BLAST, A New Lubricant Screening Tester for Space Oils & Greases

S.Gill, M K Vine & R.A.Rowntree

European Space Tribology Laboratory (ESTL)
Risley, Warrington, UK

ABSTRACT

This paper describes the design, development, commissioning and evaluation of a Boundary Lubrication Accelerated Screening Tester (BLAST) to provide a valid means of rapidly evaluating and ranking the boundary lubrication performance and degradation resistance of spacecraft liquid lubricants.

To date >60 tests of differing space lubricants, bearing materials & surface treatments/coatings have been performed. Where comparison is possible, results to date have given a ranking directly comparable with that of real-time bearing tests. The benefits (or not) of new space lubricants and novel surface treatments/coatings is described.

KEYWORDS: Liquid Lubricants, Testers, Accelerated Testing, Vacuum

1. INTRODUCTION

A major disadvantage in the use of liquid lubricants for spacecraft applications is the difficulty of predicting their long term performance. Satisfactory behaviour has, in the past, only been demonstrated by real lifetime testing. This is because simply increasing the speed of a liquid lubricated component (bearing, gear etc) can fundamentally change the lubrication conditions (film thickness, asperity interaction, film temperature, lubricant distribution etc). Such 'accelerated tests' are therefore often invalid or at best optimistic. As a consequence, the development of reliable liquid space lubricants has been slow. Real time testing also renders it impossible to rapidly screen new lubricant/material combinations, and to compare the performance of lubricant batches.

A considerable amount of real-time testing of liquid lubricants in angular contact ball bearings has been performed at ESTL (Refs. 1 - 4). However, the duration of these tests (typically > 1 year/test) limits the development and assessment of the many new liquid lubricants, alternative bearing materials and surface treatments now available. Elsewhere, a great deal of life testing has been carried out (eg Ref. 7), also over periods of years per test.

Provided that the lubricant can be operated solely in the boundary lubrication regime, as opposed to the speed-sensitive range of elastohydrodynamic lubrication, then there is a reasonable argument that accelerated testing is possible simply by an increase in the contact loading and the sliding speed. Carre (Ref. 5) has described an apparatus, based on an eccentric motion thrust bearing, in which the accelerated testing of lubricants in boundary conditions was performed. Based on this work, ESTL has built a facility for the accelerated testing of liquid lubricants under boundary conditions in vacuum.

The objective of the present work was to provide a valid means of rapidly evaluating and ranking the boundary lubrication performance and degradation resistance of spacecraft liquid lubricants.

At the outset, the test philosophy was that the tests would be carried out at nominal room temperature, using bearing and discs manufactured from conventional hardened SAE 52100 steel. The bearing torque would be used as a measure of lubricant/test disc degradation. Conditions (contact stress, speed and eccentricity) would be chosen such that a complete test cycle (ie assembly, lubrication, pump-down and test) would be possible within (say) 7 days, even with a 'good' liquid lubricant.

This paper describes the commissioning of the rig, and the results of tests performed on some commercial space oils & greases, and with alternative substrate materials & coatings.

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2. TEST DETAILS

2.1 Test Rig Description

The boundary lubricant accelerated screening tester is illustrated in Figure 1. It is designed to achieve boundary lubrication conditions through a combination of ball skidding (by imposition of a transverse ball/raceway slip) and rolling action, at contact pressures typical of, or in excess of, liquid lubricated ball bearing applications.

