HYBRID LUBRICATION AS A PRACTICAL CANDIDATE FOR SPACE MECHANISM APPLICATIONS

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ABSTRACT

Hybrid lubrication is a promising candidate for spacecraft applications. The methodology consists of the application of a viscous fluid medium (typically a low vapour pressure oil) on top of a thin-film solid lubricant coating (i.e. sputtered MoS_2), and when performed correctly can result in an extension in lubricant lifetime, greater than the sum of each of the constituent lubricants alone, without an associated increase in friction.

Hybrid lubrication can also act to protect the underlying MoS_2 during moist environment running (for example ground testing), which can reduce AIT costs and would make hybrid lubrication attractive for high load, low lifetime applications. In addition, hybrid lubrication is potentially attractive to mechanisms engineers as the low fluid volumes applied, theoretically allow one to consider hybrid lubrication for applications where fluid lubricant alone may not be applicable, such as at high or low temperature.

This paper shall present the recent investigations by ESTL into the behaviour of hybrid lubrication, leading to recommendations for use in spacecraft mechanism applications.

BACKGROUND

Hybrid lubrication is the concept of applying a layer of fluid onto a sputtered molybdenum disulphide (MoS_2) solid lubricant coating [1]. This application technique was originally proposed as a means of protecting the MoS_2 coating from periods of operation in a moist environment, with the original hypothesis being that a high vapour pressure (i.e. non-space) oil would evaporate in-vacuum, leaving the un-compromised MoS_2 layer to provide low friction. However, initial testing at ESTL determined that in addition to this moist-operation protection, the application of a low vapour pressure oil (the PFPE Fomblin Z25) behaved synergistically with the MoS_2 to produce an extension in lifetime in excess of the sum of the individual solid and fluid lubricant constituents, with the low friction coefficient being that of sputtered MoS_2 under vacuum.

However, consistently reproducing this synergistic effect has proven to be rather difficult. A model to explain how in some instances hybrid lubrication appears to be unsuccessful has been proposed [2] (Figure 1), based on experimental studies performed by ESTL. This model predicts that the success of hybrid lubrication is governed by the ratio between the thickness of the deposited MoS_2 coating, and the applied fluid layer. Tribological testing campaigns at ESTL demonstrated that if the fluid film was insufficiently thin, fluid and/or mobile then synergistic hybrid lubrication was lost [2]. The fluid film needing to be sufficiently fluid and/or mobile, generally precludes the idea of using grease as the applied fluid lubricant, with successful demonstrations of hybrid lubrication utilising oil as the medium.

This behaviour was initially demonstrated using the low fluid volumes typical of the Spiral Orbit Tribometer (SOT) but has subsequently been replicated using a Pin-on-Disc tribometer (PoD) and, more recently, at bearing level [2] [3], both under vacuum.

Given the above, hybrid lubrication may be highly attractive to mechanisms engineers; for the synergistic extension in lifetime, the protection during moist environment running, and also potentially due to the presence of the MoS_2 layer retarding PFPE degradation [1]. Hybrid lubrication also has flight heritage, being selected for use on the BepiColombo spacecraft [4].

NOVEL RESEARCH

Previous research efforts have principally focussed upon investigations of hybrid lubrication at tribological level (i.e. utilising the SOT and PoD), and at spur gear level. More recent investigations have attempted to replicate this phenomenon using a Mini-Traction Machine (MTM) and at bearing level. This novel research and the knowledge gained, leading to an updated model of hybrid lubrication, shall now be presented.

