The design and forming of composite heteromorphic components

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Abstract: In order to meet the weight reduction requirement of a tactical component, feasibility analysis by selected raw material, analyzing the stress and displacement under the working condition by finite element analysis method, a design of molding and curing are proposed. The results of feasibility by choosing suitable show that the mass of the composite component is reduced from 8.3Kg to 2.9Kg after optimization with the theoretical weight loss is 60%; the maximum stress is 50.9 MPa and the maximum displacement is 0.089mm; which meet the design requirement. The internal expansion pressure of the mold is designed as 1.0 MPa which meets the molding requirement. The design of this lightweight tactical composite component is clear, reasonable and feasible, which will have a certain guiding significance for the research of molding technology in related field.

1. Introduction

In recent years, with the continuous development of carbon fiber reinforced resin matrix composite technology, advanced resin matrix composites have become the main material for structural development in the tactical field [1-4]. Advanced resin matrix composites have high specific strength and specific modulus, as well as excellent properties such as fatigue resistance and good thermal stability, and the design of the layup sequence, layup angle, number of layers, and layup molding process can significantly improve the load-bearing efficiency of the structure [5-7]. The excellent dimensional stability and low thermal expansion coefficient make the tactical apparatus significantly more reliable for use under complex operating conditions.

Wang Zengguang et al [8-10] discussed the application of composite material technology in terms of material, structure and manufacturing process, and optimized the structure and material distribution for a typical backrest skeleton, taking into account the economics and processing feasibility, and proposed an improvement plan based on the optimization results. Qian Xiaoru et al [11-20] focused on several key issues in the design of composite blade structure for composite blade structure, and on the basis of extensive analysis and study of existing technologies of composite structure design at home and abroad, combined with actual research experience, discussed and analyzed the key aspects of material selection,
load conditions, structure selection, layup design and so on in the design of composite blade structure, and feasible opinions were given. Hou Pengliang et al \cite{21-25} compared the advantages and disadvantages of three reinforced structure molding methods, namely secondary gluing, co-gluing and co-curing, and analyzed the influence of tooling structure on product quality, but no conclusion was given on which molding method is suitable for the specific reinforced structure and what tooling structure is used. Tian Ye et al \cite{26-27} studied and analyzed the simulation technology design scheme and process parameters, and optimized the curing process curve by means of curing simulation on the basis of the simulation, which provided a feasible method for the curing process curve of composite molding, but the direction of curing adjustment was not mentioned for the specific resin system and curing conditions. For a typical multi-connector structure described in this paper, there are few reports on the analysis of the key aspects of the whole composite molding process.

This paper uses advanced resin matrix composite molding to design and analyze the feasibility of lightweight structure and process of a tactical component, and develop it to achieve the goal of reducing the weight of the tactical component and improving the stability and reliability of the tactical component.

2. Tactical component structure

Tactical component structure as shown in Figure 1, the main body of the structure is similar to the rectangular shell cabin structure, the upper and lower openings, the top with flange flanges, both sides of the wall reinforced connection.

![Figure 1 The main structure](image)

Tactical component structure is mainly for both sides of the face plus the middle connecting tendons, with a rounded surface in the middle, in order to match the installation surface, the cross-section overall trapezoidal structure, cross-section size from the flange down, in increasing order, 6 connecting tendons belong to 3 planes.

3. Raw material selection

The main raw material for resin matrix composites consists of reinforcement fibers and matrix resin. Different combinations of fibers and resin will have a great impact on the performance of the composites, and the raw material required for molding is selected in conjunction with the specific operating conditions and comprehensive costs of the components.

3.1. Selection of resin

In order to meet the technical specifications of high-performance composites, more and more resins with excellent properties have been developed. Mainly considering the use conditions of this tactical component for brush selection matching, the E51 epoxy resin system used for its assembly component molding was finally selected, produced by Shanghai Xinhua Resin Factory, which has been practically verified by various actual working conditions and meets various established use performance requirements. Its specific performance reference is shown in Table 1.
Table 1 Basic properties of epoxy resin

| number | property | standard | index |
|--------|----------|----------|-------|
| 1      | viscosity| GB/T 12007.4 | ≤2.5 (Pa·s/40℃) |
| 2      | density  |          | 1.1 g·cm⁻³ |

3.2. Fiber selection

Khan et al. [29] analyzed the influence of the structural form of reinforcement on the performance of composites, but did not specify which structural form of reinforcement is more reasonable for which structure. Considering the use demand, combined with the economic cost and molding cycle, the screening was set as T300 plain carbon cloth after simulation analysis. Its specific properties refer to Table 2 shown.

