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Manufacture and Analysis of Large Size I-shaped Composite Enclosed Beam

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Abstract. This paper analyzes the structural characteristics of the large-size I-shaped composite material closed beam, and explores the molding process plan, molding die design, curing stress-deformation prediction analysis, internal quality control, and product dimensional accuracy control. The results show that the use of the rigid mold positioning of the shape and the combination of soft mold and hard mold on the outer surface of the wing plate can improve the internal molding quality of the part. Thermal-chemical simulation calculation and curing stress-deformation prediction analysis can accurately predict product curing. For the deformed state in the process, a special process layer is designed for specific parts of the product, which solves the problem of deformation of the closed part after curing. The developed and formed multi-piece products have good internal molding quality, the shape and position and dimension accuracy of the products are controlled within the allowable range, and the mechanical properties of the furnace test pieces meet the design requirements.

Keywords: large size, I-shaped, composite enclosed beam, manufacturing technology

1. Introduction

The reinforcement beams of the existing spacecraft are mostly made of metal materials such as aluminum alloy or magnesium alloy. There are problems such as low yield of the casting process, long development cycle, and heavy product weight, which seriously restrict the spacecraft's demand for the development cycle [1-3]. Composite materials have many characteristics such as light weight, high strength, high modulus, good toughness, good designability and good manufacturability, and are especially suitable for the manufacture of high-precision, large-size and complex structural parts [4-7]. Therefore, with the development of space technology in recent years, composite materials can meet the requirements of lightweight and configuration design optimization of spacecraft structures, and are expected to replace traditional metal components, which has become an inevitable trend of new materials for spacecraft.

European and American countries have rapidly promoted the technology of applying composite materials to large-scale and complex structural parts in space vehicles. At the same time, the demand for composite materials for load-bearing structural parts such as a new generation of military fighter jets, transport aircraft, helicopters, high-speed aircraft and unmanned aerial vehicles has increased sharply, gradually showing the development from small simple and secondary load-bearing structures to large-scale complex primary load-bearing structures. The development trend of the demand from the carrier to the functional material [8,9]. For example, the amount of composite materials in the wing panels, vertical tail, fuselage skin, rudder, engine suspension joints and other parts of the F-22 and V-22 fighters in service in the United States has reached 30%-40%. UAVs such as Eagle and Predator all use composite materials for wings and tails. Boeing and Airbus, two major commercial aircraft development giants, have successively launched main passenger aircraft models with composite materials accounting for 50% of the structure [10-13] . The amount of composite materials in the J-20 military fighter aircraft developed by my country is about 27%, and the amount of composite materials in a single aircraft of the C919 large-scale civilian aircraft exceeds 16 tons [2-4]. The application of composite materials has achieved good returns in spacecraft, and the large-scale complex structural parts developed using composite

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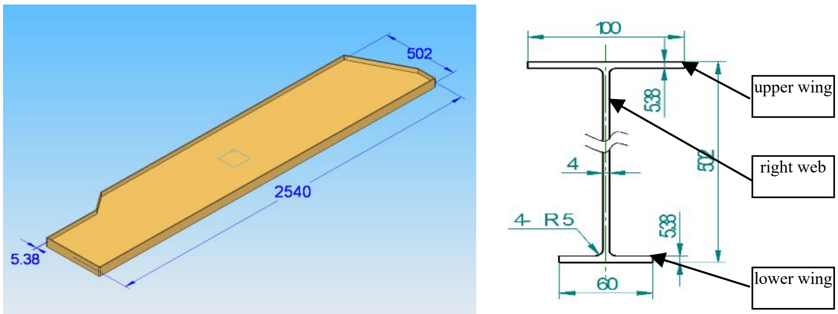
materials have a weight reduction of 60% compared with similar traditional aluminum alloy structural parts [14-16]. The United States and Russia have used advanced composite materials to produce a series of large-scale main load-bearing structures for spacecraft, such as load-bearing beams, special-shaped plate shells and reducer rods, which have also achieved significant weight reduction and performance improvement [17,18]. The launch vehicle for launching the spacecraft is one-time use, and the minimum launch cost per time is about 50 million US dollars [12]. For every 1 kg of spacecraft weight reduction, the launch cost will be saved by 10,000 to 20,000 US dollars. The cost has considerable economic benefits [19].

