

AGEING AND ENVIRONMENTAL EFFECTS ON LUBRICANTS – A PRELIMINARY STUDY

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ABSTRACT

It is usually assumed that, when correctly applied, the properties of space lubricants (both fluid and solid) remain essentially unchanged. However, evidence is emerging to suggest time-variable and environmental dependence of the tribological behaviour of some vacuum lubricants. This phenomenon needs to be better understood since, whilst lubricant performance improvement with time might be beneficial, a degradation during spacecraft storage or in flight could be mission-compromising.

Test campaigns performed by ESTL utilising both the Pin-on-Disc (PoD), Spiral Orbit Tribometer (SOT), and angular contact bearings have shown that the lifetime and frictional properties of space lubricants, particularly physical vapour deposition (PVD) MoS₂ (molybdenum disulphide), can be influenced by environment during both test and storage. These results may have implications for assumptions on what constitutes an inert environment for ground test and /or how a lubricant may mature and /or behave over time.

BACKGROUND

It is often not possible to fully characterise all lubricants at application or mechanism level, due to practical limitations such as test duration and cost. Therefore, tribometer testing (as well as component level such as bearing testing) is extensively used to establish key performance parameters, commonly friction and lubricant lifetime under controlled conditions, and to refine the tribological design early in the developmental lifetime of the programme.

However, tests at tribometer level may sometimes reveal an apparently wide variation in lubricant performance, particularly in solid lubricated sliding contacts [1]. The reasons for such variance are often not clear from the available data, and it can be difficult to ascertain if such variation is inherent to the lubricant alone, lubricant plus test method, or if it originates as a consequence of time-dependent factors, in particular subtle variations in the test or storage environment.

In addition, spacecraft mechanism components are commonly stored prior to or after spacecraft integration for a considerable time prior to launch. Whilst the

“ideally benign” storage conditions for the most sensitive lubricants (e.g. MoS₂) are typically considered as dry nitrogen (DN₂) of 1-3% ppm, for practical reasons some relaxation of this criteria is commonly followed. Extended storage at spacecraft level is often under a continuous long-term purge of semi-dry nitrogen (~10% relative humidity (RH)), with periodic exercising of the components under DN₂. Often these on-ground storage periods can continue for months if not many years before launch.

The general consideration is that this storage period under “benign” conditions will have very little impact on the tribological behaviour of the employed lubricants. However recent activities (at ESTL and elsewhere) have cast some doubt onto this idea. This doubt exists for both storage (including duration) and operational environment conditions. In particular there are growing concerns over the impact of storage on subsequent in-flight performance, especially where such storage is for “longer than desired” and / or under sub-optimal conditions.

The areas of concern regarding change in the tribological performance of lubricants can be grouped into the following three categories.

- Operational Environment – The environment in which the lubricant is sheared during operation (e.g. DN₂ for ground testing, vacuum for flight).
- On-ground Storage Environment – Non-operational exposure environment prior to shearing. Lubricants may be stored either fully applied to the respective components (such as for angular contact bearings), or prior to application (such as fluid lubricants stored within containers).
- Dwell Effects – Non-operational periods following some degree of shearing, typically without separating the contacting surfaces and often, but not always, in vacuum (e.g. during in-flight dormant periods).

A discussion of the potential effects of the above categories on the tribological performance of solid and fluid lubricants is presented within this paper, drawing from experimental data generated from numerous R&D activities performed at ESTL.

It should be noted that the focus of this paper is the tribological performance of the lubricants themselves, with little consideration of substrate effects (e.g. galvanic and substrate corrosion).

TEST EQUIPMENT

Tribological tests were performed using either a Pin-on-Disc (PoD) or Spiral Orbit Tribometer (SOT). The differences and relative merits of each form of tribometer have previously been discussed in various literature published by ESTL, but the simplest consideration is to state that the PoD operates under predominantly sliding contacts, whilst the SOT operates under predominantly rolling. Dependent upon the exact nature of the end application and the selected lubricant, one either tribometer could be more appropriate to any specific study.

Angular contact bearing tests were also performed to support certain testing activities.

Pin on Disc Tribometer (PoD)

The Pin-on-Disc tribometer is shown below (Fig. 1) and consists of a stationary pin mounted on a balanced arm, loaded against a test disc using a dead-weight. The disc is rotated by a motor positioned outside the vacuum chamber, inducing a sliding contact. The frictional force is measured according to the sideways deflection of the pin-support arm which is monitored using a PC-based data acquisition system.

