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CERAMIC GAS BEARING MATERIAL EVALUATION

John T. McCabe, et al

Mechanical Technology, Incorporated

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CERAMIC GAS BEARING MATERIAL EVALUATION

Prepared Under
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13. ABSTRACT

Flat washer specimens were experimentally tested under conditions simulating start-stop and continuous rubbing contact of a gas-lubricated thrust bearing. Minimum surface damage with a constant and low value of the friction coefficient were criteria for judging superior performance. The materials tested consisted of conventional plasma-sprayed substrates (used as reference materials), solid silicon nitride, beryllium oxide, and beryllium both coated and uncoated.

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II

FOREWORD

This report was prepared for the Office of Naval Research under Contract No. N00014-72-C-0083 by the Friction and Wear Section of Mechanical Technology Incorporated Tribology Center. Mr. Stan Doroff managed the program for the Office of Naval Research, and Dr. Eugene F. Finkin supervised virtually all of the program for MTI. S.F. Murray, Peter Albrecht, and Mike Gretter were principal contributors to the MTI effort. Dr. Peter Gielisse of the University of Rhode Island supplied the silicon nitride test specimens under a separate ONR contract. Partial support for this effort was supplied by the Naval Material Command, Strategic Systems Project Office (NSP 23).

TABLE OF CONTENTS

1.0 INTRODUCTION

Gas bearings and other applications requiring materials capable of surviving unlubricated, high-speed rubbing contact have led to technology programs, such as the present, in which the principal effort was focused on ceramic materials. The goal of the present program was to compare variations of ceramic materials and to determine the character of a material combination with the following properties:

- Sufficiently low coefficient of friction to permit dry starting of a gas bearing without hydrostatic jacking and with a minimum of torque.
- Sufficient consistency of the friction coefficient to provide restart reliability.
- Sufficiently insignificant surface damage during high-speed rubbing contact to provide long life.

Start-stop and continuous rubbing experimental tests were employed to determine the change in friction coefficient, surface roughness, and specimen weight loss due to rubbing contact at different loads and surface finishes. In all cases the rotating and stationary specimens were two flat washers with a one-inch O.D. and a one-half-inch I.D.

The thrust washer test rig used in the program has been employed as a materials screening device since 1963 and a considerable body of data, showing good field correlation in gas bearing gyros, has been generated in the interim period. This study adds three new candidate materials to the data library.

The exact relationships amoung material properties, fabrication method and application requirements have not been established. The coordinated development with the University of Rhode Island to sort out these variables is the first step towards bridging this gap.

Many factors enter into the selection of the optimum material for a gas bearing application: material cost, availability, creep resistance, thermal coefficient of expansion, thermal conductivity, resistance to wear, spalling and galling, corrosion resistance, and others.

The importance of some of these factors depends on the particular application. For instance, a material combination may be quite satisfactory from a surface damage view point, but might be judged unsatisfactory if the heat transfer characteristics of the materials lead to excessive bearing surface distortion. It is not realistic to expect a single material combination to be an optimum for all applications, thus the intent of this report is to broaden the data which gas bearing designers need to select materials that are optimum for each particular application. In addition, it is hoped that the information contained herein will also help to identify some of the material requirements that are fundamental to all gas bearing applications.

2.0 SUMMARY

Ceramic materials were subjected to start-stop and continuous rubbing tests which simulated potential operating conditions of a flat, gas-lubricated thrust bearing. Plasma-sprayed chrome oxide versus itself was used as a reference because this surface coating has performed successfully in many gas bearing applications and considerable test data is available in the literature (Ref. 1,2). The other materials tested were silicon nitride, beryllium oxide, beryllium, and beryllium coated with chrome oxide and aluminum oxide.

Silicon nitride, versus itself, proved to be a very promising combination because surface damage was minimal. The friction coefficient, ranging between 0.2 and 0.3, was lower than the reference specimens and remained relatively constant through both types of tests. However, further evaluation of this material is necessary because an unidentified white, wear-related debris formed on some of the test specimens and these specimens performed poorly. The silicon nitride was hot pressed at the University of Rhode Island from power supplied by the Norton Company.

There were indications that beryllium oxide versus itself was also a good material combination, principally because the average friction coefficient for all tests was about 0.2. However, some tests showed an exceptionally low friction coefficient suggesting the presence of a surface contaminant (Ref. 1,2). Also, virtually all specimens gained weight during testing which could be eliminated by heating. In addition, the beryllium oxide continuous rubbing tests showed a trend towards increasing friction with increasing load. Thus, more controlled tests are needed to evaluate this material. The test specimens were machined for Thermalox 995 stock.

A satisfactory way of plasma spraying beryllium oxide with ceramic coatings could not be found.

In general, metals sprayed with chrome oxide showed lower coefficients of friction than aluminum oxide and chrome carbide in start-stop tests; but all test combinations of aluminum oxide and chrome carbide showed high friction, heavy wear, or both during continuous rubbing tests.

3.0 CONCLUSIONS AND RECOMMENDATIONS

- Coated metals appear to be suitable materials for gas bearing start-stop requirements if friction coefficients between 0.2 and 0.3 are tolerable.
- More development work is needed to improve the continuous rubbing performance of coated metals.
- Tests accomplished under this program indicate solid Si_3N_4 can provide an excellent bearing surface for applications where continuous rubbing is encountered if the Si_3N_4 is processed to avoid the formation of a white debris that is wear-related and synonymous with poor friction characteristics.
- Some tests with solid beryllium oxide indicated this material to be very suitable, from a friction standpoint, for applications where the rubbing pressure is nominally 4 psi or less. This material also warrants further study to verify its characteristics because some tests indicated a low friction coefficient while others did not.
- It is essential to identify a white debris which is sometimes formed on the Si_3N_4. The formation of this material on an actual gyro bearing would certainly result in increased and erratic torque.
- Suitable cleaning techniques must be developed for beryllium oxide. It seems very unlikely that the low friction values which were measured with this this material are characteristic of the values that would be obtained with clean materials.
- More effort should be placed on evaluating the effect of operating variables, such as humidity and temperature, on sliding behavior. These variables have been shown to be major factors in determining the performance of solid Al_2O_3 versus itself and may also be important with these other materials. It has been established that the sliding chrome oxide is not affected by temperature or the type of environmental gas, but nothing is really known about Si_3N_4 or beryllium oxide.

4.0 METHOD OF TESTING AND RESULTS

4.1 Test Rig Description

The MTI flat thrust washer test facilities were used for this study. This rig has been used often in the past because it offers a simple and inexpensive way to screen gas bearing material candidates.