Table 2 T300 basic performance

| number | property   | index |
|--------|------------|-------|
| 1      | E₁/GPa     | 50.0  |
| 2      | E₂/GPa     | 50.0  |
| 3      | E₃/GPa     | 10.0  |
| 4      | G₁₂/GPa    | 3.5   |
| 5      | G₁₃/GPa    | 5.0   |
| 6      | G₂₃/GPa    | 5.0   |
| 7      | Poisson's ratio | 0.32 |
| 8      | density g/cm³ | 1.7   |

Notes: E₁, E₂, and E₃ are tensile modulus; G₁₂, G₁₃, and G₂₃ are shear modulus.

Combined with the working conditions of tactical components, T300 plain carbon cloth + epoxy resin system composite material is used. Through calculation, when the volume ratio of fiber to resin is 60:40, the tactical component weight is reduced from 8.3kg to 2.9kg, the theoretical weight is reduced by about 60%, and the weight reduction effect is obvious. In addition, the introduction of epoxy resin system enhances the anti-corrosion and anti-fatigue characteristics, which greatly improves the reliability of the tactical component.

4. Strength calibration under common working conditions

Stress analysis under service conditions is a primary consideration for lightweight molding of composite materials. Abaqus was used to calibrate the mechanical behavior of the component under service load conditions to enable better matching of service conditions and optimal production.

4.1. Calibration process and results

Abaqus was used to model and finite element mesh the component, the cells were linear hexahedral cells, cell number 112601, node number 163720, and the finite element model is shown in Figure 2.

![Figure 2 Finite element mesh model](image)

According to technical requirements.
① No. 2 crossbeam round hole subjected to 6kN horizontal (parallel to the direction of the length of the member) thrust, pointing to No. 6 crossbeam, acting on the inner wall of the hole.

② No. 6 beam sheath hole, axial (parallel to the member length direction) 4.5kN, horizontal (parallel to the member width direction) 3.2kN, vertical (parallel to the member thickness direction) 4kN, upward, acting on the inner wall of the hole.

(iii) Each of the 16 small holes in the side wall is subjected to 600N tension, acting on the inner wall, along the side wall direction.

Constraint: The bottom edge of the member and the six crossbeams are glued mounting surfaces, which are simplified to solid support in the calculation.

Constrain the members as shown in Figure 3.

The results of the calibration calculations are shown in Figures 4~6. From Figs. 4~6, it can be seen respectively that the maximum stress suffered by the member under the given working condition is 53.47 MPa, and the maximum deformation occurred is 0.01298 mm, all occurring in the middle of the sidewall, and the Tsai-Wu index is 0.1297, which is less than 1 and is not damaged.
4.2. Simulation results

After finite element calibration calculations, the stress, displacement and Tsai-Wu index distributions of the members under the given working conditions were obtained, and the specific values are shown in Table 3.

| Structure       | Stress (MPa) | Displacement (mm) | Tsai-Wu |
|-----------------|--------------|-------------------|---------|
| Tactical component | 53.47        | 0.01298           | 0.1297  |

As shown in Table 3, the stresses and displacements of the members are small and the Tsai-Wu index is less than 1, indicating that the members do not fail under the given working conditions. It shows that the selected raw materials and the optimized composite configuration meet the requirements of the operating conditions under the given operating conditions.

5. Mold design

5.1. Mold scheme design

Frerich [30] briefly introduced the process principle, materials and influencing factors of thermal expansion and applied it to develop a composite part, and sorted out the applicability of this molding process, which is more suitable for monolithic co-curing molding of multi-cavity composite parts. According to the structural characteristics of the component, the steel-silicon combination molding mold lay-up molding scheme was adopted, and the specific molding mold is shown in Figure 7. The main structure of the mold: ① the upper and lower ends of the steel core used for silicone rubber positioning and adjustment of expansion force; ② the upper and lower ends of the silicone rubber used for direct contact with the product; ③ the periphery of the overall collocation block.
As shown in Figure 7 molding mold scheme, the middle green part is the composite prefabricated block, red is the main layered continuous fiber, the upper end is in the form of silicon rubber covered steel core structure, and the lower circular section is in the form of steel core with silicon rubber attached to both sides.

