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ALUMINA BEARINGS IN GAS-LUBRICATED GYROS[*]

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Abstract

The friction and wear properties of various forms of alumina for use in gas-bearing gyros were determined. The materials studied were: 100% dense Al_2O_3 (Lucalox), cemented Al_2O_3 (Carboloy, Grade 0-30), hot-pressed Al_2O_3, and plasma-arc deposited Al_2O_3 on beryllium. Flat, thrust-washer type specimens were used, with each material tested against itself only. Experimental variables included: sliding velocity, normal force, temperature, running time and environment. Bearing surfaces were fully characterized using roughness measurements, Talysurf profilometry, interferometry, optical and electron microscopy and X-ray analysis. In general, the coefficient of friction was: (1) independent of normal force, (2) decreased at high sliding velocities (hydrodynamic lift-off), (3) not affected by relative humidity (below 80%) or temperature, (4) increased with the onset of damage. New improved resurfacing techniques were developed that provided surfaces having lower coefficients of friction and greater resistance to damage from sliding contact. Each material was tested in compression and the microcreep properties were measured at a strain sensitivity of 10^{-6}.

I. Introduction

The purpose of this program was to establish the friction and wear behavior of a selected group of ceramic materials in order to determine the optimum material for use in gas-bearing gyros. The program was initiated in recognition of the need for a detailed study of the factors influencing the friction and wear characteristics; particularly the role played by surface structure.

The use of hydrodynamic gas-bearings for gyro spin-axis applications has resulted in significant improvement in gyro accuracy, reliability and lifetime. However, when these gyros are used in inertial strap-down systems, they are subjected to very high slew rates and high g-loading. Under these conditions, the inner race comes in contact with the outer race; i.e., bottoming occurs. In addition, start-stop cycles involve sliding contact between the inner race and outer race. Consequently, the friction and wear characteristics of the bearing material are of paramount importance. Potentially one of the most useful materials for gas-lubricated gyro bearings is Al_2O_3; among its advantages are:

1. A high resistance to damage from sliding contact
2. A relatively low coefficient of friction
3. Excellent structural stiffness due to a high modulus of elasticity; therefore, Al_2O_3 is resistant to centrifugal growth at high rotational speeds.
4. A low coefficient of thermal expansion resulting in good thermal shock resistance.
5. Good impact resistance because of a high compressive strength.
6. Chemically inert, nonconducting and nonmagnetic.
7. Excellent surface finishes may be obtained with proper machining methods.
8. Good dimensional stability.

While it is generally recognized that alumina has excellent friction and wear characteristics, there has not been a systematic investigation of these properties. Information has not been available so that the most suitable of the various forms of Al_2O_3 might be selected for gyro applications.

Four forms of alumina were selected for evaluation in this study. The materials chosen were: (1) Lucalox, a new product of General Electric that is 99.9% Al_2O_3; it is fine grained and 100% dense (contains essentially no internal voids); (2) Carboloy, also from General Electric, is a cemented product composed of 90% Al_2O_3, 2% W, and 8% proprietary fluxing agents; (3) hot-pressed Al_2O_3 is made by conventional powder methods and is characterized by a 2 to 3% void content; (4) plasma-arc deposited Al_2O_3 on a Be substrate, having a deposition thickness of about 0.015 inches.

The approach utilized in this investigation was a fundamental evaluation of the friction, wear and mechanical stability characteristics of a selected group of ceramics. It was recognized that the inherent friction and wear behavior of all materials is modified by the surface structure; that is, friction and wear are essentially surface phenomena. Thus, it was necessary to develop comprehensive surface analysis methods that fully characterized the structure of the surface. The surface characteristics of interest were: finish, topology, grain size, preferred orientation, residual stress, inclusions, microcracks, pits and contaminant layers. The techniques for the surface examination included: roughness measurements, interferometry, Talysurf profilometry, optical flatness, light microscopy, replica electron microscopy, X-ray diffraction and wetting tests.

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II. Experimental Procedure

All of the alumina samples were obtained from commercial sources and in each case the vendors specified surface finish by a roughness value. However, the inadequacy of using a roughness figure to denote surface finish became obvious when a number of analysis techniques were used on one surface. Several surface analysis techniques were employed in conjunction to characterize the bearing surfaces. These methods were: 1. Roughness, reported as an arithmetic average (A.A.) in microinches; 2. Surface profile, drawn by a Talysurf profilometer; 3. Flatness, using interferometric techniques; 4. Optical microscopy, utilizing oblique illumination at magnifications up to 1000X 5. Electron microscopy, using replication methods; 6. X-ray analysis, for residual strain, grain size and preferred orientation; 7. Cleanliness, employing a "water wetting" method; 8. Grain size, by polishing and etching for examination in a metallograph.