Figure 1 shows a schematic of the test rig with the important components identified. The rotating specimen is held in the bottom fixture which is rotated via a motor-driven V-belt. Speed changes are accomplished by changing the ratio of the pulley diameters. The stationary specimen is held in a vertical spindle floated in an externally-pressurized gas bearing. Bearing friction torque is monitored by strain gages mounted on cantilevered torque arms and the spindle is constrained from rotation by pins which extend from the spindle and contact the torque arms.

4.2 Test Description

Start-stop and continuous rubbing tests were conducted for each material combination. The start-stop tests consisted of 1,000 starts and stops from 575 rpm under a load of 3.2 psi. Friction measurements were taken every 100 cycles and the roughness of the mating surfaces was measured by a Talysurf before and after each test. The specimens were cleaned in a Soxhlet extractor and then weighed before each test. The weight was again measured after testing.

The continuous sliding tests were performed at 575 rpm under a series of loads for each set of specimens. The speed was selected for convenience and to correspond to that used in previous tests. Each set was cleaned, weighed, and Talysurfed prior to testing. A complete test consisted of four 15-minute sliding periods at load levels of 2.1, 3.2, 4.8, and 6.4 psi. According to current design practice, this load range covers light loading, 2 to 3 psi, moderate loading 3 to 5 psi, and heavy loading, greater than 5 psi. The surface roughness was measured, they were Talysurfed again after each period at a specific load level, and reweighed after each complete test. Rubbing friction was monitored on startup and after two, five, and fifteen-minute time intervals. The specimens used in the start-stop tests were not used in the continuous rubbing tests.

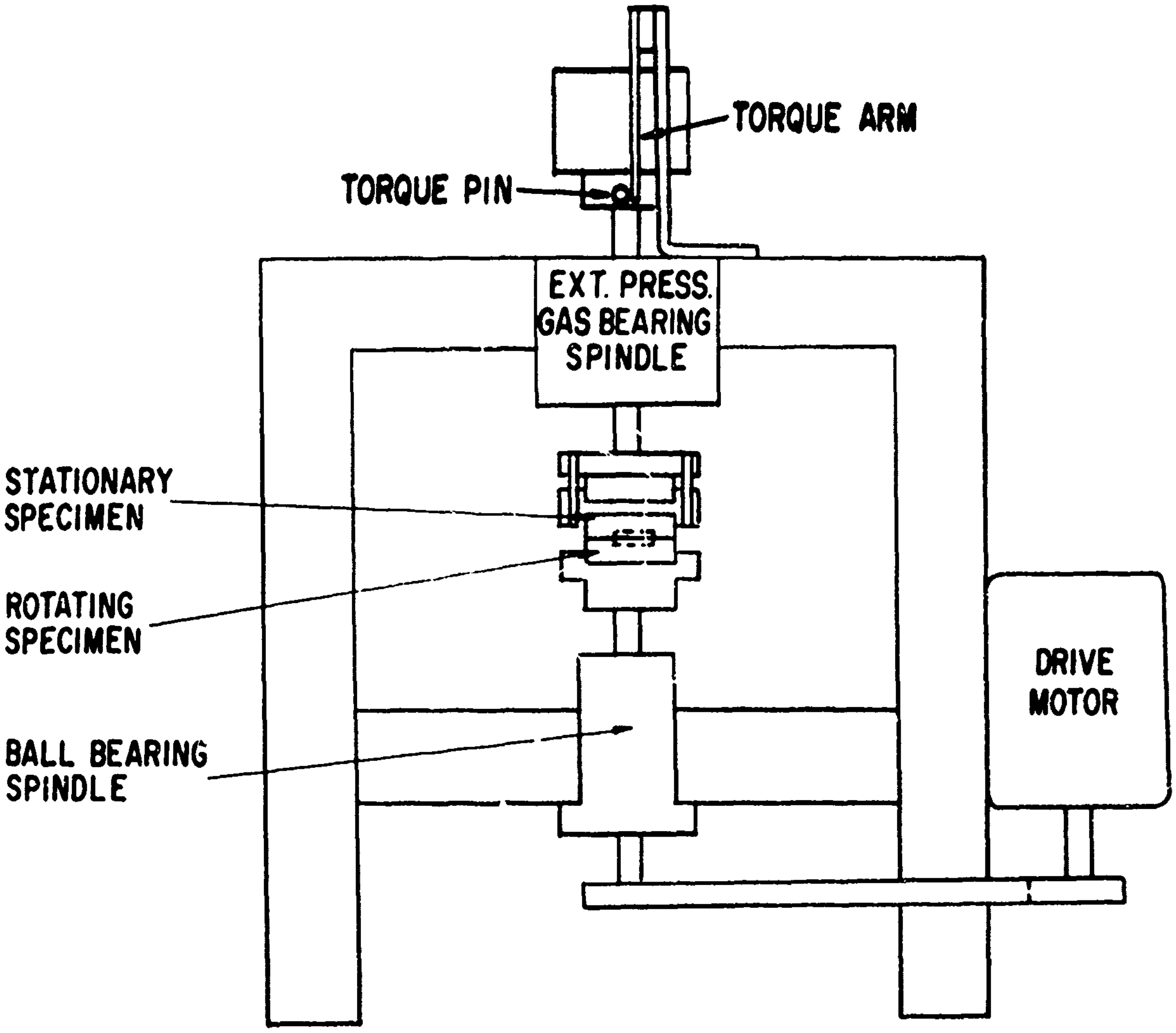

Fig. 1 Schematic of Thrust Washer Test Machine

4.3 Physical Properties of the Test Specimens

	BeO	Be	Si_3N_4
Thermal Conductivity, Btu/ft-°F-hr	152	84.4	8
Density, #/in^3	.108	.067	.113
Thermal Expansion, in/in-°F	3.16×10^{-6}	6.45×10^{-6}	1.7×10^{-6}
Modulus of Elasticity, psi	50×10^6	42×10^6	43×10^6
Poisson's Ratio	.35	.024 - .030	-
Crystal Structure	HCP*	HCP*	HCP*

4.4 Discussion and Results

The effectiveness of several candidates for gas bearing were evaluated in a thrust washer test by comparing the sliding performance of these materials with that of plasma-sprayed chrome oxide (Cr_2O_3). Both the start-stop and continuous rubbing tests were made in air with a relative humidity of 30 percent and an ambient temperature of 73°F. The combinations of materials tested are shown in Table 1, and the test results are given in Tables 2 and 3.

