Investigation of Heat Transfer Characteristics on Rod Fastening Rotor

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Abstract. In order to study the contact heat transfer characteristics on the joint interface of the distributed rod fastening rotor under the influence of different pretension and the roughness of different wheel disk. The thermal contact resistance fractal model on the joint interface of the distributed rod fastening rotor is established, and the thermodynamic calculation of the rod fastening rotor is carried out. A contact heat transfer characteristic test rig for the rod fastening rotor is designed and built. The temperature field of the rod rotor is measured with the change of the tension force of the pull rod and the surface roughness of the wheel. The results show that the heat transfer coefficient of the joint interface increases with the increase of the pretension of the rod, and decreases with the increase of the surface roughness of the wheel. The thermal contact resistance fractal model of the joint interface is verified, and it is proved that it is suitable for the study of the thermal contact resistance on joint interfaces.

1. Introduction
The distributed rod fastening rotor has the advantages of easy processing, light weight and easy cooling channel design, and is widely used in heavy duty gas turbines and aero engines [1]. There are a large number of joint surfaces between the distributed tie rod rotor disks, and the structural non-continuity makes the thermodynamic modeling and analysis more complex than the overall rotor.

A review of related databases reveals that there are few literatures on the heat transfer characteristics of the connecting surfaces of distributed rod rotor disks. Reference [2] studied the simple test device for thermal contact resistance based on the one-dimensional steady-state heat transfer principle and found that the extrusion stress was the main factor affecting the thermal contact resistance. Reference [3] calculated and designed a simple test device through theoretical calculation to prove that the thermal resistance of the contact surface has a very important influence on the heat transfer and deformation of the system itself. Reference [4] analyzed the statistical characteristics of the surface roughness profile of the machined surface and based on the single-point contact thermal conduction theory model and the elastic deformation theory model, the contact thermal resistance theoretical model was further simplified. Reference [5] built a test platform that can be used for high temperature contact thermal resistance tests. Through tests, the variation law of contact thermal resistance under different interface stresses, interface roughness, and interface temperature was obtained. With the deepening of the fractal theory research, reference [6] considered the shrinkage
thermal resistance at the contact point based on the M-T contact heat conduction fractal model and corrected the M-T model. Reference [7] and [8] used fractal theory to perform heat transfer analysis on elastic contact interfaces.

At present, the theoretical analysis of the thermal contact resistance often puts forward many assumptions to simplify the analysis process [9, 10], and the calculation parameters do not fully consider the temperature change [11] in the analysis and calculation, so the model fails to characterize the contact of the roulette face heat transfer characteristics. In the experimental study, there is no report on the contact heat transfer test of the tie rod rotor disc interface [12].

Based on the characteristics of the tie rod rotor, based on the literature [9], the influence of the physical properties of the material on the thermal contact resistance of the joint surface is dynamically considered, and the fractal model of the contact resistance of the tie rod rotor disk is improved.

2. Disc Contact Surface Thermal Resistance Fractal Model

For metal contact problems, when the temperature is lower than 900K, the share of radiation heat transfer in the total contact heat transfer is less than 2%. Therefore, the radiative heat transfer between the gaps can be ignored at normal temperatures. In general, the medium in the joint gap is lubricating oil or air, and its thermal conductivity is much smaller than that of metal materials. Therefore, the medium thermal conduction term can be neglected, and the contact surface heat transfer coefficient can be expressed as [9]:

$$h_c = \frac{1}{L_g} \frac{A_c \cdot 2 \lambda_a \lambda_b}{\lambda_a + \lambda_b}$$  \hspace{1cm} (1)

