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Improving China's Aerospace Equipment Manufacturing Capacity

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Abstract: This paper describes the capability structure of China's aerospace equipment manufacturing systems based on an analysis of the characteristics of aerospace equipment and its manufacturing process, analyzes major problems in China's aerospace equipment manufacturing industry, and then suggests improvements to China's aerospace equipment manufacturing capabilities.
Key words: aerospace equipment; aerospace manufacturing mode; aerospace equipment manufacturing system

1. Introduction

Over the past 60 years, China has built an independent and well-established aerospace industry with capabilities in both aerospace R&D and aerospace equipment manufacturing. China's aerospace industry has made significant achievements, such as the manned space flight project and lunar exploration program. It has made progress in the R&D and production of many launch vehicles, application satellites, and missile weapons. Achievements in the aerospace industry not only promote progress in science and technology and socio-economic development, but also contribute to enhancing comprehensive national power, defense capabilities, and cohesion.

Aerospace equipment is the foundation of space infrastructure construction and satellite application industry development. Aerospace equipment manufacturing falls within the sphere of advanced manufacturing. A capacity to manufacture aerospace equipment enables a country to enter, utilize, and control space, and it is therefore the cornerstone of the satellite application industry. As a national strategic emerging industry, aerospace equipment manufacturing is crucial for the development of space power. All global space powers emphasize aerospace equipment such as new generation launch vehicles, high-volume communication satellites, high-resolution remote sensing satellites, and global navigation satellites. Global space development history shows that the status of aerospace equipment reflects the national will and determines a nation's ability to conduct activities in space. The sustainable development of aerospace capabilities and the aerospace industry cannot be realized without independent and autonomous aerospace equipment manufacturing capabilities.

President Xi Jinping has pointed out that developing the space industry and building space power is an ongoing pursuit in China. At present, the global economy is undergoing complex and profound changes, and the equipment manufacturing industry is facing difficult challenges. To accomplish the strategic mission of accelerating structural adjustment, promoting industry development, and transforming from a major manufacturer to a manufacturing power and from a space-faring country to a space power, it is necessary for China to escalate its technological capabilities in the aerospace domain.

2. Overview of aerospace equipment manufacturing

2.1. Characteristics of aerospace equipment

Aerospace equipment manufacturing includes the manufacturing of launch vehicles, satellites, spacecraft, space stations, deep space probes, missile weapons, and related ground support

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equipment. Aerospace equipment is special equipment constructed on the ground, but designed to operate in the space. The characteristics of this equipment are as follows.

2.1.1. Aerospace equipment plays a strategic role

Aerospace equipment is of significant strategic importance as the material foundation of the aerospace industry, performer of national space tasks, and as a crucial means of promoting national space control capability. China must insist on independent and autonomous development in this domain rather than relying on international partners.

2.1.2. Aerospace equipment manufacturing is an intensive and complex technological process

Aerospace equipment is highly complex and requires a technology-intensive manufacturing process that integrates technologies from multiple disciplines. Aerospace equipment manufacturing is extremely explored and customized, and it involves an iterative process of systematic design and continuous technical improvement.

2.1.3. Aerospace equipment operates under harsh conditions

In-orbit aerospace equipment faces challenges from vacuums, microgravity, extreme temperatures, atomic oxygen, energetically charged particles, space debris, and other factors. Hence, aerospace equipment manufacturing must thoroughly take into consideration the impacts of the harsh space environment to adopt effective protective techniques and measures.

2.1.4. Support services for in-orbit aerospace equipment are difficult to implement

At present, all aerospace equipment in orbit is unmanned, with the exception of the International Space Station (ISS). The implementation of support services for in-orbit aerospace equipment must take technological feasibility and cost into consideration. For this reason, aerospace equipment must be extremely reliable, and this reliability can be achieved through a demanding process of equipment design, technique, production, and testing.

2.1.5. The aerospace equipment is of considerably high value

Aerospace products that have unique properties can be used to finish the special task and function in low volumes, but with a high benefit in a product. Since they are not produced in large volumes, they have low economies of scale compared to the products of other equipment manufacturing industries.

2.1.6. Safety and protection measures in aerospace equipment manufacturing are very strict

At present, aerospace equipment contains some toxic substances, for example, liquid rocket propellant is composed of nitro-oxidizer and certain hydrazine fuels. These toxic substances are highly oxidizing, corrosive, combustible, and even explosive. Therefore, strict safety and protection measures must be adopted in aerospace equipment manufacturing facilities.