The silicon nitride specimens were supplied to MTI by Dr. Peter Gielisse of the University of Rhode Island, under Office of Naval Research Contract No. N00014-68-0008. The specimens were returned to the University of Rhode Island where they are currently being inspected in an attempt to identify a white debris that formed on about 20 percent of the specimens after testing and also, to look for a relation between surface damage and material processing method. A report on these findings is anticipated in the near future.

In general, solid silicon nitride mated against itself was a very promising combination. In the majority of tests the friction measured was lower than the reference chrome oxide, and the surface appearance of the Si_3N_4 and Cr_2O_3 showed negligible wear or surface damage. However, in 20 percent of the tests a white, semi-plastic, non-crystalline debris was found smeared on the surface of the silicon nitride specimen after the test. This phenomenon had been observed before in the past with Si_3N_4 specimens manufactured in England by another process (Ref. 2). Normally, self-mated silicon nitride appears to have a coefficient of friction between 0.2 and 0.3.

*Hexagonal, close packed

TABLE 1

MATERIAL COMBINATIONS USED IN TESTS

Rotating Specimen	Vs.	Stationary Specimen
Cr_2O_3*		Cr_2O_3*
Cr_3C_2*		Al_2O_3*
Si_3N_4 (solid)		Si_3N_4 (solid)
BeO (solid)		BeO (solid)
Al_2O_3* (on Be)		Al_2O_3* (on Be)
Cr_2O_3* (on Be)		Cr_2O_3* (on Be)
Cr_2O_3* (on Be)		Be (solid)
Cr_2O_3* (on Be)		BeO (solid)

* Plasma-sprayed coating.

TABLE 2

CERAMIC GAS BEARING MATERIAL EVALUATION
SUMMARY OF CONTINUOUS TESTS

Test No.	Materials and Specimen No. (See Code Below): Rotating		Stationary		Weight Loss (grams) (- for Weight Gain): Rotating	Stationary	Surface Roughness (microinches AA): Rotating Before	Rotating After	Stationary Before	Stationary After	Coefficient of Friction: Rubbing Pressure = [illegible] psi: Start	2 Min.	5 Min.	15 Min.	[illegible] psi: Start	2 Min.	5 Min.	15 Min.	6.0 psi: Start	2 Min.	5 Min.	15 Min.	[illegible] psi: Start	2 Min.	5 Min.	15 Min.	Remarks
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Notes

(1) Code for Al_2O_3 Specimens: [illegible]

(2) Code for [illegible] Specimens: [illegible]

9.1 9.2 9.3

TABLE 2

CERAMIC GAS BEARING MATERI
SUMMARY OF CONTINUOU

Test No.	Materials and Specimen No. (See Notes Below)				Weight Loss (grams) (- for Weight Gain)		Surface Roughness (microinches CLA)				Coefficient of Fri								
							Rotating		Stationary		Rubbing Pressure = 2.1 psi				" 3.2 psi				
	Rotating		Stationary		Rotating	Stationary	Before	After	Before	After	Start	2 Min.	5 Min.	15 Min.	Start	2 Min.	5 Min.	15 Min.	Start
3[(1)]	Si_3N_4	B(E)	Si_3N_4	B(F)	.0096	- .0008	13.5		15	13	.26	.33	.48	.48	.48	.6	.43[(a)]	.34[(a)]	.65
4	Si_3N_4	B(G)	Si_3N_4	B(H)	.0001	- .0004	14	7-13	14	7-13	.18	.17	.19	.20	.13	.11	.11	.19-.23	.16-.17
6	Si_3N_4	LBL(C)	Si_3N_4	LBL(D)	.0002	- .0002	20	4-13	16	5-9	.5	.5	.4	.4	.5-.54	.48	.41-.46	.37	.66-.78
9	Si_3N_4	DG(E)	Si_3N_4	DG(F)	.0097	.0086	15	12	14	10	.44-.56	.41-.44	.43-.48	.44-.54	.31	.27-.29	.26	.28	.3-.33
10	Si_3N_4	DG(G)	Si_3N_4	DG(H)	.1054	.0380	15	4-12	14	6-11	.16-.33	.22	.2	.2	.23-.34	.20-.31	.18-.30	.16-.23	.22-.38
13	Si_3N_4	DBL(E)	Si_3N_4	DBL(F)	- .0053	.0009	9	9	6	2	.38-.82	.34-.82	.24-.92	.38-.58	.27-.38	.32-.59	.24-.26	.28-.34	.53-.62
14	Si_3N_4	DBL(G)	Si_3N_4	DBL(H)	- .0002	.0006	7	5-6	5.5	4-4.5	.10	.10	.12	.12	.12-.16	.12-.15	.11-.14	.12-.14	.16-.26
17	Si_3N_4	R(A)	Si_3N_4	R(B)	.0141	- .0002	2.1	1.2	1.8	.6-1.1	.11	.11	.11	.11	.14-.19	.11-.12	.11-.12	.1-.13	.12-.25
18	Si_3N_4	R(C)	Si_3N_4	R(D)	- .0006	.0002	1.8	1.2-1.3	1.2	.8-1.0	.15-.16	.15-.16	.15-.17	.15-.17	.22-.36	.23-.24	.23-.25	.26-.38	.24-.28
29[(2)]	BeO	TR(A) 36	BeO	TR(A) 37	- .0013	- .0015	1.3-2 2	.7-.8	1.3-2.4	.5	.475	.820	.780	.810	.130	.116	.480	.053	.254
30	BeO	TD(A) 20	BeO	TD(A) 21	- .0010	- .0106	.7-1.4	.8-1.3	.1-1.4	1.-1.4	.153	.153	.17	.195	.115	.126	.161	.167	.16
31	BeO	TR(B) 46	BeO	TR(B) 47	- .0002	.0035	2.5-7	1.3-5.8	2.7-4.0	1.0-3.7	.129	.122	.126	.126	.089	.098	.089	.082	.182
32	BeO	TD(B) 32	BeO	TD(B) 33	- .0002	- .416	4-4.6	2.2-4.9	.4-6.5	3.7-3.8	.238	.281	.274	.255	.314	.331	.340	.357	.190
33	Cr_2O_3 on Be	9	Cr_2O_3 on Be	10	- .0018	- .0020	4-9	2-7.8	3.7-10.3	3-7	.196	.255	.475	.618	.462	.424	.424	.363	.496
34	Al_2O_3 on Be	16	Al_2O_3 on Be	17	- .0028	- .0019	6-9	4.3-7.6	8-14	4.3-6.4	.143	.171	.197	.223	.075	.097	.116	.176	.237
35	Cr_2O_3 on Be	11	Be	2	.0022	.0017	2.4-4.2	8.2-16	0.8-1.2	10-18	.544	.576	.458	.510	520	.466	.517	.495	.7[illegible]0
36	Cr_2O_3 on Be	12	BeO	TD(A) 28	- .0026	- .0006	.4-3.2	.7-2.8	.6-2.0	1.4-1.8	.51	.51	.527	.527	.435	.435	.435	.508	.423
37	Cr_2O_3 on Be	13	BeO	TR(A) 44	- .0026	- .0018	.1-2.4	1.4-2.8	.3-1.4	.4-.8	.272	.306	.272	.324	.398	.398	.430	.605	.474
38	BeO	TR(A) 29	BeO	TD(A) 45	.0015	- .0193	.8-1.6	.7-1.5	.5-1.3	.6-1.1	.102	.100	.115	.115	.088	.104	.121	.121	.158

