Study on the Ice-Coated Brake Disc for EMUs Based on Force Coupling

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Abstract: Based on the abnormal wear of the brake disc of Electrical Multiple Units (EMUs), considering the ice-coated friction pair, the finite element (FE) models of the brake disc, the friction blocks and ice impurity were established in ANSYS to explore the stress characteristics of the brake disc. For the ice-coated model, it is found that the maximum equivalent stress is 956.75MPa under the condition of pad stress of 25kN and initial braking speed of 250 km/h. The value of the maximum stress on brake disc surface decreased by 400MPa while removing the ice impurity. The maximum Z-displacement on the ice-coated disc is nearly 4.7mm, and with the contact point farther away, the smaller the deformation will be. The overall trend of the equivalent stress and Z-displacement of the brake disc increases with the braking pressure increasing. Droplet-like frictional blocks can improve the maximum stress and Z-displacement of the disc. Therefore, it is suggested that droplet-like frictional blocks are used for the braking equipment. For improving abnormal wear of the brake disc in extremely cold and snow environment, the analysis provides important reference and theoretical basis for engineering.

1. Introduction

Because of the thermal stability and braking efficiency, the disc-type brake has been widely used in EMUs. During braking, the friction between the brake disc and the friction blocks generates heat and the temperature gradient caused by uneven temperature distribution result in thermal stress of the brake disc. Besides, the repeated high and low temperature cycles lead to the crack damage of the brake disc, which would cause the brake disc failed at worst. The failure of friction pair not only increase the operation cost, but also affect the operation safety of the train[1].

In 2012, China's independently developed high-speed railway from Harbin to Dalian began to operate, which is the first high-speed railway to cross the cold region. Since the operation of the EMUs, it occurred frequently that the bogie and the basic brake unit were covered with snow and ice mixed with gravel and metal debris. The heat capacity of the ice impurity is smaller and their temperature changes faster than that of the brake disc, so the hardness of the ice impurity is higher than that of the brake disc material, leading to the abnormal wear of brake discs [2].

At present, aiming at the abnormal abrasion of brake disc in high-speed EMUs under high-cold conditions, most studies focus on thermal fatigue crack. Li Jishan et al. [3] studied the abnormal scratches on brake discs and optimized the structure of brake pad for cold weather, and its performance was tested by braking dynamic test. Qian Kuncai et al. [4] studied the influence of impurities between brake pads on friction performance on 1:1 brake friction pair test bench, and the variation rule of friction coefficient was obtained. Based on original structure, Zhao Minghua et al. [5] developed a basic brake device for
EMUs in high-cold environment. Cheng Dandan et al. [6] studied the friction coefficient of brake pad under different braking pressure and environmental conditions on the pin-disc friction test rig. Lee et al. [7] studied the effect of humidity on friction coefficient at low speed on the pin-disc friction test rig. Pyung Hwang et al. [8] established the three-dimensional thermo-mechanical coupling model of the friction pair to simulate the contact friction process between the brake disc and the brake pad and analyzed the distribution of temperature field and stress field of the friction pair under contact pressure.

The above researches on the damage of brake disc of EMUs in the cold and snow environment are mostly based on the test method, which were limited by the experiment cost and the experiment conditions. In order to study the influence of the external hard particles (ice impurity) clamped between the friction blocks [9] on the brake disc and the mechanism of action, exerting different conditions of operation speed and brake pressure, this paper studied the equivalent stress and deformation of the brake disc by establishing the FE models of the brake disc, the friction blocks and ice impurity. The results can provide an important theoretical basis for engineering research.

2. The wear model of the ice-coated friction pair

2.1. The basic principle of elastic mechanics.

Due to the action of external force, the stress, strain and displacement will be generated in the friction pair in three-dimensional direction, which are continuous functions [10]. By the relationship between stress and strain and between strain and displacement, the problem can be solved [11-13]. Under certain deformation conditions, when the equivalent stress of a point in the object reaches a certain value, the plastic deformation will appear, shown in Eq. (1).

\[
\bar{\sigma} = \frac{1}{\sqrt{2}} \left[ \left( \sigma_x - \sigma_y \right) + \left( \sigma_y - \sigma_z \right) + \left( \sigma_z - \sigma_x \right) + 6 \left( \tau_{xy} + \tau_{yz} + \tau_{zx} \right) \right] \leq \sigma_z
\]  

(1)

