Effect of thermal barrier coating on thermal load of the rotor of the small aviation wankel engine

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Abstract. Due to its high-altitude, low-temperature, high-load, and air-cooled working environment, small aviation rotary engines have problems such as large component load and low heat dissipation efficiency. As the main moving part of the engine, the rotor is continuously exposed to the complex temperature field of the engine. As an effective high-temperature protective coating, the thermal barrier coating can isolate the heat load generated by the work of the combustion chamber and effectively improve the complex work condition of the triangular rotor. This paper takes the triangular rotor of a small aviation Wankel engine as the research object, and establishes the finite element model of the rotor and the coating. The engine thermodynamic simulation model is established by Simulink, and the combustion chamber temperature and heat transfer coefficient are calculated. The heat transfer coefficients of the other surfaces of the rotor were calculated by series thermal resistance, which were used as boundary conditions for finite element analysis of the rotor and the coating. The temperature field, stress field and deformation of the rotor before and after processing the thermal barrier coating are compared. The results showed that after the thermal barrier coating, the temperature of the rotor will drop by about 50K on average. The temperature of the pit and cooling hole of the rotor will drop by 17K and 16K respectively, and the temperature of the inner edge and side end surface of the sealing groove will drop by about 10K. The stress values at the inner side of the rotor seal groove, the inner cavity cooling hole, and the inner hole of the rotor are reduced by about 35.4MPa, 29.4MPa, 33.4MPa, respectively, and the stress value at the bonding layer is 150MPa, which is significantly higher than the stress value at the corresponding position of the original rotor, indicating that there is stress Concentration phenomenon. At the same time, the deformation at both ends of the rotor seal groove is reduced from 61.92μm to 52.55μm, and the difference in the axial deformation of each position is less than 3mm. It can be obtained that the thermal barrier coating can effectively reduce the radial deformation of the rotor and has little effect on the axial deformation of the rotor.

1. Introduction

Distributed cluster combat is a new form of combat on the battlefield in the future, and drone swarms composed of small drones are the main force to complete cluster combat tasks[1]. With the development of small drone technology towards miniaturization[2], its demand for power systems has gradually become prominent[3-4]. Wankel engine has the advantages of small size, simple structure, stable operation, high output power, etc., and has unique advantages in the application of non-small UAV power system[5-7].
Similar to the piston of a piston engine, the triangular rotor is the main load-bearing part and moving part of the wankel engine\cite{8-9}. The small aviation wankel engine has high speed, low heat dissipation efficiency and heavy component load due to its high-altitude, low-temperature, and high-load working environment. In addition, the high-temperature gas generated in the combustion chamber continuously exposes the working surface of the triangular rotor to a complex temperature field, making the working environment of the rotor even worse\cite{10-12}.

The thermal barrier coating has good heat insulation effect, high temperature oxidation resistance and thermal shock resistance\cite{13}. The application of thermal barrier coating to the working surface of the triangular rotor can effectively reduce the thermal load on the rotor and increase the temperature of the combustion chamber and improve thermal efficiency\cite{14-15}. Therefore, it is particularly important to study the influence of thermal barrier coating on the temperature field, stress field and deformation of the rotor. The thermal barrier coating selected in this paper is composed of a ceramic heat insulation layer (MgZrO3) and a metal bonding layer (NiCrAl). The ceramic heat insulation layer is used to insulate the heat generated in the combustion chamber, and the metal bonding layer is used to relieve the stress concentration caused by the thermal expansion mismatch between the insulation layer and the rotor substrate.

In this paper, the comparison results of the temperature field, stress field and deformation of the original rotor and the rotor after processing the thermal barrier coating are obtained by establishing the rotor and the thermal barrier coating model and performing finite element analysis on it\cite{16-17}. The simulation results show that after the thermal barrier coating, the temperature of the rotor will drop by about 50K on average. The temperature of the pit and cooling hole of the rotor will drop by 17K and 16K respectively, and the temperature of the inner edge and side end surface of the sealing groove will drop by about 10K. The temperature of the combustion chamber pits and cooling holes drops by 17K and 16K, respectively, and the stress values at the inner side of the rotor sealing groove, the inner cavity cooling hole, and the inner hole of the rotor are reduced by more than 30 MPa. At the same time, due to the stress concentration between the coatings, the stress value at the bonding layer is significantly increased compared with the original rotor. In addition, the thermal barrier coating also has a certain effect on the radial deformation of the rotor, but has a small effect on the axial deformation of the rotor. The deformation at both ends of the rotor seal groove is reduced from 61.92μm to 52.55μm. This research provides methods and technical support for the application of thermal barrier coating technology to the delta rotor of wankel engine.

