Dry Sliding Friction and Wear Study of the Worn Surface of Cu-based Powder Metallurgy Train Brake Materials

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Abstract

The characteristics of the worn surface of Cu-based powder metallurgy brake materials for trains after undergoing dry sliding working conditions were studied. A high pressure pad-on-disc tester was developed for this study. Three forms of wear mechanisms were observed during the process, namely; delamination, plowing, and abrasive. These wear mechanisms were found to be responsible for a high wear rate on samples sintered at 850°C and 900°C. The results showed that the main components of the worn surface are graphite, SO2, Fe, Cu and oxides of Fe and Cu (Fe_20_3 and CuO) and AlFe. The samples were observed to be sensitive to sintering temperature. The samples sintered at high temperature experienced lower rate of wear compared to low temperature sintered samples. The worn surfaces were characterized as: destructive, medium, and low.

Keywords: Brake materials; Sliding wear; Worn surface; Sintering temperature; Powder metallurgy.

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1 INTRODUCTION

A material's ability to withstand the conditions it is likely to encounter has a direct bearing on the material's physical and mechanical characteristics. These characteristics are most often influenced by the manufacturing processes it undergoes. Therefore, a designer or engineer is faced with the challenge of selecting the right type of materials that can meet the design requirement. A common challenge faced in the design is the selected materials ability to withstand wear [1]. However, properties which enhance wear resistance may compromise a material's ability to resist other failure types such as creep, fatigue, corrosion, fracture, seizure, etc. This often requires that reasonable compromises are made concerning material properties to prevent all types of failures.

An example of where material compromise and optimization is required is the train brake pad which plays an important role in the control of train operations. Because of their prevalence, it is important to understand how they respond to wear based on their formulation, manufacturing process, and their specific application. In the past, cast iron (usually gray cast iron) has been the most commonly used material in brake shoes [2]. Cast iron brake shoes have the disadvantage of making the wheel-tread surface rougher during braking [3]. In recent years, cast iron shoes have been replaced by composite synthetic brake shoes. It has been demonstrated that cast iron brake shoes make the wheel surface much rougher than a similar product made with a composite material [3].

Much work also has focused on aluminum matrix composites, to modify the header or footer on subsequent pages. but little research has been done on copper, magnesium, and iron-based matrix composites, yet they do have promising applications. Other sintered alloys have been used such as Fe–Cu–Cr–Sn–graphite alloy [4].

Powder metallurgy (P/M) materials may have potential for use in train brake pads. To be specific, the Cu-based powder metallurgy brake materials are made up of metal matrix, friction components, and solid lubricants. This material is preferred over the Fe-based and Cu-Fe-based brake materials due to its higher thermal conductivity and its better wear resistance [5-7]. It is widely and successfully used in automobile brake materials and also for aircraft brake materials [7].

In the past 20 years, there have been rapid developments in the railway industry which have been influenced by the increase of speed, loads, and engine power. The friction materials are required to provide a stable friction coefficient and a low wear rate at various operating speeds, pressures, temperatures, and environmental conditions. All these requirements need to be achieved at a reasonable cost. With regard to the composition, a commercial brake pad usually contains more than 10 different constituents. They are often categorized into four classes of ingredients: binders, fillers, friction modifiers, and reinforcements. Basically, the selection of the constituents is often based on experience or a trial and error method to produce a new formulation [8]. The formulation of friction materials for brake systems typically contains metallic ingredients to improve their wear resistance, thermal stability, and strength. The various types of metallic materials, such as copper, steel, iron, brass, bronze, and aluminum, serve as a form of fibers or particles in the friction material, in addition, the type, morphology, and hardness of the metallic ingredients

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can affect the friction and wear of friction materials [9].

