Springer

KSME

Journal of Mechanical Science and Technology 24 (8) (2010) 1631~1635
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-010-0508-z

Comparison of tribological characteristics between aluminum alloys and polytetrafluoroethylene composites journal bearings under mineral oil lubrication †

Boncheol Ku[1], Youngdo Park[1], Chiun Sung[1], Youngchul Han[1], Junghoon Park[1], Yujin Hwang[1], Jungeun Lee[1], Jaekeun Lee[1], Hyeongseok Kim[2], Sungyoung Ahn[2] and Soo Hyung Kim[3,*]

[1]*School of Mechanical Engineering, Pusan National University, Busan, 609-735, Korea*
[2]*Digital Appliance Research Laboratory, LG Electronics Inc., Seoul, 153-802, Korea*
[3]*Department of Nanosystem and Nanoprocess Engineering, Pusan National University, Busan, 609-735, Korea*

(Manuscript Received August 12, 2009; Revised February 10, 2010; Accepted March 25, 2010)

Abstract

This study examined the tribological behavior of journal bearings made from polytetrafluoroethylene (PTFE) composites and aluminum (Al) alloys. The PTFE composite journal bearings consisted of a steel backing with a thickness of 1.6 mm, a middle layer of sintered porous bronze with a thickness of 0.24～0.27 mm, and a surface layer of PTFE filled with fluorinated ethylene propylene (FEP) powder and carbon fibers with a thickness 0.06～0.14 mm. The other was an aluminum alloy journal bearing consisted of a steel backing with a thickness of 1.5 mm and a surface layer of an Al-6Sn-6Si alloy with a thickness 0.35～0.75 mm. A series of lubrication tests were performed using a journal bearing tester under various normal loads. The tribological properties for each journal bearing were evaluated by measuring the lubricant oil temperature and friction coefficient as a function of the applied normal load. In addition, the chemical compositions and microstructures of the journal bearing materials used in this study was analyzed by inductively coupled plasma (ICP), optical microscopy (OM), and scanning electron microscopy (SEM), respectively. The experimental results showed that the Al alloy journal bearings reduce the friction coefficient by 28 % compared to the PTFE composites bearings. In addition, the Al alloy journal bearing worked properly at the maximum load of ~ 8,000 N without adhesion. However, the PTFE composite journal bearings exhibited strong adhesion at the loads ranging from 6300 to 8000 N. This suggests that the Al alloy is a more promising material in journal bearings than PTFE composites.

Keywords: Al alloy bearing; Friction coefficient; Journal bearing; PTFE composite bearing

1. Introduction

Journal bearings have the advantage of being more accurate in rotational motion applications than ball bearings. In the case of room air conditioners, most scroll compressors are equipped with a main bearing and an eccentric bearing, which support the crankshaft. The loss of energy efficiency in the compressors is due mainly to the friction loss in the bearings. Therefore, it is very important to reduce the friction loss of bearings used in the mechanical systems.

In order to reduce friction and severe wear between the frictional surfaces in various machines, selecting the appropriate sliding materials is very important. One of the representative sliding materials is PTFE-based composites. PTFE composites are often used to make journal bearings in compressors because they have the advantages of self-lubrication and strong wear resistance. However, they also have several disadvantages, such as low mechanical strength, low thermal conductivity, and coarse surface roughness [1, 2]. In order to overcome those disadvantages of PTFE-based composites, one often selects another promising material with the Al alloys, which have excellent resistance, superior corrosion and fatigue resistance, excellent thermal conductivity, low density and moderate cost effectiveness. However, Al alloys also have the disadvantages of relatively low hardness and poor chemical resistance. In addition, Al alloys experience severe wears, even at modest load, which limits their applications. Accordingly, considerable effort has been made to improve the tribological behavior of Al alloys in view of the tribological material design and specific lubricant formulations [3-5]. Various types of Al alloys with microstructures (e.g., Al matrix with either soft Sn or strong Si microparticles) were tested. The soft Sn phase guest materials embedded in the host Al matrix can provide an easily sheared surface layer with excellent anti-friction performance, while the hard Si phase guest materials embedded in the host Al matrix can endure the

† This paper was recommended for publication in revised form by Associate Editor In-Ha Sung
* Corresponding author. Tel.: +82 55 350 5287, Fax.: +82 55 350 5683
E-mail address: sookim@pusan.ac.kr

strong normal loads with excellent wear resistance [6].

