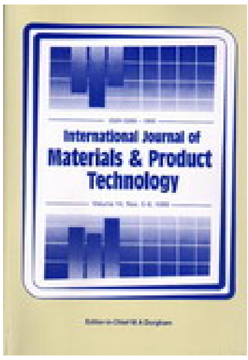

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Performance analysis of automotive braking friction materials based on surface roughness

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Abstract: The traditional friction material performance analysis method has the problem of high wear rate. Therefore, this paper proposes a performance analysis method of automobile braking friction material based on surface roughness. The calculation formula of material friction is described by classical friction law, the material performance analysis function is constructed according to Mamdani fuzzy algorithm, the influence function of friction coefficient is determined through the optimal fusion position constraints, and the multi-objective function model is constructed according to surface roughness to analyse the performance of automobile braking friction materials. The results show that the friction coefficient of the material is 0.38 at 200°C. When the service life of the friction material is 150 days, the wear rate of the friction material is 0.22%. This shows that this method can improve the friction performance of automotive braking friction materials, which has a certain practical significance.

Keywords: wear rate; cut item; roughness term; load; friction materials.

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1 Introduction

Brake friction material is an important part of automobile braking system. Its quality and performance stability are related to the effect of automobile braking and the life and property safety of drivers and passengers (Lin and Xie, 2019). With the rapid development of the automobile industry, by 2013, the number of automobiles in China had reached 137 million, and the demand for braking materials as automobile consumables was also increasing day by day. According to statistics, about h% of traffic accidents are caused by the problems of vehicle braking system, and these accidents often occur in complex special working conditions such as rain and snow, long downhill, high-speed heavy load and emergency braking (Vijay et al., 2020). Research reports show that the probability of traffic accidents on wet roads is 60% higher than that on dry roads. At the same time, China's relevant highway specifications do not have strict requirements for long slopes, so there are frequent reports of brake failure due to excessive brake temperature caused by continuous braking (Wei et al., 2020). At present, the research on brake friction materials mainly focuses on the optimisation of material composition, but there are few performance tests in the special environment of Shanghua, and the research on its friction behaviour and wear mechanism is not mature. Therefore, it is particularly important to research and improve the friction and wear performance of braking friction materials under different special working conditions, especially under water environment and continuous braking conditions (Kim et al., 2020).

Shu et al. (2020) studied the friction and wear performance of automobile friction plates, tested the tribological performance with a constant speed friction testing machine, and verified the friction and wear performance through the mass fraction experiment. The experimental results show that this method can reduce the training error and improve the calculation accuracy of friction coefficient, but the calculation process of this method is complex and the calculation time is long. Chai Changsheng's method puts forward the research on the significant influence of friction material modified filler based on analysis of variance (Chai and Chen, 2020). The analysis of variance is used to calculate the impact toughness of automobile friction materials, and the significant influence of friction material modified filler is carried out by improving the bending strength. This method can reduce the wear rate, but the calculation time is long. Ma and Fu (2019) introduced BP neural network to predict the sliding friction performance of automotive friction materials, obtained the sliding friction performance parameters according to L-M algorithm, optimised the friction torque parameters with BP neural network, and input the optimised parameters into the friction performance prediction model to realise the sliding friction performance prediction. This method can improve the accuracy of prediction results, but it takes time to predict.

With the development of science and technology, the requirements of surface properties of parts are higher and higher. Surface roughness measurement technology plays an important role in the fields of MEMS and automobile braking. Compared with the traditional two-dimensional roughness parameters, the three-dimensional surface roughness parameters can more comprehensively provide the spatial morphology characteristics of the measured workpiece surface, and have better statistical significance. Therefore, this paper proposes a performance analysis method of automobile braking friction materials based on surface roughness. The specific research ideas are as follows:

The first step is to analyse the main types of automobile braking friction materials and clarify the advantages and disadvantages of automobile braking friction materials.

