SPIRAL ORBIT TRIBOMETER ASSESSMENT OF SPACE LUBRICANTS

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ABSTRACT

We present the findings of a test program performed by ESTL to evaluate the performance (friction and lifetime) of a number of space lubricants using a Spiral Orbit Tribometer (SOT). Tests were performed on both liquid and solid lubricants.

It was found that the lifetimes of the hydrocarbons NYE 2001 and 2001A outperformed those of the PFPAEs Z25 and Z60 oil, with Z25 slightly outperforming Z60. It was also observed that liquid lubricant lifetime decreases with increasing contact stress. These observations correspond with current understandings of liquid lubricants [1] & [2].

For solid lubricants, it was found that lead displayed greatly extended lifetimes over MoS_2, speculated to be caused by re-distribution of the lead over all contact surfaces during the test. The lifetime of lead was found to decrease with increasing contact stress. In addition, the performance of MoS_2 was not found to vary with differing coating thicknesses in the range 0.1 – 0.5µm.

1. INTRODUCTION

The Spiral Orbit Tribometer (SOT) is a new test facility recently purchased by ESTL to advance the assessment of lubricants and coatings used in space applications. The facility reproduces the kinematics of an angular contact bearing, and allows for the evaluation of friction and degradation rates (i.e. consumption/wear) of lubricants in detail. The facility has the capacity to test liquid lubricants, grease lubricants and thin solid films.

In a typical test using the SOT only a very small amount of lubricant is used; of the order of micrograms. This produces meaningful results on the lifetime of the lubricants, whilst maintaining short test durations. In addition the amount of lubricant is so small hydrodynamic lift cannot occur – thus the mode of lubrication is always boundary lubrication.

As the first package of work performed on this facility, the objective was to assess the tribological behaviour of a number of established and frequently used space lubricants using the SOT.

2. SCOPE OF WORK

The following tasks were covered by this investigation.

- Set-up and familiarisation: As a new test facility, time was given to set-up and gain familiarisation of the facility to ensure good performance. This included all relevant software, hardware, and the lubrication techniques required for microgram application processes.

- Liquid lubricant assessment: The performance of four oils with heritage in the space industry was assessed for their friction and lifetime, monitored with varying contact stress. These included two synthetic hydrocarbons (NYE 2001 & 2001A, with and without additives respectively), and two perfluoropolyalkylethers (PFPAEs) (Fomblin Z25 & Fomblin Z60).

- Solid lubricant assessment: Two thin solid film coatings used within the space industry were assessed for their friction and lifetime performance, with varying contact stress and coating thickness. The two coatings assessed were sputtered MoS_2 and lead, applied by ESTL's sputter coating rig.

- Results comparison: Comparison of results with similar investigations using a SOT performed at NASA-Glenn Research Centre, Cleveland, OH.

3. APPARATUS

3.1. Spiral Orbit Tribometer

The Spiral Orbit Tribometer is essentially a thrust bearing, with a single ball held between two interchangeable flat plates, located within a vacuum chamber. A load is applied to the top plate via a spring-loaded linear translator. The lower plate rotates via a motor located outside the chamber, causing the ball to move in a spiral path with a radius ~21mm.

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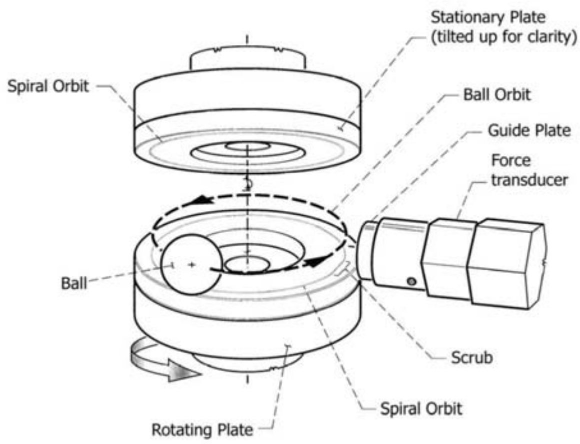

