Thermal-Structural Coupling Analysis and Failure Prediction of Disc Brake

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Abstract

According to the actual size of the disc brake, establish a finite element model of disc brake. On the basis of the determination of boundary conditions and braking conditions, the thermal-structural coupling analysis of disc brakes is performed by using the finite element software Abaqus. The disk brake's distribution map of temperature field and stress field could be obtained. And the variation curves of temperature and equivalent stress in radial, axial and circumferential directions are obtained, it is found that there is a coupling relationship between the temperature field and stress field. The maximum values of temperature and equivalent stress appear near the radial center line of the friction region, thus, the dangerous position of the failure prediction of the disc brake is determined. And the failure prediction of disc brake is carried out by using Manson-coffin formula.

Keywords

disc brake, failure prediction, stress field, temperature field, thermal-structure coupling.

1. Introduction

Disc brake has the advantages of stable braking efficiency, small size and easy maintenance. It has been widely used in various kinds of cars[1]. In the braking process of disc brake, the temperature field and stress field interact continuously, and it is a typical thermal structure coupling process, which has important influence on the service life of disc brake. The influence of thermal stress on thermal deformation during braking process of disc brake is studied by Pyung Hwang and Xuan Wu[2]. Four kinds of disc brake models with different friction coefficients are established, and the temperature field and stress field under the emergency braking condition are studied by Zhang Lijun[3]. A three-dimensional transient thermal structure model of disc brake is established, and the transient temperature field and stress field during braking are studied by Huang Jianmeng[4]. At present, the research on disc brake failure prediction is relatively few by analyzing the thermal structure coupling of disc brake. In this paper, the thermal-structure coupling analysis of disc brake is carried out by using finite element software Abaqus, the distribution of temperature field and stress field in braking process is analyzed, and the failure prediction of disc brake is carried out by using Manson-coffin formula. It has great practical significance for improving the service life and braking efficiency of disc brakes.

2. Establishment of Thermal Structure Coupling Model of Disc Brake

2.1 Basic Assumptions

(1) The brake disc and friction block are homogeneous and isotropic and do not undergo plastic deformation during braking.

(2) Without consideration of the wear between brake disc and friction block.

(3) The heat generated by the friction between the brake disc and the friction block is absorbed by the brake disc and the friction block, without considering the effect of heat radiation, and is allocated to the brake disc and the friction block in a certain proportion.

(4) The brake pressure is constant and acts uniformly on the brake disc.

(5) In the braking process, the ambient temperature remains the same, and the initial temperature of the disc brake is the same as the ambient temperature.

2.2 Friction Heat Source and Energy Distribution

The heat flux density of the disc brake disc and friction block is satisfied.

$$q(x,y,t)=\mu p(x,y,t)v(x,y,t)=\mu\frac{F(x,y,t)}{S}\times w(x,y,t)r \tag{1}$$

In the formula: q(x,y,t) represents the heat flux, μ represents the coefficient of friction between brake pairs, p(x,y,t) represents the specific pressure on a friction surface ,v(x,y,t) represents the relative speed of the brake disc and friction plate, F(x,y,t) represents the brake pressure, S represents the effective contact area of the brake disc and friction block, w(x,y,t) represents the angular speed of the brake disc, r represents the effective contact radius of the brake disc and friction block.

The heat transfer coefficient of brake disc and friction block of disc brake is satisfied.

$$\eta=\frac{q_d}{q_p}=\left[\frac{\lambda_d c_d \rho_d}{\lambda_p c_p \rho_p}\right]^{1/2} \tag{2}$$

In the formula: q_d、q_p represents the heat flux density of the brake disc and friction block, λ_d、λ_p represents the heat transfer coefficient of the brake disc and friction block, c_d、c_p represents the specific heat capacity of the brake disc and friction block, ρ_d、ρ_p represents the density of the brake disc and friction block.