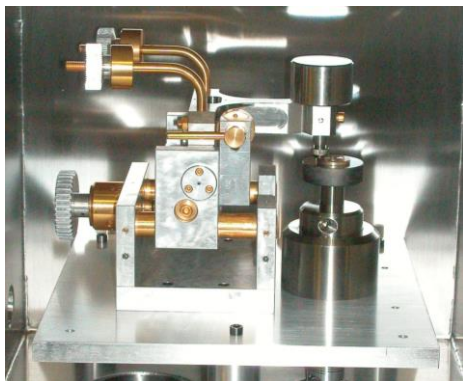


Figure 1. Pin-on-Disc (PoD) tribometer at ESTL

Typical outputs from a PoD test are lubricant lifetime (commonly stated as the sliding distance, or number of disc revolutions, achieved before a threshold friction coefficient, often ≥ 0.3 , is achieved), and steady-state friction coefficient. Other metrics such as start-up friction coefficient and substrate wear can also be measured.

Spiral Orbit Tribometer (SOT)

The SOT is essentially a thrust bearing with an individual ball held between two interchangeable flat plates (Fig. 2).

A load is applied to the top plate via a spring-loaded linear translator. The lower plate rotates via a motor housed outside the vacuum chamber. This arrangement induces the ball to experience the rolling, sliding and pivoting motions of a ball within an angular contact bearing.

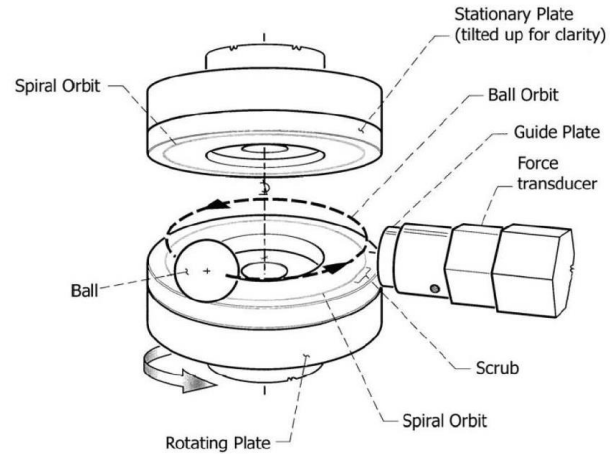


Figure 2. Internal arrangement of the SOT

A fixed guide plate is positioned to keep the ball within the flat plates and to maintain a repeatable orbit. A force transducer is located behind the guide plate, and through the measurement of the impact force the friction coefficient between the ball and plates can be inferred. As with the PoD, the SOT is commonly used to measure lubricant lifetime under controlled conditions, and steady-state friction coefficient.

Angular Contact Bearing Testing

Angular contact bearing tests were performed using ESTL's three turret bearing rig, allowing multiple bearing pairs to be tested in parallel under identical conditions. Bearing pairs are mounted on a shaft, flexibly preloaded by means of a spring, and installed within a stainless-steel housing. These are housed within a stainless-steel vacuum chamber, fitted with the usual complement of vacuum pumps, gauges, and feed-through systems. Torque is monitored using a static (type DG1.3) torque transducer which prevents rotation of the housing and permits measurement of the reacted torque. Rotation is accomplished by means of a motor located externally to the vacuum chamber. Torsionally stiff couplings are used to ensure that backlash and stick-slip are eliminated from the drive system.

Environmental control

Much of the motivation for the work described herein stems from concerns surrounding the creation and maintenance of suitable test (and storage) environments, and the subsequent impact of these environments on the tribological components within a spacecraft mechanism. All testing in this paper was conducted at room

temperature, 22 ± 2 °C, and hence “environment” herein does not include thermal considerations, which present other challenges in terms of both their control and impact not outlined in this paper.

It is frequently reported in the literature that the level of humidity control and precision of monitoring practically achieved is relatively poor, and it seems that this may contribute to the potentially unnecessary (even avoidable) variation in behaviours observed. The limitations of the most relevant methods of environmental control are outlined below. A general comment is made that test / storage environments are often not monitored with enough accuracy, nor sufficiently local to the points of tribological contact.

