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REVIEW

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Evolution and Development Trend Prospect of Metal Milling Equipment

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Abstract

The world is currently undergoing profound changes which have never happened within the past century. Global competition in the technology and industry fields is becoming increasingly fierce. The strategic competition of the major powers further focuses on the manufacturing industry. Developed countries such as the United States, Germany, and Japan have successively put forward strategic plans such as "re-industrialization" and "return of manufacturing industry", aiming to seize the commanding heights of a new round of global high-end technology competition and expand international market share. Standing at the historic intersection of a new round of scientific and technological revolution and China's accelerated high-quality development, the "14th Five-Year Plan" clearly pointed out that intelligent manufacturing is the main development trend to promote China's manufacturing to the medium-high end of the global value chain. This reflects the importance of advanced manufacturing for national strategic layout. To better grasp the development direction of advanced manufacturing equipment, the development process and current application status of manufacturing equipment are summarized, and thereafter the characteristics of manufacturing equipment in different development stages of the manufacturing industry are analyzed. Finally, the development trend of advanced milling equipment is prospected.

Keywords Intelligent manufacturing, High-quality development, Milling equipment, Evolution and development trend

1 Introduction

Manufacturing is the foundation of the real economy and supports the production of social material wealth [1]. The "14th Five-Year Plan" clearly pointed out that the focus of economic growth should be put on the development of the real economy, and the construction of the strong manufacturing and high quality country [2]. Being one of the pillar industries of the national economy, the manufacturing industry realizes the transformation from raw resources to consumer goods and industrial products. Its development quality is closely bound up with the social economy and the national comprehensive strength. Therefore, accelerating traditional manufacturing transformation and promoting the high-end manufacturing development are major strategic goals of our country.

The rising of manufacturing industry exactly benefits from the flourishing development of the machine tools. Machine tools, also known as the "industrial master machine", refers to the machine used to manufacture equipment, whose quantity, precision, manufacturing ability and application level directly affect the performance and quality of various strategic equipment. Significant breakthroughs were made in the manufacturing equipment during several industrial revolutions. The gun-barrel boring machine is the first real sense of machine tool in the world. It solved the quality problem in the machining of Watt steam engine's cylinder, laid the foundation for the extensive promotion of Watt

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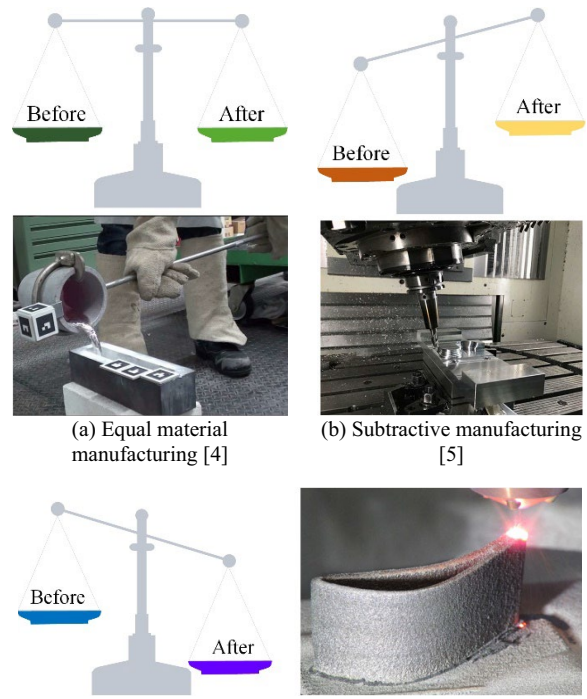
steam engine, and promoted the process of the first industrial revolution. And during the second industrial revolution, the driving mode of the machine tools changed from the centralized drive of steam engines to the individual drive of motors. Therefore, the society ushered in the flow line mode with clear division of labor and mass production, which unprecedentedly improved the production efficiency. During the process of the third industrial revolution, the emergence of the numerical control system has greatly enhanced the automation level and controlling precision of machine tools. Thus, machine tools further developed in the direction of high speed, high precision, automation and informatization, and constantly broke through the manufacturing bottlenecks in aerospace and shipbuilding, promoting the vigorous development of advanced industries.

According to the mass change (Δm) of workpieces during manufacturing, Dr. Lu [3] divided manufacturing technology into "equal material manufacturing" (Δm=0), "subtractive manufacturing" (Δm<0) and "additive manufacturing" (Δm>0), as shown in Figure 1. With the understanding of the manufacturing technology is going to deep, various new-type composite manufacturing technologies such as "additive-subtract manufacturing" emerged.

Subtractive manufacturing is one of the focuses in the high-precision manufacturing industry. Spacecraft cabin, aviation thin-walled frame-type structural parts and marine propellers are key components in the fields of aerospace and shipbuilding. Such complex parts, except for some special parts obtained by the equal or additive manufacturing, often require the subtractive manufacturing [7] to achieve its high-precision and high-quality machining. Their machining quality directly determines the performance of the equipment, which reflects the national manufacturing capacity and sci-tech strength. Therefore, the high-quality development of subtractive manufacturing is of great significance for enhancing the national comprehensive strength and major strategic planning.

This paper starts with the development history of the subtractive manufacturing machine tools. Section 2 summarizes the original motive force of promoting the equipment innovation from the events of major breakthroughs in the manufacturing equipment. Section 3 takes the manufacturing requirements of large and complex components in the aerospace field as an example to sort out the development context of high-precision and sophisticated machining equipment in the field. On this basis, Section 4 prospects the future development trend of milling equipment in advanced manufacturing industry. Section 5 concludes the paper.