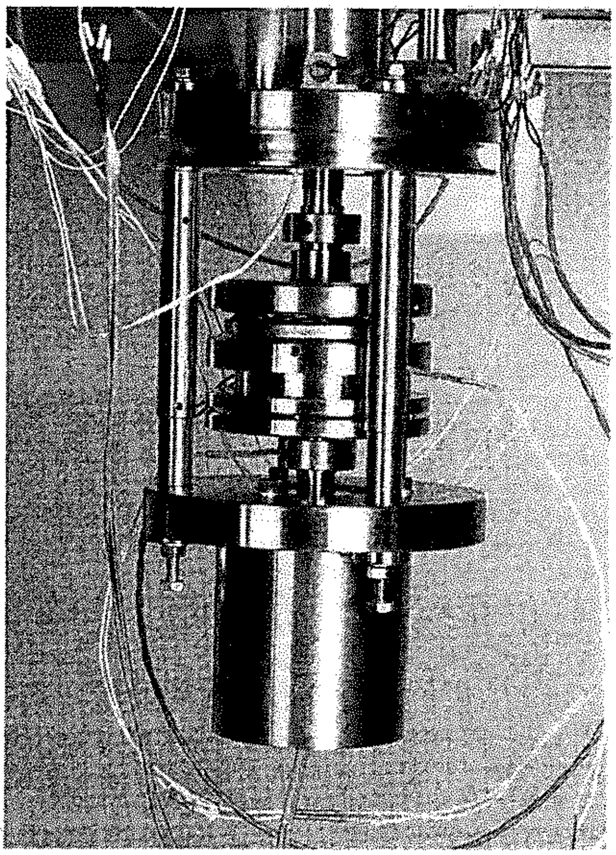


Figure 1. BLAST Rig, showing thrust bearing, thrust disc & torque transducer.

The raceway of a 52100 steel thrust bearing is attached to a lower housing, which in turn is rigidly clamped to a Teldix DG1-4 torque transducer. Opposing this is a flat disc of size 52 mm ID and 78 OD mm (INA thrust disc WS81210) and separated from the latter by the balls of the thrust bearing. The flat thrust disc is secured to the upper housing and clamped to the drive shaft. The rotational axis of the disc and thrust race are not coaxial and can be displaced to provide an eccentric motion, hence inducing ball skidding (Figure 2).

Electrical heaters are attached to the lower housing for thermal control - temperatures of up to 150°C at the bearing interface can be achieved. Both upper and lower housing are manufactured from ferritic steel for thermal expansion matching. A thermal break between the lower housing and Teldix transducer protects the latter from the high temperatures (max allowable temperature of a Teldix DG1-4 transducer is 80°C). The signal from the torque transducer is conditioned to be an analogue voltage by its associated electronics.

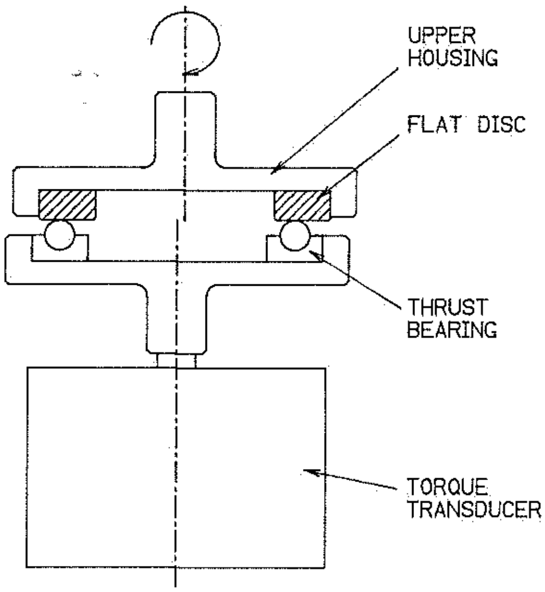


Figure 2. Schematic arrangement of key elements of BLAST rig.

The drive shaft is rigidly supported by a pair of 20mm ID angular contact ball bearings in a back-to-back configuration. The shaft is driven by an external motor (at speeds up to 3000 RPM) via a Ferrofluidic feedthrough. Axial loads up to 400 N can be applied by calibrated spring washers. By suitable choice of ball size and complement large changes in Hertzian contact stresses can be obtained (140 MPa to 750 MPa at the ball/disc interface, for the standard ball size). The entire rig is located in a 40 cm vacuum chamber and the chamber evacuated using turbomolecular and ion pumps. The test residual pressure is $<10^{-6}$ mbar.

Thermal control is achieved using a cooling bath circulating alcohol at 20°C. Torque and vacuum data are continuously recorded on a chart recorder, whilst temperatures are measured on a data logger.

