Thermal Structure Coupling Analysis of Friction Pair of Electronic Limited Slip Differential

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Abstract. In order to study the deformation mechanism of the friction pair of electronic limited slip differential, a coupled thermal-structural mathematical model of the friction pair is established. The temperature and stress field distribution of the friction pair are obtained by finite element method. This article analyzes the distribution characteristics of temperature and stress field, and obtains the relationship between temperature and pressure change of contact surface. The results show that under the differential starting condition, the temperature rise is obvious, and the steel disk has the possibility of warping deformation. In the future, during the optimal design of electronic limited slip differential, it can provides a reliable theoretical basis for the design of friction pairs.

Introduction

The electronic limited slip differential is a kind of differential which controls the automobile through the electronic control signal. When it works, it drives the wet clutch to distribute the torque of the left and right wheels so as to keep the automobile running smoothly. When a car encounters one side of the tire skidding, the electronic limited slip differential will get the signal and start to turn to the differential limited slip condition. The friction pair will begin to engage until the friction sheet and the dual steel sheet reach the same speed. In this process, the relative rotation of the friction sheet and the dual steel sheet will produce a lot of heat. The friction action in relative rotation includes not only the shearing of oil film in the clearance of friction pair, but also the shearing of micro-convex body on the surface of friction pair, which causes the internal stress of friction pair to rise until deformation and failure occur[1].

In the research of wet clutch friction pair at home and abroad, the simulation and analysis of temperature field and stress field of friction pair are mainly focused on, and the temperature distribution and stress field distribution in the process of friction pair engagement are obtained. Zagrodzki and Truncone[2,3] focus on thermoelastic instability and hot spot formation of wet clutch; Li and Barber, Jen and Nemecek[4,5] use instantaneous modal analysis method and full implicit finite difference numerical analysis method respectively to calculate temperature distribution of friction pairs. On this basis, Jiayuan Zhang and Puxian Ding[6] established the thermoelastic contact model of the friction pair, and gave the stress variation law of the friction sheet and the dual steel sheet during the bonding process.

In this paper, the thermal deformation of friction pair of electronic limited slip differential under differential starting condition is studied and analyzed. Using ANSYS finite element analysis method, the thermal-structural coupling analysis of the friction pair of the wet clutch of the electronic limited slip differential is carried out, and the temperature and stress field distribution on the friction lining and the dual steel sheet under the working condition are obtained.

Failure Type of Friction Pair of Electronic Limited Slip Differential

Electronic limited slip differential is mainly composed of differential shell, planetary gear, clutch, cycloid pump and end cover. The clutch is composed of friction discs, pistons and clutch gears. The friction pairs (friction discs) of the electronic limited slip differential clutch studied in this paper are composed of multiple friction discs and dual steel discs. Fig.1 shows the schematic diagram of the clutch of the electronic limited slip differential.

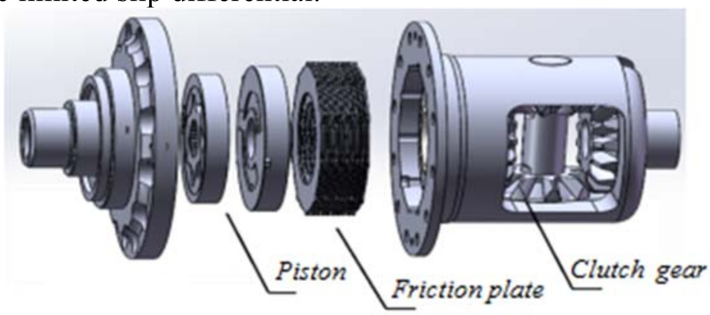

Figure 1. Schematic diagram of clutch of electronic limited slip differential

In the differential start-up process of the electronic limited slip differential, the internal friction plate and the dual steel plate of the friction pair will inevitably produce a lot of friction heat due to the relative rotation. When the heat generated too much, the temperature of the friction pair will rise. However, the uneven thermal expansion will be caused by the different degrees of temperature rise at different locations, resulting in the centralization of thermal stress. The continuous action leads to the increase of stress and stress gradient. Local high temperature and centralized stress will lead to various forms of invalidation, which can be divided into these categories:

1. The shedding of friction material.
2. Friction materials fail because of high temperature.
3. Hot spots of dual steel sheets.
4. Dual steel sheets are warped in conical and butterfly shapes.
5. Dangerous conditions such as cracks or even cracks on the surface of dual steel sheets.