(a) Equal material manufacturing [4]

(b) Subtractive manufacturing [5]

(c) Additive manufacturing [6]

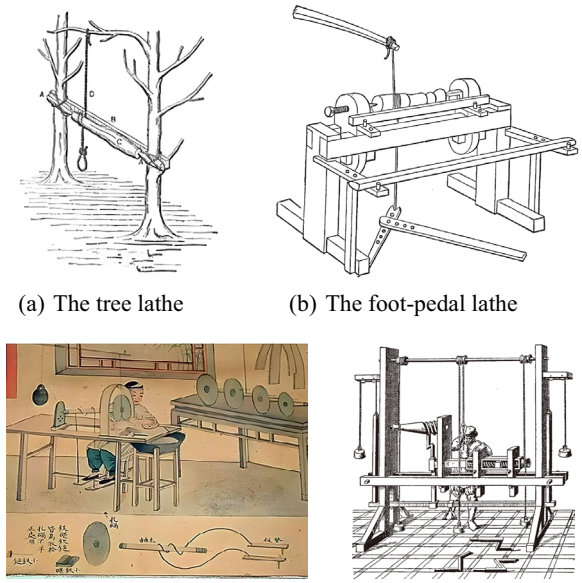
Figure 1 Industrial manufacturing classification: **a** Equal material manufacturing [4]; **b** Subtractive manufacturing [5]; **c** Additive manufacturing [6]

2 Development History of the Machine Tools

2.1 Origin and Early Development of the Machine Tools

More than 2000 years ago, purely manual methods could no longer satisfy the daily production. There was an arising demand for tools, then the first prototype of the machine tool, tree lathe, appeared, as shown in Figure 2a. When using the lathe, users would step on the lower loop with their feet to drive the middle wooden shaft to rotate by the toughness of the tree. The ends of the wooden shafts were tied with stones or shells to achieve the cutting. With the progress of society, in the early 13th century, this outdoor rough work using natural trees was migrated indoors, and the foot-pedal lathe [8] appeared, as shown in Figure 2b. Similar to the principle of the tree lathe, a flywheel structure was added to increase the inertia and the cutting force. "The Exploitation of the Works of Nature" published in Ming Dynasty recorded an ancient grinding machine [9] (Figure 2c), which used a foot pedal to drive a grinding disc to cut jade. At the beginning of the 16th century, French designer Besson developed a lathe [8] making it possible to use a screw to slide the tool, as shown in Figure 2d. It could be used to lathe screw-like objects.

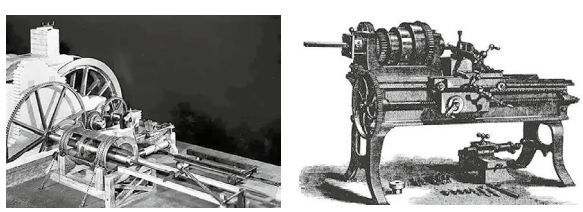
In the long history of using tools, the appearance of screw makes great progress in the lathe development, which marks that people began to hold the concept of



(a) The tree lathe (b) The foot-pedal lathe

(c) Ancient grinding machine (d) Besson lathe

Figure 2 Early machine tools [8]



(a) The gun-barrel boring machine [10] (b) Tools holder lathe [11]

Figure 3 Typical machine tools in the mechanization age: **a** The gun-barrel boring machine [10]; **b** Tools holder lathe [11]

precision for the first time. Instead of relying on experience and repeated disassembly observations, they used the characteristics of the screw pitch to obtain the ideal shape of the final product. In the early stage of the machine tools' development, manpower was the main way to drive them. With the successively growing of the productivity, the demand for larger tools increased. Manpower could no longer meet the requirements of large driving force tools, and people began to seek for some new driving methods.

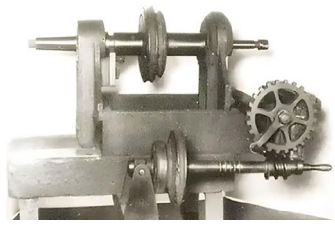
2.2 Development of the Machine Tools in Steam Age

In the early 18th century, the machinery industry was extensively explored to enhance productivity. In 1774, Wilkinson invented the world's first real machine tool, the gun-barrel boring machine [10] (Figure 3a). It directly solved the quality problem in the machining of the Watt steam engine's cylinder, which contributed to the extensive promotion of the steam engine, laid the foundation for the first industrial revolution to begin in the United Kingdom, and played an important role in the rise of the "Sun Never Sets" empire. The boring machine was also known as the "Mother of Machinery". In 1797, Henry Maudsley made the first lathe with a tools holder [11], turning manual cutting into automatic cutting, as shown in Figure 3b. The lathe is therefore called the "Father of Machinery". The emergence of the boring machines and lathes promoted the transformation of production methods from small batch manual production to mechanized mass production. Since then, human society had stepped into the age of Industry 1.0—the mechanization age [12], and the economic society had been transformed from the agriculture and handicraft industry to a new model of economic development dominated by industry and manufacturing.

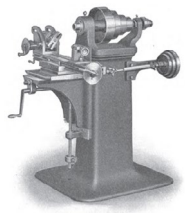
2.3 Development of the Machine Tools in Electrical Age

Boring machines and lathes were invented in the UK due to the demand for manufacturing industrial products such as steam engines during the first industrial revolution. The United States, on the other hand, concentrated on the development of milling machines to produce numerous weapons. The milling machine is a kind of equipment that mainly uses the rotation of the milling cutter, assisted by the feed movement of the table or milling head, to complete the machining of various complex surface parts, such as planes, grooves, spiral grooves, gear shapes, etc., through various shapes of milling tools. In 1818, Whitney developed the world's first horizontal milling machine, as shown in Figure 4a. At the same time, he proposed the concept of interchangeability, which made him known as the founder of the standardized production. Brown [13] developed the first universal milling machine in 1862, replacing the manual filing of twist drills, as shown in Figure 4b. This milling machine had a lifting table, which was the prototype of the lifting table milling machine. It also had a screw head directly connected with the feeding mechanism, which could realize feed distance control and thread milling. This milling machine initially had the characteristics of the modern machine tools. In 1873, Spencer invented a single-spindle automatic lathe, as shown in Figure 4c, after which he developed a multi-spindle automatic lathe.

The advent of the electrification age provided new impetus for the development of the manufacturing industry. With continuous development of the electrification process, the motor had gradually become the driving unit to achieve the cutting movement of the manufacturing equipment, realizing the conversion of electrical energy into mechanical energy. Electric drive had begun to



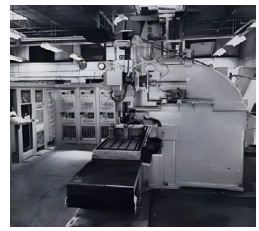
(a) Whitney horizontal milling machine



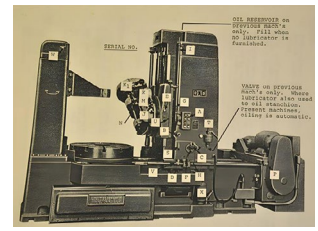
(b) Brown universal milling machine

(c) Spencer automatic lathe

Figure 4 Typical machine tools in early electrification age [11]



(a) The first CNC machine tool



(b) The first CNC machining center

Figure 5 Typical machine tools in early digitization age [14]

become a new driving method to supplement and replace steam drive, bringing human society into Industry 2.0—the electrification age.