There are a lot of reports on the manufacturing process and process research of single and open composite I-shaped beams at home and abroad [12-13], but there are few researches on the forming process of large-scale closed I-shaped cross-section lattice reinforcement beams for spacecraft. This paper expounds the manufacturing technology of this type of carbon fiber composite closed I-beam by autoclave molding from the aspects of molding process, internal quality control, and product dimensional accuracy control.

2. Structural Characteristics of Composite Enclosed Beams

The large-size I-shaped composite closed beam of the spacecraft is a carbon fiber composite laminated structure. The outer side of the closed beam is covered with a honeycomb panel structure. The raw material of the beam is M55J/4211 high-modulus carbon fiber prepreg. Its structural diagram is shown in Figure 1.



（a）3D model （b）Cross section

Figure 1. Three-dimensional model and cross-sectiondiagram of I-shaped closed beam

The main technical indicators of the large size I-shaped composite closed beam structure are: (1) Size and accuracy requirements: the maximum shape length of the structure is 2540mm, the width is 502mm, the length dimension tolerance is ±1mm, and the width dimension tolerance is ±0.5mm; (2) Requirements for the number of layers, web and flange thickness: multi-angle layers, at least 64 layers, the web wall thickness is 4mm, and the flange thickness is 5.38mm; (3) Quality control requirements: the quality of the I-beam The control requirements reach the A-level quality level of "GJB2895-97 General Specification for Carbon Fiber Composite Laminates and Laminates". (4) Mechanical properties requirements: unidirectional tensile properties of composite materials: σ (tensile) > 1200 MPa, E (tensile) > 300 GPa; compressive properties: σ (compression) > 520 MPa, E (compression) > 200 GPa.

3. Manufacturing process method

3.1 Forming process plan

In order to ensure the shape and apparent quality of the product during the forming and curing process of the closed I-beam, the smoothness of the internal air guide, the effectiveness of pressurization and the convenience of demoulding, combined with the structural characteristics and main technical index requirements of the aforementioned I-beam, the engineering The process flow of the profile beam is shown in Figure 2 below.

