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ABSTRACT

A 50/50 (weight percent) composite of graphite fibers and polyimide was studied in self-aligning plain bearings oscillating $\pm 15°$ at 1 Hertz. The friction coefficient was 0.15 $\pm$0.05 at 250 C, and 0.05 $\pm$0.02 at 315 C. Best results were obtained with a molded composite liner with chopped graphite fibers randomly oriented in the composite: The specific wear rate was $12 \pm 4 \times 10^{-11}$ cm^3/cm-kg. The dynamic unit load capacity was higher for a composite bushing (thin liner), 2.8×10^8 N/m^2 (40,000 psi) than for a composite ball, 6.8×10^7 N/m^2 (10,000 psi).

INTRODUCTION

Composite materials are needed for self-lubricating bearings to produce low friction, low wear and high load capacity. A composite widely used today is PTFE reinforced with dacron cloth. This composite is used as a liner in the outer race of self-aligning plain bearings. Requirements for airframe bearings of this type are given in military specifications and design handbooks (1-3). One problem is that vibratory loads tend to extrude the liner thus increasing the bearing clearance (the same effect as high wear). Also, this composite is limited to temperatures below 170 C.

A relatively new class of self-lubricating reinforced polymers, graphite fiber reinforced polyimide (GFRPI) has been shown to have good tribological properties to at least 340 C (650 F) (4,5). Composites of GFRPI were evaluated at temperatures up to 340 C (650 F) as the ball in self-aligning plain bearings in a preliminary study of various weight percent of chopped graphite fibers up to 60 percent (6). The best load capacity, up to 3.5×10^{7} N/m^{2} (5,000 psi), was obtained with about 50 percent (weight) graphite. The purpose of the present study was to evaluate the friction, wear and load capacity of different bearing configurations at temperatures from 25 to 340 C.

Tests were conducted using a self-aligning plain bearing oscillating $\pm15°$ at 1 Hertz. Friction and wear tests were made with a radial unit load of 2.85×10^{7} N/m^{2} (4130 psi) at bearing temperatures (25, 205, and 315 C) for 10^{5} oscillating cycles.

APPARATUS AND PROCEDURE

The apparatus for testing self-aligning plain bearings is shown in figure 1. The test bearing was held in a housing which can be heated by an induction coil. The journal was oscillated $\pm15°$ at 1 Hertz by a reciprocating hydraulic drive.

A slight axial load was hydraulically applied to the journal to provide alignment. The test load was pneumatically applied to the journal providing a radial load to the test bearing. Radial displacement of the journal was measured with a dial gage mounted on the shaft assembly. Friction and wear tests were made with the spherical bearing element (ball) oscillating against the outer race. Some load capacity tests were made with the journal oscillating in the bore of the ball. Bearing dynamic load capacities were determined by progressively increasing the radial load until a large increase occurred in the journal displacement or until the composite fractured. Friction force was measured by a preloaded piezo-electric load cell mounted in the drive arm. This signal, proportional to the tension and compression during the stroke, was recorded on a strip chart.

Tests on each bearing were usually conducted for 100 KC at three constant temperatures: 25 C (with some increase in bearing temperature due to frictional heating), 205 C, then 315 C (sometimes 340 C). For some tests, this sequence was reversed. Bearing wear measurements were usually made at intervals of 20 KC, 60 KC, 20 KC, (5-1/2 hours, 16-1/2 hours, 5-1/2 hours).

MATERIALS

The composite material used was a 50/50 (by weight) mixture of graphite and polyimide. The graphite was in the form of chopped fibers which were $6.4x10^{-3}$ m (0.25 in.) long by $7.6z10^{-6}$ m (0.0003 in.) diameter, had a tensile strength of $6x10^{8}$ N/m^2 (90,000 psi). The fibers were randomly dispersed throughout the polyimide matrix.

The polyimide resin is an addition-type, which does not release volatile reaction products during the polymerization reaction of the final cure. A polymerization product of the more conventional condensation type polyimides is water vapor which can cause voids in the final cured polymer. Polyeriazation chemistry and cure procedures are given in reference 7.

The sliding counter-face was 440-C-HT steel hardened to Rockwell C-60 and ground to a finish of 10^{-7} m (4 μin.).

