Thermal Stress Analysis for Carbon/Carbon Material Throat Lining Based on Finite Element Analysis

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Abstract. As a key part of the solid rocket motor, the nozzle always withstands a series of problems such as high-temperature, high-pressure, and chemical erosion and faces more severer environmental challenges. So its Stability plays a vital role in the normal operation of the engine. This paper takes the engine nozzle throat lining as the research object, uses the ANSYS to establish a carbon/carbon composite throat lining model in the ACP module, and analyzes the stress and displacement of the throat lining in a high-temperature and high-pressure environment. The experimental results show that under the high-temperature condition of 3500°C, the maximum stress value is 2734.8MPa, and more than 96% of the area is below 1000MPa, lower than the prescribed stress threshold. The superiority in the performance of the throat lining prepared for carbon/carbon materials is verified, and the structural integrity of the throat lining can still be guaranteed under high-temperature conditions.

1. Introduction
With the rapid development of the aviation industry, aerospace technology continues to innovate, and at the same time, the requirements for high-temperature materials have become more stringent. The rocket engine nozzle is used as the rocket's thrust device, which converts the fuel gas energy into thrust by expanding the fuel gas generated by the propulsion in the combustion chamber, so that it can fly at high speed[1]. The throat lining is located at the neck of the nozzle. When the engine is working, the throat lining is in an extremely harsh thermal environment. Its inner surface is affected by complex factors such as high temperature and high pressure, which leads to the expansion of the throat lining and changes in the nozzle structure. So that the working performance becomes poor, the efficiency becomes low, and the serious damage may lead to the failure of the engine[2]. Because of its high-temperature and high-pressure working environment, the selected material not only needs to have excellent high-temperature resistance and withstand high temperatures of 3500°C but also needs to have good high-pressure resistance to avoid cracks due to excessive thermal stress. Therefore, the performance requirements of throat lining materials are extremely strict.
Carbon/carbon composite material has the advantages of ablation resistance, low thermal expansion coefficient, etc., and overcomes the shortcomings of low strength and poor thermal shock resistance. Compared with other materials, it has obvious advantages in thermophysical and mechanical properties\cite{3,4}. It is widely used in nozzle throat lining. This paper uses the finite element method to analyze the thermal stress of the carbon/carbon composite throat lining under high-temperature conditions, and study the stress and displacement of the throat lining.

2. Structural modeling and material properties

2.1. Modeling of throat lining structure

This paper uses the ACP module in ANSYS Workbench to construct the composite material model of the throat lining. The throat liner shell element model is established in SolidWorks. The shell element is shown in Figure 1. The height of the model is 60mm, the minimum throat diameter is 50mm, and the maximum throat diameter is 60mm. Import the shell element into the ACP module. According to the ACP composite material layup principle, the material is laid out in 0° and 90° directions with the shell surface as the base surface, and one layer in each direction, with a thickness of 0.1mm, the structure of the ply unit is shown in Figure 2.

![Figure 1. Shell model of throat lining](image1.png)

![Figure 2. Structure diagram of ply unit](image2.png)

According to the structural characteristics of the throat lining variable thickness ply, choose different areas to pave the required thickness, the base layer is set to 20 layers, a total of 4mm; on this basis, the special parts are layered multiple times, so that the maximum thickness is 10mm and the minimum thickness is 4mm, the throat lining model after laying is shown in Figure 3.
2.2. Material selection and parameters
When the engine is working, the high-temperature gas in the combustion chamber is converted into thrust through the nozzle. Most of the thrust is generated at the throat lining. Due to the extremely severe working environment, it needs to withstand high-temperature and high-pressure conditions, and the selection of materials for the throat lining is also extremely strict. Carbon/carbon composite material has a lightweight and good mechanical properties of high-temperature and high-pressure resistance. Therefore, the material is selected as HTA-6K. Its raw material parameters are shown in Table 1.

Table 1. Material parameters.

| Property                   | Value                  |
|---------------------------|------------------------|
| Density                   | 1.76 g/cm³              |
| Tensile Strength          | 3920 Mpa                |
| Tensile modulus           | 235 Gpa                 |
| Thermal expansion coefficient | -0.6×10⁻⁶/℃             |
| Thermal conductivity      | 9 W/(m • K)             |
| Poisson's ratio           | 0.34                    |

3. Finite element analysis

3.1. Meshing
The meshing should follow the following basic principles: First, the number of grids is determined according to factors such as the accuracy of the calculation results, the size of the calculation scale and the type of analysis data. In general, as the number of grids increases, the scale and accuracy of calculations will increase accordingly. When analyzing the data, if only the deformation of the structure is calculated under the static analysis, the number of grids can be appropriately reduced. To calculate the stress, it is necessary to take more grids under the same accuracy requirements. Second, to better observe the law of changes in the data, in the areas where the numerical gradient changes greatly (such as the stress concentration), a denser grid is usually used[5]. The mesh size set in this paper is 2mm, the number of nodes is 153764 after the mesh is divided, the number of cells is 147996, the average quality of the mesh elements is 0.08292mm, the quality of the mesh is good, and the accuracy can meet the requirements. Figure 4 shows the completion of the grid division.
3.2. Constraints and loads
In the working state of the engine, the inner surface of the nozzle throat liner is eroded and ablated by high temperature, high pressure, high speed, and heat flow containing corrosive particles[6]. To simplify the experiment, this paper ignores the ablation effect caused by the fuel heat flow and only considers the thermal stress analysis under the high-temperature condition of the throat lining inner profile[7].