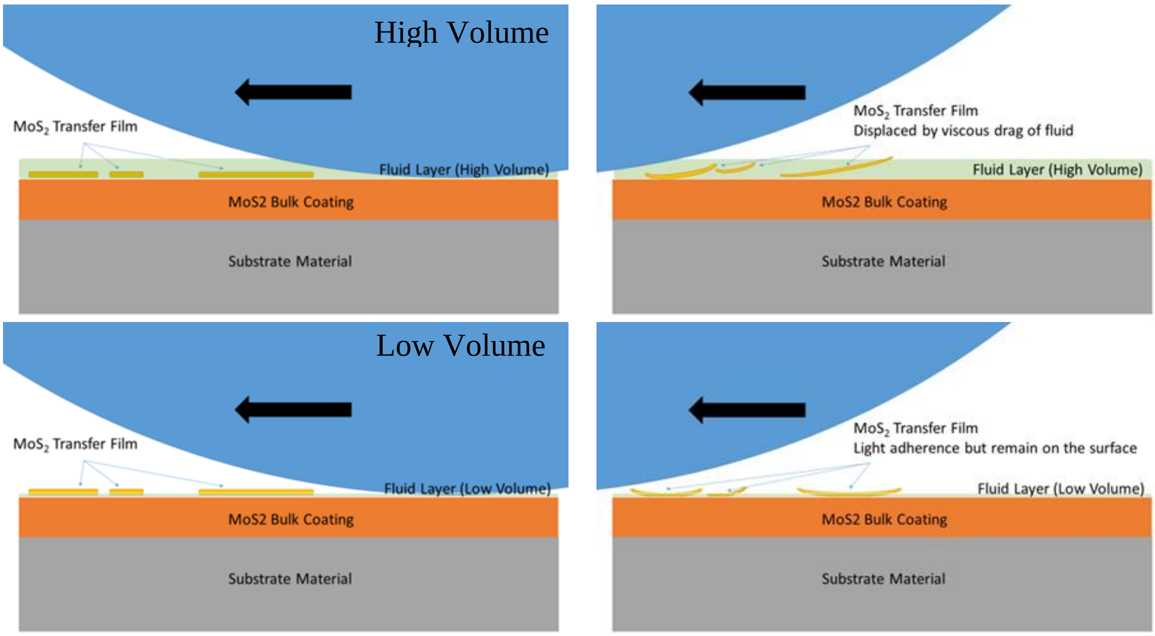

Figure 1 – MoS_2 transfer film formation (3rd body) for high and low fluid volume hybrid lubrication [2]

Mini-Traction Machine
An MTM permits the assessment of a known slide to roll ratio, which is advantageous when compared to the PoD (which is a sliding contact) and the SOT (which is predominantly a rolling contact), as well as the inclusion of a Spacer Layer Interferometer (SLIM), which can perform in-situ observations of a fluid lubricant. At the time writing it has not been possible to perform MTM assessments in a fully controlled vacuum environment, and so all results presented here were obtained in moist air. ESTL has subsequently built a vacuum-MTM which may in the future be used to conduct further in-situ investigations of hybrid lubrication.

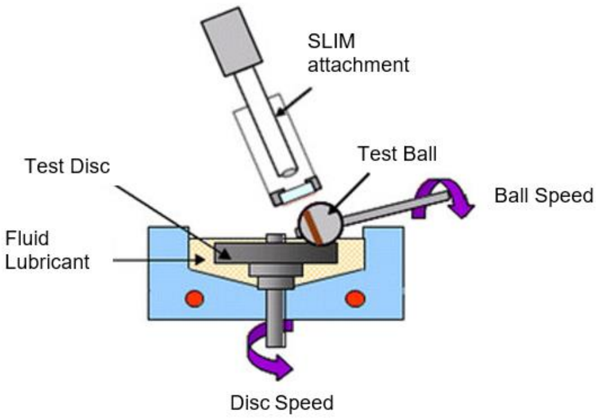

Figure 2 – Schematic of an MTM [5]

Fixed duration MTM testing was performed at Imperial College London (UK), according to the test matrix in Table 1. All tests included periodic SLIM imaging to assess the transfer and retention of solid lubricant both with and without an applied PFPE Fomblin Z25 oil. The fluid volumes used were higher than would typically be considered for spacecraft applications.

Table 1 – Test matrix for external MTM testing

Test ID	Temperature (°C)	Lubrication	Oil Amount
1.1	23/RT	Oil Only	10ml
1.2	23/RT	MoS_2 Only	N/A
1.3	23/RT	Mixed	10ml
1.4	23/RT	Mixed	10 drops
1.5	23/RT	Mixed	“Smear”
1.6	100	Mixed	10ml
1.7	100	Mixed	10 drops
1.8	100	Mixed	“Smear”

Bearing Testing
Vacuum bearing testing was performed using ESTL’s 3-turret bearing rig (detailed elsewhere [6]), which permits the testing of three angular contact bearings simultaneously under identical conditions. Bearing tests consisted of cotton phenolic cages, impregnated with Fomblin Z25 oil, with sputtered MoS_2 applied by ESTL to the balls and races of the bearings. Varying quantities of free oil were added to the bearings to produce different film thicknesses for hybrid lubrication:

- No free oil applied
- 10% of standard volume (0.1µl/mm PCD)
- Standard volume

Results - MTM

Friction coefficients were monitored throughout each MTM test (Figure 4). For the test of MoS_2-only an initially high friction of ~0.09 was measured, before stabilising at ~0.07. This friction coefficient is much higher than for the oil-only test, which achieved a friction of ~0.05 throughout the test. These baselines enable the assessment of which of the constituent portions of hybrid lubrication is dominating the performance.