The information gathered from the friction surface of brake materials working under service conditions is very important for the identification and development of wear mechanisms [10-15]. Previous research work into the friction behavior of classical brakes (organic brake pads/gray cast-iron or steel brake discs) showed that, the classical brakes are determined by the character of the brake surfaces of the disc and pad and by the friction layer between these surfaces. The formation of this friction layer on the friction surfaces is very complex and variable and also poorly understood, therefore it remains incompletely explored [16–18]. Hence, there is a need for an investigation into the wear characteristics of a novel Cu-based train pad material after undergoing working conditions.

The objective of this work was to study the effect of sintering temperature on the wear of a Cu-based brake material. A high pressure pad-on-disc tester was developed to test the wear behavior of these materials without lubrication. The counterface material was a commercially used brake pad, made of cast iron (grade HTA5/HB with a Brinell hardness of approximately 196). Scanning electron microscopy was used to examine the wear scars.

2. EXPERIMENTAL

2.1 Sample preparation

The first step was the selection of powder materials categorized as base metal for the matrix, frictional component, lubricant, and alloying element. The newly developed Cu-based brake pad powder materials with their chemical compositions are shown in Table 1, were based on the positive outcome of the formulation that was used by Kryachek [19] and Yao et al [20].

Table 1. Chemical compositions of material in mass (mass. %)

Ingredient:	Matrix	Frictional Component	Lubricant component	Alloying element
	Cu	(SiO_2, Fe)	(Graphite & MoS_2)	(Mn, Sn)
Mass(%)	50-60	15-20	15-20	5.0

The powders were mixed in a V-cone mixer or double cone mixture machine. The rotating speed of the double cone mixture was maintained at 150 rpm for nine (9) hours. After the mixing process, the mixtures were compacted in a hardened steel die using a hydraulic press machine (SANS DCS-300 Digital Hydraulic Compacting machine) under a pressure of 650Mpa. The compacts were subsequently transferred into a furnace for sintering. The sintering took 90 minutes in a controlled atmosphere furnace saturated with carbon at 850-950°C and at 0.01MPa constant pressure. After this, in order to control the level of porosity, the component was dipped into hot oil for 3 hours and the pores were filled with oil. Finally, the resulting rectangular bar with a thickness of 5mm was cut and ground to a size of 14mm × 14mm for use as test specimens. Nine pairs of specimens were prepared for the friction and wear tests.

2.2 Testing Procedures

All tests were carried out in a laboratory environment and experimental standards were observed. Friction performance of the Cu-based friction materials was tested according to the China National Standard GB5763-1998 using an X-MSM Constant Speed Friction Material Tester with a constant speed of 7.54ms^{-1} and a constant pressure of 3.13MPa. Two specimens were pressed against a gray cast iron rotating disc with total contact area of about 3.92cm^2 which produced the pressure of 3.13MPa. The rotor used was a disc made of cast iron (grade HTA5/HB with a Brinell hardness of approximately 196). The test rig is composed of the following parts: the control and monitoring unit; the disc; and the sample holder. The schematic diagram is shown in Figure 1.

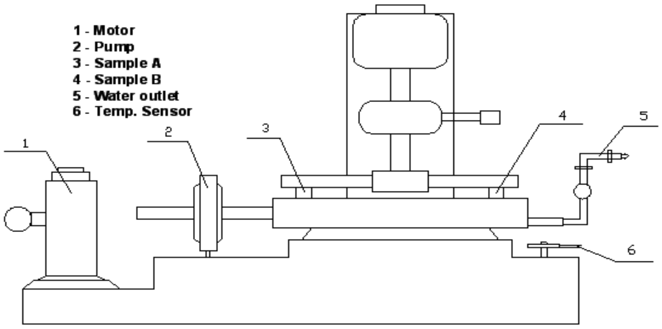


Figure 1 Schematic Diagram of Test Rig

The following temperatures (100, 150, 200, 250, 300 and 350 ◦C) were utilized during the friction test. The data of L_a which is average force of sliding friction (N) and volume wear rate (V in mm^3 N^{-1}m^{-1}) were obtained after 5000 rotations of the disc, which was gradually heated to the set temperatures 100, 150, 200, 250, 300 and 350 ◦C on the computer controlled unit.