2.2. Characteristics of the aerospace equipment manufacturing process

The aerospace equipment manufacturing system refers to the complete set of aerospace equipment production systems, which comprises the personnel, materials, energy, software, hardware, design methods, production planning and techniques, system maintenance, and management practices used to produce aerospace equipment. The aerospace equipment manufacturing system is an important part of the aerospace industry.

Aerospace equipment manufacturing system is affected and constrained by available personnel, machines, facilities, materials, environmental conditions, and many other factors. The complexity and difficulty of the aerospace equipment manufacturing process is largely a result of the technological complexity, harsh operating environment, and the difficulty of providing aerospace equipment support services. The characteristics of the aerospace equipment manufacturing process are as follows.

2.2.1. Aerospace equipment is structurally complex due to interactive coupling of sub-systems

System design is challenging, because configuration status change frequently and product data are voluminous. Aerospace equipment manufacturing involves complex techniques, including material selection, working procedures' arrangement, cutting-tool's usage, clamping methods, cutting parameters, assembly methods, quality inspections, and so on. Meanwhile, the aerospace equipment-manufacturing environment is also very complex, involving facility layout, product circulation, and resource scheduling.

2.2.2. Multiple types of aerospace equipment are typically developed simultaneously

R&D and batch production are equally important. Such manufacturing requires not only multi-product customization driven by customer demand but also platform-based, module-based, and product-based batch production. The need for both "multi-type" and "small-batch" production is widespread.

2.2.3. Aerospace equipment manufacturing demands high levels of reliability and quality, tight plan scheduling, and adaptability to changing requirements

Aerospace equipment must work accurately from first use. The sophisticated demands of aerospace equipment assembly make it difficult to automate batch-production with flow assembly lines. Thus, aerospace equipment manufacturing demands flexibility.

The Chinese aerospace industry has formulated a series of effective methods for organizational management, systems engineering, quality management, and so on, in order to cope with the complexity of the aerospace equipment manufacturing processes.

Firstly, aerospace equipment manufacturing follows a systematic and organizational management process. It is typically a complex process involving different disciplines, departments, and regions, all of which are involved in different phases of design, production, experimentation, purchasing, logistics, and testing. Aerospace equipment manufacturing follows an ordered, top-down system of organizational management. The process is led by the unit in charge of final assembly and integration, in coordination with other units that produce subsystems, stand-alone devices, and components in coordination with ancillary facilities. The core team of it is made up of the general commanders, designers, and technologists. The manufacturing process is based on a product's breakdown structure and corresponding matching table and is linked by production at all levels.

Secondly, aerospace equipment manufacturing follows strict systems engineering processes. Because of the high technological complexity of aerospace equipment, aerospace manufacturing must strictly follow the ensemble → decomposition → integration process of systems engineering, as well as a development procedure involving different phases of concept, engineering model, test sample, stereotypy. Aerospace equipment manufacturing must abide by the rule that manufacturing feasibility is determined by design, in turn, manufacturing also verifies the rationality of the design. Assembly, verification, and testing are three areas of special focus in the aerospace equipment manufacturing process. Additionally, it is important to continuously enhance the technology maturity and manufacturing maturity of the process.

Thirdly, stringent quality management is applied to aerospace equipment manufacturing. Aerospace equipment products have unique political and social impacts, and must be of high quality and highly reliability. In addition, they must meet the unique demands of small-scale production and have a "do it right the first time" ethos. China's aerospace industry adheres to a systematic quality view, and cultivates the philosophy of "rigorous," "meticulous," and "zero-flaw" quality control. A matrix product guarantee system is set up, with R&D units focusing on quality system operations, while project management units focusing on providing quality assurance. A series of related standards and rules have also been set up, for example, ISO 18238: 2015 Space systems—Closed loop problem solving management, which is a standard management practice of space systems.

2.3. Aerospace equipment manufacturing system capability

Equipment manufacturing capability is a direct reflection of the efficiency of a manufacturing system. The capabilities of an aerospace equipment manufacturing system are illustrated in Fig. 1.

