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Fractal theory based friction and wear model of automotive composite synchronizer ring

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ABSTRACT
Based on the fractal theory of abrasive wear, combined with the theory of adhesive wear and fractal contact model, a mathematical model of contact wear prediction of composite synchronizer ring is established, and the effects of rotational speed difference and lubricating oil temperature as well as the smoothness of workpiece surface on the wear rate of composite synchronizer ring are investigated in the process of shifting gears of composite synchronizer ring. The simulation results show that: the wear rate with the increase of fractal dimension D firstly decreases and then increases; with the increase of rotational speed and increase, when the rotational speed exceeds a certain value, the impact on the wear rate decreases; with the increase of lubricating oil temperature and increase, fractal dimension in the optimal solution before the lubricating oil temperature for the average depth of the wear rate of the impact is smaller than in the optimal fractal dimension after.

Keywords: *Composite synchronizer ring, Contact abrasion, Fractal theory, Factor.*

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I. Introduction

Wear is one of the most important failure forms of parts, any in the scope of work when the two parts of the surface of the mutual line into the friction vice, because of the friction vice parts of the interaction of the movement produces wear, wear is the result of the action, so the relationship between friction and wear is closely related. Serious wear parts may lose the original function, or even fracture, damage and so on, thus leading to the whole mechanical equipment can not run normally or the quality of work is seriously reduced. Composite synchronizer ring is a friction principle as the basis of the work of the parts, its wear problem is more obvious compared to other parts, composite synchronizer ring of the transitional wear will lead to synchronization time prolongation, hit the teeth, shift failure and other phenomena. This is one of the reasons for studying the wear of composite synchronizer rings.

Chen Guoan [1] et al. studied the synchronizer friction and wear model based on fractal theory and adhesion theory, and derived the influence of different parameters and working conditions of synchronizer on synchronizer friction and wear. Xu Zhan [2] et al. established a synchronizer wear life prediction calculation model based on the synchronizer wear characteristics, combined with the collection and processing of shift load spectrum and road use test, as well as the fatigue wear theoretical model, which can accurately predict and evaluate the synchronizer wear life. Hao Yan [3] et al. established a friction coefficient compensation control strategy and studied the process of friction coefficient compensation controlling the synchronizer synchronous transmission, which showed that The friction coefficient is kept near the desired value of 0.08, and the synchronization time is shortened to reduce the sliding friction.U. Stockinger [4] investigated the comparison of the load limiting and degradation behaviors of single-cone synchronizer rings with carbon friction material and multi-cone synchronizer rings, and showed that the single-cone synchronizer rings have greater wear than the multi-cone synchronizer rings at the same load level.

The above research lacks the study on the wear performance of carbon fiber composites as the lining of synchronizer rings. In this paper, according to the actual structure of the composite synchronizer ring and shift operating conditions, a mathematical model is established to predict the friction and wear of the composite synchronizer ring, and analyze the influence of fractal dimension, surface smoothness, rotational speed difference, and lubricant temperature on the wear rate of the composite synchronizer ring.

II. Composite synchronizer ring wear mechanism

The break-in of composite synchronizer rings refers to the process in which the machined parts are worn under certain conditions making the friction surfaces reach a dynamic balance of stresses and thus making the wear rate stabilize at a relatively low level. The break-in process of composite synchronizer rings can be explained by the micro-convex body theory model. The composite synchronizer ring is obtained by bonding carbon fiber cloth to the synchronizer ring through adhesive, and the surface of the newly obtained composite synchronizer ring model is rough. When two synchronizer rings are grinding, the two contact surfaces only touch each other at the top of the higher microconvex body, so the contact area between the composite synchronizer rings is actually very small compared to the macroscopic contact area. During the grinding phase, these higher microbumps are the main carriers of the loads, so that the contact stresses on the individual microbumps are so high that they exceed the yield limit of the material. Under the action of these contact stresses, the state of the microbumps appears as follows: firstly, the lighter microbumps are consolidated at the moment of contact to form abrasive debris, secondly, the protruding part of the microbumps undergoes plastic flow and is pressed into the surrounding grooves, and thirdly, the larger microbumps are locally fusion-welded due to the high temperature at the moment of contact and collision. The first two cases make the contact surface gradually smooth, large bearing capacity, the third case due to the friction surface there is rapid relative motion, the formation of localized welding micro-convex body is torn, adhesive wear occurs. When the abrasive debris produced by the first and third two cases accumulates to a certain extent, abrasive wear is triggered. When the composite synchronizer ring is fully abraded, the sharp micro-convex body is smoothed, the deep grooves are filled, the contact area of the friction surface increases, the surface protective film is formed, the wear rate decreases, and it enters the stable wear stage. Adhesive wear is the main reason for the wear loss of composite synchronizer rings.