Rotational friction and wear tests were conducted on flat thrust-washer type specimens, with each material tested against itself only. The coefficient of friction was determined and the resulting surface wear investigated for: mechanisms of damage, origins of damage, effect of damage on coefficient of friction, and type of debris particles created. In addition to the friction and wear behavior, start-stop and bottoming was simulated. The threshold for damage and the type of damage for each test was established. Test variables included sliding velocity (118 to 2090 ft./min.), temperature (72 to 250°F), normal force (1.5 to 4.5 psi), running time, and environment (helium and air with different moisture contents). An important material parameter was the surface structure which was inherently different for each material but was modified by improved finishing techniques.

All friction and wear testing was done on a Friction and Wear Test Machine designed and built by the General Precision Research Model Shop. Essentially it provides for; rotation of one specimen, the means for bringing a stationary specimen into contact with it, and a torque arm to measure the torque developed in the stationary specimen. The stationary specimen holder is attached directly to a precision spindle which is belt driven by a D.C. motor that can attain speeds in excess of 10,000 rpm. A tachometer/generator is attached to the bottom end of the precision spindle so that the actual spindle speed is measured. The precision spindle has a run-out of less than 30 millionths of an inch.

Wear surfaces were characterized both before and after testing so as to note the type and extent of damage. Since friction and wear are essentially surface phenomena, extreme care was taken before testing to insure the absence of any contaminant layers on the wear surfaces. Specimens were tested until surface damage occurred. These specimens were then resurfaced before they could be used again. Briefly stated, the resurfacing procedure consisted of surface grinding with a diamond wheel until all the damaged material had been removed. Fine grinding was then done with a finer grit diamond wheel. The next step was free abrasive machining using boron carbide particles on a steel wheel. During the remaining steps, subsequently smaller particles of boron carbide were used until a suitable surface finish was obtained.

A gas-bearing gyro in service may not be required to run continuously. It may be necessary to start and stop the gyro many times throughout a long-time mission. In a situation such as this, the bearing materials must withstand a considerable amount of wear without becoming damaged. Wear is particularly severe as the gyro is shut down, the bearing surfaces once again come into high speed sliding contact.

To simulate this situation in the laboratory, start-stop tests were devised. The test consisted of bringing the wear surfaces, at rest, into contact. The rotating specimen was then started spinning until it reached a speed of 6000 rpm (beyond 6000 rpm lift-off becomes significant). A maximum of 600 tests were run on each experimental material in the resurfaced condition except plasma-arc deposited Al_2O_3 which was tested as-received.

Severe damage may also occur in service as a result of bottoming. Bottoming may be described as impacting of bearing surfaces while running at operational gas-bearing speeds. Bottoming normally occurs during a sudden change in vehicle velocity or direction. The results of bottoming may be disastrous, particularly if the bearing surface fractures or is damaged.

To simulate these conditions, bottoming tests were run in an effort to determine the damage resistance of the materials under investigation. Once again the most severe wear conditions were chosen for the tests. The nominal stress was 4.5 psi and the test speed was 6000 rpm.

The microcreep behavior was determined for each of the ceramic materials. A high sensitivity capacitance-type extensometer was used with a General Radio capacitance bridge to determine dimensional changes on the order of 10^{-5} to 10^{-6} inches. The specimens were loaded in compression to a stress of 15,000 psi and observed for several days.

III. Results

All of the materials studied in this program suffered damage to their surfaces from sliding contact during the friction and wear testing. In addition to having varying thresholds for damage, the several materials exhibited different mechanisms of damage. At some stage during wear, debris particles were created for all materials, except Carboloy. The generation of debris particles during surface damage is one source of failure in gas-bearing gyros.

Two other factors that influence the reliability of gas-bearing gyros were the observations that following the onset of damage the coefficients of friction markedly increased and the hydrodynamic qualities of the surface were impaired.

The three principal experimental variables (sliding velocity, normal force and time duration) were closely related in a complex fashion. Test variables were selected to provide a qualitative overview of the effects due to speed, load, and time and were based on previous performance. The description of the damage introduced by sliding contact must, of necessity, be qualitative in nature. Where feasible, roughness measurements and Talysurf profiles were used. However, much of the analysis was in the form of visual observation (naked eye, optical and electron microscopy).

