Analysis of Thermoelastic Failure Mechanism of High-Speed Planar Friction Components

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Abstract. High-speed planar friction components are widely used in the compaction machinery and vehicle industries to achieve power transmission functions. During the working process, the thermoelastic coupling state of each friction pair in the high-speed planar friction component is very complicated. The finite element numerical calculation method is used to perform transient thermoelastic analysis on the friction component, and the influence of key design parameters on its thermoelastic failure is found out, which is the foundation of structure and reliability design. Taking the multi-plate clutch of the vehicle transmission system as an example, this paper analyzes the change pattern of transient thermoelastic state of each contact surface and the impact of the fixed way on the thermoelastic state during the compaction process. Research shows that the unevenness of the initial contact pressure of the friction pair increases gradually during the compaction process, and the unevenness of the first and second contact surfaces is most obvious. When the fixed steel plate is fixed only on the outside, the thermalelasticity of the contact surface is more uneven and it is prone to thermoelastic failure.

1. Introduction

High-speed planar friction components are typical parts of mechanical and transmission systems, and their main failure mode is thermoelastic failure during high-speed friction process. Taking the multi-plate shift clutch of vehicle transmission system as an example, the multiple friction plates and dual steel plates arranged alternately constitute a typical planar friction component. In the engagement process of clutch, relative sliding between the friction plates and dual steel plates generates a mass of friction heat. The heat causes a sharp rise in temperature. Thermal and mechanical stresses are coupled to each other and the thermoelastic state of each friction pair in the module is highly non-uniform under external constraints. The thermoelastic failure occurs when local temperature or stress exceeds the thresholds. Therefore, the transient thermoelastic analysis of compression process in multi-plate clutch is one of the core tasks of vehicle transmission system design.

The engagement process of the clutch friction pair is a strong non-linear process, which involves the problems of thermo-mechanical coupling dynamics, surface friction and wear, energy dissipation and high energy braking. To analysis this process, many scholars have carried out a lot of research in theoretical study and simulation technology. Yi et al. [1] found that when the speed exceeded the critical speed sufficiently, the clutch may get a hot spot on the disc even under a brief load. Zhao
Jiaxin et al. [2] established a two-dimensional theoretical model of a wet clutch based on the perturbation method, and studied the formation reasons and influence factors of local high temperature and high pressure. Ma Biao et al. [3] established a three-dimensional finite element model of the clutch to study the influence of the structural parameters of the clutch on the system's thermoelastic instability. The studied structural parameters included the clutch outer diameter, inner and outer diameter ratio, dual steel plate thickness, and friction plate thickness. Lee et al. [4] considered the thickness geometry of the dual material for the first time in the analysis of thermoelastic instability, and found that the thickness of the brake disc had an important influence on the critical speed of the system, and that the antisymmetric deformation mode was the main deformation modes during thermoelastic instability condition. Al-shabibi et al. [5] used the finite element method to study the transient thermoelastic behavior of friction systems under high-speed sliding conditions. Yi [6] used the finite element method to study the thermoelastic dynamic instability. The study found that the low frequency vibration of the unstable system was caused by the coupling of frictional heat and thermal deformation. The dynamic instability accompanied by screaming would cause the friction system sticking or slipping or high frequency vibration.

In this paper, a three-dimensional thermoelastic finite element model of a wet multi-plate clutch is established and the distribution of transient temperature and stress fields during a single engagement process is simulated by ABAQUS software. The key influence factors of the thermoelastic failure of the friction pair are obtained after the analysis of the coupling effect of the friction pairs and the stress field. The change pattern of transient thermoelastic state of each contact surface, and the effects of different fixed methods on the thermoelastic state of the friction pair are analyzed during the compression process.

2. Finite element model

A multi-plate clutch is usually composed of several ring-shaped friction plates and dual steel plates alternately, which can be considered as an axisymmetric structure. In order to reduce the calculation scale, the groove and chamfers on the surface of the friction plates are ignored, and the contact surfaces are considered smooth. The model consists of five friction plates, six dual steel plates, one piece of compression steel, one piece of fix steel and friction material coating. There are 60732 nodes and 46980 elements in the model and the element type is C3D8T. The whole model and the geometric parameters of the friction pairs are shown in Figure 1 and Table 1.
Table 1. Geometry parameters of the model.