2.2 Test Conditions

Tests were performed under the following conditions:

Lubricant Quantity:	50 microlitres of oil, or 0.1 gm grease.
Race Material:	52100 bearing steel, SKF 51210.
Disc Material:	52100 bearing steel, INA thrust disc WS 81210, 0.1 microns R_a. Other materials specified below
Cage Material:	En 3 Steel (as supplied)
Ball Material:	52100 bearing steel
No. of Balls:	14
Offset:	2 mm
Preload:	300 N
Speed:	1500 rpm
Test Duration:	10 hours in air; to failure in vacuum.
Disc Temperature:	Initial tests were performed without temperature control. Subsequent tests were at a controlled temperature of 20°C

A new bearing and thrust disc combination was used per lubricant test. Torque and pressure were continuously recorded on a chart recorder during each test. All bearing components were thoroughly ultrasonically washed in 'Arklone P' prior to lubrication and assembly into the test rig.

2.3 Lubricants & Materials Evaluated

The following lubricants were employed in these tests:

<u>Oils</u>

Fomblin Z25	(Perfluorinated Polyether)
KG80	(Refined Mineral Oil)
Fomblin Y VAC 40/11	(Perfluorinated Polyether)
BP110	(Refined Mineral Oil)
Nye PAO-6	(Polyalphaolefin)
Nye PAO-40	(Polyalphaolefin)
Nye Neopentyl Ester	(Ester)

<u>Greases</u>

Braycote 601	(Braycote 815Z + PTFE + Rust Inhib.)
Braycote 802	(Braycote 811 + PTFE)
Fomblin ZNF	(Fomblin Z25 + PTFE)
Microscal OG100	(Fomblin Z25 + Oleophilic Graphite)
Microscal OGP6	(Fomblin Z25 + Oleophilic Graphite/Lead)
Microscal GM10	(Fomblin Z25 + Oleophilic MoS_2)

2.4 Coatings and Substrates Evaluated

The following types of substrate/coating material have been tested:-

52100 Bearing Steel
440C Stainless Steel
Si_3N_4 (hot pressed monolithic)
TiN coating (arc evaporative process, 1.6 microns)
Lead (ion plated, 1.1 microns) by ESTL
MoS_2 (sputter deposition, 1.2 microns) by ESTL

All three coatings above were applied to standard INA 52100 bearing steel thrust discs. The titanium nitride coated discs were polished with 1200 grit and water prior to ultrasonic cleaning, in an effort to remove the surface nodules formed during the coating process.

It was not possible to change the ball material. The cage supplied was of the formed pressed steel type, and did not readily allow balls to be removed.

3. RESULTS

3.1 Tests in Air

Initially commissioning tests where performed in air, with a fixed period of running of 10hrs. Z25, Y VAC 40, KG80 and BP110 oils were selected as test lubricants because of their well known behaviour (and degradation performance) in ball bearings in vacuum under long term conditions. This behaviour is reviewed in reference 5.

All these lubricants showed an initial running-in period, where the bearing torque rapidly decreased, followed by a more gradual rise in disc temperature. This was followed by a stable period, where torque was reasonably constant, although the bearing lubricated with Fomblin Z25 continually rose. A similar response was found from the temperature measurements, where both the Fomblin Z25 and Y VAC 40/11 continually rose.

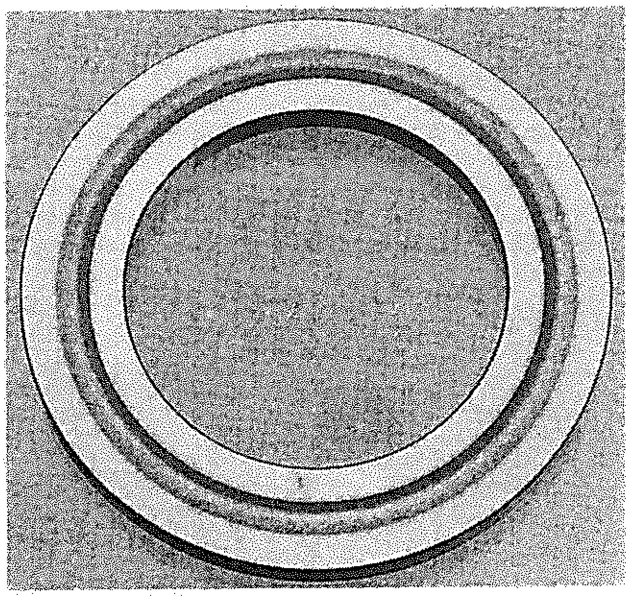
In post-test examinations (Figure 3a), the thrust disc of the Z25 lubricated bearing showed the characteristic signs of lubricant degradation, with brown lubricant residues on the inner and outer extremes of the ball track. Some brown residues were also found on the Y VAC 40 (Figure 3b) lubricated thrust disc. Minimal dark residues were present on the discs lubricated with KG80 & BP110 (Figures 3c & d respectively). In all discs 'virgin' lubricant was present both inside and outside the ball track.

