Tribological Performance of Ordered Mesoporous Carbons in Mineral Oils Under Boundary Lubricated Sliding

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Abstract The tribological performance of ordered mesoporous carbons (CMK-3) as lubricant additives is investigated at ambient temperature. The effects of CMK-3 on the frictional forces, wear amounts and cycles to scuffing are measured using a ball-on-disk tester. It was found that there was little difference in the frictional forces and wear amounts of the oils with and without CMK-3. However, the scuffing time of the oil with CMK-3 was much longer than that of the pure mineral oil in sliding tests. CMK-3 were very effective on maintaining the oil gap and protecting the surfaces in boundary lubricated sliding.

Introduction

Boundary lubrication is one of lubrication regimes involved in mechanical components and machine elements operating under the marginally lubricated condition [1]. Researches on the boundary lubrication have been conducted predominantly under metal-metal contact conditions [2]. The most important things under boundary lubrication between two mating metal surfaces are to reduce friction and wear, and to prolong the wear-life of components [3,4]. In order to achieve these purposes, carbon materials have been introduced into the contact region. These include diamond, graphite and diamond-like carbon (DLC) materials. Recently, the tribological performance of carbon nanoparticles, such as carbon nanotubes and fullerenes, has also been reported. [5,6].

In this study, the tribological effects of ordered mesoporous carbons (CMK-3) were investigated. Ordered mesoporous carbons have a unique structure of hexagonally packed mesostructured carbons, which contains well-defined nanopores around 4 nm. These are promising materials in various applications due to their remarkable properties, such as high specific surface areas, large pore volumes, chemical inertness, and good mechanical stability [7,8]. The CMK-3 were used in mixture with mineral oils to compare the tribological characteristics with those of pure mineral oils.

Experiments

In this study, repeated pass sliding tests were carried out to measure scuffing-failure times as well as friction forces and wear rates under boundary lubricating conditions.

The CMK-3 were synthesised using the following procedure [9]. First, the carbon precursor solution was prepared by dissolving 1.25g of sucrose in the 4 g of deionized water with 0.14g of concentrated H$_2$SO$_4$. The mesopores in the 300nm silica template (0.9g) were filled with the above solution by an incipient wetness method. The mixture was dried at 373 K and subsequently at 433 K. The impregnation and drying step were repeated again using 60% amount of sucrose. In the next step, the carbonization was carried out by heating the material to 1173 K under nitrogen flow for 2h. Finally, the silica template was dissolved at room temperature using a 10% HF in ethanol solution.
As shown in Figure 1, the mean diameter of spherical CMK-3 clusters was about 300 nm. The CMK-3 consist of carbon rods arranged in a hexagonal pattern containing well-defined nanopores of about 4 nm [10].

The pure mineral oil was used as a base lubricant in this test. The CMK-3 (1wt%) were dispersed in the base lubricant through ultrasonication for 4 minutes at 490 W. No flocculation of CMK-3 was observed during the boundary lubrication without the use of dispersants.

A ball-on-disk sliding tester was used to verify the characteristics of CMK-3 on surface protection as schematically shown in Fig. 2 [11]. The signal from the transducer was stored in a computer at a sampling rate of 5Hz after digitizing it using an analog/digital converter. The stored signal was subsequently converted to the coefficient of friction by a signal processing program.

![Fig. 1. SEM image of ordered mesoporous carbon (CMK-3)](image1)

For the balls, AISI 52100 steel was used with a diameter of 10 mm. AISI 1045 steel disk specimens were used for the counter part with a diameter of 60mm and a thickness of 10mm. The surface hardness was HV1N,300. All specimens were cleaned with distilled water and acetone in an ultrasonic cleaner.

A slow sliding speed of 0.04m/s (30rpm) was applied in all tests in order to maintain the condition of boundary lubrication. The load was increased from 100N, by a step size of 100N, up to the onset of scuffing. The test was performed during three minutes at each load, which was enough for the sliding surfaces to form the protective layers. The test condition was determined to allow the gradual formation of the protective layers on sliding surfaces. The catastrophic mode of surface failure is sometimes referred to as scuffing. Usually there was a sudden increase in friction on scuffing [12]. During the tests, the scuffing failure was detected by an abrupt increase in friction. Each test was repeated more than five times.

After tests, all wear tracks were analyzed by a surface profiler (Tencor Alpaha-Step 500). The structural deformation of CMK-3 was investigated using an X-ray diffractometer (XRD). XRD patterns of CMK-3 were obtained by the Rigaku D/MAX2200 XRD with Cu Kα radiation. The XRD experiments were conducted at 20 kV and 30 mA

![Fig. 2. A Schematic diagram of the ball-on-disk type sliding wear tester](image2)

**Results and Discussion**

The repeated pass sliding tests with the ball-on-disk type tester were carried out to measure the friction forces and wear amounts as well as scuffing-failure times. Figure 3 shows the results of scuffing tests. The loads were increased from 100N with a step size of 100N up to the onset of scuffing. In case of tests with the pure mineral oil, the friction coefficients show uniform values of about 0.12 and scuffing occurred at the load of 1200N. The mineral oil with CMK-3 shows almost same values of friction coefficients as those of pure mineral oils, but the sliding surface survived up to the load of 3000N.
To investigate the role of CMK-3 on wear tracks, the loads were increased from 100N with a step size of 100N up to 700N, at which scuffing did not happen on sliding surfaces. The lubrication tests were stopped at 700N, and the sliding surfaces were analyzed with a surface profiler. Figure 4 shows almost same amounts of plastic deformation on wear tracks for both samples. Even though there was little difference in wear tracks, the load carrying capacity of the oil with CMK-3 was much larger than that of the pure mineral oil.

Figure 5 shows the X-ray diffraction (XRD) patterns of CMK-3 before and after the lubrication tests. Before the tests, the CMK-3 exhibited a sharp low-angle reflection which is the characteristic of 2-D hexagonal carbon structures [10,13]. However, the sharp peak disappeared after the scuffing failure. This is indicative of the structure deformation of 2-D hexagonal carbon structures of CMK-3 during the sliding tests.

Various mechanisms have been proposed for the favorable effects of carbon nanoparticles on tribological properties. The self-lubricating properties of carbon can lead to the decrease in wear loss [14]. Especially for the improved tribological properties of carbon nanotubes, Chen et al.
attributed the improvement to the strong mechanical properties and unique hollow cylindrical structure of nanotubes [15]. Joly-Pottuz et al. related the improvement in tribological properties of carbon nanotubes to the structural deformation of nanotubes during the sliding tests [5]. We also observed the structural deformation of CMK-3 during the sliding tests. However, it is not still clear whether the deformed amorphous carbon served as a protective layer or the spherical, mesoporous carbon structure contributes to the improved tribological behavior.

Conclusions

In order to investigate the tribological characteristics of CMK-3 as lubricant additives, the ball-on-disk type sliding tests were performed in boundary lubricated environments. These results suggested the following conclusions:

1) The mineral oils with and without CMK-3 showed almost same values of friction coefficients and wear amounts. Even though there was little difference in wear tracks, the load carrying capacity of the oil with CMK-3 was much greater than that of the pure mineral oil. The scuffing time of the oil with CMK-3 was much longer than that of the pure mineral oil.

2) Before the lubrication tests, the mesoporous carbons exhibited an ordered X-ray diffraction peak, demonstrating highly ordered pore arrangements. After the scuffing failure at the load of 3000 N, the peak disappeared indicating the structural deformation of CMK-3 during the sliding tests.

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References