Keysight Technologies
Evaluation of Bearing Materials Using Nano-Scale Wear Testing

Application Note

KEYSIGHT TECHNOLOGIES

Introduction

The most common materials for bearing fabrication are metals, such as low-carbon steel, stainless steel, chrome steel and high-speed steel. Polymeric materials are alternative candidates due to their self-lubrication ability, high impact durability, high corrosion resistance, low specific gravity, and high melting temperature. Polymers have therefore received widespread attention as new tribological materials for dry, aqueous and corrosive conditions. Among these polymeric materials, polytetrafluoroethylene (PTFE), polyether ether ketone (PEEK) and also their composites are often used in tribological applications.

In fans used for cooling of computers and other electronics, it has been found that one of the main contributors to failure is degradation of the miniature ball bearings [1], with deterioration of the lubricant as the primary failure mechanism in these applications. Due to the criticality of ball bearings, diagnosis and prognosis of these failures have been of interest to the industry. There are several techniques to detect faults in ball bearings. In 2011 Oh, et al, found a correlation between acoustic emission (AE) features and bearing degradation in computer cooling fans [2]. More recently, in 2013 Kumar, et al [3] determined the failure mechanisms of polymeric bearings using the analysis of vibration, speed and acoustic emission data, together with characterization of the worn bearing surfaces and measurements of friction.

The bearing materials tested in this work were previously evaluated [3] at a rotational speed of 4800rpm in a test fixture which supports a load of approximately 1.4N. Acoustic emissions from these bearings during the initial stages of the operation of the bearings were monitored to compare the performance of these materials. These prior results are shown in Figure 1. Throughout most of the AE test, and especially near the end, the steel bearings exhibited the fewest AE events, followed by the PEEK and the PTFE bearings. Thus, from the AE test, we would rank the materials in order of performance (from best to worst) as: bearing steel, PEEK, PTFE.

However, AE testing requires a long time. Thus, the aim of the present work is to establish a rapid assessment tool for bearing materials, where indications of the performance of the material can be known in hours, rather than days. We hypothesize that the results of nano-indentation and nano-wear testing are related directly to the results of AE testing.

Abstract

Self-lubricating polymeric materials are attractive candidates to be used as bearing materials in lightly loaded applications. In this study, miniature ball bearings made of steel, polytetrafluoroethylene (PTFE) reinforced with graphite, and polyether ether ketone (PEEK) are evaluated by means of nano-indentation and nano-wear tests. As quantified by the volume of the wear track, bearing steel has the best tribological performance, followed by the PEEK and PTFE. The volume of the wear track correlates with acoustic emissions measured during life testing. Other measurements available from a nano-wear test may indicate in-product performance; these include pile-up and the production of wear debris.

Carlos Morillo, Ranjith-Kumar Sreenilayam-Raveendran, Michael H. Azarian and Michael Pecht

CALCE (Center for Advanced Life Cycle Engineering) University of Maryland, College Park, MD 20742 USA

Experimental Procedure

Samples

Three different materials were selected for testing: bearing steel, PTFE-graphite composite, and PEEK. These are the same samples used in a previous study [3]. Samples were cut and mounted in epoxy, then ground and polished to a mirror-like finish.

Equipment

For all testing, the Keysight Technologies, Inc. G200 NanoIndenter was used, having an XP head with a Berkovich tip (20nm diameter), and the continuous stiffness measurement (CSM) option.

Indentation Testing

The test method "G Series CSM Standard Hardness, Modulus and Tip Cal method" was used for the indentation tests. As the indenter was pressed into the material, a small oscillation (45Hz, 2nm) was imposed in order to measure elastic modulus and hardness as a continuous function of penetration depth. Ten indentations were performed on each material to a peak depth of 1000nm. We used data in the range of 900–1000nm to calculate average elastic modulus and hardness for the material as a whole.

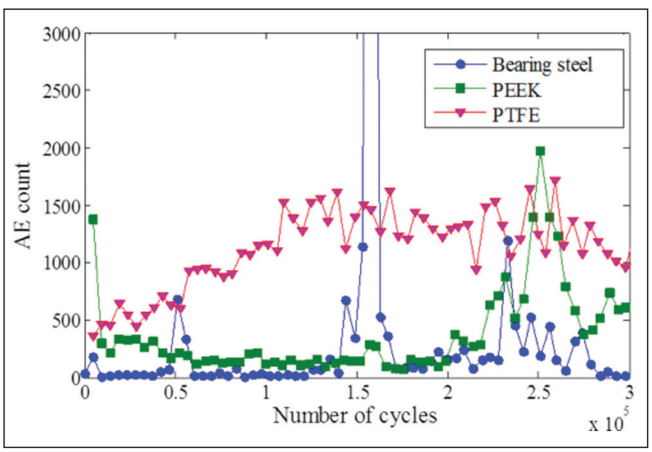

Figure 1. Acoustic emission counts for three different materials in the initial stage of the testing [3].