III. Mathematical modeling of composite synchronous ring wear

According to the working principle of synchronizer, the wear forms of synchronizer ring are adhesive wear, abrasive wear and corrosive wear. Compared with the adhesive wear, the wear amount of abrasive wear and corrosive wear is negligible, so we mainly study the adhesive wear. From the theory of adhesive wear, the material wear equation is:

$$V = K\frac{NL}{\sigma_a} \tag{1}$$

In the format: V is the amount of particle wear; K is the wear coefficient; N is the load normal to the friction cone; L is the total distance traveled by the friction pair; and is the yield limit of the softer material.

Bowden and Tabor [5] proposed the theory of frictional adhesion, where for an ideal linearly elastic material the external load equation is:

$$N = A_r \cdot \sigma_a \tag{2}$$

Synchronizer ring in the actual working process, the frictional wear of the contact is not a simple line elastic contact, but a composite state, so the wear coefficient[6] is divided into elastic wear coefficient and inelastic wear coefficient . For the friction contact surface, the formula is:

$$KA_r = K_e \cdot A_{re} + K_p \cdot A_{rp} \tag{3}$$

In the format: A_{re} is the actual contact area for elastic contact; A_{rp} is the actual contact area for plastic contact.

Majumdar and Bhushan [7] proposed a contact model based on fractal geometry, the format is:

$$\frac{A_{re}}{A_r} = 1 - \left[\frac{D \cdot a_c}{(2-D)A_r}\right]^{\frac{(2-D)}{2}} = 1 - \left[\frac{D \cdot G^2}{(2-D)\left(k \cdot \phi/2\right)^{2/(D-1)} A_r}\right]^{(2-D)/2} \tag{4}$$

In the format: a_c is the critical contact area; D is the fractal dimension; G is the surface profile fractal parameter; $k = H/\sigma_a$ is the correlation coefficient between hardness H and yield limit σ_a; $\phi = \sigma_a/E$ is the material property parameter.

Composite synchronizer ring friction cone wear is the most important wear of the synchronizer, according to the above formula composite synchronizer ring force relationship, can get the composite synchronizer ring friction cone wear expression for:

$$h^* = v\beta\frac{P}{\sigma A_a}\left\{K_e + \left(K_p - K_e\right)\left[\frac{D\left(G/\sqrt{A_a}\right)^2}{(2-D)\left(A_r/A_a\right)}\left(\frac{\pi E^2}{225\sigma_s^2}\right)^{\frac{1}{D-1}}\right]^{\frac{2-D}{2}} \psi^{\frac{(D-2)^2}{4}}\right\}\left(1+\lambda f^2\right)^{1/2} \tag{5}$$

IV. Numerical simulation analysis of composite synchronizer ring wear

Composite synchronizer ring wear is a complex process of multiple factors, which affects the wear of the main factors by the nature of the friction sub-material, surface morphology, load, lubricant temperature, friction sub relative sliding speed. This paper uses the composite synchronous ring wear prediction model obtained above to carry out numerical simulation, composite synchronous ring friction material is carbon fiber composite material.

4.1 Influence of surface morphology on the wear rate of composite synchronizer rings

The M-B fractal contact modification model uses the scale factor G and the contour fractal dimension D to characterize the surface morphology, in order to analyze the effect of scale factor and fractal dimension on the wear rate, respectively, take the lubricant oil temperature Tm = 80 ℃ under the typical working condition of the gearbox, the relative sliding speed of friction vice 1000r/min, the temperature inside the contact node Ts = 150 ℃, and the load on the contact surface is P = 300Pa to carry out numerical Analysis, get G, D on the wear rate of the influence of the law shown in Figure 1.