5.2. Silicone rubber design
Although the metal mold has good dimensional stability, but for "small mouth and big stomach", and need a certain internal pressure structure, metal mold obviously cannot meet the use of demand, molding needs to provide a certain "internal expansion force", the temperature is more sensitive and The flexible silicone rubber, which is sensitive to temperature and controllable, becomes the preferred mold material. The silicone rubber used in this paper (mass ratio of 1:1) is the E650 two-component silicone rubber developed and produced by Hubei Hangju Technology Co.

| Test project           | The test method | Performance indicators |
|------------------------|-----------------|------------------------|
| Tensile strength       | GB/T 528-2009   | 8.00MPa                |
| density                | GB/T 1033-2008  | 1.35 g·cm⁻³           |
| Coefficient of thermal expansion | GB/T 332A-2004 | 6.90×10⁻⁴/°C          |

The silicone rubber expands thermally during the molding process. By pre-setting the curing temperature interval of this tactical component, the amount of silicone rubber expansion can be regulated, as the silicone rubber will generate much more pressure in the closed mold cavity than is required to mold the composite. Therefore, a process gap between the composite and the core mold is required. Calculation formula:

\[ P = K\lambda(T_G - T_0) \]  
\[ V - V_0 = \lambda V_0(T_G - T_0) \]  
\[ P_G = K \left( \frac{V - V_0}{V} \right) \]

where \(\lambda\) is the volume expansion coefficient of rubber, 8.4×10⁻⁴/°C; \(T_0\) is the room temperature, °C; \(T_G\) is the resin curing temperature, °C; \(V\) is the volume of silicone rubber in the case of free expansion, mm³; \(V_0\) is the volume at room temperature, mm³; \(V_G\) is the volume of silicone rubber at the resin gel temperature, mm³; \(K\) is the modulus of elasticity of silicone rubber, GPa; \(P\) is the rubber generated in the closed mold cavity at the temperature of \(T_G\) at \(T_G\); \(P_G\) is the pressure at gel, N; \(V-V_0\) is the difference between the free expansion volume and the volume of the mold cavity, mm³.

The actual volume size of the silicone rubber can be deduced from the calculation of equations (1) to (3), based on the selected pressure of 1.0 MPa required for the molding and curing of the epoxy resin. Based on the experience of using silicone rubber and the wall thickness of the component, the requirements for curing and easy installation of the mold for this component are met.

6. Forming solutions
Forming solutions are the main implementation path for composite molding. Qian Xiaoru et al [11-20] compared the advantages and shortcomings of several common molding processes. Combining the characteristics of this tactical component and the actual forming conditions, the T300 plain carbon cloth quasi-parallel homogeneous lay-up forming, sidewall and connection tendons integrated co-curing scheme was used to form this tactical composite component, which is a simple and reliable forming method with a clear process flow.

6.1. Preparation of plain carbon cloth prepreg
Prepreg preparation is the main part of molding, and the quality of prepreg preparation has a direct impact on the performance of composite materials. In this paper, we mainly use plain carbon cloth brush glue to strictly control the performance indexes of prepreg with dry resin content 45±5% and volatile
content ≤2%. After actual production verification, the performance index requirements meet the product development requirements.

6.2. Curing system
Curing is a key part of composite molding, and Qian Xiaoru et al. [11-20] introduced several typical methods for controlling the curing process parameters of composite components. The control of curing parameters directly affects the quality of molding and curing, and thus the quality of composite materials, and the curing regime is a direct reflection of the curing process parameters. In this study, for the selected epoxy resin system, a dedicated curing regime (Figure 10) was analyzed and developed for the selected epoxy resin system, combined with the viscosity-temperature curve of the specific resin system (shown in Figure 8) and the DSC curve of the epoxy resin system under different temperature rise rate conditions (shown in Figure 9), giving a schematic curve of temperature step-up and pressurization pressure step-up.

6.2.1. Epoxy resin system viscosity temperature curve
Combined with its viscosity and temperature curve (as shown in Figure 8), it can be seen that on the one hand, the temperature increases linearly with time, on the other hand, the epoxy resin system at a lower temperature, viscosity is also low, with the system temperature rises, viscosity first slowly decreases, then a sharp increase in the trend of change, in the 100 ~ 180 ℃ temperature range, the resin system viscosity through a low viscosity to high viscosity transition of a state. The viscosity of resin is too low and the fluidity is too good; The viscosity of the resin is too high and the fluidity is too poor, so it is more appropriate to set the curing pressure point in the range of moderate viscosity of the resin. The temperature point in the temperature range is selected as the curing pressure point of the product. In the case of this component, the expansion force of silicone rubber is kept at the maximum at this time to maintain the internal expansion force required for molding the component.