|                    | outer diameter/mm | inner diameter/mm | thickness/mm |
|--------------------|-------------------|-------------------|--------------|
| friction material  | 200               | 140               | 0.75         |
| friction plate     | 200               | 130               | 2            |
| dual steel plate   | 210               | 140               | 3            |
| compression steel plate | 200         | 140               | 6            |
| fixed steel plate  | 210               | 130               | 6            |

The compaction process of the friction pairs is simplified in the finite element simulation. Those five pieces of friction plates are supposed to rotate synchronously and the dual steel plates are fixed. The boundary conditions of the friction pairs are shown in Fig. 2 and the inner surfaces of each friction plates are constrained to the corresponding central reference point RP by MPC BEAM constraint, and the reference point has the rotation freedom around its axis. The initial speed of the friction plate is \( \omega_0 = 1500 \text{rad/min} \), which is equal to the initial relative speed between the friction plate and the dual steel plate. The speed is reduced to zero evenly after time \( t_s \), so the speed \( \omega(t) \) can be expressed:

\[
\omega(t) = \omega_0 \left(1-\frac{t}{t_s}\right), \quad 0 < t < t_s
\]  

A uniform load \( P_0 \) which increases linearly from 0 to 1.5 MPa in 0.1s and then remains constant is applied on the compression steel plate. The degree of freedom of the dual steel plate in \( \theta \) direction is zero. The fixing steel plate is fixed in different ways (bottom fixed, inside and outside fixed and only outside fixed) which are shown in Figure 3. The influences of three fixed methods on the thermoelastic state in friction pairs are compared.

![Figure 2. Schematic of boundary condition on cross section of friction pairs.](image)
2.1. Heat flux density and heat partition coefficient

Since there is no internal heat source in the clutch, all friction heat is generated by the sliding between the friction plates and the dual steel plates. The effect of wear on the generation of friction heat during the actual sliding process is ignored, and the heat generation efficiency is considered to be 100%. The heat flux density \( q \) generated at any point on the contact surface has a relation with friction coefficient, contact force and linear velocity:

\[
q = f \rho \omega \nu r_p
\]  

(2)

where \( f \) is the friction coefficient, \( r \) is the distance from the rotating center, \( \omega \) is the relative rotate speed, and \( p \) is the contact pressure of the point.

It is assumed that the frictional heat generated by sliding flows into the friction plate and the steel plate at a certain proportion, i.e., \( q = q_f + q_e \), the empirical formula for the heat flux distribution on the contact surface is:

\[
\alpha = \frac{q_f}{q_e} = \frac{\sqrt[3]{\lambda c \rho}}{\sqrt[3]{\lambda c \rho}} \sqrt[3]{f c \rho}
\]

(3)

Where \( \lambda \) is the coefficient of heat conductivity, \( c \) is the specific heat capacity, and \( \rho \) is the density of the material.

2.2. Boundary condition for heat transfer

The wet clutch friction pairs are immersed in the lubricating oil, and the maximum temperature of the working condition is less than 150\(^\circ\)C, so the influence of heat radiation on the temperature field is neglected. The forced convection heat transfer with the lubricating oil exists in the non-contact area of the friction plate and the dual steel plate which can be expressed as:

\[
q = h(T - T_0)
\]

(4)

Where \( h \) is the convection heat transfer coefficient, \( T \) and \( T_0 \) are the temperature of the friction pairs and the ambient.

The inner and outer sides of the friction plate and the steel plate are cylindrical. The convection heat transfer coefficient is calculated by the formula of free rotated axes:

\[
h = \frac{0.133 \lambda \text{Re}^{1/2} \text{Pr}^{1/3}}{D}
\]

(5)
Where $Re$ is the Reynolds number, $Pr$ is the Prandtl number, and $D$ is the diameter of the friction plate.

The other surfaces of the friction pairs which are directly contacted with the lubricating oil are disk surface. The heat transfer coefficient $h$ can be calculated by the free rotated disk formula:

$$h = \frac{0.664 \cdot Re^{0.5} \cdot Pr^\gamma}{L}$$  \hspace{1cm} (6)

Where $L$ is the diameter of the calculation area. The parameters of lubricants in model refer to reference [7].