Figure 1. Internal arrangement of SOT, image courtesy of Spiralab

This configuration causes the ball to spiral outwards, and a fixed guide plate is positioned to keep the ball within the flat plates and to maintain a repeatable orbit. The region of each orbit for which the ball is in contact with guide plate is denoted as the scrub (see Fig. 1). A force transducer behind the guide plate measures the force exerted by the ball onto the guide plate. From this the friction coefficient for each orbit is found. This is plotted to give the performance of the lubricant over time (Fig. 2)

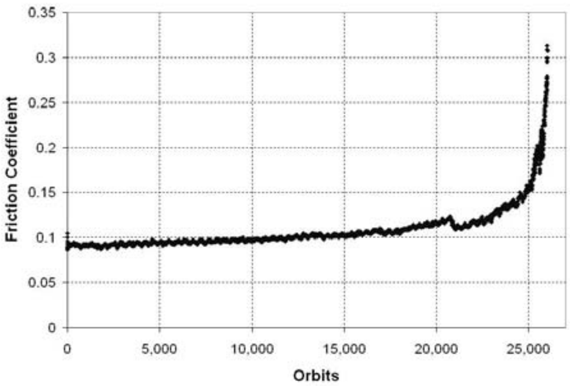

Figure 2. Typical friction plot generated with the SOT

The arrangement of the SOT allows the ball to experience rolling, sliding and pivoting – all motions experienced by a ball in an angular contact bearing. This allows for a more representative testing of a lubricant than conventional pin-on-disc testing, which only recreates sliding motion.

3.2. Samples

Test plates were manufactured from 440C steel, and polished to a surface roughness R_a<0.05microns. Balls used were either 12.7mm (1/2”) or 7.14mm (9/32”) diameter manufactured from 400C and 52100 steel respectively, depending upon the contact stress requirements of the particular test.

3.3. Controllers

The SOT is controlled by a supplied laptop PC, running a Labview based data acquisition program (DAQ).

4. PROCEDURES

4.1. Sample preparation

Prior to testing, all balls and plates were solvent cleaned in a Kerry cleaning plant using Lenium ES solvent in accordance with standard ESTL practice.

4.2. Lubrication

Liquid lubrication was achieved through the preparation of a solution of lubricant diluted into an appropriate solvent, of a known concentration. This solution was applied directly to a rotating ball. The solvent was allowed to evaporate from the ball’s surface, leaving the desired lubricant amount. This method allows for the application of very small amounts of lubricant, typically 50µg. This minuscule amount of lubricant allows for reduced test times, and ensures all tests take place under boundary conditions.

Solid lubrication was performed via ESTL’s sputtered coating rig, coating the balls only to a desired thickness. The coating thicknesses were assessed using an X-Ray Fluorescence (XRF) measurement system, taking 20 measurements of 60 seconds for each coating run.

5. TEST PROGRAMME

5.1. Liquid Lubricant Assessment

Testing was performed using the SOT, under vacuum (<1.3 x 10^{-6} mbar), and at room temperature (~23deg.C). A lubricant amount of ~50µg was applied to each ball. Tests ran until the friction coefficient exceeded 0.3 for three consecutive orbits, at which point the motion was stopped. Testing was carried out according to Table 1 below.

Table 1. Test matrix for liquid lubricant tests

Lubricant (Oil)	Mean contact stress	Ball size	Rotation speed
Z25	1.00GPa	12.7mm	30RPM
Z25	1.25GPa	12.7mm	30RPM
Z25	1.50GPa	12.7mm	30RPM
Z25	1.75GPa	7.14mm	30RPM
Z60	1.00GPa	12.7mm	30RPM
Z60	1.25GPa	12.7mm	30RPM
Z60	1.50GPa	12.7mm	30RPM
Z60	1.75GPa	7.14mm	30RPM
NYE 2001	1.00GPa	12.7mm	100RPM
NYE 2001	1.25GPa	12.7mm	100RPM
NYE 2001	1.50GPa	12.7mm	100RPM
NYE 2001	1.75GPa	7.14mm	100RPM
NYE 2001A	1.00GPa	12.7mm	100RPM
NYE 2001A	1.25GPa	12.7mm	100RPM
NYE 2001A	1.50GPa	12.7mm	100RPM
NYE 2001A	1.75GPa	7.14mm	100RPM

