Study on Friction Properties of WC Particle-Reinforced High-Chromium Iron-Based Powder Metallurgy Materials

Tao Wei¹², Mengyang Ma³*, Ziyang Li³, Shunshun Qin¹², Chengzong Wang¹² and Xiaoqiang Li³

¹State Key Laboratory of Engine Reliability, Weifang, Shandong, 261061, China
²Weichai Power Co.Ltd., Weifang, Shandong, 261061, China
³School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, Guangdong, 510640, China

*Corresponding author’s e-mail: 450855163@qq.com

Abstract. High-performance powder metallurgy high-chromium iron-based alloy reinforced by nano-WC particles were prepared by high-energy ball milling combined with hot-press sintering. The effects of different temperatures of hot-press sintering and contents of WC reinforced phase on the friction and wear properties of the materials were studied by using the M-2000 Friction and Wear Tester under dry condition. The results show that the wear property of the material increases first, and then decreases with the growth of temperature of sintering and contents of reinforced phase. The alloy has the best wear property sintered at 1050 °C with 5wt.% WC reinforced phase. By comparing with NbC reinforced phase with similar mass fraction at 5%, finding that WC particles have more significant effect on reinforcing the wear

1. Introduction

The iron-based powder metallurgy material is an alloy obtained by containing iron powder as a basic powder, adding a certain kinds of alloying-element powder, pressing and sintering [1]. Iron-based powder metallurgy materials have a series of advantages such as low cost, good machinability, good weldability, and treatable heat property [2]. Iron-based alloy is the largest amount of powder metallurgy materials, mainly used in structural parts, bearings and friction materials. Especially in the automobile manufacturing industry, powder metallurgy iron-based materials play an important role.. In addition, high-performance iron-based powder metallurgy parts have also been widely used in mechanical transmissions, engines and other general mechanical products, and the development prospects in the mechanical manufacturing industry are very broad [3].

In 1935, Bal'shin, et al. first prepared iron-based oil-impregnated bearings by powder metallurgy, which became the beginning of iron-based powder metallurgy in the 20th century. Since then, preparation of iron-based powder metallurgy material has developed rapidly and been widely used in engines and mechanical parts [4]. In recent years, high-chromium iron-based powder metallurgy materials have become a hot spot in the development of iron-based powder metallurgy materials due to their excellent toughness, hardness and wear resistance. The particle-reinforced iron-based powder metallurgy material can combine the high hardness and high wear resistance of the reinforcement with the high strength and excellent toughness of the matrix, so it is suitable for use in environments with severe service conditions (such as high temperature and poor lubricity). The particle-reinforced iron-based powder metallurgy material is a kind of new material with ideal prospect of development
In recent years, WC particle reinforced iron-based high-performance powder metallurgy materials have become one of the hotspots studied by many scholars, such as Professor Li Xiaoqiang of South China University of Technology [6,8,9], and Professor Cheng Xiaole of Xi'an Jiaotong University [10]. Research on this new material shows that WC particles can enhance the combination properties of iron-based high-performance powder metallurgy materials, especially for the wear resistance [11]. In this paper, nano-WC particles were added to Fe-10Cr-1Cu-1Ni-1Mo-2C (mass fraction, %) mixed powder, and high-performance WC particle reinforced high-chromium iron-based materials were prepared by high-energy ball milling combined with hot-press sintering technology to study the influence of sintering temperature and WC reinforcing phase content on the friction and wear properties of materials.

2. Experiment

2.1 Experimental Material

The experimental powders are water-atomized iron powder, electrolytic Cr powder, electrolytic Cu powder, electrolytic Ni powder, electrolytic Mo powder, colloidal graphite powder and WC powder. The characteristics of the initial powders are listed in Table 1.

| Elemental powder | Purity /% | Particle size /μm |
|-----------------|-----------|-------------------|
| Fe              | 99.0      | <150              |
| Cr              | 99.5      | <75               |
| C               | 99.5      | 2-3               |
| Cu              | 99.8      | <75               |
| Ni              | 99.5      | <75               |
| Mo              | 99.5      | <75               |
| WC              | 98.7      | ~0.1              |

2.2 Material Preparation

2.2.1 Powder Preparation. The initial powders were first mixed with a chemical composition of 95% (Fe-10Cr-1Cu-1Ni-1Mo-2C) + 5% WC to produce a homogenous mixture of ingredients. (mass fraction). After premixing for 48 h, the QM-2SP20-CL ball mill performs high-energy ball milling under the argon atmosphere with steel vials and tungsten carbide balls. The ball-to-powder weight ratio is 8:1. Milling speed is 226 r/min, the alternating current and reverse time is 12 min, and the time used for acceleration and deceleration are both 10 s.