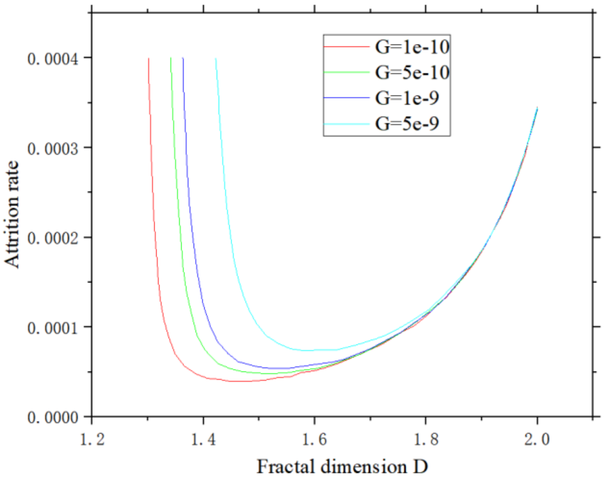

Fig. 1 Effect of fractal dimension and surface smoothness on wear rate

As can be seen from Fig. 1, the average depth wear rate decreases and then increases with the increase of fractal dimension D, which represents the existence of an optimal fractal dimension to minimize the average depth wear rate of the composite synchronizer ring. This phenomenon can be explained by the theory of micro-convex body: in the early stage of the friction surface of the carbon fiber composite synchronizer ring and the combined ring, there are various micro-convex bodies on the two contact surfaces, and the real contact area in the carbon fiber composite layer and the combined ring is very small, and the intense adhesive wear caused by elastic-plastic deformation of the micro-convex body occurs at this stage. With the carbon fiber composite layer and the bonded tooth ring abrasive wear, the higher micro-convexity of the two contact surfaces is cut away, part of the grooves are filled, and the surfaces become flat, so the fractal dimension increases. After that, the real contact area increases, the elastic contact becomes more, the plastic contact decreases, the two friction surfaces become flat, the bearing capacity of the surfaces becomes stronger, the adhesive wear slows down, and the wear rate tends to stabilize at a relatively small value, and then reaches an optimal fractal dimension. When followed by further wear so that the carbon fiber composite layer and the surface of the combined ring becomes too smooth, the fractal dimension continues to increase, the molecular force between the two friction surfaces becomes the main influence factor of adhesive wear, adhesive wear intensifies, the wear rate increases. Therefore, for the composite synchronizer ring to reduce the wear rate, the optimal fractal dimension is of great significance for its processing and bonding.

The G value is a surface profile fractal parameter that characterizes the magnitude of the contact surface profile, and the larger the G value, the larger the magnitude. From Fig. xx, it can be seen that the effect of G value on the average depth wear rate of the composite synchronizer ring can be divided into two segments: when D is smaller than the optimal fractal dimension, i.e., in the first half of the wear, the effect of G value on the average depth wear rate is larger; after that, the effect of G on the average depth wear rate gradually decreases. This is because the plastic contact of the microconvex body is the main cause of adhesive wear when the fractal dimension is small, and when the value of G is larger, the plastic contact is more; when the fractal dimension increases, the molecular force between the smooth surfaces dominates the adhesive wear.

4.2 Effect of relative rotational speed on the wear rate of composite synchronizer rings

Taking the temperature Tm=80°C,Ts=150°C, rotational speed 1000r/min,fractal dimension G=1*10-9 and load P=300Pa, numerical simulation analysis of Eq. xx is carried out to obtain the effect of relative rotational speed on the average depth wear rate of the composite synchronizer ring as shown in Fig. 2.