Test Bearings

The self-aligning plain bearings used in this study are shown in figure 2. For load capacity studies, oscillation was between the journal and the bore of the ball (fig. 2(a) and 2(c)) or between the ball and the outer race (fig. 2(b)). These bearings were assembled in a two-piece outer race (the parting line 90° from the radial load direction). The small bushing was machined to have a small projected area (length times diameter) and hence a high unit load (load per projected area). For these three bearings (fig. 2(a), (b), (c), respectively), the projected areas are 302, 368, and 40 mm^2.

For friction and wear studies, oscillation was always between the ball and the outer race. Tests were made with molded composite balls (fig. 2(b)) and with molded composite liners of three types: Inserts (fig. 2(d)) filament wound (fig. 2(e)) and molded in place (fig. 2(f)).

The inserts are machined in two pieces and assembled with a steel ball into an outer race shell (fig. 2(d)). The shell consisted of two concentric pieces which were electron-beam welded to complete the bearing assembly.

Filament wound liners were made by hoop winding a continuous filament of pre-polymer-coated graphite around the steel ball, placed in the split bearing housing, and cured under heat and pressure to complete polymer chain extension and cross-linking.

The molded liners were made by filling the space between the ball and housing with randomly oriented chopped fibers in the pre-polymer and then curing under heat and pressure.

Wear Coefficient Calculation

During testing, bearing wear was indicated by journal radial displacement. Possible errors, introduced by thermal expansion and deflection of the test apparatus, were minimized by using measurements made at constant temperature and load. After testing, the weight change was measured; however, the weight loss due to wear was often masked by either weight loss due to water desorption or weight gain due to adsorption. Decrease in the composite ball diameter was also measured after testing, but no dimensional measurements were made on the composite liners.

The wear rate data (μm/KC and mg/KC) were converted to an equivalent wear coefficient, wear volume per sliding distance per load (cm^3/cm-kg).

The wear volume was calculated as the wear depth (journal displacement or diameter change) times the projected area (length times diameter) or as the weight change divided by the density (GFRPI density 1.4 g/cc). The sliding distance for one oscillating cycle ($\pm$15°) was $\Pi/3$ radians (60°) times the bearing radius. For a load of 1.05×10^4 N (2350 pounds) the resulting conversion was:

1 μm/KC = 22.6×10^{-11} cm^3/cm-kg and

1 mg/KC = 44.0×10^{-11} cm^3/cm-kg. (1 cm^3/cm-kg = 1.02×10^{-5} m^2/N)

RESULTS AND DISCUSSION

Load Capacity

The dynamic unit load capacity for chopped graphite fiber reinforced polyimide (GFRPI) composite at 25 C (fig. 3) was higher when used as a thin wall bushing (fig. 2(c)), 2.8×10^8 N/m^2 (40,000 psi), than when used as a molded ball (fig. 2(a) and (b)), 6.9×10^7 N/m^2 (10,000 psi). In addition, the load capacity of the bushing was reduced only 13 percent when heated to 315 C, whereas that of the ball was reduced by more than 50 percent at 340 C.

Bushings failed when the strength of the composite was exceeded; whereas the molded balls with steel reinforced bores (fig. 2(b)) usually failed due to severe scoring, and the unreinforced balls (fig. 2(a)) usually failed due to fracture from stress concentrations at the edge of the outer race.

The greater load-carrying capacity of the composite bushings (and presumably the outer race liners) compared to the composite balls is due to the support and constraint provided by the rigid steel backing. This is predictable by strength of materials analyses (8). These results indicate that for high load, low speed applications (such as aircraft control surface bearings), thin GFRPI liners should be useful to at least 315 C.

Wear - Molded Ball

A series of tests was conducted on GFRPI composite molded balls (fig. 2(b)). These tests were made at constant temperatures of 25, 205, and 315 C (or 340 C) with total journal oscillations from 30 to 250 kilocycles. Specific wear rates were calculated from measurements of ball diameter change, ball weight change and journal displacement. Each measurement has relative advantages and different sources of error. The results (fig. 4) show fairly good correlation between the three methods; the wear coefficients were about 10×10^{-11} cm^3/cm-kg except for some higher coefficients calculated based on weight change. It is suggested that the weight loss measured is not all due to wear but includes moisture desorption from the bearing.

To further investigate the adsorption-desorption characteristics of GFRPI composite balls, two balls were subjected to a bake-out in air at 200 C and to a degassing in a 1 micron vacuum at nominal room temperature. The initial weight loss from heating at 200 C is shown in figure 5(a). This indicates that desorption is complete in about five hours. Also shown is the subsequent weight gain due to adsorption from room air (about 20 percent relative humidity). Even in short times, less than 10 minutes exposure (fig. 5), significant adsorption occurred (more than 5 mg).