For tests performed at 23°C utilising the high and low fluid volumes, the friction behaviour was noisier than for oil-only but was not significantly higher with an average coefficient of ~0.06. However, the medium volume test performed at 23°C, displayed significantly higher friction coefficient, greater than that measured for MoS_2-alone at ~0.1. This observation suggests that, for the medium volume, more MoS_2 debris was retained within the contact, resulting in the elevated friction coefficient more akin to MoS_2-alone.

At elevated temperature, the observed friction coefficients for all tests were lower than for the equivalent tests at 23°C, understood to be as a result of the reduced viscosity of the fluid. However, despite the reduction in the fluid viscosity, the medium volume test still produced the highest friction coefficient, suggesting that the reduced viscosity as a result of temperature, was not significant enough to impact which applied fluid volume was the most favourable (i.e. which volume retained the most MoS_2 debris).

During this campaign, the SLIM was utilised to visually assess the retained solid lubricant. Following demonstration that the MoS_2 3rd-body transfer film could be observed using this technique (Figure 3 shows the transferred material), an assessment was preformed to investigate the extent of the MoS_2 debris retained for each of the hybrid tests

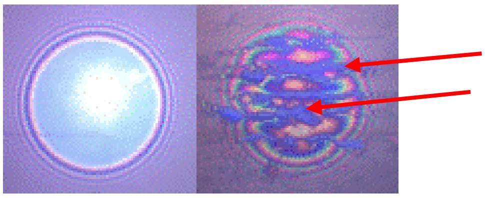

Figure 3 – End of test SLIM assessments for oil only (left) and MoS_2 only (right) MTM tests

The SLIM analysis supports the friction coefficient data in that the two medium volume tests retained more debris than the high and low fluid volumes (at both assessed temperatures). In addition, higher volumes of captured MoS_2 debris were observed for the room temperature tests in comparison to the elevated temperature, indicating that the reduced viscosity at the higher temperatures reduced the ability of the applied fluid to successfully retain the MoS_2 debris

This test campaign demonstrates that the environmental temperature plays a significant part in the ability of a fluid medium to retain MoS_2 debris. Interestingly this test campaign would also appear to suggest that the optimal fluid volume to achieve hybrid lubrication (for both room and elevated temperature) is significantly higher than previously presumed.

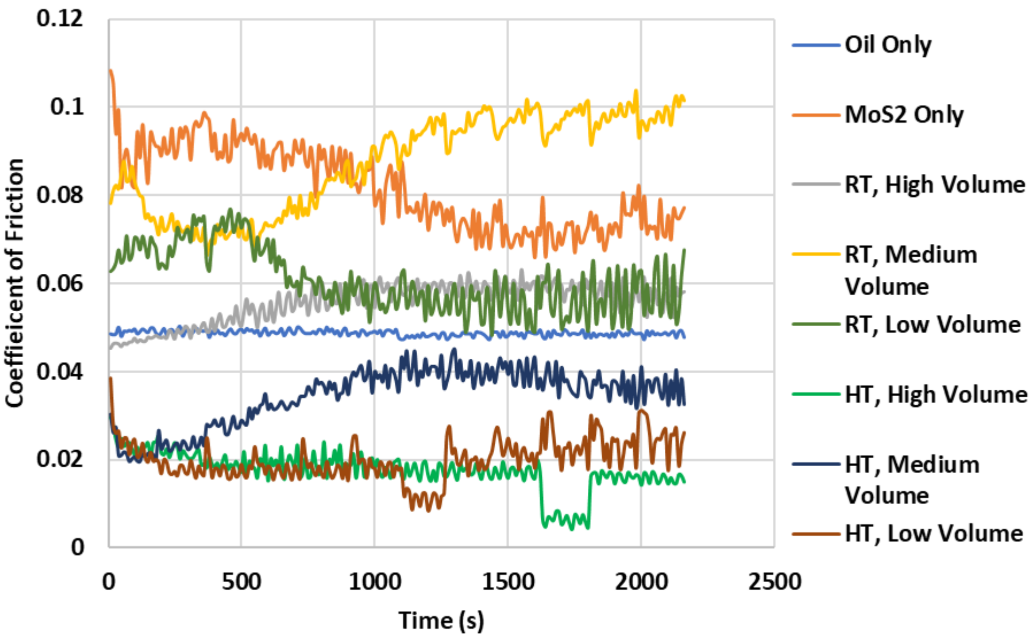

Figure 4 – Friction progression for MTM tests

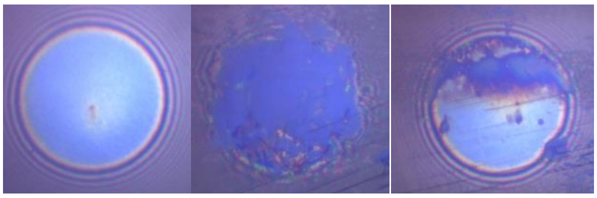

Figure 5 – Mid-test SLIM assessments for room temperature hybrid tests, with high fluid volume (left), medium fluid volume (centre) and low fluid volume (right)

