

Dry Sliding Studies of Porosity on Sintered Cu-based Brake Materials

Glenn Kwabena Gyimah^{1,✉}, Dong Chen², and Ping Huang²

Abstract: Cu-based composites with its promising engineering application due to their excellent thermophysical properties coupled with better high temperature mechanical properties as compared to pure copper and copper alloys. An investigation on a Cu-based composite frictional material re-inforced with other elements for train brake was treated under P/M route for its wear behavior in terms of sintering temperature and porosity. The dry sliding wear characteristics investigation test with a high pressure pad-on-disc tester was developed for the three different sintering temperatures samples. The optimal porosity was obtained at the highest sintering temperature of 950°C. That same optimal porosity gave the lowest wear frictional coefficient, and the highest coefficient of friction. Three forms of wear mechanisms were observed during the dry sliding process, namely, delamination wear, plowing wear and abrasive wear. High wear rates were found on samples sintered at 850°C and 900°C. Abrasive wear and the delamination wear were the main cause of high wear coefficient, low wear number and low coefficient of friction. The nature of abrasive surfaces observed were classified into three divisions, namely, smooth abrasive surfaces; rough abrasive surface; and the highly abrasive surface. The dominance of wear is discussed in the light of SEM photography of the worn surfaces.

Keywords: Brake Materials; Wear; Porosity; Wear Mechanism; Sintering Temperature.

1. INTRODUCTION

Recently, much attention has been given to the effect of porosity on Cu-based matrix composites, due to its indispensable influence on tribological and mechanical behavior of sintered composites. The influence of Porosity is very high in the determination of a material's application.

The porosity of material influences its ability to withstand wear since it has an impact on the properties of the Cu-based composite material. In view of this, powder metallurgist has devoted much into minimized porosity because of higher porosity results in lower values in all mechanical properties of sintered steels.^[1] In comparison

with the numerous studies concerned with other mechanical properties, the influence of porosity on wear behavior of sintered steels has not been extensively investigated^[1].

The principal factors that influence the sliding wear of the composites include: extrinsic factors such as sliding distance, sliding velocity, applied load, atmosphere temperature, etc. and intrinsic factors such as reinforcement type, shape, size, volume fraction and distribution, interface between reinforcement and matrix, matrix material, heat treatment, porosity, etc^[2].

The use of different copper and nickel particle sizes provided the ability to modify the porosity size and spacing.^[3] Lee et al.^[4] studied the effect of sintered porosity in powder metallurgy (PM) 6061 monolithic alloy and 6061: SiCp composites on dry abrasive wear, indicating that the wear rate of 6061 alloy increases drastically with increasing porosity, while for its composites, the porosity effect is not significant.

The effect of porosity on the wear and friction of metals has been studied by Vardavoulias et al.^[5]. They claimed that the pores enhance the surface roughness of the materials and decrease the real area of contact between two sliding surfaces and consequently increase the contact pressure and promote particle detachment during sliding.

Suh^[6] has argued that the increase in porosity content of the composite reduces the required length of crack propagation to link-up with other cracks in order to cause delamination. Thus, porosity decreases the wear resistance and coefficient of friction of the composite.

For different sintered composites materials those effects are not constant depending on factors such as the composition and heat treating condition. Therefore, until now, it has been very difficult to make a universal conclusion about the influence of pores on various sintered materials.

In this paper, a careful evaluation of the samples wear behavior before and after practical application was done. The influence of sintering temperature on the porosity during the dry sliding wear behavior of sintered novel Cu-based composite train brake material was investigated.

This work was supported by the Key Laboratory of Specially Functional Materials and Advanced Manufacturing Technology, Ministry of Education, South China University of Technology.

¹ ✉ Glenn Kwabena Gyimah is with School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, 510640, P. R. China. (Email: gk.gyimah@yahoo.com),

² Dong Chen is with and Ping Huang are with School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou, 510640, P. R. China. (Email: cityeast@scut.edu.cn; mephuang@scut.edu.cn).

RECEIVED: 10, FEB., 2013; REVISED: 16, APR., 2013; ACCEPTED: 22, APR., 2013; PUBLISHED: 26, APR., 2013.

ISSN: 2345-234X



010205021902242013000142

2. EXPERIMENTAL DETAILS

A. Sample preparation

The specimens used for this study are made by powder metallurgy technique, which process includes mixing, compacting and sintering. The first step was the selection of powder materials categorized under based metal as the matrix, frictional components, lubricants and alloying elements. These were based on the outcome of Kryachek [7] review and Yao et al. [8-9]. The newly developed bronze based brake pad powder material with its chemical composition is given in Table 1.

