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# Study on the coupling characteristics of frictional-thermal structure of automobile composite synchronous ring

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***ABSTRACT***
*In order to improve the change of friction material properties caused by the local high temperature and contact wear generated by the synchroniser friction pair shifting process. A composite synchronizer ring using carbon fibre composite material as friction material is proposed. In order to study the influence of different working condition parameters on the temperature distribution of the working surface of the composite synchronous ring, the thermal structure coupling characteristics of the friction pair surface of the composite synchronous ring are analysed. Based on the heat transfer science, the finite element analysis software is used to establish the finite element analysis model of the friction dyadic surface of the composite synchronous ring, and to study the temperature distribution of the friction dyadic surface of the composite synchronous ring under different rotational speed differences and loads. As a result, for every 100N increase in load and 100r/min increase in rotational speed difference, the maximum temperature of the friction plate temperature increases by approximately 15°C. The temperature of the friction plate increases by approximately 15°C for every 100N increase in load and 100r/min increase in rotational speed difference.*

***Keywords*** *: Composite synchronizer ring, Frictional contact, Temperature characteristic, Factor*

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## I. Introduction

Synchroniser, as a key part of automotive transmission, has a significant impact on automotive gearshift. The frictional heat generated by the friction process of the friction dyadic surfaces during the shifting process causes uneven contact on the joint surfaces, which in turn will affect the shifting control accuracy of the synchroniser. In order to improve the friction, wear resistance and durability of synchroniser taper surfaces, carbon synchronisers are widely used. Under rigorous testing and operating conditions, carbon synchronisers exhibit higher wear resistance and durability compared to brass synchronisers. Fibre-reinforced composites are used in a wide range of automotive and aircraft manufacturing applications[1]. Scholars in various countries have also worked extensively on synchroniser contact surface temperatures. Haggstrom et al [2] and others investigated the effect of synchroniser friction factors on the performance and functional dimensions of transmissions, developed a new contact friction model for lubricated molybdenum steel and developed a simplified thermal model. Barathiraja K [3] et al. investigated the effect of torsional vibration of synchroniser generated by rotational speed on the life of synchroniser and concluded that torque generated by high rotational speed affects the life of synchroniser and the wear of carbon sleeve of synchroniser makes the wear gap tends to zero. Meng Fei [4] et al. combined the synchroniser control mechanism as well as the calculation methods of synchroniser torque and friction metric to derive the synchroniser friction performance index. Wang Kefeng [5] and others investigated the influence law of different operating parameters and structural parameters on the temperature field of the synchroniser friction pair, and concluded that the increase in the speed difference, slip time and shift force of the synchroniser friction pair will make the friction pair temperature increase and stress increase. Zhang Zhigang [6] and others used the thermal-structural coupling method to simulate the temperature characteristics of the synchroniser synchronisation process, and the conclusions showed that the maximum temperature of the synchroniser lock ring friction lining and friction surface was 106°C, which lays the foundation for the analysis of the mechanism and form of the synchroniser ring friction surface thermal failure.

In this paper, according to the actual structure of the composite synchronous ring and shift working conditions, the temperature of the friction sub-structure of the composite synchronous ring is studied and analysed. The finite element simulation is used to establish a simulation model of the friction sub-structure jointing process, and the temperature characteristics of the thermal structure of the composite synchronous ring are analysed under the typical working condition parameters, so as to study the influence of different working condition parameters on the temperature of the composite synchronous ring, and to provide a basis for improving the control strategy of the composite synchronous ring gearshift process.

## II. Modelling of temperature rise at the friction dyad surface of composite synchronizer rings

In order to study the temperature field distribution of the friction dyadic surface of the composite synchronous ring during the synchroniser shift synchronisation process, the temperature model of the composite synchronous ring in the synchroniser shift process is established.