Technological capabilities comprise system capabilities and professional capabilities. System capabilities reflect the system's technological level and aggregate effectiveness, including manufacturing system digitization and automation levels, such as computer-aided design (CAD), computer-aided process planning (CAPP), computer-aided engineering (CAE), and computer-aided manufacturing (CAM); information levels , such as manufacturing resource planning (MRP), enterprise resource planning (ERP), and product lifecycle management (PLM); production line layout optimization levels; and unitized flexible manufacturing levels. System capabilities are a direct reflection of enterprise manufacturing modes. Professional capabilities are the special manufacturing capabilities formed on the basis of aerospace technologies and aerospace product properties. The process of aerospace equipment manufacturing involves large heterotypic structural component machining and molding, micro high-precision special component production, and composite material machining and manufacturing. Related technologies include machining, welding, molding, casting, heat treatment, and other relevant professional verification and testing technologies. Any weakness or bottleneck in these fields will directly constrain the operating effectiveness and efficiency of the manufacturing system.

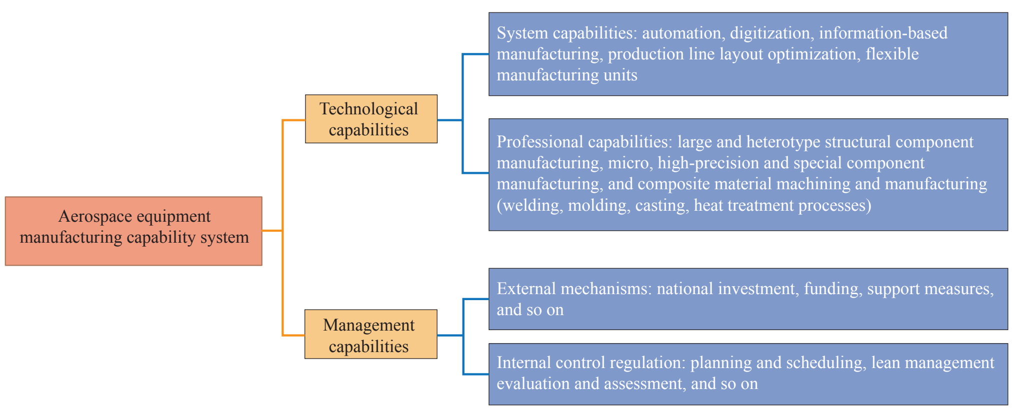

Fig.1. Aerospace equipment manufacturing system capabilities.

Management capabilities include external system mechanisms and internal control regulations. External system mechanisms mainly refer to the external policy environment, national investment, and support measures. Internal control regulations mainly refer to internal operational mechanisms of the manufacturing system, which involve planning and scheduling, synergy between units, as well as evaluation and assessment.

3. Development trends of aerospace equipment manufacturing

3.1. Extreme manufacturing

Extreme manufacturing refers either to products, components, and systems of extreme scale, or to high-functionality manufacturing under extreme conditions or environments. The extreme features of aerospace equipment manufacturing become increasingly evident with the transition of human space activities from near earth to deep space exploration and from unmanned to manned space flight.

3.1.1. Large scale and heavy duty

Space infrastructure construction is becoming increasingly large-scale and heavy-duty. For instance, space station construction requires staged building in space. High-volume satellites require large satellite platforms to support. Heavy-lift launch vehicles require large block structure manufacturing. Payloads and fuel carried by satellite are becoming increasingly larger and heavier in order to meet multipurpose requirements and achieve longer lifespan.

3.1.2. Precision and miniaturization

Assembling aerospace equipment is a complex process that requires high precision in dimensions, surface quality, and fabrication techniques. For example, the roundness, cylindricity, and surface roughness of satellite meter bearing require nanometer-scale precision. Meanwhile, the design and manufacturing of high-performance micro space vehicles, such as micro sensors, micro controllers, micro energy, and micro optical devices pose challenges for the manufacturing of related equipment.

3.1.3. High performance and uniqueness

Aerospace equipment manufacturing has many unique requirements, such as special techniques and special materials. The key components of aerospace products, such as frames, trusses, joints, and segments are largely made of titanium alloys, high-strength and high-temperature alloy steels, engineering ceramics, all of which are difficult to machine. Owing to the demand in small volumes, a discontinuous supply and failures to maintain a production line occasionally occur. Hence, aerospace equipment manufacturing requires synergy and coordination between all industrial departments.

