The influence of copper content on the braking performance of iron-based powder metallurgy friction materials

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Abstract. Three iron-based powder metallurgy friction materials with different Cu content were prepared by powder metallurgy. The friction and wear properties of the materials were evaluated by the MM3000 friction and wear tester, and the effect of Cu content on the friction coefficient, wear rate and surface morphology was studied. The results show that with the increase of copper content, the matrix components are alloyed at high temperature, and the hardness and strength are significantly improved. The coefficient of dynamic friction and wear rate decreased significantly, and the coefficient of static friction and friction stability increased at high temperature. When the copper content is low, abrasive wear, spalling wear and fatigue wear are the main causes, while when the copper content is high, only slight abrasive wear occurs.

1. Introduction

Mechanical brakes are an important factor that determines vehicle mobility and driving safety\textsuperscript{[11]}. The current transportation, machinery industry and other fields are constantly developing in the direction of high speed and heavy load of goods. The braking power density has increased significantly, and the braking conditions have become more It is complicated and demanding, which leads to frequent failure problems such as thermal decay and lock-up of the friction plate at high temperatures\textsuperscript{[12-14]}. Therefore, it is of great significance to develop new high-temperature resistant brake friction materials.

At present, powder metallurgy friction materials are commonly used in the friction pairs of heavy-duty vehicles in China, and iron-based powder metallurgy materials have a stable friction coefficient and high wear resistance. But when the friction temperature is too high, the friction factor will attenuate and the wear rate will increase, which limits its application range\textsuperscript{[5,7]}. This is mainly because iron and the mating material used with it have a greater affinity. Adhesion occurs, often by adding copper alloy elements to reduce the plasticity of the iron-based brake material, improve the strength and hardness of the material, thereby improving the anti-adhesion properties of the material\textsuperscript{[8]}. Xiao et al.\textsuperscript{[9]} designed an iron-copper-based composite material that exhibits good friction and wear performance at high temperatures. When the braking speed is increased to 250~380km/h, the friction coefficient can still be maintained in the stable range of 0.3-0.41 Inside. Zhao et al.\textsuperscript{[10]} studied the friction properties of iron-copper-based composites and found that copper and iron elements are easily
compacted to form a continuous friction film under cyclic stress and oxidation during braking, thereby reducing the wear rate and improving the stability of the friction coefficient.

Based on this, the article uses powder metallurgy to prepare three iron-based powder metallurgy materials with different copper content, and examines the friction coefficient, wear rate and surface morphology under high-energy continuous braking conditions. They are used under high-temperature conditions. The development of brake materials provided the basis.

2. Sample preparation

Three kinds of iron-based powder metallurgy materials with different copper content were prepared by powder metallurgy. The composition is shown in Table 1. Figure 1 is the cross-sectional SEM morphology of sample 2#, where A zone is an iron-copper alloy matrix, B zone is a lubricating component graphite, and C zone and D are divided into reinforced particles SiC and SiO₂. The overall material is dense and the bonding condition is good. There is no reinforcement phase agglomeration.

| Number | Composition (W/%) |
|--------|------------------|
|        | Cu  | C   | SiO₂ | SiC | Fe |
| 1#     | 2   | 16  | 5    | 3   | Margin |
| 2#     | 10  | 16  | 5    | 3   | Margin |
| 3#     | 14  | 16  | 5    | 3   | Margin |

Fig. 1. 2# SEM morphology of cross section of friction sample

3. Experiment method

The MM3000 friction and wear performance testing machine is used for continuous braking test, and the spouse is 45 steel samples.

Run-in: Run-in treatment of the sample before the test. The working parameters are: specific pressure 0.44MPa, rotation speed 2000rpm (equivalent radius linear velocity 6.697m/s), inertia 0.035kg·m², running-in standard is that the friction pair surface is more than 80% Wear scars appear on the area. After the running-in is completed, use a measuring tool with an accuracy of 0.01 mm to measure and record the initial thickness of the sample; use a balance to weigh.

