Research of Materials and Manufacturing Technology System for On-orbit Manufacturing

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Abstract. On-orbit manufacturing is affected by space microgravity, high vacuum, large temperature variation, strong radiation and other environmental factors, which also puts forward new requirements for materials and process methods suitable for on-orbit manufacturing. This paper summarizes the current research status of different scholars on materials and technologies for on-orbit manufacturing. The main application scenarios and requirements of on-orbit manufacturing are analysed. The technical capability requirements under different application requirements are analysed. Then according to the material source, material use and manufacturability, the material system for in-orbit manufacturing is established. According to different technical requirements, the manufacturing technology system of on-orbit manufacturing is established. From the point of view of materials and technology, the key technical directions that should be broken through in on-orbit manufacturing are put forward. It can provide reference for the subsequent research on materials and process technology of on-orbit manufacturing.

1. Introduction

On-orbit manufacturing is an important technical basis for supporting human long-term on-orbit activities and sustainable exploration of space, and is also a frontier technology field that space powers are competing to explore. Materials and processes are the research basis of on-orbit manufacturing technology. The United States, China and other countries have formulated special plans to carry out relevant technical research. On April 4, 2022, the White House Office of Science and Technology Policy released “the National Strategy for Space Service”, Assembly and Manufacturing, which raised In-space Servicing, Assembly and Manufacturing (ISAM) to a national strategic height. This will be an important strategic fulcrum for the United States to enhance its scientific and technological innovation capacity and strengthen its global competitiveness and leadership [1]. “China’s Space Program: A 2021 Perspective” lists the key development direction in the aerospace field " build the on-orbit service and maintenance system, and form the capability of orbital rescue, fault repair, on-orbit assembly and processing" [2].

In terms of materials and technology of on-orbit manufacturing, European and American countries have carried out a series of tasks: "SpiderFab Project" [3-4], "Architect Project" [5], "OSAM" [6-7], "Space Factory Plan" [8], "ISRU" [9], "NOM4D" [10], and completed the ground environmental test verification of typical structural members such as boom, antenna adapter arm, truss, lunar base dome structure [11-13]. The thermoplastic composite systems such as PEEK, PEI, ABS, ULTEM9085 plastic, carbon fiber reinforced composite, UTEP composite, etc., which are suitable for on-orbit manufacturing have been established [14]. The technological routes of space 3D printing, electron beam fusion deposition rapid prototyping, melt deposition molding, extrusion molding, electron beam welding and other processes have been explored [15-17]. The Chinese Academy of Sciences Chongqing Green Intelligent Technology Research Institute has studied the melting deposition molding technology of engineering plastics and composite materials in microgravity environment, and carried out the forming experiment of metal/ceramic composites on-orbit. Harbin University of Technology, Northwest University of Technology, Xi'an Jiaotong University and other universities have successively carried out research on 3D printing raw materials such as continuous fiber composites and melt deposition molding (FDM) technology [18-20]. Aerospace Science and Technology Group has established a space friction stir welding laboratory, carried out research on space welding technology. However, relevant research is mainly carried out for specific projects. The research on materials and process technology system has not formed a complete on-orbit manufacturing system.