### *2.1 Composite synchronous ring friction sub heat generation model*

When a composite synchronizer ring is synchronised in a synchronizer, the frictional torque generated by the friction between the carbon fibre layer friction inner cone and the outer cone of the engagement ring is the key to synchronous shifting of the composite synchronizer ring, and a large amount of frictional heat is generated by the relative slippage. The heat is applied to the inner friction cone of the composite synchronising ring and the friction contact surfaces of the engagement ring in the form of heat flow density. The heat flow density of the composite synchronous ring is calculated by the formula [7] as：

$$q(r,t)=\mu prw(t) \tag{1}$$

Formula：$q$ is the heat flow density， $\mu$ is the friction coefficient, $p$ is the positive pressure on the friction surface during synchronization, $w$ is the rotational speed of the composite synchronizer ring and friction cone ring, $t$ is the synchronization time, r is the friction radius.

To show the distribution ratio of the two friction surfaces in terms of heat flow density, the distribution ratio of heat flow density between the two friction surfaces of the friction vice is calculated by the formula [8] as：

$$\beta=\frac{q_w(r,t)}{q_n(r,t)}=\left(\frac{\lambda_w\rho_w c_w}{\lambda_n\rho_n c_n}\right)^{0.5} \tag{2}$$

Formula： $q$ is the heat flow density, The subscripts $w$ , $n$ represent the outer and inner ring cones of the composite synchronizer ring respectively, $\lambda$ is the coefficient of thermal conductivity, $\rho$ is density , $c$ is the specific heat capacity.

### *2.2 Composite synchronous ring friction sub heat transfer model*

#### *2.2.1 Modelling of heat conduction in the friction pair of composite synchronous rings*

The study of the thermal conductivity of the composite synchronous ring is to obtain the distribution law of the temperature of the friction dyadic surface with the spatial position and the change law with time under certain boundary conditions. The temperature of the friction dyadic surface of the composite synchronising ring during the synchronisation phase of the gearshift process varies with time and belongs to transient heat transfer. According to the theory of heat transfer, for solving the temperature field without heat source, the three-dimensional heat conduction differential equation [9] is given as：

$$\rho_i c_i\frac{\partial T_i}{\partial t}=\lambda_i\left(\frac{\partial T_i}{\partial x^2}+\frac{\partial T_i}{\partial y^2}+\frac{\partial T_i}{\partial z^2}\right) \tag{3}$$

Formula：T is the temperature, t is the joining time,λ is the thermal conductivity of the material,c is the specific heat capacity.

To find the unique solution of equation (3), it is necessary to give specific initial and boundary conditions. According to the actual composite synchronous ring working environment, the initial temperature of the composite synchronous ring is set to 22°C.

#### *2.2.2 Calculation of convective heat transfer coefficient*

Convective heat transfer mainly occurs in the friction vice composite synchronous ring inside and outside the ring rear face and meshing gear ring front face there is a gap, composite synchronous ring carbon fibre outer ring and inner ring friction cone and the lubricating oil there is convective heat transfer, convective heat coefficient [10] formula is：

$$h_h=C\frac{\lambda_p}{d_{(i,o)}}\left(\frac{v_{(i,o)}d_{(i,o)}}{v_p}\right)^n \mathrm{Pr}^{\frac{1}{3}} \tag{4}$$

Formula： $\mathrm{Pr}$ is the Prandtl factor for transmission lubricants ; $v_{(i,o)}$ is the carbon ring surface linear velocity, $d_{(i,o)}$ is the diameter of the carbon ring; a constant (math.) C=0.193，n=0.705.

Composite synchronous ring before and after the end face, meshing gear ring before and after the end face in the working process and the lubricating oil contact is in a rotating state, the end face of the convective heat transfer can be equated to the fluid swept away from the flat plate convective heat transfer, and its convective heat transfer coefficient [11] is:

$$h_s = 0.332\frac{\lambda_p}{r_0}\left(\frac{wr^2}{v_p}\right)^{\frac{1}{2}}\mathrm{Pr}^{\frac{1}{3}} \quad (5)$$

Formula： $r_0$ is the equivalent radius of the outer friction cone of the carbon fiber inner ring.