Long time exposure (fig. 5(a)) shows that adsorption equilibrium is not attained until at least a week. Finally, the molded composite balls were exposed to vacuum with no heating (fig. 5(a)). Almost two weeks of vacuum exposure were required to remove most of the moisture that had adsorbed during exposure to the room atmosphere.

Wear - Liners

Graphite fiber reinforced polyimide composite liners with two types of graphite fiber distribution were compared. Randomly oriented chopped fibers in one bearing (fig. 2(d)) and a continuously wound filament with fibers parallel to the sliding direction in the other bearing (fig. 2(e)). The results (fig. 6) clearly show that randomly oriented fibers produced a better composite than the ordered structure. The wound liner tended to delaminate due to the stresses in the liner. Lavengood (9) showed a similar effect with short-fiber reinforced composites of glass fiber in epoxy resin. He compared the strength properties of systems with aligned and with randomly-oriented fibers. He concluded that the uniform strength of the random composites makes them preferable in applications where the stresses are multiaxial.

The final bearing design tested (fig. 2(f)) had a molded liner composite. Wear coefficients calculated from journal displacement are shown in figure 7. The molded liners have a specific wear rate of $12 \pm 4 \times 10^{-11}$ $cm^3/cm\text{-}kg$. The machined inserts have a specific wear rate of $20 \pm 10 \times 10^{-11}$ $cm^3/cm\text{-}kg$ and appear to be moisture sensitive, with wear rates up to 70×10^{-11} $cm^3/cm\text{-}kg$

when completely dry. The low wear rate for bearing number 3 appears due to moisture readsorbed during the 25 C portion of the test conducted at high room humidity (65 percent RHO. For all the molded liners, the wear rate appears to be about the same at all temperatures. Moisture effects were low, possibly because the enclosed bearing design exposed only a small area for adsorption or desorption.

Friction Coefficient

The average friction coefficient for the wear tests with machined inserts, molded inserts, and molded balls are shown in figure 8. The friction characteristics are similar for all three bearing geometries. At 25 C the average friction coefficient is 0.15 ±0.05; at 315 C, 0.05 ±0.02. These values represent the friction after run-in. Before a good transfer film forms on the steel counter-face, friction coefficients can be as high as 0.28, even at 315 C. The generation of the film usually takes about 3 to 10 KC of oscillation (one of three hours of sliding). Any change in the sliding geometry, such as during bearing disassembly, usually disrupts the transfer film and run-in occurs again with the new geometry.

SUMMARY OF RESULTS

A 50/50 (weight percent) composite of graphite fibers and polyimide was studied using several different designs of self-aligning plain bearings oscillating ±15° at 1 Hertz at temperatures up to 315 C. Wear tests were made with a radial unit load of 2.85×10^7 N/m^2 (4130 psi). The main results were:

1. Polyimide composites containing randomly oriented graphite fibers and molded as an outer race liner gave the best results. The average specific wear rate was 12 $\pm$4 $\times 10^{-11}$ cm^3/cm-kg.

2. When the composite was used as a thin wall bushing, the dynamic load capacity was 2.8×10^8 N/m^2 (40,000 psi) at room temperature, and 2.4×10^8 N/m^2 (35,000 psi) at 320 C.

3. Friction coefficients after run-in were constant, ranging from 0.15 $\pm$0.05 at 25 C, to 0.05 $\pm$0.02 at 315 C. Before run-in, friction coefficients up to 0.28 were measured.