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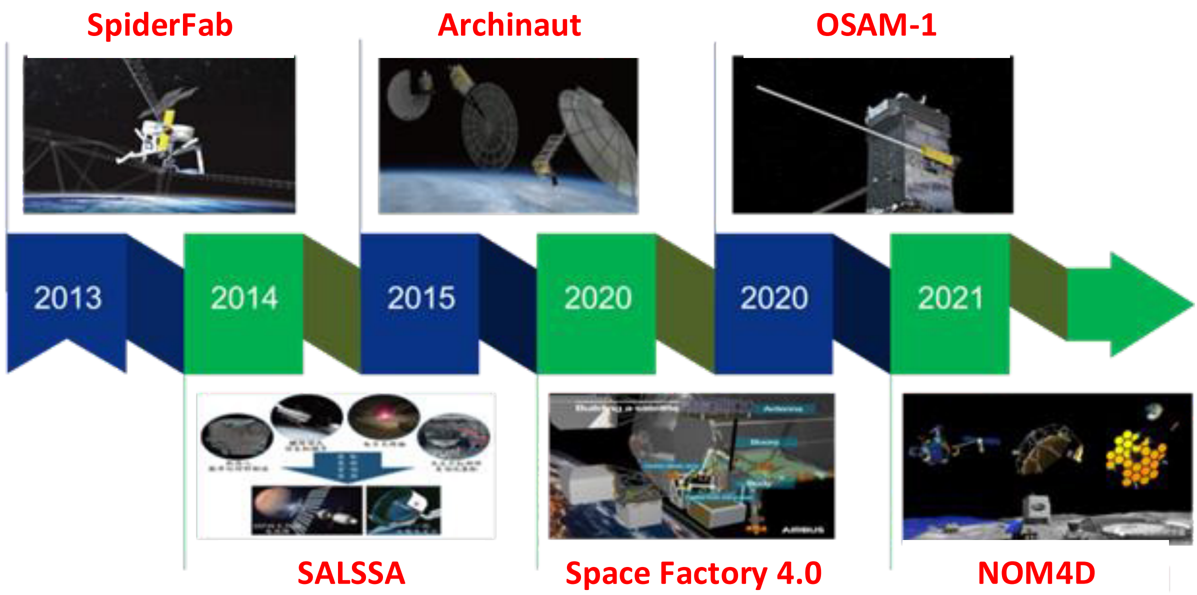

Figure 1. Progress of research projects on on-orbit manufacturing

On-orbit manufacturing is affected by space microgravity, high vacuum, large temperature variation, strong radiation and other environmental factors, which also puts forward new requirements for materials and process methods suitable for on-orbit manufacturing. The space microgravity environment is an important factor affecting the interlayer bonding, structural strength and density of materials. The polymer in the molten state shows the agglomeration mainly based on the surface tension, and its viscosity change and rheological characteristics are very different from those made on the ground.

The vacuum environment has no conduction and convection cooling, which has a great impact on the welding and melting connection technology. Vacuum environment also affects the volatilization of polymers. Solvents, low-molecular additives and volatiles will lead to porosity and performance degradation of composites.

On-orbit manufacturing mainly refers to manufacturing on-orbit or on the surface of other celestial bodies. Launch raw materials and parts from the ground to space, and carry out the manufacturing, assembly, testing, maintenance and repair of spacecraft parts.

This paper mainly analyzes the application requirements, materials and process technology of on-orbit manufacturing, establish the material system and manufacturing technology system for the basic manufacturing technology of on-orbit manufacturing, and promotes the research of basic manufacturing technology of on-orbit manufacturing.

2. Application analysis of on-orbit manufacturing technology

Requirements for on-orbit operation of space station: For the long-term on-orbit operation and maintenance of the space station, there are a large number of system module maintenance, parts replacement, structural defect/damage repair, platform expansion and other requirements. On-orbit manufacturing and maintenance capabilities can effectively support the long-term on-orbit operation and maintenance of the space station and reduce the operating costs of the space station. Take the International Space Station as an example, we need to launch spare parts for equipment maintenance.

According to historical statistics, the weight of the spare parts on-orbit of the International Space Station is 13170kg, and the average weight of the spare parts launched each year is 3190kg, which is used for repair and maintenance. However, the spare parts consumed each year are 450kg, and the spare parts utilization rate is less than 5% [21].

Requirements for on-orbit assembly of large space equipment: Large-scale space structure is one of the important directions of spacecraft development. High-resolution earth observation satellites, space-based radar early warning systems, and large-capacity communication satellites all put forward requirements for large size and large bearing capacity of spacecraft structures.