## III. Finite element model of composite synchronizer ring friction sub

According to the structure of the synchroniser can be divided into atmospheric synchroniser, inertial synchroniser and self-boosting synchroniser. The inertial synchronizer is widely used in modern automobiles, and this paper takes the locking ring inertial synchronizer as the research object, and establishes a finite element model for the coupled analysis of the thermal structure of the composite synchronous ring.

### *3.1 Modelling and meshing of the friction pair of composite synchronizer rings*

In order to reduce computer requirements and computational time, the actual composite synchronous ring geometric model is simplified and deleted, for example, the threaded grooves, chamfers, and rounded corners on the composite synchronous ring are deleted, and the simplified synchroniser model is shown in Fig. 1

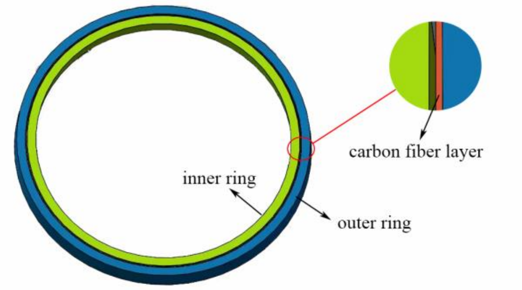



**Fig.1** Simplified Model of Synchronizer

Through the geometric model, the finite element mesh model is generated as in Fig. 2. There are two forms of mesh division: tetrahedral mesh and hexahedral mesh. When the density of the grid is the same, the hexahedral mesh has fewer cells and nodes than the tetrahedral mesh, which can effectively reduce the amount of calculation, and the results of the hexahedral mesh are more accurate. Therefore, the geometric model was divided using the hexahedral mesh method with a grid cell size of 1 mm.

**Fig. 2** Finite element mesh model

### *3.2 Composite synchronised ring friction sub-material characteristics*

Referring to the actual material type of the composite synchronous ring, the friction and wear performance as well as the service life of the composite synchronous ring are taken into account. According to the material of the actual synchronizer, this paper selects the composite synchronous ring main body material for copper-zinc alloy, its parameters are shown in Table 1, the friction surface to create a larger thickness of carbon fibre composite material as the friction material of the composite synchronous ring, and its material parameters are shown in Table 2.

**Table 1** Copper-zinc alloy material parameters

| Temp T/℃ | indoor temperature |
|---|---|
| density / ( kg·m$^{-3}$ ) | 8500 |
| elastic modulus /(Pa) | $1.2\times10^{11}$ |
| Poisson's ratio | 0.35 |
| thermal conductivity /(W·m$^{-1}$·K$^{-1}$) | 86 |
| specific heat capacity /(J·kg$^{-1}$·K$^{-1}$) | 368 |
| coefficient of thermal expansion /(1·℃$^{1}$) | 1.89e-5 |

**Table 2** Carbon fiber material parameters

| parameters | carbon fiber | epoxy resin | carbon fiber composites |
|---|---|---|---|
| density /(kg·m$^{-3}$) | 1760 | 1300 | 1600 |
| thermal conductivity /(W·m$^{-1}$·K$^{-1}$) | 84 | 0.2 | 55 |
| specific heat capacity /(J·kg$^{-1}$·K$^{-1}$) | 795 | 1200 | 1058 |
| coefficient of thermal expansion /(10$^{-6}$°C$^{1}$) | -0.41 | 57 | 0.26 |

The analysis is carried out with the typical working conditions of the composite synchronous ring. According to the actual working process for parameter setting, the above thermal theory combined with the actual heat convection distribution coefficient, convective heat coefficient and other data substitution for analysis.