In the second step, the calculation formula of material friction is described by classical friction law, the material performance analysis function is constructed according to Mamdani fuzzy algorithm, the influence function of friction coefficient is determined through the optimal fusion position constraints, and the high-temperature wear rate is calculated.

The third step is to build a multi-objective function model according to the surface roughness to analyse the performance of automobile braking friction materials.

The fourth step is to analyse the change of friction coefficient under different parameters such as pressure and temperature, draw a conclusion and summarise the full text.

2 Analysis of advantages and disadvantages of automobile braking friction materials

Asbestos friction materials occupied the dominant position of automobile braking friction materials before the 1970s (Candeo et al., 2021). However, due to the obvious 'heat recession' during high-temperature use and the environmental pollution caused by asbestos dust, carcinogenic particles are even produced. After the 1970s, the search for new fibre substitutes has become a hot spot in the field of brake material research (Ilyushchanka et al., 2021).

The types of asbestos free automobile braking friction materials widely used at present are shown in Table 1.

1. when paired with the brake disc, it has a sufficiently high friction coefficient
2. it is not easy to destroy and decompose at high humidity, and the tribological properties do not decline
3. maintain stability during braking.

Table 1 Types of common automobile brake pads

Type	*Main components*
Metal base	Mainly composed of metal
Semimetallic base	It is mainly a mixture of metal and organic components
Non-metallic base	Mainly organic matter, such as mineral fibre, rubber, etc.

At present, the components of automobile brake pad materials mainly include the following:

a friction additives improve the wear resistance of materials

b packing to save cost and improve the manufacturing process of brake pads

c adhesive to bond other components of the brake pad together

d reinforced fibre to improve the mechanical properties of braking materials.

The materials of soldering casting are mainly steel and cast iron, and monomer metal materials are rarely used because of their poor properties. Powder metallurgy friction materials are formed by compacting matrix powders such as iron and copper, and then sintering at high temperature (Wongpayakyotin et al., 2021; Guo et al., 2019; Essosnam et al., 2020; Monreal et al., 2021). Their types are divided into iron base, copper base and copper iron base according to different components. Iron-based materials have a wide range of raw materials, good economy, high soldering point of iron, good heat resistance and thermal conductivity, and can maintain high strength and hardness during use: copper-based materials have higher thermal conductivity than iron-based materials, and powder metallurgy materials show excellent performance under high-temperature braking and transmission conditions. Reinforced fibre materials can make friction materials have greater strength and effectively ensure the integrity of braking materials (Ali et al., 2021; Inoue et al., 2020). There are many kinds of fibres used at present. The characteristics of several commonly used reinforcing fibres are shown in Table 2.

Table 2 Advantages and disadvantages of several common fibres

Fibre type	*Advantage*	*Shortcoming*
Metal fibre	The friction coefficient is stable, the decline of friction coefficient at 300~500°C is less, and the wear at high temperature is small	Too high content will lead to casting corrosion, reduce tribological properties and damage the dual parts
Aromatic fibre	High initial resistance, excellent wear resistance and heat decay resistance	It is soft and needs to be mixed with other fibres
Glass fibre	Good heat resistance	It is brittle and begins to soften after about 600°C
Ceramic fibre	Good heat resistance and high specific strength	Brittleness
Ingot acid bell whisker	Good wear resistance	Harmful to human health

With the deepening of research in recent years, researchers have found that the mixed use of several fibres can make up for the shortcomings and shortcomings of friction materials with single reinforced fibre (Yu et al., 2019). The finer ferrite bell whisker is easy to adhere to the aromatic fibre. The hybrid strengthening effect of the two fibres helps to form a friction film on the sliding surface, so as to improve the friction coefficient stability and wear resistance of the material, which cannot be achieved by a single reinforced fibre.