TABLE 1.
CHEMICAL COMPOSITIONS OF MATERIAL IN MASS (WT. %)

| Ingt: | Matrix | Frictional component | Lubricant component | Alloying element |
|-------|--------|-------------------------|--------------------------------|------------------|
| | Cu | (SiO ₂ & Fe) | (Graphite & MoS ₂) | (Mn & Sn) |
| Wt%. | 50-60 | 15-20 | 15-20 | 5.0 |

The powders listed in Table 1 were weighed in a Sartorius BS224 S (Max 220g d=0.0001g) with their given proportion, the well prepared powder were mixed in a V-cone mixer or double cone mixture machine. The rotating speed of double cone mixture was maintained at 150 rpm for nine 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 the pressure of 650Mpa.

The compacts were subsequently transferred into a sintering furnace for sintering. The sintering took 90 mins in a controlled atmosphere furnace saturated with carbon at 850-950°C at 0.01MPa constant pressure. The sintered materials were then driven out when oil-cooled. Finally, the resulting rectangular bar with thickness of 5mm was cut and grounded to a size of 14mm × 14mm test specimens. Nine pairs of specimens were prepared for the friction and wear test.

B. Testing Procedures

1) Characterisation test

The density of friction materials was determined according to a procedure proposed in ASTM D792, which is based on Archimedes' principle. This was done on all the samples at different sintering temperatures and the average results are recorded in Table 3a.

A digital microhardness tester HVS - 1000 instrument was used for the hardness and the hardness values were taken in the Vickers scale using 10N within 20 seconds. Prior to the hardness test, the samples were ground and polished with sand paper of grit 180, 240, 320, 600, 800, 1000, and 1200 successively, and were also cleaned in alcohol in an ultrasonic cleaner. For each specimen, the hardness measurements were repeated ten times and an average of the ten was taken.

A microstructure and tribosurfaces analysis was carried out with OM and SEM. An optical microscope (OM) and a scanning electron microscope (SEM) were employed to

examine microstructures of the specimen before and after the wear test. The surfaces of the specimens were first polished with sand paper of grit 180, 240, 320, 600, 800, 1000, and 1200 successively, followed by two polishing stages of 3µm and 0.05µm, respectively. The OM and the SEM helped analyze the nature of the microstructure for the likely pores available and the wear surfaces, and they were done both before and after the wear test.

2) Performance test

The schematic diagram of the test rig is shown in Fig. 1. During the tribotests, the performance test includes the determination of coefficient of friction, friction force, wear loss and type of wear. These were tested according to the China National Standard GB5763-1998 using an X-MSM Constant Speed Friction Material Tester with constant speed 7.54ms⁻¹ and constant pressure 3.13MPa. As a rotor, the disc made of cast iron (grade HTA5/HB with Brinell hardness in the range of 196) was used. The test rig is composed of the following parts: the control and monitoring unit; the disc; and the sample holder. The friction test was performed at these selected temperatures (150, 200, 250, 300 and 350°C). Two specimens were pressed against a gray cast iron rotating disk with a total contact area of approximately 3.92cm² and rotated for 5000 revolution. The machine was originally made to apply 0.98MPa and cover 25×25mm of surface area. Modification of the sample holder was done, reducing the surface area to 14×14 mm and thereby increasing the pressure on the sample to 3.13MPa.

The friction coefficient data was obtained automatically by the tester. Five sample pairs were tested for each specimen and an average of the experimental data was taken as the result. The wear coefficient k in mm³ N⁻¹m⁻¹ was calculated after 5000 revolutions of the disc. Since the system cannot measure the wear loss directly, the volume wear rate by pad-on-disk wear testing (ASTM G99-95a) was used.

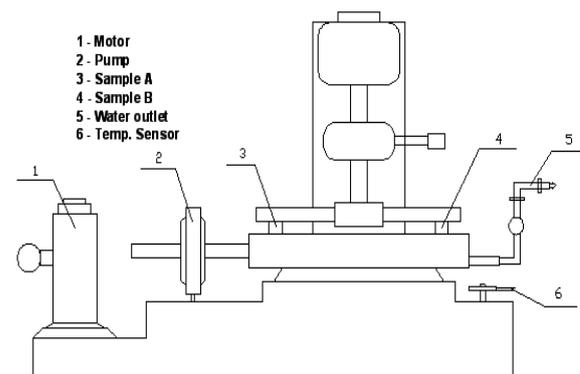


Fig. 1 Schematic Diagram of Test Rig.