Notes

(1) Code for Si_3N_4 Specimens:

B(E), B(F), B(G), B(H)	Black 30 Microinch Rotary
LBL(C), LBL(D)	Light Blue 30 Microinch Surface
DG(E), DG(F), DG(G), DG(H)	Dark Green 15-20 Microinch Surface
DBL(E), DBL(F), DBL(G), DBL(F)	Dark Blue 8 Microinch Surface
R(A), R(B), R(C), R(D)	Red

(2) Code for BeO Specimens:

TR - Thermalox 995, Regular Porosity
TD - Thermalox 995, Draper Porosity
(A) - A Finish, 2-3 rms
(B) - B Finish, 8-10 rms
(C) - C Finish, 20-60 rms

9.1

9.2

TABLE 2

CERAMIC GAS BEARING MATERIAL EVALUATION
SUMMARY OF CONTINUOUS TESTS

m)	Surface Roughness (microinches CLA)				Coefficient of Friction																
in)	Rotating		Stationary		Rubbing Pressure = 2.1 psi				3.2 psi				4.8 psi				6.4 psi				
ry	Before	After	Before	After	Start	2 Min.	5 Min.	15 Min.	Start	2 Min.	5 Min.	15 Min.	Start	2 Min.	5 Min.	15 Min.	Start	2 Min.	5 Min.	15 Min.	
	13.5		15	13	.26	.33	.48	.48	.48	.6	.43[a]	.34[a]	.65	.39[a]	.27-.58[b]	.49	.63	.72	.45	.42	[a]Stick-slip. [b]Cyclic sti
	14	7-13	14	7-13	.18	.17	.19	.20	.13	.11	.11	.19-.23	.16-.17	.21	.23	.25	.19-.25	.18-.24	.18-.24	.23-.29	Stick-slip (slight to modera
	20	4-13	16	5-9	.5	.5	.4	.4	.5-.54	.48	.41-.46	.37	.66-.78	.6-.66	.54-.69	.48-.63	.52-.77	.45-.68	.36-.5	.34-.41	Surfaces polished after test,
	15	12	14	10	.44-.56	.41-.44	.43-.48	.44-.54	.31	.27-.29	.26	.28	.3-.33	.27-.32	.27-.34	.37-.47	.3-.52	.36-.43	.39-.54	.38-.48	Stick-slip except in the run
	15	4-12	14	6-11	.26-.33	.22	.2	.2	.23-.34	.20-.31	.18-.30	.16-.23	.22-.38	.20-.23	.20-.22	.20-.23	.11-.43	.22-.33	.25-.28	.26-.28	Moderate stick-slip, severe
	9	9	6	2	.38-.82	.34-.82	.24-.92	.38-.58	.27-.38	.32-.59	.24-.28	.28-.34	.53-.62	.29-.47	.29-.32	.27-.38	.18-.34	.11-.27	.16-.25	.27-.32	Large amount of white debris
	7	5-6	5.5	4-4.5	.10	.10	.12	.17	.12-.16	.12-.15	.11-.16	.12-.14	.16-.26	.16	.18-.21	.13-.17	.13-.15	.12-.13	.12-.13	.12-.13	Narrow glossy wear rings appe
	2.1	1.2	1.8	.6-1.1	.11	.11	.11	.11	.14-.19	.11-.12	.11-.12	.1-.13	.12-.25	.16	.10	.10	.13-.15	.04-.17	.06-.15	.11-.18	Occasional periods of stick-
	1.8	1.2-1.3	1.2	.8-1.0	.15-.16	.15-.16	.15-.17	.15-.17	.22-.36	.23-.24	.23-.25	.24-.38	.24-.28	.16-.19	.15-.17	.15-.17	.24-.30	.13	.12-.19	.13-.2	Smooth run.
	1.3-2.2	.7-.8	1.3-2.4	.5	.475	.820	.700	.810	.130	.116	.490	.053	.254	.292	.272	.220	.766	.820	.740	.680	Periods of high stick-slip
	.7-1.4	.8-1.3	.1-1.4	1.-1.4	.153	.153	.17	.195	.115	.126	.161	.167	.16	.217	.267	.232	.29	.404	.382	.372	Severe stick-slip with 6.4 p
	2.5-7	1.3-5.8	2.7-6.0	1.0-3.7	.129	.122	.126	.126	.089	.098	.089	.082	.182	.175	.307	.287	.516	.462	.468	.480	Periods of stick-slip with 6.
	4-4.6	2.2-4.9	.4-6.5	3.7-3.8	.238	.281	.274	.255	.314	.331	.340	.357	.190	.503	.621	.511	.218	.245	.462	.490	Severe stick-slip with 4.8 p
	4-9	2-7.8	3.7-10.3	3-7	.196	.255	.475	.518	.462	.424	.424	.363	.496	.467	.453	.467	.599	.416	.443	.443	Severe stick-slip with 3.2 p
	6-9	4.3-7.6	8-14	4.3-6.4	.143	.171	.197	.223	.075	.097	.116	.176	.237	.279	.321	.354	.320	.371	.397	.438	Specimen #17 chipped before
	2.4-4.2	8.2-16	0.8-1.2	10-18	.544	.576	.458	.510	.520	.466	.517	.495	.730	.656	.693	.693	.899	.872	.845	.818	Coating is powdering after r
	.4-3.2	.7-2.8	.6-2.0	1.4-1.8	.51	.51	.527	.527	.435	.435	.435	.508	.423	.326	.555	.473	.627	.654	.681	.665	Stick-slip with 6.4 psi run;
	.1-2.4	1.4-2.8	.3-1.4	.4-.8	.272	.306	.272	.324	.398	.398	.430	.605	.474	.584	.511	.474	.463	.436	.573	.550	Periods of stick-slip with r
	.8-1.6	.7-1.5	.5-1.3	.6-1.1	.102	.100	.115	.115	.088	.104	.121	.121	.158	.219	.205	.196	.140	.172	.163	.168	One slight wear ring on #45;