Optical and Talysurf examination of the Z25 test revealed notable wear in the ball track of the thrust disc, with two distinct regions of wear. Some minor pitting was visible when viewed by scanning electron microscopy. Banding of the ball track was visible, but not so extensive on the Y VAC 40 test disc. There was no visible change in the surface texture of the ball track on the thrust discs from the KG80 and BP110 tests.

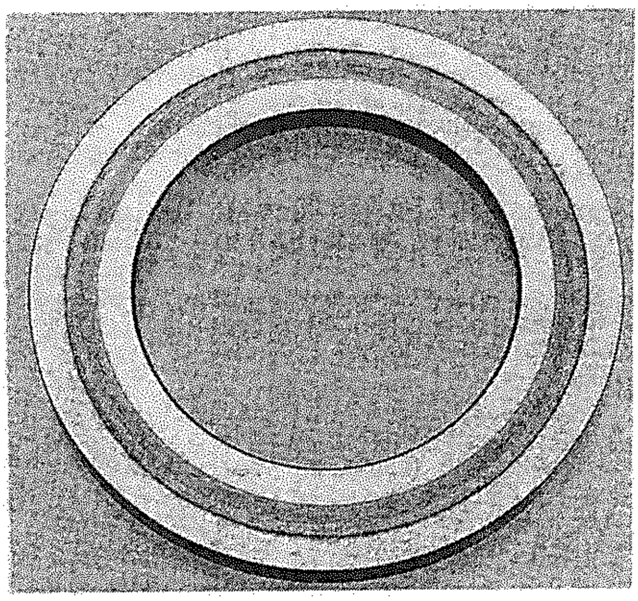
During these tests the rapid onset of boundary lubrication was confirmed by measuring the electrical contact resistance across the thrust bearing & disc, as an indicator of asperity interaction.

3.2 Tests In Vacuum

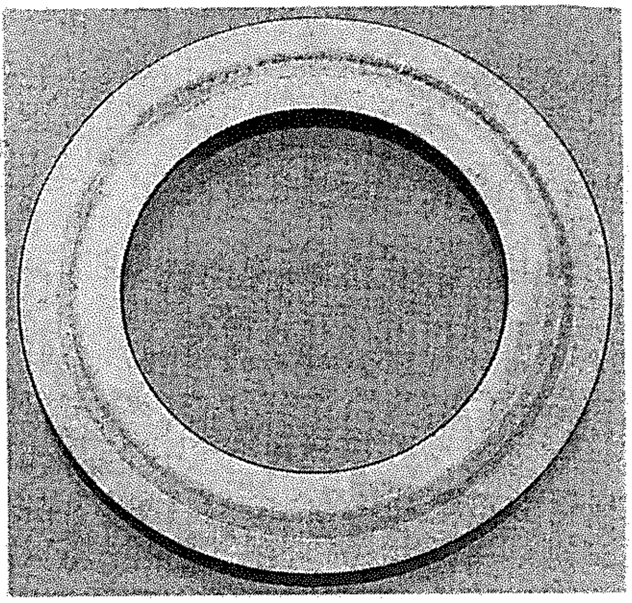
Initial tests in vacuum with bearings lubricated with Z25 and KG80 were curtailed due to a rapid increase in the bearing temperature (>75 deg C).