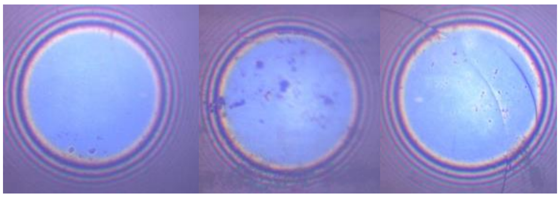

Figure 6 – Mid-test SLIM assessments for high temperature hybrid tests, with high fluid volume (left), medium fluid volume (centre) and low fluid volume (right)

However it must be remembered that this test campaign was performed in moist air, where the wear rate and subsequent production of MoS_2 wear debris is known to be significantly higher than in vacuum. Given that the retention of MoS_2 debris appears to be key for the success of hybrid lubrication, this may suggest that a relationship exists between the operational environment and the amount of fluid lubricant required for successful hybrid lubrication.

Results – Bearing

The results of the bearing tests show that the bearings lubricated with the lowest volume of free oil provided the longest operational lifetime, with the shortest lifetime obtained from the bearings with the largest amount of applied free oil (Figure 7).

Hypothesis

A hypothesis to explain these observations is presented below as Figure 8. The coloured regions can be described as follows.

- The blue region corresponds to MoS_2-only behaviour.
- The red region corresponds to a fluid lubricant only behaviour.
- The yellow region corresponds to a reduced lifetime (compared to MoS_2-only) but with an MoS_2 dominated torque behaviour.
- The green region corresponds to an extension in lifetime of MoS_2 dominated behaviour.

Our hypothesis suggests that the concentration of MoS_2 debris particles held within the liquid is highly significant to the success of hybrid lubrication. This concentration is likely impacted by the wear rate of the MoS_2 (i.e. the production rate of the debris), but also by the fluid film thickness and/or viscosity (i.e. the retention potential of the fluid film).

The next section shall consider the different factors that may affect this concentration in turn and will attempt to envelope the conditions whereby hybrid lubrication can be successfully applied. Following this, consideration shall be provided to space mechanism applications.

FACTORS AFFECTING HYBRID LUBRICATION SUCCESS

Temperature/ Fluid Viscosity

The viscosity of a fluid is highly dependent upon temperature, potentially restricting the space mechanism applications for which fluid lubrication can be considered. Given that for hybrid lubrication the reflow of the fluid medium into the contact is also likely to be fundamental (as this will influence the in-contact concentration of MoS_2-debris), it is reasonable to assume that temperature will also influence the success of hybrid lubrication.

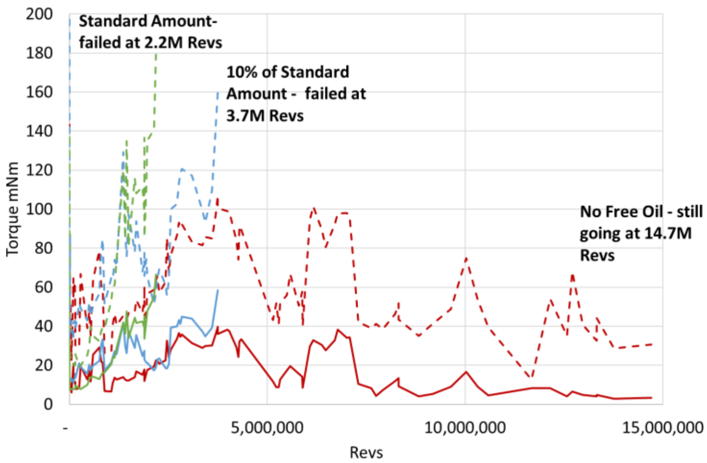

Figure 7 – Hybrid lubricated 7004C bearing lifetimes under vacuum (varying fluid volumes)