Generally, in the friction pair of electronic limited slip differential, the choice of friction lining material is divided into bronze material and paper-based material. Paper-based material is a new type of friction material which can work in oil medium. It has the advantages of similar dynamic and static friction coefficient, strong torque transfer ability, soft and stable combination, but it also has the problems of low heat resistance. Therefore, this paper mainly studies the heating problem of friction material on the friction pair of electronic limited slip differential clutch and the hot spot and warping deformation of dual steel sheet.

Mathematical Model of Thermal-Structural Coupling for Friction Pairs

Mathematical Model of Heat Conduction Theory

In the electronic limited slip differential we studied, the friction pair can be regarded as an axisymmetric structure because its geometric structure and load are symmetrical to the central axis. Assuming that the heat conduction of the materials in the friction pair is isotropic, the physical parameters do not change, and there is no heat source in the inner part of the electronic limited slip differential, we can get the following results:

$$\rho_i c_i \frac{\partial \Theta_i}{\partial t} = k_i \left(\frac{\partial^2 \Theta_i}{\partial r^2} + \frac{1}{r}\frac{\partial \Theta_i}{\partial r} + \frac{\partial^2 \Theta_i}{\partial z^2} \right) \tag{1}$$

Among them, the density, specific heat capacity and heat conductivity of the three materials (dual steel sheet, friction lining and friction sheet substrate) are expressed by ρ_i, c_i and k_i. θ represents temperature, r,z represents radial and axial direction of the friction pair, and t_1 represents boundary friction time.

Boundary Conditions

In classical thermodynamic heat transfer theory, thermal boundary conditions can be classified into three categories, and three different boundary conditions can be established on the contact surface of friction pairs. Fig.2 is a schematic diagram of the constraint and boundary conditions on a pair of contact surfaces of friction pairs.

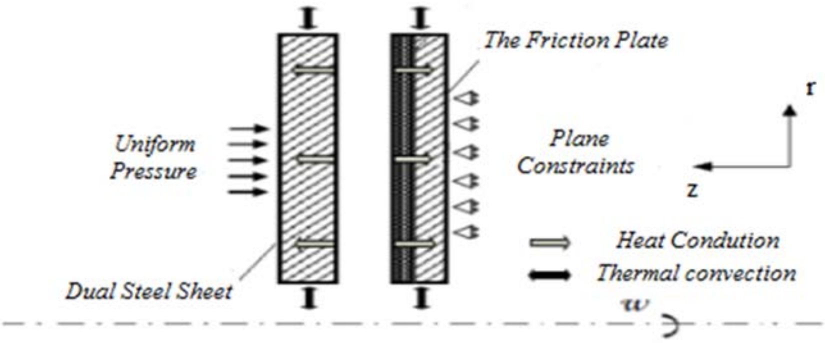

Figure 2. Schematic diagram of constraints and boundary conditions of friction pairs

The first kind of boundary condition is given initial temperature (initial oil temperature), which can be expressed as:

$$\Theta(r,z,t)|_{t=0} = \Theta_0(r,z) \tag{2}$$

The second kind of boundary condition is given heat flux. The heat transfer between the dual steel sheet and the friction sheet is a transient process, and the heat input between the contact surfaces is expressed by the heat flux. For any microelement, assuming that the sliding work caused by the relative rotation of the friction pairs during the joining process is all converted into heat energy, the heat flux can be expressed as follows:

$$q(r,t) = \mu p w(t) r \tag{3}$$

The third kind of boundary condition is given surface convective heat transfer. In the working process of the electronic limited slip differential, the heat dissipation of the friction pair is realized by the heat exchange between the lubricating oil film and the friction surface, in which the heat exchange is mainly concentrated in the friction contact area. The convective heat transfer effect between the dual steel sheet and the friction sheet is not obvious, which can be neglected. The main convective heat transfer area is distributed on the inner and outer surfaces of the friction pair along the radial direction. The heat flux of convective heat transfer can be expressed as:

$$q' = h(\Theta - \Theta_0) \tag{4}$$

ANSYS Modeling

In this paper, ANSYS is used to model a pair of contact surfaces of friction pairs. The finite element partition structure model is shown in Fig.3.

