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Review

Progress in Lightweight Design Methods for Large-Size Panel Structures in Manned Pressurized Capsules

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Abstract: The pressurized capsule structure provides the pressure environment for astronauts or payloads in space, which is thus considered as the most crucial structural component for manned spacecraft. The manned deep space exploration mission (MDSEM) brings new challenges to the pressurized capsule structure: extremely low structural weight, long service life, reusability and adaptability to the harsh deep space environment. The conventional welded panel pressurized capsule structure (WPPCS) is not able to meet these new requirements. To address the above challenges, this paper comprehensively expounds why the current WPPCS cannot meet the requirements of MDSEMs based on the analysis of the vibration environment and structural characteristics of the pressurized capsule structure. Furthermore, a new type of integrated panel pressurized capsule structure (IPPCS) is proposed, showing the lightweight advantage compared with WPPCS. Finally, the technical details and research results of the strength criterion, design method, material upgrading and structural integrity manufacturing process of the IPPCS are fully introduced. The conclusions drawn in this paper will provide useful and meaningful references for the future development of large-size, lightweight pressurized capsule structures.

Keywords: manned pressurized capsule; pressurized capsule; lightweight design; welded panel; integrated; manned deep space exploration mission

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1. Introduction

With the accumulation of achievements in human manned spaceflight and unmanned lunar exploration, initiating a manned deep space exploration mission starting from manned lunar exploration is an inevitable development direction [1]. Lightweight design is an essential requirement for deep space exploration systems where payload weight determines the scale of exploration. The pressurized capsule structure, due to its advantages of high specific stiffness and high specific strength, is widely used as the primary load-bearing structure in spacecraft. The structural weight proportion is extremely high in this application. Therefore, conducting research on the lightweight design of the pressurized capsule structure is one of the crucial technological challenges and bottleneck problems that need to be addressed in manned deep space exploration missions.

The lightweight technology of structures is not only an interdisciplinary engineering science but also a comprehensive system engineering approach. Achieving a high lightweight level in structures requires consideration of various factors, such as rational design criteria, efficient design and optimization methods, high-performance structural materials and advanced manufacturing processes. To significantly reduce the weight of the pressurized capsule structure, it is necessary and feasible to comprehensively apply the lightweight technology. Pressurized capsule structures have distinct characteristics compared to general spacecraft structures and impose higher requirements in terms of functional performance, mechanical performance, sealing requirements, safety reliability, fatigue life and fracture control. These structures are subject to multiple constraints and exhibit complex mechanical responses. Therefore, conducting lightweight design for pressurized capsule structures under these multiple constraint conditions presents significant challenges. Conducting targeted research on all aspects of pressurized capsule structure design and thoroughly exploring each element to reduce structural weight is an important approach for improving the lightweight level of these structures.

Currently, a widely used structural component for manned pressurized capsule structures in space station missions is the welded panel pressurized capsule structure [2–5]. In comparison to near-Earth spacecraft, manned deep space exploration spacecraft have higher requirements for structural weight, service life, reusability and adaptability to space environments [6,7]. The inherent limitations of WPPCS hinder its direct application in manned deep space exploration missions. Based on current trends in structural design development, it is understood that higher structural integration leads to a lower number of components and structural connectors, thus guiding efforts toward reducing structural weight. Expanding upon the foundation of WPPCS, an IPPCS has gradually become the prevailing structural component for manned deep space exploration compartments, driven by the concept of enhancing structural integration. To comprehensively summarize the development trends of panel pressurized capsule structures, research and analysis will be conducted from two perspectives in this paper: the advancement of pressurized capsule structure technology and the requirements of the MDSEM. This approach will not only capture the patterns of technological upgrades in pressurized capsule structures but also provide valuable insights for forecasting future development trends.

The remainder of this paper is organized as follows. Firstly, the function, type, and flight environment of the pressurized capsule structure are analyzed, the characteristics of the design load conditions are summarized, and the design constraint system of the pressurized capsule structure is constructed. Then, the higher requirements and new demands of the MDSEM for the pressurized capsule structure are analyzed, and the development direction of the pressurized capsule structure technology is defined. Next, it is analyzed that the current WPPCS cannot meet the requirements of the MDSEM, and a new structure of IPPCS is proposed to meet the new requirements. Subsequently, the key technology analysis of the IPPCS is carried out, and four key technologies such as strength criterion, design method, material upgrading, and manufacturing process are identified. The progress of each key technology is investigated and analyzed in detail. These advances show that the technology of the IPPCS has made a comprehensive breakthrough and has the engineering application conditions, which makes a good structural technical reserve for the MDSEM.

2. Overview of Pressurized Capsule Structure

2.1. Pressurized Capsule

The pressurized capsule, also known as a capsule, is a component of a spacecraft that requires a specific internal pressure to meet the needs of astronauts or equipment such as payloads during operation. It is a special section of the spacecraft that must withstand and transmit both the aerodynamic loads generated by the launch rocket and a certain internal pressure load. The pressurized capsule can create a living environment close to the ground atmosphere for astronauts in space. Therefore, the pressurized capsule is an indispensable core module for manned spacecraft.

Manned spacecraft mainly include three types: space station (orbital experiment module) [3], manned spaceship and space shuttle. According to whether the pressurized capsule returns to the ground completely, the pressurized capsule of manned spacecraft can be divided into the returnable type and the non-returnable type. Among them, the pressurized capsule of the space station (orbital experiment module) is the non-returnable type, and the pressurized capsule of the manned spaceship and space shuttle is the returnable type.

There are many famous manned spacecraft pressurized capsules. In China, these include the reentry capsule and orbital capsule of the *Shenzhou* manned spacecraft (as shown in Figure 1a), the experimental module of the *Tiangong*-1 space laboratory (as shown in Figure 1b), and the large column capsule, small column capsule, and node capsule of the *Tianhe* core module (as shown in Figure 1c); other countries' include Russia's *Soyuz* manned spacecraft reentry capsule and orbital capsule (as shown in Figure 1d), the United States' *Apollo* crewed capsule (as shown in Figure 1e) and lunar module, the International Space Station Japanese Experiment Module (JEM) (as shown in Figure 1f), the Columbus experimental module [3] and so on.

Figure 1. The pressurized capsule structures of spacecraft, experimental module and space station.

2.2. Typical Flight Environment

The non-returnable pressurized capsule mainly experiences flight environments such as ground stage, launch stage, space orbit stage and so on. The mechanical loads such as vibration, impact, and acceleration experienced during the launch process and the internal pressure load of capsule in space are the main design load conditions of the non-returnable pressurized capsule structure [8].

In addition to the flight environment of the non-returnable pressurized capsule, the returnable pressurized capsule experiences entry, deceleration and landing (EDL: A set of procedures required for a vehicle in space to safely land on the earth surface) from the space orbit, as shown in Figure 2. The aerodynamic thermal load, deceleration and acceleration load, and landing impact load of the EDL process are the main design loads of the third part of the structural design of the returnable pressurized capsule [8].

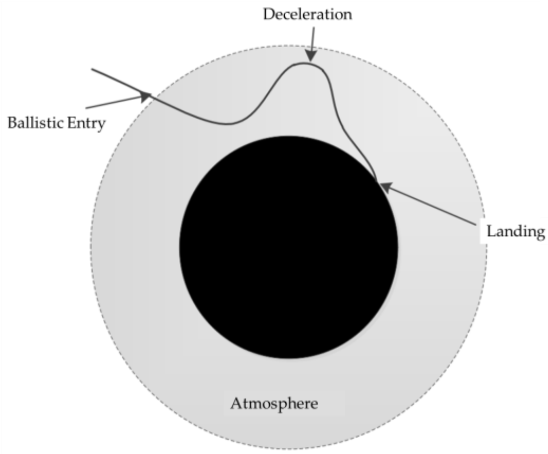


Figure 2. EDL procedures of manned spacecraft (For example: Ballistic Entry) [8].