3.2. Digitalization, networking, high reliability, low cost, and high efficiency

3.2.1. Digitalization

Foreign space industry, represented by renowned institutions and companies like NASA, Boeing, Airbus, and Lockheed Martin, has realized large improvements in product quality, synergy efficiency, and R&D capability through design and manufacturing digitalization [1]. In 2014, U.S. president Obama announced the establishment of the Digital Manufacture and Design Innovation Institution in Chicago—a public-private partnership. This institution was founded to enable the rapid realization of computer design and engineering prototype development; production of complex designs via advanced manufacturing technology; and faster cost effective construction, testing, and trial flight processes of NASA's next generation aerospace systems.

3.2.2. Networking

Major space contractors have commonly realized networking synergy in design and manufacturing. NASA has carried out intelligent synthesis environment (ISE) research [2], which effectively combines high-performance computer, high-speed networking, digital products and knowledge-based design, artificial intelligence, and human-computer interaction techniques to form a virtual synergy environment across various regions. Using this platform, specialists and engineers conduct aerospace products' synthesis design, testing, and prototype manufacturing to improve the cost and efficiency of satellite R&D [3].

3.2.3. High reliability

As space exploration stretches to further and deeper domains, the implementation of deep space exploration project, such as the manned lunar-landing and mars probes in particular, place more stringent demands on aerospace equipment reliability. *NASA Strategic Plan 2014* notes that it is committed to overcome the challenges of space radiation, logistical support, and long-term reliability, and the high reliability of aerospace equipment manufacturing is an ongoing focus.

3.2.4. Low cost

Major aerospace contractors in foreign countries have endeavored to promote low-cost manufacturing technology. On the one hand, manufacturing costs have been reduced in terms of design, process, and environment by technologies including design-to-cost, concurrent engineering, integrated product development, digitization design, network-based manufacturing, modeling and simulation. On the other hand, the emerging satellite platform, micro-satellites, reusable launching vehicles, and other space technologies have further reduced space mission costs. Furthermore, lean production and new commercial modes also contribute significantly to cost reduction.

3.2.5. High efficiency

To improve efficiency and shorten delivery cycles, the United States has proposed the *Lean Aerospace Initiative* (*LAI*), which is an initiative from an organization led by Massachusetts Institute of Technology with participation from the government and major aerospace contractors. It aims to achieve better aerospace production quality in a shorter timeframe and at a lower cost. At the same time, some commercial aerospace companies have achieved remarkable efficiency improvements. For example, SpaceX spent only four and half years on the first launch of the Falcon 9 rocket, while the building and first flight of the Dragon took only four years.

3.3. Fast development and application of advanced manufacturing technology

Aerospace manufacturing industries in foreign countries have achieved advancements in advanced molding and joining technology, composite material manufacturing technology, as well as digital manufacturing and equipment technology. Many new manufacturing techniques and technologies have emerged. For instance, NASA and Lockheed Martin worked together to develop integral molding technology for propellant tanks, a development that has reduced requirements for welding and testing. Another example of such advancement is in digital manufacturing technologies such as digital assembly and virtual laboratories, applied by Boeing, Airbus, and Lockheed Martin to shorten production cycles and reduce costs. In-orbit assembly and aerospace additive manufacturing (3D printing) have become increasingly important fields attracting wide attention. NASA has implemented large-scale system assembly in space, which could be a game changer in the field. Defense Advanced Research Projects Agency (DARPA) has contracted with Space System/Loral (SS/L) for the *Dragonfly Project,* which aims to automatically assemble geostationary communication satellites in-orbit. Raytheon, Lockheed Martin, and Airbus have all researched potential applications of 3D printing technology in the launch vehicle, missile, and satellite design and development, and all have achieved good results.

4. Status quo and problems of aerospace equipment manufacturing in China

Accomplishing research, development, and production tasks in the aerospace field requires both advanced technology and manufacturing capabilities. In recent years, China's technological level of aerospace equipment manufacturing has improved significantly. Numerous breakthroughs in key technologies have been achieved, such as large-scale storage tank manufacturing and assembly of both new-generation launch vehicles and integral welding and milling equipment. The modes of production that products replace the specialization division as the center to establish production unit are commonly implemented. Manufacturing techniques and equipment are being upgraded at an accelerated pace. The informationization platforms such as process management systems, production dispatching systems, and workshop manufacturing execution systems have been widely introduced. There are also some breakthroughs in fields like 3D digital prototype development and design-process synergy and simulation. In a word, China's aerospace equipment manufacturing industry has already started a digital transition.