4. Continuous filament graphite fiber liners wound parallel to the sliding direction delaminated resulting in high wear.

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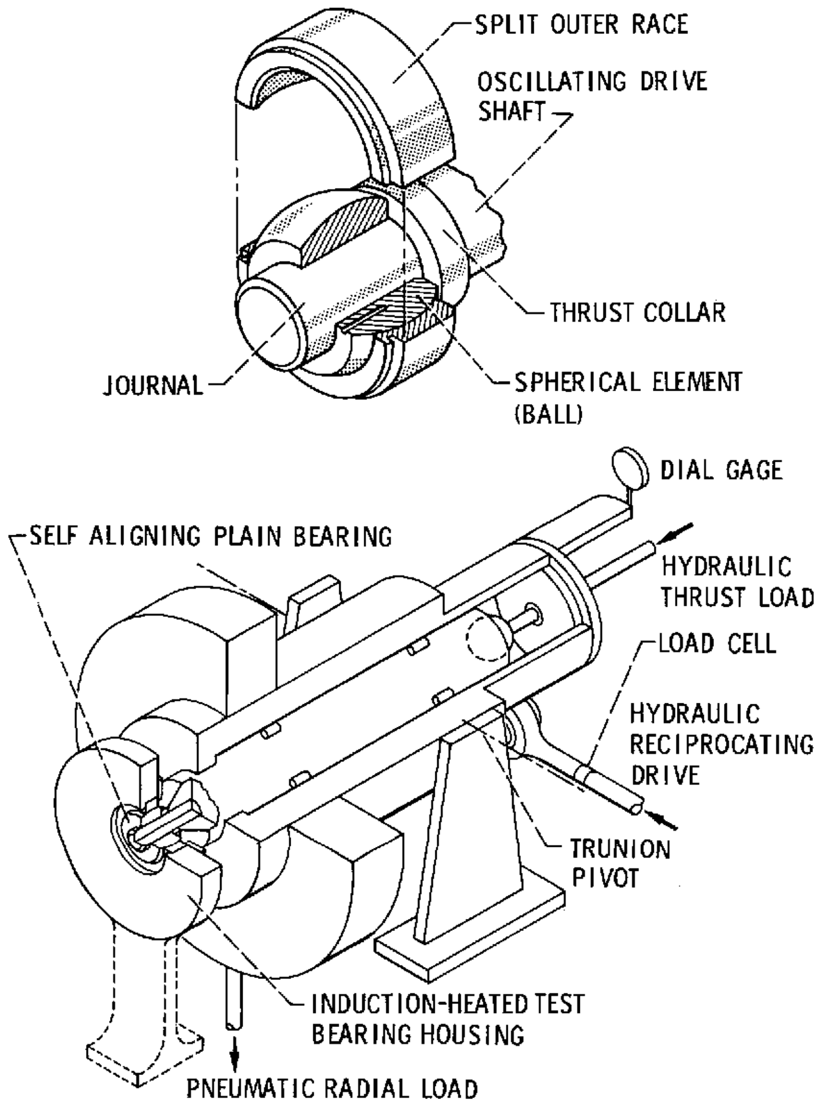

Figure 1. - Friction and wear apparatus (schematic) for testing self-aligning plain bearings.

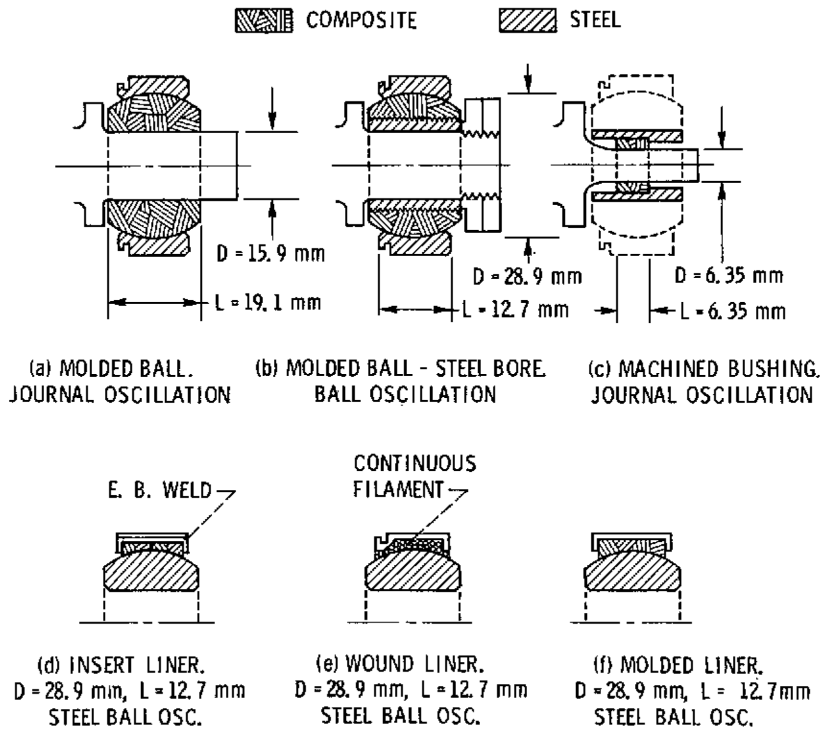

Figure 2. - Self-aligning plain bearing designs using graphite fiber reinforced polyimide composite.