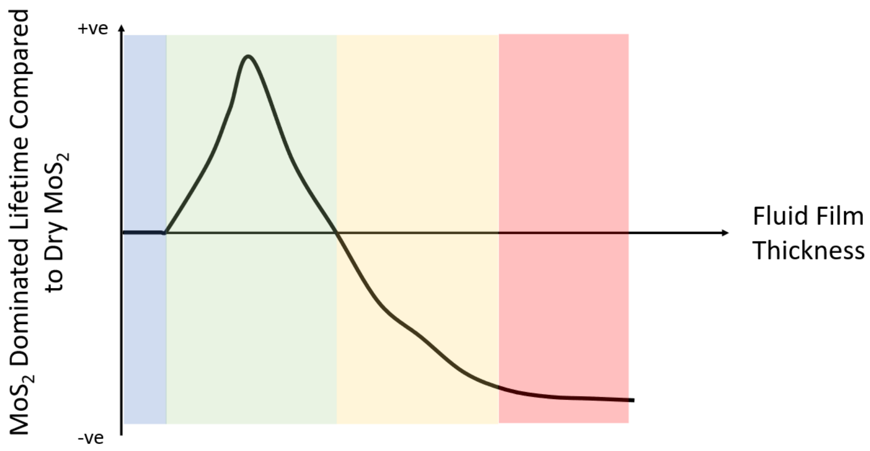

Figure 8 – Relationship between successful hybrid lubrication and fluid film thickness [3]

If the fluid lubricant is unable to be entrained back into the contact, then the concentration of debris may increase beyond that which is ideal. Conversely if the entrainment rate is too low then the MoS_2-debris concentration may fail to achieve equilibrium, again reducing the success of hybrid lubrication. Therefore, the viscosity of the lubricant must be considered in conjunction with the applied fluid amount to ensure an appropriate film is achieved.

When considering high temperature, one must typically consider the evaporative behaviour of the fluid lubricant over time. However, the very thin films used for successful hybrid lubrication, in vacuum, are less susceptible to evaporative losses than the larger films used for fully fluid lubrication. However it has been shown that for very thin films of fluid (i.e. typical of the amount proposed for successful hybrid lubrication under vacuum), the Langmuir equation can predict significant over-estimations of the evaporation rate for both PFPE and MAC based fluid mediums, with errors of at least one order of magnitude for PFPE's and two orders of magnitude for MACs [6]. Therefore the evaporative behaviour of the fluid film at elevated temperatures is not considered to be as restrictive as one would initially assume.

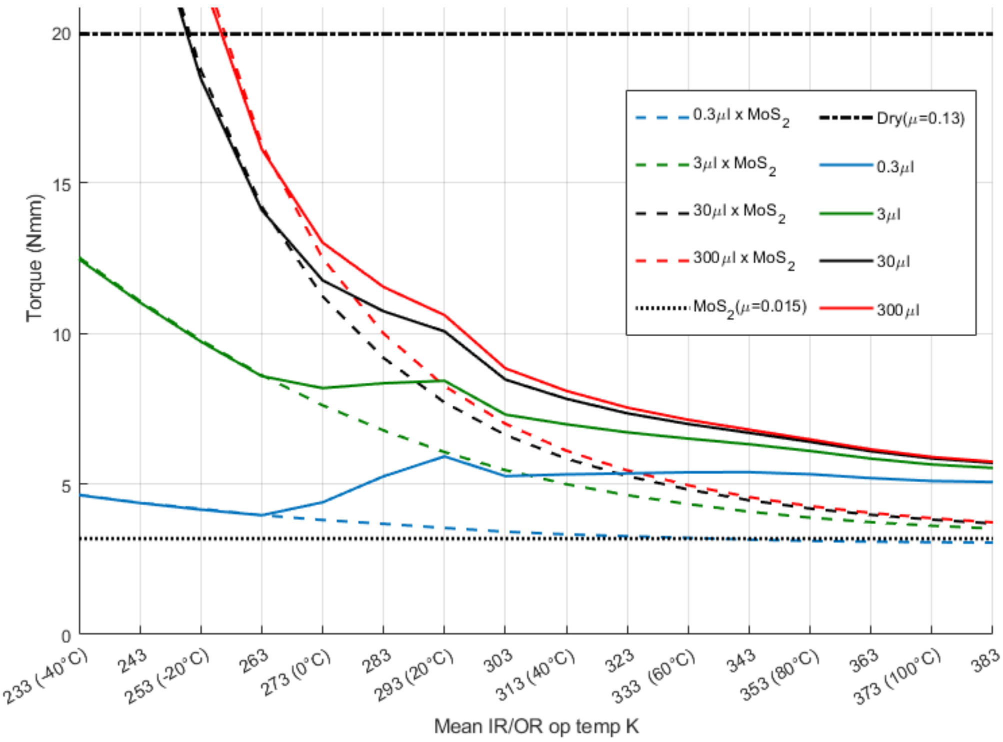

Figure 9 – Torque estimations for 7004C bearing pairs (31mm PCD) (iso-thermal housing), lubricated with Z25 only (solid) and hybrid lubrication (dashed), or varying volumes. "Dry" equates to no effective lubrication (μ=0.13)