Figure 3. ANSYS model of friction pair

Taking the starting condition of electronic limited slip differential as an example, the relative sliding time between friction plates is 0.6 seconds, and the thermal-structural coupling analysis of friction pairs is carried out. The working parameters of the friction pair are shown in Table 1 and the material performance parameters of the friction pair are shown in Table 2.

Table 1. Working parameters of friction pairs

Friction factor	Pressure	Initial speed	Slip time
μ	p/MPa	$\omega/(r \cdot \min^{-1})$	t/s
0.14	0.5	400	0.6

Table 2. Material Performance Parameters of Friction Pairs

Characteristic parameter	The friction plate	Dual steel sheet
Density $\rho/(kg/m^3)$	833	7850
Modulus of elasticity E/GPa	0.588	206
Poisson ratio ν	0.12	0.3
Heat capacity $c/(J/(kg \cdot K))$	1740	490
Thermal conductivity $\lambda/(W/(m \cdot K))$	0.24	53
Coefficient of linear expansion $\alpha/(\times 10^{-5}/K)$	0.17	1.06

Simulation Analysis

Temperature Field Analysis

Fig. 4 shows the temperature distribution of dual steel sheet and friction lining at the end of t=0.6s sliding.Fig. 5 shows the time-varying curves of surface temperature of dual steel sheet and friction lining under differential operating conditions.

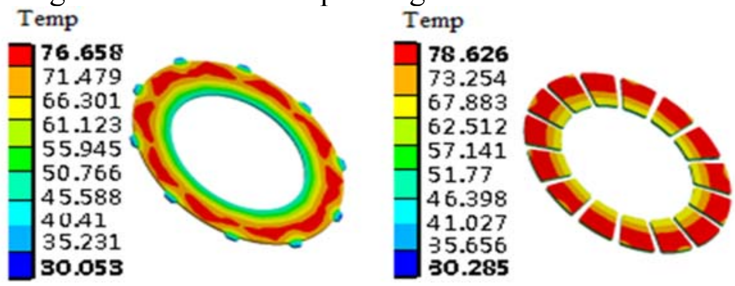

Figure 4. Temperature distribution

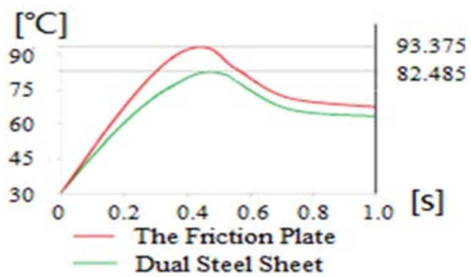

Figure 5. Time-temperature curve

From the distribution of temperature field, it can be seen that under differential start-up, the characteristics of temperature distribution are obvious, and the temperature of friction region increases with the increase of radius. The temperature difference between the outer spline area and the friction area of the dual steel sheet is large because it does not participate in friction and is cooled by oil. There is a large temperature gradient at the spline part and a lower temperature at the spline root. The annular high temperature zone along the outer frictional zone forms a local high temperature zone at the spline interval. From the radial point of view, the higher temperature on the outer side makes the thermal expansion trend of the outer side of the dual steel sheet larger than that on the inner side, which makes the dual steel sheet have the tendency of dish deformation. From the circumferential point of view, the temperature increases periodically along the circumference, and the thermal expansion trend in the high temperature region is larger than that in the low temperature region, so the dual steel sheet has the tendency of wavy deformation. Because of the clamping effect of the front and back friction plates, the deformation will not appear directly in the working process, and this deformation trend will lead to the change of contact pressure on the friction surface, thus deepening the deformation trend of the dual steel sheet.