The performance and reliability of journal bearings are also strongly dependent on the lubrication conditions. When a lubricant film (i.e., hydrodynamic lubrication regime) with sufficient thickness is formed between the shaft and bearing, bearings work in a stabilized manner. However, bearings are often damaged when there is a broken lubricant film, which results from the application of unacceptably high loads or shaft revolution speeds. This causes partial contact between shaft and bearing, which is called the boundary lubrication regime [7] so that the friction coefficient of the contacting surfaces is increased significantly with increasing normal load. Therefore, maintaining the hydrodynamic lubrication regime in journal bearing operations is very important for decreasing the magnitude of friction and wear.

Generally, the friction coefficient of pure PTFE is lower than that of pure Al-100Cr6 in dry rubbing conditions. In the dry rubbing between metal-metal contacts, adhesion occurs with accompanying high friction coefficients and wear rates. In order to illustrate the adhesion effect on the dry rubbing between metal-metal contacts, some material pairs were tested in a pin-on-ring tribometer, which is the one of thrust bearing types. The test conditions for extracting friction coefficients in the pin-on-ring tribometer are given by a normal load of 100 N, a rubbing speed of 1 m/s, and duration of 30 min in dry contact (i.e., air). This indicates that the dry lubrication condition is located in the boundary regime [8, 9]. However, we had little information about the tribological characteristics of new journal bearings made from PTFE composites and Al alloys under the oil-lubricated friction.

This study examined the tribological characteristics of new journal bearings made from PTFE composites and Al alloys under the operating conditions of various compressors. In this study, a new journal bearing tester was constructed to determine the tribological properties of both PTFE composites- and Al alloy-based journal bearings. A series of lubrication tests were carried out under various normal loads in the journal bearing tester. The tribological properties were evaluated by measuring the friction surface temperature and friction coefficient as a function of the applied normal load. The chemical compositions and microstructures of the PTFE composite and Al alloy journal bearings were analyzed by inductively coupled plasma (ICP), optical microscopy (OM), and scanning electron microscopy (SEM).

2. Experimental

2.1 Materials of journal bearings

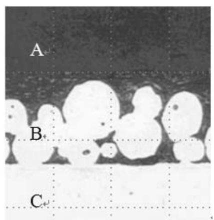
The crank shaft used in this study was SUM 32 (resulfurized free cutting steel, Korea Standard D 3567-02), which was composed of C (0.12 ~ 0.20 wt%), Mn (0.60 ~ 1.10 wt%), P (< 0.040 wt%) and S (0.10 ~ 0.20 wt%). The carburizing heat treatment on the crankshaft was carried out at 930 ºC, which resulted in a tempered martensite transformation. The depth of the heat treatment was approximately 1.2 mm under the surface, and the Vickers hardness (Hv) was 600 ~ 700 at a depth of ~ 0.5 mm. The surface roughness, Rz (ten point height), was ~ 0.8 µm. The crankshaft was prepared by machining to the shape of the real operating parts, 32.5 mm in diameter and 35 mm in sliding length.

The bearing used in this study was the PTFE composites, which consisted of a steel backing (SPCC: cold rolled mild steel), a middle layer of sintered porous bronze and a surface layer of PTFE filled with FEP powder and carbon fibers. The compositions of the steel backing were 0.11 wt% C, 0.36 wt% Mn, 0.02 wt% P, and 0.005 wt% S with the balance consisting of Fe. The steel backing was 1.6 mm thick to increase the mechanical strength and minimize the coefficient of thermal expansion. The middle layer was composed of 10 wt% Sn and 90 wt% Cu with a thickness of 0.24 ~ 0.27 mm to prevent separation of the surface layer from the steel backing, and to avoid contact between the steel backings and counter face.