At low temperatures, hybrid lubrication behaves more like fluid only lubrication, with the torque dominated by the increased viscous effects. However, as hybrid lubrication typically employs lower fluid volumes than the traditional fluid lubrication (1µl/mm PCD), the increase in torque observed with a reduction in temperature would be less pronounced for hybrid lubrication (shown by CABARET models in Figure 9). In addition, at higher temperatures the torque for a hybrid lubricated bearing is predicted to be lower due to the presence of the MoS_2 protecting against any degree of unlubricated contact.

Viscosity of the fluid can also be time dependent. The viscosity of the oil is partially governed by its chemical structure, and as the molecular chains begin to degrade and polymerise (through shearing) the viscosity can increase. The rate of polymerisation is non-linear and does not necessarily correlate with the rate of MoS_2 debris production. However in a hybrid application, the presence of a solid lubricant may act to retard the polymerisation process (which for PFPEs is driven by reactions of the sheared fluid with the steel substrate [7]). This chemical degradation rate is also influenced by temperature.

For PFPE lubricants there are also concerns regarding autocatalytic degradation [8], the hypothesis that the presence of iron can result in a non-tribological chemical degradation of a lubricant. As the presence of an MoS_2-film will reduce the risk of iron exposure, the impact of autocatalytic degradation is considered to be reduced for hybrid lubrication.

Fluid Volume

Previous papers concerning hybrid lubrication have demonstrated the significance of applied fluid volume (and subsequent film thickness) [1], [2].

Buttery et al. [2] detailed how MoS_2 debris can be removed from the contact by a significant fluid film and can stop the presence of a 3rd-body transfer film of MoS_2 from forming. However, [3] has shown that a true excess of fluid lubricant instead transitions to an entirely fluid lubricant dominated regime (both torque behaviour and lifetime). Additionally, if the fluid volume is only marginally too high this can result in a non-synergistic hybrid performance, with an MoS_2 dominated torque but a reduced lifetime (compared to MoS_2-only).

If too little fluid lubricant is applied, (or the viscosity of the oil is such as to further reduce the film thickness), then the behaviour observed is akin to that for MoS_2-only. Therefore, there is no significant disadvantage of selecting a non-optimum fluid volume, instead there is simply no advantageous synergy.

Substrate Properties

The substrate roughness (R_a) is known to affect the chemical degradation and lifetime of fluid lubricants. In addition other surface parameters (such as skewness and kurtosis) can also affect the degradation rate, if the R_a is sufficiently low [9]. As the chemical degradation will affect the viscosity of the lubricant (and hence the fluid film thickness), it is necessary to consider how this variable may influence the success of hybrid lubrication.

The effect of surface roughness on the performance of sputtered MoS_2 has been considered previously [10]. This study found that an optimum substrate roughness exists (R_a of 0.2µm), providing the longest in-vacuum MoS_2 lifetime.

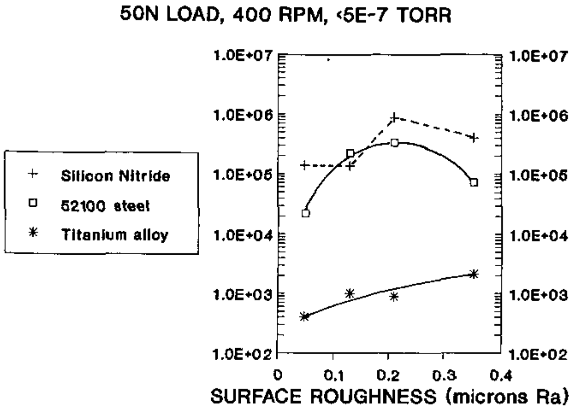

Figure 10 – Variation of MoS_2 film durability (number of disc revs completed) with the surface roughness of three different substrate materials [10]

However this roughness is sufficiently high as to result in increased fluid lubricant degradation, and so a trade-off may be necessary to produce the optimum roughness for a given hybrid lubricated application.