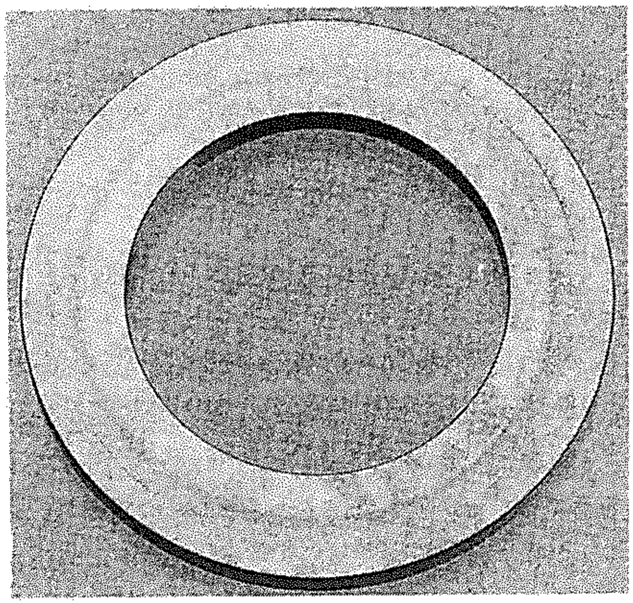
(a) Fomblin Z25



(b) Fomblin Y VAC 40/11



(c) BP 110



(d) KG 80

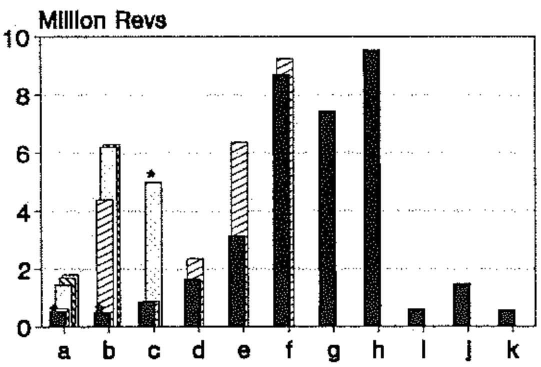
Figure 3. Thrust Discs after 10hrs running in air

Examination of the bearings & discs after testing showed the oil had migrated away from the contact zone. A new bearing housing equipped with an integral cooling channel was therefore manufactured and tests repeated. A second set tests still gave greater variations than anticipated, and investigations revealed some unforseen load changes. This was caused by the load-setting gap closing up during running, as a result of swash in the rig. Additional modifications, allowing an increase in the load setting gap for the same applied load, much reduced these load variations.

The full results obtained after the above modifications are shown in Figure 4 (modified loading and integral cooling). All the bearing sets now had lubricant remaining on all their components. All discs exhibited lubricant residues at the edges of the ball track, together with varying amounts of degraded lubricant, particulate debris and track wear.

The lubricant residues from the Z25-based grease lubricants (Braycote 601, Fomblin ZNF, Microscal OG100, Microscal OGP6, Microscal GM10) were similar in each case, akin to black wet 'tea leaves'. These lubricants also tended to generate more larger particle debris, than the other types tested.

Figure 4. BLAST Lubricant Evaluation



Key: a - Fomblin Z25, b - Fomblin Y VAC 40/11, c - Nye PAO-6, d - Nye PAO-40, e - Nye Neopentyl Ester, f - Braycote 601, g - Braycote 802, h - Fomblin ZNF, i - Microscal OG100, j - Microscal OGP6, k - Microscal GM10.

* suspected load variations

Figure 5. BLAST Evaluation of alternative substrates & lubricants

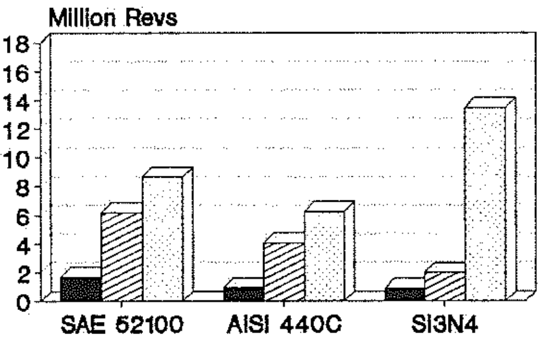
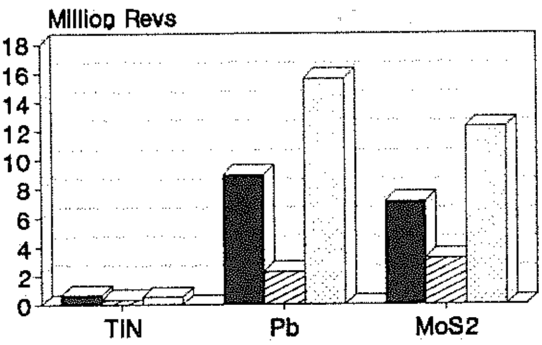


