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Wear of hybrid radial bearings (PEEK ring-PTFE retainer and alumina balls) under dry rolling contact

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ABSTRACT

Wear of poly ether-ether-ketone (PEEK) radial ball bearing (composed of PEEK ring, PTFE composite retainer and alumina balls) was investigated. The PEEK radial bearings were produced by lathe machining, and their rolling contact wear tests were carried out at high rotational speed in dry condition. The PEEK adhesion film including PTFE and graphite wear particles was observed on the raceway of the bearing's inner ring during the test. Due to the PEEK–PTFE adhesion film accumulation, the wear rate decreased to one tenth of all-PEEK bearing. Moreover alumina balls were not stuck, and the operation temperature was less than glass transition temperature of PEEK. It was found that the PEEK–PTFE adhesion film improved dramatically wear and rotational performance of the bearing.

1. Introduction

Nowadays premium plastic frictional parts of lightweight and custom-made for low-volume production are expected in various assemblies or equipment such as bearings, joints, food conveyor, semiconductor, car elements, pump parts etc. under dry, steam and chemical environments [1–3]. These mechanical components are often used under cyclic stress. In polymer and polymer composite material parts under friction, the severe wear influences their stable operation. Since Friedrich et al. [4] stated that the most important points of their component design are mechanical stresses and environments, some researchers investigated various polymer/composite materials for maintenance improvement of the frictional parts in special environments such as dirty, harmful, acid or alkaline situations [5,6].

Tribological performance of poly ether-ether-ketone (PEEK) and poly tetra-fluoro-ethylene (PTFE) among polymer materials has been researched extensively in the recent years to characterize their practical applications [7–9]. However, there is only a few rolling fatigue wear evaluation data of PEEK ring under cyclic high compressive stress of alumina ball [10,11]. Koike et al. reported that PEEK wear particles were caused by friction between PEEK inner ring raceway and alumina ball under cyclic high compressive stress, and PEEK adhesion film was formed between the interfaces of PEEK inner ring raceway and alumina balls at an 88 N load under dry condition. Almajid et al. presented specific wear rate at 50 N ranging from 3×10^{-7} to 6×10^{-7} $mm^3\,N^{-1}\,m^{-1}$, and the local damages such as fiber fracture or matrix disruption were observed on the wear surface in the PEEK/CF rolling wear test against 100Cr6 steel ball under loads ranging between 50 and 300 N [12]. Qiao et al. stated that in the block-on-ring wear test of PEEK blocks reinforced with nano/micro-alumina (Al_2O_3) particles on carbon steel ring, the transfer PEEK–Al_2O_3 film improved the wear durability of the PEEK–Al_2O_3 composite blocks [13]. The wear behavior of PEEK and alumina combination under dry contact at a 196 N load was better than that of PEEK and 100Cr6 steel combination [12,13]. However, Koike et al. reported PEEK film had negative affection on the wear durability. Because of a lot of PEEK film adhered to alumina balls, the alumina balls stuck to the PEEK inner ring and stopped the bearing rotation [11]. In a plastic bearing under cyclic high compressive stress, the severe wear, melting or seizure on the bearing raceway are caused by friction heat and overloading. This means that a suitable load of polymer bearing is generally lower than that of ceramic or steel bearings.

When no film at the interface between a sliding polymer and its metallic counterpart, severe wear is generally promoted [5].

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Voort et al. proposed that adhesion of the transfer film to a pin face protected its surface from wear. They also stated that in a pin-on-disk wear test of PEEK/PEEK–CuS–PTFE composite pin and AISI 02 tool steel disk, bonding between PEEK transfer film and the disk substrate increased the wear durability due to chemical reactions occurring between the PEEK pin and the steel disk [14,15]. Bahadur et al. studied the wear of PEEK and PTFE transfer film under sliding conditions against a steel disk, and revealed that the wear resistance increased by the adhesion between them [16]. Yamada reported fragmentary PTFE transfer films appeared on the polyacetal disk in PTFE pin-polyacetal disk wear test and PTFE transfer film decreased wear rate [17]. Additionally, PTFE or graphite particles reduced the coefficient of friction and improved the thermal failure such as scuffing or seizure [18,19]. Friedrich et al. presented that in a pin-on-disk test using PEEK including PTFE and graphite filler, PTFE and graphite improved the PEEK tribological performance [20].

Although the transfer films are extensively investigated, the relation between, PEEK, PTFE and alumina balls in polymer bearings is not understood well. In the paper, the PEEK ring and PTFE composite retainer of bearings were produced by using a lathe machine, and the rolling contact wear tests of the custom-made PEEK–PTFE–alumina ball bearings were performed, in order to investigate the PEEK–PTFE adhesion film formation mechanism and wear resistance in the bearings. The adhesion film, specific wear rate, and operation temperature on the bearing were measured.

