Simulation of the Thermal Contact Resistance Characteristics on Rod Fastening Rotor

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Abstract. The thermal contact resistance model of the rod fastening rotor is improved, which can be more suitable for the engineering condition. By means of numeric simulation, the relationships between characteristics of the heat transfer between contact interfaces and the pre-tightening force of the tie rod, the surface roughness and the temperature of the contact interface are revealed intuitively. The simulation results show that the coefficient of contact heat transfer between the contact interfaces will increases with the pre-tightening pretension of the tie rod, will decreases with the increase of the surface roughness, and will increases with the increase of the surface temperature. It is also shown that the thermal contact resistance between the contact interfaces will have an important influence on the overall temperature distribution and heat transfer of the rod fastening rotor, and the thermal contact resistance between the interfaces must be considered when the temperature field distribution of the rod fastening rotor are accurately researched.

Keywords: rod fastening rotor; thermal contact resistance; numeric simulation; temperature field analysis.

1. Introduction
Because of the advantages of higher rigidity, higher strength, lighter weight, easier assembly and disassembly, and realization of cooling channels, rod fastening rotor is widely used in heavy duty gas turbines\[1\]. Structurally, it is no longer a continuous whole. The structural non-continuity makes its thermodynamic analysis more complex than conventional rotors. The connecting surface of the rod fastening rotor discs is complete state in contact with the two surfaces in the macroscopic view. However, because of the microscopic unevenness of the surface, the two contact surfaces only contact with each other at some micro-convex peaks, and the actual contact area of the bonding surface less than nominal contact area\[2\].

Research shows that thermal contact resistance is a strongly nonlinear problem influenced by many factors such as surface topography, material thermal properties and load, temperature, and medium\[3\]–\[6\]. The traditional model uses statistical parameters such as root mean square gradient and instrument resolution. The measurement results of different instruments are not unique. Fractal theory uses fractal dimension-independent parameters such as fractal dimension when describing rough surfaces to provide surface roughness information that exists on fractal surfaces. For this reason, literature\[7\] considered the shrinkage thermal resistance at the contact point based on the M-T contact thermal model and corrected the M-T model. Literature\[8\] and\[9\] used the fractal theory to perform heat transfer analysis on elastic contact interfaces. Literature\[10\] applied fractal theory and traditional heat conduction theory to establish a fractal model of thermal contact resistance, which makes it more suitable to study the contact thermal resistance of the connecting surfaces.
2. Model of Contact Surface Thermal Resistance

Figure 1 is a simple model to study the thermal resistance characteristics of the connecting interfaces of the rod fastening rotor. The rod fastening rotor is consist of five discs pressed by eight circumferential rods. The outer diameter of the disc $D=140\text{mm}$, inner diameter $d=80\text{mm}$, and thickness of each disk were same, and uniformly distributed 8 holes in the circumferential direction.

![Figure 1. Model of the thermal contact resistance of the connecting interfaces.](image)

There are three ways to transfer heat between the coupling surfaces of the rod fastening rotor. It has shown that for metal contact problems, when the temperature is lower than 900K, the radiation heat transfer is less than 2\% in the total contact heat transfer \[11\]. Therefore, the radiative heat transfer between the gaps can be ignored. The medium in the connecting interfaces is lubricating oil or air, and its thermal conductivity is much smaller than that of metal materials. Therefore, the medium heat conduction can be neglected, and the heat transfer coefficient of the contact surface $h_c$ can be expressed as:

$$ h_c = \frac{1}{L_g} \frac{A_c}{A} \frac{2\lambda_A\lambda_B}{\lambda_A + \lambda_B} $$ \hspace{1cm} (1)

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

Among them, $h_c$ is the heat transfer coefficient of the contact surface, $W/(m^2.K)$; $L_g$ is the thickness of the connecting interfaces gap to participate in heat transfer, $m$; $A_c$ is the actual contact area of the connecting interfaces, $m^2$; $A$ is the nominal contact area of the connecting interfaces, $m^2$; $\lambda_A$ and $\lambda_B$ are the thermal coefficient of the disk, $W/(m.K)$. The thermal contact resistance $R_c$ is in inverse proportion to the contact heat transfer coefficient $h_c$.

When the surface roughness of the two disks is the same, the thickness $L_g$ of the connecting interfaces gap can be expressed by the following equation:

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

$\delta_l$ is the maximum deformation of the micro-convex peak of the connecting interfaces, $m$; $z$ can be taken as the height of the roughness $R_z$, $m$. According to the fractal theory \[12\]:

$$ \delta_l = G^{d-1}(2a_l)^{\frac{2-d}{2}} $$ \hspace{1cm} (4)

$a_l$ is the largest contact area between the connecting interfaces, $m^2$. Bringing equation (4) into equation (3), it can be obtained:

$$ L_g = 2[z - G^{d-1}(2a_l)^{\frac{2-d}{2}}] $$ \hspace{1cm} (5)

Based on the fractal theory, the actual contact area $A_c$ of the connecting interfaces is obtained \[8\]:

$$ A_c = \frac{D}{2 - \frac{D}{2}} \psi^{\frac{2-d}{2}} a_l $$ \hspace{1cm} (6)
In the formula, $D$ 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 rod preload and the actual contact area of the connecting interfaces is as follows [13].