As a result, the society's production model underwent an enormous transformation. The social production ushered in the clear division of labor and the mass production of the flow line mode, leading to an unprecedented development of production efficiency. However, people were not satisfied with this way of monitoring the machining quality by the engineering experience, and began to explore new models of automated production. The emergence of numerical control system provided a new way for the manufacturing industry to change from manual control to digital control. Since the 1940s, the arithmetic device of the numerical control system, after going through several changes in electronic tubes, transistors and small integrated circuits, was eventually replaced by the minicomputers. With the constant improvement of the operational capability and reliability of the numerical control system, the automation control level of the machine tools was also increased, promoting the development of the manufacturing industry to a deeper level of digitization and informatization, and laying a solid foundation for the arrival of the Industrial 3.0—the digitization age.

2.4 Development of the Machine Tools in Digitization Age

In 1948, Parsons Corporation was commissioned by the U.S. Air Force to develop machining equipment for propeller blade contour samples. Due to the complex and diverse geometry of the model and the high precision requirements, general machining equipment was difficult to perform its manufacturing tasks. Therefore, the idea of numerical control of machine tools was put forward. In 1952, Parsons developed the world's first numerical controlled (NC) machine tool in collaboration with the MIT Servo Institute [14, 15], as shown in Figure 5a. This machine tool successfully realized the three-axis linkage function and was officially put into operation in 1957. It was a breakthrough in the development of manufacturing technology, marking the beginning of the numerical control machining age [16] in the manufacturing field. The arithmetic core of numerical control device was an electronic computer, also known as computer numerical control (CNC) device. Different from the mode of manually monitoring machining quality, the emergence of CNC system made automatic manufacturing possible. In 1958, the first NC machining center [17] was successfully developed by Carney-Trek Company, as shown in Figure 5b. Based on CNC machine tools, automatic tools changing device was added. The workpiece could be machined in various processes such as milling, drilling, boring or tapping in one clamping, which improved the reusability of machine tools. In the same year, Tsinghua University and Beijing First Machine Tool Factory jointly developed the first CNC machine tools in China, laying the foundation for the prosperous development of our country's industry.

With the continuous improvement of machine tools' performance, the establishment of common standards for machining performance evaluation became a hot spot. Machining accuracy is one of the key indicators throughout the entire life cycle of a machine tools. As a good method to test the actual machining performance of machine tools, test piece cutting had received extensive attentions. NASA proposed the NAS979 test piece [18] in 1969 to evaluate the performance of contour machining. This made the comparison between different equipment possible, and therefore promoted their advanced development.

The technical change of machine tools was also inseparable from the development of electronic and

information technology. With the advancement of the Industry 3.0 process, the performance of automatic control devices had been continuously optimized and upgraded, such as single-chip microcomputers, PLCs, and industrial computers. It had greatly improved the control accuracy and automation of machine tools. At the same time, computer-aided manufacturing (CAM)/design (CAD) technology had been rapidly developed and applied for toolpath planning, trajectory tracking control, parametric modeling, strength analysis, etc. It further improved the level of digitization and greatly enhanced the machining efficiency of machine tools. With the prosperous development of information and communication technology, the digital twin-based CAD and CAM verification systems [19] have been developed, promoting the integration and intelligence of machine tools.

2.5 Development of the Modern Machine Tools

In the 1980s, IBM launched the first personal PC with a 16-bit microprocessor. Since then, numerical control devices had shifted from specific manufacturer monopolistic products (hardware and software) to general PC-based computer products, which spawned the opening CNC system. New machining concepts such as high-speed machine tools [20] and compound machining centers [21] had been rapidly iterated and applied in practice. With the development of configuration design, control, measurement and computer technology, manufacturing equipment had been advanced to a higher level of digitization and networking. During this period, there emerged various types of equipment, such as high-performance three-axis machining centers, four-axis machining centers (for machining arc surface features of rotating parts), five-axis machining centers, five-axis gantry centers and six-axis gantry machining centers, as shown in Figure 6. These machines had been successfully applied to the machining of key components in aerospace, shipbuilding, energy and other fields. In the current industrial field, five-axis machining centers are still the main force of high-precision manufacturing.

For the performance testing of five-axis machine tools, there were some deficiencies in existing methods. As an early test piece, NAS979 was mainly used for performance testing of three-axis machine tools. As for the five-axis machine tools, Japanese scholars proposed a quadrangular pyramid test piece [22], which could directly detect errors of straightness, perpendicularity, and parallelism, but this test piece could not be used to reflect the ability in machining complex surfaces. To realize the comprehensive testing of the five-axis machine tools, the German NCG company proposed the NCG2004 test piece [23]. It contains various features

Figure 6 Mature application of manufacturing equipment: **a** Three-axis machining center [25]; **b** Four-axis machining center [26]; **c** Five-axis gantry machining center [26]; **d** Six-axis gantry machining center [27]

such as conical, spherical and U-shaped surfaces. Due to its complex structure, cumbersome machining procedures and long machining time, it is not easy to be popularized. According to the actual machining and production experience, The Aviation Industry Corporation of China (AVIC) proposed the "S" standard test piece [24]. It contains a wider range of tool spatial postures and is simple in form. The machining performance of the variable curvature and open-and-closed angle conversion regions could be effectively tested, which could reflect the dynamic accuracy of the machine tools. In September 2012, the "S" test piece was certified as an additional test piece of the ISO10791-7 standard group, and officially became the international standard test piece. The proposal of the "S" test piece is of great significance to the performance improvement of high-end equipment in the manufacturing field in China and even the world, marking an important step from "Made in China" to "Created in China".

With the development of artificial intelligence, manufacturing industry paid more and more attentions to the intelligence of machine tools besides their machining performance. Industry 4.0 is one of the high-tech strategic development plans proposed by the German government [28], which put forward new requirements for the manufacturing industry. Industry 4.0 aims to promote industrial revolution through information technology. It emphasizes the importance of "smart factories", "smart production" and "smart logistics", and creates an era of interconnected intelligent manufacturing in which multiple fields such as mechanical manufacturing, information

sensing, artificial intelligence and data analysis are integrated.