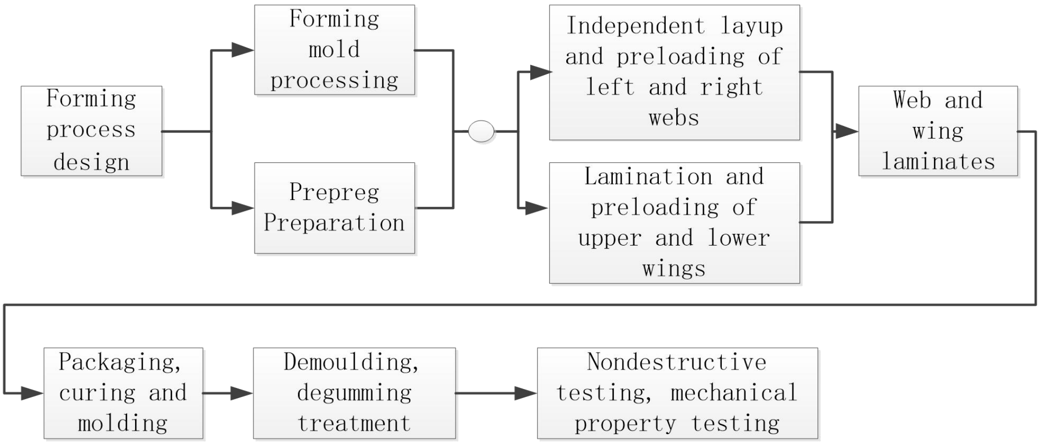


Figure 2. Process flow chart of closed beam

The design scheme of the closed beam forming process needs to take into account many aspects (see Figure 3 below). First of all, the area of the web is large. In order to ensure flatness and facilitate subsequent assembly, a steel mold is used, which is divided into upper and lower molds. Then, in order to facilitate the precise adjustment of the thickness of the wings on both sides, the outer surface is pressed in the form of a combination of soft mold and hard mold. Secondly, gas is easy to appear during the curing process of the I-beam, and the air guide channel is arranged inside the mold. Finally, the demoulding scheme design of large-sized I-beams is taken into account in the whole mold design process.

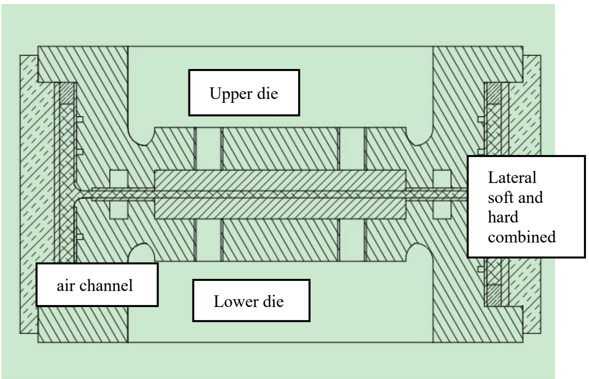


Figure 3. Schematic diagram of the structure of the closed beam curing forming mold

According to the above design, it can be seen that the closed beam I-beam forming process scheme has the advantages of simple mold structure and convenient operation, and the flatness of the I-beam web is good, which can improve the bonding quality of the honeycomb core; The bonding quality of the joints between the plate, the wing, the web and the wing is high; the glue content at the wing is easy to control, and the thickness of the wing can be precisely controlled.

3.2 Forming Die Design

Different from conventional metal materials, the molding of composite components is completed by means of molds. That is, while the material is solidified and formed, the composite material blank structure is finally shaped. In this study, the length of the composite large-size I-shaped closed beam is 2540mm, the width is 502mm, and the thickness of the wing plate is 5.38mm. It can be seen that the beam size is large, the overall area of the auxiliary plate is large, and there is a special-shaped closed cross-section, which makes it difficult to control the pressure and internal

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defects during the forming process. Therefore, the mold design needs to consider the structural form of the I-shaped closed beam.

The thermal expansion coefficient of cast aluminum commonly used in molds is 23.8×10-6/℃, and the thermal expansion coefficient of carbon fiber composite materials after curing is almost 0. The thermal expansion coefficients of carbon fiber composite materials and molds are quite different. big. The maximum temperature difference of the large-sized composite structure during the molding process is close to 150 °C, and the expansion of the mold in the length direction is theoretically close to 9 mm. Therefore, the mold design needs to take into account the thermal mismatch problem. In addition to considering the thermal expansion mismatch, the outer dimensions of the molding surface of the mold also need to consider the curing shrinkage of the composite material.

According to the above problems, combined with the engineering experience and the process test results of the test pieces, the deformation of the I-beam parts before and after curing can be calculated as follows:

$$\Delta l = k\alpha(T_c - T_0)l \tag{1}$$

Directions：

k ——Engineering constant, related to the material of the mold；

α ——Coefficient of Thermal Expansion of Cast Aluminum， 10^{-6}/℃；

T_c ——curing temperature，℃；

T_0 ——ambient temperature，℃；

l ——Overall length of mold forming surface，mm。

According to the above formula, it can be seen that by introducing the temperature influencing factors, the geometric dimensions of the composite mold structure are corrected and compensated to ensure that the dimensions of the formed structural parts meet the product design requirements. In a word, this study innovatively proposes a mold surface correction and compensation technology considering temperature factors to solve the problems of difficult to control molding, thermal mismatch, and hot and cold deformation.