2.3 Heat Conduction Equation and Boundary Conditions

The three-dimensional transient temperature field and heat conduction equation of brake disc and friction block of disc brake are satisfied.

$$\left.\begin{aligned}\rho_d c_d\frac{\partial T_d}{\partial t}&=\lambda_d\left[\frac{\partial}{\partial x}\left(\frac{\partial T_d}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial T_d}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\partial T_d}{\partial z}\right)\right]\\ \rho_p c_p\frac{\partial T_p}{\partial t}&=\lambda_p\left[\frac{\partial}{\partial x}\left(\frac{\partial T_p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\partial T_p}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\partial T_p}{\partial z}\right)\right]\end{aligned}\right\} \tag{3}$$

In the formula: T represents the temperature of the disc brake disc and friction disc when the time is t.

In order to have the unique solution of the heat conduction differential equation, the following initial conditions and boundary conditions for the specific heat conduction problem are given.

$$\left.\begin{aligned}&\Gamma_1: T=T_0\\ &\Gamma_2: k_x\frac{\partial T}{\partial x}+k_y\frac{\partial T}{\partial y}+k_z\frac{\partial T}{\partial z}=q(x,y,t)\\ &\Gamma_3: q=h(T-T_C)\end{aligned}\right\} \tag{4}$$

In the formula: Γ_1 represents the forced boundary condition and gives a temperature T at the boundary, Γ_2 represents the natural boundary conditions and the heat flux density of the given contact area at the boundary is q(x,y,t), Γ_3 represents the natural boundary conditions and the comprehensive heat transfer conditions are given on the boundary, h represents the convective heat transfer coefficient, T_C represents the ambient temperature.

2.4 Thermal Structure Coupling Relationship

By Saint Venant principle: when we analyze the structure, thermal load and other mechanical loads can be linear superposition [5]. If the linear expansion coefficient is α, the temperature variation is ΔT, the positive strain due to temperature changes is shown as follows.

$$\varepsilon_t = \alpha \Delta T \tag{5}$$

For structural analysis, the thermal strain and other strains can be superimposed. Therefore, when the disc brake is subjected to thermal-structural coupling analysis, the total strain of the brake disc and the friction block is shown as follows.

$$\varepsilon = \varepsilon_t + \varepsilon_m \tag{6}$$

In the formula: ε_m represents the strain produced by other loads.

According to the linear elastic constitutive relation between stress and stress tensor, the relation between stress σ and strain ε can be obtained.

$$\sigma = D\varepsilon = D(\varepsilon_t + \varepsilon_m) \tag{7}$$

In the formula: D represents the material elastic matrix.

The thermal-structure coupling relationship of the disc brake is shown in figure 1.

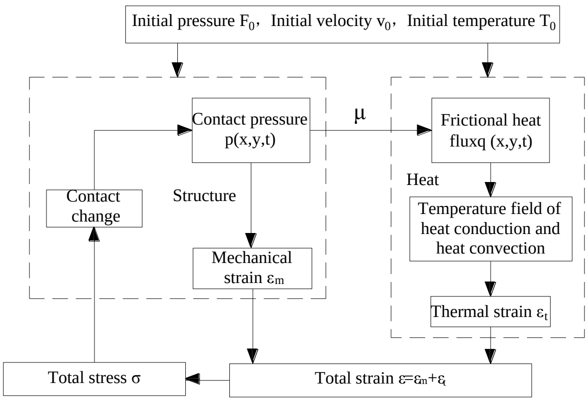


Figure.1. thermal-structural coupling relationship of disc brake

2.5 Manson-Coffin Formula

In the braking process of disc brake, due to the change of temperature, the brake disc will be subjected to cyclic thermal stress, which will affect the thermal fatigue life of material of the brake disc. The thermal fatigue life of material of the brake disc belongs to the low cycle fatigue life. When the thermal fatigue life is analyzed, the commonly used method is the strain range thermal fatigue life method [6]. When the strain, temperature, cycle range and strain increment of the brake disc are determined, the thermal fatigue life of materials of the brake disc can be calculated by using the Manson-coffin formula. The Manson-coffin formula is shown as follows [7].

$$\varepsilon_a = \varepsilon_{ea} + \varepsilon_{pa} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \tag{8}$$

In the formula: ε_a represents the total strain, ε_{ea} represents an elastic strain component, ε_{pa} represents a plastic strain component, σ_f' represents the coefficient of fatigue strength, E represents the modulus of elasticity, ε_f' represents the coefficient of fatigue ductility, N_f represents the number of stress cycles that indicate failure of materials, b represents the index of fatigue strength, c represents the fatigue ductility exponent.