From the Time-temperature curves of the maximum surface temperature of the dual steel sheet and the friction lining , the temperature rises sharply in the first 0.4 seconds, which is due to the serious relative sliding in the first 0.4 seconds, the relative speed of the friction sheet and the dual steel sheet is relatively high, and the temperature rises sharply. Dual steel sheets reach the highest surface temperature of 82.485 degrees Celsius in 0.44 seconds and friction linings reach the highest surface temperature of 93.375 degrees Celsius in 0.42 seconds.

On this basis, in order to study the temperature change effect of sliding time on the friction pair, we changed the sliding time to 0.8s and 1s in the differential starting condition. The maximum temperature of the friction lining is 105.575 degrees Celsius and 116.825 degrees Celsius at 0.59s and 0.73s, respectively. It can be seen that under differential start-up conditions, the longer the sliding time is, the more heat accumulated between the friction pairs, which leads to higher temperature.

Stress Field and Deformation Analysis

Figure 6 shows Von Mises stress distribution of dual steel sheet at t=0.6s.

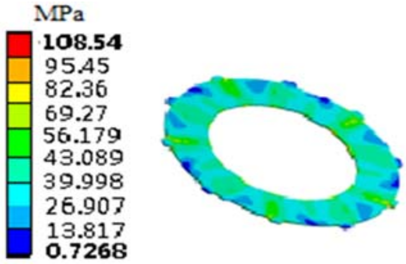

Figure 6. Von-Mises stress distribution

According to Von-Mises stress distribution, Von-Mises stress on the dual steel sheet shows a more obvious non-uniform distribution, which is smaller near the inner side and higher and concentrated on the outer side. Comparing with the temperature distribution results, it can be seen that the stress distribution results on the dual steel sheet are highly correlated with the temperature distribution. The stress in the higher temperature area is concentrated, while the stress in the lower temperature area is smaller. Similarly, the Von-Mises stress distribution is more concentrated near the outside of the contact area, and the local high stress area is distributed along the circumferential interval.

Conclusion

In this paper, ANSYS software is used to establish the finite element model of the friction pair of the electronic limited slip differential. The temperature and stress distribution on the surface of the friction pair are calculated directly by using the method of transient structure analysis command stream with appropriate boundary conditions. The conclusions are as fellow:

(1)The stress distribution on the surface of the dual steel sheet is similar to that of the temperature distribution. Generally speaking, the stress distribution in the region with high temperature is also concentrated. In the radial direction, the temperature and stress increase gradually from the inside to the outside, in the circumferential direction, the temperature and stress show periodic distribution.

(2)Under differential start-up conditions, the temperature rise is mainly caused by the relative rotation between the friction plate and the dual steel plate. The simulation results show that reducing differential start-up time can reduce the temperature rise between friction pairs under differential start-up conditions

References

[1] Yongqiang Yang, Xiaoying Li, Cao Botao, et al. Thermal-mechanical coupling analysis of friction discs of wet friction clutch [J]. Mechanical transmission, 2016, 40 (1): 153-156.

[2] Zagrodzki P. Thermoelastic instability in friction clutches and brakes-Transient modal analysis revealing mecha-nisms of excitation of unstable modes. Int J Solids Struct, 2009, 46 (11): 2463

[3] Zagrodzki P, Truncone S A. Generation of hot spots in wet multidisk clutch during short-term engagement. Wear, 2003, 254 (5/6): 474

[4] Li J Y, Barber J R. Solution of transient thermoelastic contact problems by the fast expansion method. Wear, 2008, 265 (3/4): 402

[5] Jen T C, Nemecek D J. Thermal analysis of a wet-diskclutch subjected to a constant energy engagement. Int JHeat Mass Transfer, 2008, 51 (7/8): 1757

[6] Jiayuan Zhang, Puxian Ding, Changgeng Li et al. Coupling analysis of thermal structure of wet clutch based on finite element method [J]. Machinery manufacturing. 2015, 53 (5): 4-8.