- Evacuation of the chamber – The quality and level of the vacuum achieved within a testing chamber depends not only on the dimensions of the chamber itself, its contents and the pump system but also the provenance of the hardware both in terms of maintenance and chemical exposure. Also, it is not normally possible to define an absolute operating pressure for the full duration of any tests, rather tests are defined by a threshold start pressure with the chamber pressure allowed to (usually) decrease at some uncontrolled rate after the test starts.
- Gas purging – Not only does the quality of purge gases vary but the concentration of trace elements is often impossible to determine or control. Also, particularly for larger test setups, leaks of moist air into the test chamber are possible and not always appropriately mitigated, monitored or minimised. The progression of purge gasses into the tribological contacts of a mechanism, particularly where convoluted pathways or labyrinth seals are employed, must also be considered. Without integrated and direct purge lines, transport of purge gas into the cavities within mechanism of gear systems may be relatively slow/ineffective.
- Laboratory air – Appropriate conditions are well defined for the space industry, but the specifications allow for significant variation in factors such as temperature and RH. This variation is inevitable as the costs of maintaining a tight tolerance on the environment of a cleanroom would be prohibitive for most companies due to diurnal and annual fluctuations caused by both human and natural activities.

In the activities herein described great care has been taken to monitor the true operational conditions during the tests, and where possible to control / limit their variation. Relative humidity was controlled from 0.02%

to 65% RH using a two-gas feed line combining DN₂ and moist N₂ from a deionised water gas bubbler line, mixed to achieve the desired RH. Manual (course) flow gauge controls were used alongside a mass flow controller receiving feedback from a humidity sensor to maintain the desired humidity.

OPERATIONAL ENVIRONMENT

It is well known that the tribological properties of certain lubricants are highly dependent upon operational environment. Sputtered MoS₂ for example is known to display significantly higher friction coefficient and increased wear rates when operating in moist air due to rapid degradation of the thin film at the exposed boundaries of the S-Mo-S layers, caused by the presence of moisture and oxygen acting to degrade the good shear properties of the film. The favourable properties of the lubricant under vacuum are known to be reversible, with cycling of the test environment between air and vacuum allowing the performance of the lubricant to recover [2]. However, it is also known that some duration of in-air running, even if short, can have a profoundly detrimental effect on the subsequent life of the MoS₂ coating under vacuum due to the increased wear rate of the lubricant film in the presence of moisture [3].

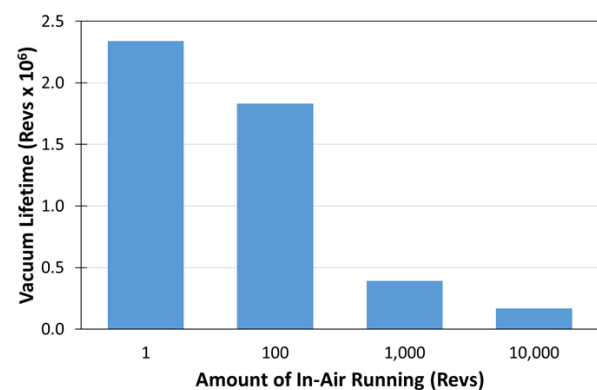


Figure 3. Low-torque life of MoS₂ lubricated bearings in vacuum as a function of the amount of in-air operation prior to vacuum testing [3]

The tribological properties of sputtered MoS₂ under DN₂ are also not consistent with those achieved in vacuum, with an extension in sliding lifetime under DN₂ first reported by [4]. Subsequent work performed by ESTL to support the Euclid mission [5] and elsewhere [6] observe the same behaviour, with the latter describing this increase in durability as a consequence of beneficial contamination from the DN₂ environments acting to improve the efficiency of the MoS₂ 3rd body lubrication. It is clear therefore that DN₂ is not an accurate representation of vacuum for the operation of sputtered MoS₂.

One perennial question often asked of ESTL is, “How

moist is too moist for operation or storage?” ESTL’s guidelines [7] state that for solid lubricants (i.e. MoS₂):

- Prior to use solid lubricated components should be stored in sealed bags purged with a dry inert gas (i.e. DN₂).
- Any operational cycles should be performed under a DN₂ atmosphere (<15 ppm moisture) as this is known to be “safe”.
- Operation in environments with humidity levels above 5% RH is known to cause MoS₂ coatings to degrade i.e. the lifetime of the lubricant coating decreases.