2

ATERIAL EVALUATION
INUOUS TESTS

ent of Friction								
4.8 psi				6.4 psi				
Start	2 Min.	5 Min.	15 Min.	Start	2 Min.	5 Min.	15 Min.	Remarks
.65	.29[a]	.27-.58[b]	.49	.63	.72	.45	.42	[a]Stick-slip. [b]Cyclic stick-slip; white degris formed after run with 3.2 psi.
.16-.17	.21	.23	.25	.19-.25	.18-.24	.18-.24	.23-.29	Stick-slip (slight to moderate) increased to a maximum at about 8 min. with 6.4 psi test.
.66-.78	.6-.66	.54-.69	.48-.63	.52-.77	.65-.68	.36-.5	.34-.41	Surfaces polished after test, no white debris.
.3-.33	.27-.32	.27-.34	.37-.47	.3-.52	.36-.43	.39-.54	.38-.48	Stick-slip except in the run with 3.2 psi rubbing pressure.
.22-.38	.20-.23	.20-.22	.20-.23	.11-.43	.22-.33	.25-.28	.26-.28	Moderate stick-slip, severe at start of 6.4 psi test.
.53-.62	.29-.47	.29-.32	.27-.38	.18-.34	.11-.27	.16-.25	.27-.32	Large amount of white debris deposited on surface after test.
.16-.26	.16	.18-.21	.13-.17	.13-.15	.12-.13	.12-.13	.12-.13	Narrow glossy wear rings appeared after 4.8 psi run.
.12-.25	.10	.10	.10	.13-.15	.04-.17	.06-.15	.11-.18	Occasional periods of stick-slip; specimen A chipped near edge after 4.8 psi run.
.24-.28	.16-.19	.15-.17	.15-.17	.24-.30	.13	.12-.19	.13-.2	Smooth run.
.254	.292	.272	.220	.766	.820	.740	.680	Periods of high stick-slip and wear rings visible on both surfaces from 4.8 psi run on.
.16	.217	.247	.232	.29	.404	.382	.372	Severe stick-slip with 6.4 psi run; no visible wear marks.
.182	.175	.307	.287	.514	.462	.468	.480	Periods of stick-slip with 6.4 psi run; slight dark wear ring on #46, no visible damage on #47.
.190	.583	.621	.511	.218	.245	.462	.490	Severe stick-slip with 4.8 psi; cyclic stick-slip with 6.4 psi; wear rings on both surfaces.
.496	.467	.453	.467	.559	.416	.443	.443	Severe stick-slip with 3.2 psi; fairly smooth with other runs, wear rings on both surfaces.
.237	.279	.321	.354	.320	.371	.397	.438	Specimen #17 chipped before test; smooth run.
.730	.656	.693	.693	.899	.872	.845	.818	Coating is powdering after run with 2.1 psi; severe stick-slip; many wear rings on both surfaces, white on #11.
.423	.526	.555	.473	.627	.654	.681	.665	Stick-slip with 6.4 psi run; many wear rings on both surfaces.
.474	.584	.511	.474	.463	.436	.573	.550	Periods of stick-slip with runs of 3.2 psi and 4.8 psi. Slight wear ring on #44; very noticeable on #13.
.158	.219	.205	.196	.140	.172	.163	.168	One slight wear ring on #45, no visible marks on #29. Very smooth run.