2.6 New Machining Equipment: Parallel Machine Tools

With the development of high-end manufacturing industries such as aviation, aerospace, and shipbuilding, higher machining efficiency is required, which has promoted the exploration of new mechanism configurations for machine tools. In 1965, D. Stewart proposed a 6-DoF parallel mechanism [29]. The mobile platform is connected to the base through six parallel telescopic rods, as shown in Figure 7. This mechanism could be used for the flight simulation training of pilots. Stewart platform is one of the earliest parallel mechanisms that have been applied in practice, which laid the foundation for the transformation of parallel structures to machine tools. With its successful application, parallel mechanism had attracted the attentions of the manufacturing industry by virtue of its high dynamic characteristics [30] and high stiffness to weight ratio [31]. Since then, the exploration for the application of parallel machine tools (virtual axis machine tools) in manufacturing industry has begun.

At the Chicago International Machine Tool Show in 1994, Giddings & Lewis and Ingersoll of the United States exhibited their own parallel machine tools, which attracted the attention of the entire machine tool industry. The Variax [32] parallel machine developed by Giddings & Lewis is shown in Figure 8a. This machine is a vertical machining center based on the Stewart platform. The six drive rods are paired in an "X" shape. The position and posture of the spindle are controlled by the telescopic rod to complete the machining. It was later supplied to the College of Engineering of University of Nottingham as project equipment for agile manufacturing. Ingersoll developed the VOH-1000 vertical machining center and the HOH-600 horizontal machining center successively. The base of the HOH-600 adopts an octahedral truss structure, as shown in Figure 8b. This kind of structure has high rigidity and closed force flow characteristics, which reduces the requirements for the base when the machine tools is installed and improves the installation convenience. The maximum feed speed of the actuating unit is 30 m/min, the acceleration is 0.5*g*, the spindle speed is 20000 r/min, the maximum power is 37.5 kW, and the maximum torque is 49.1 N · m.

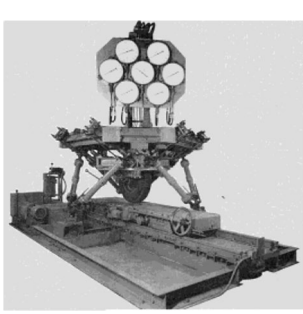
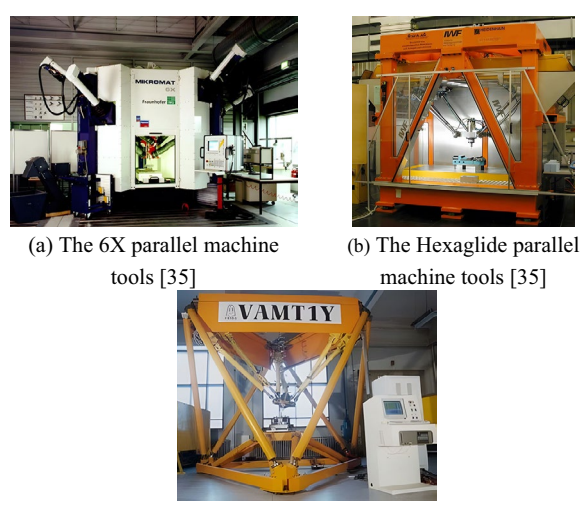


Figure 7 Flight simulator using Stewart mechanism

(a) Variax parallel machine tools [33,34] (b) HOH-600 horizontal parallel machine tools [35]

Figure 8 Early parallel machine tools products: **a** Variax parallel machine tools [33, 34]; **b** HOH-600 horizontal parallel machine tools [35]

The active exploration of parallel machine tools by Giddings & Lewis and Ingersoll had inspired many research institutions in various countries. Around 2000, with the significant progress in kinematics principle, mechanism design method, control technology and dynamic performance research, many practical parallel machine tools appeared at home and abroad. Examples included the 6X machine tools developed by Mikromat in Germany (Figure 9a), the Hexaglide parallel machine developed by the Swiss Federal Institute of Technology in Zurich (Figure 9b), the VAMT1Y parallel machine tools developed by Tsinghua University and Tianjin University (Figure 9c). The emergence of parallel machine tools [36]



(a) The 6X parallel machine tools [35] (b) The Hexaglide parallel machine tools [35]

(c) The VAMT1Y parallel machine tools [37]

Figure 9 Parallel machine tools developed by institutions: **a** The 6X parallel machine tools [35]; **b** The Hexaglide parallel machine tools [35]; **c** The VAMT1Y parallel machine tools [37]

has changed the original design mode of machine tools and provided new ideas for the machine tool design with the mechanism analysis and design methods introduced, which is of great significance to the innovation and development of the machine tool industry.

From the above analysis, the development of subtractive manufacturing has a long history. In the process of continuous iteration of machine tools, the subtractive manufacturing equipment have experienced several important development stages such as manual drive and manual control, steam drive and mechanical control, electrical drive and automatic control, digital control. High performance, multi-function and intelligence have always been the unremitting pursuit of the manufacturing industry. The development of machine tools is always coupled with the process of the industrial revolution, and its development is crucial to the progress of the manufacturing and even the entire industry.

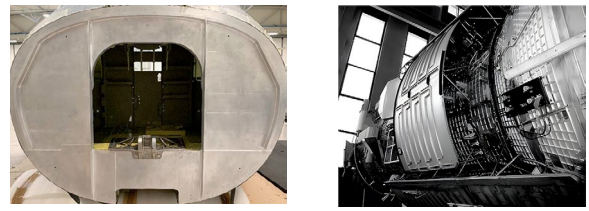
China's modern industry started relatively late, the remarkable achievements since the 21st century cannot conceal the fact that China has always been a "follower" in the manufacturing industry. At the critical stage of manufacturing optimization, China should accelerate the transformation and upgrading of manufacturing industry, thereby promoting its high-tech, intelligent and green development. Only in this way can China become the "pacesetter" in the manufacturing industry.

3 Development of Manufacturing Equipment in Aeronautic and Astronautic Fields

The advanced manufacturing industry represented by aerospace reflects the comprehensive scientific and technological strength of a country. Therefore, taking the machining requirements of large-scale complex structural parts in aerospace field as examples, the development status of related manufacturing equipment is summarized.

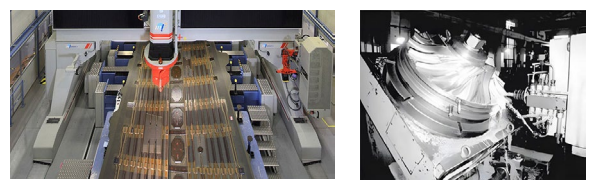
Large-scale complex structural parts are the core components of aerospace equipment, typical large-scale complex parts include aircraft frame structure (Figure 10a), space station cabin structure (Figure 10b), etc. They usually have common characteristics such as large size, complex shape, contour accuracy and surface quality requirements, and are always associated with thin-walled structures. Their high-efficiency and high-quality machining have always been the unremitting pursuit of the industry.