2.3. Pressurized Capsule Structure

The pressurized capsule structure is the main component of the pressurized capsule, which maintains the sealed state of the pressurized capsule and bears the load of the pressurized capsule. Compared with the general spacecraft structure, the pressurized capsule structure not only has the basic functions of providing configuration, bearing (generally excluding internal pressure load) and equipment installation but also has the most important function of bearing internal pressure load and ensuring the sealing function of the capsule structure. Therefore, the manned pressurized capsule structure is a special pressure vessel.

Generally, the ratio of the wall shell thickness t (generally 1–5 mm) of the manned pressurized capsule structure to the minimum curvature radius R (generally more than 1000 mm) of the middle surface is far less than 1, so it can be regarded as the thin-walled shell structure of the pressure vessel. In the pressure vessel design specification, the stress caused by internal pressure load on the thin-walled shell can be divided into primary stress P (divided into primary overall film stress P_m, primary local film stress P_L), secondary stress Q and peak stress F. Figure 3 is the stress classification of a typical pressure vessel shell under internal pressure. It can be seen that the stress in the spherical region A is composed of the primary overall film stress P_m, the secondary stress Q and the peak stress F. The stress in the shell connection regions B and C with different shapes is composed of the primary overall film stress P_L, the secondary stress Q and the peak stress F. According to the different effects of various stresses on the failure of the pressure vessel structure, the specified allowable stress limit value is calculated and checked according to the corresponding strength theory.

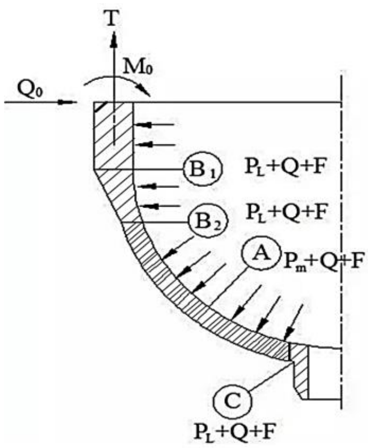


Figure 3. Stress analysis of typical parts of pressure vessel thin-walled shell structure under internal pressure load.

If the pressurized capsule structure is only subjected to internal pressure load, it can be designed as a thin-walled shell like a pressure vessel, that is, a smooth shell structure. In fact, as a part of the spacecraft, the pressurized capsule has to bear the inertial load during the launch phase. Therefore, there are very few pressurized capsules with smooth shell structures in practice. In addition to the internal pressure load, the pressurized capsule structure generally bears various loads such as axial pressure, axial tension, transverse shear force, bending moment and local concentrated force. These external loads produce complex stress on the pressurized capsule structure. On the other hand, the pressurized capsule structure needs to undergo different load conditions in different flight profiles, and the load composition and load history of each load condition are very complex. In summary, the pressurized capsule structure is a special structure that meets the requirements of both the unmanned spacecraft structure and the pressure vessel structure. Its stress state is complex, and it is very difficult to carry out stress analysis and stress classification. Therefore, the lightweight design of the pressurized capsule structure is a huge challenge.

For the pressurized capsules, the internal pressure load is often one of the main loads. In order to withstand internal pressure loads, the outer surface of the pressurized capsule structure is generally designed as spherical, cylindrical, conical and other rotary shapes. According to the different connection forms of the reinforcement parts and the wall shell, the pressurized capsule structure generally adopts the smooth shell structure, the semi-monocoque shell structure (Figure 4a) and the panel structure (as shown in Figure 4b). The reinforcement parts of two kinds of pressurized capsule structure are the partition frame/truss of the semi-monocoque shell structure of Figure 4a and the panel stiffener of the welded panel structure of Figure 4b [2–6,9–13]. Among them, the reinforcement parts and the wall shell of the semi-monocoque shell structure are independent parts, which are connected into a whole by riveting, welding and so on. The Multi-Purpose Logistics Module (MPLM) capsule structure strengthens the reinforcement parts and the wall shell as a whole, and there is no need for riveting, screwing, welding and other connections between the two parts.

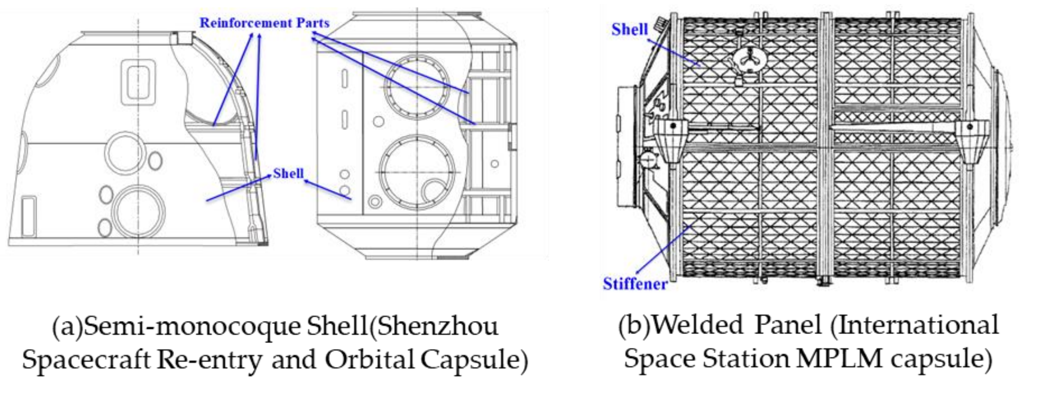


Figure 4. Reinforced component of semi-monocoque shell and panel pressurized capsule structure.

2.4. The Development Course of Pressurized Capsule Structure

The development of the pressurized capsule structure has gone through three stages: monocoque shell structure, semi-monocoque shell structure and the panel structure. The monocoque shell structure has no reinforcement parts, and the overall structure stiffness is low, so it is not suitable to bear large concentrated load and compression load. The semi-monocoque shell structure has longitudinal and transverse reinforcing members, which can withstand large axial and bending loads, and has large stiffness. For example, the Shenzhou spacecraft reentry module (as shown in Figure 5a), the Russian 'Soyuz' spacecraft orbit capsule and the Russian 'Salyut' space station pressurized capsule structure are all semi-monocoque pressurized capsule structures (s-MPCSs).

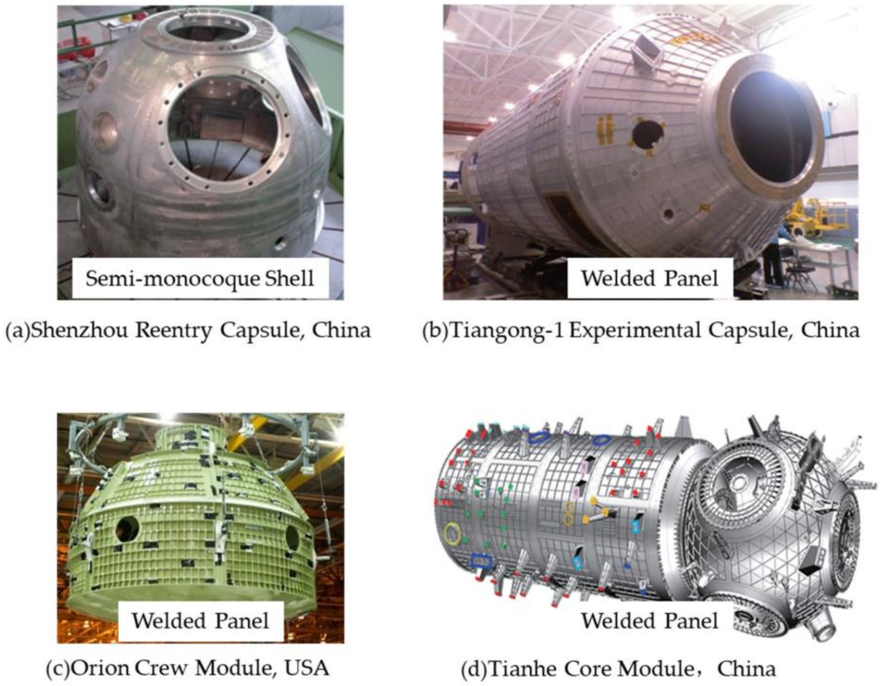


Figure 5. Semi-monocoque shell and panel pressurized capsule structure.