A 0.06 ~ 0.14 mm thick surface layer was formed to increase the heat resistance and minimize friction loss.

Table 1 shows the composition and components of the PTFE composite bearing used in the journal bearing of a scroll compressor. It has a surface roughness, Rz, of ~ 16 µm, an operating temperature ranging from -200 ℃ to 280 ℃, and a limiting pressure-velocity value (PV) of 490 MPa·m/min. The bearing was pre-pared to the shape of real operating parts,

Table 1. Composition and components of the PTFE composite journal bearings used in a scroll compressor.



Layer		Composition
A	Resin	PTFE+FEP+Carbon Fiber+Sn
B	Alloy	90Cu+10Sn
C	Steel	SPCC

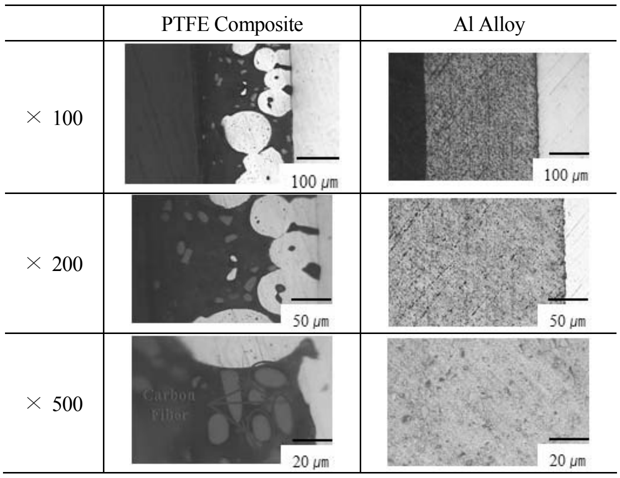


Fig. 1. Micrographs of the profile structure of the PTFE composite and Al alloy journal bearings observed by optical microscopy and scanning electron microscopy before the friction test.

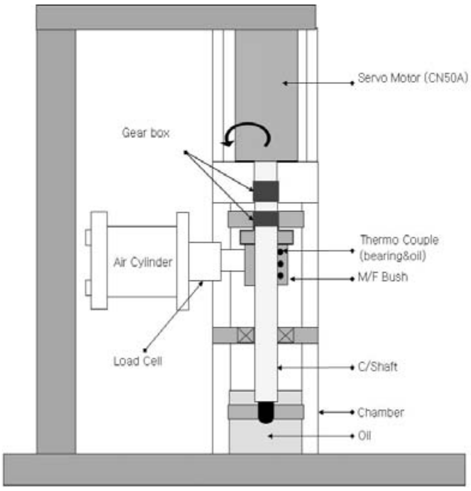


Fig. 2. Schematic of the journal bearing tester for evaluating the friction performance.

32.5 mm in diameter and 35 mm in sliding length.

The Al alloys used in this study consisted of a ~ 1.5 mm thick steel backing with a surface layer of Al-6Sn-6Si alloy. The compositions of the steel backing were 0.11 wt% C, 0.36 wt% Mn, 0.02 wt% P, and 0.005 wt% S, with the balance consisting of Fe. The compositions of the 0.35 ~ 0.75 mm thick surface layer were 5.03 wt% Sn, 5.31 wt% Si, and 0.96 wt% Cu, with the balance consisting of Al. The alloy had a surface roughness of ~ 1 μm. The Al alloys were prepared by machining to the shape of real operating parts, 32.5 mm in diameter and 35 mm in sliding length. Fig. 1 shows OM and SEM images of the structures of the PTFE composite and Al alloy journal bearings before the friction test. The PTFE composites had PTFE, Cu-Sn, steel layers and carbon fibers. In the structures of the Al alloy journal bearing, the white phase was the Al matrix, the eutectic Si was sparkling and spherical, and the gray Sn phase was distributed uniformly.