The setting is done by selecting the set temperature and is maintained as the average operating temperature. There is a water cooling system on the disc whereby a pump is used to circulate water to regulate over heating or temperature above the set temperature.

After the test, friction surfaces of samples were observed using the scanning electron microscope (SEM) to reveal surface and wear features on the specimens. In addition, X-ray diffraction (XRD) was used to reveal detailed information about the chemical composition and crystallographic structure of the tested specimen.

3. ABRASIVE WEAR MODE THEORY

The widely used quantitative relationship for adhesive wear rate, material properties, load, and sliding speed at the interface between two bodies loaded against each other in relative motion was formulated by Archard [21]. The Archard wear equation derived for adhesive wear situations has also been found to be useful in the representation of abrasive wear. Specially, the volume of worn material removed per unit sliding distance can be expressed as

$$\frac{V_C}{s} = K\frac{L}{H} \tag{1}$$

where V_C is the volume worn, L is the load, H is the hardness, s is the sliding distance and the K is abrasive wear coefficient which depends on the geometry of the abrading asperities and typically ranges between 10^{-6} to 10^{-1}.

Practical Volume Worn

The device cannot measure the volume wear rate directly; therefore the volume wear rate, V_p was calculated by

$$V_p = \frac{1}{2\pi R} \times \frac{A\left(d_1 - d_2\right)}{nL_a} \tag{2}$$

where R is the distance between the center of specimen and the center of the rotating disk (0.15m), n is the number of rotations of the disk during testing (5000), A is the area of the specimen (196mm^2), d_1 is the average thickness of specimen before experiment (mm), d_2 is the average thickness of specimen after experiment (mm), and L_a is average force of sliding friction (N). The volume wear rate by pad-on-disk wear testing (ASTM G99-95a) was used. Under the operating conditions, various frictions and wear processes occurred and the volume wear rate was calculated with [22]:

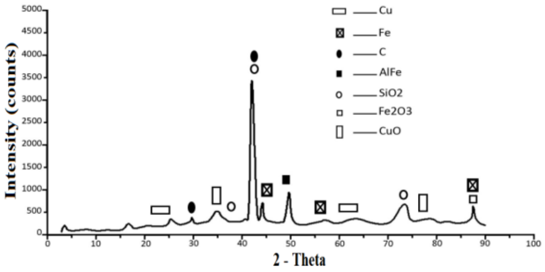
$$K = \frac{\text{Wear volume}}{\text{load} \times \text{sliding distance}} \tag{3}$$

Equation (1) indicates that the volume loss of a material is inversely proportional to its hardness. Hence, the higher percentage reinforcement elements in the test specimens, the better wear resistance and reduction rate of volume loss.

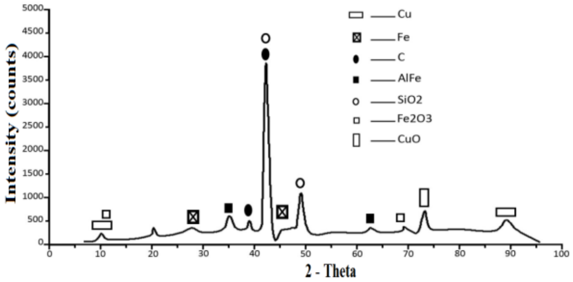
4. RESULTS AND DISCUSSION

4.1 Worn surfaces characteristics with XRD and SEM

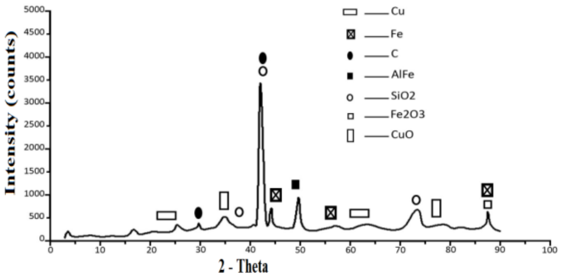
The peaks and the relative intensities of the XRD indicate a good level of homogeneity and a good average bulk composition, even though there was an excessive worn surface on the test materials. Figure 2(a, b, and c.) shows the XRD pattern of the worn surface at sintering temperatures of 850, 900 and 950^{o}C respectively.



