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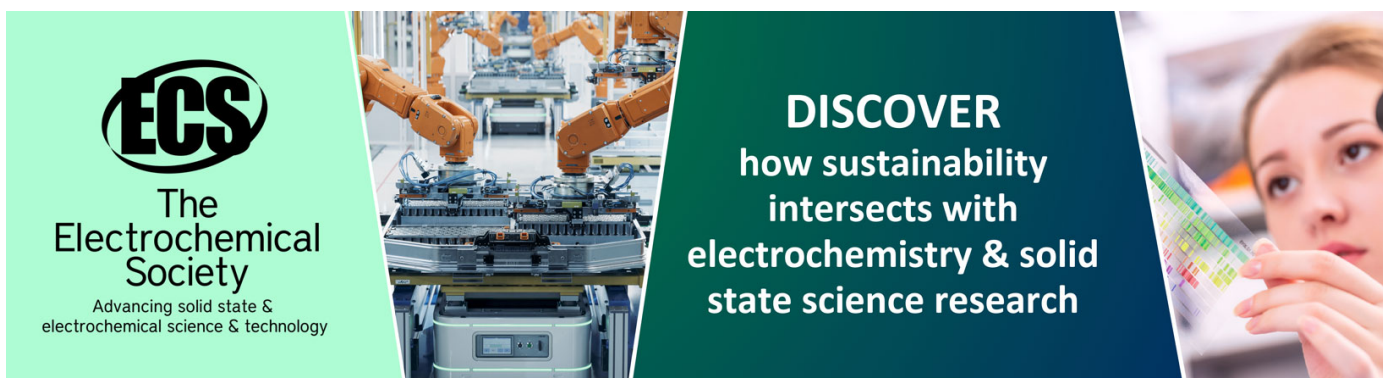
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Fatigue Life Calculation of High-Power Disc Brake under Thermal-Mechanical Coupling

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Abstract. The fatigue failure mode of the brake disc is the initiation and expansion of the fatigue crack on the surface of the brake disc until the brake disc brakes. Therefore, considering the fatigue failure mode of the brake disc, the fatigue life of the brake disc is calculated. Firstly, the thermo-mechanical coupling model of the brake disc and pad is established by Abaqus software, so that temperature and stress of the brake disc could be obtained. Then, the surface crack initiation life of the brake disc is calculated by fe-safe software. Finally, the fatigue crack growth life of the brake disc is calculated by nCode software. The calculation and analysis results show that the fatigue crack of the brake disc appears on the outer side of the brake disc friction surface under the working condition of this paper. The crack initiation life is that the number of braking is 12830 and the crack propagation life is 695000 for the number of braking.

1. Introduction

Disc brake has many advantages, such as simple structure, light weight, fast heat dissipation and convenient adjustment. It is widely used in large-scale equipment, such as railway vehicles, mining machinery, and metallurgical machinery, as a deceleration device for shaft rotating parts[1]. With the increasing load, speed and power of the machine, the braking condition becomes more and more severe. Especially, under the emergency braking conditions, the braking friction generates a lot of heat energy. Most of heat is absorbed by brake discs and pads and diffused through heat conduction. The heat that is too late to diffuse causes the temperature of the brake disc to rise sharply, and a temperature gradient is generated inside. In addition, structural constraints cause thermal stress inside the brake disc. Under the action of cyclic thermal stress, the brake disc appears the phenomenon of thermal fatigue cracking[2-3]. In recent years, a large number of scholars have studied the fatigue failure of brake discs. Based on the direct coupling analysis results of friction pair thermal force and the Manson-Coffin fatigue prediction model, considering the cyclic stress-strain curves of the brake disc, Yang Wei used the fe-safe software to calculate the number of braking of the brake disc during the whole life cycle. , [4]. During the non-destructive testing process, F. Bagnoli et al. found that a large number of fire truck brake discs used to support aviation activities cracked, and the crack length was 1-7.5cm. The analysis concluded that the repeated cycles of thermal stress were the causes of cracks[5]. In this paper, Abaqus is used to conduct thermo-mechanical coupled finite element analysis of the brake disc. The temperature and stress results are imported into fe-safe software for surface fatigue failure analysis, so as to obtain the location, life and crack length of fatigue crack initiation on



the brake disc surface. Finally, the nCode software is used to analyze and calculate the crack life of the brake disc, and the complete fatigue life prediction method of the brake disc is obtained.