3. Finite Element Model of Thermal Structure-Coupling of Disc Brake

3.1 Determination of Basic Parameters

The disc brake of a certain type of car is studied in this paper. The material of the brake disc is ZG1Cr13, and the material of the friction block is resin matrix composite. The geometric dimensions of the disc brake are shown in Table 1. The material performance parameters of the brake disc and friction block are shown in table 2 and table 3[8-9].

Table 1. The geometric dimensions of disc brakes

Frictio-nal pairs	Inner radius d1/mm	Outer radius d2/mm	Thickness δ/mm	Wrap angle θ/℃
Brake disc	78	144	24	360
Friction block	97	142	12	60

Table 2. The material performance parameters of disc brakes

Performance parameter	Brake disc	Friction block
Density ρ/(kg·m-3)	7 228	2 595
Poisson's ratio μ	0.3	0.25
friction coefficient	0.38	0.38
Thermal conductivity λ/(w·m-1·k-1)	48.46	As the temperature changes
Specific heat c/(J·kg·K-1)	419	As the temperature changes
Coefficient of thermal expansion α/(10-6K-1)	11	As the temperature changes
Modulus of elasticity E/Gpa	175	As the temperature changes

Table 3. The material property parameter of friction block changing with temperature

Temperature t/℃	20	100	200	300
Thermal conductivity λ/(w·m-1·k-1)	0.9	1.1	1.2	1.15
Specific heat c/(J·kg·K-1)	1200	1250	1295	1320
Coefficient of thermal expansion α/(10-6K-1)	10	18	30	32
Modulus of elasticity E/Gpa	2.2	1.3	0.53	0.32

3.2 The Finite Element Model is Built

First, the three-dimensional model of disc brake is established by using 3D modeling software SolidWorks, Then, the 3D model is imported into the mesh division tool Hypermesh, and the mesh is divided by hexahedron. At the same time, to ensure the accuracy of analysis and reduce the computation time, the mesh density of the friction block is slightly larger than the brake disk when meshing the mesh. Finally, the three-dimensional model of meshing is imported into the finite element analysis software Abaqus, and the finite element model of disc brake is established.

3.3 Working Condition Setting

The working conditions of disc brakes are set as follows. The initial angular speed of the brake disc is 63.28 rad/s (equivalent speed is 100 Km/h). A deceleration is performed at a braking pressure of 4 MPa, the braking time is 3.274 s until the speed is zero. The initial temperature is the same as the ambient temperature, which is 25℃. Convection heat transfer coefficient and other parameters are set according to empirical formula. Because when the brake disc is braking, the friction block moves in the direction of the axis of the brake disc, so the freedom of the friction block in the X and Y directions is restrained, and the rotational freedom of the Z direction is retained. In addition, since the brake disc can rotate along the axis, the rotational freedom of the disc along the axis is retained.

To analyze the distribution of temperature field and stress field of brake disc reasonably, several nodes are selected on the brake disc section for analysis. The location of the node is shown in figure 2.