(a) At 850 ^{o}C



(b) At 900 ^{o}C



(c)At 950 ^{o}C

Figure 2. XRD of pattern of the worn surface at various sintering temperatures

The result indicates that graphite, SO2, Fe, Cu and oxides of Fe and Cu (Fe_2O_3 and CuO), Al_2O_3 and AlFe are on the worn surface. Graphite has a layered structure with wide interlayer spacing, which tends to cleave along the layers. So, it is widely used as lubricant to eliminate seizure and make the brake process stable. Consequently, the tribological properties of brake materials are improved with the addition of graphite [23]. The resistance and hardness of SiO2, Al_2O_3 and CuO particles are much higher than those of the Cu and Fe matrix resulting in particulate hardening. Also, the presence of Al_2O_3 can be viewed as a factor for reducing the compressibility of the powder, this results in a reasonable increase in porosity amount, therefore lowering the density of the materials. Therefore, the friction coefficient was increased remarkably as a result of SiO_2 and Al_2O_3 particles sliding against their counterpart because the relative movement of friction pairs is inhibited giving a high friction coefficient in the range of 0.3 to 0.42 as shown in Figure 3.

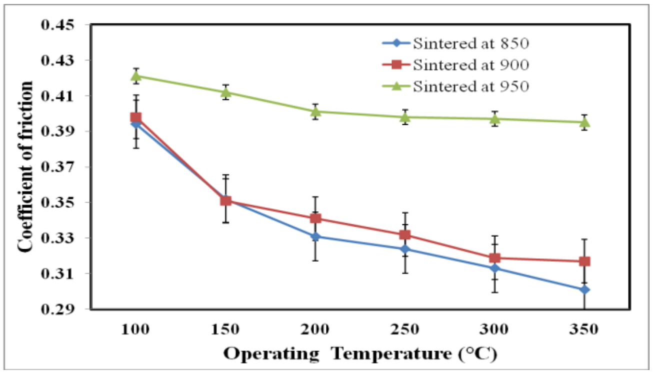


Figure 3. Friction coefficient versus the operating temperature

However, the heat generated due to the friction braking increases the interface temperature and this in turn decreases the friction coefficient.

The typical SEM microphotographs of the worn surface and friction surface for Cu-based composite are shown in Figure 4(a) and (b), the worn surface is surface which has a higher wear rate and the friction surface is surface which has less wear rate. The surface sintered at 850°C (a-1) and (a-2) shows abrasive scratches, indicating abrasive wear. The groove (in a) reveals plowing wear also occurred during sliding; this is material displacement to the side of the wear track. The surface sintered at 900°C (b-1) and (b-2) shows flake-like fragments, and pits. These are a result of stress caused by high pressure exerted on the material during operation which results in delamination wear of medium-large flake-like fragments.