It is now generally recognized that materials suitable for unlubricated tribological application (e.g. bearing, brake, wheel/rail, cam/tappet, piston/cylinder, work piece/tool, etc.) under the operating conditions (load F_a , speed v , temperature T , operating duration t , sliding distance s), various friction and wear processes may occur and must

fulfill the following criteria ^[10]:

$$\text{wear coeff.} = \frac{\text{wear volume}}{\text{load} \times \text{sliding dist.}} \quad (1)$$

$$k = \frac{1}{2\pi Rn} \times \frac{\text{volume change}}{\text{average friction force, } f_a} \quad (2)$$

the volume change is $A(d_1 - d_2)$.

where R is the distance from the center of the rotating disk to the center of the specimen ($=0.15\text{m}$), n is the number of rotations of the disk during testing (5,000 rev), A is the area of the specimen (196mm^2), d_1 is the average thickness of the specimen before the experiment (mm), d_2 is the average thickness of specimen after the experiment (mm), and f_a is the automatically obtained average force of sliding friction (N) from the test rig.

They were obtained at temperatures of 100, 150, 200, 250, 300 and 350°C, respectively. The test rig was equipped with a temperature control unit with a pump to circulate water under the disc to maintain a controlled temperature. The average force was also recorded from the test rig at every operating temperature. The volume change was obtained by calculating the difference between initial volume before test and the final volume after test. These and the other parameters of the test rig were entered into equation (2) to obtain the results in Table 3.

Also, wear numbers were also adopted. These were calculated, and used as a means of knowing the wear resistance level of the design material. The mass of the specimen was measured before and after the wear test to obtain the mass loss after 5,000 revolutions, at temperatures of 100, 150, 200, 250, 300 and 350°C, respectively. The densities were obtained by the procedure proposed by ASTM D792 after the tribo test. This was done and the wear number was obtained as:

$$\text{Wear number } (W_n) = \frac{\text{Density}}{\text{Mass loss}} = \frac{1}{\text{Volume}} \quad (3)$$

where W_n is the wear number. Physically, it is per unit volume of the sample. The higher the wear number, the more effective the wear resistance of the material ^[11]. The results are tabulated in Table 3.

General porosity means the fraction of pore volume to the total volume. The porosity calculations were done using equation (4) after obtaining the various densities.

$$\text{Porosity, } P = \left(1 - \frac{\rho}{\rho_t}\right) \times 100 \quad (4)$$

3) Test conditions

All tests were done under strict laboratory environmental and experimental standards. During the experiments, a constant rotation of 480rpm was maintained (sliding velocities of 7.54ms^{-1}); and the constant pressure

was 3.13MPa based on the surface area of the specimen. The test rig is equipped with a temperature controlling unit with a pump to circulate water under the disc to maintain a controlled temperature.

3. RESULTS AND DISCUSSION

A. Porosity Effect on Friction and Worn surface

The effect of porosity and the sintering temperature on friction and worn surfaces of the sintered Cu-based composite rubbing against a rotor, the disk made of cast iron (grade HTA5/HB with Brinell hardness in the range 196), are shown at Fig. 2. The worn surfaces of the composite specimen and wear debris were examined by SEM. The operating condition for pressure and sliding speed for all the samples are 3.13MPa and 7.4m/s.

The typical SEM microphotographs of the worn surface for Cu-based composite are shown in Fig. 2(a) to (c). The sections marked *A* on the microphotograph indicates the destructive wear sections during the tribo testing. The *B* sections are the relatively medium wear surfaces, which indicate mild wear occurred during sliding. The section *C* has low wear surface, glassy luster and integrated friction film, which shows this section has better wear resistance property. The surface sintered at 850°C (a) containing 17.53% porosity, 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) containing 15.82% porosity, 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. The larger the flakes the more severe the delamination and therefore the greater the rate of wear observed. The surface (c), sintered at 950 °C containing 14.04% porosity, shows iron particles rich in carbon on the surface. The iron rich carbon formation increased resistance to wear and this resulted in a very smooth surface as shown.