However, much of the experimental evidence for these guidelines is limited and based on historical data which may no longer be accurate. In addition, the region of moisture between that defined as “safe” and “deleterious” is not well documented (Fig. 4) and, although this region of uncertainty should be avoided whenever possible, due to the issues of achieving dry conditions these test environments may represent many practically achievable test environments.

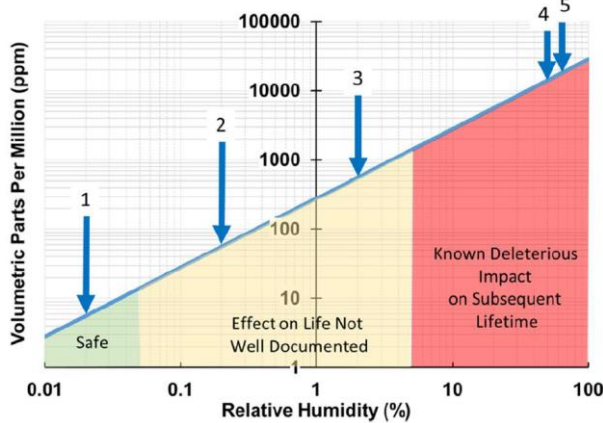


Figure 4. Regions of safe and deleterious impact on MoS₂ lifetime

A recent PoD test campaign was performed to investigate the tribological performance of sputtered MoS₂ within this hitherto poorly documented humidity region. These tests suggest that in an environment of up to 2% RH / ~500 ppm moisture (achieved in N₂), there is no evidence of a detrimental effect of water vapour on the tribological lifetime of the lubricant (Fig. 5). Above this value the anticipated drop-off in lifetime is observed. This suggests that the deleterious effect of moisture does not occur until a moderately high RH, and the statements for operation given above are somewhat conservative.

The impact of a short duration (i.e. not fully to failure) of operation under these “safe” and “deleterious” environments on the subsequent vacuum lifetime of sputtered MoS₂ was also investigated. In each case the

MoS₂ coating was sheared under N₂ at a controlled moisture level for some predefined number of revolutions, before evacuating the chamber and allowing the test to continue to failure under vacuum. This method allows for representation of some degree of ground running before application on orbit.

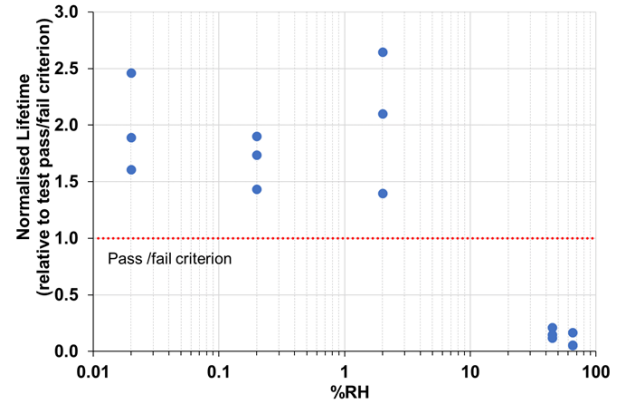


Figure 5. Normalised lifetime of sputtered MoS₂ vs. humidity (in N₂). Performed at 1.5GPa Peak Hertzian contact stress

Results showed that, for the “safe” region (~0.02% RH DN₂), the total lifetime obtained (N₂ revolutions performed plus subsequent vacuum life) was comparable to the predicted vacuum lifetime assuming no prior running (Fig. 6). This suggests that running periods within this “safe” region do not impact the subsequent vacuum performance of the lubricant.

In contrast the subsequent in-vacuum behaviour of the sputtered MoS₂ was much harder to predict following a prior period of sliding in moist nitrogen (assessed with N₂ having 45% and 65% R.H. respectively). Whilst in some instances a reduction in the total life was observed following some degree of sliding in a moist environment (as one would expect), in other cases an extension in life was observed, particularly when the period of moist N₂ operation was relatively short.