In addition, for ideal MoS_2 lubrication, the steel substrate must be sufficiently hard, necessitating that softer materials (such as those used in gear applications) typically require surface hardened prior to coating. If the substrate is too soft, and therefore the rate of debris production of the MoS_2 is too high, this may impact the concentration of debris within the hybrid lubricant suspension. Therefore, a limiting factor for the success of hybrid lubrication, is likely that the substrate features appropriate hardness and roughness. These are less stringent for the fluid lubrication aspect but are more severe for the solid lubrication aspect.

MoS_2 Debris Generation

The impact of contact stress on hybrid lubrication success has previously been investigated at SOT level [2], with an increased contact stress decreasing the extension in life compared to the summation of equivalent MoS_2 and oil lifetimes (see Figure 11). As these tests were conducted under the same conditions (with the exception of contact stress), including fluid volume, it can be hypothesised that the increase in MoS_2 debris generation due to the increased contact stress is responsible for this apparent difference in success.

In order to fully capture the MoS_2 debris, it may be necessary for higher load scenarios to employ higher fluid lubricant volumes in order to ensure a sufficiently thicker fluid layer is present.

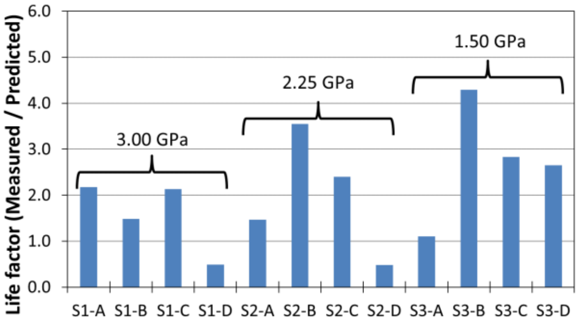

Figure 11 – Measured lifetimes of hybrid Fomblin Z25/MoS_2 lubrication as a factor of predicted life (defined as the summation of the oil and MoS_2 only lifetimes) [2]

It must also be considered however that MoS_2 wear debris is not generated linearly; with the majority of the debris generated early in life. The rate of MoS_2 debris production is significant for the success of hybrid lubrication because it influences the concentration of debris within the hybrid suspension. If debris is generated too quickly (such as under high stress or during initial run-in) then the suspension becomes saturated, and the beneficial tribological hybrid behaviour is not observed, and may also result in high torque noise, typically observed for insufficiently run-in MoS_2 only applications. Therefore, it is necessary to run in any hybrid lubricated mechanisms, as would be the case for MoS_2 only mechanisms, to ensure that the period of rapid debris generation does not occur during fundamental application of the mechanism (i.e. in-flight).

DISCUSSION

Previous investigations performed by ESTL have demonstrated many advantages for hybrid lubrication [1], [2]:

- Extension in lifetime compared to solid lubrication
- Reduction in torque compared to fluid lubrication
- Ability to protect an MoS_2 coating during in-air running

The successful synergy between MoS_2 and a fluid lubricant can result in an extension in MoS_2 dominated lifetime. Depending on the specific requirements of a given mechanism this extension can be several times longer than the expected lifetimes of each of the constituent lubricants alone. This extension is attractive for mechanisms where the torque typical of MoS_2 would be advantageous, but dry MoS_2 can give a shorter than desirable lifetime, such as in gear applications. For applications where one would typically employ a fluid lubricant, hybrid lubrication may be attractive as, when performed successfully, it can result in a reduction in torque towards that observed for dry MoS_2.

Additionally, hybrid lubrication may be useful to protect underlying MoS_2 layers in situations where it is necessary to perform some degree of moist air running. The applied oil layer shields the MoS_2 coating, preventing the deleterious effect of moisture, with no subsequent negative effect on the in-vacuo performance. The impact on the torque, of having added a small quantity of oil, is negligible and may instead produce the advantageous synergistic extension in lifetime described above. This would be advantageous for applications which experience high contact stresses but have short in-vacuum life, (such as hold down and release mechanisms) where ECSS requirements for on-ground actuations are considerably greater than the in-flight application itself, potentially reducing AIT costs as the requirement for testing in a dry (i.e. vacuum, or other cover gas) environment may be removed.

Hybrid lubrication may be used across a wider range of temperatures than fluid lubrication alone; with the lower quantity of fluid required reducing the viscosity-induced torque increases at lower temperatures (as shown in Figure 9). Hybrid lubrication can also be considered to extend MoS_2 lifetime at higher temperatures than might be assumed, as the Langmuir equation is less applicable to the very thin fluid films required. This increased operational temperature range makes hybrid lubrication attractive for a wider range of mechanism applications than fluid lubrication alone. Hybrid lubrication may also be considered for applications where cleanliness requirements would ordinarily preclude the use of a fluid lubricant, again due to the inapplicability of the Langmuir equation to these very thin films.