The higher the porosity value of the samples, the lower coefficient of friction, lower wear number and high wear coefficient resulting to high volume loss.

From the discussions above, the general observation of the worn surfaces may be grouped into three types; namely, destructive wear (found mostly on (a) and (b)); medium wear (mostly on (a) and (c)); and low wear (only on (c)).

B. Porosity Effect on Hardness and Wear

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 (3.13MPa and 7.54m/s respectively) ^[12]. Wear rates are often quoted in terms of a wear coefficient or dimensionless wear coefficient as derived from the Archard treatment of wear processes ^[11].

The average hardness values measured with a Vickers hardness tester (Table 3) on all the materials shows a similar tendency as the results of the sintering as shown in Fig. 2.

The materials with less porosity and sintered at high sintering temperature exhibited high hardness as shown in Table 3 with low porosity at low sintering temperature. This confirmed the fact that, porosity influences the hardness, and therefore, affects the rate of wear of the material. From the same table, the wear rate was also greatly affected by the porosity values obtained at their respective sintering temperatures.

lowest wear rate was observed at the 950°C sintered material. This could be attributed to the fact that there was sufficient heating to reduce porosity, which also brought about increase in hardness to optimize the wear properties of the material.

TABLE 2
PHYSICAL PROPERTIES OF CU-BASED COMPOSITE

| Rule Of Mixture | |
|----------------------------------------------------------------|-------------------|
| $\rho_t (g.cm^{-3})$ | 7.973 $g.cm^{-3}$ |
| Experiment Data | |
| Average $\rho (g.cm^{-3})$ | 6.714 $g.cm^{-3}$ |
| Average Microhardness (HV) | 294 |
| Average Porosity %, $P = \left(1 - \frac{\rho}{\rho_t}\right)$ | 15.79% |

TABLE 3
PROPERTIES OF THE CU-BASED COMPOSITE MATERIAL

| Sint. Tem. T_{sin} | Density, ρ | Porosity, P | Hardness, H_v | Wear Coeff. k | Wear num. W_n | Coeff. Frict. μ |
|----------------------|-----------------|---------------|-----------------|-----------------|-----------------|---------------------|
| 850°C | 6.51 | 17.53 | 272 | 0.000154 | 8.7191 | 0.336 |
| 900°C | 6.71 | 15.82 | 287 | 0.000166 | 9.8499 | 0.343 |
| 950°C | 6.85 | 14.04 | 304 | 0.000044 | 10.128 | 0.404 |