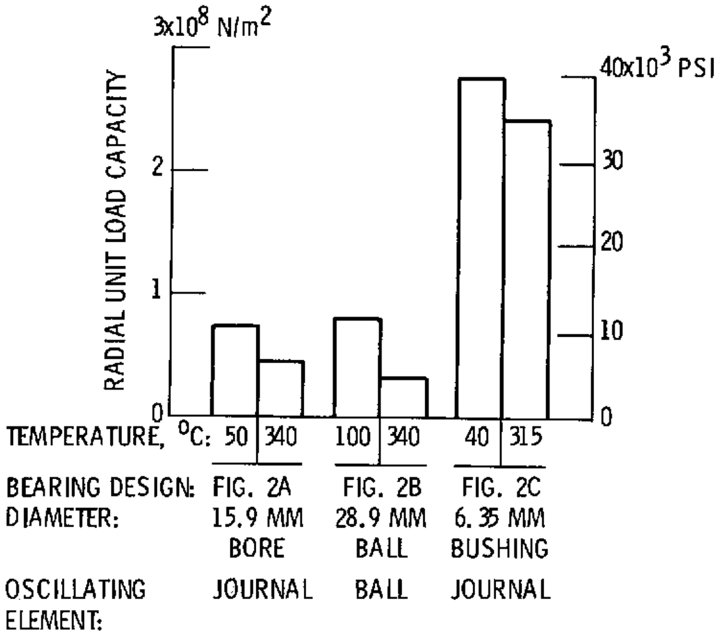

Figure 3. - Dynamic unit load capacity for graphite fiber-reinforced polyimide composite in three bearing designs (fig. 2); effect of temperature, oscillating ±15° at 1 Hz.

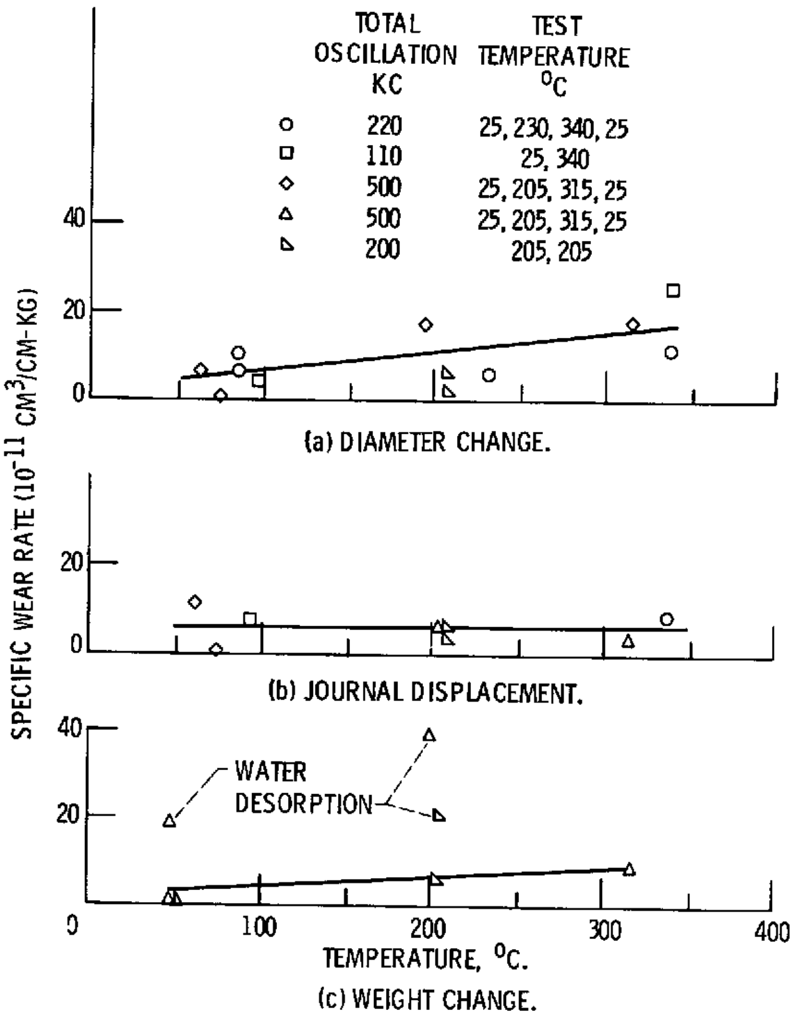

Figure 4. - Specific wear rate for five molded composite balls at three temperatures calculated from wear measurements made by three different methods - graphite fiber reinforced polyimide composite in self-aligning plain bearings oscillating ±15° at 1 Hz under a radial unit load of $2.8x10^7$ N/m^2 (4130 psi).