Among them, $h_c$ is the contact surface heat transfer coefficient, $\frac{W}{m^2 \cdot K}$; $L_g$ is the thickness of the joint surface gap space to participate in heat transfer, $m$; $A_c$ is the actual contact area of the joint surface, $m^2$; $A$ is the nominal contact area of the joint surface, $m^2$; $\lambda_a$ and $\lambda_b$, are the thermal coefficient of the two-wheel disk, $W/(m \cdot K)$. The surface contact thermal resistance $R_c$ is in inverse proportion to the contact surface heat transfer coefficient, ie:

$$R_c = \frac{1}{h_c A}$$  \hspace{1cm} (2)

When the surface roughness of the two disks is the same, the thickness $L_g$ of the heat transfer surface in the interstitial space can be expressed by the following equation:

$$L_g = 2(z - \delta_L)$$ \hspace{1cm} (3)

In the formula, $\delta_L$ is the maximum deformation of the micro-convex peak of the combined surface, $m$; $z$ can be taken as the height of the micro-level ten points $R_z$, $m$. According to the fractal theory, the maximum deformation of micro-convex peaks at the combined surface $\delta_L$ is [14]:

$$\delta_L = G^d \cdot \left(2\delta_L \right)^{2-d/2}$$ \hspace{1cm} (4)
In the formula, \( a_L \) is the largest contact area between the bonding surfaces, \( m^2 \). Bringing equation (4) into equation (3) yields the thickness \( L_a \) of the heat transfer surface in conjunction with the interstitial space:

\[
L_a = 2 \left[ \frac{1}{2} - \frac{G^{\beta-1}}{a_L} \right]^{\frac{1}{2-\beta}} \]

(5)

\[
A_c = \frac{D}{2 - D} \psi^{\frac{2-D}{2}} a_L \]

(6)

In the formula, \( A_c \) is the actual contact area, \( D \) is the fractal dimension, which is related to the surface roughness; \( \psi \) is the domain expansion factor of the micro-contact size distribution (\( \psi > 1 \)), which can be found in the literature [8]. The relationship between the tie rod preload and the actual contact area of the joint surface is [15]:

When \( 1 < D < 2 \) and \( D \neq 1.5 \)

\[
P = \frac{2^{\frac{12-3D}{2}} D_{c}^{\frac{1}{2}} G^{\frac{1}{2}}}{3^{D}} \left( \ln \gamma \right)^{\frac{1}{2}} \frac{D}{a_L} \left( \frac{3-2D}{a_L^2} - \frac{3-2D}{a_e^2} \right) + \frac{2^{\frac{2-D}{2}} D}{2 - D} \frac{2-D}{a_L a_e^2} \]

(7)

When \( D = 1.5 \)

\[
P = 2^\frac{7}{4} \pi \frac{1}{2} G^{\frac{1}{2}} E^{\frac{1}{2}} \psi^{\frac{1}{2}} \left( \ln \gamma \right)^{\frac{1}{2}} \frac{a_c}{a_e} + 6 K Y^{\frac{1}{2}} E^{\frac{1}{2}} a_L^{\frac{3}{2}} a_e^{\frac{3}{2}} \]

(8)

\[
E^* = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \]

(9)

\( E_1, E_2, \nu_1, \nu_2 \) are the elastic moduli and Poisson’s ratio of the two contact materials respectively; \( G \) is the fractal roughness, \( m \), related to the surface roughness; \( \gamma \) is the spatial frequency of the random profile, \( \gamma = 1.5 \) is more suitable for high spectral density the random phase and phase; \( a_c \) is the critical contact area of the microbump, \( m^2 \). \( K \) is the ratio of the hardness \( H \) of the softer material to its yield strength \( Y \). Micro convexity critical contact area \( a_c \) is:

\[
a_c = \frac{G^2}{\left( H/2E^* \right)^{\frac{\beta-1}{2}}} \]

(10)

\[
H = \frac{\sigma_b}{3.4} \]

(11)

In the formula, \( \sigma_b \) is the tensile strength, Mpa. The relationship between the fractal parameters \( D \), \( G \) and the surface roughness parameter \( R_a \) is [16]:
\[ D = 1.515 \frac{1}{Ra^{0.088}} \]  