Table 1 summarizes the structure forms of common manned spacecraft pressurized capsules in the world. It can be seen from the table that the panel pressurized capsule structure gradually replaces the s-MPCS and becomes the mainstream form of the pressurized capsules.

Table 1. Summary of manned spacecraft pressurized capsule structures.

Serial Number	Type	Spacecraft	Nation/Institution	Module Name	First Launch Date	Structure Form
1	manned spacecraft	Vostok	Russia	pressurized capsule	April 196	s-MPCS
2	manned spacecraft	Mercury	USA	pressurized capsule	February 1962	s-MPCS
3	manned spacecraft	Voskhod	Russia	pressurized capsule	October 1964	s-MPCS
4	manned spacecraft	Gemini	USA	pressurized capsule	March 1965	s-MPCS
5	manned spacecraft	Soyuz	Russia	reentry capsule orbital capsule	April 1967	s-MPCS
6	manned spacecraft	Shenzhou	China	reentry capsule orbital capsule	November 1999	s-MPCS
7	manned spacecraft	Apollo	USA	command capsule	July 1969	s-MPCS
8	cargo spacecraft	Progress	Russia	cargo pressurized module	January 1978	WPPCS
9	cargo spacecraft	Automatic transfer of aircraft	European Space Agency	cargo pressurized module	March 2008	WPPCS
10	cargo spacecraft	Tianzhou	China	cargo pressurized module	April 2017	WPPCS
11	space laboratory	Salyut	Russia	docking module orbital module	April 1971	WPPCS
12	space laboratory	Skylab	USA	orbital module	May 1973	WPPCS
13	space laboratory	Tiangong-1 space laboratory	China	experiment module	September 2011	WPPCS
14	space station	Mir	Russia	core module	February 1986	WPPCS
15	space station		Russia	Quantum-I/1 module	April 1987	WPPCS
16	space station		Russia	Crystal module	May 1990	WPPCS
17	space station		Russia	Spectrum module	May 1995	WPPCS
18	space station		Russia	Priroda module	April 1996	WPPCS
19	space station	International Space Station	Russia	Zarya cargo module	November 1998	WPPCS
20	space station		USA	Unity node module	December 1998	WPPCS
21	space station		Russia	Zvezda service module	July 2000	WPPCS
22	space station		USA	Destiny experiment module	February 2001	WPPCS
23	space station		USA	Quest airlock module	July 2001	WPPCS
24	space station		Russia	Mooring compartment module	September 2001	WPPCS
25	space station		USA	Harmony node module	October 2007	WPPCS
26	space station		European Space Agency	Columbus experiment module	February 2008	WPPCS
27	space station		Japanese	Japanese experiment module	March 2008	WPPCS

Table 1. *Cont.*

Serial Number	Type	Spacecraft	Nation/Institution	Module Name	First Launch Date	Structure Form
28	space station	China Space Station	China	Tianhe core module	April 2021	WPPCS
29			China	Wentian lab module	July 2022	WPPCS
30			China	Mengtian lab module	October 2022	WPPCS

The panel pressurized capsule structure includes the development of the semi-monocoque shell structure. The integrity of the structural components greatly improves the structural efficiency and reliability, and effectively reduces the structural quality. Compared with the traditional semi-monocoque shell structure relying on riveting and other connection methods, the panel structure has the advantages of less parts, small assembly workload, short process cycle, large overall strength and stiffness, and superior sealing performance and anti-fatigue performance. High reliability and high structural efficiency make the panel structure the best choice for the pressurized capsule structure of long-term service manned spacecraft represented by the space station. Russia and the United States have developed the welded panel pressurized capsule structure on the 'Mir' space station and the International Space Station. China, the United States, Russia and other countries have designed and developed a number of WPPCS, such as the MPLM capsule structure of International Space Station with WPPCS (as shown in Figure 4b), experimental capsule structure of Tiangong-1 with WPPCS (as shown in Figure 5b), Orion manned spacecraft crew capsule structure with WPPCS (as shown in Figure 5c) and pressurized capsule structure of Tianhe core module with WPPCS (as shown in Figure 5d).

3. Structural Requirements of Manned Deep Space Exploration Pressurized Capsule

Manned deep space exploration missions refer to extraterrestrial missions targeting the Moon, asteroids, Mars and its satellites, in which human astronauts are directly involved in the exploration. According to the different target celestial bodies for landing, manned deep space exploration can be divided into missions such as manned lunar exploration, manned Mars exploration and so on. Manned lunar exploration is the starting point and foundation of manned deep space exploration, and is a hot spot of international manned deep space exploration [6,7]. For example, since 2004, the United States has launched the Project Constellation, Artemis and so on to develop spacecraft such as Orion, as shown in Figure 6.

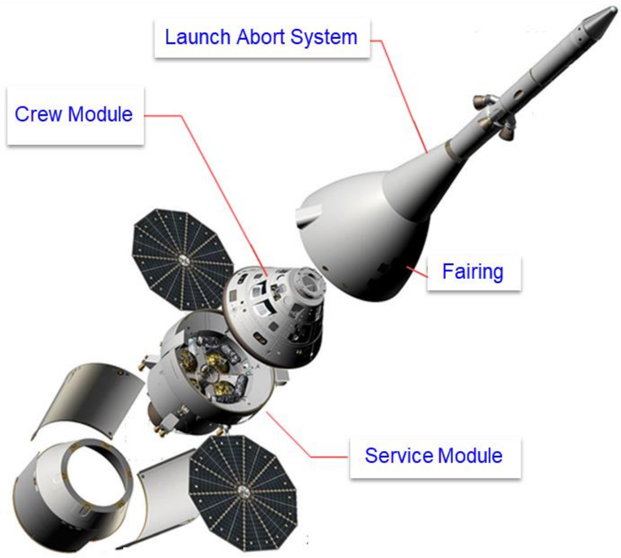


Figure 6. A schematic diagram of the composition of Orion manned spacecraft, USA.

The main structure of manned lunar exploration aircraft, whether manned spacecraft or lunar module, is the pressurized capsule structure, which requires higher requirements [14,15]. These requirements include

(1) Lower structural weight [16]

The launch cost of manned lunar exploration is several times or even dozens of times higher than that of near-earth orbit, which requires lower weight and higher efficiency of spacecraft structures. At present, the structural weight/launch weight ratio of manned spacecraft in China is about 25–35%, which is far from meeting the structural weight requirements of manned lunar exploration missions. Therefore, structural weight reduction requirements are extremely urgent to achieve the goal of reducing this ratio to less than 20%.

(2) Longer structural life requirements

In order to realize the in situ detection and resource development of lunar resources, the working life of manned lunar exploration aircraft in orbit will be longer than 15 years, such as for the lunar orbit residence platform, lunar base, etc. This requires that the pressurized capsule structure have a lifespan of more than 15 years under complex load environments [14].

(3) Reusable function

In order to reduce the mission cost and improve the economy, the manned spacecraft sealing cabins such as the space-to-ground round-trip transportation system and the space-to-moon round-trip transportation system for manned lunar exploration should have reusable functions [6,7].