Figure 6. BLAST evaluation of alternative coatings & lubricants



Test failure in vacuum was characterised by a change in the torque behaviour (typically an increase in both the mean torque and the torque noise) and a rapid rise in the chamber pressure. The chamber pressure typically rises from $<10^{-6}$ mbar to $>10^{-5}$ mbar over a period of about 15 minutes. Various pressure excursions were also observed throughout these tests (during 'acceptable' lubricant behaviour).

3.3 Alternative Coatings & Substrates

The number of revolutions to failure for each of the tested combinations is shown in Figures 5 & 6. Coatings were applied to the 52100 thrust disc substrate only.

All the bearing sets had lubricant visibly remaining after testing, on all their components. All exhibited lubricant residues at the edges of the ball track, together with varying amounts of degraded lubricant, particulate debris and track wear. Apart from the TiN-coated disc results, the visual condition of the lubricated ball track, in each thrust disc, is consistent with the relative lifetime of the lubricant/material combination.

4. DISCUSSION

4.1 Tests in Air

Although the test conditions were chosen at random (but based on those used by Carre), from the measurements of disc wear, torque and temperature change, it is possible to rank the lubricants in order of increasing boundary lubrication efficiency. This ranking (worst:Z25, Y VAC 40, KG80, BP110:best) is entirely in agreement with results from long term vacuum tests performed on ball bearings lubricated with these oils. As such it gives a measure of confidence in the principle of the boundary lubricant tester.

4.2 Tests in Vacuum

Initial tests in vacuum did not give consistent results. Only with subsequent close temperature and load control were repeatable results obtained for a given lubricant.

Using Fomblin Z25 behaviour as the 'datum' for the other oils, then PAO-40, Y VAC 40 & Neopentyl Ester all have superior boundary lubrication efficacy. This in agreement with ESTL ball bearings results. This gives further confidence in the validity of the test method. It predicts that superior performance in ball bearings (compared to Z25) will be achieved with PAO-40 & the Neopentyl Ester. This was broadly confirmed in subsequent bearing tests at ESTL, Amongst the greases, Braycote 601, 802 and Fomblin ZNF all give a similar boundary lubrication performance. Braycote 601 and ZNF give similar results, as might be expected since these greases have essentially the same composition (Z25 + PTFE), although they are from different manufacturers. Braycote 802 uses a different base oil (Brayco 811), although its properties are not much different to 601. The outstanding feature is the significant improvement in boundary lubrication with the presence of PTFE.

There is a marked reduction of performance of the Microscal-thickened greases relative to their base oil Fomblin Z25. These results imply that none of the oleophilic additives are effective in Z25, by contrast these same additives were highly effective in BP110 and BP135 oils. From the examination of the test bearings both lead and MoS_2 are deposited to some minor degree by the Microscal greases in the ball tracks.

4.3 Alternative Coatings & Substrates

Comparison of the results obtained using Y VAC 40 and Z25 with standard bearing steels, 52100 and 440C, confirms the superiority of the former under boundary lubrication conditions. There is also a strong similarity in the relative performance trends of the two Z25 based lubricants (ie Z25 & Braycote 601) for the overall test matrix of materials and coatings.

From previous work at ESTL (Ref. 8), where Z25 was evaluated in both 52100 & 440C ball bearings at 1400rpm (ie under elasto-hydrodynamic conditions), the stainless steel samples were expected to out-perform the plain 52100 steel samples. This was not found in these tests and three factors may contribute to this. Firstly the INA-supplied 52100 steel discs have a hardness of around 800Hv, whilst the stainless steel samples were specially made for ESTL and their hardness is only 700Hv (a typical stainless steel bearing hardness). Secondly this test may require the whole of the test sample to be of stainless steel. Interaction between the lower thrust race and the balls, both 52100 bearing steel, could be masking the real performance of stainless steel. Thirdly 440C bearings (as used in Ref. 8) are usually supplied as 'passivated' thereby ensuring a surface consisting essentially of chromium oxides. The 440C discs used in these tests were not passivated and the possibility exists, therefore, of these discs having more chemically active surfaces.