- A smaller ball size was used for tests at 1.75GPa to allow the higher contact stress to be reached without requiring excessive strain on the linear translator. However a preliminary investigation at ESTL using Z25 demonstrated no dependence of the lubricant performance upon ball size for this lubricant.

- The original test plan called for all tests to be performed at 30RPM. However this was increased for the tests on the hydrocarbons as it was believed these tests would display excessively long test durations. A preliminary investigation at ESTL using Z25 demonstrated no apparent dependence of lifetime upon rotation speed for this lubricant.

5.2. Solid Lubricant Assessment

Tests were performed in vacuum (<1.3 x 10^{-6} mbar), at room temperature (~23deg.C). Tests ran until the friction coefficient exceeded 0.3 for three consecutive orbits, at which point the motion was stopped. For all tests a 52100 steel ball of diameter 7.14mm and rotation speed of 100RPM was used. Testing was carried out according to Tab. 2 below.

Table 2. Test matrix for solid lubricant tests

Lubricant (Thin solid film)	Coating thickness	Mean contact stress
MoS_2	800Å	1.50GPa
MoS_2	2300Å	1.50GPa
MoS_2	5300Å	1.50GPa
Lead	850Å	1.50GPa
Lead	850Å	1.75GPa
Lead	850Å	2.00GPa

- For MoS_2 the coating thickness was varied with constant mean contact stress.

- For lead the mean contact stress was varied with constant coating thickness.

6. RESULTS

6.1. Liquid Lubricant Assessment

Figs. 3 & 4 below show the life and frictional behaviour of the test oils as a function of mean contact stress. Lifetimes are normalized to orbits/microgram of lubricant. Steady state friction values are calculated by averaging 100 readings around the 400th orbit of each test.

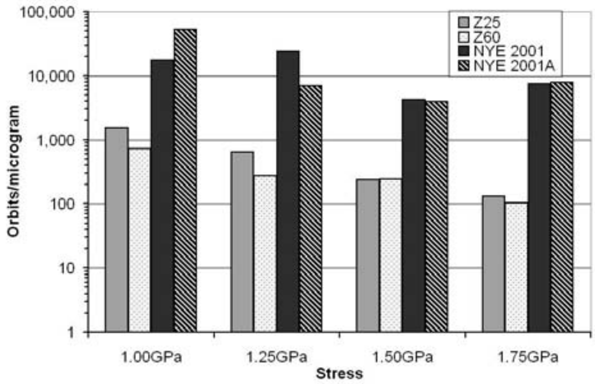

Figure 3. Lifetimes of liquid lubricants under varying mean contact stresses

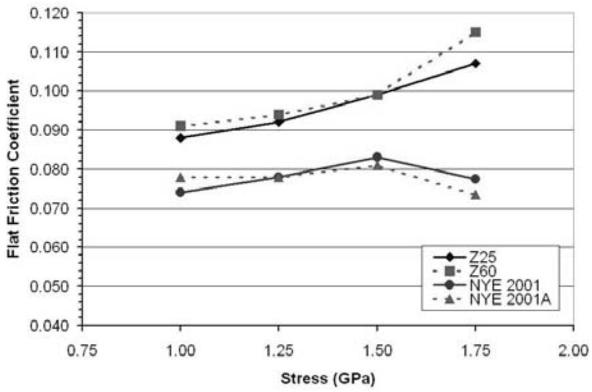

Figure 4. Steady state friction coefficients of liquid lubricants as a function of mean contact stress

6.2. Solid Lubricant Assessment – MoS_2

Figs. 5 & 6 summarise results for sputtered MoS_2 of varying thickness, applied to the ball only. Two tests were performed at each thickness, and the range of values are represented on the plots. Steady state friction coefficients are calculated by averaging 100 values around the 100,000th orbit for each test.