(4) More complex load conditions [7]

During the reentry of manned spacecraft in deep space exploration, the reentry velocity increases by more than 40% as it enters the Earth, reaching the second cosmic velocity of 11.2 km/s, and the reentry overload condition becomes larger. New emergency rescue systems, such as self-escape, result in the aerodynamic load of the ascending segment acting directly on the spacecraft. Large-scale impact loads during landing, parachute opening and landing/water landing directly affect the pressurized capsule structure. Therefore, the load environment experienced by the pressurized capsule structure is extremely complex [8].

(5) Higher spatial environmental adaptability

The manned spacecraft extends from the near-Earth orbit manned spacecraft and space station to the manned lunar landing spacecraft, the lunar orbit station platform and the lunar base. The pressurized capsule structure of these spacecraft is subjected to complex load conditions and more demanding environmental factors, including high and low temperatures, as well as radiation. Consequently, the pressurized capsule structure needs to possess enhanced environmental adaptability and be capable of providing long-term and reliable service in extreme temperature, radiation, lunar dust and other harsh environments [8].

4. Technical Analysis of MDSEM

4.1. Problems Existing in WPPCS

The panel structure includes the development of the semi-monocoque shell structure. The strengthening components and the shell of the panel do not need to be riveted, screwed, welded or connected by other methods but are manufactured as a whole, semifinished product. Compared with the semi-monocoque shell structure, the panel structure greatly improves the load-bearing efficiency, fatigue resistance and reliability, effectively reduces the structural quality, and has the advantages of less parts, short process cycle, high strength and stiffness [2–4].

Figure 7 is a typical schematic diagram of welded panel parts. The welded panel parts can be divided into stiffener zone and weld zone. The structural feature of the stiffener zone is composed of stiffeners and shells, which are integral. The structural feature of the weld zone is only composed of thickened shells. Obviously, the stiffeners in the stiffener zone cannot extend to the weld seam.

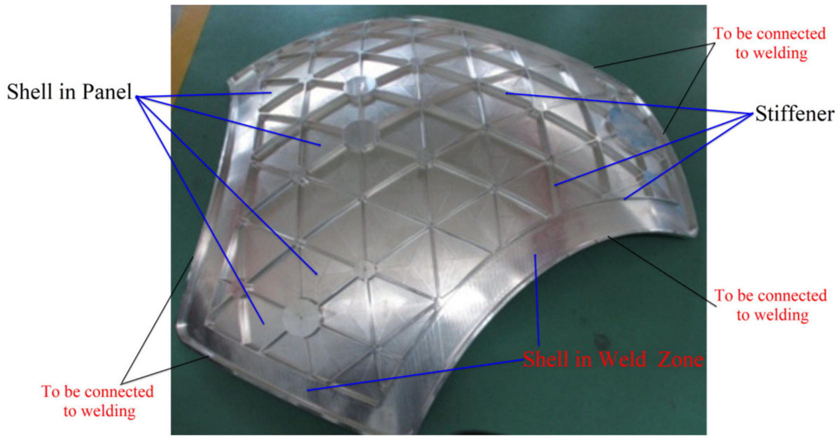


Figure 7. Schema of typical welded panel parts [4].

The WPPCS is a whole structure welded by several frames and several panels on the basis of precise control of the dimension of the welding interface. Figure 8 is a typical WPPCS; the typical local structure in the Figure 8 consists of four parts, which are panel 1, panel 2, panel 4 and frame 3. The four parts are connected into a whole structure by welding. The stiffeners of each panel are discontinuous in the weld zone [2].

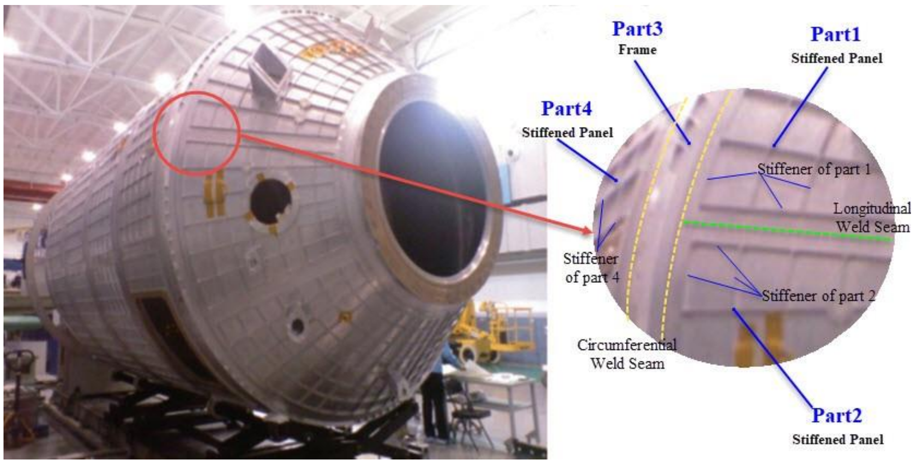


Figure 8. Structure diagram of WPPCS [4].

Obviously, due to the limitations of structural characteristics and process constraints, the WPPCS has no stiffeners at the weld zone, and the discontinuous stiffeners between the panels lead to the non-direct continuity of the force transmission path, which is an insurmountable unreasonable structural design [2,14,16,17]. On the other hand, the weight of the frame of the WPPCS accounts for more than 50% and cannot be significantly reduced. The above two shortcomings make it impossible to further improve the lightweight level of the WPPCS, which hinders the application of the panel structure in the MDSEM.

4.2. The Emergence of IPPCS

With the increasing maturity of the overall manufacturing process technology such as spinning of large-size parts, the IPPCS becomes possible. The integrated panel pressurized capsule is an integral part without connections (such as welding on the welded panel pressurized capsule, etc.), and the panel features are directly processed on the whole semifinished products with the final capsule shape. Since the design domain does not have the segmentation of the weld zone, the design space of the panel is extended to the global capsule, and a better design can be obtained through structural optimization [17–22]. The IPPCS not only realizes the global stiffeners' continuity of the capsule, but also the weight is reduced by replacing the frame with a local panel structure (as shown in Figure 9), which overcomes the shortcomings of the WPPCS and significantly improves the lightweight level of the pressurized capsule structure.

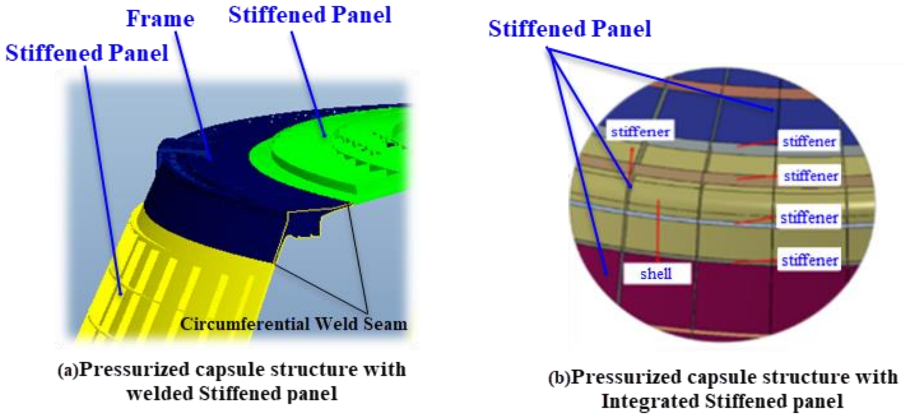


Figure 9. Structural comparison of shape transition zone between WPPCS and IPPCS.

Compared to the WPPCS, the IPPCS eliminates welding influences, further reducing structural defects and weak points. It allows for a wider range of structural materials and significantly enhances the reliability of the pressurized capsule structure, improving its level of lightweight design [23]. Therefore, the integrated panel pressurized capsule represents a new development direction for panel-based sealed compartments.