2.2.2 Sintering Process. For each time of sintering, 20 g of powder was put in a graphite mold with an inner diameter of 20 mm and then sinter by an HP-12 hot-press furnace. After vacuumizing to about 1.3×10-2 Pa, the WC particle-reinforced high-chromium iron-based powder was heated from room temperature to 400 °C at a rate of 5 °C/min, and then heated to 800 °C at a rate of 20 °C/min. After keeping the temperature for 20 min, it was raised at 10 °C/min to different sintering temperatures for holding 30 min, and then the sample was cooled to room temperature with the furnace, with 50 MPa axial pressure applied when during heating and holding.

2.3 Friction and Wear Test

The friction and wear test was experimented by the M-2000 Friction and Wear Tester. The friction counter-pair consists of a block sample and a wear ring. The size of the block sample is 10 mm × 10 mm × 6 mm, the material of wear ring is GCr15 with the size of d(46-10)mm×10mm. The testing method is line contact friction and wear with testing pressure of 200 N, rotational speed of 200 r/min, and testing time of 1000 s.
For the friction and wear test of the M-2000 tester, some friction data can be obtained directly including the test force, the friction torque, and the friction coefficient. The conversion equation of friction torque and friction coefficient is:

\[ \mu = \frac{F}{P} = \frac{M}{P \times r} \]  

\( \mu \) is the friction coefficient, \( F \) is the friction force (N), \( P \) is the positive pressure (N); \( M \) is the friction torque (N/mm); \( r \) is the radius of the grinding ring (mm).

The BMT Expert 3D Surface Profiler shown in Fig.1 is used to measure the wear scar profile. The main technical parameters of the surface profiler are that vertical measuring range is 1 mm, working distance is 24 mm, spot size is 6 \( \mu \)m, minimum step length is 0.5 \( \mu \)m, and lateral resolution is 30 \( \mu \)m. It also has the functions of line scanning and surface scanning, and the wear volume is measured to evaluate the wear amount of the prepared sample. After the end of the friction and wear test, measuring the width of the wear scar with the surface profiler. Finally, the wear volume of the sample can be calculated by the calculation equation (Equation 2) of wear volume. Equation for calculating wear volume by width of wear scar:

\[ \Delta V = B \left[ r^2 \sin^{-1} \left( \frac{b}{2r} \right) - \frac{b}{2} \left( r^2 - \frac{b^2}{4} \right)^{\frac{1}{2}} \right] \approx \frac{Bb^3}{12r} \]  

\( \Delta V \) is the wear volume (mm\(^3\)) of the sample. The meanings of \( B, b, r \) are shown in Fig.1, and the unit is mm. \( B \) is the width of the bulk sample, \( b \) is the width of the wear scar, \( h \) is the depth of the wear scar, and \( r \) is the radius of the wear ring.

![Figure 1. Schematic of block-on-ring friction](image)

After obtaining the wear volume of the sample, the volume wear rate of each sample can be calculated by equation 3.

\[ W_s = \frac{\Delta V}{P \times L} = \frac{\Delta V}{P \times 2\pi r n t} \]  

\( W_s \) is the wear rate of the sample (mm\(^3\)/mN), \( P \) is the positive pressure (N); \( r \) is the radius of the grinding ring (m); \( n \) is the rotation speed of the grinding ring (r/min); \( t \) is the time of wear (min).

3. Results and Discussion

3.1 Friction Coefficient Analysis

In general, the friction coefficient curve can intuitively reflect the smoothness of the material during the wearing process. The larger the fluctuation of the friction coefficient curve means that the wearing process is more unstable. Conversely, it means that the friction process is more stable. Fig.2 shows the friction coefficient curves of samples obtained by sintering at different temperatures. It can be seen from the fig that the friction coefficient curves of each sample has large fluctuations, which is a typical property of particle-reinforced powder metallurgy materials under dry friction condition. Since the
sintered alloy contains an external WC reinforced phase and a self-generated hard phase, in the dry friction and wear test, the alloy is in contact with the grinding ring, and the relatively softer phase is worn away firstly, followed by the harder phase protruding and flaking process. The process of the hard phase protruded and peeled off emerge repeatedly in friction and wear text, so the friction coefficient always fluctuates significantly.