When $1 < D < 2$ and $D \neq 1.5$

$$P = \frac{12 - 3D}{2} \frac{D - 1}{D} \frac{D}{3} \left( \ln \gamma \right) ^{\frac{1}{2}} \frac{2 - D}{2} \frac{D}{a} \left( \frac{3 - 2D}{a^2} - \frac{3 - 2D}{a_c^2} \right) + \frac{2 - D}{2} \frac{D}{a} \left( \frac{3 - 2D}{a^2} - \frac{3 - 2D}{a_c^2} \right)$$

(7)

When $D = 1.5$

$$P = 2^4 \pi \frac{\gamma}{3} \frac{E^*}{\psi^4} \left( \ln \gamma \right) ^{\frac{1}{2}} \frac{3}{a^2} \frac{1}{a_c^2} \ln \frac{a_c}{a} + 6KY \psi^4 \frac{1}{a^2} a_c^4$$

(8)

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

(9)

$E^*$ is the composite elastic modulus, MPa. $E_1, E_2, \nu_1$ and $\nu_2$ are the elastic modulus and Poisson's ratio of the materials respectively; $G$ is the fractal roughness parameter, m, which is related to the surface roughness; $\gamma$ is the spatial frequency of the random profile, $\gamma = 1.5$ is more suitable for high spectral density; $a_c$ is the critical contact area of the connecting interfaces, m$^2$; $K$ is the ratio of the hardness $H$ of the softer material to its yield strength $Y$. According to literature [13], $\sigma_b$ is the tensile intensity, MPa, $a_c$ and $H$ are as follows:

$$a_c = \left( \frac{G^2}{H/2E^*} \right)^{\frac{1}{2D-1}}$$

(10)

$$H = \frac{\sigma_b}{3.4}$$

(11)

The relationship of the fractal parameters $D, G$ and the surface roughness parameter $R_a$ is as follows [14].

$$D = \frac{1.515}{R_a^{0.088}}$$

(12)

$$G = 10^{8.259}$$

(13)

The traditional thermal contact resistance model only considers the variation of individual or partial parameters with temperature, which does not completely calculate the actual thermal contact resistance. When the rod fastening rotor actually operates in the gas turbine, the physical parameters of each component will change with the temperature. The rod fastening rotor model materials in figure 1 are all No. 45 steels. The physical properties of the rods can be obtained from the manual of the metal materials as shown in table 1. The parameters are brought into equations (7) ~ (13) to find $a_c$, and bring $a_c$ to equations (5) and (6) to find $L_{sr}, A_c$; then bring $L_{sr}, A_c$ into equation (1). The surface contact heat transfer coefficient $h_c$ can be obtained.

In summary, the contact surface heat transfer coefficient and the rod pre-tightening force are both functions of the actual contact area of the connecting interfaces, and the nonlinear relationship between them is established by the above equations. The above solution step can obtain $h_c$ at different conventional temperatures. From equation (2), the thermal contact resistance can be obtained. $h_c$ is often used in finite element analysis. Therefore, only $h_c$ will be analyzed and solved in the following.
Table 1. Physical parameters of rod fastening rotor

| Temperature (°C) | Elastic Modulus (×10^5 MPa) | Tensile Strength (MPa) | Poisson's ratio | Thermal Conductivity (W/m.k) | Thermal diffusivity (×10^-6 m^2/s) | Specific heat capacity (J/kg.℃) |
|-----------------|-----------------------------|------------------------|-----------------|-------------------------------|-----------------------------------|---------------------------------|
| 20              | 2.09                        | 639                    | 0.269           | 48.2                          | 11.7                              | --                              |
| 100             | 2.07                        | 605                    | 0.270           | 48.1                          | 11.2                              | --                              |
| 200             | 2.02                        | 702                    | 0.290           | 46.5                          | 10.3                              | 578                             |
| 300             | 1.96                        | 728                    | 0.312           | 44.0                          | 9.2                               | 624                             |
| 400             | 1.86                        | 573                    | 0.309           | 41.4                          | 8.3                               | 649                             |
| 500             | 1.74                        | 383                    | 0.308           | 38.1                          | 7.0                               | 716                             |