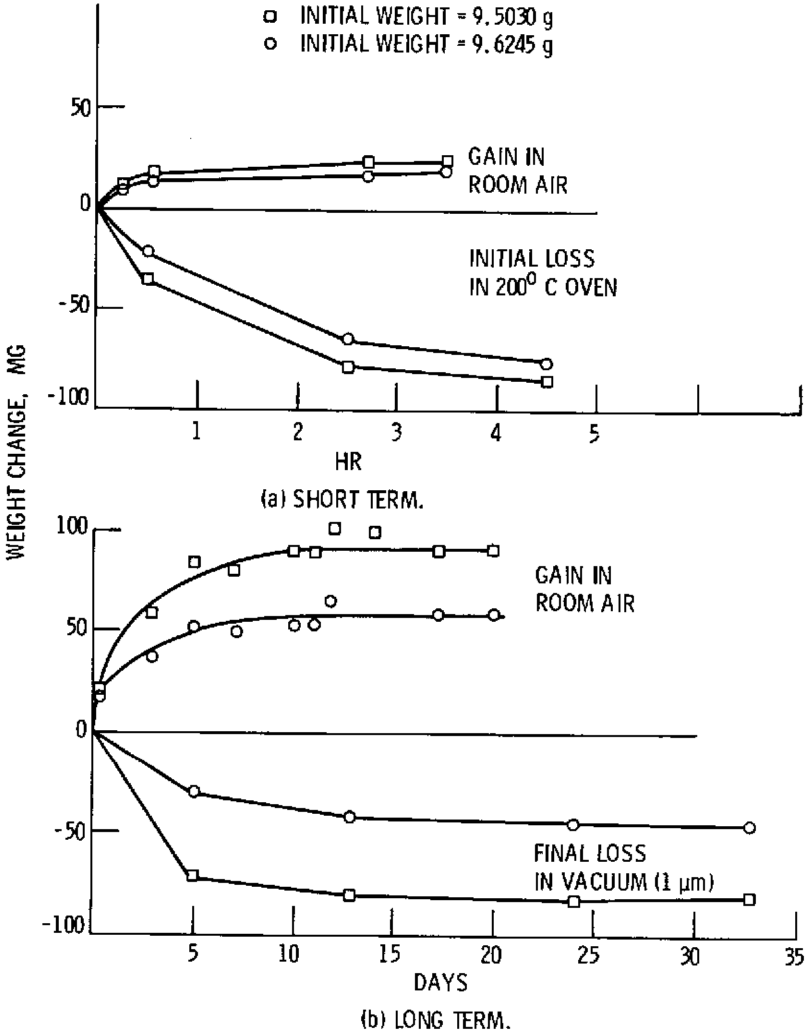

Figure 5. - Moisture adsorption and desorption for two graphite fiber reinforced polyimide molded composite balls.

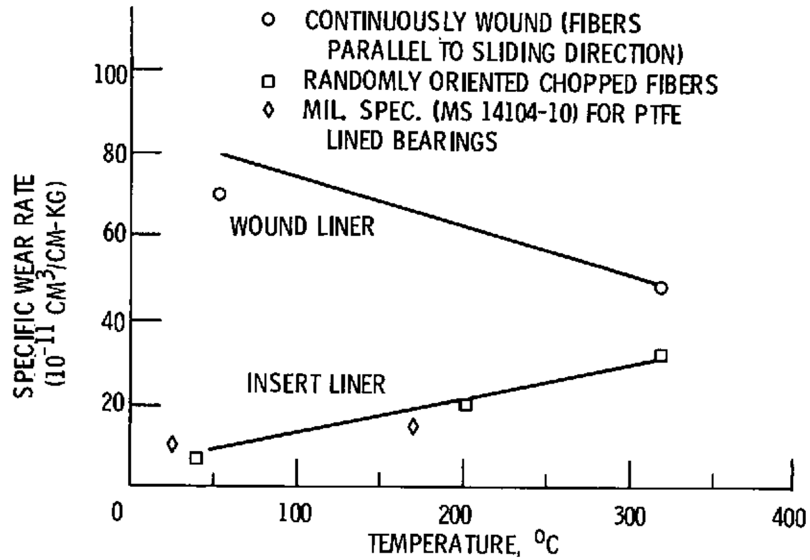

Figure 6. - Influence of graphite fiber distribution on wear of composite liners in self-aligning plain bearings oscillating $\pm 15^0$ at 1 Hz under a radial unit load of 2.8×10^7 N/m^2 (4130 psi). (Specific wear rate calculated from radial displacement of the journal.)