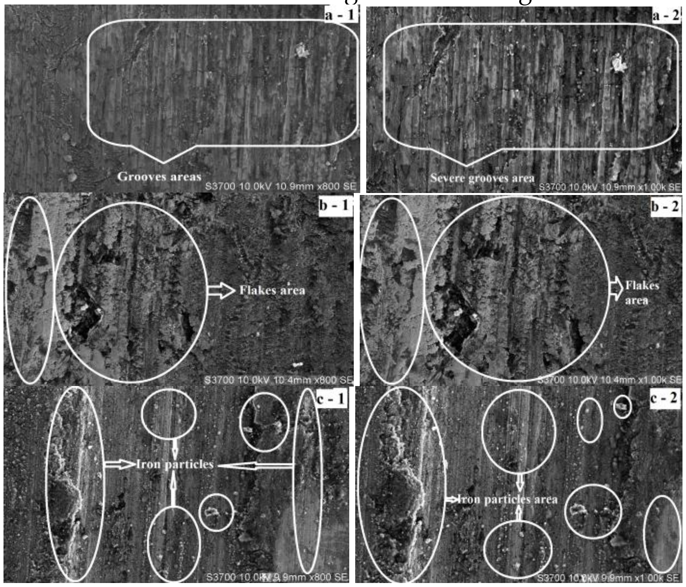


Fig. 4(a). SEM microphotographs of the worn surface for Cu-based composite. ((a) 1&2, 850°C; (b) 1&2, 900°C; (c) 1&2, 950°C)

The larger the flakes the more severe the delamination and therefore the greater the rate of wear observed. The surface (c-1) and (c-2), sintered at 950 °C, shows iron particles rich in carbon on the surface. The iron rich carbon formation may increase resistance to wear and result in a very smooth surface as shown.

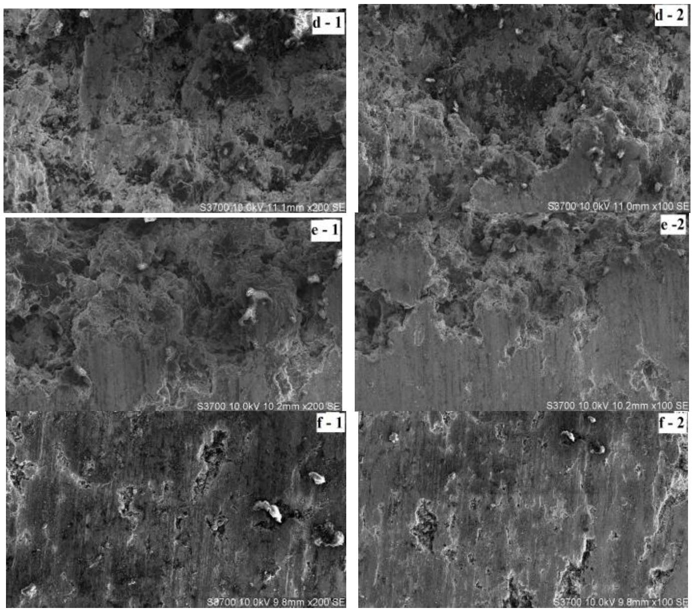
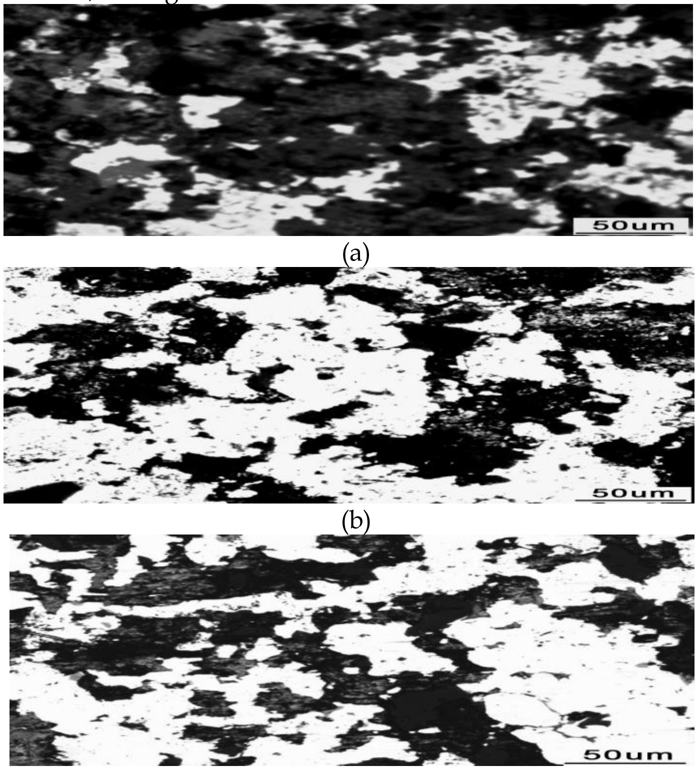