5. Research Progress on Key Technologies of IPPCS

The lightweight level of spacecraft structure depends on structural design criteria, structural design and optimization methods, structural material properties and manufacturing process capabilities. The key technologies that need to be broken through to realize the lightweight of the IPPCS include

(1) The strength criterion of the pressurized capsule structure based on shakedown: the shakedown limit of the structure is taken as the ultimate bearing capacity of the internal pressure load of the pressurized capsule structure, which improves the bearing capacity of the structure (the post-yield performance of the material is applied) and the safety of the bearing capacity of the structure whose local material is in the plastic stage.
(2) The design method of the IPPCS: a design process and optimization method for the IPPCS is proposed, which can guide the design of both local and overall structures.
(3) Upgrading of pressurized capsule structure material: through the application research, the promotion of material upgrades for the pressurized capsule structure to materials such as 5B70 aluminum alloy.
(4) The overall manufacturing process of pressurized capsule structure: master the spinning process of large-size parts and lay the foundation for the overall manufacturing of the pressurized capsule.

5.1. The Strength Criterion of the Pressurized Capsule Structure Based on Shakedown

5.1.1. Problems of Conventional Strength Criterion

The pressurized capsule configuration is generally composed of a cylinder, a cone and a sphere. Under the action of internal pressure load, the local area of the shape change (shape transition zone) will produce a large stress concentration, as shown in Figure 10. When the internal pressure load reaches a critical value, the stress of these stress concentration areas will quickly approach the yield limit strength of the material. Completely eliminating these stress concentration areas through structural strengthening will cost a lot of weight, which is not conducive to reducing the weight of the structure [23,24].

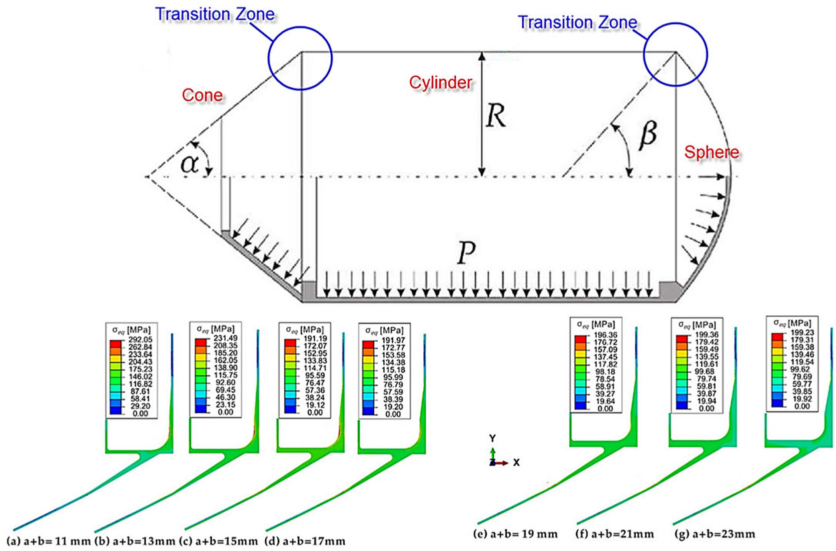


Figure 10. Local stress concentration in transition zone under internal pressure load [24].

In practice, such as the internal pressure overload test of the pressurized capsule, it is found that the pressurized capsule structure can still bear stable internal pressure load after local plastic deformation, but it is not known what is the limit of stable internal pressure load after plastic deformation of the pressurized capsule structure, and it is also not known whether the stable load is safe and reliable.

5.1.2. Application of Shakedown Theory on Pressurized Capsule Structure

In structural shakedown, the ideal elastic-plastic structure produces a favorable residual stress field after a certain amount of plastic deformation under cyclic loading, which improves the elastic limit load of the structure. Moreover, the accumulated plastic deformation is stable, which does not affect its initial design function and the failure mode.

From the definition, it can be seen that shakedown theory can analyze and evaluate the ultimate load that a structure with plastic deformation can withstand. Therefore, based on the shakedown theory, conducting structural shakedown analysis can evaluate the feasibility and load-bearing safety of the pressurized capsule structure allowing local plastic deformation [23–29,29–36].

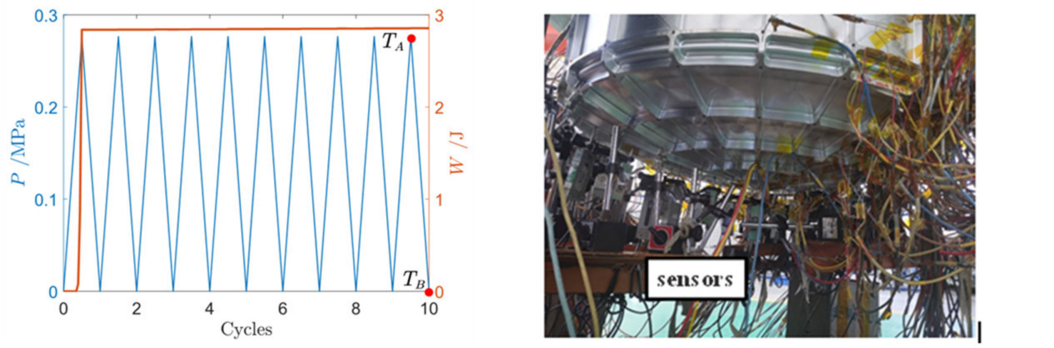
(1) Shakedown analysis of pressurized capsule structure [23–29,29–36]

The finite element solid model of the large pressurized capsule structure is large in scale, and the shakedown analysis is difficult to be carried out directly in the solid model because the number of independent variables and constraints is above one million levels and the solution time is long and the calculation amount is huge. Since the structure of the pressurized capsule and the load are symmetrical, the axisymmetric model can be used for the shakedown analysis. Compared with the solid model, the axisymmetric model is smaller, the solution time is shorter, and it is more convenient to combine with the parametric modeling method. By comparing the analysis results of the shakedown analysis of the pressurized capsule with the solid model and the axisymmetric model, it is shown that the three-dimensional solid model and the two-dimensional axisymmetric model have similar characteristics in the shakedown numerical analysis, and it is reasonable to transform the solid model into the axisymmetric model. The shakedown analysis model is reduced to a two-dimensional axisymmetric model, which reduces the operation scale and calculation amount, and lays the foundation for the design and optimization of the pressurized capsule structure through shakedown analysis.

Through the shakedown analysis, the shakedown load of the pressurized capsule structure is calculated (under this load, the structure is in a shakedown state, and the local stress is higher than the yield strength of the material). The maximum shakedown load is the elastic shakedown limit of the pressurized capsule structure. The elastic shakedown limit of the pressurized capsule structure is greater than the elastic limit load (the structure is globally in elastic deformation, and the maximum stress is equal to the yield strength of the material).

(2) Experimental verification of shakedown limit analysis of pressurized capsule structure

In order to verify the validity of the shakedown numerical analysis method and whether the shakedown limit exists, it is necessary to carry out experimental verification research. To study the shakedown behavior of the structure by experiment, the key is to investigate if residual strain and displacement at all critical locations identified by simulation would stop developing after several load cycles. The design ultimate limit load for the internal pressure is 0.15 MPa, while the calculated stable ultimate limit load is 0.2765 MPa. Therefore, experimental testing will be conducted at the calculated load of 0.2765 MPa. In the study of [36], the research object was a pressurized capsule of reduced size. Firstly, the plastic dissipation of the structure gradually converged after 10 times of shakedown limit cyclic loading through the shakedown analysis (as shown in Figure 11a). Secondly, the strain and displacement changes at locations of interest were observed by cyclic internal pressure loading experiments (as shown in Figure 11b). Finally, the numerical analysis was compared with the experimental results. The experimental results show that the structure has attained a shakedown state from the time profile of displacement and strains measured in critical regions.