It was found that the wear characteristics of Lucalox, Carboloy, and plasma-arc deposited Al_2O_3 were clearly superior to those of hot-pressed Al_2O_3. This conclusion was reached on the basis of: the type of damage, threshold for damage, rate of increase of damage, effect of damage on the coefficient of friction, and debris particles generated. The onset of damage was always accompanied by an increase in friction; this effect was least for Carboloy and greatest for hot-pressed Al_2O_3. Debris particles were generated from those materials that have pre-existing pits (or pull-outs) in the surface.

Lucalox damage is by pull-outs, that is, creation of new pits in the surface and enlargement of existing pits. The severity of damage, for a given load and speed, depends upon the size and density of pre-existing pits. Debris particles as large as 2 microns were observed. When the surface was improved by new machining techniques the load and speed threshold for damage was increased and the subsequent damage was minimized. Re-surfacing also had the effect of lowering the coefficient of friction from values such as 0.22 to 0.16.

The mechanism of damage in Carboloy was in the form of buffing or polishing. Following wear tests, the surface was found to be smoother than the as-machined condition. This was established by roughness measurements, Talysurf profiles, optical and electron microscopy. Damage was observed only at the highest loads and speeds. Surface finishes obtained by free-abrasive machining improved the resistance to damage and lowered the coefficient of friction to values of 0.1 to 0.2. Carboloy surfaces do not have well-defined pits and no debris particles were formed during sliding contact damage.

Hot-pressed Al_2O_3, having a profusion of surface pits, showed massive surface damage at relatively low loads and speeds. The coefficient of friction was of the order of 0.4 and rapidly increased with the onset of wear.

In the plasma-arc deposited surfaces, damage started in the form of fine circular scratches which multiplied and increased in width to form wide wear tracks about 6 to 8 microinches below the original surface. Debris particles were observed after damage set in. A typical value for the coefficient of friction was 0.28.

In general, the coefficient of friction was: 1. independent of normal force; 2. decreased at high sliding velocities due to hydrodynamic lift-off; 3. not affected by relative humidity changes (except for very high values) or temperature increases; 4. minimized as the surface condition was improved; 5. increased with the onset of damage.

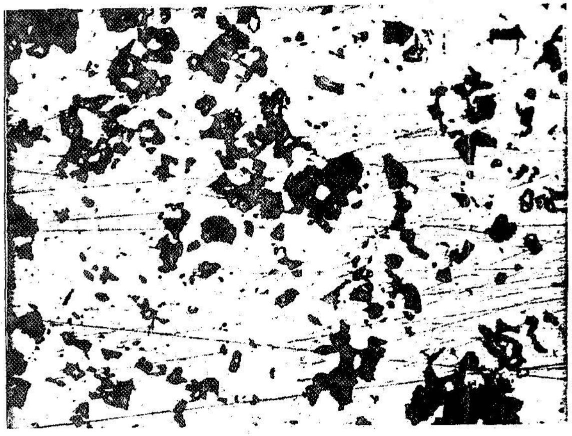

Figure 1 - As-received Lucalox wear surface (150X)

Figure 1 is a photomicrograph of an as-received Lucalox surface having a roughness arithmetic average of 37 μ-in. The dark areas represent pits or pull-outs, primarily created by the finishing operation. Some finishing scratches are also visible.

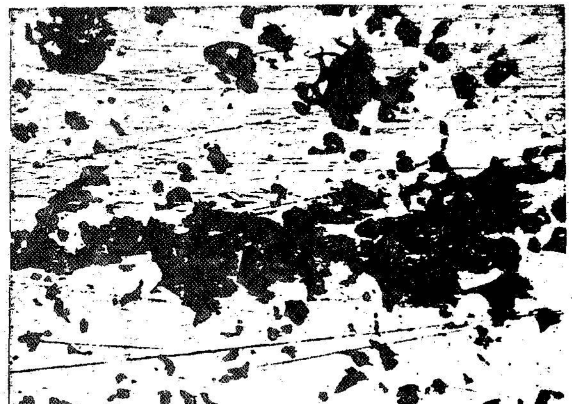

Figure 2 - Initiation of wear track in Lucalox (150X)

Figure 2 shows the same specimen after it has been very slightly damaged. The damage first appears as a very fine wear track which consists of a series of pull-outs. As wear progresses, the wear track widens and more material is pulled from the surface.