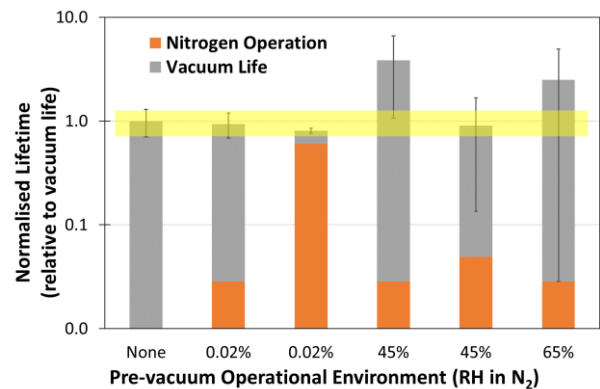


Figure 6. Normalised total sliding life of sputtered MoS₂ following varying periods of N₂ operation

2.25 GPa Peak	PFPE (Braycote 601EF)			MAC (MAPLUB SH100-b)		
	Vacuum	Air	DN₂	Vacuum	Air	DN₂
Life (rolling - SOT)	198	741	1,686	1,376	137,830	758,741
Friction (rolling - SOT)	0.10	0.11	0.15	0.09	0.09	0.10
1.5 GPa Peak	PFPE (Braycote 601EF)			MAC (MAPLUB SH100-b)		
	Vacuum	Air	DN₂	Vacuum	Air	DN₂
Life (sliding - PoD)	44	11,812	33,253	51,207	13,806,101	No data
Friction (sliding - PoD)	0.19	0.15	0.18	0.13	0.09	No data

Table 1. Summary of fluid lubricant performance in sliding and rolling regimes under varying environments [12]

A similar observation has previously been made by ESTL [8] in which a small degree of operation in a moist air environment appears to increase the subsequent lifetime of sputtered MoS₂ under vacuum at low preloads. The reasons for differences between these current observations and those reported by [3] is not clear but may be related to the rate of moisture desorption from the coating due to frictional heating. Nevertheless, it is clear that operation, even briefly, in a non-optimal environment has the potential to increase variability in the subsequent performance of the lubricant and may result in early catastrophic failure under vacuum.

Little experimental evidence exists as to the impact of operational environment on thin lubricating films of lead. [9] states that an oxide layer of lead does not adversely influence the friction coefficient of the bulk material, but recent SOT activities performed by ESTL show clear differences in the tribological properties of lead when rolling under vacuum and laboratory air. The friction coefficient of lead under air on the SOT was measured as ≥ 0.13 , in comparison to ≤ 0.05 under vacuum, with a lifetime of $\sim 10^6$ orbits in air (typically 2×10^7 achieved under vacuum).

Considering fluids, ESTL does not provide specific guidelines on environment for the operation of fluid lubricated components. Historically it often assumed that the tribological behaviour of a fluid lubricated component will be relatively insensitive to operational environment, but this may be a simplification. Test campaigns conducted using the SOT at NASA Glenn showed that the tribo-consumption rate of PFPE oil is greatly affected by the presence of small quantities of water vapour [10]. The degradation rate of PFPE lubricants is also known to be influenced by surface cleanliness [11], leading to the suggestion that the presence of water vapour (or other contaminants such as an oxide layer) on the substrate surface acts to retard the degradation rate of the PFPE. Under shear the native oxide layer present on the surface of the substrate steel is removed, revealing the nascent metal. This nascent steel is much more reactive than the original oxide layer, resulting in accelerated chemical degradation of the fluid.

In an ambient air environment however, and if oxidation occurs fast enough, this oxide layer can be replenished, subsequently retarding the degradation rate of the fluid. Recent evidence suggests that MAC lubricants are also susceptible to the same surface chemistry effects [12].

Detailed studies at ESTL have expanded upon this work, with investigations performed at both PoD (sliding) and SOT (rolling) level on a PFPE and MAC-based grease (Braycote 601EF and MAPLUB SH100-b) [13]. Results show that in both sliding and rolling regimes, DN₂ does not provide an environment in which similar lifetimes are obtained to vacuum operation for PFPE or MAC lubricants (Tab. 1). Similar observations are found for tests in moist air, which provides both longer lubricant sliding lifetimes and lower friction coefficients than for operation under vacuum. Under rolling conditions, the friction coefficient observed in moist air is similar to that found under vacuum, though as in DN₂, the lifetime in air is considerably higher than that found in vacuum. However, there is no suggestion that operation in moist air or DN₂ acts to reduce the subsequent operational life of fluid lubricants under vacuum (as occurs for MoS₂ for example), leading to the suggestion that, as long as the expected friction / torque differences are considered, on-ground operation of fluid lubricated components in non-vacuum environments can be considered “safe”.