At present, large-scale complex structural parts are mainly processed by gantry multi-axis CNC machine tools, as shown in Figure 11. As high-tech equipment with wide application range, the gantry five-axis machine tools have unique advantages in machining parts with curved surface features: (1) integrated machining, complex parts can be machined in one clamping, which simplifies the machining process; (2) five-axis linkage, free-form surface machining can be realized; (3) serial structure, motion control and accuracy guarantee technology are relatively mature.



(a) Aircraft frame structure [38] (b) Space station cabin structure

Figure 10 Typical large-scale complex structural parts: **a** Aircraft frame structure [38]; **b** Space station cabin structure



(a) Five-axis milling of large-scale aerial thin-walled parts [39] (b) Blisk machining [40]

Figure 11 Multi-axis machining of large-scale complex structural parts: **a** Five-axis milling of large-scale aerial thin-walled parts [39]; **b** Blisk machining [40]

However, with the increasing manufacturing demand for large-scale complex parts in the aerospace field, the inclusive machining mode represented by gantry multi-axis machine tools gradually shows its limitations: (1) the machining mode usually does not have the flexibility and parallel manufacturing capability; (2) the machining object is specific, and the unreconfigurable equipment is not adaptive for diverse machining environments; (3) the machining stroke gradually cannot meet the requirements of large-scale structural parts. At the same time, the bottleneck of extreme manufacturing technology makes it impossible to sustain the unlimited increase of the machine size. Based on this background, the industry has carried out many beneficial explorations on new machining modes.

In recent years, serial mobile robots are gradually applied to the manufacturing of large-scale complex parts [41]. Fraunhofer IFAM developed a mobile machining robot with an industrial serial robotic arm and a mobile platform, as shown in Figure 12a. This machining robot uses a laser tracker to achieve global positioning in large scenes, with additional secondary encoder system on every axis of robot arm (Figure 12b). An advanced

(a) A320 tail drilling (b) Secondary encoder feedback system

Figure 12 Mobile machining robot developed by Fraunhofer IFAM [42]

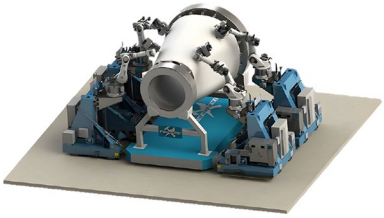


Figure 14 Mobile multi-machine collaborative manufacturing system of EI

control strategy is implemented, which greatly improves the precision of the serial robotic arm. The repeated positioning accuracy could reach 0.06 mm, and the absolute positioning accuracy could reach 0.19 mm. The machining robot has been successfully applied to drilling of large carbon fiber reinforced polymer (CFRP) components in the aerospace industry, such as A320 aircraft tail.

Also for drilling requirements, Electroimpact (EI) of the United States developed a mobile robotic drilling system [43] by integrating a serial industrial robotic arm and a linear mobile platform, as shown in Figure 13. This system has been successfully used in the surface drilling of Boeing 737 ailerons. On this basis, EI further constructed a mobile multi-machine collaborative manufacturing system [44], as shown in Figure 14, which has been successfully applied to the surface drilling of the Boeing 787 aircraft fuselage. By using this system, drilling holes and fastener installation in the same area have been realized. As a result, the installation efficiency (approximately 30%) has been greatly improved, and the production time cost of Boeing 787 fuselage has been reduced.

The mobile machining robot, which is an "open" machining concept for flexible processing scenarios, avoids the problem that the equipment is difficult to be infinitely large in "inclusive" machining mode. The adoption of mobile unit expands the reachable space, reduces the cost of machining equipment, and makes the entire production system flexible. Mobile opening machining mode improves the adaptability of manufacturing equipment to different machining objects and provides a new solution for the machining of large-scale complex structural parts. But there are still some problems in practical applications. Generally speaking, the stiffness of the serial robotic arm is much lower than that of the machine tools, only 1 N/μm, which is 1/50 of the machine tools' stiffness [45], and the serial robotic arm is not suitable for bearing alternating loads. Therefore, this kind of "mobile platform + serial robotic arm + terminal manipulator" mobile robot system is often used in non-contact or small contact force conditions such as polishing, spraying, welding, grabbing, etc., and it is difficult to be used for milling with complex interaction forces. On the other hand, the stiffness and precision of serial robotic arm vary widely within its workspace, resulting in poor performance consistency. When the angle between the two arms of the robot is too large or too small, its performance decreases rapidly, so the workspace available for actual machining is limited [46–48]. Thus it can be seen that, the above application cases of mobile machining robots are undoubtedly successful in the investigation of a new machining mode for large-scale parts, and the inherent limitations of traditional machining equipment have been broken through. However, when it comes to the milling of large-scale complex parts, the current mobile machining equipment still has key technical problems that need to be optimized or even to be broken through.

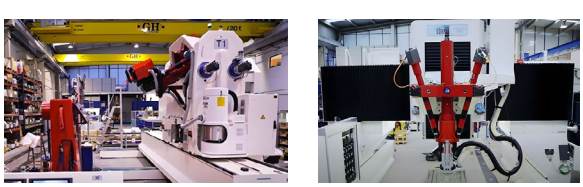
Figure 13 Mobile robot drilling system of EI

The development of manufacturing equipment has always been accompanied by the continuous innovation of mechanism principles [49] and configurations [50]. Parallel mechanisms [51] have attracted extensive attentions due to their compact structure, lightweight and quick dynamic response characteristics. Following the mobile machining equipment of "mobile platform + serial robotic arm", "mobile platform + parallel/hybrid machining module" has become the preferred solution for large-scale complex structural parts. Parallel robots have been hailed as the most innovative engineering design in past 20 years. Its compact structure and lightweight characteristics make the miniaturization, portability and modularization of machining equipment possible, which facilitates on-site transportation. Flexible machining modes based on portable and modular

parallel module can improve machining accessibility, operational flexibility and machining efficiency for large-scale complex parts. The application of parallel robots makes up for the shortcomings of traditional heavy-duty gantry machine tools in terms of response speed, acceleration, and stiffness to weight ratio. Compared with serial machining robots, although parallel robots have certain limitations in workspace, their stiffness and machining efficiency are significantly improved, which is an effective supplement between machine tools and serial machining robots.