Hybrid lubrication may also provide options for certain medium-to-short bearing applications, where the use of an impregnated phenolic cage would enable lower torque performance than the traditional self-lubricating cage/solid lubricant combination.

Recommendations For Use

Based upon the test campaigns performed by ESTL (detailed here and elsewhere), initial recommendations for the safe use of hybrid lubrication can now be made.

Hybrid lubricated bearings would still require the same degree of running-in as traditional MoS_2-only lubricated bearings, to remove the large quantity of debris generated in early actuation and to avoid similarly high torque noise as would be found for MoS_2 only bearings. ESTL generally recommends that this running-in occur in the absence of the fluid lubricant and that any oil only be added to the component once the running-in has occurred. Once the oil has been added, after there is a suitable reduction in the running-in torque noise, it is then necessary to characterise the bearings to confirm that the tribological performance is still MoS_2 dominated (i.e. low torque) and to ensure that a suitable initial concentration of debris is present within the hybrid lubricant suspension.

ESTL also recommends that, when considering hybrid lubrication for a given application, one considers how the application might behave if lubricated instead with solid-only or fluid-only methods. Whilst hybrid lubrication can be more widely applied than other lubrication options; there are circumstances when different constituents of the suspension may be more susceptible to different conditions; therefore, it is necessary to consider whether this is a possibility for the specific application (such as if the mechanism may experience different temperatures or environments).

The requirement to suitably demonstrate and validate the lubricant selection is of course still valid for hybrid lubrication. Hybrid lubrication has proven difficult to replicate reliably, with each contact and application being different and many factors being shown to be integral to its success; therefore, early-stage testing is perhaps even more crucial to design success. To confirm that an appropriate ratio between the fluid and solid lubricants has been selected for a given application, it is necessary to perform specific and fully representative tests. However it is hoped that, with further investigative studies (and higher-level component/mechanisms tests) it should be possible to make more general recommendations on successful synergistic performance, to reduce the risk of the selection of hybrid lubrication going forwards.

CONCLUSIONS

From our investigative studies of hybrid lubrication to date, we conclude the following.

- For any given application where hybrid lubrication is considered, it is necessary to think about how the operational conditions may impact both the solid lubricant constituent and the fluid lubricant constituent, as well as the interaction between the two within the contact.
- Hybrid lubrication can be applied across a wider range of conditions than may be traditionally anticipated. For example, temperature extremes (both hot and cold) are not anticipated to impact the success of hybrid lubrication as severely as for fluid-alone (due to reduced viscosity effects and the potential inaccuracy of the Langmuir equation).
- The success of hybrid lubrication should be considered a system property, and as such appropriate consideration early in the design process (together with appropriate testing) is necessary to fully de-risk this lubricant option.

REFERENCES

[1] Buttery, M. et al, (2015), 'The Synergistic Effects of MoS_2 and Liquid Lubrication', Proc. 16th ESMATS, ESA SP-737.

[2] Buttery, M. et al, (2018), 'Hybrid Lubrication of PFPE Fluids and Sputtered MoS_2', Proc. 44th Aerospace Mechanisms Symposium, NASA/CP—2018-219887

[3] Bingley, R. & Cropper, M. (2020), 'A Further Assessment of Considerations for Hybrid Lubrication', ESA-ESTL-TM-0247 01-

[4] Campo, P. et al, (2015), 'Testing of BepiColombo Antenna Pointing Mechanism, Proc. 16th ESMATS, ESA SP-737.

[5] Zhang, Jie & Spikes, Hugh. (2016). On the Mechanism of ZDDP Antiwear Film Formation. Tribology Letters. 63.

[6] Kent, A. et al (2019), 'Evaporation Lives of Space Oils', ESA-ESTl-TM-0162 01-

[7] Buttery, M. et al (2013), 'Fomblin Z25: A New Method for its Degradation Assessment & Proposal for Safe Operation in Space, Proc 15th ESMATS, ESA SP-718.

[8] Buttery, M. et al (2019), 'Aging and Environmental Effects on Lubricants – A Preliminary Study', Proc. 18th ESMATS.

[9] Bingley, R. et al (2019), 'The Effect of Surface Production Techniques on the Tribological Behaviour of Fluid Lubricants', Proc.18th ESMATS

[10] Roberts, E W., Williams, B J. & Oglivy, J A. (1992). The effect of substrate surface roughness on the friction and wear of sputtered MoS_2 films. J. Phys. D: Appl Phys. 25, A65-A70.