Overall the above activities show that it is important, whenever possible, to operate both solid and fluid lubricated mechanism components under environments representative of their intended application if life is under assessment. However, if one is concerned only with parameters such as motorisation torque margins it is reasonable for some lubricants (i.e. fluids), to use alternative environments, if the lubricant has been fully characterised.

ON-GROUND STORAGE ENVIRONMENT

In addition to operational environment, attention must be given to pre-operational storage environment for lubricated components. Storage conditions are ideally selected on the assumption that the environment is benign, but often this has not been explicitly

demonstrated.

Recently ESTL has become aware of anecdotal evidence (internally and from external clients) to suggest that sputtered MoS₂ may “mature” upon storage, such that the lifetime and friction of freshly deposited MoS₂ differs from that of MoS₂ exposed to a short period of storage (e.g. several months). To explore this in detail ESTL performed a series of PoD tests on a single batch of sputtered MoS₂ lubricated 52100-steel discs over a period of 60 days. All tests were performed under identical vacuum conditions, with each individual test coupon stored in DN₂ prior to assessment.

Results demonstrated a marked increase in lubricant lifetime (and increased life variance) as storage duration increases, suggesting that exposure to the commonly considered benign DN₂ acts to alter the lubricant performance (Fig. 7). Start-up friction measured during these tests also showed a strong correlation with storage duration. A parallel test campaign performed on the SOT displayed the same behaviour, demonstrating that this maturation effect is not unique to sliding motion.

Exactly how the MoS₂ interacts with a DN₂ environment, and how this interaction provides a subsequent increase in sliding lifetime is not clear. The behaviour may be related to the observation from [6] that the presence of contaminants (including H₂O, CO₂, O, N₂ and H₂) within an operational environment is favourable for the MoS₂ lubrication. Assuming that sputtered MoS₂ films can adsorb these contaminants under storage, extended exposure may act to modify the tribological properties of the lubricant coating. However, it is not clear how this interacts with the 3rd body model of lubrication, given that this adsorbed contaminant must likely permeate beyond the surface layer in order to produce an extension in lifetime.

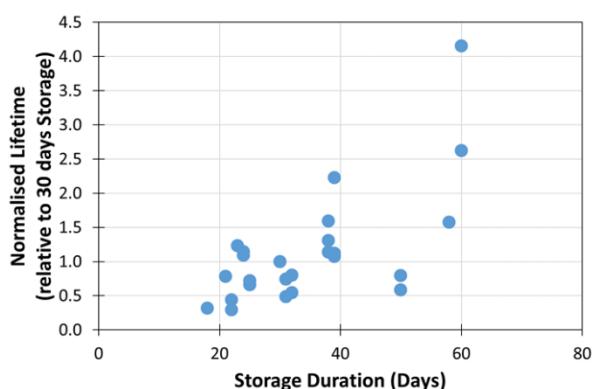


Figure 7. Normalised sputtered MoS₂ lifetime vs. DN₂ storage duration on PoD tribometer

Steady state friction coefficient did not show strong correlation with storage environment, and no relationship between steady-state friction and lifetime was observed

during these tests. Little evidence was seen of a correlation between coating thickness and tribological performance (over the range 1.25 – 1.50µm), in agreement with previous observation reported by [11].

A follow-up campaign of PoD tests was performed under identical conditions, with sputtered MoS₂ lubricated samples stored for up to 12-months (in DN₂ and laboratory air) at ESTL. Results from this “medium term” campaign were mixed, with evidence of increasing lubricant lifetime measured over the first 60 days, followed by a plateau in which the tribological behaviour (including lifetime) was unchanged. However limited data and high variability from the PoD (known to be inherent of this assessment method) makes detailed analysis of this activity complicated.

For assessment of longer storage periods, one must take advantage of “opportunistic” lubricant samples. As part of ESTL’s in-house quality control for production of sputtered MoS₂ coatings, sample depositions are produced on 52100-steel coupons and assessed on a PoD tribometer under controlled conditions. These samples are often retained at ESTL once the MoS₂ coated components are despatched to the customer. A survey by ESTL identified samples dating back to 16yrs of storage in an uncontrolled moist air environment (i.e. the ESTL office). When re-tested, under identical conditions as the original QA tests, these lubricated coupons showed no statistically significant change in coating lifetime as a result of such storage (Fig 8). Although complicated by limited data sets (only a single coupon is stored per coating run), this does provide some confidence into the long-term storage impact (or lack of) on sputtered MoS₂.