9.3

TABLE 3

CERAMIC GAS BEARING MATERIAL EVALUATION
SUMMARY OF START-STOP TESTS

Rubbing Pressure = 3.2 psi

Test No.	Materials and Specimen No.[3] Rotating		Stationary		Weight Loss, gram[6] Rotating	Stationary	Surface Roughness microinches, CLA Rotating Before	Rotating After	Stationary Before	Stationary After	Break-away Coefficient of Friction Start	500 Cycles	1000 Cycles	Average[2]	Avg. Change Per Cycle	Running Coefficient of Friction Start	500 Cycles	1000 Cycles	Avg.[2]	Avg. Change Per Cycle	Remarks
A[1]	Cr_2O_3	3	Cr_2O_3	3	.0004	.0009	10	8	10	8	0.30	0.48	0.50	.47	9.32×10^{-4}	0.32	0.48	0.40	.39	7.06×10^{-4}	Oscillating.
B[1]	Cr_3C_2	9	Al_2O_3	6	0	-.0013	2	2	12	16	.22	.2-.62	.65	.50	9.9×10^{-4}	.18	.62	.65	.50	10×10^{-4}	Severe stick-slip.
1	Si_3N_4	B-A	Si_3N_4	B-B	0	-.0011	15	16	16	18	.5	.1-.5	.1-.5	.35	$7. \times 10^{-4}$	.42	.12	.22	.19	3.87×10^{-4}	Stick-slip, both surfaces scored.
2	Si_3N_4	B-C	Si_3N_4	B-D	.0002	0	12	20	16	18	.3	.25	.25	.26	5.125×10^{-4}	.3	.25	.25	.26	5.125×10^{-4}	No stick-slip; edge of washers polished.
5	Si_3N_4	LBL-A	Si_3N_4	LBL-B	0	.0001	16	12	16.2	8.3	.5	.5	.13	.30	7.6×10^{-4}	.35	.32	.13	.20	5.075×10^{-4}	Surfaces polished.
7	Si_3N_4	DG-A	Si_3N_4	DG-B	.00045	0	13	26	16	28	.55	.6	.6	.62	8.45×10^{-4}	.6	.6	.6	.38	7.55×10^{-4}	White debris in the wear tracks (removed before weighing).
8	Si_3N_4	DG-C	Si_3N_4	DG-D	-.0002	.0001	15	7-12	16	5-12	(5)	(5)	(5)	(5)	(5)	.13	.16	.18	.16	3.145×10^{-4}	A few spots were polished.
11	Si_3N_4	DB-A	Si_3N_4	DB-B	.0313	.0016	-	18	-	22	.42	.34	.30	.425	8.5×10^{-4}	.30	.36	.30	.31	6.2×10^{-4}	Large quantities of white debris on surface (not cleaned prior to weight measurement). One heavy scratch on specimen A.
12	Si_3N_4	DB-C	Si_3N_4	DB-D	-.0006	-.0007	8	3-7	5.5	25-5	.15	.56	.39	.67	9.6×10^{-4}	.15	.56	.39	.47	9.6×10^{-4}	White debris showed up slightly in both specimens.
15	Si_3N_4	Y-E	Si_3N_4	Y-F	.0002	.0002	1.5	9	2.5	10	.66	.3-.56	.26	.63	8.6×10^{-3}	.40	.37	.26	.32	6.5×10^{-4}	Severe stick-slip, stabilized out after 500 cycles to no stick-slip
16	Si_3N_4	Y-G	Si_3N_4	Y-H	-.0016	-.0106	1.2	1.0	.8		.305-.06	.215	.170	.26	5.20×10^{-4}	.305-.06	.215	.170	.26	5.28×10^{-4}	Surfaces highly polished and shiny.
19	BeO	TR(A) 41	BeO	TR(A) 42	-.0018	-.0017	1-2	1.2-1.6	1-2	1.2-1.6	(5)	(5)	(5)	(5)	(5)	.3	.11	.13	.16	2.75×10^{-4}	Scratches on surfaces before test, polished and glossy after test.
20	BeO	TD(A) 25	BeO	TD(A) 26	-.0007	-.0003	.8-1.6	1.-1.8	1.4-.26	1.2-1.6	(5)	(5)	(5)	(5)	(5)	.07	.09	.07	.08	1.6×10^{-4}	Glossy surfaces with some rings formed from smearing.
21	BeO	TR(B) 40	BeO	TR(B) 49	-.0017	-.0023	6	6	6	6	(5)	(5)	(5)	(5)	(5)	.130	.253	.326	.236	4.27×10^{-4}	Surfaces appeared dull before and after test, no scratches or blemishes
22	BeO	TD(B) 36	BeO	TD(B) 35	-.0015	-.0006	4-6	2-6	3-6	4-5	(5)	(5)	(5)	(5)	(5)	.176	.310	.208	.20	5.2×10^{-4}	Dull surfaces before test, specimen #36 appeared glossy after test.
23	Cr_2O_3 on Be	4	Cr_2O_3 on Be	5	-.0010	-.0009	4-6	3-6	4-5	4-5	(5)	(5)	(5)	(5)	(5)	.127	.130	.168	.167	2.95×10^{-4}	Partial wear rings slightly visible; no visible scratches.
24	Al_2O_3 on Be	14	Al_2O_3 on Be	15	-.0020	-.0017	11-16	9-13	8-16	8-16	(5)	(5)	(5)	(5)	(5)	.18	.30	.31	.265	5.09×10^{-4}	A number of small polished patches appeared after test.
25	Cr_2O_3 on Be(C)	6	Be(A)	1	.0006	.0035	4-5.5	-	1	12-22	(5)	(5)	(5)	(5)	(5)	.41	.83	.82	.66	13.2×10^{-4}	Very noticeable surface damage to both specs., white wear rings on coated specimens.
26	Cr_2O_3 on Be(C)	7	BeO	TD(A) 23	.0066	-.0109	2-5	2-3	1-2	1-2	(5)	(5)	(5)	(5)	(5)	.23	.33	.29	.32	6.36×10^{-4}	Wear marks appeared on both surfaces.
27	Cr_2O_3 on Be(C)	8	BeO	TR(A) 39	-.0013	-.0001	3-6	3-4	1-3	1-2	(5)	(5)	(5)	(5)	(5)	.32	.23	.21	.26	4.8×10^{-4}	Wear marks appeared before and after test. Very light wear rings appeared after test.
28	BeO	TR(A) 40	BeO	TD(A) 24	-.0017	-.0016	1-2	1-1.8	1-2	.6-1.6	(5)	(5)	(5)	(5)	(5)		Erratic				Repeated erratic readings on friction coefficients.

Notes

(1) Reference specimens; plasma sprayed on 410 S.S.

(2) Averaged over readings at 100, 300, 500, 600, 700, 800, 900, and 1000 start-stop cycles.

(3) Code for Si_3N_4 Specimens:

Black 30 Microinches Rotary: B-A, B-B, B-C, B-d
Light Blue 30 Microinches Surface: LBL-A, LBL-B
Dark Green 15-30 Microinches Surface: DG-A, DG-B, DG-C, DG-D
Dark Blue 8 Microinches Surface: DB-A, DB-B, DB-C, DB-D
Yellow 1-2 Microinches: Y-E, Y-F, Y-G, Y-H

(4) Code for BeO Specimens

TR - Thermalox 995 Regular Porosity
TD - Thermalox 9/5 Deeper Porosity
(A) - A Finish 2-3 rms
(B) - B Finish 8-10 rms
(C) - C Finish 20-60 rms

(5) Break-away Coefficients of Friction not detectably different from running coefficients of friction.

(6) Negative sign indicates gain in weight.

10.1

10.2

10.3

MTI-13565

TAB

CERAMIC GAS BEARING
SUMMARY OF ST

Rubbing Pres

Test No.	Materials and Specimen No. (3)				Weight Loss, gram (6)		Surface Roughness microinches, CLA				Break-away Coefficie		
	Rotating		Stationary		Rotating	Stationary	Rotating Before	Rotating After	Stationary Before	Stationary After	Start	500 Cycles	1000 Cycles
A (1)	Cr_2O_3	5	Cr_2O_3	3	.0004	.0009	10	8	10	8	0.39	0.48	0.50
B (1)	Cr_3C_2	9	Al_2O_3	6	0	- .0013	2	2	12	16	.22	.2-.62	.65
1	Si_3N_4	B-A	Si_3N_4	B-B	0	- .0011	15	14	14	18	.5	.1-.5	.1-.5
2	Si_3N_4	B-C	Si_3N_4	B-D	.0002	0	12	20	14	18	.3	.25	.25
5	Si_3N_4	LBL-A	Si_3N_4	LBL-B	0	.0001	16	12	14.2	8.3	.5	.5	.13
7	Si_3N_4	DG-A	Si_3N_4	DG-B	.00045	0	13	26	14	28	.55	.4	.4
8	Si_3N_4	DG-C	Si_3N_4	DG-D	- .0002	.0001	15	7-12	14	5-12	(5)	(5)	(5)
11	Si_3N_4	DB-A	Si_3N_4	DB-B	.0313	.0010	-	18	-	22	.42	.54	.30
12	Si_3N_4	DB-C	Si_3N_4	DB-D	- .0006	- .0007	8	3-7	5.5	25-5	.15	.56	.39
15	Si_3N_4	Y-E	Si_3N_4	Y-F	.0002	.0002	1.5	9	1.5	10	.66	.3-.54	.26
16	Si_3N_4	Y-G	Si_3N_4	Y-H	- .0014	- .0186	1.2	1.0	.8	.8	.385-.86	.215	.170
19 (4)	BeO	TR(A) 41	BeO	TR(A) 42	- .0018	- .0017	1-2	1.2-1.4	1-2	1.2-1.4	(5)	(5)	(5)
20 (4)	BeO	TD(A) 25	BeO	TD(A) 26	- .0007	- .0003	.8-1.4	1.-1.8	1.4-.24	1.2-1.4	(5)	(5)	(5)
21 (4)	BeO	TR(B) 48	BeO	TR(B) 49	- .0017	- .0023	8	6	6	4	(5)	(5)	(5)
22 (4)	BeO	TD(B) 34	BeO	TD(B) 35	- .0015	- .0004	4-6	2-4	5-6	4-5	(5)	(5)	(5)
23	Cr_2O_3 on Be	4	Cr_2O_3 on Be	5	- .0010	- .0009	4-6	3-4	4-5	4-5	(5)	(5)	(5)
24	Al_2O_3 on Be	14	Al_2O_3 on Be	15	- .0020	- .0017	11-14	9-13	8-16	8-14	(5)	(5)	(5)
25	Cr_2O_3 on Be(C)	6	Be(A)	1	.0006	.0035	4-5.5	-	1	12-22	(5)	(5)	(5)
26 (4)	Cr_2O_3 on Be(C)	7	BeO	TD(A) 23	.0088	- .0189	2-5	2-3	1-2	1-2	(5)	(5)	(5)
27 (4)	Cr_2O_3 on Be(C)	8	BeO	TR(A) 39	- .0013	- .0001	3-6	3-4	1-3	1-2	(5)	(5)	(5)
28 (4)	BeO	TR(A) 40	BeO	TD(A) 24	- .0017	- .0014	1-2	1-1.8	1-2	.6-1.6	(5)	(5)	(5)