2. Thermo-mechanical coupling simulation of brake disc

2.1. Modeling of brake disc

In order to simulate the thermo-mechanical coupling of brake disc, it is necessary to establish the model of the brake disc and pad. The dimension parameters of a certain type of brake disc and pad are shown in table 1.

Table 1. Dimensional parameters of brake disc and pad.

	Inner radius r_0	Outer radius r	Thickness h	Wrap angle θ
Brake disc	100mm	400mm	40mm	360°
Brake pad	260mm	380mm	24mm	60°

The brake disc material is Q345b, and the brake pad material is copper-based powder metallurgy. The thermo-mechanical coupling parameters of the material are shown in table 2 and table 3.

Table 2. Material parameters of brake disc and pad.

Material parameters	Density (kg/m ³)	Thermal conductivity (w/m·°C)	Specific heat capacity (J/kg·°C)	Modulus of elasticity (Pa)	Linear expansion (/°C)	Poisson ratio
Brake disc	7850	48	462	2.08×10 ¹¹	1.28×10 ⁻⁵	0.31
Brake pad	5500	30	550	5.2×10 ⁹	1.5×10 ⁻⁵	0.3

Table 3. Material parameters of brake disc varying with temperature[6].

Temperature (°C)	Thermal conductivity (w/m·°C)	Specific heat capacity (J/kg·°C)	Modulus of elasticity (Pa)	Linear expansion (/°C)
100	48	462	2.08×10 ¹¹	1.28×10 ⁻⁵
200	40.9	507	2.12×10 ¹¹	1.34×10 ⁻⁵
300	39.6	548	1.94×10 ¹¹	1.39×10 ⁻⁵

Since the brake disc topography and force are symmetrical about the middle section, half of the brake disc and one brake disc are taken as simulation models for simulation.

2.2. Setting of thermo-mechanical coupling simulation conditions

Thermo-mechanical coupling simulation of the braking process was performed using Abaqus. The unsteady heat conduction differential equation of the three-dimensional temperature field is described as follows.

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{q}{\rho c} \quad (1)$$

where, T is the surface temperature of the brake disc; t is the braking time, s; λ is the thermal conductivity; ρ is the density; c is the specific heat capacity; q is the heat flux.

The braking load of 17000N was applied to the upper surface of the brake pad. The initial braking speed is 1000r/min and the braking time is 19.16s.

2.3. Simulation results and analysis

The braking time of the maximum stress in the braking process is selected. It can be seen from figure 1-3 that the stress, temperature and axial strain on the brake disc surface are basically the same, and are distributed in an annular shape, and the maximum value is in the outer region of the brake disc friction region.

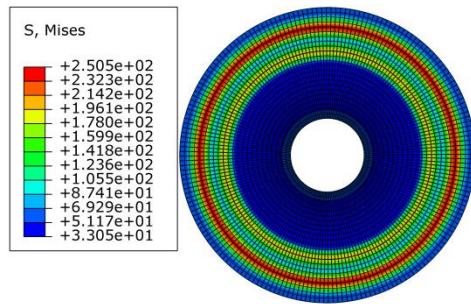


Figure 1. The cloud diagram of the brake disc stress at 14.06 seconds.