Figure 2. Optical images of bearing samples top view [1].

Wear Testing

The test method "G-Series Pass and Return Wear Test" used to perform one multi-pass, constant-load wear test on each sample. The chronology of a single test was as follows: The indenter profiled the original surface along the length of the anticipated wear test, then returned to its starting position (profile length = 120µm, profile force = 50µN). The indenter then performed a beginning profile (10µm, 50µN), increased the applied force to the wear load and performed the first wear pass (100µm, 20mN), then performed an ending profile (10µm, 50µN), and finally returned to its starting position to complete the first wear cycle. The beginning and ending profiles for each wear pass were used for leveling. Ten wear cycles were performed in the same way (profile, wear, profile). After the wear cycles, the indenter performed a final profile along the entire length of the wear test (120µm, 50µN), then performed a final cross-profile of the wear track (100µm, 50µN) at its midpoint. Each wear test returned measurements of scratch width, depth, deformation area, and pile-up. Post-test imaging of the wear tracks by scanning-electron microscope gave further qualitative information about each material. One wear test was performed on each sample.

Material	Modulus (GPa)	SD	Hardness (GPa)	SD
Bearing Steel	234.90	22.60	9.92	1.31
PEEK	4.40	0.40	0.18	0.02
PTFE (Carbon Filler)	16.60	2.40	3.21	0.51
PTFE (Matrix)	5.00	0.40	0.28	0.08

Table 1. Mechanical properties of bearing materials.

Results and Discussion

The mechanical properties measured by the indentation tests are shown in Table 1. The values of the bearing steel are in line with those reported in literature; also the properties for PEEK compare well with reported values [4]. Although it gives accurate results, indentation alone is not entirely adequate as a rapid evaluation tool. In the PTFE, individual indentations are not large enough to comprehend the matrix and filler together, but rather are dominated by one material or the other. Further, the ordering of materials according to their indentation properties does not clearly correlate with performance in the AE test. These limitations lead us to consider the nano-wear test, not only because of its larger scale, which encompasses the PTFE components in aggregate, but also because the test itself more closely mimics in-service exposure.

Material	Wear Deformation (µm)²	Scratch Width (µm)	Pile up (nm)	Scratch Depth (nm)
Steel Bearing	2.48	11.1	129	317
PEEK	14.1	18	774	791
PTFE Composite	43.1	58.2	206	1275

Table 2. Scratch test results of different bearing materials.

Results and Discussion *continued*

Figure 3 shows a typical cross profile from a nano-wear test. The groove of the wear track is clear, as is the pile-up caused by plastic deformation. From this profile, we quantify several aspects. We quantify “pile-up” as the average of the heights of points O and P, relative to the original surface elevation. The “scratch width” is the distance between the points O and P. The “scratch depth” is the depth of the center of the groove, relative to the original surface elevation. Finally, we approximate the cross-section of the wear track as a triangle, and define the “wear deformation” as the area of that triangle, or half the product of the scratch width and the sum of the scratch depth and pile-up height.

Figure 4 compares the cross profiles from all three bearing materials. The nano-wear test leaves the smallest wear track in the bearing steel. The PEEK shows the greatest degree of pile-up, which means that that the wear test causes material to plastically flow to the sides of the wear track. By far, the nano-wear test leaves the largest wear track in the PEEK, as evidenced by both the depth and breadth.

Table 2 summarizes the nano-wear testing results. In order of increasing wear deformation area, the nano-wear test causes us to rank these materials relative to each other as we did following the AE test: (1) bearing steel, (2) PEEK, and (3) PTFE composite. However, the nano-wear test is much faster, even with the additional sample preparation.

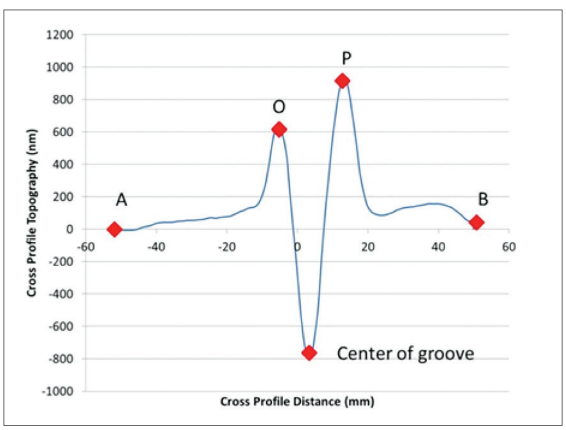

Figure 3. Cross profile of a nano-wear test.