At present, developed countries have once again recognized the value of the manufacturing industry and are striving for a leading position in a new round of advanced manufacturing competition. The technological level of aerospace equipment manufacturing in China falls behind that of developed countries, and cannot meet the fast development requirements of the aerospace industry.

4.1. Establishing an effective manufacturing mode is required

Aerospace equipment manufacturing in China combines batch production with R&D, and lacks scalability in batch production. Conflicts between R&D and batch production affect batch production capabilities. Meanwhile, the multiple types and small batches of manufactured aerospace products lead to frequent product changes in the manufacturing process. In addition, owing to a lack of in situ detection devices and support systems for rapid product assembly and modification, it is difficult to improve the efficiency of manufacturing units.

The digital technology level of aerospace equipment manufacturing is relatively low; labor-intensive manual manufacturing mode is commonly used. Data between the design, process, and onsite production line are not shared, and thus, the digital models generated in the design phase can rarely be applied in the production phase. Digital manufacturing capabilities, such as process simulation and virtual assembly, are weak.

Design and manufacturing are not well integrated. Process design and product design are not carried out concurrently (a best practice), which results in poor manufacturability of product designs. Because of differences between the system platforms, software, and annotation standards used in the design and production phases, it is difficult to share design models and data throughout the manufacturing process.

4.2. Advanced process methods required

Processes are currently insufficiently emphasized in the aerospace industry. Historically, China's aerospace industry has been R&D oriented, and has valued R&D and design more than production and process. Therefore, there is an urgent requirement for the development of an independent, comprehensive process system to improve aerospace equipment manufacturing capabilities.

Current process levels cannot meet the fast development requirements of space missions. As new technology, facilities, and materials are more widely used in aerospace equipment manufacturing, process methods must be similarly strengthened. However, there have few researches in aerospace processes, without sufficient innovation. It is not uncommon to see decades-old manufacturing process methods still in use.

Existing advanced processing methods are insufficient. Compared to CAD and CAM, the application of CAPP has become the bottleneck in aerospace digital manufacturing, which leads to poor consistency in process specification and poor efficiency. These challenges make it difficult to effectively accumulate, manage, and reuse the advanced knowledge and best practices for processing methods.

4.3. Professional capabilities to be improved urgently

With transition of national aerospace activities from near-earth to deep space exploration, from single task to multi-task, and from short stay to long-term resident, the structural size and complexity of aerospace equipment will increase largely. This will also create a higher demand for the machining and molding of large, complex heterotypic structural components. Breakthroughs are required urgently in the field of assembly and measurement technology of large and heterotypic structure product, in situ manufacture technology of large-diameter launch vehicle tanks, as well as automatic riveting equipment for large shell segments, integral storage tank base spinning equipment, and equipment for precision shaping of large aluminum alloy annular structural components.

The precision manufacturing capabilities of aerospace should be further improved. At present, the precision and ultra-precision manufacturing of inertial components, microelectronics, and optical remote sensors has shifted from macro to micro manufacturing. Components must be precisely manufactured at the submicron or even nanometer level. These precision demands poses significant challenges for precision manufacturing technologies such as precision machining, precision molding, and precision assembling. Although new-generation, high-precision inertial instruments and platforms in China come close to achieving advanced international levels in terms of design and performance, the precision manufacturing technology is still at low level, which impedes improvement in product quality and batch production capability.

There is a gap between manufacturing capability of China's aerospace composite material and that of its advanced counterparts. The consumption of aerospace high-performance composite material is rapidly increasing. Increasingly, many structural components of spacecraft, such as the shells of launch vehicles and missiles, spacecraft components, and satellite antennae, are made of composite materials. China's aerospace manufacturing industry lags behind developed countries in the following: the molding, connecting, and additive manufacturing technologies of new-type light materials such as aluminum-lithium alloys and high-melting titanium alloys; advanced functional composite material technologies such as thermal protection materials, high modulus carbon fiber, and ablation-resistance fiber ceramics; and machining equipment used in automatic molding.

4.4. Flaws within the management mechanism

Investment and support for aerospace equipment manufacturing enterprises is relatively insufficient. Manufacturers have a small voice in the aerospace industry, and are not able to attract sufficient resource inputs and financial support. Fixed asset investment in the national military industry is normally marked for specific project characteristics. Investment in fundamental aerospace manufacturing capabilities, such as forging, casting, welding, and testing, is relatively insufficient. Aerospace manufacturers serve multiple design companies, undertaking R&D projects and batch production simultaneously. Therefore, they commonly face problems of production resource shortages and heavy workload.