In general, the three-dimensional deformation stress-strain relationship of isotropic elastic materials meets the Hooke's law, shown in Eq. (2) and Eq. (3).

\[
\varepsilon_x = \frac{1}{E} \left[ \sigma_x - v \left( \sigma_y - \sigma_z \right) \right], \quad \varepsilon_y = \frac{1}{E} \left[ \sigma_y - v \left( \sigma_x - \sigma_z \right) \right], \quad \varepsilon_z = \frac{1}{E} \left[ \sigma_z - v \left( \sigma_x - \sigma_y \right) \right]
\]

\[
\gamma_{xy} = \frac{\tau_{xy}}{G}, \quad \gamma_{yz} = \frac{\tau_{yz}}{G}, \quad \gamma_{zx} = \frac{\tau_{zx}}{G}
\]

(3)

where \( \sigma_x, \sigma_y, \sigma_z \) and \( \varepsilon_x, \varepsilon_y, \varepsilon_z \) are the stress and strain in three coordinate directions. \( E \) is the elasticity modulus. \( v \) is the Poisson ratio. \( \tau_{xy}, \tau_{yz}, \tau_{zx} \) and \( \gamma_{xy}, \gamma_{yz}, \gamma_{zx} \) are the shear stress and shear strain. \( G \) is the shear modulus, and \( G = \frac{E}{2(1+v)} \).

2.2. The geometric model of the ice-coated friction pair

Referring to the real shape of friction pair of EMUs (shown in Fig. 1), the simplified geometric models of ice impurity, friction blocks and the brake disc were established in SolidWorks. For the brake disc, the inner diameter and the outer diameter are 350 mm and 640 mm, and its thickness is 22 mm. The length of the friction blocks with hexagon-like shape is 27 mm and the thickness is 22 mm. Besides, the model of the friction blocks with droplet-like shaped was established to study the influence of the structure of friction blocks on the stress characteristics of the brake disc. The ice impurity model was established in the gap between friction blocks, shown in Fig. 2.

2.3. The FEM of the ice-coated friction pair

The geometric model was imported into ANSYS to establish the non-linear FE contact models of brake disc and different shaped friction blocks. The material of the brake disc is cast steel, which the yield strength is 935 MPa, the Poisson's ratio is 0.3, and the density is 7800 kg/m³. The density of the brake pad is 5500 kg/m³. Considering the effects of temperature, the related material parameters of friction block and brake disc were shown in Table 1. The FE models were meshed by SOLID164 elements,
shown in Fig. 2. The connection relationship of the friction blocks and the ice impurity was defined based on Boolean operation. The contact relationship between brake disc and the friction blocks and between the brake disc and ice impurity were defined respectively. The friction coefficient was constant of 0.35.

Referring to the fact, the angular velocity of counterclockwise rotation was applied to the brake disc and the degree of freedom of the friction blocks along the Z-axis was released for applying brake pressure. The simulated calculations under different working conditions were carried out, including brake pressure (18kN, 25kN and 30kN), initial brake speed (80 km/h, 160 km/h and 250 km/h) and two kinds of friction block shape (hexagon shape and droplet-like shape).

![Figure 1](image1.png) The ice-coated brake unit of the alpine EMUs.

![Figure 2](image2.png) The solid model and finite element model of the ice-coated friction pair

| Parameter       | Thermal conductivity W/(m * °C) | Heat capacity J/(kg * °C) | Elastic modulus (GPa) | Linear expansion (10^-6/K) |
|-----------------|---------------------------------|---------------------------|-----------------------|---------------------------|
| Friction Block  | 74                              | 436                       | 180                   | 11.1                      |
| Brake Disc      | 51.9                            | 462                       | 209.9                 | 10.2                      |

3. Simulation results

3.1. The stress characteristics of the brake disc
In the process of contact friction, under the contact stress between the friction pair and the propagation of the stress wave, points on the brake disc generate stress. The distribution of the equivalent stress of the disc surface at different times were shown in Fig. 3. During the friction process, the equivalent stress
of the brake disc first increases and then decreases. Due to inertia force, the distribution of contact pressure on the brake disc surface is uneven, causing the equivalent stress to distribute uniformly. Under the condition of braking pressure of 25kN and initial braking speed of 250 km/h, the maximum stress is 956.75MPa, which occurs at 28.2ms. For the value of the maximum stress exceeds the yield limit of the material, the plastic deformation would occur on the disc.