With the improvement of environmental protection laws and regulations, the future development of automotive braking materials will pay more attention to fuel efficiency and reduce rhino emissions as the current development trend of automotive industry. This shift towards environmental protection has been seen in hybrid models such as Toyota Prius, Honda Insight and Ford Escape SUV (Chen et al., 2019). In the selection of friction materials, it is also necessary to choose environment-friendly materials, that is, materials that do not include toxic substances such as asbestos. Of course, there are still some unfamiliar toxic substances that may also cause damage to the public environment. For example, the USA has confirmed that the diffusion of copper in automobile brake pads with rainwater is one of the important factors leading to the transformation of the water body in the south of San Francisco Bay into a ‘damaged water body’, which means that some components in the existing friction materials are not completely safe. Another factor that needs to be deeply studied and investigated is the choice of binder for friction materials (Li and He, 2021). At present, when the material components are relatively fixed and the selection is limited, the development of non-enzymatic resin binder is an important research field. Sealed wet brakes may be the best solution in the future (Zhai et al., 2019). The braking device will be completely sealed, neither dust nor any harmful substances will flow out, so as to maximise environmental friendliness. Since no external substances enter the braking system, the braking performance of this braking system can maintain high stability (Sun and Zhou, 2019). Rain, soil, sand and oil will not affect the braking effect, but also reduce the corrosion of brake components – brake discs. In addition, the rotating wear of the brake disc will be greatly reduced, thus reducing the cost of brake maintenance to the greatest extent. However, considering the complexity and cost of this brake, it is only used on off-road and mining vehicles.

3 Performance analysis of automobile braking friction materials based on surface roughness

3.1 Construction of material property analysis function based on Mamdani fuzzy algorithm

The basic idea of Mamdani fuzzy control is to use computer to realise human control experience, and human control experience is generally expressed by language, and the control rules expressed in these languages are quite fuzzy. According to this fuzzy relationship and the detected value of process variables at a certain time, the control quantity at this time is obtained by fuzzy logic reasoning, which is the basic idea of fuzzy control system. The input of Mamdani fuzzy controller is basically consistent with the amount of information obtained by people in manual control. Therefore, fuzzy control has some unique control characteristics, which are summarised as follows:

1 Mamdani fuzzy control method does not need to establish an accurate mathematical model. Generally, it only needs to establish the corresponding fuzzy rule base based on the experience knowledge and operation data of field operators, and then make appropriate use of fuzzy rules and membership functions to realise the intelligent fuzzy automatic control of the system field in the field of industrial control through the process of fuzzy logic reasoning.

2 Mamdani fuzzy control has strong robustness, insensitive to parameter changes, and strong adaptability to process and environment changes and disturbances.

3 Mamdani fuzzy control is a rule-based control. The control rules are expressed by language variables instead of conventional mathematical variables. The control mechanism and strategy are easy to accept and understand, and can be realised by

simple software and hardware. It is easier to establish language variable rules. For the basic fuzzy controller, only simple table lookup operation is required in the actual operation, and other processes can be carried out offline.

Therefore, Mamdani fuzzy algorithm is used to analyse the properties of automobile braking friction materials. Firstly, it is necessary to determine the surface roughness objective optimisation function of automobile braking friction materials, and different friction properties will be obtained under different conditions. In this paper, a simplified formula for calculating the friction of automotive braking friction materials is obtained by introducing classical friction law, which is expressed as

$$\mu = F / N \tag{1}$$

In formula (1), μ is used to describe the surface friction coefficient of automobile braking friction materials, F is used to describe the friction of automobile braking friction materials, and N is used to describe the normal load acting on automobile braking friction materials.

In order to comprehensively analyse the performance of automobile braking friction materials, Mamdani fuzzy system can be introduced to analyse the performance of automobile braking friction materials, and its analysis function is expressed as

$$f(x) = \frac{\sum_{l=1}^{M} y^l \left\{ \prod_{i=1}^{n} \exp\left[-\left(\frac{x_i - x_i^l}{\sigma_i^l} \right)^2 \right] \right\}}{\sum_{l=1}^{M} \left\{ \prod_{i=1}^{n} \exp\left[-\left(\frac{x_i - x_i^l}{\sigma_i^l} \right)^2 \right] \right\}} \tag{2}$$

In formula (2), M is used to describe the number of fuzzy rules of friction materials, n is used to describe the number of rules satisfying the if function, x_i, x_i^l is used to describe the function variables in the fuzzy system, y^l is used to describe the fuzzy set centre of Mamdani type fuzzy system, and x_1, x_2, …, x_n is used to describe the system input parameters.