Since the 1990s, parallel/hybrid robotic equipment have made great progress under the promotion of numerous enterprises and institutions in the United States, Sweden, Germany, China and other countries. Some of these companies have successfully applied their equipment in industrial production. One of the typical representatives is the Spanish company LOXIN. This company acquired part of the former Swedish company Neos Robotics which developed Tricept [52], and expanded Tricept on this basis. For the manufacturing requirements of large-scale complex parts, this company developed a mobile drilling robot with integrated slide and rotary tool head (Figure 15a), which had been applied to the drilling of A350XWB aircraft panels. Milling equipment (Figure 15b) had been developed by combining the 3-DoF gantry structure and the Tricept hybrid robot, and had been applied to the milling of rail transit body panels.

The core component of the above-mentioned equipment is the modular hybrid robot Tricept which can realize multi-axis motion and has the characteristics of lightweight (550 kg) and high precision (repeat positioning accuracy ± 0.02 mm). At the same time, a direct measurement system is equipped to provide additional accuracy through the redundant encoder. The above features make the equipment own the advantages of high response speed, high stiffness and high precision, while the machining module can be flexibly arranged, so that the machining system has flexible machining capability and better performance. The Tricept hybrid robots have reached more than 300 installations worldwide in just a few years, and have been widely used in industrial fields such as automobiles and aviation.



(a) Mobile drilling robot (b) Gantry milling robot

Figure 15 Mobile machining center based on parallel robot [53]

The parallel module of the Tricept hybrid robot (Figure 16) has 3 DoFs and enables spatial positioning. To realize five-axis machining, a serial A/C swing head is added. However, the serial A/C swing angle head has its limitations. First, when the C-axis is collinear with that of the cutter, a small change in posture might lead to a wide range of motion in C-axis, resulting in unfavorable tool marks scratched by high-speed rotating tools [54, 55]. Secondly, the serial A/C swing angle realized 2-DoF rotation through synthetic motion, which leads to dynamic delay error between the two different axes and poor response speed, also a loss of machining accuracy. These disadvantages limited the further improvement of the dynamic performance.

Based on the technical foundation of Tricept, Karl-Erik Neumann, its inventor, developed a new hybrid machining robot, Exechon, and established a company called EXECHON. The company has excellent achievements in the lightweight design of hybrid machining robots, and has developed the Xmini [57] which is the first hybrid machining robot mainly composed of carbon fiber structures, as shown in Figure 17a. Xmini can achieve five-axis machining. Its lightweight (300 kg), high accuracy (repeatable positioning accuracy ±0.05 mm), high flexibility, high dynamic response performance, and modular design concept brought considerable advantages to its

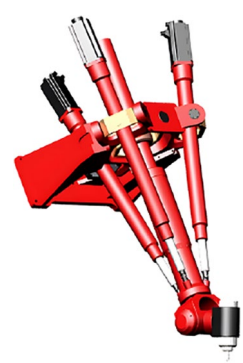
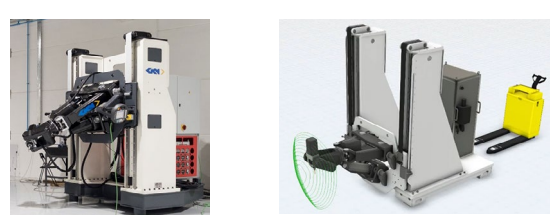


Figure 16 Tricept hybrid machining robot [56]



(a) Xmini hybrid machining robot [61] (b) Xmobile mobile machining robot [62]

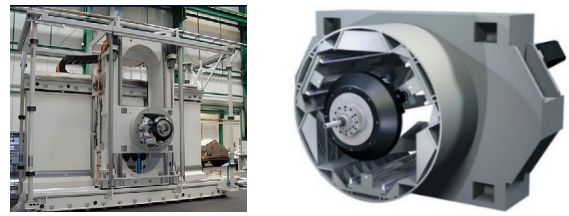
Figure 17 Exechon products: **a** Xmini hybrid machining robot [61]; **b** Xmobile mobile machining robot [62]

mobile machining application [58]. Based on the Xmini hybrid machining robot, EXECHON further developed the Xmobile [59], as shown in Figure 17b. Being installed on a mobile platform, the Xmini module could be easily relocated to different areas of the factory by using a standard pallet truck or forklift. As a mobile machine tool, XMobile can replace specialized or large machine tools, and can perform different machining tasks at different locations in the factory.

The hybrid machining robot TriMule-600 [60] (Figure 18a) developed by Tianjin University adopts a 5-DoF hybrid configuration based on "3-DoF parallel module + 2-DoF serial wrist". It has the advantages of large workspace, high stiffness to weight ratio, reconfigurable, and closed-loop feedback of end position. Its repeated and absolute positioning accuracy could reach 0.01 mm and 0.05 mm, respectively. Based on this hybrid machining robot, Tianjin University further developed the mobile hybrid equipment (Figure 18b) for the machining of large-scale complex parts, which can be applied to high-speed milling of aviation structural parts, and can also be used for the grinding and polishing of the automobile panel die.

The parallel/hybrid machining robots developed by the above institutions have been successfully applied in the industrial production. The design concept of mobile machining robots based on "mobile platform + parallel/hybrid machining module" has been successfully verified. Nevertheless, the performance of such equipment still has room for improvement since the adoption of the A/C swing head limits the further improvement of the accurate and quick response capability to a certain extent.

To break through the limitations of the attitude synthetic motion of A/C swing head, many institutions made a lot of endeavours in the development of 3-DoF parallel machining modules [64–66] with two rotational DoFs and a translational DoF, and one of the typical representatives is the DS-Technologie. This company developed the Ecospeed (Figure 19a), a hybrid machining center with parallel spindle head, according to the milling process characteristics of aircraft structural components. Its parallel spindle head Sprint Z3 (Figure 19b) adopts three PRS kinematic branches to realize the coupled attitude motion of the A/B axes, allowing to describe any path within a spherical cone of ±45° with an axis speed of up to 90°/s and an acceleration of up to 685°/s^2. Compared with the attitude synthetic motion of the A/C swing head, the attitude coupling motion of Z3 has higher efficiency and shows great advantages in the milling of aviation complex structural parts [67]. However, the parallel mechanism adopted by the Z3 spindle head only has 3 DoFs, and the other freedoms are complemented by guide rails. This makes the Ecospeed hybrid machining center heavy and difficult to realize miniaturization and lightweight design. In addition, the Ecospeed suffers from inertia mismatch of each axis when realizing high dynamic five-axis motion, which affects the further improvement of its dynamic performance. Although Ecospeed has achieved successful application in the industry, it still needs to increase the machine size to fit to the size of the workpiece when it comes to the milling of large-scale complex parts, which limited the expansion of its application scenario.