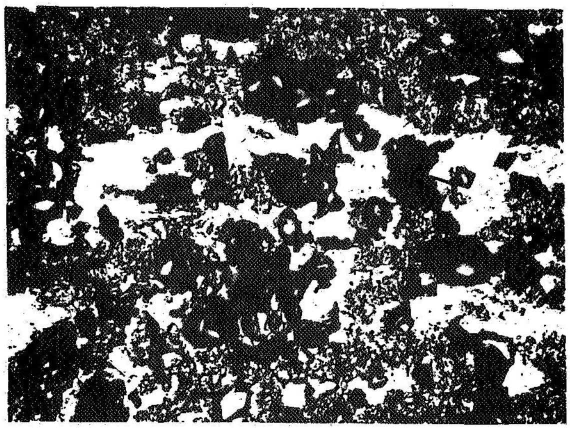

Figure 3 - Severely damaged Lucalox surface (250X)

If wear continues until severe damage has set in, a surface such as that shown in Figure 3 is created. This micrograph is characterized by very large pits with very little of the original surface (the light-colored areas) remaining. A heavily damaged surface such as this causes the coefficient of friction to increase and also contributes wear debris particles which are free to migrate throughout the surroundings.

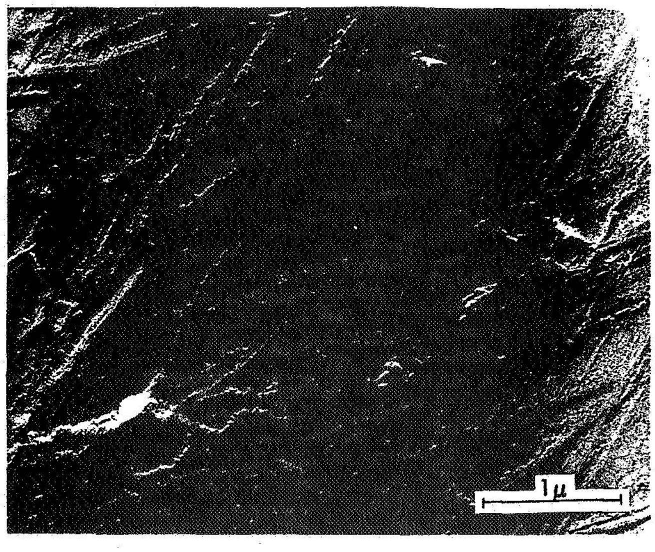

Figure 4 - As-received Lucalox surface, negative replica

The surface structure can be seen on a much finer scale with the aid of electronmicrographs. Figure 4 shows the surface of a Lucalox specimen in the as-received condition. Here the finishing scratches are seen in more detail and appear to be made up of tiny pits. The larger surface pits are seen to be quite irregular in shape and are not bounded by any distinct crystallographic directions. There was not any direct relationship between grain size of the Lucalox and the surface pits, i.e., the smallest pits were considerably smaller than the minimum grain size observed, and conversely, some pits were larger than the biggest grains. Figure 5 is an electronmicrograph of an as-received Carboloy surface. The surface is very irregular with no strong evidence of grain boundaries or second phases.

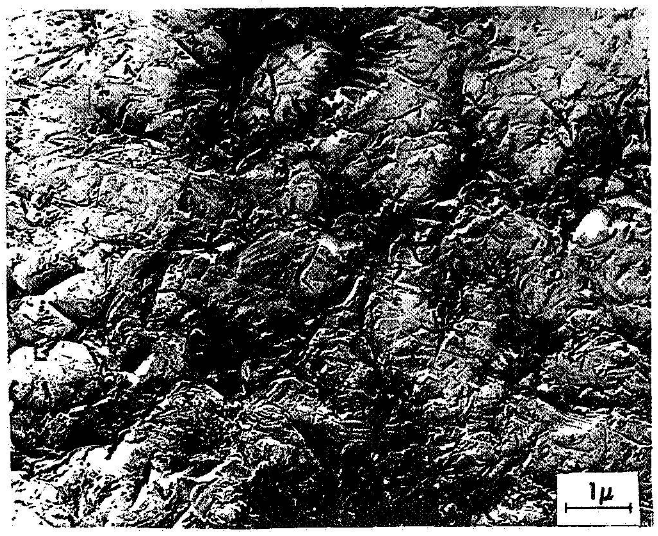

Figure 5 - As-received Carboloy surface, negative replica

The wear characteristics of plasma-arc deposited Al_2O_3 on beryllium are illustrated in Figure 6. Although the Al_2O_3 coating was only .015 inches in thickness, the coating was never penetrated after long periods of wear, i.e., only the surface was damaged. Damage began as fine scratches which upon further wear widened into wear tracks such as that shown in Figure 6.