(12)

\[ G = 10^{\frac{8.259}{Ra^{0.088}}} \]  

(13)

The scope of application of formulas (12), (13): grinding of parts surface, roughness Ra = 0.1 ~ 3.2.

| Temperature /°C | 20   | 100  | 200  | 300  | 400  | 500  |
|-----------------|------|------|------|------|------|------|
| Elastic Modulus $E/ \times 10^5$ MPa | 2.09 | 2.07 | 2.02 | 1.96 | 1.86 | 1.74 |
| Tensile Strength $\sigma_b$ (MPa) | 639  | 605  | 702  | 728  | 573  | 383  |
| Poisson's ratio $\nu$ | 0.269 | 0.270 | 0.290 | 0.312 | 0.309 | 0.308 |
| Thermal Conductivity $\lambda / \text{W·(m·K)}^{-1}$ | 48.2 | 48.1 | 46.5 | 44.0 | 41.4 | 38.1 |
| Thermal diffusivity $a / \times 10^{-6} \text{m}^2\text{s}^{-1}$ | 11.7 | 11.2 | 10.3 | 9.2 | 8.3 | 7.0 |
| Specific heat capacity $c / \text{J·(Kg·°C)}^{-1}$ | -- | -- | 578 | 624 | 649 | 716 |

The rods of the lever rotor and the tie rod are made of No.45 steel. The physical properties of the rod at different temperatures can be found in the manual for metal materials, as shown in Table 1. The parameters are brought into equations (7)~(13) to find $L_a$, and bring $L_a$ to equations (5) and (6) to find $g$, $A_c$; then bring $g$, $A_c$ into formula (1). The surface contact heat transfer coefficient $h_c$ is obtained.

3. Test platform Introduction

The entire test device consists of a rod fastening rotor test piece, a preloading system, a heating system, and a temperature measurement system. Based on Atec F-10/380T-G1F18 portable medium frequency induction heater, a test platform suitable for the contact heat transfer study of the distributed lever rotor disc interface is constructed, as shown in Figure 1.

3.1. Rod Rotor Specimen

The rod fastening rotor presses the four discs in series by means of eight circumferentially uniform tie rods. Each block has an outside diameter of $D=140\text{mm}$, an inside diameter of $d=80\text{mm}$, a thickness of $H=37\text{mm}$, and eight rod holes of $\phi=11\text{mm}$ are uniformly distributed in the circumferential direction.

In order to study the influence of surface roughness of different discs and pre-tightening force of different rods on the contact heat transfer between the disc and the disc surface, two discs with $Ra=0.4$ and 0.8μm were set up, $P=40$, 75, 100KN. Three kinds of target rod preload. The rod rotors with different roughness grades and tie rod preloads are assembled by different combinations.
3.2. Fastening Rod Preload Force Loading System
The pre-tightening force of the rod rotor test piece is measured through axial strain during the tensioning process. Because the pressure sensor is not resistant to high temperatures, it is not possible to carry out a heating test with the sensor. Therefore, by assembling the pre-tightening force calibration device of the rod and connecting the pressure sensor acquisition and processing system, the torque value of the digital torque wrench and the pre-tightening force of the rod are fitted, and the relation between the tightening nut torque and the pre-tightening force of the rod is obtained, so that the rod will be pulled. The preload applied by the rotor translates into tightening the nut torque.

Based on the above research platform, the contact heat transfer test of the rod rotor specimen is carried out. The heating time is 1 hour, and the temperature time history of each measuring point is measured.

4. Results and Analysis

4.1. Test Result
After importing the data of the acquisition software into the MATLAB software, the test parts of the rod fastening rotor with roughness of Ra=0.3492 are obtained. The temperature time history of each thermocouple under the pretightening force of different pull rods is shown as shown in Figure 2. Based on the first section fractal contact thermal resistance theoretical calculation model, the axial temperature distribution of the outer surface of the pull rod rotor is calculated by the ANSYS software, for example, the axial simulation of the temperature distribution of the outer surface of the rotor of a pull rod rotor for 1 hours is shown in Figure 3 as a pull rod rotor (Ra=0.3492 m).