(a) (b)

Figure 11. (**a**) Evolution of the plastic dissipation and (**b**) experimental testing of the shakedown behavior.

5.2. Research on the Design Method of IPPCS

Since the design space of the IPPCS is the global space of the capsule, the structural optimization method plays a more significant role in the design. However, due to the high coupling degree of structural characteristics of the IPPCS, it is not easy or even impossible to carry out global optimization directly for all structural parameters. In order to reduce the difficulty of optimization, following the principle of bottom-up, according to the type of key structural features, the IPPCS design procedure is deconstructed into four steps of shell cross-section, basic stiffener configuration, transition zone stiffener configuration and local structure, and optimized design is carried out at each step.

Based on the above ideas, the design process of the IPPCS is proposed, as shown in Figure 12.

(1) Design of shell cross-section [19,21]

Based on the outline shape of the pressurized capsule, the two-dimensional axisymmetric shape cross-section is taken firstly. Then, the preliminary design of the shell cross-section is carried out. Finally, the section parameters optimization under internal pressure load is carried out, and the shell cross-section of the pressurized capsule structure is determined.

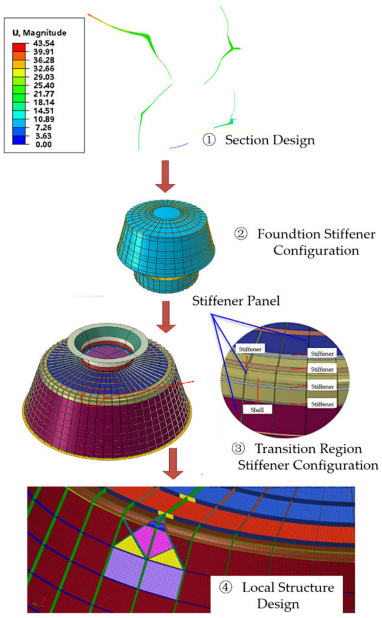


Figure 12. The optimization design process of the IPPCS.

(2) Design of basic stiffener configuration of pressurized capsule [17,18,21,22,37–40]

According to the two-dimensional results obtained in the previous step, a three-dimensional finite element model of the pressurized capsule shell structure is established. On this basis, the optimization design of the basic configuration is carried out, and the design scheme of the stiffened configuration is optimized. However, the pressurized capsule structure has the characteristics of non-straight generatrix and variable curvature section, which leads to the difficulty of parametric modeling of stiffeners. At the same time, there are too many stiffener parameters in the pressurized capsule, and the single analysis takes a long time, resulting in insufficient efficiency of structural optimization design. Aiming at the difficulty of parametric modeling, Tian et al. [38] proposed a data-driven complex surface modeling method. By training the mapping relationship between the simple plane and the complex surface solid domain, the simple plane stiffened shell mesh is mapped to generate a complex curved stiffened shell. Compared with the traditional modeling method, the modeling accuracy and efficiency are greatly improved. On this basis, Li et al. [18] combined the Nonuniform Rational B-Splines (NURBS) method to establish a variable thickness integral stiffened shell modeling method, which can consider the variable thickness modeling and optimization of ribs and skins, and fully tap the potential of lightweight structure. Compared with the traditional curve design, NURBS [39,41] is the best representative form for the curve and surface. Since the forming curve is smooth and the curvature can be kept continuous after local modification, the NURBS curve can fit a variety of complex shapes. The method is verified by the example of the pressurized capsule in the project. Aiming at the problem of insufficient optimization ability of the pressurized capsule structure, an analysis method based on Bloch wave acceleration is proposed [42]. This method performs buckling analysis on a part of the rotating body structure and simulates the overall buckling analysis results of the structure by setting boundary conditions. Compared with the overall structure's analysis, the analysis efficiency is greatly improved. At the same time, many data-driven methods have been proposed to apply to structural optimization design so as to improve its optimization ability and efficiency. Among them, Li et al. [40] optimized the parameters of the pressurized capsule structure based on the multi-objective Covariance Matrix Adaptation Evolution Strategy (CMA-ES) method. CMA-ES [43] is a stochastic-derivative-free numerical optimization algorithm for complex (non-convex, pathological, multimodal, rugged, noisy) optimization problems in continuous search spaces, and is considered to be one of the most successful continuous black-box optimization algorithms. Compared with the traditional method, the optimization ability is stronger.

(3) Design of transition zone stiffener configuration [18]

Based on the stiffener configuration of the pressurized capsule structure, the stiffened configuration of the transition zone is considered as a separate design, in which the lightweight optimization is carried out with the goal of the strength and stiffness under axial tensile or compressive load. Then, the stiffened configuration of the transition zone is determined.

(4) Design of local structure [37,44]

Aiming at the local structure's design, such as local concentrated load diffusion and opening flange of the pressurized capsule, the local structure's optimization is carried out, and the local structure's design for the pressurized capsule structure is determined.

For the local opening flange problem, the traditional method usually first carries out the global reinforcement optimization, and then optimizes the local opening position on the basis of the global reinforcement optimization. In order to meet the mechanical performance of the structure, the structure is often seriously overweight. Therefore, in order to solve this problem, local structural design problems are combined with overall design, and collaborative optimization is carried out. Collaborative optimization design has lighter weight and better mechanical performance.

5.3. Material Upgrading of the Pressurized Capsule Structure

5.3.1. Application Analysis of Al-Mg-Sc Alloy in Pressurized Capsule Structure

Figure 13 shows the optional aluminum alloy materials for the pressurized capsule structure in China. The 2219 aluminum alloy is a heat-treatment strengthening material. The size of the pressurized capsule structure is huge, and the heat treatment of the whole capsule cannot be carried out in China, which greatly reduces the allowable performance of structural materials. The 2195 aluminum alloy in China is not stable, and the supply specifications are limited. Therefore, it cannot be applied to the pressurized capsule structure at present. 5A06 aluminum alloy is the most mature weldable and corrosion-resistant aluminum alloy material used in China's pressurized capsule structure. Compared with 5A06 aluminum alloy, the yield strength and tensile strength of 5B70 aluminum alloy are increased by more than 70% and 20%, respectively, and the specific yield strength is significantly improved [45]. By comprehensive comparison, the performance characteristics of 5B70 are medium strength, weldable and corrosion-resistant. The comprehensive performance of 5B70 is excellent, which meets the material selection requirements of the pressurized cabin structure, and has great potential to replace 5A06 in the pressurized capsule structure.

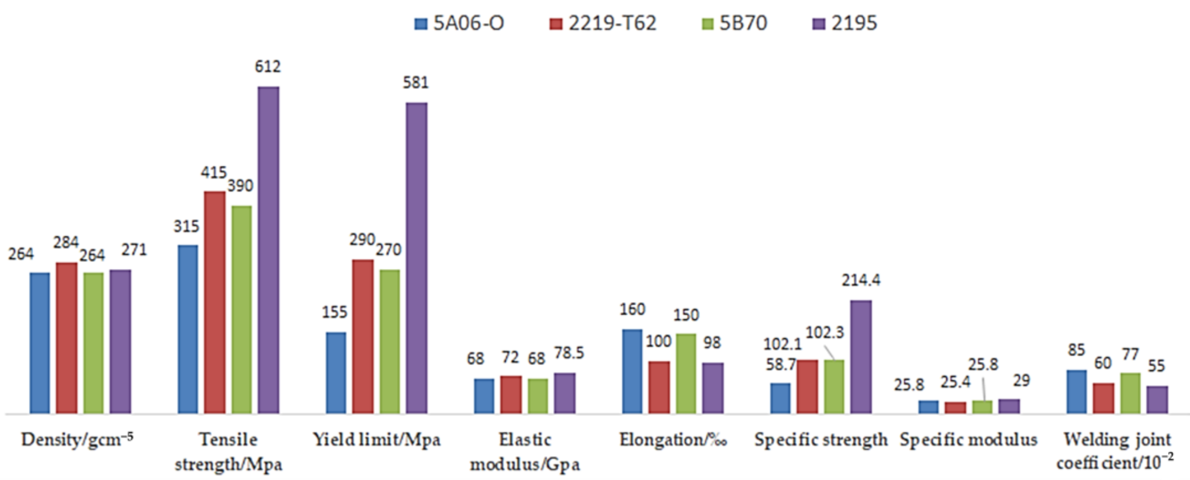


Figure 13. Typical aluminum alloy performance parameters for pressurized capsule structures [45].