For example, the space solar power station requires a platform structure of 1000m to achieve the power supply capacity of MW level. Such large spacecraft structures need to be realized through on-orbit manufacturing technology, such as on-orbit manufacturing of large structures, on-orbit printing of connecting joints, large telescope lenses and other typical components.

Requirements for lunar base construction: China will work with international partners to build a long-term operational and comprehensive scientific experimental facility on the moon. Carry out multi-disciplinary and multi-objective scientific research activities such as lunar exploration, moon-based observation, basic scientific experiments and technical verification. The construction of the lunar base also has a large demand for on-orbit manufacturing.

The technological capability of on-orbit manufacturing is the support for the application demand of on-orbit manufacturing. The technological capability of on-orbit manufacturing can be divided into five categories: on-orbit forming capability, on-orbit connection and assembly capability, on-orbit maintenance and repair capability, in-situ material utilization capability and on-orbit detection capability. According to the above application requirements, the requirements for the application capability of on-orbit manufacturing technology are summarized as follows:

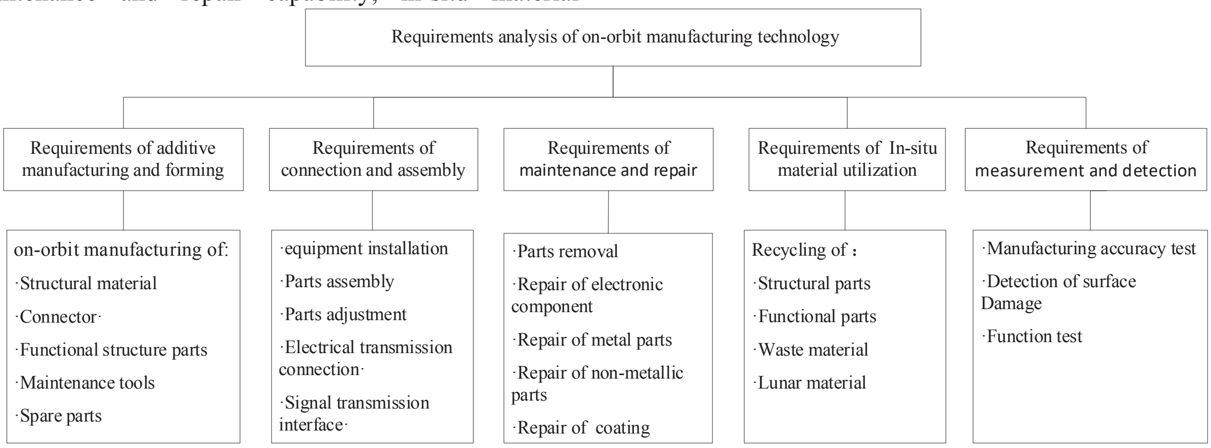

Figure 2. Application requirements of on-orbit manufacturing technology

3 Materials and manufacturing technology system for on-orbit manufacturing

3.1 Material system model

On-orbit manufacturing mainly refers to manufacturing in earth orbit space or other celestial bodies. Firstly, the overall division is made according to the availability, manufacturing cost and feasibility of materials. Then the on-orbit manufacturing materials are divided according to the material sources; Then, the materials are further divided according to their different uses, functional requirements and manufacturability. The formation of the material system for on-orbit manufacturing is shown in Figure 3.