3. Analysis of Heat Transfer Characteristics on the Connecting Interfaces

Based on the above improved model, the effects of different roughness, different rod pre-tightening forces, and different temperature on the thermal contact resistance of the connecting interfaces were calculated. Three kinds of discs with roughness Ra = 0.2, 0.4, and 0.8μm are set, pre-tightening forces P = 30, 40, 50, 75, 100, 125kN, temperature T = 20, 100, 200, 300, 400, 500℃. By analyzing and comparing the calculated data, the change rule of h_c with Ra, P and T can be drawn. Figure 2(a) to (f) respectively shows the relationship between the contact heat transfer coefficient h_c of the connecting interfaces and the surface roughness Ra of the disc and the pre-tightening force P at different temperatures T. h_c increases as the P increases. This is because the increase of the pre-tightening force makes the micro-convex peaks in the connecting interfaces deformed. As the pre-tightening force increases, the contacting interfaces undergo elastic deformation, which results in contact between the bonding surfaces. The number of micro-convex peaks and the contact area increase, which directly results in an increase in the area where the heat transfer between the bonding surfaces actually participates, resulting in an increase of h_c. h_c decreases as the roughness Ra increases. When Ra is the smaller, the surface of the wheel is the smoother. Under the ideal conditions, there is no thermal contact resistance for the smooth contact surfaces.
The surface contact heat transfer coefficient $h_c$ first increases, then decreases, and then increases again as the joint surface temperature $T$ rises, and $h_c$ increases as a whole. The main reason is that the temperature will affect the physical properties and surface contact conditions of the disk material. For steel 45, as $T$ increases, its elastic modulus $E$ and thermal conductivity $\lambda$ decrease, while the hardness $H$ changes first, then increases, then decreases.

4. Temperature Field Analysis

The hindrance to the heat flow is mainly caused by the thermal contact resistance between the connecting interfaces of disks. Each disk is simplified to have the thickness, the same inner and outer diameters. Since the rod fastening rotor is an axisymmetric structure, its eighth model is used to simplify the analysis. The heat transfer coefficient between the connecting interfaces solved by the above equations is used in ANSYS.

Figure 3 shows cloud diagram of the temperature field distribution of one-eighth rod fastening rotor with one-hour heating under conditions of $R_a=0.4 \mu m$ and $P=30kN$. The highest temperature occurs on the first disk. It can be found that the temperature distribution is not continuous at the first disk. The temperature distribution at the connecting interfaces of the second, third, and fourth disks is actually discontinuous, since ANSYS only uses one colour to represent the temperature difference section, the display is not obvious.

Figure 4 shows the variation of the axial temperature of the outer surface of the rod fastening rotor. The horizontal ordinate indicates the axial position of the rod fastening rotor, and the longitudinal coordinates indicates the temperature. Due to the fact that the variations of the roughness are consistent, the results of the roughness $R_a=0.4 \mu m$ are only shown. In figure 5(a), it is found that there are jumps in the temperature distribution at the axial positions of 37mm, 74mm, 111mm, and 148mm. The temperature difference occurs at the positions. Comparing figure 5 (a) to (f), it can be found that, when the pre-tightening force $P$ increases, the temperature of the rotor end also increases after heating for 1 hour. The rotor end temperature with different pre-tightening forces was 279.469°C, 290.734°C, 297.34°C, 305.746°C, 309.733°C, 312.006°C. It is clear that at $P=125kN$, the end temperature is
higher than that at $P=30\text{kN}$. In addition, with the increase of the pre-tightening force $P$, the temperature jump at the connecting interfaces between the same discs becomes less and less obvious. That is, the temperature difference at the connecting interface becomes smaller and smaller, and the continuity of the temperature field becomes better and better.

Further research results show that, when the surface roughness $R_a$ increases, the temperature of the rotor end decreases. When $R_a=0.2\mu m$, the rotor end temperature is higher than when $R_a=0.8\mu m$. The pre-tightening force $P$, the surface roughness $R_a$ of the disc, and the temperature $T$ of the joint surface have a great influence on the contact heat transfer coefficient $h_c$ of the connecting surface. Heat flow has an important impact. Therefore, in order to obtain a precise temperature field, the contact thermal resistance of the wheel and the disk must be taken into consideration.

**Figure 4.** The axial temperature variation of the rotor with pre-tightening force $P$

5. Conclusion
The improved fractal model makes it more suitable to study the thermal contact resistance of the connecting interface of the rod fastening rotor, which reveals the non-linear implicit function
relationship between the contact heat transfer coefficient of the connecting interface and the pre-tightening force of the rods, and the surface roughness of the discs. The heat transfer coefficient of the connecting interface would increase when the pre-tightening force of the rod increases, and surface roughness of the disks decreases, the temperature of the disk surface increases. The thermal contact resistance of the connecting interface have an important influence on the overall temperature field distribution and heat transfer of the rod fastening rotor. Therefore, in order to obtain a precise temperature field of the rod fastening rotor, the thermal contact resistance of the connecting interface must be taken into consideration. In the paper, when the fractal model of contact thermal resistance of the joint surface is established, the relationship between fractal parameters $D$, $G$ and roughness $R_a$ is established according to the reference [14], which may have some influence on the research results. The future research would be to establish the relationship between the parting parameters and the roughness of the joint surface, which could further improve the model accuracy.

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