continue Project 04 be launched so that the momentum in high-end manufacturing equipment innovation and development can be maintained. The overall mission should be shifting China from a follower to a leader. In particular, the new program should be led by major stakeholders in the target sectors and implemented through a new whole-nation system that enables coordinated tackling of key problems through collaboration between enterprises, universities, and research institutions. The efforts should be focused on establishing a domestic capacity for supplying high-end manufacturing equipment needed in the aerospace, military, nuclear energy, information product, and new-energy vehicle industries, and a sustainable development capability that keeps up with the times.

The research on CNC machine tools and basic manufacturing equipment (casting, forging, and welding) should focus on high efficiency, high precision, reliability, and accuracy retention. Furthermore, the focus should be expanded to ultraprecision machine tools; large equipment for machining composite materials; large, high-efficiency equipment for additive manufacturing of metal products; hybrid equipment combining hot and cold processing, macro-, micro-, and nano-level structures, and high-energy beam manufacturing; and the smartization of manufacturing equipment. Attention should be paid to the industrial application of the achievements of major research projects. Corresponding supporting policies should be introduced to consolidate innovations and improve economic efficiency.

6.2 Coordinated national polices and evaluation systems

The process for purchasing national science and technology innovations should be improved. In particular, science and technology innovations should be cataloged to facilitate their promotion for application. State-owned enterprises should give preference to the use of domestic science and technology innovations and domestic-made high-end equipment for technological upgrading. In particular, tax subsidies should be provided according to the percentage of domestic innovations adopted, thereby substantively reducing the burdens and operational costs borne by manufacturing enterprises. Reforms should be made to adjust enterprise tax ratios, reduce the price of public services, explore new financing mechanisms for the manufacturing industry, and guide financial institutions to reduce the financing cost of manufacturing enterprises. Supporting policies should be introduced to help manufacturing enterprises retain talent and prevent talent outflow.

The index system for evaluating the faculty performance of higher education and vocational education institutions should be reformed. In particular, indices of faculty performance, talent selection, and talent cultivation should be reformed to shift the focus to the achievement of practical results, and the satisfaction of urgent needs. Efforts should be made to cultivate engineering and technological professionals who are bold, innovative, and dedicated to industrial development through scientific research and practice. Efforts should also be made to promote engineering application of research findings, patents, and other research achievements. To cultivate manufacturing professionals,

DOI 10.15302/J-SSCAE-2020.02.005

focus should be placed on the knowledge, research, and application of intelligent manufacturing sensors, software, and big data while emphasizing the importance of laying a solid foundation and encouraging interdisciplinary collaboration.

6.3 Establishing a scientific collaboration system for innovating the common technologies of high-end manufacturing equipment as represented by machine tools

China's high-end manufacturing equipment industry should transition gradually away from tracking, introducing, and absorbing overseas science and technology to independent innovation, and finally to leading through original innovation. The reform of the national science and technology system should be deepened, with the aim of establishing a new mode that enables coordinated innovations throughout the entire supply chain of the high-end manufacturing equipment industry according to the needs of the aerospace, military, and other key sectors. Weaknesses in core technologies, critical components, and manufacturing processes and equipment, and weak links and gaps in the supply chain should be identified and evaluated. Collaborations between enterprises, universities, and research institutions should be established based on the coordinated innovations center in high-end manufacturing equipment. Efforts throughout the entire supply chain should be coordinated to facilitate innovation and the tackling of key technological problems. The organization of the supply chain should be reformed to facilitate the division of labor, cooperation, and benefit sharing between the upstream, midstream, and downstream enterprises.

The national key laboratories, national engineering laboratories, and engineering research centers of higher education institutions and research institutions should be reorganized based on the manufacturing innovation centers that are being developed, thereby establishing a long-term mechanism that facilitates collaboration between enterprises, universities, and research institutions, and forming distributed, networked clusters of new research institutions. These nonprofit research institutions will provide technological support to manufacturing enterprises, particularly small and medium enterprises. Furthermore, they will bridge the large gap between the basic research pursued by higher education institutions and research institutions, and product and industrial technology innovations pursued mainly by enterprises.

It is suggested that a national laboratory for machine tools that focuses on the R&D of forward design, critical components, big data, intelligent technologies, and their enabling software should be developed. It could enable integration of basic research, research into cutting-edge technologies, and social commonwealth research, thereby supporting the advancement of the machine tool industry and the industrial application of new technologies.

A batch of world-class enterprises should be fostered to drive upstream–downstream cooperation and matching, thereby greatly improving the overall competitiveness of the industry and fostering industry clusters equipped with cutting-edge technologies and sustainable innovation capabilities.

Machine tool enterprises with poor competitiveness should be guided to become providers of special-purpose equipment needed in the civil or defense-military sectors; leaders in the transformation, upgrading, and smartization of the manufacturing industry; and providers of integrated manufacturing solutions. Small and medium-sized enterprises should become more specialized and unique. In particular, they should be given tax incentives and financial support so that they can be better specialize in areas of basic parts, materials, components, sensors, industrial software, and special-purpose equipment, thereby realizing differentiated development.

Acknowledgement

We thank Professor Zhao Jiyuan for his contributions to the translation of this article.

References

[1] Shen L C. Further discussion on the development strategy of the new generation of intelligent manufacturing [J]. China Instruments, 2018 (4): 27–28. Chinese.

[2] Chen H R. 40 years of China machine tool industry [J]. Economic Herald, 2019 (2): 42–52. Chinese.

[3] China Machine Tool Industry Association. CIMT2019: The latest wind vane of global machine tool industry development [J]. World Manufacturing Engineering & Market, 2019, 161(2): 23–26. Chinese.

[4] Wohlers Associates. Wohlers report 2019: 3D printing and additive manufacturing state of the industry [R/OL]. Fort Collins: Wohlers Associates, Inc. (2019-03-26) [2019-12-15]. http://wohlersassociates.com.

[5] CCID Thinktank. Development report of China's additive manufacturing industry (2017) [EB/OL]. (2017-07-28) [2019-12-15]. https://www.sohu.com/a/162128762465915. Chinese.