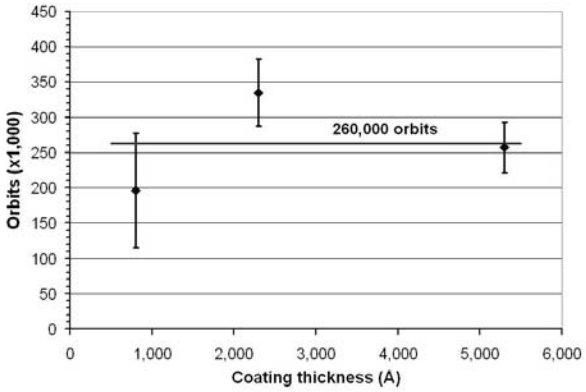

Figure 5. Lifetimes of MoS_2 coatings as a function of coating thickness

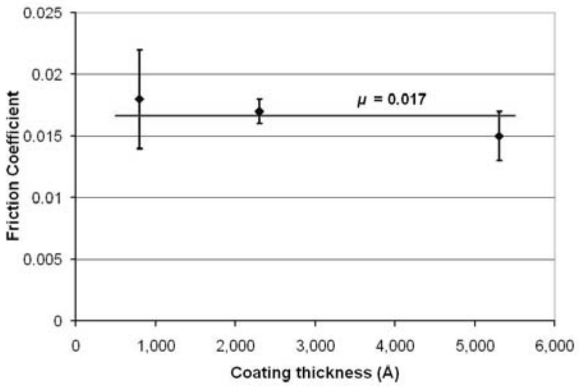

Figure 6. Friction coefficient of MoS_2 coatings as a function of coating thickness

6.3. Solid Lubricant Assessment – Lead

Figs. 5 & 6 demonstrate the performance of sputtered lead applied to the ball only, under varying mean contact stresses. Steady state friction coefficients are calculated by averaging 100 values around the 1,000,000th orbit of each test.

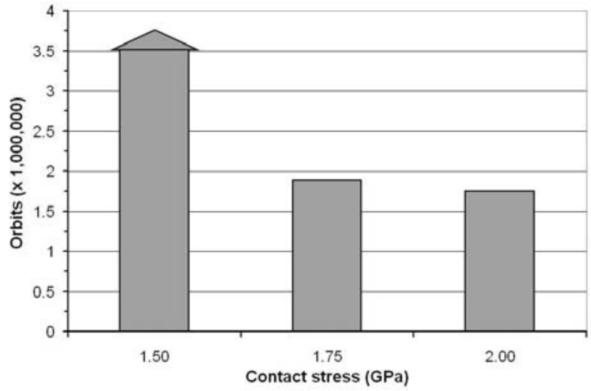

Figure 7. Lifetime of lead coatings under varying contact stresses

The test performed at 1.50GPa mean contact stress did not reach friction coefficient $\mu \geq 0.3$, and was stopped manually after displaying low friction for over 3.5 million revolutions.

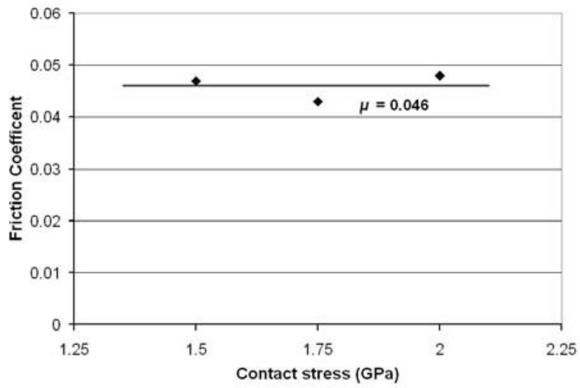

Figure 8. Friction coefficient of lead coatings as a function of contact stress

7. DISCUSSION

7.1. Liquid Lubricant Assessment

The friction plots of all oils were broadly similar, with steady-state friction being maintained until rapidly increasing to $\mu = 0.3$ as the lubricant was consumed. Fig. 2 demonstrates a typical plot displaying this behaviour.