Fig.3 shows the average friction coefficient and friction coefficients with various testing distance for samples at sintered different temperatures. It can be seen from the fig that as the sintering temperature increasing, the friction coefficient shows a trend with initial decrease and then increase. After the sliding distance of the friction and wear test reaching 200 m, the average friction coefficients of the samples remind a relatively stable level. Among them, the friction coefficient of the sample at 1100 °C is the highest, and the friction coefficient of the sample at 1050 °C is the lowest.

![Figure 2. Friction coefficients of samples sintered at various temperatures: (a) 950°C; (b) 1000°C; (c) 1050°C; (d) 1100°C.](image1)

![Figure 3. (a) Average friction coefficients; (b) friction coefficients with various testing distance for samples sintered at different temperatures.](image2)

Fig. 4 shows the scanning electron micrographs of the samples after sintering for 30 min at different temperatures [9]. Compared with the microstructure of the as-sintered alloys, the density of the samples sintered at 950 °C is slightly lower than that of the other samples. There are small pores dispersed evenly, and the microstructures of the pores are larger compared with that of other temperature (Fig. 4(a)). As the sintering temperature rising from 950 °C to 1000 °C, the atomic diffusion capacity is greatly improved and the elements diffuse mutually and react sufficiently, promoting the densification process. SEM photograph of samples sintered at 1000 °C and 1050°C is
illustrated in Fig. 4 (b) and (c), respectively. There is no pore observed, the microstructure of the samples show a large number of small, differently shaped and raised phases, which have various shapes including block, dot and fine needle, and the growth of grains at 1100 °C has appeared (Fig. 4(d)). As a result, the samples morphology at 1000 °C and 1050 °C are optimal. By comparing the microstructures of samples sintered at different temperatures, can conclude that the materials with higher the compactness of the microstructure have the smaller friction coefficient.

![Figure 4. SEM microstructures of the etched samples sintered at various temperatures (a)950°C; (b)1000°C; (c)1050°C; (d)1100°C [9].](image)

### 3.2 Effect of Sintered Temperature on Friction and Wear Properties of Alloys

Fig. 5 is an SEM image of the worn surface profile of samples sintered at different temperatures. It is clear from the fig that the furrow of worn surface of alloy sintered at 560 °C and 1100 °C is deeper, and there is partial flaking, indicating that there is adhesive wear during the test. That is due to the higher hardness of the grinding ring and the microstructure of the sintered sample is ferrite with lower hardness. Therefore, the wear ring has a more significant effect on the worn surface of the sample in dry condition than sliding condition, which leads to wear scars and soft phase (such as ferrite) that can attach to the grinding ring and the sample, and then fall off. At the same time, it can be seen from Fig. 5(a) that there are deeper wear scars on the worn surface of the sample, may because the density of the sample sintered at 950 °C is lower than that of the sample sintered at other temperatures. During the process, the flaking of the hard phase near pore leads to a larger pit of the profile. The furrows of worn surface of the samples sintered at 1000 °C and 1050 °C are relatively shallower, and fine abrasive particles can be observed on the worn surface, indicating that there is abrasive wear in the test (a large number of abrasive particles on the surface of the sample have been cleaned before the experiment). Due to the relatively higher hardness of the sample, the wear of the grinding ring on the sample is weakened. In addition, the fine abrasive particles (such as WC and carbide) can also effectively reduce wear of material and thus improve wear resistance.

Comparing with the wear volume of the samples sintered at different temperatures in Fig. 3, the wear volume of the samples sintered at 950 °C and 1000 °C is very close, while the wear volume of the samples sintered at 1050 °C is the smallest, indicating that the wear resistance is the best. Combining the factors of the microstructure, hardness, friction coefficient and worn profile of the samples sintered at different temperatures, it can be known that the denser microstructure of the material has the properties that the higher the hardness and the smaller the friction coefficient and the better the wear resistance [12].
Figure 5 shows the worn surface profile of samples: (a) 950°C; (b) 1000°C; (c) 1050°C; (d) 1100°C.

Fig. 6 shows the line scan image of the wear scars of samples sintered at different temperatures. The width of the wear scars can be identified by a line scan image, and the amount of wear can also be calculated with Equation (1). The width of wear scars and wear volume are shown in Table 2.