Synergy among different aerospace equipment manufacturing companies needs to be further strengthened. At present, aerospace design and manufacturing companies are categorized as different interest demand, which leads to inadequate communication and poor co-operation between the design and production phases of a manufacturing project. Schedule planning between competent organization and unites at all levels, or upstream and downstream companies, is not conducted on a rational basis.

It is very difficult for R&D managers to effectively support and promote aerospace equipment manufacturing capabilities. Because aerospace products must be highly reliable, the aerospace management attitude towards new technologies and process methods has typically been conservative. New technologies and process methods will be applied only if they have been proven successful on other projects. As a result, the adoption of new manufacturing technologies and process methods is relatively slow. The standardization and commercialization of aerospace equipment is low, which makes it difficult to improve aerospace manufacturing efficiency.

5. Suggestions for China aerospace equipment manufacturing capability promotion

As indicated above, China's aerospace manufacturing industry must improve its systematic planning, optimize its manufacturing resource allocation, and solve critical manufacturing bottleneck problems. Improvements in these areas will help to promote Chinese aerospace equipment manufacturing capabilities and realize sustainable development of an independent and autonomous aerospace industry.

5.1. Propel advanced manufacturing mode

(1) Unify and normalize platforms, software, and annotation standards between upstream and downstream companies, so that a comprehensive digital model can be applied

throughout the manufacturing process.

(2) Streamline the model-based aerospace equipment development and manufacturing process, and vigorously promote integrated product development to realize the integration between aerospace equipment design and manufacturing.

(3) Establish a collaborative aerospace engineering environment that allows for aerospace equipment manufacturing digitalization, networking, and integration to be realized.

5.2. Reinforce process methods innovation

(1) Enhance planning for aerospace technology development, improve incentive mechanisms for innovation, and accelerate the engineering adoption of innovative technology.

(2) Implement a CAPP application trial project, strengthen support for workflows, process, methodologies and related software and tools, and give full play to the pivotal role of processes in the aerospace manufacturing system.

5.3. Overcome the bottlenecks

(1) Increase investment in the development of high-end aerospace manufacturing equipment that is difficult to import from abroad.

(2) Address key issues in aerospace manufacturing, such as unavailability of ultra-precision manufacturing equipment for key components, advanced functional composite material manufacturing equipment, large and heterotypic structure manufacturing equipment, automatic flexible docking and fitting equipment, and advanced testing equipment.

5.4. Strengthen talent cultivation for aerospace equipment manufacturing

(1) Learn from the successful talent cultivation experiences of aerospace R&D teams, and strengthen manufacturing leadership by establishing a chief commander system.

(2) Expand professional promotion channels for aerospace manufacturing talent to accelerate high-end talent cultivation for aerospace manufacturing.

(3) Encourage the adoption of integrated product teams, facilitating communication and collaboration between the design and production teams.

5.5. Promote management change

(1) Strengthen the integration of resources and construct an independent and sustainable aerospace equipment manufacturing system under the conditions of civil-military integration and national cooperation, promoting independent control of core and high-end aerospace manufacturing technologies, and introducing competitive civil manufacturing resources to improve efficiency and reduce cost.

(2) Build a strong industrial base by increasing investment in fundamental aerospace manufacturing capabilities like casting, forging, and thermal treatment.

(3) Establish aerospace manufacturing research institutions, which are responsible for generic technologies exploration and related standards setting; implement advanced manufacturing technology strategy management; carry out advanced research on the areas of additive manufacturing, digital manufacturing, and intelligent manufacturing; and provide comprehensive support to meet not only the today's space mission requirements but also the future needs of space capabilities development.

6. Conclusion

Aerospace equipment is the material base of space infrastructure and satellite application industry. Aerospace equipment manufacturing is extremely complex and special. At present, China aerospace advanced manufacturing mode and technologies are witnessing rapid development. Simultaneously, the future space missions and programs bring forward higher request for aerospace equipment manufacturing capabilities. Hence, there are urgent demands for improving aerospace equipment manufacturing capabilities to overcome the bottleneck problems of China aerospace manufacturing. By developing advanced aerospace manufacturing methods, enforcing process innovation, addressing bottlenecks in aerospace manufacturing, strengthening talent cultivation, and creating a favorable management environment, it is expected that China's aerospace equipment manufacturing capabilities will be strengthened comprehensively.

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