2. Test materials and models

Taking a single-rotor small, air-cooled methanol aviation rotary engine as the research object, the main parameters of the research model are shown in Table 1.

| Table 1. Main parameters of the engine. |
|----------------------------------------|
| Project | Value  |
|--------------------------------------------------|
| Rated speed (r/min) | 15000 |
| Weight (g) | 335 |
| Displacement (mm²) | 4970 |
| Fuel | Methanol |
| Fuel consumption (kg/cycle) | 1.2×10⁻⁵ |
| Number of cylinders | 1 |
| Compression ratio | 8.5 |
| Shape parameter | 7.06 |
The material used for the triangular rotor substrate is aluminum alloy, which has the advantages of high strength and light weight. The ceramic layer material is MgZrO3, which has good heat insulation effect, strong oxidation resistance, and good toughness. The bonding layer material is NiCrAl, which is used to relieve the thermal expansion between the substrate and the heat insulation layer due to the deformation mismatch during the working process of the rotor. The stress concentration of the three materials is shown in Table 2.

| Material performance | Rotor substrate | MgZrO3 coating layer | NiCrAl bonding layer |
|----------------------|-----------------|----------------------|----------------------|
| Density (kg/m³)      | 2.77×10³        | 5.6×10³              | 7.87×10³             |
| Young's modulus of elasticity (MPa) | 7.1×10⁴ | 4.6×10⁴              | 9.0×10⁴              |
| Poisson's ratio      | 0.33            | 0.2                  | 0.27                 |
| Specific heat capacity (J·kg⁻¹K⁻¹) | 875     | 650                  | 764                  |
| Coefficient of thermal expansion (K⁻¹) | 2.3×10⁻⁵ | 8×10⁻⁶               | 1.2×10⁻⁵             |
| Thermal conductivity (W·m⁻¹K⁻¹) | 175       | 0.8                  | 16.1                 |

As shown in Figure 1, the thermal barrier coating is processed on the three working surfaces of the rotor substrate. The thickness of the ceramic layer material and the bonding layer material are 0.35mm and 0.15mm, respectively. During the modeling process, bonding connection between the coating and the substrate is adopted. The multizone meshing method is used to divide the rotor and the coating into high-order tetrahedrons. The mesh size of the rotor and coating are respectively 0.5mm and 0.1mm, and the mesh size of the contact surface is encrypted. The result is shown in Figure 2. The model has 1295045 finite element nodes and 2136803 units.
3. Determination of the heat transfer boundary

3.1. Thermal process simulation in the studio

A model of the thermal process in the cylinder of the rotary engine is established for zero-dimensional simulation\cite{18}. The initial data of the gas temperature and heat transfer coefficient in the cylinder are calculated by simulink\cite{19,20}, which are used as the heat transfer boundary conditions of the rotor analysis. At a speed of 15000r/min, the instantaneous temperature and heat transfer coefficient changes with time in a single cycle of the working chamber are shown in Figure 3.

![Graph](image)

**Fig.3 Variation of studio temperature with time**

3.2. Thermal boundary conditions of the rotor

After obtaining the instantaneous temperature and the instantaneous heat transfer coefficient, the average heat transfer coefficient and the average gas temperature of the rotor working surface in a single cycle can be obtained according to equations (1) and (2).
In the equation (1) and equation (2): $\alpha_{gm}$ is the average heat transfer coefficient, $T_{gm}$ is the average temperature, $\alpha_g$ is the instantaneous heat transfer coefficient and $T_g$ is the instantaneous temperature of the combustion chamber. The heat transfer coefficients of other parts of the rotor are corrected by the way of series thermal resistance, then, according to the temperature value in the actual working condition of the rotor, the selected position is shown in Figure 4, and the calculation results are shown in Table 3.

\[ \alpha_{gm} = \frac{1}{0.012} \int_0^{0.012} \alpha_g dt \]  
\[ T_{gm} = \frac{\int_0^{0.012} (\alpha_g \cdot T_g) dt}{\int_0^{0.012} \alpha_g dt} \]

4. Finite element analysis of the rotor

4.1. Analysis of temperature field

Using the boundary conditions obtained in Table 3, the temperature field cloud diagram of the rotor is obtained, and the result is shown in Figure 5(a). It can be seen from the figure that the highest temperature of the original rotor is 474K, which is located on both sides of the sealing groove at the top of the working surface, and the lowest temperature is about 456K, which is at the inner wall of the round hole at the waist. The temperature field of the rotor substrate for processing the thermal insulation
coating is shown in Figure 5(b). It can be seen that the temperature field distribution of the substrate and the original rotor are roughly the same. The highest temperature is about 464K, and the lowest temperature is about 443K.