The PFPAEs (Z25 & Z60 oil) displayed appreciably shorter lifetimes in comparison to the hydrocarbons 2001 & 2001A (Fig. 3). There is also a small but clear distinction between the friction coefficients of the PFPAEs and the hydrocarbons (Fig 4). Z60 was found to perform similarly to Z25, with slightly shorter lifetimes and increased steady-state friction coefficients. Of the two hydrocarbons, no significant difference was observed between them.

In general, all lubricants displayed a decrease in lifetime with increasing contact stress. However an exception occurred with the hydrocarbons operating at 1.75GPa mean contact stress, which displayed extended lifetimes. The cause of this is not clear.

Post test-inspection of the samples showed markings on the sample test surfaces. Inspection with a low powered optical microscope revealed these marks to be brown-coloured residue deposited away from the ball tracks, with the majority deposited in the scrub region. This deposited material is the residue of the consumed lubricant.

7.2. Solid Lubricant Assessment – MoS_2

The friction profiles of tests on sputtered MoS_2 were characterised by a long period of low friction before a dramatic increase to failure. A large range of lifetimes was observed, particularly for repeated tests at the thinnest coating.

Considering this range of values Fig. 5 demonstrates that for MoS_2 the lifetime until failure is not dependant upon coating thickness, displaying a mean of 260,000 revolutions over all thicknesses. It is speculated than the outer layers of MoS_2 are removed early in the test, and the ball runs on a much thinner coating for the majority of its lifetime. A greater initial thickness of MoS_2 merely results in a greater volume of material being lost in the early stages, with the ball running on a similar thickness for all initial coating thicknesses.

A similar result is seen if we consider steady state friction, with a mean of $\mu = 0.017$ found over all coating thicknesses (Fig. 6).

XRF analysis of the samples post-test showed no evidence of MoS_2 remaining on the ball after failure, with only trace amounts detectable on the flat and guide plates. These results demonstrate that failure of these tests is caused by removal of MoS_2 from the ball by the actions of rolling, sliding and pivoting.

7.3. Solid Lubricant Assessment – Lead

For lead coatings, increasing the contact stress acted to reduce the lifetime of the lubricant but did not significantly change the friction coefficient, with the mean µ of 0.046 displayed over all contact stresses (Fig. 8). This figure is some 2.5x higher than the values found for MoS_2. Conversely start-up friction values were found to be slightly lower for lead than MoS_2.

XRF analysis was performed on the 1.50GPa mean contact stress samples that had not failed, even after completion of 3.5 million revolutions. A reading of 100Å lead was detected on the ball (reduced from 850Å at coating), as well as low but appreciable readings on the guide and flat plates. Large lead deposits were also found in the scrub region (Fig. 9).

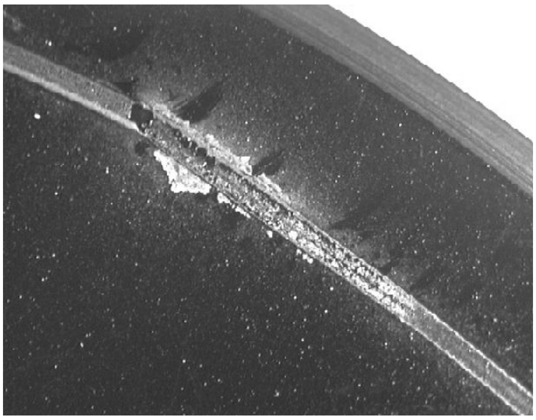

Figure 9. Flat plate (top) of 1.50GPa contact stress test on lead, displaying lead deposits in scrub region

It is speculated that during the running of the test, lead is re-distributed from the surface of the ball over all contact surfaces. The ductility of lead promotes transfer between contact surfaces, and it is believed that this is the cause of the extended lifetimes of lead in comparison to MoS_2, which is of a more friable nature.