Braking test: under the working conditions of specific pressure 0.44MPa and speed 6000rpm (equivalent radius linear velocity 19.4m/s), inertia 0.035kg·m², 100 times of braking, braking interval of 25 seconds, each braking Measure the friction coefficient and absorbed work (Eᵣ, J) of the friction material at dynamic intervals, and calculate the volume change (∆V, cm³) and mass change (∆m, mg) of the material, according to formula (1), (2) Calculate the volume wear rate (Wᵣ, cm³/J) and mass wear rate (Wᵣ, mg/side-cycle).

\[ W_r = \frac{\Delta V}{E_s} \]  (1)
\[ W_m \Delta m/n \]  \quad (2)

4. Results and analysis

4.1 Coefficient of friction

The curve of friction coefficient of the three materials with the number of joints is shown in Figure 1. It can be seen that as the Cu content increases, the friction coefficient decreases as a whole, and the stability is significantly improved. This is mainly due to the higher strength and hardness of Fe compared to Cu, as well as the better affinity between Fe and steel. However, when the Cu content is high, the adhesive tendency between friction pairs is reduced and the embedding degree of the micro-convex body of dual material is shallow, so the friction resistance is small and the friction coefficient is lower\(^{[1]}\). In addition, the copper and iron matrix are prone to plastic deformation and oxidation at high temperatures, and form a continuous friction film under the cyclic action of normal stress and frictional force, that is, the black part in Figure 4, which also slows the friction of the friction pair in the joint. Vibration improves braking stability\(^{[2]}\). Comparing the three samples at the same time, it can be seen that higher Cu content is beneficial to the formation of friction film. The friction film of 1# sample is almost not formed, and the average friction coefficient has been fluctuating during the continuous braking process. At the same time, the meshing degree between the pairs is deeper and the friction coefficient is higher; The coefficient gradually decreases in the late stage of the joint; the 3# sample forms a friction film in the early stage of the joint, so the friction coefficient remains between 0.35 and 0.44 as the number of joints increases, with an average value of 0.398.

![Graphs showing friction coefficient over time for different samples.](image-url)

Fig. 2. Continuous braking friction coefficient curve of friction samples with different Cu content

Table 2 shows the static friction coefficients of the three materials at room temperature and high temperature. The high temperature is measured after continuous braking, and the average value of 5 measurements is taken. It can be seen that although the static friction coefficient of 1# sample is higher than that of 2# and 3# samples at room temperature, it has a slight decline at high temperature. On the contrary, the static friction coefficient of 2# and 3# samples increased at high temperature. This is
mainly after the braking test is stopped, the energy on the surface of the material is reduced, the film formation balance is broken, and the wear debris re-forms the furrow effect on the sample surface, which increases the friction coefficient.

Table 2. Average static friction coefficient of friction samples with different Cu content

| Number | Room temperature | Elevated temperature |
|--------|------------------|----------------------|
| 1#     | 0.566            | 0.541                |
| 2#     | 0.475            | 0.572                |
| 3#     | 0.513            | 0.624                |

4.2 Wear rate

Figure 3 shows the volume wear rate and mass wear rate of the three materials after braking, showing a law similar to the friction coefficient. This is also because the wear of the material is closely related to the formation of the friction film. When the Fe content is high, it will produce greater meshing force and adhesion when friction with the counterpart, and then peeling wear and adhesive wear will occur, and the wear rate will be higher. The friction film can effectively inhibit the "metal-metal" contact\cite{13} and protect the substrate from damage. It can be seen from Figure 4 that sample 1# has obvious furrow and peeling morphology, while the surface of sample 2# and 3# is relatively flat. On the other hand, Cu has better heat dissipation capacity and fluidity than Fe, so it can avoid surface cracking under high-temperature braking conditions. It can be seen in Figure 4 that the 1# sample has less Cu content and heat appears on the outside of the friction plate. Stress cracks also lead to an increase in wear rate.

![Graph showing wear rate](image)

Fig. 3. Continuous braking wear rate of friction samples with different Cu content

4.3 Surface morphology of wear scar

Figure 4 shows the macroscopic morphology of the surfaces of the three materials after continuous braking. It can be seen that the black friction film area on the outer side of the friction pair is relatively larger than the inner side. With the increase of Cu content, the friction film has a wider distribution area, and the friction film is more likely to be distributed outside the friction pair. This is due to the higher linear velocity in the outer region of the friction pair, and the high temperature is more conducive to the formation of the friction film. Obvious distribution of tri-color bands can be seen on the wear scar surface of sample 3, the outer dark friction film area effectively reduces the direct contact with the steel counterpart, and the addition of copper alloys the iron matrix, improves the surface hardness, and protects Role\cite{14-15}. However, the area where the friction film is not formed on the inner side has a slight furrow phenomenon, and the surface is relatively rough. The 1# sample has a low Cu content, a large thermal expansion coefficient of the material, which leads to obvious cracks,
and almost no friction film is covered. This is because the sample is under high temperature and high pressure, internal stress and thermal stress lead to micro-cracks. When in the flake graphite agglomeration zone, due to the mismatch of the thermal expansion coefficient, the micro-cracks propagate and meet under repeated thermal fatigue action, resulting in chipping and peeling, mainly by abrasive wear, spalling wear and fatigue wear.