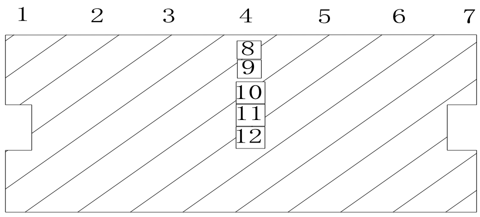
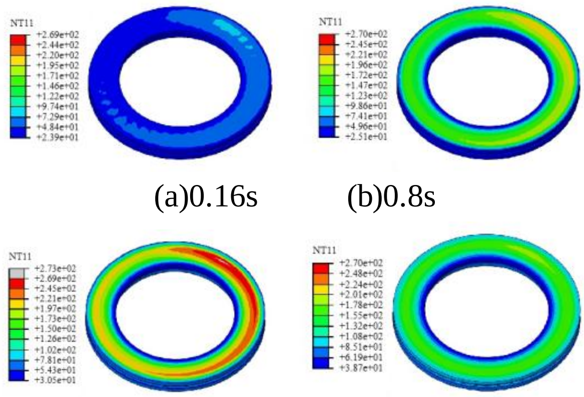


Figure.2. The position distribution of the brake disc cross section node

4. Analysis of Temperature Field and Stress Field of Disc Brake

4.1 Temperature Field Analysis

During the braking process of disc brakes, four temperature profiles of different time points were intercepted, as shown in figure 3.



(a)0.16s (b)0.8s

(c)1.9s (d)3.3s

Figure.3. The temperature field distribution of brake disc

As you can see from Fig.3. In the braking process of disc brake, the temperature of the surface of the brake disc shows a trend of rising at first and then decreasing, and the temperature at the surface of the brake disc reaches the maximum at about 1.9s. Because in the initial braking stage of disc brake, when the speed is large, the friction between the brake disc and the brake block causes a great deal of friction heat, and the temperature of the surface of the brake disc keeps rising. In the late braking stage, the speed decreases, and the friction heat decreases gradually. At the same time, the convective heat transfer intensity between the brake disc and the surrounding air and its internal heat conduction strength increased gradually, resulting in the temperature of the surface of the brake disc decreased gradually. In addition, it can be seen that the temperature of the friction zone between the friction block and the brake disc is high relatively, the temperature at the inner diameter of the brake disc does not change substantially. Because the braking time is short, the friction heat can not be delivered to the inside diameter of the brake disc in time. In order to further study the temperature distribution of disc brakes, a number of nodes are selected on the brake disc, and the distribution of the temperature field is analyzed, as shown in figures 4, 5 and 6.

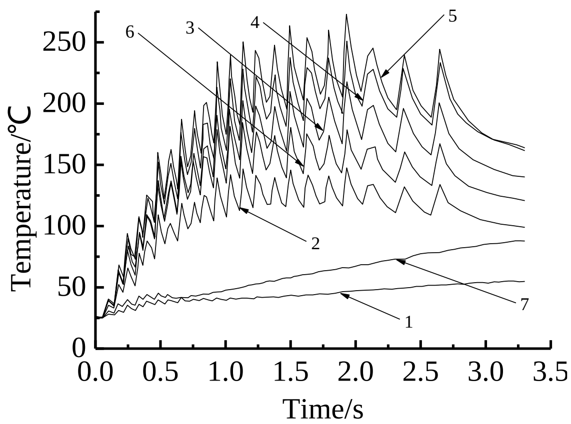


Figure.4. Variation of temperature of radial node of brake disc with time

As you can see from Fig.4. The temperature at the nodes 2, 3, 4, 5, and 6 varies in zigzag shape, however, the temperature at the nodes 1 and 7 varies are smooth relatively. Because nodes 2, 3, 4, 5 and 6 are located in the friction region, the temperature is governed by frictional heat and convection heat transfer. The node 1 and node 7 are outside the friction zone and are less affected by frictional heat. Therefore, the temperature of nodes in different regions will show different trends. In addition, it can be seen that the node 6 is located at the outermost part of the friction region, although the relative velocity is high, but the temperature is not the highest. Because the convection heat effect is better here, so the highest temperature does not occur at the node 6. Instead, it appears at the position of node 5, which is adjacent to the outside of the friction zone.