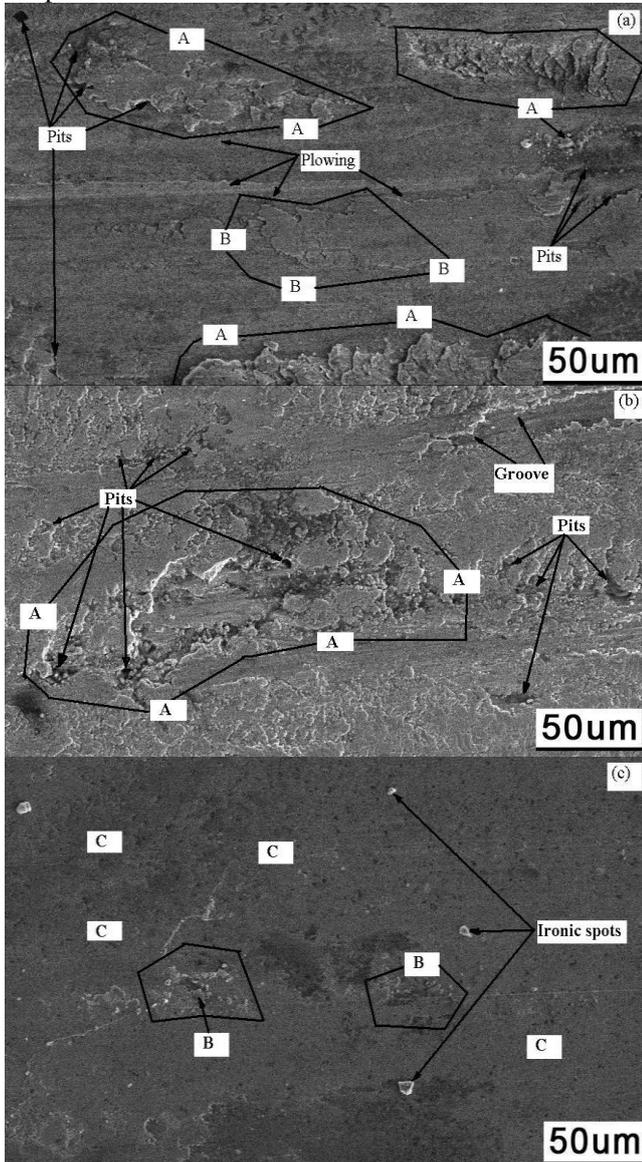


Fig. 2. Shows cross-sectional SEM micrograph of the nature of smoothness of friction surfaces at different sintering temperatures: (a) 850°C, (b) 900°C and (c) 950°C.

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 [13]. 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. According to Table 3, the

C. Abrasive Surfaces Classification

In view of the advancement of technology, the application of computer-based technology and image-processing methods have lead to a fully automated classification system of tribological surfaces. Such a system has been useful in classifying (i) surfaces during manufacturing processes (quality control), (ii) wear surfaces in the failure analysis of engineering components, or (iii) wear particles in machine condition monitoring. The hybrid fractal-wavelet method is used here to demonstrate how an unknown abrasive surface can be classified into one of three classes of abrasive surfaces [10]. 3-D surface morphology images are shown in Fig. 3 to identify the different kinds of abrasive surfaces.

The investigation (Fig. 3) shows that the abrasive surfaces can be classified into three divisions, named as smooth abrasive surface (mirror surface and integrated friction film) which has better wear resistance property because it demonstrated minimal wear rate, rough abrasive surface (rough surface) indicates moderate wear rate and a highly abrasive surface (much rough surface) showing excessive wear. Examples of the 3-D surface morphology images of the surface from each division are shown in Fig. 3.

The (a) is observed to be the one with a highly abrasive surface; this is as a result of having fewer peaks that are ironic or hard to withstand pressure from the braking system. The (b) was also observed as the rough abrasive

surface with moderate peaks withstanding the exerted pressure of the braking system. The (c) is the one that was observed as having enough ionic peaks to withstanding the exerted pressure and therefore given a smooth abrasive surface.

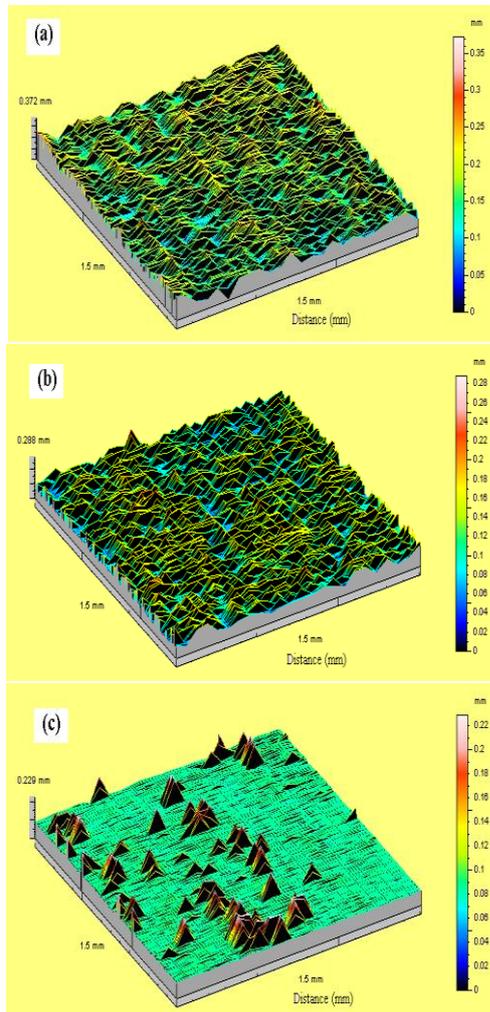


Fig. 3. 3-D surface morphology images of the surface (a) at 850 °C, (b) at 900 °C and (c) at 950 °C.

4. CONCLUSION

The wear resistance properties of the novel Cu-based composite material against a cast iron disc (grade HTA5/HB with Brinell hardness in the range 196) tested under a full laboratory condition, reveals a strong influence of porosity over the mechanical and tribological characteristics of the material. Investigation and observations concerning the effect of porosity on the mechanical and tribological characteristics have led to the following conclusions:

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 as a result

of the high sintering temperature which ensured complete diffusion.