Fig. 4(b). SEM microphotographs of the friction surface for Cu-based composite.
((a) 1&2, 850°C; (b) 1&2, 900°C; (c) 1&2, 950°C)

Generally, the worn surfaces observed may be grouped into three types; namely, destructive wear (found mostly on (a-2) and (b-1 and 2)); medium wear (mostly on (a-1) and low wear (only on (c)). An optical microscope was used to observe the pores before the wear test on all samples tested which indicated that high porosity was found with those samples of low sintering treatment temperature (850°C and 900°C), but at 950°C porosity was less which contributed to high resistance to wear, see Figure 5.



(a)

(b)

(c)

Fig. 5. Optical Micrograph before wear test (a) at 850°C, (b) at 900°C and (c) at 950°C.

The hardness values measured with a Vickers hardness tester (Figure 6) on all the materials shows a similar tendency as the results of the sintering as shown in Figure 3. The materials sintered at high sintering temperature exhibited high hardness as shown in Figure 6 with low porosity as shown in Figure 7. This confirmed the fact that, porosity influences the hardness, and therefore, affects the rate of wear of the material.

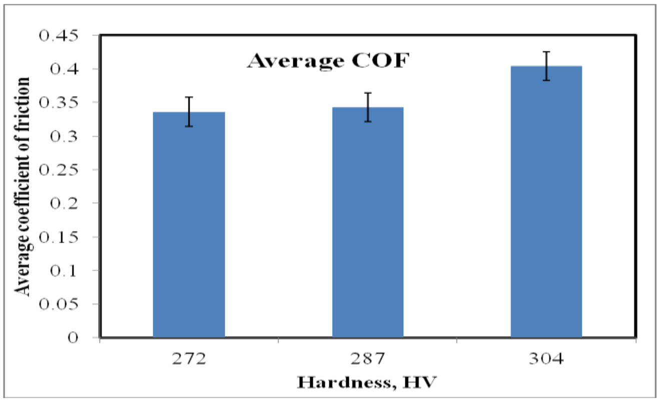


Fig. 6. Friction coefficient and hardness

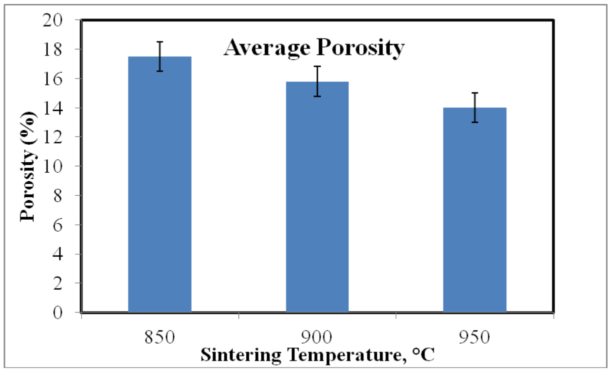


Fig. 7. Relationship between porosity and sintering temperature

This Cu-based composite is composed of several elements with different wear resistance properties. The elements with much harder particles have higher wear resistance than the soft elements. Therefore, the hard particles projected on the friction surface; whereby the relative motion between composite and counterpart is inhibited which produce a higher coefficient of friction than the soft particles. Figure 4(b) shows the nature of the friction surfaces. The surfaces shown in figure (d-1) and (d-2) were sintered at 850°C. It could be observed that material losses as a result of sliding were significant. The surface shown on (e-1) and (e-2) which were sintered at 900°C demonstrated less wear loss as compared with the former. The surfaces (f-1) and (f-2) were sintered at 950°C, they showed minimal wear and therefore could be seen as the optimized material for development into commercial brake pads in the future.