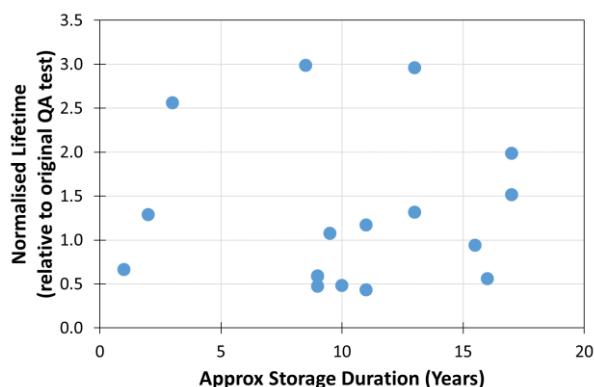


Figure 8. Normalised sputtered MoS₂ lifetime vs. moist air storage duration on PoD tribometer

Taken together these results imply that sputtered MoS₂ is more susceptible to environmental storage conditions in the first few months after its deposition, with the potential for maturation and an increase in lubricating lifetime during this period. In subsequent months to years however this susceptibility reduces, with the lubricant “passivated” by the storage environment, and no change

in the tribological performance of the lubricant observed.

Fluid lubricants are particularly susceptible to effects of on-ground storage which may influence their tribological properties. These include oxidation effects which have the potential to change the viscosity of lubricants over time (particularly MAC-based oils), absorption of moisture, loss of additives, and chemical degradation as well as physical effects such as base oil separation and creep. As a result, fluid lubricant manufacturers often provide guidelines for lubricant storage (often at low temperatures) and shelf lives of typically ~5yrs.

However, preliminary results of SOT testing on PFPE oils, some dating back to the late 1970s and stored in uncontrolled (office air) conditions for ~40yrs at ESTL, show very similar tribological behaviour to new as-formulated PFPE oils, with no reduction in lubricating lifetime. This indicates that there is no significant effect of uncontrolled air storage on the tribological performance of PFPE oils. Testing is continuing to identify if the same resilience to storage conditions is displayed by MAC oils.

Although tentative these results suggest that the commonly employed spacecraft lubricants are fairly robust to long periods of storage, even under uncontrolled conditions. This shall be explicitly investigated in a systematic and controlled manner in the upcoming long-term storage activity at ESTL.

DWELL EFFECTS

The influence of in-situ (vacuum and air) dwell periods on the subsequent in-vacuum tribological properties of PVD MoS₂ and lead was investigated at PoD and angular contact bearing level.

When experiencing pure sliding (i.e. PoD) exposure to an in-air dwell period acted to increase the start-up friction coefficient of sputtered MoS₂ (assessed at 1 – 1.50MPa peak Hertzian contact pressure) The rate of increase in friction with exposure time appears to level off at exposure periods of 10⁵ seconds. Steady-state friction values were unaffected by in-air dwell periods, but the recovery period (i.e. the number of disc revolutions required to re-establish low friction in vacuum) increases logarithmically (Fig. 9).

MoS₂ lubricated bearings (fitted with PGM-HT cages) developed higher start-up torque in vacuum as a result of periods of dwell in both laboratory air and vacuum environments. The most significant increase in torque was a factor of ~2.75x higher than the run-in torque (i.e. less than the equivalent effect observed under pure sliding motion but potentially significant in relation to mechanism torque margins), occurring after an exposure period of 10⁶ seconds in air. The number of revolutions

required to recover low torque also increased with increasing dwell time, in a similar manner to that seen at PoD level.

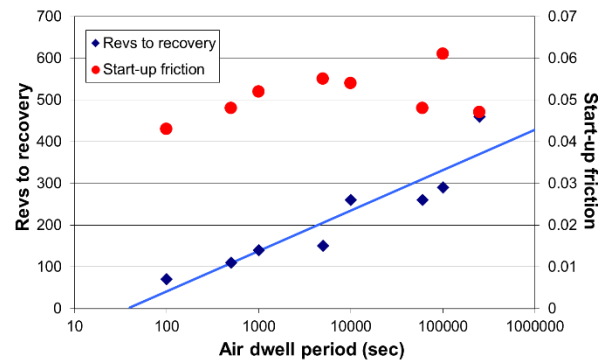


Figure 9. Start-up friction and revs to recovery under vacuum of sputtered MoS₂ following in-air dwell (data shows 1.50GPa Peak Hertzian contact pressure)

After being correctly run-in in vacuum, lead-lubricated bearings displayed no measured effects of dwell, either in vacuum or laboratory air, up to 10⁶ seconds.