5.3.2. Analysis of Application Potential of Al-Mg-Sc Alloy in Deep Space Exploration Pressurized Capsule Structure

The application potential analysis of 5B70 was carried out to meet the requirements of fatigue characteristics, fracture characteristics and large-scale material preparation of the pressurized capsule structure in deep space exploration.

(1) Fatigue limit

The change of fatigue characteristics was studied by comparing the high-cycle fatigue tests of 5B70 and 5A06. The high-cycle fatigue tests of the two materials were conducted under the same conditions, with both materials in the H32 state with a thickness of 6 mm. The test conditions were set at Kt = 1 and R = 0.1. Under a given life of N = 10^7 cycles, the median fatigue strength of 5B70 is σ_{50} = 272 MPa, while the median fatigue strength of 5A06 is σ_{50} = 160 MPa, as shown in Figure 14. The test data indicate that the fatigue limit of 5B70 has been significantly improved.

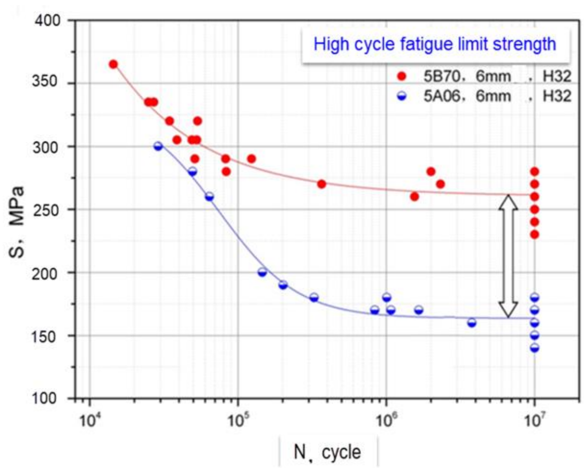


Figure 14. High cycle fatigue properties of 5B70 and 5A06.

(2) Fracture toughness

The difference in fracture characteristics between 5B70 and 5A06 was studied through a comparison of fracture toughness tests. Both materials, 5B70 and 5A06, were in the H32 state with a thickness of 5mm. The specimen orientations included along the L direction (rolling direction) and along the T direction (perpendicular to the rolling direction). The fracture toughness test results for both L and T directions are presented in Table 2. In both directions, the fracture toughness of 5B70 was found to be superior to that of 5A06, indicating that 5B70 material has better fracture resistance.

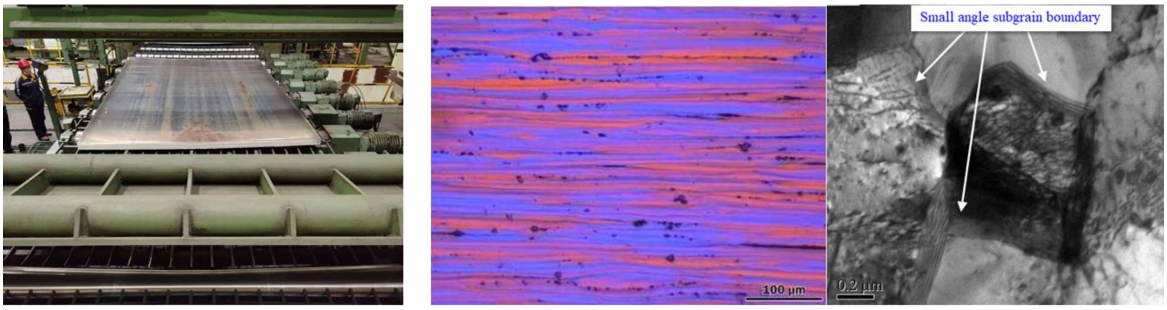
Table 2. Fracture toughness of 5A06 and 5B70.

Preset Crack Orientation	5A06 KR(MPa·$m^{1/2}$)	5B70KR(MPa·$m^{1/2}$)
Direction L	105.6	115.018
Direction T	110.2	120.237

(3) Large size and ultra-large thickness plate supply

With breakthroughs in key technological processes such as the stabilized control technology for ultra-thick plates, China has acquired the capability to mass-produce large-size, ultra-thick plates of 5B70 with widths exceeding 3500 mm and thicknesses exceeding 50 mm. As the engineering application of 5B70 material is being promoted, the usage of 5B70 material is gradually increasing and surpassing the minimum supply threshold. The increased usage beyond the threshold helps to ensure continuous production and stable quality of the raw materials and can significantly reduce the raw material prices.

It can be seen from the microstructure picture of the sampling of the plate after rolling in Figure 15 that the deformation band structure is evenly distributed along the rolling direction. In the deformed matrix, a large number of dislocations are entangled at the grain boundaries and within the grains to form a large number of dislocation wall interfaces. The dislocation wall within the grains divides the grains into smaller dislocation cell blocks, and the dislocations are rearranged around the cell blocks to form a large number of small-angle subgrain boundaries. This indicates that the deformation matrix of 5B70 mainly undergoes dynamic recovery during the whole rolling process, and no dynamic recrystallization and grain growth occur. The rolling process does not adversely affect the material properties.



(a)Ultra-thickness plate (b)The microstructure of 5B70 ultra-thick plate after rolling

Figure 15. Large-size ultra-thickness plate.

5.4. Research Progress on Manufacturing Technology of Pressurized Capsule Structure

5.4.1. Analysis of the Spinning Process

Spinning forming is an advanced plastic forming process with less or no cutting (process principle is shown in Figure 16). This process has been widely used in aerospace and aviation fields because of its advantages of good metal deformation conditions, high material utilization rate and improving product performance [46,47].

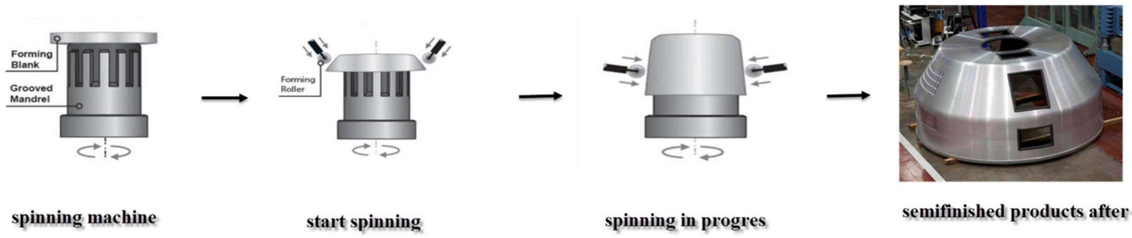


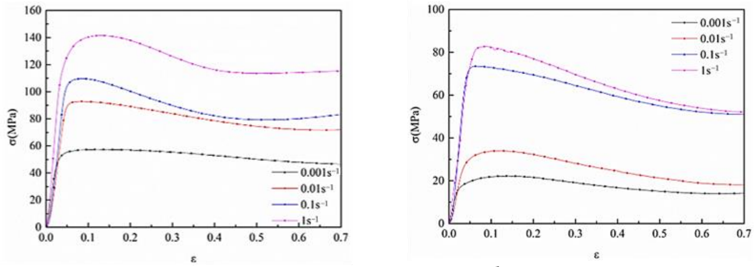
Figure 16. Spinning process schematic diagram [46,47].