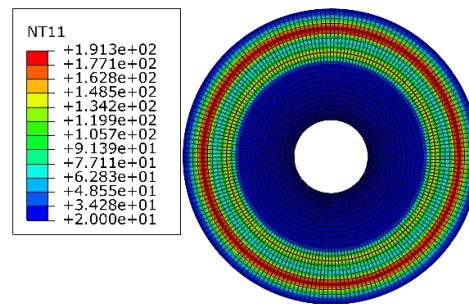


Figure 2. The cloud diagram of the brake disc temperature at 14.06 seconds.

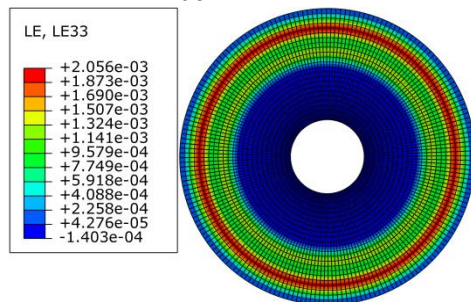


Figure 3. The cloud diagram of the axial strain of the brake disc at 14.06 seconds.

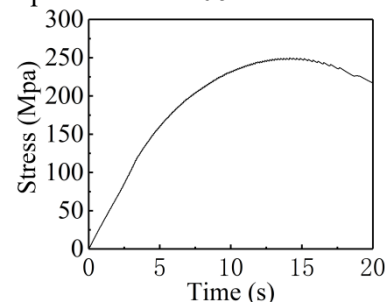


Figure 4. Stress curve of the maximum stress point on the surface of the brake disc.

It can be seen from figure 4-6 that the curve trend of stress, temperature and axial strain at the stress concentration of brake disc is basically the same.

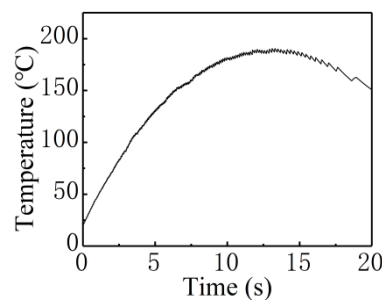


Figure 5. Temperature curve of the maximum stress point on the surface of the brake disc.

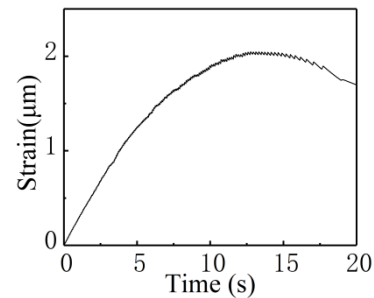


Figure 6. Axial strain curve at the maximum point of stress on the surface of the brake disc.

The axial strain curves of the contact surfaces of the brake disc and pad are as shown in figure 7 and figure 8. It can be seen that the axial strain of the brake disc and pad in the external friction region is larger at 14.06 s. Therefore, when the brake pad is in contact with the surface of the brake disc, the

contact pressure of the larger strain portion is greater than the contact pressure of the remaining portion.

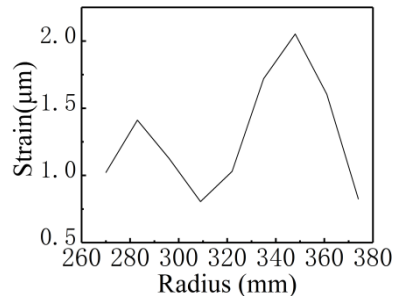


Figure 7. Axial strain curve of the contact surface of the brake disc at 14.06 seconds.

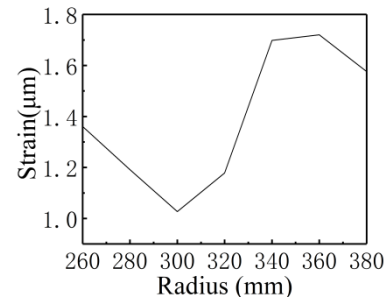


Figure 8. Axial strain curve of the contact surface of the brake pad at 14.06 seconds.