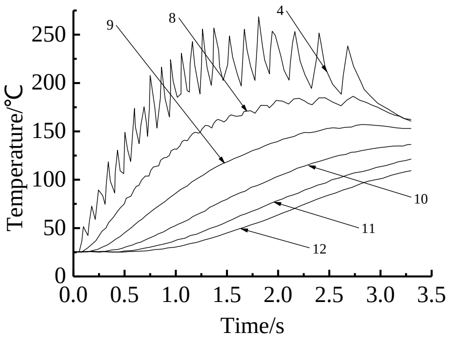


Figure.5. Variation of temperature of axial node of brake disc with time

As you can see from Fig.5. At the position of node 4, the temperature exhibits an obvious serrated change, at the position of node 8, the serrated changes in temperature are less obvious, at the position of nodes 9, 10, 11 and 12, the temperature change is smooth relatively. Because node 4 is governed by frictional heat and convective heat transfer, node 8 is closer to the surface of the brake disc, and the moving heat source also has a certain influence on it, the nodes 9, 10, 11 and 12 are only subjected to heat conduction. Therefore, the temperature of each node along the axial direction will show the change trend shown in Fig.5.

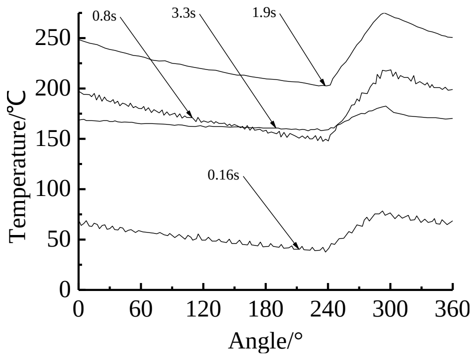
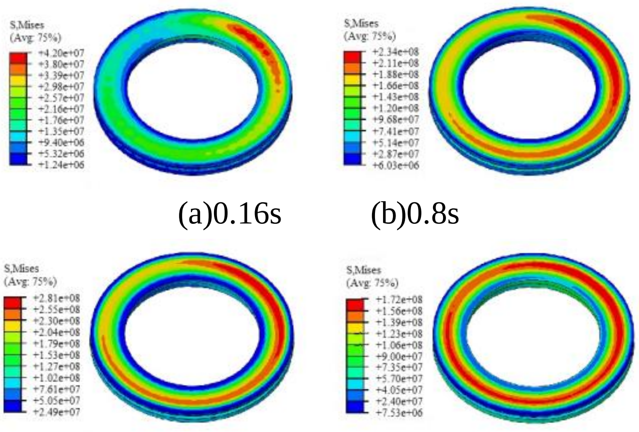


Figure.6. Variation of temperature of circumferential node of brake disc with angle

As you can see from Fig.6. The temperature gradient of the axial node of the brake disc is small relatively. At the same time, the temperature of each node of the brake disc fluctuates periodically. Because when the node enters the friction zone, it is affected by the friction heat flow and the temperature rise. when the node leaves the friction zone, it is affected by the convection heat transfer and the temperature decreases. In addition, it can be seen that in the initial braking stage and the late braking stage, the temperature of the circumferential surface of the brake disc is smaller than that of other time periods. Because in the initial braking stage, the brake disc speed is relatively large and the friction heat input time is short, in the late braking stage, the brake disc speed is small relatively and the friction heat is small relatively.

4.2 Stress Field Analysis

In the braking process of disc brake, the equivalent stress field distribution of the brake disc at four different time points is shown in figure 7.



(a)0.16s (b)0.8s

(c)1.9s (d)3.3s

Figure.7. The equivalent stress field distribution of brake disc

As you can see from Fig.7. In the braking process of disc brake, the equivalent stress on the surface of the brake disc shows a trend of increasing at first and then decreasing, and the trend is almost the same as that of the temperature. At about 1.9s, the equivalent stress reaches the maximum value at the center of the radial line in the friction region. Because as the frictional heat of the friction region continues to enter, a temperature gradient is generated in the axial and radial direction of the brake disc. In addition, it can be seen that in the late braking stage, the equivalent stress on the surface of the brake disc decreases, but the residual stress remains large when the brake is finished. In order to further study the equivalent stress field distribution of disc brake, a number of nodes are selected on the brake disc, and the equivalent stress field distribution is analyzed, as shown in figures 8, 9 and 10.