The majority of large-sized spin-formed components are thin-walled parts with thicknesses ranging from 10 mm to 20 mm. The contour dimensions are predominantly in the range of 1000 mm to 2000 mm in diameter. However, there is a lack of literature discussing the spin forming of large-sized (diameter exceeding 3000 mm) and ultra-thick (thickness greater than 50 mm) aluminum alloy components.

5.4.2. Research on Spinning Process of 5B70

The deformation property of 5B70 under high temperature is the basis of the spinning forming process. The key to achieving the spinning manufacturing of large-sized (diameter over 3000 mm) and ultra-thick (thickness over 50 mm) 5B70 aluminum alloy sheets lies in understanding and obtaining the high-temperature deformation properties of 5B70 aluminum alloy.

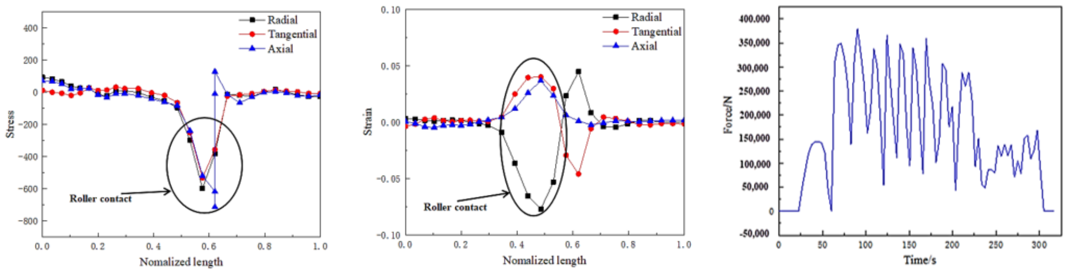
The high temperature deformation properties of 5B70 under different strain states were studied by forming experiments. The basic mechanical properties and thermal deformation evaluation indexes at different temperatures were obtained, including strain rate sensitivity, temperature sensitivity, elongation and other material performance parameters. The influencing factors and influencing rules of deformation properties were revealed, which provided support for obtaining the optimal process parameters of high temperature deformation [47]. Figure 17 is the stress–strain curve of 5B70 at different strain rates at different temperatures. From the figure, the strength of the material decreases with the increase of temperature and increases with the increase of strain rate.



(a)Temperature T1 (b)Temperature T2

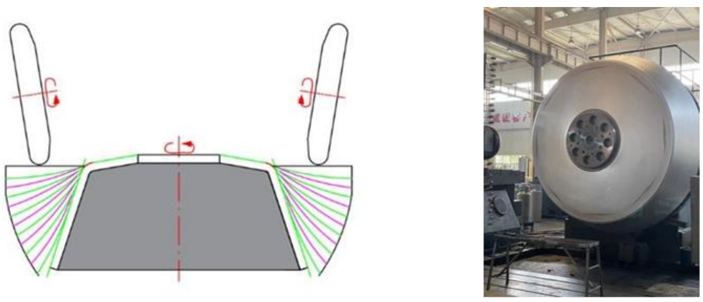
Figure 17. The stress–strain curves corresponding to different strain rates of 5B70 at different temperatures (T1 = 300 °C, T2 = 390 °C) [47].

After fully obtaining the high temperature thermal deformation law of 5B70, the process simulation of the spinning process was carried out. Through the strain analysis, stress analysis, roller force analysis, wall thickness analysis and defect analysis of the spinning process, the whole field strain distribution, stress distribution, force value of roller force, wall thickness and defect-sensitive parts (as shown in Figure 18) of the spinning process were mastered, which provided the basis for optimizing and determining the spinning times and process parameters. According to the law of spinning process simulation, the spinning process parameters of 5B70 structural parts with 70 mm thickness and large size were formulated, and 5B70 spinning parts with 70 mm thickness and Φ3500 mm diameter were successfully prepared (as shown in Figure 19).



(a)Strain distribution curve in bus direction (b)Stress distribution curve in bus direction (c)Pressure distribution curve of Roller

Figure 18. Spinning process simulation results [47].



(a) Spinning trajectory (b)Spinning structural parts

Figure 19. Φ3500mm with 70 mm thickness 5B70 spinning structural parts.

6. Concluding Remarks

The lightweight technology of the pressurized capsule structure is a critical technology and bottleneck in the MDSEM. In this study, research was conducted from two perspectives: the development of pressurized capsule structure technology and the demand-driven traction of the MDSEM. The analysis led to the following conclusions:

(1) As an essential section of the manned spacecraft, the pressurized capsule structure is the key to realize the functions of bearing and sealing. With the stiffer requirements of the life and reliability of the pressurized capsule structure, the panel pressurized capsule structure represented by the WPPCS instead of the semi-monocoque shell type is the current mainstream pressurized capsule structure.

(2) The MDSEM requires the pressurized capsule structure to have extremely low structural weight, long space service life of more than 15 years, reusability and adaptability to the harsh deep space environment. The conventional WPPCS has inherent shortcomings such as low bearing efficiency, large structural weight and conservative strength criterion, which makes it unable to be widely used in MDSEMs. As a method to meet the new requirements, the new structure of the IPPCS replaces the frame by the local panel structure, eliminates the segmentation of the weld zone, realizes the global stiffener continuity of the capsule, overcomes the shortcomings of the WPPCS and significantly improves the lightweight level of the pressurized capsule structure.

(3) The key technology research progress of the IPPCS is rapid and has the engineering application conditions. The technical progress is organized as follows: Firstly, through the internal pressure cyclic loading experiment, the validity of the numerical analysis technology of the internal pressure shakedown limit of the pressurized capsule structure is verified. The bearing safety of the pressurized capsule structure with local plastic deformation can be evaluated by the shakedown analysis. A strength criterion of the pressurized capsule structure is added, that is, the allowable stress level of the local area of the pressurized capsule structure in the shakedown state should be higher than the yield strength of the material. Secondly, the IPPCS design method is proposed including four steps of shell cross-section, basic stiffener configuration, transition zone stiffener configuration and local structure, which guides the full realization of the optimization-based structural design in engineering applications and provides a tool guarantee for the structural design of the IPPCS. Thirdly, the 5B70 has excellent comprehensive performance, with the advantages of medium strength, weldability and corrosion resistance. It also meets the material selection requirements of the pressurized capsule structure, and can be widely used in the pressurized capsule structure instead of 5A06. Fourthly, the spinning process of large-size ultra-thick plates can realize the structural integrity manufacturing of the pressurized capsule structure, which provides a process guarantee for the development of the IPPCS.

The progress of the IPPCS technology has initially reserved the structural technology for MDSEMs. In view of the long-term service requirements of the pressurized capsule structure in the harsh deep space environment in the future, it is recommended to further strengthen basic research as follows:

(1) The quantitative prediction method of internal pressure shakedown limit load of the pressurized capsule structure will be studied: The calculation time of numerical methods for the shakedown limit load is long, and sometimes it does not meet the need of rapid evaluation of bearing capacity. The establishment of approximate prediction formulas can quickly calculate the shakedown limit prediction load.

(2) The structural technology of lightweight pressurized capsule structures with large temperature gaps will be studied: Extreme high and low temperature alternation is one of the challenges of MDSEMs. Providing suitable temperature conditions for the pressurized capsule structure through an independent thermal control subsystem is not conducive to reducing the weight of the spaceflight. The structural technology of

the pressurized capsule adapted to the boundary of large temperature differences is the key to optimize the system scheme and cancel the thermal control subsystem.

(3) The reuse design and verification technology of the IPPCS will be studied: Reuse can reduce the service cost of the high pressurized capsule structure. How to carry out the reuse design and verification of the pressurized capsule structure is the key technology that needs to be overcome in the future.

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