3.3 Thermal Finite Element Analysis

During the autoclave molding of composite materials, the molding process temperature and the curing heat release of the resin are a complex nonlinear coupling behavior. The change of the surface temperature of the workpiece has a significant impact on its molding quality. Thermochemical finite element calculation of composite material molding can provide support for component deformation prediction and reduce mold development costs. In this section, the thermodynamic chemistry of the autoclave forming process of the composite I-shaped closed beam will be simulated, the temperature and stress distribution of the I-shaped closed beam will be studied, and the deformation of the closed beam will be predicted.

3.3.1 Finite Element Modeling

The closed beam curing molding die is composed of upper and lower molding die. The closed beam product is placed in the middle of the upper and lower forming molds. The closed beam product and the meshed model of the solidified molding die are shown in Figure 4. In the heat transfer calculation model, the convection heat transfer boundary condition is applied to the surface of the closed beam and the solidification mold assembly, and the ambient temperature changes according to the solidification process temperature. In the mechanical calculation, a fixed constraint is imposed on the lower end face of the closed beam.

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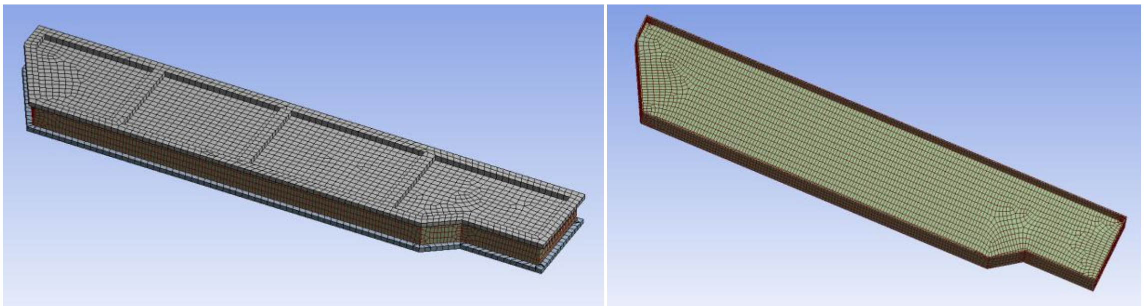
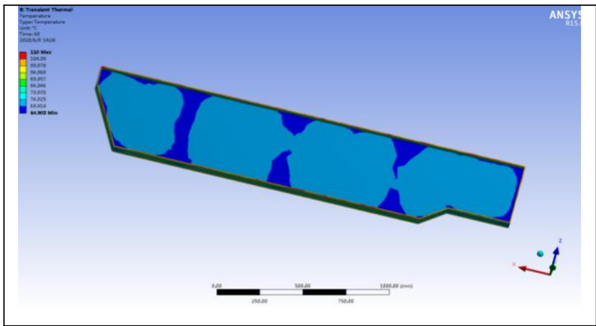


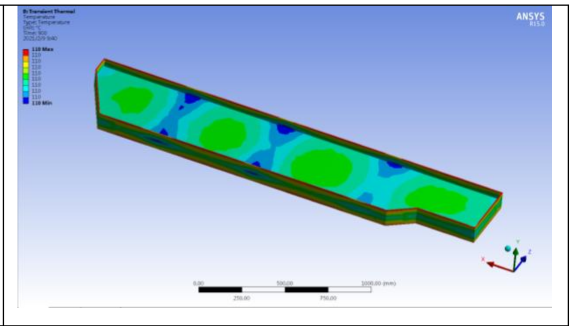
Figure 4. The closed beam product and the finite element model of the solidified forming mold