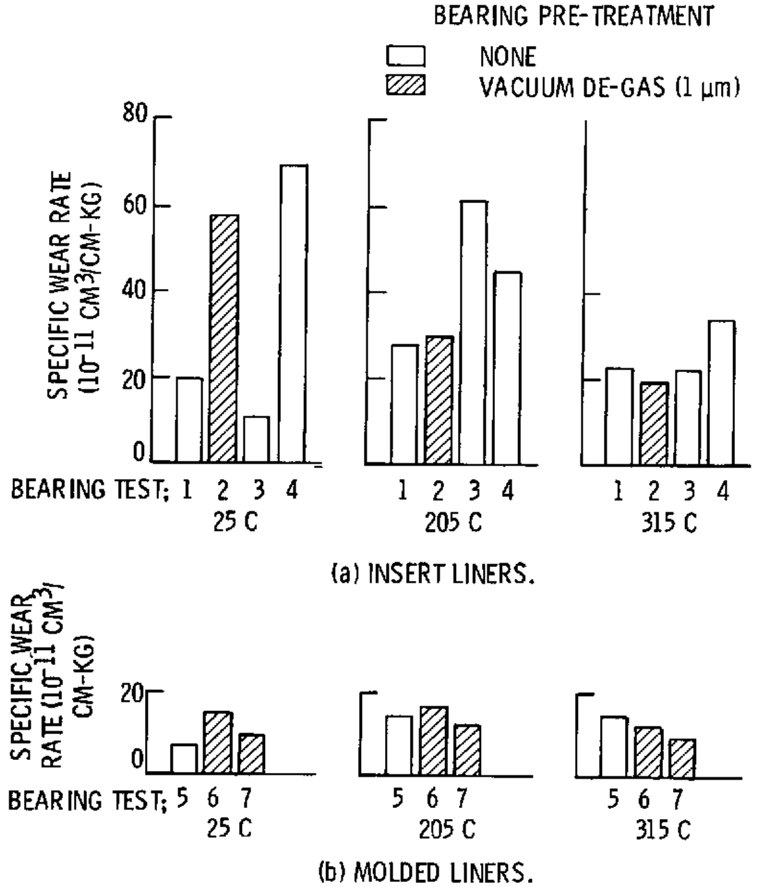

Figure 7. - Specific wear rate at three test temperatures for chopped graphite fiber reinforced polyimide composite liners in outer race of self-aligning plain bearings, oscillating $\pm 15^{\circ}$ at 1 Hz and a radial unit load of 2.8×10^{7} N/m^2 (4130 psi).

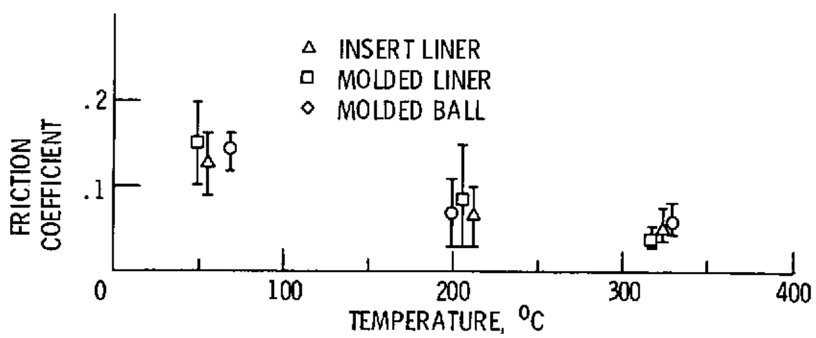

Figure 8. - Friction-temperature characteristics; Average and range for chopped graphite fiber reinforced polyimide composite in self-aligning plain bearings. Ball oscillating $\pm 15^{\circ}$ at 1 Hz, under 2.8×10^{7} N/m^2 (4130 psi) radial unit load.