3.2 Construction of multi-objective function model based on surface roughness

In order to realise the reliable prediction of automobile braking friction materials, the iterative training of parameters affecting the performance of friction materials is carried out by recursive regression analysis method, and the minimum training error function e is expressed as:

$$e = \sum_{p=1}^{n} \frac{1}{2} \left[f\left(x_0^p - y_0^p \right) \right]^2 \tag{3}$$

In formula (3), e is used to describe the training error of parameters affecting the performance of friction materials; x_0^p, y_0^p is used to describe the input parameters and output values of the minimum training error function. In combination with the above, formula (1) can be rewritten as follows:

$$\mu = \frac{F}{N} = \mu^{*}\left(1 + \frac{N_0}{N}\right) \tag{4}$$

In formula (4), N_0 is used to describe the value of intermolecular gravity. Analyse the obtained friction of automobile braking friction materials, determine the iteration times of automobile braking friction materials for surface friction performance verification, and use the obtained iteration times to give the constraint conditions for the optimal fusion position of automobile braking friction materials. Assuming that the iteration process is n times, the constraint is:

$$\Delta f_n < \Delta f_{n-1} \tag{5}$$

Under this condition, the obtained friction pheromone of automobile braking friction materials is introduced into the solution function to obtain the optimal solution group of automobile braking friction materials, complete the update of friction pheromone of automobile braking friction materials, and then call ant algorithm again for cyclic operation. Where,

$$\Delta f_n = f_{\max}^{n} - \overline{f}^{n} \tag{6}$$

In formula (6), $f_{\max}^{n}$ is used to represent the maximum fitness of genetic operation of the n^{th} generation population, and $\overline{f}^{n}$ is used to represent the average fitness of genetic operation of the nth generation.

The processing efficiency of automobile braking friction materials is selected as the first objective of optimisation, and Q_1 is used to represent the removal rate of automobile braking friction materials per unit time (also known as the processing efficiency of automobile braking friction materials). The processing efficiency Q_1 of automobile braking friction materials is expressed as

$$Q_1 = a_e f_z a_p Zn \tag{7}$$

In formula (7), Z is used to describe the number of machined teeth of automobile braking.

Substituting known conditions such as $Z = 2$, $n = 1{,}000\ v_c/\pi D$, $D = 10$ mm into equation (7) above can obtain:

$$Q_1 = a_e f_z a_p Zn = \frac{1000 v_c}{\pi D} \cdot a_e f_z a_p z = 63.662 v_c f_z a_p a_e \tag{8}$$

In formula (8): v_c represents the engine speed of the vehicle, and D represents the braking force of the vehicle. The surface roughness of automobile braking friction materials is selected as the second objective of optimisation. The empirical formula of surface roughness is obtained according to the test data, and the objective function can be expressed as

$$Q_2\left(v_c, f_z, a_p, a_e\right) = Ra = CV_c^{b_1} f_z^{b_2} a_p^{b_3} a_e^{b_4} = 10^{1.2444} V_c^{-0.3039} f_z^{0.3042} a_p^{0.1029} a_e^{0.5644} \tag{9}$$

where the selection of coefficient C is determined by the corresponding material factors; b_1, b_2, b_3, b_4 is the undetermined coefficient.