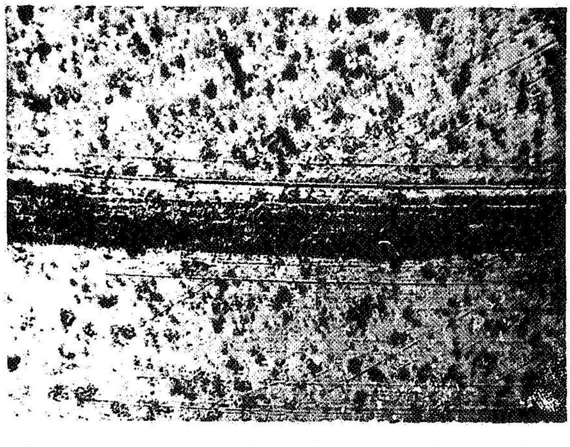

Figure 6 - Wear track in plasma-arc deposited Al_2O_3 (150X)

As with Lucalox and hot-pressed Al_2O_3, debris particles on the order of 1 to 2 microns were created after severe wear.

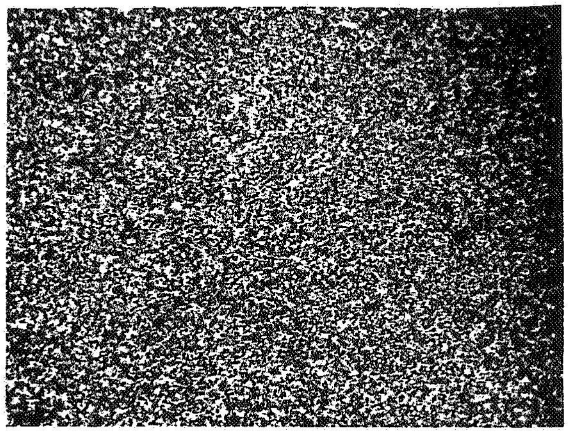

Figure 7 - As-received Carboloy surface (150X)

Figure 7 is a photomicrograph of an as-received Carboloy surface at 150X magnification. The surface asperities are very shallow resulting in a roughness reading of 10 μ-in. This surface was dark gray-brown in color, very dull in appearance, and contained no visible scratches. Since the mechanism of damage in Carboloy was in the form of buffing or polishing, the damaged area became much smoother than the original surface. This condition is illustrated in Figure 8 which shows the edge of a wear track.

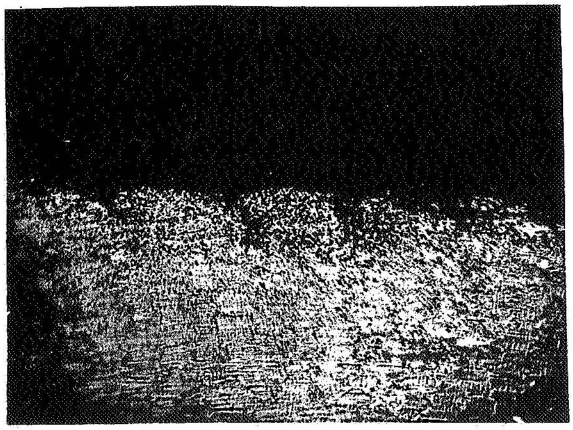

Figure 8 - Edge of Carboloy wear track (45X)

The top portion of the figure shows the original undamaged surface, whereas, the lower portion is the actual wear track. Since the wear track is actually smoother (roughness value of 5 μ-in), it reflects light better and appears lighter than the original surface. Carboloy does not generate debris particles and since the surface becomes smoother during wear, the coefficient of friction does not increase.

An as-received plasma-arc deposited wear surface is shown in Figure 9. Finishing scratches and pull-outs are very prevalent in this surface, which has a roughness value of approximately 5 μ-in. Similar pits and scratches can be seen greatly magnified in Figure 10, which is also an as-received deposited surface. This electronmicrograph is similar to Figures 4 and 5, which also are negative replicas, i.e., pits in the actual surface appear as a protuberances in the micrograph.