Tribological test conditions for extracting the friction coefficients of PTFE composites and Al alloys are given by a normal load of ~ 8,000 N with a holding time of 30 minutes, a rotating speed of 2 m/s, and a radial clearance of journal bearings of 60 μm. The lubrication oil used in this study was a mineral oil with a viscosity of 10 mm^2/s at 40 ºC (HTS 60MT, JOMO, Japan). Every lubrication test started with a 10 min aging step under the load of 100 N. Before each lubrication test, the initial temperature of the lubrication oil was maintained at 60 ºC.

2.2 Journal bearing tester

Bench-scale journal bearing testing equipment was constructed to observe the frictional performance and wear features of the various journal bearings. Fig. 2 shows a schematic diagram of the journal bearing tester, which was composed of a power source, power delivery, testing section, load applier, temperature measuring section, and friction coefficient measuring section. A load was applied using an air cylinder system and controlled by a proportional-integral-derivative (PID) controller, which controls the air pressure with high accuracy. The magnitude of the normal load was measured using a load cell installed under the air cylinder, and the rotating speed of the crankshaft was controlled by the inverter of a servomotor. The lubricant oil contained in the chamber was applied to the bearings by shaft rotation. The oil applied to the journal bearings finally returns to the oil storage section by gravity. The rotational speed of the servo motor was fixed to 3,600 rpm, which is equivalent to the standard 60 Hz compressor in an air conditioner. The load was controlled from 0 to 8,000 N in 500 N increments. The temperature of the lubrication oil on the surface of the crankshaft and bearings was measured by puncturing the bearing surface and inserting a K-type thermocouple. Fig. 2 shows that the shaft connected to the gear box was rotated by the servo motor. The load cell was designed to apply a normal force to the journal bearings. The friction coefficient can be calculated using the magnitude of torque at each applied load.

The torque (T) is proportional to the input current to the servo motor as follows:

$$T = K_T \cdot I \tag{1}$$

where K_T is a constant for the servo motor torque [N·m/A], and I is the incoming current of the servo motor [A].

The torque of the shaft related to friction is also proportional to the load of the bearings as follows:

$$T = \mu \cdot F \cdot R \tag{2}$$

where μ is the friction coefficient, F is the bearing load [N], and R is the bearing radius [mm]. The friction coefficient can be calculated by combining Eqs. 1 and 2 as follows:

$$\mu = \frac{K_T \cdot I}{F \cdot R} \tag{3}$$

Depending on the lubrication regime, different surface interaction mechanisms can occur between friction surfaces, which results in distinct wear and friction responses. Generally, the friction coefficient can be characterized as a function of the ηN/F factor (i.e., Sommerfeld number) in the Stribeck diagram [7]. The Sommerfeld number is defined as follows [10]:

$$So = \frac{2 \cdot \rho \cdot \eta \cdot N \cdot R \cdot L}{F} \left(\frac{R}{C}\right)^2 \tag{4}$$

where ρ is the oil density [kg/m^3], η is the oil viscosity [m^2/s], N is the rotation speed of the servo motor [Hz], L is the bearing length [m] and C is the bearing clearance [μm].