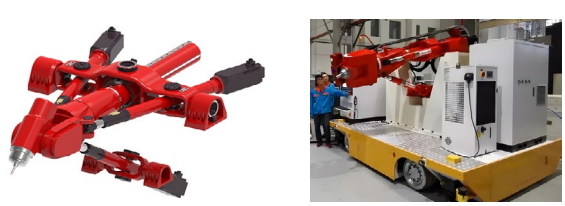


(a) Ecospeed hybird milling center (b) Sprint Z3 spindle head

Figure 19 DS-Technologie products [68]

To meet the requirements of high-performance mobile flexible machining system for the integrated machining and maintenance of large-scale parts or assemblies, the fully parallel five-axis milling equipment with modular design has become a hot topic in the field.

Metrom has developed a fully parallel five-axis milling robot [69], as shown in Figure 20. Benefiting from the modular design, the milling robot can be flexibly arranged according to different requirements [70],



(a) Hybrid machining robot TriMule (b) Mobile hybrid machining robot

Figure 18 Hybrid machining robot of Tianjin University [63]

Figure 20 Metrom milling robot [71]

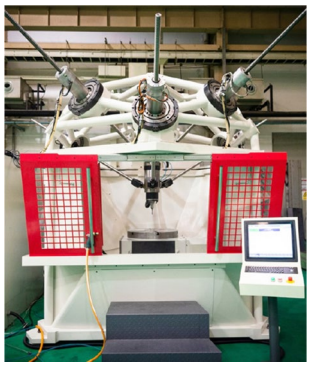


Figure 21 Five-axis milling robot Diarom-600

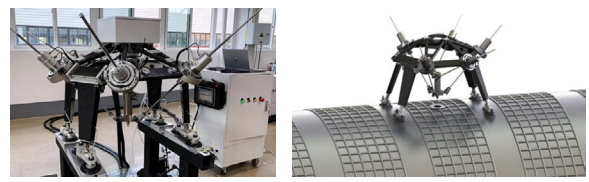
therefore its adaptability has been improved. This robot and its layout form are of great significance to the in-situ milling of large-scale complex structural parts.

For high-efficiency and high-quality milling of the complex structural parts, Tsinghua University developed a five-axis fully parallel milling robot DiaRoM-600 [72, 73], as shown in Figure 21. This milling robot gives fully play to the advantages of parallel mechanisms in the aspects of lightweight characteristics and the high efficiency performance benefiting from its coupling attitude adjustment capability. The parallel robot weighs 800 kg, and its lightweight feature makes modular and portable design possible. The workspace of the robot is 600 mm×600 mm×400 mm, A/B linkage range can reach 30°, and the rotational output capability is greater than 110° around the A axis, so the robot can realize the conversion between vertical and horizontal milling modes. Its positioning accuracy is ±0.0091 mm, and it can be used for the finishing milling of complex parts such as aerospace structural components, turbine blades, and special-shaped parts.

This robot has been systematically verified in the 5G laboratory of AVIC. The milling of key components such as the aircraft frame structure, cover plate, reinforcement frame, and connecting plate has been completed. The maximum error of the machined parts is 0.068 mm, and the machining accuracy is much better than the precision requirements of such parts. On this basis, to realize five-axis milling at anytime and anywhere, Tsinghua University proposed a solution for in-situ flexible milling of large complex components based on "mobile platform + high stiffness arm + five-axis milling module", and developed a mobile milling robot CraftsRobot-300 [74] (Figure 22a). This robot is capable of wide range of positioning and local fine machining, and has the characteristics of high efficiency and high precision. Its vertical stroke is 1450 mm, and the repeated positioning accuracy is better than ±0.01 mm when the mobile platform and the arm are

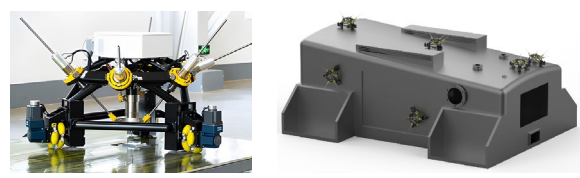
(a) CraftsRobot-300 (b) Cabin milling

Figure 22 (Color online) Mobile milling robot and its application



(a) Vacuum adsorption milling robot (b) Cabin top mounting surface milling

Figure 23 Vacuum adsorption milling robot and its application



(a) Magnetic adsorption milling robot (b) Surface milling of large magnetic materials

Figure 24 Magnetic adsorption milling robot and its application

locked. At present, this robot has been successfully used in multi-station finishing milling of the device bracket mounting surface of the space station cabin (Figure 22b). The machining accuracy is better than 0.2 mm, the flatness of the machined surface is better than 0.1 mm, and the surface roughness is better than *Ra* 1.6.

In response to the in-situ milling requirements of large-scale components such as spacecraft cabins and satellite structures, Tsinghua University has further developed a vacuum adsorption milling robot [75] (Figure 23) and a magnetic adsorption milling robot [76] (Figure 24) based on the portable parallel module. The vacuum and magnetic adsorption moving unit can realize the autonomous movement, positioning and locking on the surface of large parts. In combination with the lightweight 5-axis fully parallel milling module, it makes in-situ milling of large parts possible. Similarly, the gantry truss milling robot [77] can be developed by using the hybrid configuration of "large stroke gantry + lightweight five-axis fully parallel milling module" (Figure 25) to realize the

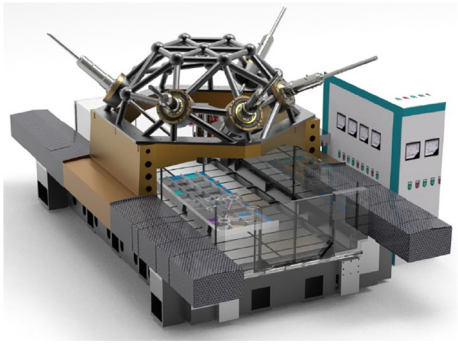


Figure 25 Gantry hybrid milling robot

manufacturing of large aspect ratio aircraft parts in one clamping.