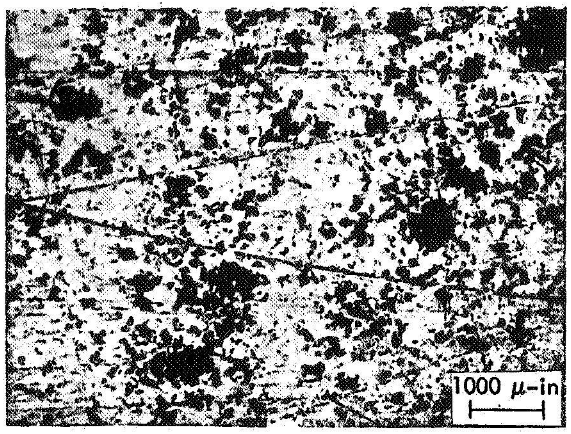

Figure 9 - As-received plasma-arc deposited Al_2O_3 surface (500X)

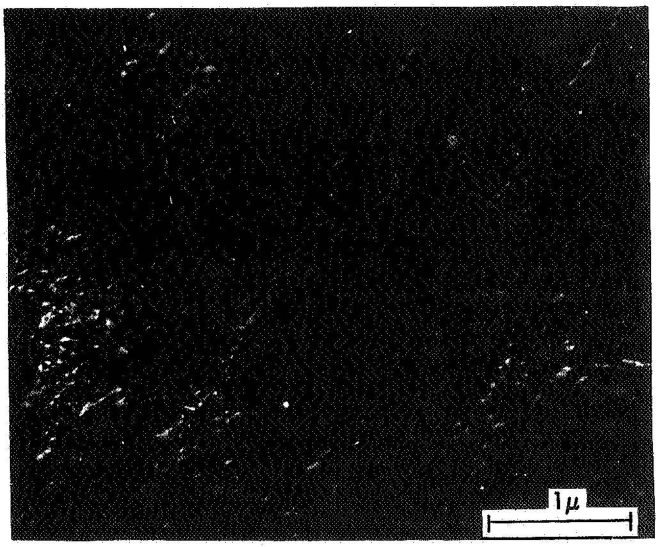

Figure 10 - Electronmicrograph of as-received plasma-arc deposited Al_2O_3 surface, negative replica

Resurfacing the friction and wear specimens after damage resulted in a lower coefficient of friction and improved wear resistance. These improvements can be directly attributed to the enhanced condition of the surface. After resurfacing, the number, width, and depth of finishing pits and scratches were reduced by more than 50 per cent when compared to the as-received condition. This reduction is obvious when Figure 1 is compared to Figure 11.

All experimental materials were polished metallographically and etched to delineate their grain boundaries, so that grain size measurements could be made. The average grain sizes were as follows: Lucalox, 24 microns; Carboloy, 2 microns; plasma-arc deposited Al_2O_3, less than 2 microns; and hot-pressed Al_2O_3, 4 microns.

The results of the microcreep tests indicated that a compressive stress of 15,000 psi applied over several days does not cause any microcreep (deformation) whatsoever for

Figure 11 - Photomicrograph showing resurfaced Lucalox (150X)

the ceramic materials since there was no measurable change in length. However, the microcreep behavior was considerably different for the plasma-arc deposited Al_2O_3 on beryllium. This specimen was loaded to 509 psi which resulted in significant microcreep. The behavior observed in this specimen was attributed to the beryllium substrate, and is illustrated in Figure 12. The curve shows microstrain plotted against time. The insert shows the short-time behavior up to 100 minutes. The data points A, B, and C on the insert refer to points A, B, and C on the long-time curve. The creep rate appeared to decrease after 8.3 hours which corresponds to a strain of 5×10^{-4}.

X-ray analysis indicated no preferred orientation or residual strains in the wear surface. Preferred orientation, in particular, can have a strong influence on wear resistance of Al_2O_3 since this material's wear resistance is known to vary with crystallographic orientation.

The results of the start-stop tests indicated that Lucalox, Carboloy, and plasma-arc deposited Al_2O_3 exhibited no damage after 600 tests. The hot-pressed Al_2O_3, however, showed signs of damage after 442 tests; the damage becoming severe following 450 tests.

In general, the experimental materials had quite good bottoming damage resistance. Carboloy, plasma-arc deposited Al_2O_3, and hot-pressed Al_2O_3 revealed no severe damage after 2000 tests. Carboloy was given 3000 tests and still no severe damage appeared. The Lucalox specimens, however, were damaged after only 180 tests. This behavior was in contrast to the excellent abrasion resistance of Lucalox, especially in the resurfaced condition. The Lucalox tests were repeated with essentially the same results. The plasma-arc deposited Al_2O_3 showed some slight wear scratches after 400 tests. This damage was slight, and there was little tendency to initiate severe wear tracks. After the remaining 1600 tests had been completed, there was no noticeable increase in damage. In summary, except for Lucalox, the experimental materials exhibited good resistance to damage from bottoming.