Silicon nitride has only shown an improvement for the grease tested, Braycote 601. This result needs further investigation, however it is postulated that some characteristic of Si_3N_4 discs may cause the PTFE filler particles to become trapped thus enhancing the boundary lubrication performance.

PVD coatings of titanium nitride have been shown, in dry-lubricated ball-on-disc evaluations, to give unpredictable results at ESTL in the past (Ref. 9). The life reduction has been previously considered to be caused by the breaking off of titanium-rich nodules formed during the coating process (despite careful attempts to remove all the nodules by polishing with diamond paste). On the other hand Carre (Ref. 10), shows an improvement of 5-10 times for TiN coated samples over the life of plain 440C samples. This is almost certainly due to the fact that his samples were reactively sputter coated with TiN (unlike those at ESTL which were arc- evaporative coated). The reasons for the short lubricant lifetimes when using TiN coatings in these BLAST tests is not clear.

Ion-plated lead coating has shown a significantly increased life for Fomblin Z25 oil and its related grease Braycote 601. This is in agreement with verbal information received from sources in the United States. No literature references have been found to date.

Sputter-coated MoS_2 again only aids the performance of the Z25-based lubricants. The sample showing the vastly reduced life of 180,000 revolutions with Y VAC 40 showed signs of fatigue failure. This is the first such failure in more than fifty tests performed to date, and was probably due to the poor manufacture of this particular thrust disc.

The significant reduction of life for the Y VAC 40 samples when in the presence of either hard ceramic or solid lubricant coating is interesting and the reason may become evident during the degradation study planned for 1992/93.

Implications for the future test-work on this rig are that the surface finish and hardness of the samples must continue to be monitored. Also a new cage design is urgently required to allow the insertion of new balls such that the whole test sample can be of like material.

4.3 Pressure Variations

The trips on the test rig are set to stop the test as a result of either an increase in torque level or an increase in the chamber pressure. However, the tests are invariably stopped as the result of a pressure rise, because the changes in the torque levels lag behind marginally in time .

The gases evolved, at and in some cases before failure, appear to be fractions of the lubricant polymer chain. Due to limitations of the control equipment, full mass spectra have not been obtained at the time of failure, since the mass spectrometer has been set to scan certain peaks and write the results to a printer every 20 minutes. The outgassing phenomena are of great interest in both the understanding of the degradation processes, and in their possible contamination of clean spacecraft surfaces.

4.4 Disc Analysis

The bearing sets have not been examined in any way (other than visually) and so the remnants of the lubricants and their degradation products have not been analysed. The analysis of future specimens in parallel with pressure monitoring will yield a comprehensive knowledge of the degradation processes taking place.

5. CONCLUSIONS

5.1 The Boundary Lubricant Accelerated Screening Tester is commissioned and capable of running accelerated tests on oils and greases in vacuum, and assessing the effects of differing coatings & substrates. Results to date have given a ranking directly comparable with that of real life tests. However, some rogue results have occurred, and careful monitoring is required to remove these.

5.2 There is a strong similarity in the relative performance of the Z25 based lubricants (ie Z25 & Braycote 601) for the overall test matrix of materials and coatings.

5.3 MoS_2 and lead coatings have been shown to consistently increase the life of Fomblin Z25 oil and its related grease Braycote 601. Y VAC 40 does not benefit from the application of these coatings, and indeed suffers some reduction in performance. The addition of oleophilic solid lubricant additives was detrimental to performance of the Fomblin Z25.

5.4 Tests on unpassivated 440C stainless steel show a reduced level of performance, relative to 52100 steel. Further tests need to be performed to investigate why this result appears to be at odds with previous work. Tests with an all 440C system would be necessary.

5.5 Arc-evaporative titanium nitride has again shown its susceptibility to unpredictable tribological performance in lubricated contacts.

5.6 Silicon nitride appears to only benefit the grease, Braycote 601. Further work is required to understand this result, however the characteristic surface finish may cause the trapping of PTFE filler particles to provide this improvement.

5.7 Detailed analysis of the debris, coupled with computer control of the mass spectrometer measuring released species would give a greater insight into the degradation processes of these oils and greases.

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