3.3.2 Temperature distribution results

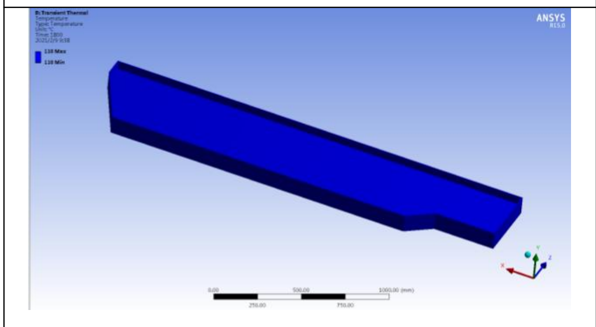
Based on the established three-dimensional composite component heat transfer model, the thermo-chemical simulation process of the autoclave forming process of the closed beam product was completed. Figure 5 shows the time distribution of the temperature field of the two heat preservation and curing inflection points of 110 °C and 165 °C during the curing and heating process of the closed beam.



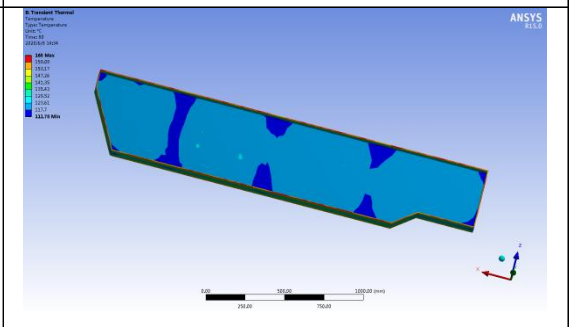
（a）0 min（110℃）



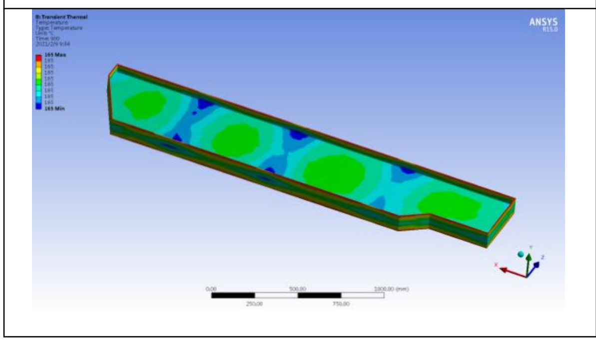
（b）15 min（110℃）



（c）30 min（110℃）



（d）0 min（165℃）



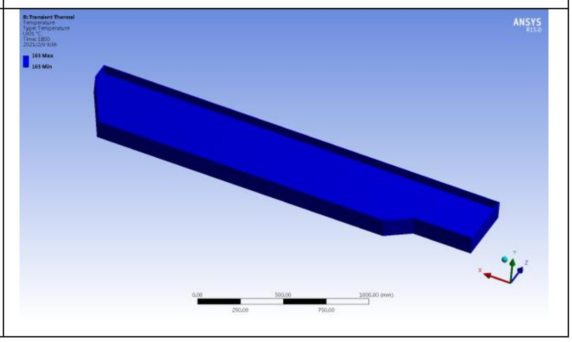


Figure 5. Temperature distribution at the inflection point of the closed beam product on the curing process curve

From the temperature distribution diagram of the closed beam in the curing process simulation, it can be seen that the closed beam product can quickly reach the temperature point required for

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curing within 15min-30min, indicating that the surface temperature of the structure can quickly achieve a dynamic balance with the ambient temperature.

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3.3.4 Stress Simulation Results

In the actual autoclave curing process, the deformation analysis of composite components is a complex problem, and its boundary conditions change at any time. In this study, the demoulding process of the composite closed beam is equivalent to releasing the constraint of the lower end face of the closed beam, and the curing stress and curing deformation of the closed beam are studied.