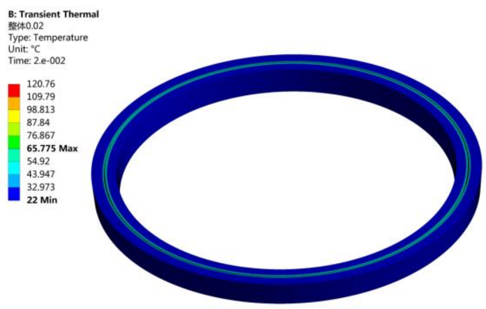
*3.3 Thermal structure coupling method for the friction pair of composite synchronous rings*

Thermal-structural coupling is a relatively common multi-field coupling method in finite element analysis. Combined with the research object of this paper, the friction process of the composite synchronous ring friction vice friction process produces a large amount of heat distribution is not uniform, resulting in high heat at the high temperature and thermal expansion, low heat at the low temperature and thermal expansion, this situation will lead to the surface of the friction cone of the composite synchronous ring friction heat inhomogeneity aggravated. Therefore, this paper selects the sequential coupling method to simulate and analyse the thermal structure of the friction ring of the composite synchronous ring.

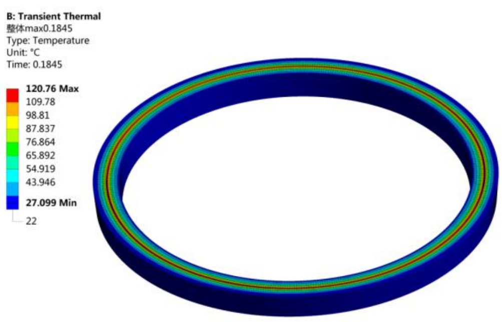
## IV. Thermodynamic analysis of the friction pair of composite synchronous ring under typical working conditions

*4.1 Temperature field analysis under typical operating conditions*

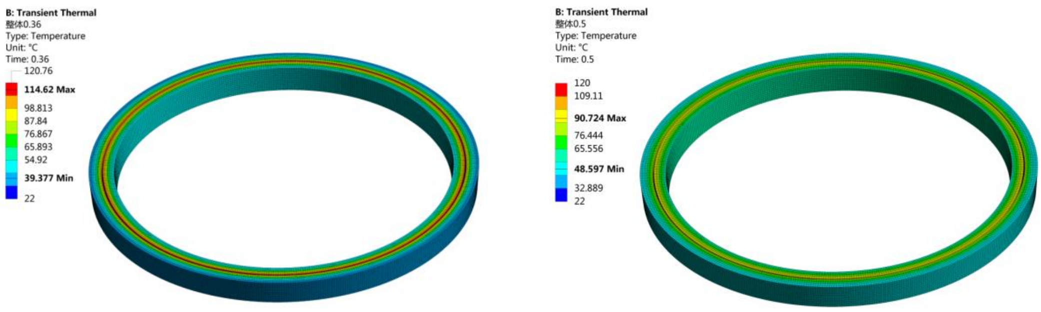
Through the finite element analysis software on the composite synchronous ring friction dyadic surface thermal structure coupling analysis, the carbon fibre composite material dyadic surface and the friction surface friction surface distribution, composite synchronous ring temperature field distribution as shown in Figure 3.




(a) t=0. 02s




(a) t=0. 1845s




(b) t=0. 36s (d) t=0. 5s

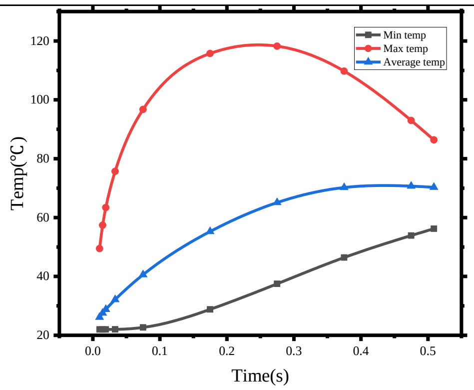
**Fig. 3** Overall temperature distribution

It can be concluded from Fig. 3 that during the friction process of carbon fibre composites. The highest temperature is mainly concentrated in the middle part, the temperature on both sides is slightly lower than the middle part, and the lowest temperature appears on the back side of the contact surface, which is due to the fact that during the friction process, the heat generated on the same side of the middle friction region is the same, but due to the fact that the friction surface and the air undergoes forced convection heat transfer instead of the friction surface undergoes natural convection heat transfer and the heat generated by the friction contact surface is transferred by heat conduction to a lower temperature place.