2.3. Material property parameters

The material property parameters of friction material and steel plate are shown in Table 2. The friction material is paper-based material. The substrate friction plate and dual steel plate have the same material, which is assumed to be isotropic and does not change with temperature during the compaction process. The friction coefficient is 0.07. The initial temperature of the lubricant is 50°C and remains stable. The initial temperature of the friction pairs is 50°C.

| Physical parameters                  | Steel plate | Friction material |
|-------------------------------------|-------------|-------------------|
| Density $\rho$ / (kg/ m$^3$)        | 7800        | 2000              |
| Specific heat capacity $c$/(J/(kg $^\circ$C)) | 563        | 1200              |
| Thermal conductivity $\lambda$/(W/(m $^\circ$C)) | 54         | 1                 |
| Expansion ratio $10^{-5}$           | 1.2         | 1.5               |
| Modulus of elasticity $E$/(GPa)     | 125         | 0.3               |
| Poisson's ratio                     | 0.3         | 0.25              |

3. Results and discussions

The temperature field and pressure field in the compaction process are obtained based on the use of thermal-mechanical coupling module in ABAQUS to solve the problem. Since the paper-based friction material has low stiffness and poor thermal conduction performance, it is easy to wear in practice with less incoming friction heat flux. The dual steel plate has high stiffness and good heat conduction performance, and it is prone to thermoelastic failure in actual usage. Thus, the variation of thermoelastic state in the compaction process for the dual steel plate is focused in this paper.

The grooved surface and other factors are ignored in the model. The calculation results show that the contact pressure, the node temperature and the equivalent stress distribution are similar on each contact surface when the compaction is completed. The variation in the circumference is not significant which can be regarded as symmetrical distribution.
In order to analyze and compare the results, it is marked that the sliding contact surface which is near the compression steel plate is the first contact surface. In turn, the sliding contact surface near the fixed steel plate is the tenth contact surface. The dimensionless parameter of pressure ratio \( \eta \) is introduced as the ratio of contact pressure \( P_c \) on the sliding contact surface and the uniform load \( P_0 \) applied on the compression steel plate.

Since the contact state of the compaction process for the friction pairs is influenced by the initial contact state obviously, the statics state of the three fixing models is simulated for comparison. The radial contact pressure curves for each contact surface are shown in Fig. 4. It shows the difference of the contact states of friction pairs in the three conditions. The contact pressure on each contact surface is almost the same under bottom fixed situation, since the bottom surface of the fixed steel plate is tempered. Parameter \( \eta \) is approximately equal to 1, and the initial contact state of friction pair is uniform. When the inside and outside is fixed, the contact pressure on the contact surface near the fixed steel plate (9th, 10th) has certain changes with low pressure in the middle area and high pressure on the inner and outer sides. The D-value of contact pressure ratio is 0.25. When the outside is fixed only, the contact state of each contact surface is obviously different from others. The tenth contact surface has the maximum radial contact pressure gradient. The contact pressure on the outside is bigger where \( \eta = 1.3 \), and the inner region is smaller where \( \eta = 0.3 \). The D-value of contact pressure is close to 1. The uneven degree of contact pressure for other contact surfaces decreases in turn.

The contact pressure is generated by the interaction of thermal stress and uniformly distributed load \( P_0 \) during the compaction process. Figure 5 shows the radial contact pressure curve of each contact surface at the end of compaction process. Compared with Figure 4, the contact pressure of the first and second contact surfaces change most obviously that the inner and outer sides are lower and the middle area is higher. The outer region of the first contact surface is reduced to a smaller value for \( \eta = 0.5 \) with the D-value of the maximum and minimum contact pressure ratio of 0.75. For the inside and outside fixed condition, the initial pressure on the inner and outer sides is high in the ninth and tenth contact surfaces.
surfaces, thus the contact pressure gradient decreases at the end of the compaction. When only the outside of the steel plate is fixed, the contact pressure on the outer region of the tenth contact surface (r=90mm) is high for $\eta=1.5$. The contact pressure on the inner region is close to zero with a trend of dis-compaction.