Notes

(1) Reference specimen; plasma sprayed on 410 S.S.

(2) Averaged over readings at 100, 300, 500, 600, 700, 800, 900, and 1000 start-stop cycles.

(3) Code for Si_3N_4 Specimens:

Black 30 Microinches Rotary: B-A, B-B, B-C, B-d
Light Blue 30 Microinches Surface: LBL-A, LBL-B
Dark Green 15-20 Microinches Surface: DG-A, DG-B, DG-C, DG-D
Dark Blue 8 Microinches Surface: DB-A, DB-B, DB-C, DB-D
Yellow 1-2 Microinches: Y-E, Y-F, Y-G, Y-H

(4) Code for BeO Specimens:

TR - Thermolox 995 Regular Porosity
TD - Thermolox 995 Draper Porosity
(A) - A Finish 2-3 rms
(B) - B Finish 8-10 rms
(C) - C Finish 20-60 rms

(5) Break-away Coefficients of Friction not detectably different from running coefficient of friction.

(6) W

TABLE 3

CERAMIC GAS BEARING MATERIAL EVALUATION
SUMMARY OF START-STOP TESTS

Rubbing Pressure = 3.2 psi

...t Loss, gram(6)		Surface Roughness microinches, CLA				Break-away Coefficient of Friction					Running Coefficient of Friction					
		Rotating		Stationary												
...ng	Stationary	Before	After	Before	After	Start	500 Cycles	1000 Cycles	Average(2)	Avg. Change Per Cycle	Start	500 Cycles	1000 Cycles	Avg.(2)	Avg. Change Per Cycle	
...4	.0009	10	8	10	8	0.39	0.48	0.50	.47	9.32×10^{-4}	0.32	0.48	0.40	.39	7.86×10^{-4}	Oscillating.
	- .0013	2	2	12	16	.22	.2-.62	.65	.50	9.9×10^{-4}	.18	.62	.65	.50	10×10^{-4}	Severe stick-slip.
	- .0011	15	14	14	18	.5	.1-.5	.1-.5	.35	$7. \times 10^{-4}$	.42	.12	.22	.19	3.87×10^{-4}	Stick-slip; both surface...
...2	0	12	20	14	18	.3	.25	.25	.26	5.125×10^{-4}	.3	.25	.25	.26	5.125×10^{-4}	No stick-slip; edge of w...
	.0001	16	12	14.2	8.3	.5	.5	.13	.38	7.6×10^{-4}	.35	.32	.13	.28	5.675×10^{-4}	Surfaces polished.
...45	0	13	26	14	28	.55	.4	.4	.42	8.45×10^{-4}	.4	.4	.4	.38	7.55×10^{-4}	White debris in the wear...
...2	.0001	15	7-12	14	5-12	(5)	(5)	(5)	(5)	(5)	.13	.16	.18	.16	3.145×10^{-4}	A few spots were polished...
...3	.0010	-	18	-	22	.42	.54	.30	.425	8.5×10^{-4}	.30	.36	.30	.31	6.2×10^{-4}	Large quantities of white... to weight measurement). ...
...	- .0007	8	3-7	5.5	25-5	.15	.56	.39	.47	9.4×10^{-4}	.15	.56	.39	.47	9.4×10^{-4}	White debris showed up a...
...	.0002	1.5	9	1.5	10	.66	.3-.54	.26	.43	8.6×10^{-3}	.40	.37	.26	.32	6.5×10^{-4}	Severe stick-slip; stabi...
...	- .0186	1.2	1.0	.8	.8	.385-.86	.215	.170	.26	5.28×10^{-4}	.385-.86	.215	.170	.26	5.28×10^{-4}	Surfaces highly polished...
...	- .0017	1-2	1.2-1.4	1-2	1.2-1.4	(5)	(5)	(5)	(5)	(5)	.3	.11	.13	.14	2.75×10^{-4}	Scratches on surfaces be...
...7	- .0003	.8-1.4	1.-1.8	1.4-.24	1.2-1.4	(5)	(5)	(5)	(5)	(5)	.07	.09	.07	.08	1.6×10^{-4}	Glossy surfaces with som...
...7	- .0023	8	6	6	4	(5)	(5)	(5)	(5)	(5)	.138	.253	.324	.236	4.27×10^{-4}	Surfaces appeared dull b...
...	- .0004	4-6	2-4	5-6	4-5	(5)	(5)	(5)	(5)	(5)	.176	.310	.280	.26	5.2×10^{-4}	Dull surfaces before test...
...	- .0009	4-6	3-4	4-5	4-5	(5)	(5)	(5)	(5)	(5)	.127	.138	.148	.147	2.95×10^{-4}	Partial wear rings sligh...
...	- .0017	11-14	9-13	8-16	8-14	(5)	(5)	(5)	(5)	(5)	.18	.30	.31	.285	5.69×10^{-4}	A number of small polish...
	.0035	4-5.5	-	1	12-22	(5)	(5)	(5)	(5)	(5)	.41	.83	.82	.66	13.2×10^{-4}	Very noticeable surface ... specimens.
	- .0189	2-5	2-3	1-2	1-2	(5)	(5)	(5)	(5)	(5)	.23	.33	.29	.32	6.36×10^{-4}	Wear marks appeared on b...
	- .0001	3-6	3-4	1-3	1-2	(5)	(5)	(5)	(5)	(5)	.32	.23	.21	.24	4.8×10^{-4}	Wear marks appeared befo... after test.
...	- .0014	1-2	1-1.8	1-2	.6-1.6	(5)	(5)	(5)	(5)	(5)			Erratic			Repeated erratic readings...