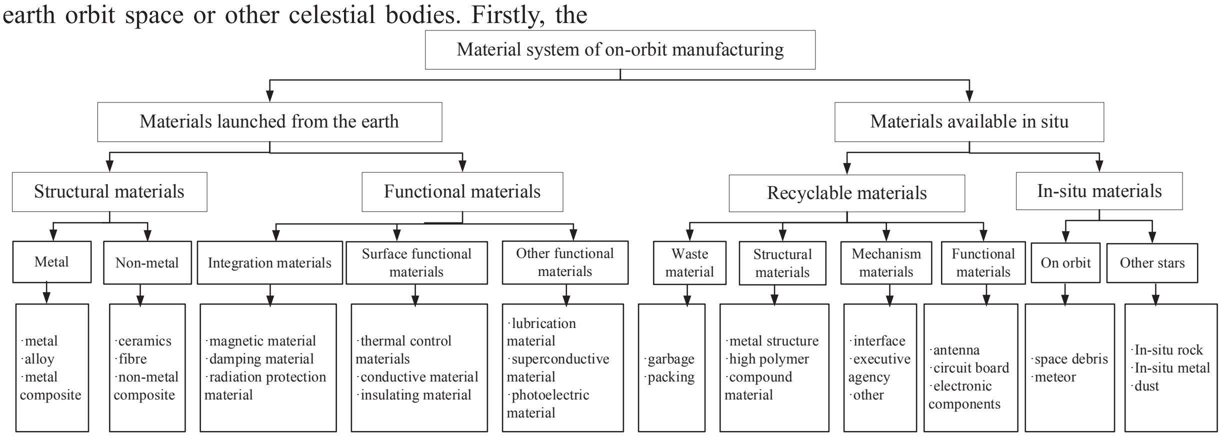

Figure 3. Material system of on-orbit manufacturing

Structural material of on-orbit manufacturing: This field mainly studies the performance maintenance and manufacturability of materials in the space environment. Including manufacturing cost, manufacturing resource demand, manufacturing efficiency and manufacturing performance. The current research focus is on high-performance non-metallic materials and composites, which have the advantages of light structure, high performance and good manufacturability. It is especially suitable for the structural manufacturing of ultra-large spacecraft.

Functional materials of on-orbit manufacturing: It mainly considers the special space environment requirements and structural application requirements (structural conductivity requirements, structural thermal stability requirements, etc.), and focuses on the on-orbit preparation and on-orbit implementation technology research of functional materials.

Recyclable materials of on-orbit manufacturing: Domestic garbage, plastic packaging boxes of the space station and parts of failed satellites are mainly considered. The project focuses on the research of raw material recycle technology and in-situ treatment technology of plastic packaging.

In-situ material of on-orbit manufacturing: In order to make full use of space resources and reduce the dependence on earth materials, research on the extraction and preparation technology of materials such as space asteroids and lunar soil has been carried out.

3.2 Manufacturing technology system

According to the application capability requirements of on-orbit manufacturing, it is divided into five aspects

(Figure 4).