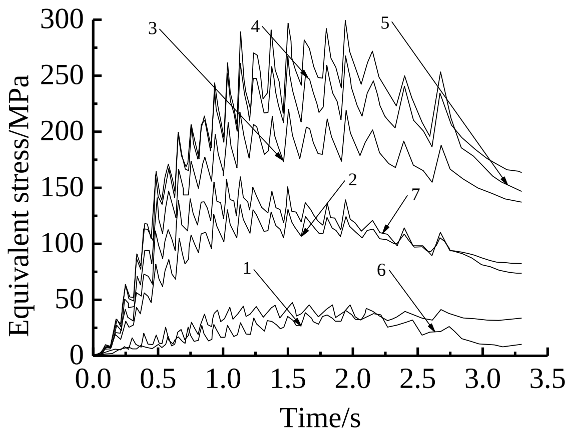


Figure.8. Variation of equivalent stress of radial node of brake disc with time

As you can see from Fig.8. The variation trend of the equivalent stress of the radial node of the brake disc with time is consistent with the trend of its temperature with time. Because at the initial braking stage, the brake disc is rotating at a great speed. As the friction heat continues to enter, the temperature of the surface of the brake disc rises rapidly in a short time, resulting in a larger temperature gradient, thereby increasing the equivalent stress on the surface of the brake disc rapidly. In the late braking stage, with the decrease of the friction heat, the temperature gradient decreases and the equivalent stress decreases.

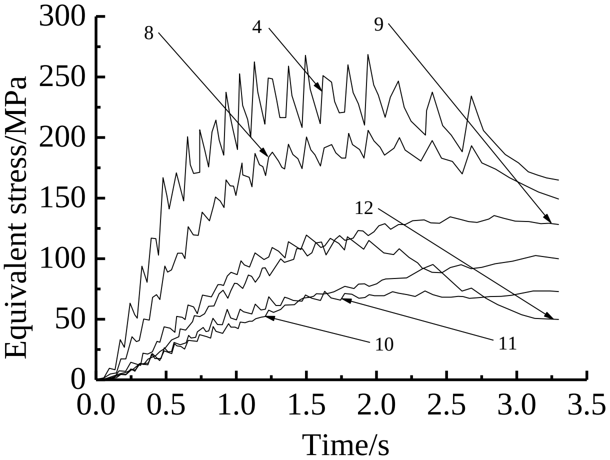


Figure.9. Variation of equivalent stress of axial node of brake disc with time

As you can see from Fig.9. The variation trend of the equivalent stress of the axial node of the brake disc with time is consistent with the trend of its temperature with time. on the surface of the brake disc and the position near the surface, the trend of zigzag change is more obvious, and the maximum equivalent stress appears on the surface of the brake disc and near the surface of the brake disc, the farther away from the surface of the brake disc, the smaller the equivalent stress. Because the nearer to the surface of the brake disc, the greater impact of the moving heat source.

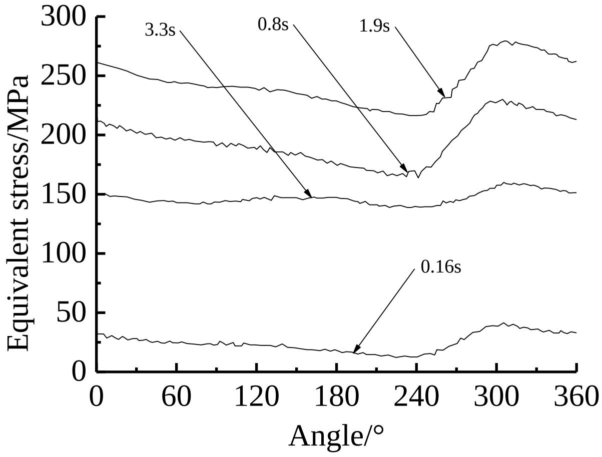


Figure.10. Variation of equivalent stress of circumferential node of brake disc with angle