The nozzle model is shown in Figure 5. During the simulation process, constraints are imposed on the model with reference to the position of the fixed layer. Fixed constraints were imposed on the side of the throat lining. Since the stiffness of the carbon/phenolic composite is smaller than that of the throat liner carbon/carbon material, there is no restriction on the contact part[8].

The gas temperature of a solid engine can reach 3500°C. To simulate its working environment, a high-temperature load of 3500°C is applied to the inner surface of the throat lining, and a temperature load of 1000°C is applied to the other surfaces[9].

3.3. Throat Lining Strength Analysis
The thermal stress analysis simulation is performed at a high temperature of 3500°C to analyze the displacement and stress of the throat lining under high-temperature conditions. The displacement cloud diagram is shown in Figure 6, and the stress cloud diagram is shown in Figure 7.
According to the displacement cloud diagram of the throat lining model at high temperature, it can be seen that under high-temperature conditions, there is no huge deformation in each part of the throat lining. The maximum deformation value is 0.0497mm, and the amount of deformation is small\cite{10}. It can be seen from the stress cloud diagram that the maximum stress of the throat lining appears in the neck when subjected to high temperatures. The maximum stress value is 2734.8 MPa and the average stress is 166.3 MPa, both of which are less than the tensile strength of the material, 3920 MPa.

The stress results of the throat liner are derived by ANSYS, which has a total of 157,521 stress points. To ensure the rationality of the experiment, this paper assumes that the engine throat lining driving stress threshold is 1000MPa, and 152153 stress points are lower than 1000MPa, which is lower than the engine throat lining driving stress threshold, accounting for about 96.592%, 5368 stress points are higher than 1000MPa, accounting for only 3.408%. The force distribution ratio of the model is shown in Table 2.

| Stress range       | Ratio   |
|--------------------|---------|
| 0~1000MPa          | 96.592% |
| 1000MPa~2734.8MPa  | 3.408%  |

It can be seen from the above table that in the entire force model of the throat lining, the stress in more than 96% of the area is lower than the driving stress threshold of the engine throat lining. The structural integrity of the throat lining can be guaranteed under high-temperature conditions, and the engine will not be damaged due to excessive thermal stress.

4. Conclusion
The simulation results show that the maximum structural displacement value of the throat liner is 0.0497mm and the maximum stress value is 2734.8MPa under the high-temperature working environment of 3500°C. More than 96% of the area is lower than the driving stress threshold of the
engine throat lining, which can ensure the integrity and effectiveness of the lining under the working environment. The carbon/carbon composite throat lining has good resistance to high-temperature and high-pressure, which provides a certain theoretical basis for the subsequent ablation simulation experiment and fluid-solid coupling experiment of the engine throat lining.

The research method in this paper still has certain limitations. In the simulation process, the complicated fluid, temperature, chemical reaction, and other issues are simplified to a high-temperature environment. In the subsequent experiments, the focus is on the fluid problem of the throat lining, so as to provide more accurate experimental data for the ablation experiment of the engine throat lining.

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References
[1] Abdulrahman, A., Mohamed Z., Hamad, M.A., Abdulrahman, A. (2020) Thermal performance analysis of gas turbine engines based on different compressor configurations. Heat Transfer—Asian Research, 49: 2717-2745.
[2] Mina, A. (2020) The Impact of Engine Heat on the Erosion of its Parts Using Biofuels. Journal of Mechanical, Civil and Industrial Engineering, 1: 36-38.
[3] Liu, X., Deng, H.L., Zheng, J.H., Sun, M., Cui, H., Zhang, X.H., Song, G.S. (2021) Mechanical and thermal conduction properties of carbon/carbon composites with different carbon matrix microstructures. Carbon, 174: 759-759.
[4] Li, B.L., Guo, J.G., Xu, B., Xu, H.T., Dong, Z.J., Li, X.K. (2021) Preparation, microstructure and properties of three-dimensional carbon/carbon composites with high thermal conductivity. Carbon, 174: 758-759.
[5] Mohammadi, B., Abdoli, Z., Anbarzadeh, E. (2021) Investigation of the Effect of Abutment Angle Tolerance on the Stress Created in the Fixture and Screw in Dental Implants Using Finite Element Analysis. Journal of Biomimetics, Biomaterials and Biomedical Engineering, 6330: 63-76.
[6] Wei, X.G., Li, G., Chen, J., Dong, H. (2011) Ablation Properties Experiments of C/SiC Throat-Insert in Operational Environment of Rocket Engine. Advanced Materials Research, 1362: 165-168.
[7] Hu, Z.F., Fei, H. (2021) THERMAL COUPLING EFFECT ANALYSIS OF GEOTECHNICAL ENGINEERING REINFORCEMENT MATERIALS BASED ON FINITE ELEMENT ANALYSIS. Thermal Science Journal, 25: 4067-4073.
[8] Liu, L.L., Li, F.L., Huang, D.H. (2018) Research on the Restrained Stress of Early Age Concrete Under the Temperature Stress Test Machine. In: The 3rd International Conference on Material Engineering and Application (ICMEA 2018). Hongkong. pp. 28-29.
[9] Arya, R.K., Dvivedi, A. (2019) Thermal Loading Effect During Machining of Borosilicate Glass Using ECDM Process. In: 2019 4th International Conference on Advanced Materials Research and Manufacturing Technologies (AMRMT 2019). Oxford. pp. 12-17.
[10] LIN, W.F. (2019) Analytic Deformation and Stresses Solutions of Functionally Graded Rotating Disk under Mechanical and Thermal Load. In: 2019 4th International Conference on Automation, Mechanical and Electrical Engineering (AMEE 2019). Xiamen. pp. 277-283.