![Image of temperature field cloud map](image1)

Fig.5 Temperature field cloud map of the rotor before and after the improvement

Figure 6 shows the temperature comparison between the original rotor and the rotor after processing the thermal barrier coating. The position numbers are shown in Table 3. It can be seen that the temperature of the rotor on both sides of the seal groove, the side edge of the seal groove, and the inner edge of the rotor is relatively high. Due to the heat transfer of the rotor structure and the cooling holes, the temperature of the center of the working surface of the chamber is about 10K lower than that on both sides of the sealing groove. After processing the thermal barrier coating, the temperature of all parts of the rotor dropped by about 10K, among which the temperature of the combustion chamber pit and the cooling hole dropped significantly, which were 17K and 16K respectively.

![Image of temperature comparison](image2)

Fig.6 Position and number of the rest of the rotor surface

Figure 7 shows the temperature cloud diagram of the thermal insulation coating and the bonding layer. It can be seen from the figure that the temperature of the upper surface of the thermal insulation coating is significantly higher than that of other surfaces. The maximum temperature of the thermal insulation coating reaches 524.4K, and the maximum temperature of the bonding layer is about 468K.
At the same time, due to the low thermal conductivity and high thermal resistance of the coating, the edges of the pits and coating edges have edges and corners, so the temperature here is relatively high and the temperature gradient is relatively large.

Select the three positions on both sides of the coating seal groove, the center of the cavity of the combustion chamber, and the side of the pit to solve the temperature perpendicular to the working surface. The result is shown in Figure 8. It can be seen that the maximum temperature at the edge of the sealing groove is about 512K. After passing through the heat insulation layer, the temperature drops to 464K, and after passing through the adhesive layer, the temperature drops to 462K, with a decrease of 48K and 2K respectively. The average temperature at the center and edge of the pit is about 10K lower than that of the insulation layer, and the drop is similar to the edge of the seal groove. Compared with the other three places, the temperature at the sides of the sealing groove has dropped significantly. After the heat insulation effect of the heat insulation layer, the temperature drops from 524K to 467K. The results show that the thermal insulation layer has a more obvious thermal insulation effect than the adhesive layer, which can effectively isolate the high temperature impact of the combustion chamber, and the side edge of the sealing groove has a more obvious temperature drop due to the boundary heat exchange effect.
4.2. Analysis of stress field

The heating of the rotor will produce axial thermal stress and thermal deformation, so a cylindrical constraint is imposed on the inner hole of the rotor to constrain its radial and circumferential displacement.

Figure 9 shows the stress field distribution of the original rotor and the rotor substrate with thermal insulation coating. It can be seen from Figure 9 that the stress at the inner hole and cooling hole of the rotor is relatively large, and the stress on both sides of the sealing groove is relatively small. This is because the edge of the rotor inner hole and the structure of the cooling hole have obvious changes and the temperature gradient is large, and there is a phenomenon of stress concentration. Compared with the original rotor, the stress distribution on the working surface of the rotor substrate with the heat insulation layer is more uniform. The maximum stress of the original rotor is 317.5MPa, and the maximum stress of the rotor matrix after processing the thermal insulation coating is 298.4MPa, which all appear at the edge of the inner hole of the rotor.

![Stress field cloud map of the rotor before and after the improvement](image-url)
Figure 10 shows the comparison result of the thermal stress value of the main position of the original rotor and the rotor with thermal insulation coating. It can be seen from Figure 10 that after processing the thermal barrier coating, the stress values at the inner edge of the sealing groove, the inner hole of the rotor, and the cooling hole of the inner cavity are all reduced. The three places have been reduced from the original 195.35MPa, 302.1MPa, and 143.9MPa to 159.96MPa, 272.66MPa, and 110.5MPa, respectively, with a significant decrease. At both ends of the combustion chamber pit and the sealing groove, the stress value of the rotor matrix is larger than that of the original rotor, and the increase is about 12.7MPa and 12.9MPa. This is because the thermal expansion between the matrix and the bonding layer does not match, resulting in stress concentration, so that the surface stress value of the substrate increases.