Much lower wear coefficient, high wear number and high coefficient of friction were obtained at low porosity samples (14.04% at 950°C) tested. These show high resistance to wear; given good tribological characteristics and good mechanical properties.

The dominant wear mechanisms found were plowing, delamination and abrasive wear. Abrasive wear and the delamination wear were the main cause of high wear coefficient, low wear number and low coefficient of friction. The nature of abrasive surfaces observed were classified into three divisions, namely, smooth abrasive surfaces (mirror surface and integrated friction film) which has better wear resistance properties because it demonstrates minimal wear rate; the rough abrasive surface (rough surface) indicates moderate wear rate; and lastly, the highly abrasive surface (much rough surface) showing excessive wear and has a high degree of surface destruction. This is as a result of the rate of wear that occurred during the dry sliding.

ACKNOWLEDGMENT

We are grateful to the staff of The Key Laboratory of Specially Functional Materials and Advanced Manufacturing Technology, Ministry of Education, South China University of Technology. We are also grateful unto the staffs of these Analytical and Testing Center of South China University of Technology particularly Prof. Zhang Da Xue and Mr. Zhu Fan Kang (Chang Zhang) where we carried out the Experiments and the test.

REFERENCES

- [1] J. Wang, Y. He, and H. Danninger, Influence of Porosity on the Sliding Wear Behavior of Sintered Fe-1.5Mo-0.7C Steels, *ASM International, JMEPEG* (2003) 12:339-344
- [2] M. Gui, S. B. Kang, J. M. Lee, Influence of porosity on dry sliding wear behavior in spray deposited Al-6Cu-Mn:SiCp composite, *Materials Science and Engineering, A293* (2000) 146-156
- [3] T. M. Cimino, A. H. Graham and T. F. Murphy, The effect of microstructure and pore morphology on mechanical and dynamic properties of ferrous P/M materials, Presented at pM2TEC '98
- [4] H.L. Lee, W.H. Lu, S.L. Chan, Abrasive wear of powder metallurgy Al alloy 6061-SiC particle composites. *Wear* 159 (1992) 223
- [5] M. Vardavoulias, C. Jouannt-Tresy, M. Jeandin, Sliding wear behaviour of ceramic particle reinforced high-speed steel obtained by powder metallurgy, *Wear* 165 (1993) 141-149.
- [6] N.P. Suh, An Overview of the Delamination Theory of Wear, *Wear* 44 (1977) 1-16.
- [7] V. M. Kryachek, *Sintered Metals and Alloys Friction Composites: Traditions and New Solutions (Review)*. Powder Materials, Powder Metallurgy and Metal Ceramics, Vol. 43, Nos. 11-12, 2004 Spring Science + Business Media, Inc.

- [8] Xiong X., Sheng H, Chen J, Yao P, Effects Of Sintering Pressure And Temperature on Microstructure and Tribological Characteristic of Cu-Based Aircraft Brake Material, *Trans. Nonferrous Met. Soc. China* 17(2007) 669-675
- [9] Yao P, Sheng H, Xiong X., Huang B., Worn Surface Characteristics of Cu-Based Powder Metallurgy Brake for Aircraft, *Trans. Nonferrous Met. Soc. China* 17(2007) 99-103.
- [10] G. W. Stachowiak, G. B. Stachowiak, D. De Pellegrin, P. Posiadlo. Characterization and Classification of Abrasive Particles and Surfaces, *Wear—materials, mechanisms and practice*. Edited by G. Stachowiak 2005 339-368.
- [11] Williams J. A., *Engineering Tribology* Oxford Science Publications, Oxford University Press, New York 1994.
- [12] Kato K., Classification of Wear Mechanisms/Models, *Wear – Materials, Mechanisms and Practice*, Edited by G. Stachowiak , 2005, 9-20,.
- [13] Neville A. and Morina A., *Wear and Chemistry of Lubricants, Wear – Materials, Mechanisms and Practice*, Edited by G. Stachowiak , 2005, 71-94.

Available online at:

<http://tsest.org/index.php/TCMS/article/view/142>

Download full text article at:

<http://tsest.org/index.php/TCMS/article/download/142/92>

Cite this work as:

Glenn Kwabena Gyimah, Dong Chen, and Ping Huang, "Dry Sliding Studies of Porosity on Sintered Cu-based Brake Materials," *TSEST Transaction on Control and Mechanical Systems*, Vol. 2, No. 5, Pp. 219-224, May, 2013.