![Figure 2](attachment:fig2.png)

**Figure 2.** Temperature time history of each thermocouple in a pull rod rotor (Ra=0.3492μm).

![Figure 3](attachment:fig3.png)

**Figure 3.** Rod Rotor (Ra=0.3492μm) ANSYS Calculation Temperature.

The temperature of each measuring point heated 1 hour (3600s) in Figure 2 is extracted and compared with the temperature calculated by simulation and analysis in Figure 3. As shown in Figure 4, a comparison diagram of the axial temperature distribution of the outer surface of a rod fastening rotor is shown for 1 hour. The real line represents the measured temperature field in the figure, and the virtual line represents the temperature field of ANSYS simulation.
4.2. Test Analysis
Compared with Figure 9 (a) and (b), the smaller the roughness of the wheel faces, the greater the contact heat transfer coefficient of the wheel joint under the same tension preload. The smaller the face roughness of the wheel is, the better the continuity of the temperature field of the rod fastening rotor is, and the higher the temperature at the end of the rod fastening rotor. The temperature gradient of the joint of the Ra=0.3492 rod fastening rotor is smaller, and the temperature of the rotor end is higher than that of the Ra=0.92 rod fastening rotor. This is because the decrease of the surface roughness of the wheel will not only lead to the increase of the contact area in which the surface is actually involved in the heat transfer, but also the increase of the thermal conductivity of the specimen and the decrease of the hardness of the interface. These factors make the resistance of the heat transfer smaller, thus reducing the contact thermal resistance of the interface.

In the same roughness, the greater the pre tension force of the pull rod is, the greater the contact heat transfer coefficient is, the greater the pretension of the pull rod, the better the continuity of the temperature field distribution of the rod fastening rotor, the smaller the temperature step of the connecting plane of the rod fastening rotor and the higher the end temperature of the end of the rod fastening rotor in Figure 4 (a) and (b). This is because the increase of the pretension of the pull rod makes the micro convex peak of the contact between the joint surfaces of the rod fastening rotor disc compression deformation. With the increase of the pre tightening force of the pull rod, the elastic deformation occurs in the joint surface, which leads to the increase of the number of micro convex peaks and the contact area of the contact surface, which directly results in the actual participation of the interface. The area of heat transfer increases, which leads to the increase of the contact heat transfer coefficient of the connecting rod of the rotor.

The measured data (solid line) and theoretical calculation data (dashed line) of Figure 4 (a) and (b) are compared. Although there is a large error in the measured temperature of the 2 point and the theoretical calculation temperature, it may be because in the actual measurement process, the number 2 thermocouple is close to the Haff single loop inductor, which is greatly disturbed and cannot reflect the temperature of the 2 point. Ignoring the error of point 2, the results of theoretical models are very close to the measured results either from the numerical or the trend. It can be seen that the contact surface thermal resistance fractal model can be applied to the study of contact thermal resistance of the distributed rod rotor disc joint surface.

5. Conclusion
(1) It is feasible to use fractal theory to study the contact thermal resistance of the connecting rod of the rotor.

(2) The fractal model of the contact thermal resistance of the wheel disk is verified by the test method. It is suitable for the study of the contact thermal resistance of the disc of the distributed rod fastening rotor. The model can be applied to the general engineering calculation.
(3) The test data show that the pretension of the draw bar and the surface roughness of the disc will have an important influence on the overall temperature field distribution and heat flux transmission of the rod rotor.

(4) When the surface roughness of the roulette is constant, the contact heat transfer coefficient increases with the increase of tension force.

(5) When the tension force of the pull rod is constant, the contact heat transfer coefficient increases with the roughness decreasing.

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