Table 2: Wear volume and width of wear scar samples sintered at different temperatures.

| Temperature /°C | Width of Wear Scar/mm | Wear Volume/mm³ |
|-----------------|------------------------|-----------------|
| 950             | 3.2                    | 1.187           |
| 1000            | 2.8                    | 0.795           |
| 1050            | 2.6                    | 0.637           |
| 1100            | 2.9                    | 0.884           |

Fig. 7 illustrates the wear volume of samples sintered at different temperatures. In the fig, the wear volume first decreases and then rises. The wear volume of sample sintered the 950 °C is 1.187 mm³. When the sintering temperature rises to 1050 °C, the wear volume of the sample is only about half of 950 °C. As the sintering temperature continues to rise to 1100°C, due to the growth of the grain
microstructure, the friction coefficient increases, while the wear resistance decreases, consequently the wear volume increases. The wear rates of samples sintered at different temperatures calculated by Equation (2) are shown in Fig.8. It can be known from the equation that the larger the wear volume contributes to the higher the wear rate, and thus the tendency of the wear rate and the wear volume varied with the sintering temperature are consistent. Similarly, at the sintering temperature of 1050 °C, the wear volume \( t \) and wear rate of the sample reached the minimum, indicating that the sample sintered at 1050 °C has the best wear resistance.

![Figure 7. Wear volume of samples as a function of sintering temperature](image1)

![Figure 8. Wear rate of samples sintered at various temperatures](image2)

### 3.3 Effect of WC Content on Friction and Wear Properties of Sintered Alloy

Fig.9 shows the friction coefficient curves for sintered alloys with different WC contents. It can be seen from the fig that the friction coefficient of the material tends to decrease first and then increase with the growth of the WC reinforced phase. The sintered alloys containing 0 wt.% WC, 3 wt.% WC, 5 wt.% WC and 8 wt.% WC were sintered by the optimum sintering process, and then the friction coefficient was experimented in the same friction and wear testing condition. From the above analysis of the friction and wear test of the samples sintered at different temperatures, it can be seen that the smaller the friction coefficient contributes to the better the wear resistance of the material. The frictional coefficients of sintered alloys containing 0wt.% WC, 3wt.% WC, 5wt.% WC and 8wt.% WC are 0.687, 0.535, 0.319 and 0.589, respectively, indicating that the wear resistance of materials containing a certain amount of WC reinforced phase is better than that without WC reinforced phase obviously. The microstructure of the alloy is affected by WC content. With the growth of WC content, the austenite increases and the pearlite decreases. The increase of the lower hardness austenite content is beneficial to enhance the reinforcing effect of WC and the wear property [13]. However, too much WC in the sample leads to agglomeration easily, and concentrated flaking may occur during the wear process, so the wear volume of the sample containing 8 wt.% WC is increased.

![Fig.9 Friction coefficient of samples with various WC contents](image3)

It is can be known from the previous section that wear volume of samples has a similar tendency with friction coefficient of samples generally. In the experiment for testing the effect of WC content
on wear volume of alloy, a set of data of 5wt.% NbC reinforced phase was introduced to compare with WC reinforced phase at same content to study which particles have more positive influence on friction and wear property of alloy. Fig.10 shows the worn profile of sintered samples containing 0wt.% WC, 5wt.% WC, 8wt.% WC and 5wt.% NbC. Similar to the worn profile of Fig.5, abrasive wear and adhesive wear are the dominant wear mechanism[14]. The wear volume of each sample is shown in Fig.11. The wear volume of the sample with a mass fraction of 5% is the smallest, indicating that the wear resistance is the best. For the samples containing the same amount of WC and NbC reinforced phrase, WC has a more significant effect on the wear resistance compared with NbC.

![Figure 10. Worn surface morphology of samples (a) 0wt.% WC; (b) 5wt.% WC; (c) 8wt.% WC; (d) 5wt.% NbC](image)

![Figure 11. Wear volume of samples](image)

4. Conclusions
In this paper, the effects of different sintering temperature and different WC content on the friction and wear properties of the materials were studied by the test and analysis of friction and wear properties. The main conclusions are as follows:

1) In the friction and wear test, the friction coefficient fluctuates with time, and abrasive wear and adhesive wear are the main wear mechanism of the samples, in which the sample sintered at 1100 °C has the largest friction coefficient and the sample sintered at 1050 °C has the smallest friction coefficient.

2) As the increase of sintering temperatures, the wear volume and rate of the material first decrease and then increase. Since the wear volume and rate of the material at 1050 °C is the minimum, the alloy sintered at this temperature has the best wear resistance.

3) Compared with the material without the reinforced phase, a certain amount of WC enhances the
wear resistance of the alloy. In addition, as the content of WC reinforced phase increasing, the trend of reinforced effect on the wear resistance of the material increases first and then decreases, in which the material containing 5 wt.% WC has the best wear resistance and is better than that containing the same mass fraction of NbC reinforced phase.

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