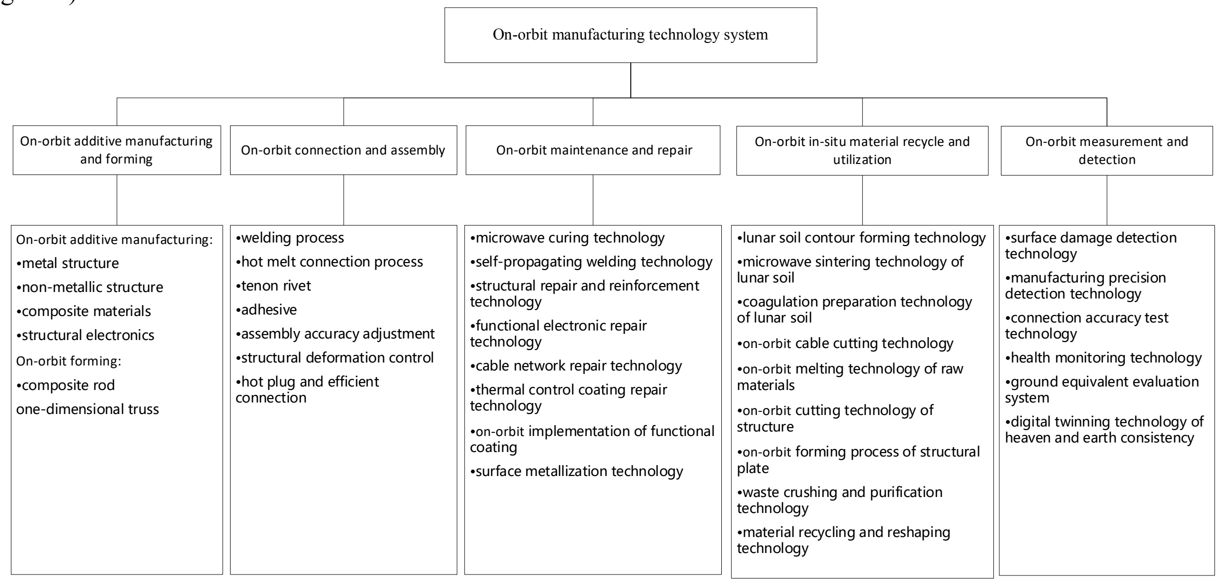

Figure 4. On-orbit manufacturing technology system

3.2.1 On-orbit additive manufacturing and forming

On-orbit additive manufacturing forming are the key to realize on-orbit manufacturing of materials, parts and integral structural parts. It mainly includes:① on-orbit additive, equal and reduced material manufacturing based on earth materials, such as the manufacturing of small structural parts, connection joints, and complex structural parts. ② On-orbit manufacturing of functional components, such as on-orbit printing of electronic components and sensors. ③ Manufacture of maintenance tools and spare parts.

3.2.2 On-orbit connection and assembly

On-orbit connection and assembly technology are the key technology to realize the on-orbit assembly and construction of complex structural parts, mechanism parts and large structural systems. It mainly includes the following aspects: ① On-orbit assembly of standard modules, such as spacecraft structure expansion, replacement of failed parts, equipment upgrading and replacement, etc. ② On-orbit assembly of large spacecraft, such as mechanical interface assembly, on-orbit welding assembly, bonding assembly, etc. On-orbit assembly capability directly affects the efficiency and complexity of on-orbit manufacturing tasks of large spacecraft.

3.2.3 On-orbit maintenance and repair

On-orbit maintenance and repair technology are the necessary technical capability to ensure long-term on-orbit operation of spacecraft, it mainly includes the following aspects: ①Repair of functional coating on structural surface, such as preparation of thermal insulation coating, preparation of multifunctional protective coating on track, repair of coating damage on structural surface, etc. ② Repair of cracks or damage to spacecraft structures, including repair of metal structures and non-metallic structures. ③ Repair of electronic components, including on-orbit repair of electronic components, circuit boards, cables, etc.

3.2.4 On-orbit in-situ material recycle and utilization

In situ material recycle and utilization technology on-orbit is the necessary technical capabilities for the utilization of spacecraft waste materials and the preparation of in-situ materials for extraterrestrial objects.

It mainly includes the following aspects: ① Recycling of structural functional parts, such as cable cutting and structural part cutting; ② Recycling of plastic products such as packaging and coating, such as melting plastic packaging into raw materials on track; ③ On-orbit direct manufacturing based on lunar surface in-situ materials, such as lunar soil contour molding, lunar soil microwave sintering, etc.

In-situ material utilization capability can significantly reduce the cost of on-orbit manufacturing tasks, and increase the flexibility and emergency capability of tasks.

3.2.5 On-orbit measurement and detection

The premise of effective execution of on-orbit manufacturing task is the accurate measurement of space object, including its structure size, motion attitude, centroid position and other necessary parameters. n the complex space environment, especially the change of lighting conditions, it is difficult to identify and measure the shape parameters of the target.

In order to perform on-orbit missions in various environments, accurate measurement technology is the key technical ability to achieve mission success. It mainly includes the following aspects: ① On-track detection and identification of material damage and defect; ② On-track measurement of structure size and shape; ③ On-track test and evaluation of product performance after manufacturing.

4 key technology research

On-orbit manufacturing is the future trend of aerospace technology development, leading the development direction of aerospace technology in military and civil fields. At present, the United States, China and other countries have entered a new space era of large-scale spacecraft construction represented by the space station.