![Fig.10 Comparison of the thermal stress values of the main positions of the rotor before and after the improvement](image)

Figure 11 shows the stress cloud diagram of the thermal insulation coating and the bonding layer. It can be seen that the stress value of the bonding layer is significantly higher than that of the heat insulation layer. This is because the bonding layer acts as a transition between the heat insulation layer and the rotor base to relieve the stress concentration caused by the mismatch of thermal expansion. Due to its greater hardness, the thermal stress generated during deformation is greater.
Figure 12 shows the relationship between the distance and the stress value in the direction perpendicular to the pit of the combustion chamber. It can be seen that the stress value of the original rotor on the surface of the pit is about 49 MPa, and it gradually increases as the distance increases. At a distance of 2mm from the pit, due to the cooling effect of the cooling hole, the temperature gradient gradually increases and the stress rises more obviously, and finally the stress value at the inner hole of the rotor reaches 300MPa. The initial stress value of the rotor processed with thermal barrier coating is relatively high. After reaching the boundary of the bonding layer, the stress value instantly increases to a peak of 150 MPa, and then gradually decreases along the bonding layer. After reaching the rotor base, the stress value gradually rises, reaching the maximum value of 274MPa at the inner hole of the rotor. The stress value of the coated rotor base is generally lower than that of the original rotor. And the closer the position is to the inner hole, the more obvious the effect of the thermal insulation layer on the improvement of the rotor stress field is.
4.3. Analysis of Deformation Field

Figure 13 and Figure 14 show the deformation cloud diagram of the original rotor and the rotor substrate with thermal barrier coating and the comparison diagram of the deformation of the main rotor positions. It can be seen from the figure that after processing the thermal barrier coating, the deformation of the rotor at the combustion chamber pit, both sides of the sealing groove, the side edge of the sealing groove, and the cooling hole decreases significantly, and respectively reduced from the original 28.39μm, 61.92μm, 50.29μm, 47.2μm to 24.44μm, 52.55μm, 46.34μm, 36.99μm. The maximum deformation of the rotor also decreased from 69.8μm to 63.23μm, and both occurred on both sides of the seal groove. The difference between the axial deformation of the original rotor and the rotor base is no more than 3mm. It can be seen that the thermal barrier coating mainly reduces the radial deformation of the rotor, but has little effect on the axial deformation of the rotor.

![Deformation field cloud map of the rotor before and after the improvement](image)

Figure 15 is the deformation cloud diagram of the thermal insulation layer and the bonding layer, and Figure 16 is the relationship between the radial distance to working surface and the deformation amount of each position of the coating. It can be seen from the figure that the distribution of deformation...
on the upper and lower surfaces of the heat insulation layer and the bonding layer is basically the same, which is the same as that of the rotor. The maximum deformation appears on both sides of the sealing strip near the end surface because of the influence of axial deformation. And due to the small thermal expansion coefficient of the thermal insulation layer and the bonding layer, the deformation of the rotor hardly changes after reaching this area.

Fig.15 Deformation cloud map of the thermal insulation layer and the bonding layer

Fig.16 Change of deformation with distance in the direction perpendicular to the working surface

5. Conclusion
In this paper, the finite element simulation of the rotor and the thermal barrier coating shows the influence of the thermal barrier coating on the temperature field, stress field and deformation of the rotor. And after comparing with the temperature, stress, and deformation of original rotor, the following conclusions are obtained.
(1) The thermal barrier coating can effectively isolate the heat of the combustion chamber. After the thermal barrier coating, the temperature drops by about 50K on average, and the cooling effect of the thermal insulation layer is significantly higher than that of the adhesive layer. The temperature of the rotor substrate for processing the thermal barrier coating is reduced by about 10K compared with the original rotor, and the combustion chamber pits and cooling holes are reduced by 17K and 16K respectively.

(2) After processing the thermal barrier coating, the stress field distribution of the rotor matrix is more uniform, and the stress values at the inside of the rotor seal groove, cooling hole and rotor inner hole are reduced from 195.35MPa, 301.1MPa, and 143.9MPa to 159.96MPa and 273.66, respectively. MPa and 110.5MPa, the decrease rate is obvious. At the same time, due to the thermal expansion mismatch between the matrix, the bonding layer, and the heat insulation layer, stress concentration occurs on the bonding layer and the matrix surface, and the stress value increases to 150MPa.

(3) The thermal barrier coating can effectively reduce the radial deformation of the rotor. The deformation of the two ends of the coated rotor seal groove and the cooling hole are reduced from 61.92μm and 47.2μm to 52.55μm and 36.99μm, respectively, and the maximum deformation decreased from 69.8μm to 63.23μm. However, it has little effect on axial deformation. Due to the small thermal expansion coefficient of the thermal insulation layer and the bonding layer, the deformation of the rotor hardly changes after reaching the coating area.

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