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A study on friction and wear reduction due to porosity in powder metallurgic gear materials

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ABSTRACT

It has been widely acknowledged that controlled texturing on a surface can contribute to friction and wear reduction at lubricated sliding contact interfaces. This paper investigates the influence on friction and wear of different pore size distributions of powder metallurgy gear materials. The pore sizes are controlled by different densities of the powder metallurgic materials. Two different kinds of powder metallurgy (PM) gear materials were applied and a standard gear material are used as a reference. The friction and wear coefficients of PM materials sliding on PM materials increase with increasing pore size. The friction and wear coefficients of regular steel sliding on PM materials decrease with increasing pore size. No matter what the material of the disc, peeling is one of the main damage mechanisms of powder metallurgy pins with the biggest porosity.

1. Introduction

A number of studies have investigated the effect of surface texture on friction and wear in lubricated contacts. Powder metallurgic (PM) gear material has an inherent porosity that makes it somewhat similar to surface texture in that both have surface cavities that can hold lubricant. Pettersson et al. [1] showed that under specific conditions applying a texture to a sliding surface yields a lower friction and wear coefficient because the textures on the surface act as oil reservoirs enabling good lubrication. Kovalchenko et al. [2] studied the effect of laser surface texture (LST) on lubricated parallel sliding surfaces and found that the beneficial effects of such texture are more pronounced at higher speeds with higher oil viscosities. Etsion et al. [3] evaluated the effect of partially laser textured piston rings on fuel consumption and found that the partial LST piston rings yielded up to 4% lower fuel consumption. Shinkarenko et al. [4] developed a theoretical model to study the potential use of LST in the form of spherical micro-dimples for soft elasto-hydrodynamic lubrication (SEHL) and predicted that LST would effectively increase load capacity and reduce friction in SEHL. Krupka and Hartl [5] investigated the effect of surface texture on film formation under lubricated sliding/rolling conditions and showed that the depth of the micro-dents has a significant effect on lubricant film formation for a positive slide-to-roll ratio. Krupka et al. [6] also studied the effect of surface texture based on shallow micro-dents within mixed lubricated non-conformal contacts and demonstrated that lubricant emitted by the micro-dents increased the local minimum film thicknesses. Krupka and Hartl [7] investigated the changes in film thickness distribution within the lubricated contact between a steel ball and glass disc. The results showed that thin viscous boundary films that form on surfaces can reduce asperity interactions. Even though these boundary films do not separate surfaces completely, they still provide some protection against excessive friction and wear. By doing pin-on-disc experiments Wakuda et al. [8] showed that texturing a lapped smooth surface could reduce the friction coefficient from 0.12 to 0.10 compared to surfaces without texturing. By combining pin-on-disc frictional and FZG efficiency results, Li and Olofsson [9] showed that the porosity of PM gear material surfaces facilitates good lubrication conditions that can lead to higher gear mesh efficiencies for PM gears. Lots of studies [10–12] showed that the pores in sintered bearings can provide lubricant themselves with the lubricant contained in the pores of itself.

All the above studies show that both artificial texture and porosity from the manufacturing process of PM material can modify friction and sometimes wear. This is because texturing and porosity can act as oil reservoirs and thus enable good lubrication. In order to make full use of the inherent porosity characteristics of PM gear materials, it is necessary to study the effect of different pore sizes on the tribological properties of PM gear materials. In this study we will use pin-on-disc tests to investigate the influence of three different pore size distributions on friction and wear.

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Nomenclature

PM	powder metallurgy
RS	16MnCr5
AQ	Distaloy AQ+0.2% C
CrA	Astaloy CrA+1.8% C
A–B	the former is the disc material, the latter the pin material
μ	friction coefficient
K	wear coefficient (m^2/N)
P_{max}	maximum contact pressure (GPa)
$E_{1,2}$	Young's modulus (Pa s)
$\nu_{1,2}$	Poisson's ratios
ρ, ρ_o	density (g/cm^3)
η	dynamic viscosity (Pa s)
h_o	minimum film thickness (m)
R'	reduced radius of curvature (m)
E'	reduced Young's modulus (Pa s)
N	normal load (N)
v	sliding speed (m/s)
V	volume loss of the pin (m^3)
h	height of the worn part of the pin tip (m)
d	diameter of the wear scar (m)
s	sliding distance (m)

2. Experimental set-up

2.1. Pin-on-disc equipment

Sliding part of the gear tooth contact was simulated by pure sliding of pin-on-disc equipment. Pin-on-disc equipment as shown in Fig. 1 comprised a horizontal rotating disc and vertical pin. The tip of the pin was half sphere with diameter of 10 mm. Friction force was measured by a load cell and recorded automatically.

Here the load was set to 7 N. All specimens were cleaned in an ultrasonic bath, first in heptane, then in methanol, and dried finally with temperature of 100 °C before experiment. Filtered lubricant with ambient temperature was supplied between pin and disc contact by a pneumatic system with a syringe and brush. Note that this test set-up is the same as in previous studies [9,13].