...0,

...G-C, DG-D
...DG-D

(4) Code for BeO Specimens:

- TR - Thermolox 995 Regular Porosity
- TD - Thermolox 995 Draper Porosity
- (A) - A Finish 2-3 rms
- (B) - B Finish 8-10 rms
- (C) - C Finish 20-60 rms

(5) Break-away Coefficients of Friction not detectably different from running coefficient of friction.

(6) Negative sign indicates gain in weight.

10.2

LE 3

MATERIAL EVALUATION
ART-STOP TESTS

sure = 3.2 psi

t of Friction		Running Coefficient of Friction					
verage(2)	Avg. Change Per Cycle	Start	500 Cycles	1000 Cycles	Avg.(2)	Avg. Change Per Cycle	Remarks
.47	9.32×10^{-4}	0.32	0.48	0.40	.39	7.86×10^{-4}	Oscillating.
.50	9.9×10^{-4}	.18	.62	.65	.50	10×10^{-4}	Severe stick-slip.
.35	$7. \times 10^{-4}$	.42	.12	.22	.19	3.87×10^{-4}	Stick-slip; both surfaces scored.
.26	5.125×10^{-4}	.3	.25	.25	.26	5.125×10^{-4}	No stick-slip; edge of washers polished.
.38	7.6×10^{-4}	.35	.32	.13	.28	5.675×10^{-4}	Surfaces polished.
.42	8.45×10^{-4}	.4	.4	.4	.38	7.55×10^{-4}	White debris in the wear tracks (removed before weighing).
(5)	(5)	.13	.16	.18	.16	3.145×10^{-4}	A few spots were polished.
.425	8.5×10^{-4}	.30	.36	.30	.31	6.2×10^{-4}	Large quantities of white debris on surface (not cleaned prior to weight measurement). One heavy scratch on specimen A.
.47	9.4×10^{-4}	.15	.56	.39	.47	9.4×10^{-4}	White debris showed up slightly in both specimens.
.43	8.6×10^{-3}	.40	.37	.26	.32	6.5×10^{-4}	Severe stick-slip; stabilized out after 500 cycles to no stick-slip.
.26	5.28×10^{-4}	.385-.86	.215	.170	.26	5.28×10^{-4}	Surfaces highly spolished and shiny.
(5)	(5)	.3	.12	.1?	.14	2.75×10^{-4}	Scratches on surfaces before test; polished and glossy after test.
(5)	(5)	.07	.09	.07	.08	1.6×10^{-4}	Glossy surfaces with some rings formed from smearing.
(5)	(5)	.138	.253	.324	.236	4.27×10^{-4}	Surfaces appeared dull before and after test; no scratches or blemishes.
(5)	(5)	.?76	.310	.280	.26	5.2×10^{-4}	Dull surfaces before test; specimen #34 appeared glossy after test.
(5)	(5)	.127	.138	.148	.147	2.95×10^{-4}	Partial wear rings slightly visible; no visible scratches.
(5)	(5)	.18	.30	.31	.285	5.69×10^{-4}	A number of small polished patches appeared after test.
(5)	(5)	.41	.83	.82	.66	13.2×10^{-4}	Very noticeable surface damage to both specs.; white wear rings on coated specimens.
(5)	(5)	.23	.33	.29	.32	6.36×10^{-4}	Wear marks appeared on both surfaces.
(5)	(5)	.32	.23	.21	.24	4.8×10^{-4}	Wear marks appeared before and after test. Very light wear rings appeared after test.
(5)	(5)			Erratic			Repeated erratic readings on friction coefficients.

Negative sign indicates gain in weight.

.2

10.3

When higher friction values were measured, they were generally associated with the presence of this white wear product.

Attempts to relate the effect of surface roughness to the sliding performance of Si_3N_4 were disappointing since the roughness of the test specimens did not have enough variation. The centerline average of the specimens before testing ranged from one to eighteen microinches. Neglecting the specimens with white wear debris, there seems to be a very slight increase in friction as the CLA roughness increases up to about 15 microinches. Above this there seems to be a sharp increase in friction. Unfortunately, there were few samples with roughness above 15 microinches and even those were shown to have widely scattered coefficients of friction. No significant trend could be discerned in the variation of the coefficient of friction of silicon nitride as a function of stress.

Beryllium oxide sliding against itself appeared to be an effective combination, but the friction values in many cases are so low that it is very likely that the surfaces were contaminated. The possibility of some reaction product being formed between the solvent used to clean the specimens and the BeO surface is a potential source of this contamination. The combination of very low friction and a polishing effect, such as was observed in the start-stop test numbers 19 and 22, generally points to the presence of a reactive film on the surfaces. The beryllium oxide combinations showed a definite trend toward increasing friction with increasing load. No pattern of frictional variation with changes in the surface roughness of the BeO could be detected, at least in this range of surface roughnesses (~ 1-6 microinches).

Comparisons between the regular porosity BeO and the Draper porosity material do not indicate any strong trends. In some of the tests, such as test numbers 30 and 32 under continuous sliding conditions, or test number 26 of the start-stop series, the Draper porosity specimens showed much higher wear than the regular porosity BeO. However, because of the possibility of contaminating films being present, it is difficult to interpret these results as being due to the effect of porosity. Of the other combinations, Cr_2O_3 coated beryllium versus BeO did not show any particular promise. Cr_3C_2 versus Al_2O_3 resulted in some surface damage to the Al_2O_3 during the start-stop test. Al_2O_3 versus Al_2O_3 gave low friction, but moderate wear. Past experience (Ref. 2) has shown that this combination is very sensitive to humidity effects, and in dry environments or at higher temperature levels sudden increases in friction and surface damage should be anticipated, especially at higher stress levels. Finally, when Cr_2O_3-coated beryllium was mated with plain beryllium, considerable damage was incurred on both specimens.

In the continuous rubbing tests all of the sliding surfaces, except for the chrome oxide versus beryllium, showed improved surface finishes after the sliding tests had been concluded.

5.0 REFERENCES

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