![Figure 6](image1.png)

(a) bottom fixed (b) inside and outside fixed (c) outside fixed

**Figure 6.** Radial temperature distribution of each contact surface at the end of compaction.

The radial temperature distributions of each contact surface at the end of the compaction for three working conditions are shown in Figure 6. It can be seen that the variation of radial temperature on each contact surface is similar and the temperature increases gradually from inside to outside. Since there is a lot of heat flow in the outer spline region, the temperature decreases significantly in the radius larger than in 95mm region. The compression steel plate and fixed steel plate improve the heat capacity of the friction pair, therefore the first and the tenth contact surface temperature is significantly lower than other surfaces. Affected by contact pressure, the maximum temperature position of the first and second contact surfaces is near $r=86$mm, and the highest temperature point of the other contact surfaces is gradually offset outward. The highest temperature point of the tenth contact surface is near $r=95$mm. The outside fixed condition has the maximum temperature gradient that the temperature near the outer part is obviously higher than the surrounding region. The local high temperature position and high pressure region is formed on each contact surfaces as shows in Fig. 5 (c).

![Figure 7](image2.png)

(a) bottom fixed (b) inside and outside fixed (c) outside fixed

**Figure 7.** Cross section temperature contour at the end of compaction.

Fig. 7 is the temperature contour on the cross section at the end of the compaction for three fixing conditions. According to Equation (3), only 10% of the friction heat generated on the contact surface flows into the friction plate. The thermal conductivity of paper-based friction material is poor that the heat mainly maintains in friction material. The temperature in the substrate of the friction plate is low, and there is high temperature gradient through the thickness. The dual steel plate has good thermal conductivity that the temperature gradient in thickness direction is not obvious. Consequently, in order to reduce the temperature gradient in the thickness direction, a friction material with high thermal conductivity can be chosen.
During usage, if the clutch with high relative speed is at semi-bound state for a long time or shifts frequently, the contact pressure on the steel plate surface will increase obviously. It can be predictable that the contact pressure gradients on the first and the second contact surface are the most obvious. The contact pressure on both the inner and outer side decrease rapidly until the contact is detached while the contact pressure of the middle region increases. The region with high contact pressure generates higher friction heat than the surrounding area, resulting in the increasing of the thermal expansion and non-uniform contact pressure distribution. The local high temperature and high pressure phenomenon will exacerbate friction wear, shorten the service life of the clutch, and generate plastic deformation leaving residual strain, which will cause thermal fatigue failure, sintering and crack.

![Figure 8. Variation of maximum temperature versus time.](image1)

![Figure 9. Variation of maximum equivalent Mises stress versus time.](image2)

The variation of maximum temperature and maximum equivalent Mises stress versus time in the friction pair under three conditions are shown in Figure 8 and Figure 9, respectively. It can be seen that the highest temperature and the maximum equivalent Mises stress under different conditions increase first and then decrease. At 0.1s, the friction pairs have high relative rotational speed and the maximum contact pressure of the model reaches its peak. The maximum temperature and the maximum equivalent Mises stress value reach the maximum value at about 4/5 of the total compaction time. With the decreasing of relative speed, the heat produced by friction reduces gradually according to Equation (2). The maximum temperature increases slowly at the middle and late stage of the compaction process and decreases at the last stage. According to the above analysis, when only the outside is fixed, high pressure region will be generated on the contact surface of the friction pair. Thus, the highest temperature value, the maximum Mises stress and the growth rate in the early stage of the compaction are larger than the correspondence value under the other two fixed conditions.

4. Conclusion

In this paper, a three-dimensional model of a high-speed planar friction component is established based on the finite element method to simulate one single compression process of the friction pairs.
The thermoelastic failure states between contact surfaces under the coupling of temperature and stress fields are analyzed. The effects of different fixed methods for the fixing steel plate on the temperature field and contact pressure distribution are obtained. Some conclusions are drawn:

The distribution pattern of the contact pressure of each contact surface during multi-plate clutch compression process is studied. The unevenness of the initial contact pressure is exacerbated during the compression process. The first and second contact surfaces have maximum gradient of the contact pressure.

The fixed methods of the fixing steel plate have a significant effect on the thermoelastic state of the friction pair. The study finds that when the paired steel plates are fixed only on the outside, the thermoelasticity unevenness of the contact surface is the highest. It is easy to form a local high temperature and high pressure region in the radial direction, which will cause the thermoelastic failure.

The change pattern of the maximum temperature and the maximum equivalent Mises stress of the friction pair during the compression process is obtained. The temperature and stress of the friction pair in the middle position of the friction component are significantly larger than on broadsides. The study finds the higher relative sliding speed of the friction pair has, the faster temperature and stress increase. With the friction pair close to the compressed state, the temperature and stress reach the maximum value. When the pressing process lasts long enough or the friction pair is frequently pressed, the friction components will occur thermoelastic failure.

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