2.2. The test specimens

The pin and disc specimens were manufactured from three gear materials: one standard gear steel (16MnCr5) and two kinds of PM materials (Distaloy AQ+0.2% C and Astaloy CrA+1.8% Cr). The chemical compositions of RS and AQ are the same as that of [9] CrA has 97.6% of Fe, 0.6% C and 1.8% Cr. RS, AQ, and CrA will be used in the remainder of this paper to identify 16MnCr5 (RS), Distaloy AQ +0.2% C (AQ), and Astaloy CrA+1.8% Cr (CrA). Both AQ and CrA specimens were sintered for 45 min at 1250 °C in 90% nitrogen and 10% hydrogen atmosphere. All specimens were case hardened; CrA through low pressure carburizing, the others through gas carburizing. Different densities were achieved by using different pressures. AQ1/2/3 and CrA1/2/3 will be used to identify densities of 6.8, 7 and 7.25 g/cm^3 of AQ and CrA specimens respectively. Different densities were used in order to obtain different size distributions of porosities. The standard gear steel, 16MnCr5, is well-known wrought steel with Young's modulus of 210 and Poisson's ratio of 0.3. Sintered steels are porous, their density decide their mechanical properties. The elastic properties of PM materials are calculated according to Beiss [14].

$$E=E_o(\rho/\rho_o)^{3.4} \quad (1)$$

$$\nu = (\rho/\rho_o)^{0.16}(1-\nu_o)-1 \quad (2)$$

where ρ_o, E_o, and ν_o are the density, Young's modulus, and Poisson's ratio, respectively, of solid steel. For PM materials with the three different densities, the Young's modulus varies between 138 and 154 GPa. As shown in Fig. 2 the pin tip was in half sphere with diameter of 10 mm. The radius of disc was 100 mm. The lubricant used was BP Castrol Syntrans 75W-80. 3D surface roughness all test specimen were measured using a Taylor Hobson Form Talysurf in order to calculate the film parameters. The 3D surface roughness parameters (S_a) of pin and disc are 0.09 and 0.06 respectively. The details of the calculation of film parameters as well as the lubricant characteristics can be found in Li et al. [13]. Both the pin surface and the disc are ground, so the porosities on the tip of new pins are closed by grinding. And if the role of grinding enables any surface densification will be studied in the next step.

The hardness of the tip of the new pin and the hardness of surface of new disc specimen were measured (HV 0.1). Here the hardness was measured at five points that were distributed evenly across the surface of specimens to a depth of 0.5 mm. Fig. 3 shows the hardness of new pin and disc specimens (HV 0.1) of CrA1, CrA3, AQ1, AQ2, AQ3 and RS materials with mean value (mean value of the five points) and standard deviation. The results showed that pins of different materials and densities have nearly the same hardness. This is also true for the discs.

Fig. 4 shows the porosity structure of AQ and CrA specimens with different densities. Note that all the statistics result come from image analysis of the cross section of specimens and this maybe deviate from the real value. Fig. 4a–e show the porosity structure of the pins, while a′-e′ show the disc porosity. Note that there are numerous pores both on the surface and in the bulk of PM specimens. From Fig. 4 we can see that the number and size of the porosities decrease as the density increases for both pins and discs. In order to fully study the influences of the porosity of PM gear materials on wear and friction reduction, porosity structure statistics was obtained using Leica QWin software. This process takes a picture at 10 times magnification and measures the porosity characteristics using the software, then moves the sample automatically to an adjacent area, photographing and calculating characteristics until the whole surface is covered. For example, Table 1 shows the important parameters of the porosity structure statistics for the AQ1 pin at all 25 areas of the pin. The same statistics were also calculated for the AQ2, AQ3, CrA1 and CrA3 specimens. In Table 1 Med-porarea is the average area of the pores in the measured field; Max porarea is the area of the largest pore in the measured field; Med-length is the average of the linear dimension of the pores; Max length is the largest linear dimension of all pores; Field area is the percentage of surface covered by pores; Measured area is the total area covered in that particular picture; Tot-pore is the total number of pores for each picture. Summing the individual pictures (frames) for the AQ1 pin yields a total measured area of 27.82 mm^2, and there are altogether 239,915 porosities.

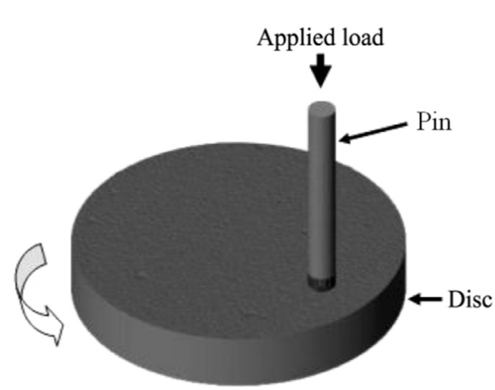

Fig. 1. Configuration of the pin-on-disc equipment [9].