By analysing the above results, it can be concluded that the maximum temperature stress occurs in the external friction region between the brake disc and pad, which is due to the larger external linear velocity of the brake disc, resulting in more heat production and higher temperature in the external friction region of the brake disc, so the thermal deformation caused by temperature rise is more obviously than other contact regions. Thermal deformation will lead to uneven distribution of contact pressure between the brake disc and pad, which will increase the brake pressure in the external friction region of brake disc, and further affect the heat production and temperature there. Under the combined action of temperature and thermal deformation, the stress concentration of brake disc in the external friction region is caused.

The crack direction of brake disc is generally radial and axial propagation, and this fatigue crack direction is generally caused by surface circumferential stress. It can be seen from figure 9 and figure 10 that the distribution of circumferential stress is basically the same as that of stress. The stress curve of the maximum stress point on the brake disc surface is basically the same as that of the circumferential stress curve, which proves that the circumferential stress is the main stress on the brake disc surface.

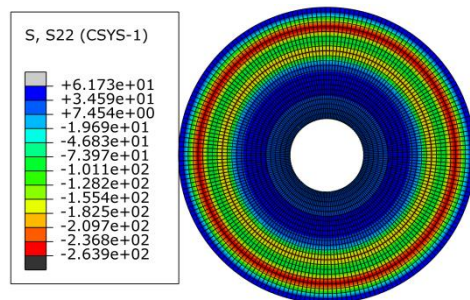


Figure 9. The cloud diagram of the brake disc circumferential stress at 14.06 seconds.

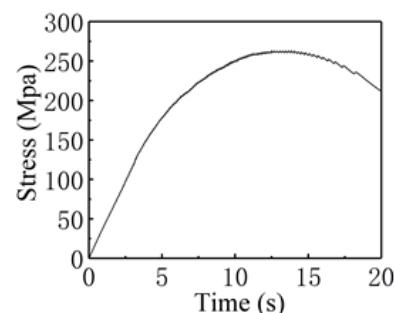


Figure 10. Circumferential stress curve of the maximum stress point on the brake disc surface.

3. Brake disc fatigue failure analysis

3.1. Fatigue analysis method of brake

On the basis of thermo-mechanical coupling analysis, the crack initiation life and the crack initiation location of the brake disc are obtained by fe-safe surface fatigue analysis. Then, with the circumferential stress of the location as input, the crack propagation life of the brake disc is analysed by nCode software, and the complete fatigue life of the brake disc is obtained.

3.2. Crack initiation life of brake disc

The surface fatigue of the brake disc is analysed by fe-safe stress-life analysis method. Because the temperature of the brake disc varies greatly during braking, the S-N curve of the brake disc material Q345b at different temperatures is needed. The safety factor is 2.0, and the fitting result of the stress-life curve of the material is as shown in table 4.

Table 4. Fitting results of stress life of Q345b at different temperatures[7].

Temperature(°C)	Stress-life curve	Stress ratio
20	$S_a = 148.25 / N_f^{0.1065} + 109.25$	
150	$S_a = 178.32 / N_f^{0.1237} + 112.08$	
250	$S_a = 224.60 / N_f^{0.1432} + 113.85$	-1
300	$S_a = 637.67 / N_f^{0.2268} + 116.32$	

Fe-safe software uses Miner's linear fatigue cumulative damage criterion to calculate the fatigue damage caused by combined loading under various working conditions. The formula is as follows:

$$D = \sum_{j=1}^k D_i = \sum_{j=1}^k \frac{n_i}{N_i} \quad i = 1, 2, 3, \dots \quad (2)$$

where, D is the fatigue damage value of the brake disc, when $D = 1$, it indicates that the surface of the brake disc has fatigue failure; k is the total number of loads obtained by rain flow counting method; N_i is the number of cycles required for the fatigue failure of the brake disc under i load; n_i is the number of cycles of the brake disc under i load, so D_i is the fatigue damage value of the brake disc under i load. When the sum of damage value of all loads is 1, fatigue failure occurs on the surface of the brake disc.