Fig. 4. Continuous braking friction coefficient curve of friction samples with different Cu content

Figure 5 shows the SEM microscopic morphology of the friction film area of the 1# and 3# samples. It can be seen that the surface of the 1# sample has obvious scratches and peeling traces along the sliding direction. According to the morphology of the wear debris in Figure 6, the wear debris produced by the braking of the 1# sample is mainly granular and flake, and the size of the wear debris is relatively large and less than 500μm. The hard particles of the material fall off during the braking process to produce granular wear debris. The formation of flake wear debris is mainly due to the inability of the wear surface to effectively generate a continuous oxide layer, and the formed oxide layer is not firmly bonded to the substrate. It is easy to fall off from the base body during braking. However, there are only small cracks on the surface of the 3# sample, which is inferred to be caused
by the thermal stress caused by the thermal expansion coefficient of the friction film and the matrix under high temperature conditions.

Fig. 5. SEM morphology of wear scar of 1# and 3# samples

Fig. 6. SEM morphology of wear debris of 1# sample

5. Conclusion
Three iron-based powder metallurgy materials with copper content were prepared by powder metallurgy, and continuous braking friction and wear tests were carried out. The main conclusions obtained are as follows:

(1) With the increase of copper content, a dense friction film is formed on the surface of the material and the meshing degree between the friction pairs is reduced, and the dynamic friction coefficient is generally reduced and more stable. The static friction coefficient of samples with higher copper content decreases slightly at high temperature, while the static friction coefficient of samples with higher copper content increases instead at high temperatures;

(2) When the copper content is high, it is easy to alloy with iron to improve the surface hardness and strength, reduce adhesion and meshing, and then reduce the wear rate;
When the copper content is low, the material will form fatigue cracks under the action of thermal stress and internal stress, and the surface will peel off and the furrow morphology will be obvious, mainly abrasive wear, adhesive wear and fatigue wear; when the copper content is high, the existence of the friction film avoids direct contact between metals, and is mainly caused by slight abrasive wear.

References
[1] S. Venkatesh, K. Murugapoopathiraja, MATER TODAY, 16 (2019)
[2] R. Holinski, D. Hesse, P I MECH ENG D-J AUT, 217, 9 (2003)
[3] M. Okada, N.S. Liou, V. Prakash, et al. WEAR, 2001, 249, 8 (2001)
[4] S. Zhang, Q. Hao, Y. Liu, K. Miyoshi. Math. Probl. Eng, 38, 2 (2019)
[5] F.W. Xie, G. Sheng R. Xuan, et al. Recent Pat. Mech. Eng, 8, 1 (2015)
[6] J.X. Liu, C. Zhang, J.L. Fan ;Y.W. Li, Y. Song, D.J. Jia. Powder Metallurgical Industry, 28, 6 (2018)
[7] A.M. Kovalchenko, O.I. Fushchich, S. Danyluk, WEAR, 290-291 (2012)
[8] M. Han, J.H. Du, K.Y. Ning, H. Li, Z.Y. Wang, Q. Qiu. Powder Metallurgy Science & Technology, 37, 1 (2019).
[9] Y. Xiao, Z. Zhang, P. Yao, K. Fan, H. Zhou, T. Gong, Tribol Int, 119 (2018)
[10] S. Zhao, Q. Yan, T. Peng, X. Zhang, Y. Wen, WEAR, 448-449 (2020)
[11] X. Xiong, J. Chen, P. Yao, B. Huang, WEAR, 262, 9-10 (2007)
[12] X. Ma, C.H. Luan, S.W Fan, J.L. Deng, L.T. Zhang, L.F. Cheng. Tribol. Int., 154 (2020)
[13] M. Godet, WEAR, 100, 1-3 (1984)
[14] T. Peng, Q. Yan, G. Li, X. Zhang, Z. Wen, X. Jin, Tribol Lett, 65 (2017)
[15] T. Peng, Q. Yan, G. Li, X. Zhang, Tribol Lett, 66 (2017)