The development of on-orbit manufacturing and service technology in the future can not only solve the problem of spacecraft scale expansion constrained by launch conditions, but also independently complete more tasks without human participation. It can save a lot of human, material and financial resources, and also avoid the danger of astronauts' space operations. Therefore, on-orbit manufacturing is an important technical approach for the manufacturing of large space structures in the future. For on-orbit manufacturing, the following key technologies and development trends are proposed from the perspective of materials and manufacturing.

(1) High-performance composites that can be manufactured on-orbit

The change of temperature and space particle irradiation will cause thermal stress deformation, radiation damage, material embrittlement and property degradation of the composite. Therefore, it is necessary to carry out relevant research on high performance composite for on-orbit manufacturing.

(2) Multi-material 3D printing and deformation control technology in space.

Aiming at the long-term on-orbit operation of the space station and the on-orbit construction of large space facilities, the 3D printing deformation control technology in the space environment is studied. Breakthrough the material system applicable to space 3D printing, the 3D printer applicable to the space station's interior and exterior environment, the in-situ detection of 3D printing components and other key technologies and core equipment. Break through the material system, manufacture space 3D printers, space in-situ testing and other key technologies and core equipment.

(3) Structural connection and repair technology in space environment.

The space environment is complex, and the ground manufacturing technology cannot be directly applied. For the basic structural materials of metal and composite materials, research on the connection and repair manufacturing technology of low energy consumption and high reliability materials in space, such as vacuum electron beam welding, ultrasonic welding or forming, contact hot melt welding, etc, Study the influence mechanism of space environment on different connection manufacturing technologies and the influence rule of interface performance and precision. Solve the problems of low energy consumption, high reliability connection and repair of materials in space environment.

(4) On-orbit assembly and adjustment methods.

Research the technology of on-orbit assembly plan, assembly path planning and rapid assembly. Analysis the influence of space gravity, floating vibration, thermal vibration and other factors on the assembly accuracy of large structural components. The Analysis the influence of space environmental stress on the precision, stiffness, strength and other comprehensive properties of large assembly structures. Optimize the assembly strategy and parameters, and break through the real-time and accurate adjustment technology of large components for different task requirements.

(5) On-orbit detection method under the condition of insufficient space resources.

In view of the limited assembly resources, observation means and control methods under space conditions, the surface damage detection of large structures, high-precision measurement and control technology of multi-target bodies are studied. Break through the key technologies such as high-precision detection of super-large structures under the effects of insufficient space resources environment and complex lighting conditions, insufficient field of view, occlusion and other factors, and solve the accuracy measurement and adjustment problems during the on-orbit manufacturing of space super-large structures.

(6) Equivalence and evaluation method of space-to-earth consistency of on-orbit manufacturing.

In order to carry out the equivalent simulation and quantitative test and evaluation of space on-orbit manufacturing behavior and manufacturing efficiency in the Earth environment. It is necessary to break through the basic problems such as low/microgravity compensation method and environmental coupling effect simulation method during the construction of large structures on-orbit. Build a ground test and verification environment that can evaluate the manufacturing scheme, manufacturing technology and comprehensive performance economically, efficiently and quantitatively. The ground test verification is carried out from the aspects of truss module configuration and storage, module connection interface pretreatment, module assembly manufacturing plan and manufacturing path planning, module assembly connection and position detection.

5 Conclusions

(1) This paper has carried out a systematic analysis of the on-orbit manufacturing tasks, and combed the technical capability requirements in five aspects for different applications: on-orbit forming, on-orbit connection assembly, on-orbit maintenance and repair, on-orbit material utilization and on-orbit measurement.

(2) The material system and manufacturing technology system of on-orbit manufacturing have been initially established, which can lay a foundation for the subsequent research on materials and technology of on-orbit manufacturing.

(3) From the perspective of the whole process of on-orbit manufacturing, such as materials, manufacturing,

connection, assembly, and measurement, the key technologies of on-orbit manufacturing are proposed, and further research can be carried out on this basis to form the technical capability of the whole process of on-orbit manufacturing.

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