3. Results and discussion

Fig. 3 shows the evolution of the oil temperature of the

PTFE composite- and Al alloy-journal bearings on the crankshaft as a function of the normal load. The oil temperatures of both journal bearings increased with increasing normal load. When two surfaces come into sliding contact, the frictional heat produced at the interface increases the temperature of the lubricant oil. It should be noted that the temperature of the lubricant oil of the PTFE composites journal bearings was much higher than that of the Al alloy journal bearings. This is because PTFE composites journal bearings have higher surface roughness and asperities of the exposed carbon fibers than the Al alloy journal bearings. In practice, the bearings of Al alloys and PTFE composite are machined to meet specifications of inner diameter roundness. The Al alloy journal bearing has much lower surface roughness (i.e., Rz= 1μm) than the PTFE composite journal bearing (i.e., Rz= 16μm) whose fillers are pulled out from the matrix. Fig. 4a presents the evolution of the friction coefficients for both PTFE composite- and Al alloy-journal bearings on the crankshaft as a function of the normal load. The friction coefficients of both PTFE composites- and Al alloy-based journal bearings decreased with increasing normal load, indicating that it is in the hydrodynamic lubrication regime [7, 11]. It was also noted that the friction coefficient of the Al alloy journal bearing was ~ 28% lower than that of the PTFE composites journal bearing at loads up to ~ 6,300 N. The shear response of fluids is a key factor in controlling the friction between the sliding parts in hydrodynamic conditions formed by oil lubrication. The wear rate of pure PTFE can be reduced by the addition of hard fillers. In order to decrease the friction and the wear of pure Al, Al alloys contain two or more phases of soft (Sn) and harder (Si). The increased temperature occurred by rough surface and fillers (see Fig. 1) exposed would result in the reduction of mechanical strength and load carrying capacity of PTFE. Therefore, Al alloy journal bearings reduce the friction coefficient by 28% and increase the energy efficiency ratio by 0.5 % compared with the PTFE composites bearings. In order to identify the critical load, which makes partial contact between the crank shaft and journal bearings, both Al alloy- and PTFE composites-journal bearings were tested by increasing the normal load to ~ 8,000 N. The critical load of the Al alloy journal bearings was ~ 8,000 N, while that of the PTFE composite journal bearing was ~ 6,300 N. It suggests that Al alloy journal bearings have better tribological behavior and wear resistance in shaft-bearing rotating system than PTFE composites journal bearings.

Fig. 4(b) shows the Stribeck curve of the PTFE composite- and Al alloy-journal bearings on the crankshaft as a function of the normal load at a fixed rotational speed of 3,600 rpm. The friction coefficient of the PTFE journal bearings decreased with increasing normal load to a Sommerfeld number of ~ 0.014 determined by Eq. 4 with a normal force of 6,300 N. However, after the normal load was increased to more than 6,300 N, the friction coefficient began to increase suddenly with further increases in applied normal load.

This suggests that the lubrication regime had finally transformed into a boundary lubrication regime from a hydrodynamic and mixed lubrication regime due to local contact between the rough surfaces of the sliding parts (i.e., Rz= 16 μm) and the viscoelastic deformation of the PTFE composites resulting from the significant increase in temperature. In the mixed lubrication regime around the lowest friction coeffi-

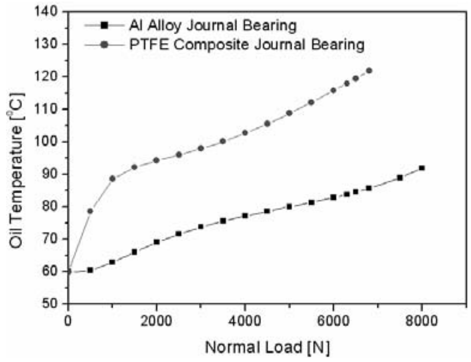
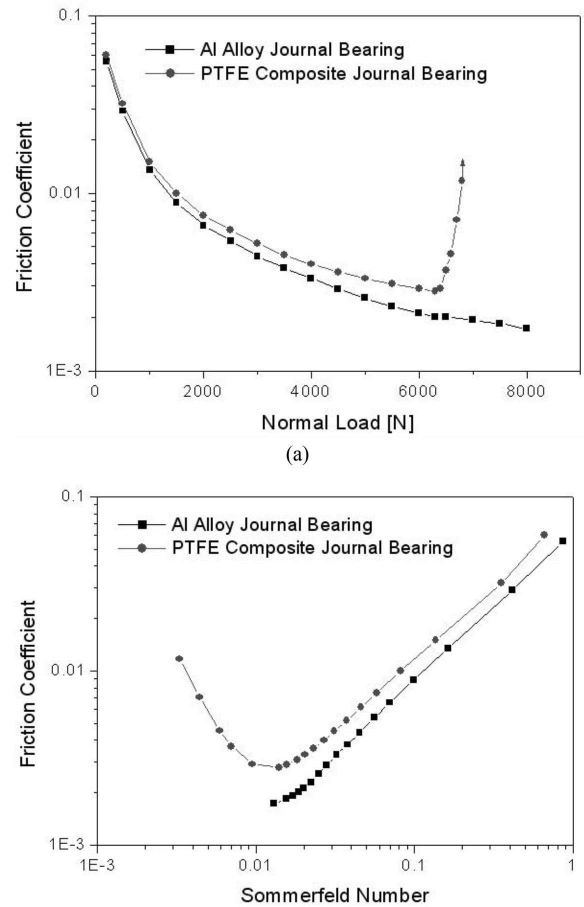