4.2 Wear rate

Table 2 shows the physical properties of the Cu-based composite. The wear rate changes through the repeated contact process under constant load and velocity (3.13PMa and 7.54m/s respectively) [24]. Wear rates are often quoted in terms of a wear coefficient or dimensionless wear coefficient as derived from the Archard treatment of wear processes [25].

Table 2. Physical properties of Cu – based composite

Rule Of Mixture (ROM)	
$\rho_t\ (g.cm^{-3})$	$7.973\ g.cm^{-3}$
Experiment Data	
$Average\ \rho\ (g.cm^{-3})$	$6.7136\ g.cm^{-3}$
$Average\ Microhardness$ (HV)	294
$Average\ Porosity\ \%,\ P = (1 - \frac{\rho}{\rho_t}) \times 100$	15.79%

The wear volume rate (V_w) is calculated as shown in equation (1); where K is the wear coefficient (dimensionless), W the normal load and H the hardness. The Archard treatment of wear has been shown to be valid for cases where mechanical influences are dominant [26]. Wear is often associated with hardness of the materials in contact. Basically, the harder the material, the more wear resistant it is, but it is also more brittle and therefore more sensitive to the detachment of particles. The variation in wear volume rate of the composite specimen treated at different sintering temperature is shown in Figure 8.

The material sintered at 900°C and tested at the above mentioned conditions on the pad-on-disc tribotester demonstrated high wear rate during dry sliding process. The 850°C sample also followed suit but was a little better than that of the first one under the same operating conditions.

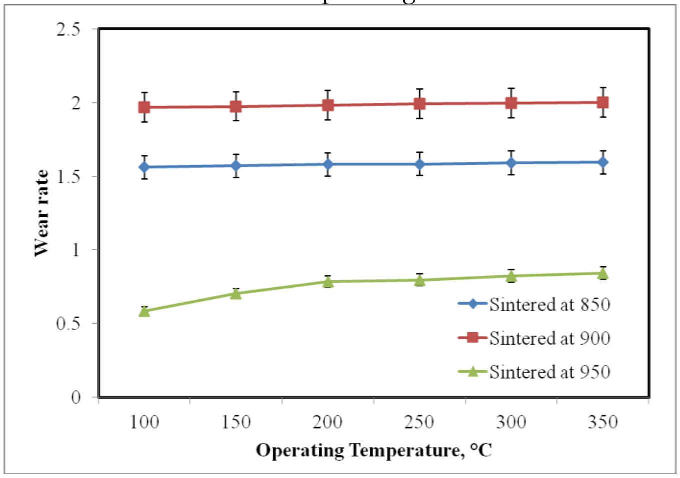


Figure 8. Effect of sintering temperature on rate of wear, W $10^{-4}mm^3/Nm$

The lowest wear rate was observed for the 950°C sintered material. This could be attributed to the fact that there was sufficient heating to reduce porosity, shown in Figure 6 and increase hardness, shown in Figure 7 which has direct influence on the wear properties of the material.

5. CONCLUSIONS

The material was temperature sensitive, and the tribological characteristics were found to be better for high sintering temperature. The friction coefficients at high sintering temperature were relatively high values and at the same time demonstrated low rate of wear [27]. The porosity level affects the mechanical properties. High porosity is not the best if optimizing the performance of the novel material, which leads to weakening of the materials as a result of low sintering temperatures but this can be further improved and considered for manufacturing commercial brake pads. On the other hand, low porosity samples gave a high resistance to wear. This was a result of the high sintering temperature which ensured complete diffusion.

Three forms of wear mechanisms were observed during the process, namely; delamination, plowing, and abrasive. These wear mechanisms were found to be responsible for a high wear rate on samples sintered at 850°C and 900°C. The main components of the worn surface are graphite, SO2, Fe, Cu and oxides of Fe and Cu (Fe_20_3 and CuO) and AlFe.

The samples were observed to be sensitive to the sintering temperature. The samples sintered at a high temperature experienced lower rate of wear compared to low temperature sintered samples. Three types of worn surfaces were observed: destructive, medium, and low.

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