When the processing efficiency and surface roughness of automobile braking friction materials are selected as the first and second objectives, the multi-objective function optimisation mathematical model of friction performance of automobile braking friction materials is shown in the following formula (10):

$$\begin{cases} \min Q\left(v_c, f_z, a_p, a_e\right) \\ s.t.\ g_i\left(v_c, f_z, a_p, a_e\right) \leq 0 \quad (i = 1, ..., 10) \end{cases} \tag{10}$$

Based on this, the multi-objective function optimisation model of the friction performance of automobile braking friction materials is obtained, and the friction performance optimisation of automobile braking friction materials is realised. This function is applied to the experiment to analyse the performance of friction materials.

4 Friction and wear performance test

4.1 Test conditions

1 Equipment calibration is a key step in the test. If the calibration is not accurate, it will not correctly reflect the magnitude of friction. Therefore, it shall be calibrated every other period of time in the test.

2 The speed of friction disc of automobile braking friction material is 400~500 R/min.

3 Take two test pieces of automobile brake friction materials from the same product.

4 The friction area of automobile brake friction material test piece is 25 mm × 25 mm, allowable deviation –0.2 mm. No blistering is allowed on one side.

5 The thickness of automobile brake friction material test piece is 5~7 mm, and the allowable deviation is ± 0.2.

6 The wear depth of the disc friction surface shall not be greater than 0.2 mm. After each test, the surface shall be treated with JB / t7498 P240 abrasive paper to keep it clean and clean, and wiped with a clean soft cloth.

7 Pressing force knife: 10 kgf/cm (0.98 mpa).

8 The friction direction of automobile brake friction material test piece is the same as that of brake lining.

9 Friction and wear data are automatically recorded and processed by computer.

4.2 Test method

1 First grind the surface of the test piece of automobile brake friction material, and then run in the test piece at room temperature until the contact surface between the test piece and the disc reaches more than 95%.

2 Measure the thickness of the test piece of automobile brake friction material with a micrometre. Five points shall be measured for each test piece and input into the computer as required.

3 Record the friction force during 5,000 revolutions when the disc is 100°C. Measure the thickness after friction when the test piece is cooled to room temperature.

4 Conduct the same test when the disc temperature is 150°C, 200°C, 250°C, 300°C and 350°C.

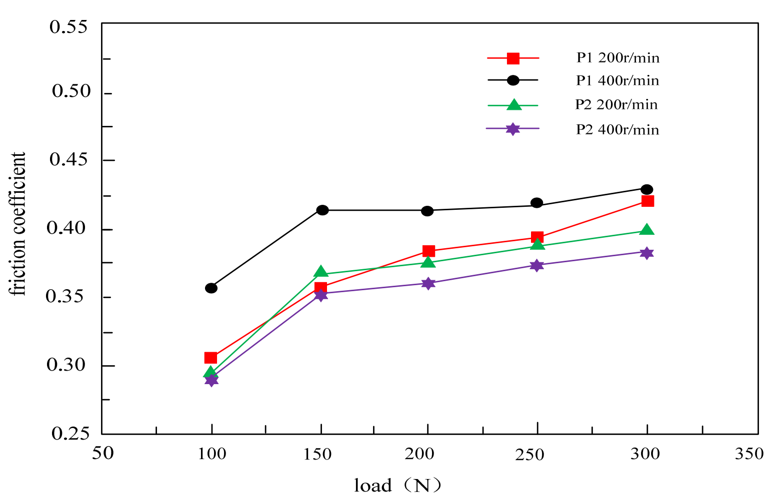
5 After the measurement of the maximum experimental temperature, measure the friction force of the disc during 1,500 revolutions from the maximum temperature every 50°C to 100°C. However, the temperature drop to the next stage should be within 500 revolutions.