As you can see from Fig.10. The variation trend of the equivalent stress of the circumferential node of the brake disc with angle is consistent with the trend of its temperature with angle. In the braking process of disc brake, the equivalent stress on the surface of brake disc is not symmetrical. In addition, at 0°~240°, the equivalent stress decreases, at 240°~300°, the equivalent stress increases gradually and reaches the maximum value. Because between 0°~240° belong to the non friction area, the surface temperature and the equivalent stress of the brake disc decreases as a result of convection heat transfer, between 240°~300° belong to the friction area, as the friction heat continues to enter, the temperature and the equivalent stress of the surface of the brake disc increases.

5. Failure Prediction of Disc Brake

From the above analysis, it can be seen that the equivalent stress of the brake disc reaches the maximum value of 299.43MPa at 1.942s. The average equivalent stress of the 9 nodes near the center of the radial line of the friction region at the moment is calculated, by calculation, we can get σeq=298.09MPa. In addition , E=175 000. Therefore, according to formula $\varepsilon_a = \frac{\sigma_{eq}}{E}$, the total strain of the brake disc is 0.001703. The fatigue performance parameters of the material of the brake disc are shown in table 4.

Table 4. The fatigue performance parameters of ZG1Cr13

Fatigue strength coefficient σf'/MPa	Fatigue strength index b	Fatigue ductility coefficient εf'/%	Fatigue ductility index c
935	-0.12	7.4	-0.6

The data in the last table is substituted into formula (8):

$$e_a = e_{ea} + e_{eq} = \frac{935}{175000}(2N)^{-0.12} + 0.074(2N)^{-0.6} \tag{9}$$

The strain-life curve of disc brakes is plotted using the software Origin, as shown in figure 11.

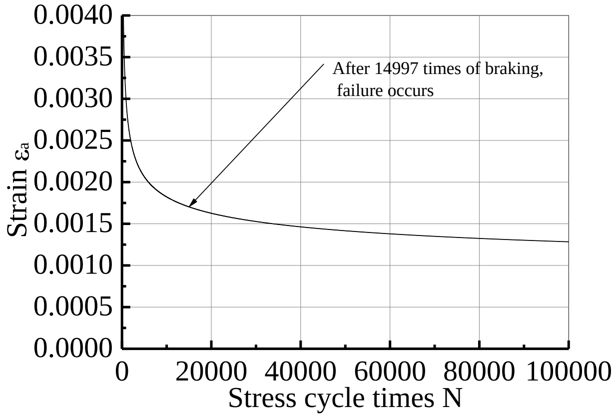


Figure.11. Strain-life curve of disc brake

As you can see from Fig.11. When the disc brake is under the emergency braking at the initial speed of 100 Km/h and the braking pressure is 4 MPa, after 14997 cycles of stress, the brake disc failed.

6. Conclusion

(1) In the braking process of disc brake, there is a coupling relationship between temperature field and stress field. Frictional heat produced by friction between pairs of friction pairs, the brake disc produces a temperature gradient in the radial, axial, and circumferential directions, thus, the brake disc generates corresponding thermal stresses in three directions. However, the thermal deformation of the brake disc will change the contact pressure between the friction pairs, and have a certain influence on the heat of friction, and then affect the temperature of the brake disc.

(2) During the braking process of disc brake, the temperature field and stress field of the surface of the brake disc and near the surface of the brake disc showing a sharp serrated trend. This is due to the combined effects of frictional heat and convective heat transfer.

(3) During the braking process of disc brake, the maximum values of temperature and equivalent stress appear in the vicinity of the radial center line of the friction region. This position is a critical part of the failure prediction of disc brakes.

(4) According to the simulation analysis of the braking process of disc brake, the Manson-coffin formula is used to predict the service life of the disc brake in this condition.

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