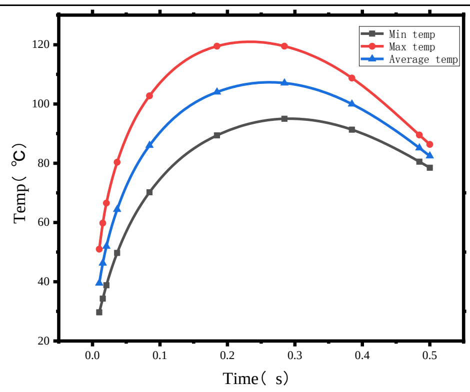
At the beginning of the friction phase, the highest temperature on the friction cone of the coupling ring occurs at one end of the contact surface. This is because the heat flow density of the friction cone of the coupling ring is input at intervals, only the surface of the inner cone of friction with the composite synchronizer ring, that is, the carbon fibre friction surface, has heat flow density input, and the uncontacted surface absorbs the heat of the contact surface by means of heat conduction, the heat flow density input in the middle of the friction cone of the coupling ring exists with the transfer of heat to the two end surfaces, and the heat flow density of the two end surfaces of the friction cone of the coupling ring is transferred to the other parts of the coupling ring only by means of inner heat conduction. The heat flow density at the two end surfaces of the friction cone of the coupling ring is only transferred to the other parts of the coupling ring by means of heat conduction in the inner layer. The energy transferred by convective heat transfer from the outer side of the ring in contact with the air is significantly less than the energy lost by heat conduction, so the highest temperature at the beginning of the friction phase occurs at one end of the contact surface. As the friction synchronisation process progresses, the surface temperature of the friction cone of the coupling ring gradually tends to be uniformly distributed. The temperature at the end of the largest cylindrical surface of the friction cone of the combined ring is higher than other positions, which is due to the fact that in the same time, in the case of the same heat flow density input, the position of the contact surface of the larger the higher energy, the position of the contact surface of the larger the higher energy。

The highest temperature of the friction lining surface of the composite synchronizer ring occurs on the carbon fibre layer. During the synchronisation of the composite synchronous ring, most of the heat generated by the carbon fibre friction cone surface is absorbed by the steel structure of the composite synchronous ring itself, and the temperature of the structure itself is rising. The radial temperature change gradually decreases from inside to outside. The highest value of the temperature occurs at the carbon fibre layer of the composite synchronous ring, due to the characteristics of the carbon fibre composite material, resulting in a large amount of heat being absorbed by the carbon fibre material and transferred to the low temperature through the form of heat transfer and heat conduction.

Due to the different materials of the friction cone surface of the composite synchronous ring and the combined gear ring, the heat flow density input of the two surfaces and the thermal conductivity of the materials are different, so the maximum temperature of the friction cone surface of the composite synchronous ring and the friction cone surface of the combined gear ring are different. In order to study and analyse the change rule of composite synchronous ring temperature field, the temperature change curve of the friction cone surface of composite synchronous ring, i.e., the carbon fibre composite friction surface and the friction cone surface of the combined gear ring with time and the temperature change curve of the combined gear ring in the friction process are extracted as shown in Fig. 4.