IN-FLIGHT STORAGE

In-flight storage (i.e. prolonged stasis in vacuum) provides a further unique set of considerations, challenges and mitigations.

Where possible for fluid-lubricated mechanisms, the orientation of the spacecraft or mechanism should be selected to minimise its average temperature during the in-flight storage period. This is because creep, degradation (including due to potential autocatalysis of PFPEs, see below), and evaporation of oils are all strong functions of temperature. This measure will inhibit most degradation phenomena and maintain to the maximum extent the fluid lubricant within the mechanism.

For in-flight storage the environment can be highly variable dependent on the mission profile. Whilst typically high / ultra-high vacuum and ranging from, for example, -40 to +80°C, the environment for in-flight storage can also encompass more extreme thermal excursions for exposed items. For mechanisms on science missions where worst case temperatures could be as low as ~20K or as high as ~600K and mission specific environments might include CO₂, H₂, traces of CH₄ or, for LEO, atomic oxygen could be envisaged to impact mechanisms depending on their location.

AUTO-CATALYTIC DEGRADATION

Perfluorinated oil-based fluid lubricants such as the grease Braycote 601EF or Fomblin Z25 oil are highly susceptible to chemical degradation, whereby a reaction occurs between the fluorine released from the oil by the action of shearing and iron within the substrate steel [14].

This reaction produces the compound FeF_3 which further increases the rate of the fluid degradation.

This reaction acts to destroy the long-chain polymers within the fluid, removing the attractive shear properties of the fluid, causing a rapid increase in friction coefficient and ultimately restricting the lifetime of these lubricants. Although usually understood to occur during operation (i.e. shearing), it is theoretically possible that once this reaction has been initiated through the shearing of the fluid (for example during mechanism run-in, acceptance test or initial in-flight commissioning), degradation can continue when the fluid is not being sheared due to the existing presence of FeF_3 within the contacts [15].

Such behaviour is referred to as the Autocatalytic Effect (ACE) and can potentially cause continued degradation of PFPE lubricants, following initial shearing, when stationary (e.g. degradation potentially continuing during both ground storage and during periods of in-flight inactivity, such as for missions having a long cruise phase). The concern is that such behaviour could impact the overall lubricant lifetime or produce significantly higher torques upon restart of a mechanism following an extended dwell period.

To date there is limited experimental data to confirm the existence of auto-catalytic degradation at component / lubricant level [15, 16], but this exists as a possibility, if only theoretically.

LONG TERM STORAGE CAMPAIGN AT ESTL

Due to the increasing trend in in-flight lifetimes and perceived benefits of production of planned sequences of satellites, long-term on-ground storage of spacecraft mechanisms components is a concern for several spacecraft programmes. Although some best practice guidelines exist (including those discussed above) very little experimental verification has been performed. Where experimental data does exist, this is often “opportunistic” and of questionable statistical confidence.

To provide additional confidence, ESTL is commencing a real-time assessment of long-term storage (LTS) effects on selected mechanism components, commencing summer 2019. Stored mechanism components include fluid and solid lubricants, angular contact bearings, self-lubricating cage materials, magnets, and creep barriers. Mechanism components will be stored within a custom designed storage facility for ~20yrs under representative storage environments (moist N_2 ~10% RH, and laboratory air). Periodic assessments will be performed on the stored components, and the experimentally generated data shall be analysed in comparison with existing predictive tools and models. In total over 870

samples will be stored as part of the LTS programme, with over 1,800 individual measurements / tests planned.

CONCLUSIONS

All space lubricants are tribologically susceptible to environment during operation and storage, but with widely differing degrees of severity. As a result, the monitoring and understanding of storage and operational environments is extremely important to gain confidence in the tribological performance of spacecraft mechanism components. Characterisation of lubricated components, and subsequently their parent mechanisms, should also be performed under representative environments whenever possible, considering reasonable levels of experimental variance for the assessment methods.

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