Fig. 3. Change in oil temperature of the PTFE composite- and Al alloy-journal bearings on the crankshaft as a function of the applied normal load in the journal bearing tester.



(a)

(b)

Fig. 4. (a) Results of the step-load test for evaluating the load limit and (b) Stribeck curve of the PTFE composite and Al alloy journal bearings on the crankshaft as a function of the normal load using the journal bearing tester.

cient, the thickness of an oil film must be reduced because metal-to-metal contact with increasing load causes a rapid increase in lubricant temperature. This subsequently causes the formation of rough asperities of the PTFE composite journal bearings. After the repetition of severe coarse friction, there was a sudden increase in friction coefficient and finally the PTFE journal bearing was stuck completely at some point due to mechanical bonding or local welding between the roughness peaks of the sliding parts [12]. Unlike the PTFE journal bearing, the friction coefficient of the Al alloy journal bearings (Fig. 4b) decreased continuously without turning into a boundary lubrication regime due to the presence of a relatively low surface roughness (i.e., Rz= 1 μm). This suggests that the friction performance of Al alloy journal bearings is much better than that of the PTFE composites journal bearings with increasing normal load.

4. Conclusions

This study examined the tribological characteristics of journal bearings made from PTFE composites and an Al alloy under a variety of compressor operating conditions. A series of lubrication tests were carried using a journal bearing tester under various normal loads. As a result, the Al alloy journal bearing showed much better friction performance than the PTFE composite journal bearing. In particular, the friction coefficient of the Al alloy journal bearing was ~ 28% lower than that of the PTFE composite journal bearing at a normal load range of ~ 6,300 N. Even the Al alloy journal bearing worked properly at a normal load of 6,300 ~ 8,000 N, whereas the PTFE composite journal bearing was stuck due to severe friction as a result of the coarse surface and subsequent viscoelastic deformation of the PTFE composite. This suggests that the proper selection of bearing materials and optimum operating conditions are very important for the tribological characteristics of journal bearings in the scroll compressors.

Acknowledgment

This study is supported financially by LG Electronics Inc., Korea and the authors gratefully acknowledge this financial support. The authors also would like to thank AC Research Laboratory of LGE for their cooperation in carrying out this work and for their permission to publish the results of this research.

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Soo Hyung Kim received his B.S. degree from Pusan National University, M.S. degree from Gwangju Institute of Science and Technology, and Ph.D. degree from University of Minnesota. He is currently an Assistant Professor in the Department of Nanosystem and Nanoprocess Engineering of Pusan National University in Korea. His research fields are synthesis and characterization of nanostructured materials and their applications into nanofluids-based energy systems.

Bon Cheol Ku received his B.S. and M.S. degree from Pusan National University, Korea in 1984 and 1998, respectively. He is currently a Ph.D. student of the department of mechanical engineering of Pusan National University, Korea. His research fields are tribology, compressor and cogeneration.