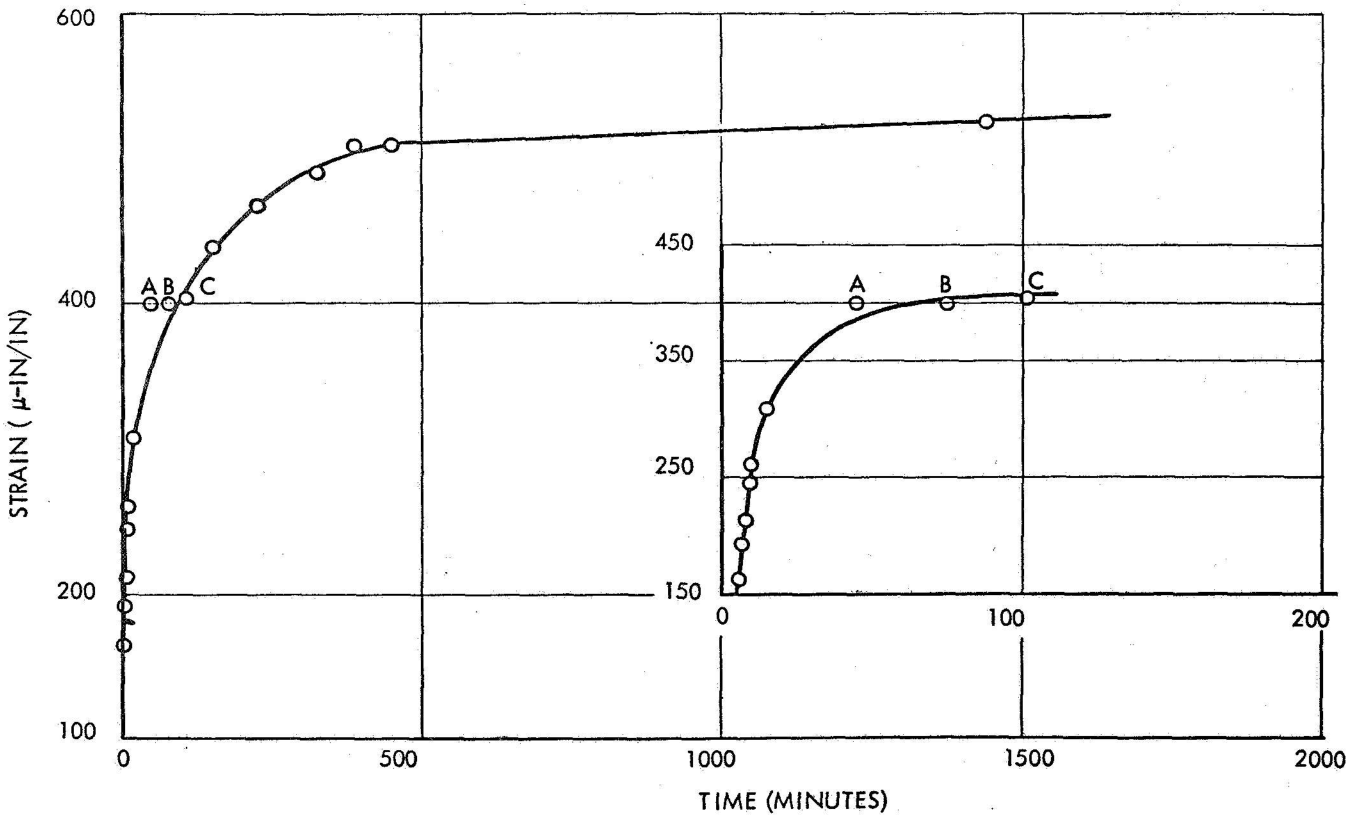

Figure 12 - Microcreep of S200 beryllium for a stress of 509 psi

	Coefficient of Friction	Resistance to Damage	Debris Particles	Start-stop	Bottoming	Micro-creep resis-tance	Density gm/cm^3	Thermal Conductivity cal/sec./cm^2/$^\circ$C/cm
Lucalox	low	good	yes	good	poor	good	3.98	.05 (@100°C)
Carboloy	low	excellent	no	good	good	good	4.15	~.05 (@ 100°C)
Hot-pressed Al_2O_3	high	poor	yes	fair	good	good	3.93	.072 (@ 100°C)
Plasma-arc deposited Al_2O_3	low	good	yes	good	fair	poor	1.85 (Be)	.35 (Be @ 20°C)

Table 1 - Summary of Test Results

Table 1 is a compilation of test results which lists the relative advantages and disadvantages of each experimental material. In addition, the density and thermal conductivity of each material is included since these are factors to be considered in the design of gas-bearing gyros.

IV. Remarks

There is a distinct need for bearing materials with a low coefficient of friction. The prime reason is that lower friction is accompanied by smaller starting torques, which in turn demand lower power requirements.