4.3 Performance analysis of automobile braking friction materials

4.3.1 Influence of braking parameters on dry friction coefficient

There are many factors affecting the performance of friction braking materials, and braking parameters are an important one. The parameters affecting braking in actual working conditions mainly include speed, load and temperature. The increase of the speed will accelerate the shear rate of the friction surface. At this time, the contact conversion rate of the micro convex body on the friction surface is accelerated, and the surface temperature of the friction pair rises sharply. The effects of these conditions on the resin-based braking friction materials mainly include the change of the actual contact area, the decomposition and oxidation of organic matter and the decrease of the mechanical strength of the material, May aggravate the wear of friction materials. Load is one of the important parameters affecting the braking rate and stability. Different loads have a certain impact on the formation rate, distribution of friction film and the cycle process of formation failure re-formation. However, the research is more difficult because the friction surface morphology in the braking process cannot be directly observed. Although the change of speed and load will make the properties of friction materials change and fluctuate greatly, which affects the tribological properties of materials. The research shows that the main failure reason of resin-based braking friction materials is the thermal decline of matrix materials caused by temperature rise, which leads to the decline of tribological properties and braking failure.

Figure 1 Friction coefficient of sample a under dry friction condition (see online version for colours)



In order to analyse the influence of vehicle braking parameters on dry friction coefficient, the change of dry friction coefficient of sample a is obtained under the conditions of 200 r/min and 400 r/min under the pressures of P1 (200 Pa) and P2 (500 Pa). The results are shown in Figure 1.

According to the analysis of Figure 1, there is a certain relationship between the load of sample a and the friction coefficient under the condition of dry friction. When the pressure is P1 and the load is 100 N, the friction coefficient of sample a is 0.32 at 200 r/min and 0.37 at 400 r/min; When the pressure is P2 and the load is 100 N, the friction coefficient of sample a is 0.29 at 200 r/min and 0.27 at 400 r/min; At this time, the greater the pressure and rotating speed, the greater the friction coefficient of the sample. When the pressure is P1 and the load is 100N, the friction coefficient of sample a is 0.38 at 200 r/min and 0.42 at 400 r/min; When the pressure is P2 and the load is 100 N, the friction coefficient of sample a is 0.37 at 200 r/min and 0.36 at 400 r/min; At this time, the friction coefficient of sample a is the largest at P1 pressure and 400 r/min, which is 0.42. The above results show that in order to reduce the friction coefficient of automobile, the pressure between automobile parts can be appropriately reduced.