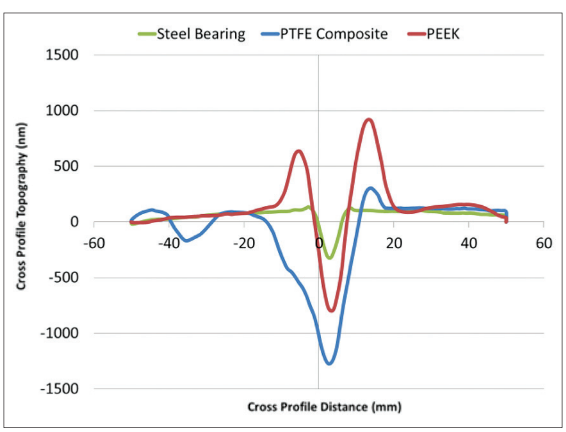

Figure 4. Comparison between the cross profile of different bearing materials.

Figure 5 compares the scanning-electron micrographs of the wear tracks on the various materials. Much qualitative information can be gained from these images. From 5(a), we see that the wear track from the PEEK has no debris. In light of the large pile-up manifest in the cross profile, we understand that the material flows plastically to the sides of the wear track, rather than shedding as debris. From 5(b) and 5(d), we see that although the wear track is smaller, the bearing steel sheds significant debris. These debris particles may be a concern for long-term performance. As this kind of debris accumulates in the lubricant, it becomes an additional source of wear, and the deterioration of the bearing may accelerate. This kind of debris may be the cause of brief spikes in the number of acoustic events during the AE test (Figure 1). Figure 5(c) helps us understand the complex deformation in the PTFE composite. The wear track is indeed very wide. When the probe is in contact with the matrix, the deformation is relatively large, but when the probe passes over the filler particle, the particle bears the load, thus reducing the interaction between the tip and the matrix. There is some debris, but it remains in the wear track.

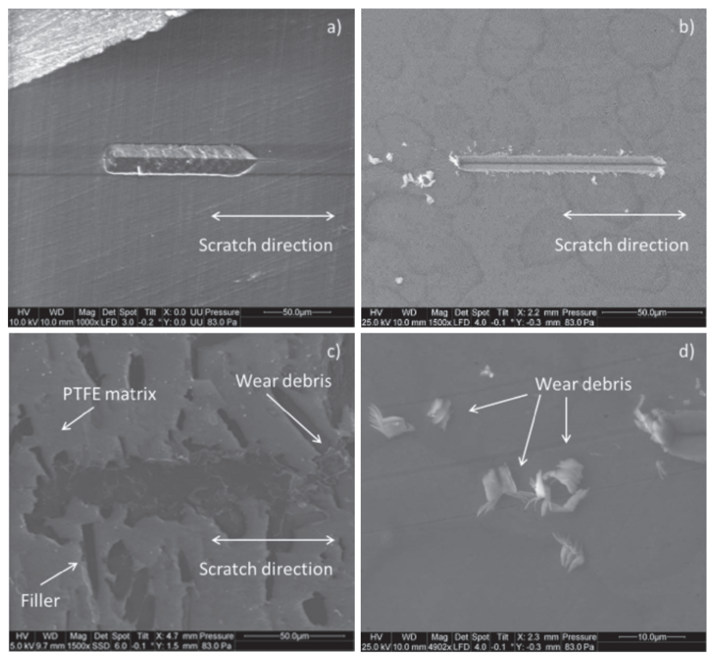

Figure 5. ESEM images of the scratch surfaces a) PEEK, b) Steel, c) PTFE, d) Steel (magnified).

Conclusions

Because bearing failures are critical in electromechanical systems, manufacturers estimate longevity using complex and time-consuming endurance tests. However, there is a need for rapid evaluation of new candidate materials. In this work, we use nano-indentation and nano-wear testing to evaluate bearing materials which were previously tested by acoustic-emission analysis. Results from the nano-indentation tests, though accurate, do not clearly correlate with results from acoustic-emission analysis. However, the cross-sectional area of the wear track caused by the nano-wear test does correlate with the results of the acoustic emission analysis. The bearing steel has the smallest wear track, followed by PEEK and a PTFE composite. Thus, we conclude that nano-wear testing can be used to quickly qualify candidate materials for bearings. Further, the nano-wear test provides additional insight into the mechanisms of deformation which are not available from the acoustic emission test. In this case, subsequent imaging of the wear track reveals that the bearing steel deformed by shedding debris, whereas the PEEK deformed without shedding debris by plastically flowing to the sides of the wear track.

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