Figure 3 The distribution of the equivalent stress of the disc surface at different times

3.2. The Z-displacements of the brake disc
When the brake disc rotates at high speed, the friction blocks and the disc surface are in a cyclic contact friction, causing deformation of the disc surface. Besides, the stress wave will propagate from the contact position to the outside and make the disc surface deformed. The above maximum stress node was selected to analyze the failure trend at different locations of the disc. With the mutual friction between ice impurity and the brake disc, the contact stress and large deformation were occurred on the brake disc, and the deformation will recover slightly with time going on. As shown in Fig. 4, comparing E and G or F and C, it can be seen that the position with larger deformation has smaller recovery during braking. The ratio of the maximum displacement ranging from large to small in order is F, C, H, G, A, E, B, D, which the deformation ratio refers to the ratio of the maximum deformation of the observation point to the maximum deformation position. Since the disc was rotating counter-clockwise, the displacement of the position after the maximum equivalent stress node is larger than that of the position before node.
3.3. Effect of speed and pressure on the brake disc

Fig. 5 shows the maximum Z-displacement and the equivalent stress of the brake disc surface under the conditions of different initial braking speed and brake pressure. It can be seen that the change of brake pressure and the braking speed has a greater impact on the disc. For the maximum Z-displacement, it changes slightly with pressure at low speed condition, while the brake disc has large Z-displacements under a small pressure at high speed condition. For the maximum equivalent stress, its difference is not obvious at high speed, but obvious at low speed. This is because that the maximum equivalent stress of the disc is close to the yield limit of the material at high speed, even applying small pressure. Therefore, when the initial braking speed is high, it is recommended to exert smaller brake pad pressure, which can reduce the maximum stress and the Z-displacement on the disc surface.

3.4. Effect of ice impurity on the brake disc

Maintaining the consistency of other variables, removing the ice impurity and the simulation results were compared and analyzed. Under the condition of brake pressure of 30kN and initial braking speed of 250km/h, the equivalent stress curves of two models were shown in Fig. 6. The equivalent stress of the ice-covered model is much larger than that of ice-free model and the maximum stress difference is nearly 400 MPa. For the ice-covered model, the average equivalent stress value of the disc is between 600 MPa and 800MPa and the maximum value is 993.6MPa, which exceeds the yield limit of the material. For the ice-free model, the average equivalent stress value is about 300 MPa. If the ice impurity was always embedded between the friction pair, the disc surface would be under high stress condition repeatedly, which eventually leads to the failure.
3.5. Effect of friction block shape on the brake disc

Keep the material properties of the friction blocks unchanged, the ice-coated friction pair model with the droplet-like-shaped friction blocks was established, as shown in Fig. 7b. Under the condition of brake pressure of 30kN and initial braking speed of 250km/h, the equivalent stress curves of two models were shown in Fig. 8. For the hexagon-shaped friction blocks, the average equivalent stress on the disc surface is about 700MPa and the maximum value is 993.6MPa, while the average equivalent stress is below 300MPa for model with droplet-like-shaped friction blocks. It shows that changing the shape of friction block from hexagon to droplet-like can improve the stress characteristics on the brake disc during braking.
4. Conclusion
In order to study the abnormal wear of the brake disc, the FEM of the ice-coated brake pad and the brake disc was established, and simulated calculation under different operation conditions were carried out. The contact characteristics of the brake disc were analyzed, which provides a reference for improving the scratch phenomenon of the brake disc of the alpine EMUs. The main conclusions are as follows:

1. During the braking, under the combined action of inertial force and pressure, the contact stress on the contact surface of friction pair distributes unevenly and the equivalent stress concentration area is on the brake disc surface. Besides, with the stress wave propagating from the contact position to the outside, the disc surface shows different degrees of deformation.

2. The maximum equivalent stress and the Z-displacement of the brake disc become larger with the brake pad pressure increasing. At the same initial braking speed, the maximum value of the stress advances with the pressure increasing.

3. The ice impurity makes the stress and the Z-displacement of the disc much larger than the model without the ice impurity. The maximum difference of the stress between the two models is about 400 MPa. Under the initial braking speed of 250 km/h and the pressure of 25kN, the maximum value of the equivalent stress of the ice-coated model is about 956 MPa, which exceeds the yield strength of the material.

4. The friction blocks with droplet-like shape can decrease the maximum stress and Z-displacement, that is improving the stress and deformation on the brake disc surface during braking. It is suggested to use droplet-like friction blocks.

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