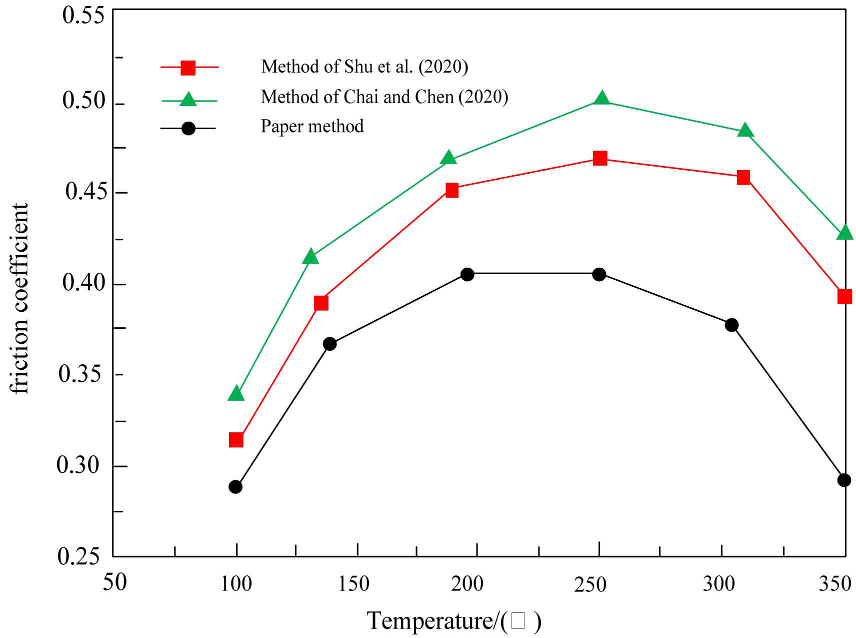
4.3.2 Environmental impact

Cars often encounter different climatic environments and road conditions during driving. Because the working environment of friction brake pads is not sealed, they need to face different media environments, mainly including water, oil, sand, etc. For water medium and oil medium environment, due to the formation of water film or oil film on the surface of friction pair, the actual contact area of surface and the contact size of surface micro convex body will be reduced, making the friction conditions become boundary lubrication or even fluid lubrication, greatly reducing the friction coefficient and bringing great hidden dangers to braking safety. All polymer-based friction materials will absorb water and oil. When water enters the matrix, the polymer matrix will swell, which will reduce the glass transition temperature of the composite. Swelling causes the fibre to produce a shear stress, which will cause debonding between the interfaces; at the same time, moisture will weaken the bonding ability between the composites and promote the expansion of small cracks in the materials, and the crack expansion will make more external media enter the materials. The interface between the matrix and the reinforcing fibre will produce internal stress in these media, which will aggravate the falling off and cracking of the materials.

Therefore, this paper takes temperature as an environmental factor for experimental verification, and the results are shown in Figure 2.

According to the analysis of Figure 2, when the temperature is 100°C, the friction coefficient is 0.31 under the method of Shu et al. (2020), 0.33 under the method of Chai and Chen (2020), and 0.28 under the method of this paper. This method always has a low friction coefficient, which shows that this method can improve the friction performance of automotive braking friction materials, which has a certain practical significance.

Figure 2 Relationship between temperature and friction coefficient under different methods (see online version for colours)



4.3.3 Wear rate

In order to verify the wear performance of automobile braking friction materials under different methods, the methods of Shu et al. (2020), Chai and Chen (2020) and this paper are used to detect the wear rate of automobile braking friction materials, analyse the wear resistance of automobile braking friction materials prepared under different methods, and the results are shown in Table 3.

Table 3 Wear rate of automobile braking friction materials under different methods

Duration/day	*Wear rate of automobile braking friction materials/%*		
	Shu et al. (2020) methods	*Chai and Chen (2020) methods*	*Paper method*
5	0.33	0.53	0.01
30	2.56	1.43	0.05
60	5.77	4.34	0.12
90	6.76	12.32	0.16
120	8.54	16.43	0.19
150	9.34	21.23	0.22

It can be seen from Table 3 that the wear rate of automobile braking friction materials is different under different methods. When the service life of automobile braking friction materials is five days, the wear rate of automobile braking friction materials according to the method of Shu et al. (2020) is 0.33%, the wear rate of automobile braking friction materials according to the method of Chai and Chen (2020) is 0.53%, and the wear rate of automobile braking friction materials according to the method of this paper is 0.01%. The wear rate of automotive braking friction materials by this method is always at a low level.

5 Conclusions

This paper proposes to introduce surface roughness to study the properties of automotive braking friction materials. The training error function is given by using the surface roughness, the friction calculation formula of automobile braking friction materials is described by classical friction law, the friction factor analysis function is obtained by Mamdani fuzzy algorithm, the constraint conditions of the best fusion position of automobile braking friction materials are determined, the influence function of friction coefficient is determined, and the high-temperature wear rate is calculated. The multi-objective function model is constructed according to the surface roughness to analyse the performance of automobile braking friction materials, and the change of friction coefficient is analysed under different parameters such as pressure and temperature. The following conclusions are drawn through experiments:

1 When the pressure is P1 and the load is 100 N, the friction coefficient of sample a is the largest at 400 r/min, which is 0.42. This shows that in order to reduce the friction coefficient of automobile, the pressure between automobile parts can be reduced appropriately.

2 When the temperature is 200°C, the friction coefficient is 0.38. This method always has a low friction coefficient, which shows that this method can improve the friction performance of automotive braking friction materials.

3 When the service life of automobile braking friction material is 150 days, the wear rate of automobile braking friction material is 0.22%. The wear rate of automotive braking friction materials by this method is always at a low level.

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