Based on the analysis of above application cases, combining the requirements of in-situ machining, the high efficiency of parallel mechanisms capable of coupling attitude adjustment, and the modular and lightweight design concept, creating the mobile machining equipment with the configuration of "five-axis fully parallel milling module + mobile platform", is an ideal solution for high-efficiency and high-quality milling of large-scale complex structural parts. This kind of mobile machining equipment reflects an advanced design concept of "machining large parts with small machine tools" and "reconfigurable manufacturing system", and presents a development trend featured by robotization, miniaturization and portability. As a result, it will become the preferred choice for efficient milling of large-scale complex parts with aluminum alloys or composite materials, an effective way for heavy equipment manufacturing and remote maintenance, and a new development direction for energy-saving, efficient and flexible manufacturing equipment.

4 Development Trend of Manufacturing Equipment

For the milling requirements of the large-scale complex structural parts in the high-end manufacturing fields such as aerospace, the existing equipment have solved some of the problems. However, with the upsizing development of high-end equipment, the size of its core components is increasing, such as the space station cabin (over 4.5 m in diameter), aircraft rib components (over 5 m in length) and large rocket tank (over 10 m in diameter). Under this circumstance, the performance of milling equipment needs to be improved accordingly, and there are great challenges. Future milling equipment are supposed to have the following characteristics: (1) robotization, miniaturization, and portability are the main features; (2) on-site intelligent collaboration of multi machines is realized; (3) measurement, milling and detection are all integrated in one system; (4) the performance of the robotic system in the whole life cycle is self-sustaining.

4.1 Robotized, Miniaturized and Portable Milling Equipment

For the complex surface characteristics of large parts, individual serial/parallel manufacturing equipment can meet the machining requirements of some workpieces. However, as its size enlarges, the inherent limitations of equipment with single configuration will limit the further improvement in accuracy and efficiency, and may even encounter the problem of accessibility in space. In this context, the robotization, miniaturization and portability of milling equipment will become an important development trend. On the one hand, the fully parallel five-axis milling module has the advantages of compact structure, lightweight, high stiffness, and good dynamic characteristics. Advanced design methods, such as dimension synthesis and energy efficiency optimization, make the designed milling equipment capable of high-precision and high-efficiency milling of complex surface features. On the other hand, the modular and portable design concept makes the five-axis parallel milling module replaceable, so it can be matched with mobile units such as vacuum adsorption device, magnetic adsorption device, high-rigidity arm, or mobile platform to extend its machining accessibility according to the actual milling scene. In this way, the high-efficiency and high-precision milling requirements of various large-scale complex parts can be satisfied.

4.2 Multi-machine In-situ Intelligent Collaborative Manufacturing

With the growing demand for enlargement design and efficient milling of complex components, the manufacturing mode of multi-machine in-situ intelligent collaborative milling has emerged [78]. Facing the diverse milling requirements of the complex structural parts, the multi-robot in-situ collaborative milling method is adopted. In this way, the miniaturization of portable robots can be fully utilized to construct multiple types of robotic equipment such as parallel, array, mirror, and other intelligent collaborative manufacturing systems, thus realizing efficient in-situ milling of large-scale complex components. With the deep integration of new generation information technology and advanced manufacturing technology, the manufacturing mode will be promoted from individual-machine manufacturing to multi-machine networked collaborative and intelligent manufacturing.

4.3 Integration of Measurement, Milling and Detection in One System

According to the milling requirements of complex curved surface features of large-scale parts, the milling system incorporating scene information fusion, online milling and real-time detection is going to be constructed to realize efficient manufacturing and inspection of various surface features of large-scale components. The manufacturing equipment is able to realize the visual/laser autonomous navigation, the matching of machining features in large scenes and complex processes, the online machining quality assessment, and the real-time correction of milling parameters. The robotic collaborative milling system integrated with multi-source information will be able to realize the integration of measurement, milling and detection, and it will be further combined with digital twin technology to form virtual-real interaction, data information sharing, online optimization decision-making and precise control, making the whole process of manufacturing transparent and controllable.

4.4 Performance of Robotic System is Self-sustainable in the Whole Life Cycle

During the long-time milling process of large-scale complex components, the wear of tools, bearings and other key parts will lead to the degradation of milling performance, and brings great challenges to the maintenance of the equipment. Therefore, it is necessary to construct a multi-sensor fusion monitoring and performance self-healing system for milling equipment. Firstly, research on the online performance monitoring technology needs to be carried out. Secondly, the discriminant criterion and parameter optimization strategy should be constructed by extracting nonlinear fault features of key components. Then, the intelligent monitoring and diagnosis system is going to be established to realize the fault self-diagnosis and ensure the stability of milling process. Finally, intelligent algorithms such as machine learning will be used to break through the bottleneck in robot self-diagnosis and performance prediction, making the robot have self-recovery capability and promoting its cyber and digitization development. Consequently, it is expected to enable the health self-maintenance of milling equipment throughout its life cycle.

5 Conclusions

Throughout the development history of manufacturing equipment, the continuous improvement of equipment has played a vital role in improving social productivity. With the continuous changes of social production requirements, machining equipment has gone through many stages, from the simple human-driven machine tools, to those driven by steam and electricity, to today's high-performance milling centers and the emerging mobile milling systems. The machining equipment presents a diversified configuration development trend of serial, parallel or hybrid style, and is developing towards portability, miniaturization, and roboticization. The manufacturing mode is developing from individual-machine offline planning to online intelligent optimization and multi-machine coordination.

With the rapid development of the new round of global technological and industrial revolution, the cross-interaction between manufacturing and electronic information, material science and other fields will be further deepened, bringing opportunities and challenges to advanced manufacturing industry. To promote the high-end and intelligent development of the manufacturing industry, developed countries such as the United States, Germany, and Japan have proposed a series of major strategies. China's "14th Five-Year Plan" also highlights the strategic position of manufacturing in national development. Bold attempts have been made in the research and development of integrated manufacturing equipment for large-scale complex components, the manufacturing verification and personalized application have also been completed, which brings a turnaround for the development and independent control of the high-end intelligent manufacturing technology and equipment in China.

Looking towards the future, complying with the machining equipment development trend of robotization and intelligence, promoting the deep integration of manufacturing equipment, information technology and artificial intelligence, and realizing the independent control of the high-end manufacturing core technology and equipment are of great significance for improving the core competitiveness of the country and ensuring national security.

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Authors' Contributions

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