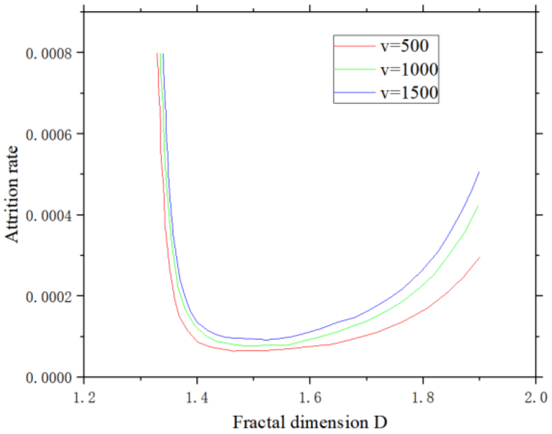

Fig. 2 Effect of rotational speed on average depth wear rate

As can be seen from Fig. 2, the average depth wear rate of the composite synchronizer ring increases with the increase of rotational speed, and the influence on the wear rate decreases when the rotational speed exceeds a certain value. This is because in the composite synchronizer ring friction process, the composite synchronizer ring and the combination of the rough surface of the ring and the same micro-convex body of the elastic-plastic contact number is the main factor affecting the depth of the wear rate, the rotational speed becomes larger, the number of contact times per unit of time will become more, and then the wear rate will become larger. When the speed of the composite synchronous ring exceeds the critical value, the carbon fiber layer of the composite synchronous ring and the combination of the ring between the formation of the lubricant film, the oil film will be separated from the friction side contact surface and bear part of the load, making the two contact area is reduced. The increase of rotational speed leads to the increase of friction contact times and increase wear, caused by the carbon fiber layer and the metal bonding surface contact area to reduce the wear, the joint effect of these two makes the rotational speed for the composite synchronizer ring average wear rate impact is reduced.

4.3 Effect of lubricant temperature on the wear rate of composite synchronizer rings

Taking the temperature Ts=150℃, rotational speed 1000r/min,fractal dimension G=1*10-9, load P=300Pa, G=1*10-9, numerical analysis of Eq. xx yields the effect of lubricant temperature on the average depth wear rate of the composite synchronizer ring as shown in Fig. 3.

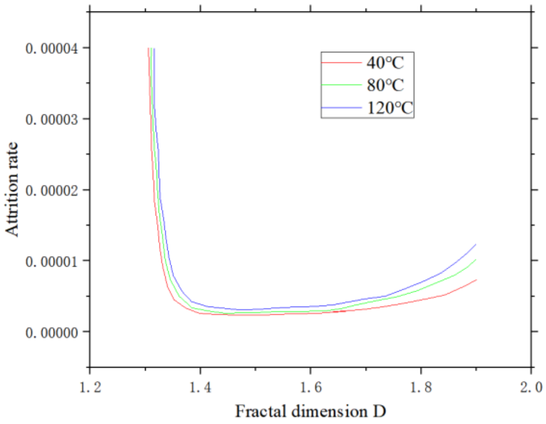

Fig. 3 Effect of lubricant temperature on average depth wear rate

From Fig. 3, it can be seen that the average depth wear rate of the composite synchronizer ring increases with the increase of the lubricant temperature, and the effect of the lubricant temperature on the average depth wear rate before the optimal solution of the fractal dimension is smaller than that after the optimal fractal dimension. The higher the lubricant temperature, the lower the viscosity of the lubricant and the more difficult it is to form an oil film, which leads to a higher wear rate. In the early stage of wear, the elastic-plastic contact of the micro-convex body between the friction parts of the composite synchronizer ring is the main cause of wear, and at this time, the oil film has a small effect on the contact wear between the two; when the optimal fractal dimension is reached, the friction part of the surface of the elastic contact between the two surfaces, and the friction part of the surface of the friction part of the distribution of many small grooves can store the lubricating oil, and the temperature has a reduced effect on the formation of the oil film; when the fractal dimension is increased further. When the fractal dimension further increases, the surface of the friction sub-surface tends to smooth surface, the storage of lubricant grooves become less, the temperature becomes smaller, the adsorption capacity of the oil film molecules become stronger, the easier it is to form a film of oil, this time the oil film will be separated from the contact surface so that the molecular force between the contact surfaces is reduced, thus reducing the wear rate. Therefore, the smoother the contact surface, the greater the effect of lubricant temperature on the average depth of wear rate of composite synchronizer rings.

V. Conclusion

Using the adhesive wear formula and fractal contact model, a mathematical model of composite synchronizer ring wear was established, and the composite synchronizer ring shift process was analyzed by numerical simulation. The effects of fractal dimension, relative rotational speed, and lubricant temperature on the average depth wear rate of the composite synchronizer ring are obtained. The numerical simulation results show that the average depth wear rate decreases with the increase of fractal dimension D, which represents the existence of an optimal fractal dimension that minimizes the average depth wear rate of the composite synchronizer ring; the average depth wear rate increases with the increase of rotational speed, and the influence on the wear rate decreases when the rotational speed exceeds a certain value; the average depth wear rate increases with the increase of lubricant temperature, and the fractal dimension decreases with the increase of lubricant temperature before the optimal solution; and the influence of the fractal dimension on the average depth wear rate is reduced with the increase of the relative speed. The effect of lubricant temperature on the average depth wear rate is less before the optimal solution of fractal dimension than after the optimal fractal dimension.

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