6.2.2. DSC curves of epoxy resin system under different heating rate conditions
The DSC curves of the epoxy resin system at different heating rates (as shown in Figure 9). The slower the heating rate, the smoother the exothermic peak, indicating that the internal reaction of the system is smoother, but the more advanced the peak point, indicating that the internal reaction of the system is advanced; the faster the heating rate, the steeper the exothermic peak, indicating that the internal reaction of the system is more intense at the peak temperature, but the more advanced the peak point, indicating that the internal reaction of the system is delayed. The faster the heating rate, the steeper the exothermic peak, the more intense the reaction is at the peak temperature, but the more backward the peak point, the more delayed the reaction is; this indicates that the epoxy resin system has different curing reactions under different heating rate conditions.
6.2.3. Curing system
Comprehensive epoxy resin system viscosity temperature curve (Figure 8), DSC curve under different temperature rise rate conditions (Figure 9) and the actual production equipment, analysis to determine the hot press tank curing system shown in Figure 10. The actual production verification, the curing system is suitable for this component curing molding.

7. Experimental results

From Fig. 11, it can be seen that the composite shaped components are very much in line with the design requirements, and the components are installed on the launch barrel for hydrostatic test according to the standard "ADK13 Launch Barrel Assembly Implementation Rules for Static Test", and the experimental result is that no damage occurs in the composite shell compartment, which is consistent with the simulation calculation results, further verifying the feasibility of the design and molding method.
8. Conclusion
In view of the weight reduction requirements of this tactical component, combined with the structural characteristics of the component, several process difficulties were screened out for research and analysis based on the feasibility analysis of its composite lightweight molding, with the following specific conclusions.

(1) Raw material selection: comprehensive economy, usage demand and processability, T300 plain carbon cloth + epoxy resin system was selected as the main raw material for the molding of this component.

(2) Strength verification: Through the simulation analysis of the selected raw materials under the use conditions, the selected raw material combination was verified to meet the mechanical requirements under the use conditions, and none of them failed under the given work conditions.

(3) Mold structure design: for its special structural form, a steel-silicon combination molding mold method was used to ensure both internal pressurization of the components and to meet the process requirements, with reliable mold structure and simple and convenient loading and unloading.

(4) Curing system: By analyzing the viscosity curve of the selected resin system and the DSC curve at different heating rates, a special curing system for the molding of this component was developed, and the curing system was verified to be suitable for the curing of this component by actual production.

Through the analysis and pre-production of the above process difficulties, we successfully developed this composite tactical component to achieve the set weight reduction target and to improve the stability and reliability of this tactical component.

References
[1] Sha J, Dai J, Li J, et al. Measurement and analysis of fiber-matrix interface strength of carbon fiber-reinforced phenolic resin matrix composites[J]. Journal of Composite Materials, 2014, 48(11):1303-1311.
[2] Zhao D L, Qiao R H, Wang C Z, et al. Microstructure and Mechanical Property of Carbon Nanotube and Continuous Carbon Fiber Reinforced Epoxy Resin Matrix Composites[J]. Advanced Materials Research, 2006, 11-12:517-520.
[3] Zhao D L, Qiao R H, Wang C Z, et al. Microstructure and Mechanical Property of Carbon Nanotube and Continuous Carbon Fiber Reinforced Epoxy Resin Matrix Composites[J]. Advanced Materials Research, 2006, 11-12:517-520.
[4] Tsujimoto A, Barkmeier W W, Erickson R L, et al. Influence of the number of cycles on shear fatigue strength of resin composite bonded to enamel and dentin using dental adhesives in self-etching mode[J]. Dental Materials Journal, 2018, 37(1):113-121.
[5] Kwon D J, Kim J H, Park S M, et al. Damage sensing, mechanical and interfacial properties of resins suitable for new CFRP rope for elevator applications[J]. Composites, 2019, 157(JAN,15):259-265.
[6] Nonn S, Kralovec C, Schagerl M. Damage mechanisms under static and fatigue loading at locally compacted regions in a high pressure resin transfer molded carbon fiber non-crimp fabric[J]. Composites Part A Applied Science & Manufacturing, 2018, 115:57-65.
[7] Jintao P, Tianbin R. The latest application status of carbon fiber reinforced resin matrix composites[J]. china adhesives, 2014.
[8] WANG Zheng-feng, ZHOU Yi-wei. The Main Types of Composite Materials and Advanced Manufacturing Technology for Aviation[J]. Instrumentation Technology, 2018.
[9] Luo J, Wang H, Zuo D, et al. Research on the Application of MWCNTs/PLA Composite Material in the Manufacturing of Conductive Composite Products in 3D Printing[J]. Micromachines, 2018, 9(12).
[10] Craciun A L, Hepuț, T, Pinca-Bretotean C. Aspects regarding manufacturing technologies of composite materials for brake pad application[J]. Iop Conference, 2018, 294.
[11] Qian X, Yan P, Han W. Multidisciplinary Design Optimization of the Composite Cooling Structure for Nickel-based Alloy Turbine Blade[J]. International Journal of Turbo and Jet Engines, 2019.
[12] Yu G Q , Ren Y R, Zhang T T, et al. Hashin Failure Theory Based Damage Assessment Methodology of Composite Tidal Turbine Blades and Implications for the Blade Design[J]. China Ocean Engineering, 2018, 32(2):216-225.