2. Experimental procedure

2.1. PEEK/PTFE Hybrid bearing samples

Fig. 1a and b shows the hybrid bearing specimen. Rolling contact wear tests were performed on single raceway radial 9-ball bearings. The bearing's inner rings and outer rings were machined from a PEEK shaft (VICTREX®, grade: 450G). PEEK has a high glass transition temperature of 143 °C, good wear and heat resistances, and can be easily machined. Retainers were produced from PTFE composite shaft (Du Pont-Mitsui Fluor chemicals), containing 25% graphite and 75% PTFE. Alumina balls were acquired from Industrial Tectonics Inc. Alumina has a high hardness of 1500 HV, a melting point over 2000 °C and a good wear durability. The specimen dimensions are shown in Table 1. Microgrooves on the raceway were made by machinery cutting at 0.12 mm/revolution feed rate and 800 rpm rotating speed. After cutting of the inner ring's raceway, the microgrooves in the raceway were formed and their average roughness (R_a) was 1.4 µm (Rz 27.0 µm). R_a was measured by ISO4287. The PEEK inner ring raceway surface profiles were measured before and after RCF testing. All samples prior to and after the test were measured by Fourier Transform Infrared Spectroscopy (FT-IR), in order to investigate tribo-chemical reaction by cyclic stress and frictional heat. Clear peaks such as the ether group peak (1305 cm^{-1} or 1280 cm^{-1}), the carbonyl group peak (1730 cm^{-1}), the K-phenyl group peak (1491 cm^{-1}), and the di-phenyl group (1215 cm^{-1}) were compared to the results of Ref. [21]. Chemical composition of the transfer film on the inner ring raceway surface after the test was investigated by means of X-ray photo-electron spectroscopy (PHI-Quantera SXM from Ulvac-Phi. Inc.). The excitation source was Al-Kα radiation ($h\nu$=1486.6 eV). The peak positions were determined with reference to the carbon at 284.8 eV. The fluorine binding energy peak (F(1s)=688.5–689 eV) and phenyl C bonded to O in PEEK (C(1s)= 285.9 eV) were compared to the results from Ref. [17,22].

2.2. Rolling contact wear

Fig. 2a shows the schematic illustration of a rolling contact wear test machine. Weight is suspended on an arm, opposite side to the test sample. The outer ring of a bearing was set in a SUS304 (304 stainless steel; AISI304) fixture in an upward radial load direction (Fig. 2b). The inner ring of the bearing was placed on a 17 mm-diameter stainless steel shaft and fixed by collars. There are two types of wear in PEEK ring-alumina ball bearing using PTFE composite retainer as shown in Fig. 2c. One is the wear between the alumina balls and the PTFE retainer, and the other is between the alumina balls and the PEEK ring. It is well known that failure of the radial ball bearing under cyclic high stress and at high speed rotation is caused by the slip of ball on the contact surface. Stolarski stated that the contact between the rolling elements and the rings consists of sliding rather than actual rolling [3]. In the present research, the tests were performed under radial loads (F_{load} as shown in Fig. 2b) ranging from 88 N to 284 N at 600–3000 rpm rotation speed (1.0–5.0030 ms^{-1} sliding velocity). The sample was removed from the wear test machine at every 1.4×10^5 fatigue cycles. The maximum Hertzian contact stress P_{max} values were calculated to be 77 MPa and 114 MPa from Hertzian theory (Eq. 1) and Stribeck's equation (Eq. 2) when the radial loads were 88 N and 284 N.

$$P_{max}=\frac{3Q}{2\pi ab} \tag{1}$$

$$Q=5/9\times F_{load} \tag{2}$$

where Q is the maximum radial load of a ball, a is half length of the major axis of an ellipse contact area, and b is half length of the short axis. Weight of all bearing components was measured using an electronic Shimadzu balance with a 0.1 mg accuracy in order to calculate their specific wear rates. The specific wear rate W_s [mm^3 N^{-1} m^{-1}] was calculated from wear loss, using the following equation :

$$W_s=W_v/(F_{load}\times L) \tag{3}$$

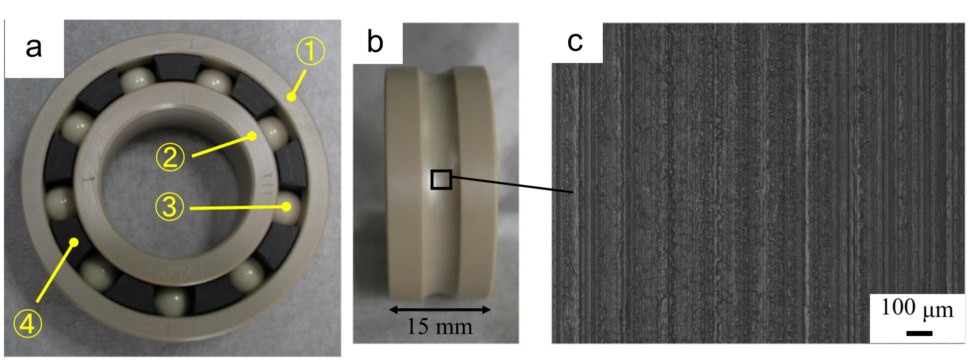

Fig. 1. (a) PEEK bearing sample; (1) outer ring, (2) inner ring, (3) alumina ball, (4) retainer, (b) bearing's inner ring prior to test: 1.5 mm width, (c) laser confocal microscope images of the microgrooves on the raceway of the bearing's inner ring by lathe machining.