8. COMPARISON

A comparison of our results was made against similar studies performed using the Spiral Orbit Tribometer by NASA. Fig. 10 below demonstrates exponential decrease in lifetime with increasing contact stress, supporting the results found at ESTL (Fig. 3). This relationship is more apparent in Fig. 10 however, as the results plotted are the means of a minimum of four tests, demonstrating the need to perform multiple tests at each condition with the SOT.

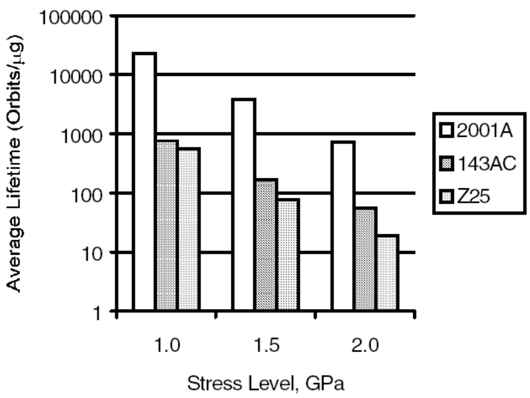

Figure 10. Lifetimes of Pennzane 2001A, Krytox 143AC, and Fomblin Z25 using the SOT [2]

A comparison of the lifetimes and friction coefficients of 2001A reveals good correlation between ESTL and NASA's results (Tab. 3 below).

Table 3. Friction and lifetime results of tests on 2001A oil at 1.50GPa, performed by NASA and ESTL

Source	Lifetime (orbits/μg)	Friction coefficient
ESTL	3,937	0.081
[2]	3,800	--
[3]	4,113	0.078

When considering Z25 oil however, lifetimes obtained at ESTL are some 3x greater than those at NASA. This discrepancy may be due to differences in the sample cleaning techniques. As degradation of the lubricant is caused by tribochemical attack on the lubricant's molecules from the metal samples, the lubricant can be shielded by impurities on the metal surface [4]. As such a 'cleaner' surface would result in a shorter lifetime.

No data was available for comparison with solid lubricants.

9. CONCLUSIONS

The following conclusions are drawn in relation to the oils. These conclusions are specific to these oils operating under boundary lubrication.

- The lifetimes of hydrocarbons NYE 2001 & 2001A outperform those of PFPAEs Z25 & Z60 oil.
- The steady state friction yielded by the NYE oils is slightly less than that yielded by the PFPAEs.
- The performance of Z60 is similar to that of Z25, with slightly reduced lifetimes.
- Liquid lubricant lifetime decreases with increasing stress.
- There occurs a slight increase of running friction with load/stress.

The following conclusions are drawn in relation to MoS_2 and lead coatings.

- Lifetimes of lead coatings are greatly extended in comparison with MoS_2, due to the re-distribution of the lubricant over the test surfaces.
- Lead displays a steady state friction coefficient ~2.5x greater than MoS_2.
- The performance of MoS_2 is not dependant upon coating thickness, with no strong relation when considering lifetime or friction.
- The lifetime of lead decreases with increasing load/stress.

The Spiral Orbit Tribometer performs well in such investigations. It enables comparative life tests to be made on oils and solid lubricant coatings on a much shorter timescale than ball bearing tests.

10. REFERENCES

1. ESTL, '*Space Tribology Handbook (4th Ed)*'
2. Jansen, M. J., et al (2001), '*NASA/TM-2001-2109966 Relative lifetimes of Several Space Liquid Lubricants Using a Vacuum Spiral Orbit Tribometer (SOT)*'
3. Pepper, S. V., Kingsbury, E. P., (2002), '*Pepper2.JanTT03 Spin Orbit Tribometry – Part II: Evaluation of Three Liquid Lubricants in Vacuum*'
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