Lower coefficients of friction may be obtained through the use of lubricants. However, the lubricants themselves can create problems of their own. If they are not applied properly, they can cause the bearing to "freeze up" or substantially increase its friction instead of decreasing it. Lubricants may also degrade over long periods of time. It was primarily for these reasons that alumina was chosen for study - it works well unlubricated.

Good wear resistance is necessary, particularly on long-time missions, under strap-down conditions, in order to eliminate bearing degradation as the result of many starts and stops and also as a result of any bottoming which may occur.

In some cases, thermal conductivity may be an important consideration. Low thermal conductivity increases warm-up time by prolonging the period necessary for thermal equilibrium. If thermal equilibrium is not achieved, bearing parts may become distorted as a result of temperature gradients.

Gas bearing reliability may be substantially reduced by the presence of debris particles created during severe wear. These particles may become lodged in the lift and support grooves thereby degrading the hydrodynamic properties of the bearing. In addition, debris particles as large as the bearing surface clearances have been observed. These very abrasive particles may increase surface damage by abrading the bearing surfaces.

In actual gas-bearing applications, lift and support grooves are cut in the bearing surface. These can be sites of damage since they contain edges and micro-cracks resulting from the cutting operation. In order to simulate actual gas-bearing operational conditions, grooves should be cut in the bearing surface followed by testing as outlined in this paper.

The results of the plasma-arc deposited alumina microcreep tests indicate that, because of the beryllium substrate, this material has poor resistance to microcreep at an applied compressive stress of 509 psi. This conclusion is misleading since the beryllium can actually withstand stresses higher than 509 psi without further microcreep. The reason for this phenomenon can be explained using the dislocation "exhaustion" theory. In metals, dislocation motion (which results in plastic deformation) can be either easy or difficult. The absence of dislocation barriers permits dislocations to move freely; however, the presence of barriers will restrict their motion. In the microcreep tests, the initial application of 509 psi stress (a small fraction of the yield stress) provides the force necessary to move dislocations over easily surmountable barriers. After several minutes, the creep rate begins to decrease. The decreasing creep rate is due to the exhaustion of the barriers which the dislocations are able to overcome. To put it another way; creep will stop after those easily movable dislocations have overcome their low energy barriers and have reached high energy barriers over which they cannot move. Once this dislocation "equilibrium" has been achieved at a given stress level, the microcreep rate becomes essentially zero (the curve in Figure 12 levels off). The load may then be removed and reapplied without any further creep. In order to make the material creep further, it is necessary to increase the force moving the dislocations by increasing the applied stress. Therefore, if the beryllium test specimen had been pre-stressed above 509 psi, no microcreep would have taken place at 509 psi. Thus, pre-stressing is a good method for increasing creep resistance. In this discussion, the effects of thermal activation have been neglected since these only become important at higher temperatures and over longer periods of time.

V. Summary

It has been shown the Lucalox, Carboloy and plasma-arc deposited Al_2O_3 are good materials for use in gas-bearing gyros based on their excellent friction and wear properties. Each material has different damage mechanisms that are strongly dependent upon surface structure. Friction and wear behavior is improved when the surfaces are machined so that they have lower pit densities and smaller pit sizes (width and depth). Surfaces (such as Carboloy) that are free from pull-outs do not generate debris particles during damage. In the other materials (Lucalox, hot-pressed Al_2O_3 and deposited Al_2O_3) that have surface pull-outs, damage creates particles as large as 2 microns. Except for Carboloy, the onset of damage is accompanied by an increase in friction. In general, these materials have excellent properties but each has certain deficiencies as outlined in Table 1. For example, plasma-arc deposited Al_2O_3 has a relatively low coefficient of friction, good resistance to damage, good start-stop damage resistance, and low density because of the Be substrate. However, it has only fair bottoming resistance, creates debris particles, and has poor microcreep resistance.

It has been shown that the characterization of a surface by only a roughness figure is inadequate. Complete characterization requires: (1) Talysurf profilometry, (2) optical and electron microscopy, (3) X-ray analysis and (4) grain size determination. It has also been shown that surface structure has a pronounced effect on the friction and wear properties of Al_2O_3 and that improvement in the surface structure through carefully controlled resurfacing techniques can result in considerable reduction in friction and enhancement of wear resistance.

Acknowledgment

The authors would like to express their gratitude to Kenneth J. Zwoboda, Supervisor, and the members of the General Precision Research Model Shop for their valuable assistance in the development and implementation of the improved resurfacing techniques.