(1)Cure Stress Analysis

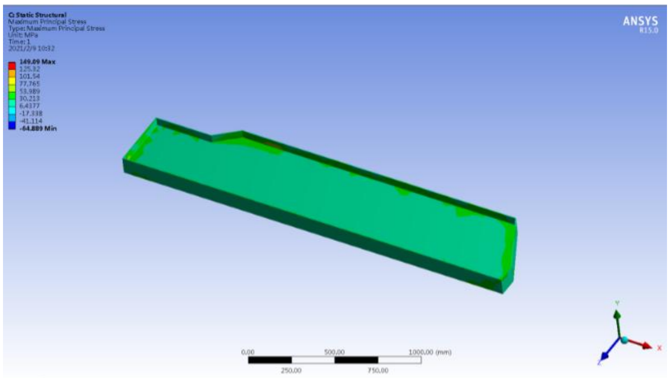

Figure 6. Curing stress cloud diagram of closed beam products

It can be seen from the solidification stress cloud diagram of the closed beam product (Fig. 6) that the solidification stress of the closed beam is relatively large due to the combined restraint force of the forming die and external pressure at the connecting corners and end positions of the web and the wing plate of the closed beam. is 149.09 MPa. Compared with the wing plate, the stress of the large area web is generally small.

(2)Deformation prediction analysis

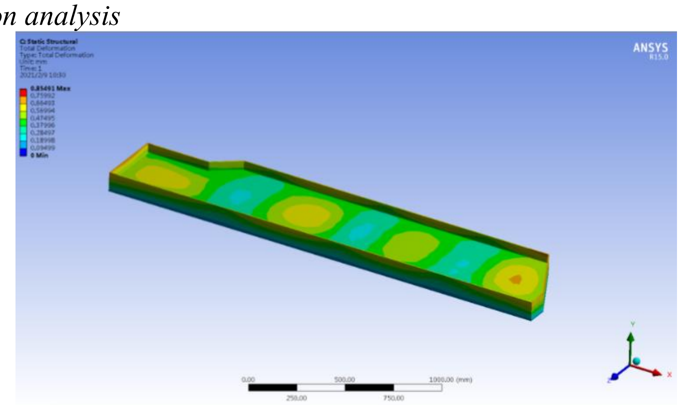

Figure 7. Curing deformation cloud diagram of closed beam products

It can be seen from the cloud diagram of the solidification deformation of the closed beam product (Figure 7) that there is basically no deformation at the constrained position where the reinforcement bars on the web of the closed beam correspond to the forming die. The deformation

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is related to the strain, and the deformation will accumulate. The accumulation of these deformations mainly occurs at the edge of the wing plate at the farthest end of the closed beam, that is, the farther away from the restrained position, the greater the deformation, and the maximum deformation of the edge of the wing plate at the farthest end of the closed beam is 0.85 mm, which meets the requirements of the component drawings ± 1mm deviation requirement.

(3) A subsection

To sum up, through finite element simulation of the curing process of the composite closed beam, the deformation state can be accurately predicted, and the deformation of the component can be reduced or offset by changing the curing process parameters or other processes. Finally, the rationality of the forming scheme of the closed beam structure is verified, which provides guidance for the development of the mold.

3.4 Internal Quality Control

The I-beam wings and webs are arranged in a "T" shape, enclosing the I-beam into a closed structure, and the parts and mold tooling during the curing process expand according to their respective thermal expansion coefficients. Therefore, the mismatch of thermal expansion coefficient may cause internal residual stress of the material, which will have a certain impact on the perpendicularity of the beam web and the wing plate, and then affect the bearing capacity of the closed beam. At the same time, due to the large size and thickness of the closed beam parts, the composite materials often bring a large amount of air and a small amount of water vapor into the laminate parts during the layup process, and the thick size is not conducive to the smooth discharge of gas and water vapor. , which will cause diffuse micro-porosity defects inside the parts, and even cause local bulging and delamination defects, which will seriously affect product quality.