It can be seen from figure 11 that the location of the fatigue failure on the surface of the brake disc is the location of the maximum stress on the brake disc surface, that is, the external friction region of the brake disc. The crack initiation life is that the number of braking is 12830.

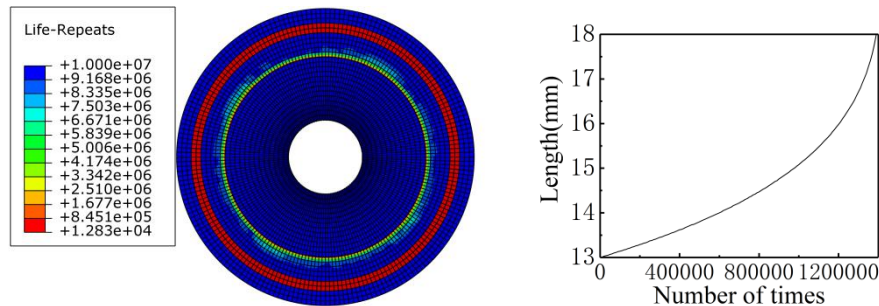


Figure 11. Fatigue life nephogram of brake disc surface. **Figure 12.** Crack depth-life curve.

3.3. Crack propagation life of brake disc

The location of the crack initiation node can be obtained by fe-safe, and the circumferential stress of this node is taken as the load of the crack propagation model. Data processing is carried out by rainflow technique, and then Paris formula is used for calculation. Paris formula is as follows:

$$\frac{da}{dN} = C(\Delta K)^m \quad (3)$$

where, C and m are material constants, determined by experiments, C is $5.5131e^{-12}$, m is 3.3231[7]; a , N and ΔK are crack length, load cycle number and stress intensity factor amplitude.

The main parameters of the crack are crack length $2c$ and crack depth a . The surface crack is taken as the model for software calculation. The width of the model is 80mm and the thickness of the model is half 20mm. The tensile force of the model is the circumferential stress amplitude of the crack

initiation node braking once. As can be seen from figure 11, fatigue failure occurs in two elements in the radial direction of the brake disc. Therefore, it can be inferred that the length of the crack is two elements and the length of the element is 13 mm, so the length of the crack is 26 mm. The selected crack shape is semi-circular, so the crack depth a of the brake disc is 13 mm.

The fatigue failure is assumed to extend the crack depth to the complete fracture of the model. The calculation results of crack growth are shown in figure 12. The crack growth life is that the number of braking is 1390000. Taking the safety factor as 2.0, the crack propagation life of the brake disc is that the number of braking is 695000.

4. Conclusions

Taking Q345b brake disc as the object of analysis, this paper established a thermo-mechanical direct coupling finite element analysis model. The temperature and stress of brake disc during braking process were calculated, and the crack initiation life and crack propagation life of brake disc under this braking condition were analysed. In this paper, the following conclusions are obtained by calculation:

- The maximum stress of the brake disc appears in the friction region outside the brake disc. The reason is that the linear velocity of the brake disc outside leads to a larger heat production, a faster temperature rise, and a larger thermal stress than the rest of the surface, and obvious thermal deformation, resulting in uneven distribution of contact pressure, which increases the heat production of the friction region outside the brake disc and makes the stress rise.
- By fe-safe stress-life analysis method, the crack initiation life of brake disc is 12830 times. The location of crack initiation is the same as that of stress concentration during braking process, which is the external friction area of brake disc.
- The crack propagation model is established, and the crack propagation life of brake disc is that the number of braking is 695000. The total life of brake disc is that the number of braking is 707830.
- This paper provides a complete fatigue life analysis and calculation method for brake discs, which makes the life analysis of brake discs more accurately.

Acknowledgments

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