[13] Bender J J , Hallett S R , Lindgaard E . Parametric study of the effect of wrinkle features on the strength of a tapered wind turbine blade sub-structure[J]. Composite Structures, 2019, 218(JUN.):120-129.

[14] Li L , Wan H , Gao W , et al. Reliability based multidisciplinary design optimization of cooling turbine blade considering uncertainty data statistics[J]. Structural and Multidisciplinary Optimization, 2018, 59(5).

[15] Kuahai Yu, Xi Yang, Zhufeng Yue. Aerodynamic and heat transfer design optimization of internally cooling turbine blade based different surrogate models[M]. Springer-Verlag New York, Inc. 2011.

[16] He Q , Li Y S , Ao L B , et al. Reliability and multidisciplinary design optimization for turbine blade based on single-loop method[J]. Tuijin Jishu/journal of Propulsion Technology, 2011, 32(5):658-663.

[17] Fitzpatrick O T , Blade M , Fishback L A , et al. Snowpack, Tree Size, and Ecological Legacies Promote Seeding Establishment in Tree Islands at the Treeline[J]. 2020.

[18] Singh G , Gorton J P , Schappel D , et al. Impact of control blade insertion on the deformation behavior of SiC-SiC channel boxes in BWRs[J]. Nuclear Engineering and Design, 2020, 363:110621.

[19] Deveaux B , Fournis C , Brion V , et al. Experimental analysis and modeling of the losses in the tip leakage flow of an isolated, non-rotating blade setup[J]. Experiments in Fluids, 2020, 61(5).

[20] Saveliev A G , Mikhailovskaya V A . Ultimate loads, arising on the blade during exploitation, according to existed design positions for calculations[J]. IOP Conference Series Materials Science and Engineering, 2020, 786:012020.

[21] Pengliang H , Anran Z , Weidong W , et al. Failure mechanism of glass-fiber reinforced laminates influenced by the copper film in three-point bending[J]. International Journal of Adhesion & Adhesives, 2018, 84:368-377.

[22] Yipei W . One-Step Molding Technology of the Secondary Structure Without Changes in the Whole Stiffness of the Structure of Buildings[J]. urbanism and architecture, 2019.

[23] Afonin A V , Sterkhova I V , Vashchenko A V , et al. Estimating the energy of intramolecular bifurcated (three-centered) hydrogen bond by X-ray, IR and 1 H NMR spectroscopy, and QTAIM calculations[J]. Journal of Molecular Structure, 2018, 1163.

[24] Deng C , Jin B , Zhao Z , et al. The influence of hoop shear field on the structure and performances of glass fiber reinforced three-layer polypropylene random copolymer pipe[J]. Journal of Applied Polymer Science, 2019, 136(3):n/a-n/a.

[25] Quintana M , Frontini M. Development of the layered structure in a double-gated glass fiber-reinforced polypropylene injection molding: Experimental and simulated results[J]. Journal of Reinforced Plastics and Composites, 2018:073168441877052.

[26] Tian Y , Huang H , Xu X . Optimization of the curing process of phenolic impregnated carbon ablator[J]. Journal of Applied Polymer Science, 2018, 135(18).

[27] Yan H , Hu Z , Suan T S . Application of Numerical Simulation Technology on the Design of Camera Shell during Die Casting Process[J]. Advanced Materials Research, 2007, 26-28:1041-1044.

[28] Wu M L , Lan J S. Simulation and Experimental Study of the Warpage of Fan-out Wafer-level Packaging: The Effect of the Manufacturing Process and Optimal Design[J]. IEEE Transactions on Components Packaging & Manufacturing Technology, 2018:1-1.

[29] Khan A A, Al-Kheraif A A, Mohamed B A , et al. Influence of primers on the properties of the adhesive interface between resin composite luting cement and fiber-reinforced composite[J]. Journal of the Mechanical Behavior of Biomedical Materials, 2018, 88:281-287.
[30] Frerich T, Brauner C, Jendrny, Jörg, et al. Modeling the influence of interleaf layers in composite materials on elastic properties, thermal expansion, and chemical shrinkage[J]. Journal of Composite Materials, 2019.