In order to improve the lay-up quality of the part and reduce the number of defects inside the part, the following process measures are taken in this study: (1) Prepreg pretreatment. Due to the large and thick parts, the water vapor in the prepreg is difficult to discharge, which will seriously affect the final performance of the parts. Therefore, the prepreg can be pre-baked to remove most of the moisture. (2) Pre-press-adhesion technology. In order to reduce the air brought into the part during the lamination process, the pre-pressing-adhesive process is carried out after the lamination of the part's web. For I-beams with larger dimensions, the air in the layup can be minimized by increasing the number of preloads. (3) Component molding packaging design. The upper and lower outer surfaces of the wing plate are the instrument installation surfaces, and the requirements for surface flatness and perpendicularity to the web are relatively high. In the forming process of the I-beam, the method of combining the pressure equalizing plate and the rubber soft mold is adopted to achieve the surface flatness and pressure uniformity, so as to ensure that the deformation degree of the material parts is small and the product forming quality is high.

3.5 Dimensional accuracy control

Due to the large size, thick thickness, complex shape and closed surrounding of the girder I-beam, the pressure transmission path is complicated during its forming and curing process. At the same time, the closed structure is not conducive to the uniform pressure acting on all parts of the workpiece, and it is easy to cause the internal pressure transmission path of the I-beam to be blocked. This will have a greater impact on the appearance quality, compactness and thickness uniformity of the product. Such as the flatness of the web and the outer wing, the parallelism of the upper and lower wings, and the flatness of the upper and lower wings.

At the position where the webs and annular flanges of composite structural parts form sharp-R angles, when the layup deformation capacity of the prepreg cannot meet the deformation amount caused by the sudden change of the layup direction of the mold or part, the layup is difficult to control. When the prepreg bridges the R angle, a cavity appears between the blank and the mold. When curing, the resin flow fills the surface cavity to form a resin-rich. When the surface resin has

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poor fluidity or the prepreg resin content is insufficient, surface poor glue will be formed. A few fibers on the surface layer are bridged. Under the action of pressure, the bridged fibers are stressed on both sides, which will lead to the breakage of the fibers at the R angle in severe cases. During the layup operation, the fiber extension at the R corner is hindered, and after curing, there is more material piled at the R corner of the part, and wrinkles appear.

During the curing process, the lamination of the I-beam parts will be stretched with the expansion of the upper and lower forming molds (the maximum expansion is 9mm). If the movement of the lamination is restricted at this time (especially at the corners of the I-beam parts) layer), the stress accumulated in the part cannot be released, which will eventually affect the perpendicularity of the I-beam web and the wing plate, which may seriously cause the I-beam part to be deformed into a twist shape. Therefore, in order to reduce the internal stress level at the corners of the I-beam parts, when laying the web, a special process is designed to ensure that the mechanical properties of the parts at the corners are not affected.

4. Results and Performance Evaluation

Using the manufacturing technology of large-size I-shaped composite closed beams, a total of 24 composite I-shaped beams were developed through curing, demoulding, trimming, performance testing, machining and assembly of closed beams (see Figure 8 below). All of these products were successfully cured and demolded smoothly. After molding, the appearance surface and inner cavity of the products were visually inspected to be flat, smooth, and free of wrinkles. The wall thickness of each part of the web and wing plates was uniform, and there were no areas with poor or rich glue.

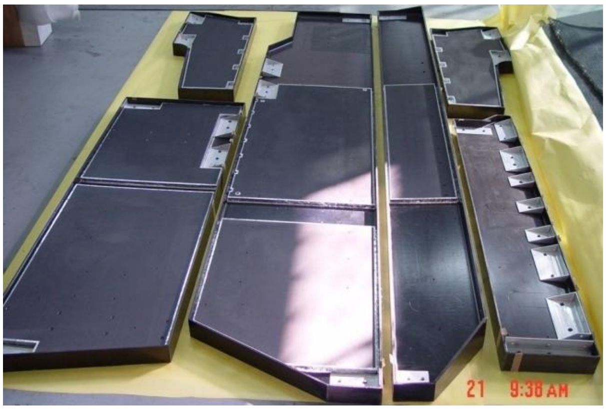

Figure 8. Many pieces of large-size I-shaped composite material closed beams

4.1 Internal molding quality of products

After testing, the fiber volume content of the closed beam products is (60±3)%, which meets the GJB2895-97 Grade A standard. Ultrasonic non-destructive testing instrument was used to test the web and wing area of the part, and no obvious defects such as delamination and porosity were found, and the internal quality of the part met the requirements of Class A of GJB2895-97.