Combined ring temperature




Carbon fibre layer temperature

**Fig4.** Temperature profiles of the combined ring and carbon fibre friction surfaces

From figure 4 can be obtained, composite synchronous ring and combined with the highest temperature change rule of the ring is basically the same. As the synchronisation time passes, the temperature first rises and then decreases, the two reach the highest point of the temperature of the moment is basically the same. In the simulation analysis of the synchronous process of composite synchronous ring under typical working conditions, the highest temperature of composite synchronous ring friction cone surface is 120.84 ℃, combined with the highest temperature of the friction cone surface of the ring is 118.23 ℃. The difference in the maximum temperature on the surface of the friction cone of the combined ring and the composite synchronous ring is due to the difference in the materials of the two, which have different material performance parameters, and the difference in the heat flow density input values of the two friction pair surfaces. According to the above mentioned heat flow density distribution coefficient formula, composite synchronous ring friction cone got the whole friction process friction heat 48%, the remaining 52% of the friction heat is combined with the tooth ring friction cone absorbed, the two friction contact area is the same, so at the beginning stage of the composite synchronous ring friction cone surface of the highest temperature is slightly smaller than the combined with the tooth ring friction cone surface of the highest temperature. With the passage of time, the temperature difference between the two is getting bigger and bigger, the reason is that there are two material properties to decide, the thermal conductivity of carbon fibre composite material is slightly inferior to the thermal conductivity of No. 45 steel, so the composite synchronous ring friction cone to get the heat of the slower speed, combined with the tooth ring friction cone surface of the maximum temperature change faster.

As the synchronisation time goes on, the temperature of both reaches the highest value, the surface temperature of the composite synchronising ring and the combined ring starts to decrease, and the speed difference between the two is getting smaller and smaller. Resulting in the friction surface of the heat flow density input value continues to decrease, composite synchronous ring friction and combined gear ring away from the friction contact surface of the structure through heat conduction from the friction contact surface, the heat input into the contact surface per unit of time is less than per unit of time from the friction contact surface through heat conduction to the heat inside the geometric structure. As a result, the maximum temperature of the inner cone of the composite synchro ring friction and the friction cone of the combined gear ring is decreasing over time during the second half of the composite synchro ring shift.

*4.2 Influence of working condition parameters on the coupling characteristics of the thermal structure of the friction subassembly of a composite synchronous ring*

By quantitatively analysing the temperature distribution law of the dyadic surface of the composite synchronous ring under different loads and different rotational speeds, it lays the foundation for the establishment of the temperature rise compensated composite synchronous ring shift control strategy, which is of great significance for the composite synchronous ring to improve the shift control accuracy.

*4.2.1 Effect of load on the temperature field field of the friction pair*

Taking the composite synchronous ring anti-mo process as the research object, the effects of different loads of 200N, 300N, 400N and 500N on the temperature distribution are analysed. Taking the highest point of temperature of the friction surface of carbon fibre composite material as the research object, the change curve of the highest point temperature under different loads is analysed, as shown in Fig. 5.

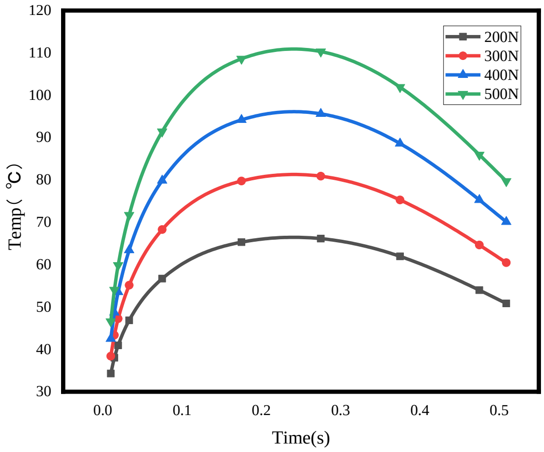



**Fig. 5** Temperature profiles of friction surface of carbon fibre layer under different loads

From Fig. 5, the temperature change rule under four working conditions is basically similar, in the case of the same friction coefficient, shift synchronisation time, rotational speed difference and friction material, the larger the load, the higher the temperature between the friction contact surfaces and the time to reach the maximum temperature value is basically the same. The time to reach the maximum temperature on the friction surface of the carbon fibre layer of the composite synchronizer ring is t=0.274 s. The maximum value of the surface temperature of the composite synchronizer ring increases by about 15°C for every 200N increase in load. The temperature inconsistency between the composite synchronizer ring and the combined ring is mainly due to the material properties of the two friction surfaces, which are different, one is a carbon fibre composite material and the other is structural steel. The two friction contact surface of the heat flow density value and thermal conductivity is different, these two factors on the composite synchronous ring and combined gear ring contact surface of the maximum temperature size plays a decisive role.