4.2 Product dimensional accuracy

After testing, all the dimensional indicators of the closed beam products meet the design requirements. Among them, the external dimension tolerance is ±0.3mm, and the thickness deviation of the product is less than 8%. The results show that the lateral (outer surface of the wing plate) soft mold and hard mold combined pressure technology method can achieve uniform pressure on the large surface of the web and the thickness direction of the wing plate. The uniform pressure on each side and corner of the "T"-shaped structure of the wing and the web when it is solidified, and the pressure is transmitted in place.

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4.3 Mechanical properties of products

During the development of the closed beam, the furnace tensile and compression test pieces consistent with the technical state of the product were produced as required, and the 0° tensile properties, Compression performance was tested. The test results are shown in Table 1 below. The results show that the mechanical properties of the products meet the design index requirements.

Table 1. Mechanical properties of closed beam with furnace parts

Test content	Tensile Strength / MPa	Tensile modulus / GPa	compressive strength / MPa	Compression modulus / GPa	interlaminar shear strength / MPa
Design specifications	＞1200	＞300	＞520	＞200	＞40
Measured performance	1492	324	719	254	49.0

4.4 Application of results

After the product is assembled by components (show at Figure 9), compared with the metal material of the same structure, the weight is reduced by about 100kg, which is more than 60%, and makes a great contribution to the weight reduction of the spacecraft. The composite girder assembly has successfully passed the vibration test and mechanical static test of the whole device, and passed the flight test.

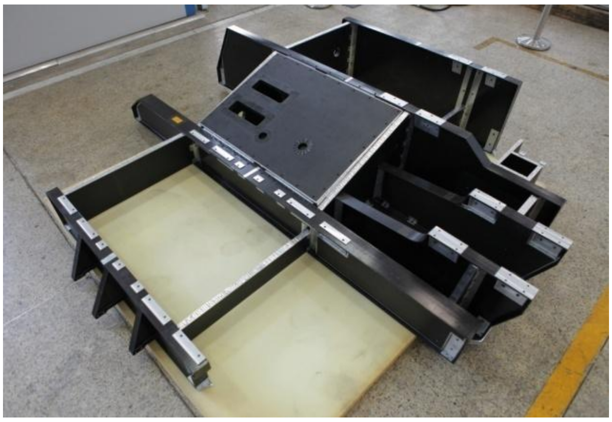

Figure 9. The physical assembly of the large-size I-shaped composite material closed beam assembly structure

5. Conclusion

Aiming at the large-size I-shaped closed beam structure of composite materials, through the analysis of structural characteristics, process design, and control of manufacturing accuracy, this paper proposes the positioning of the shape steel mold and the combined pressure forming technology of the outer surface of the wing plate with soft mold and hard mold. Solve the problem of difficult exhaust of large-sized parts. The mold shape design theory considering the mismatch of thermal expansion between mold and resin is constructed, the mold structure is optimized, and the molding accuracy of the part is improved. The thermo-mechanical finite element model of the solidification process of the closed beam is established, the solidification deformation state of the I-shaped seal is predicted, and the rationality of the forming scheme of the closed beam structure is verified. A special lay-up process is designed to solve the problem of deformation of closed parts after curing, and to improve the internal molding quality of the parts. The manufacturing technology developed in this research has been successfully applied to the development of many models of similar structures, which greatly shortens the product development cycle and improves product

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quality. It will lay a solid theoretical foundation for the development of subsequent models of products in my country, and accumulate valuable engineering experience, which will help improve the development level and capability of my country's new space vehicles.

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