*4.2.2 Effect of speed difference on the temperature field of the friction pair*

Taking the composite synchronous ring anti-mo process as the research object, the effect of different loads of 200 r/min, 300 r/min, 400 r/min and 500 r/min on the temperature distribution is analysed. Taking the highest point of temperature of the friction surface of carbon fibre composite material as the research object, the change curve of the highest point temperature under different loads is analysed, as shown in Fig. 5.

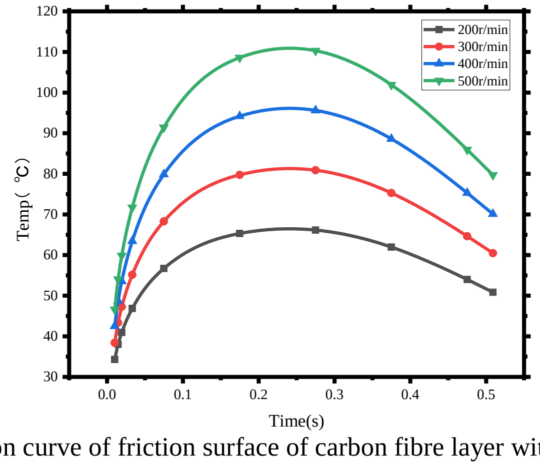



**Fig. 6** Temperature variation curve of friction surface of carbon fibre layer with different speed difference

From Fig. 6, the temperature distribution under four different working conditions is basically the same. Under the conditions of load, friction material, synchronous time and friction coefficient being the same, the higher the speed difference is, the higher the temperature of the friction contact surface is, and the moment of reaching the maximum temperature is the same. The time for the carbon fibre layer friction inner cone surface of the composite synchronous ring to reach the maximum temperature is t=0.274 s. For every 100 r/min increase in the rotational speed difference of the composite synchronous ring, the maximum value of the friction surface temperature of the carbon fibre layer increases by about 15°C. The temperature of the carbon fibre layer friction contact surface is the same at the same moment. The change of rotational speed difference affects the change of the magnitude of convective heat transfer coefficient, which further affects the temperature distribution of the friction contact surface of the composite synchronous ring and the combined gear ring, by comparing the results of the rotational speed difference and the effect of load on the temperature. The maximum value of convective heat transfer on the temperature of the friction contact surface of the composite synchronous ring has a small effect.

## V. Conclusion

(1) The temperature change of the friction surface of the composite synchronous ring is analysed by the finite element simulation method of thermal-structural coupling, and it is verified that the highest temperature rise occurs in the middle of the friction contact surface of the composite synchronous ring during the synchronous shift process of the composite synchronous ring; and the temperature of the friction pair surface of the composite synchronous ring during the shift process rises from 20℃ to 120.76℃. The temperature of the two contact surfaces of the friction pair is different between the composite synchronous ring and the combined ring because of the different material performance parameters.

(2) The temperature change trend of the carbon fibre friction surface of the composite synchronizer ring and the temperature change curve trend of the combined gear ring are both increasing first and then decreasing; for the carbon fibre friction surface of the composite synchronizer ring, the maximum surface temperature of the carbon fibre friction surface increases by about 15°C for every 200N increase of the load; and the same temperature of the carbon fibre surface increases by about 15°C for every 100r/min increase of the rotational speed difference. The temperature distribution of the friction contact surface is obtained by simulating the shifting process of automobile composite synchronous ring through finite element simulation, which lays the foundation for establishing the temperature compensation of the shifting process and is of great significance for improving the shifting strategy of composite synchronous ring.

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