APPLICATION OF SURFACE FUNCTIONALISATION IN SPACE MECHANISMS

Michael Buttery (1), Rachel Bingley (1), Kristine Brittain (1), Olly Poyntz-Wright (1), Achilleas Vortselas (1), Manuela Talbot (2), Stefan Dittenhauser (2), Verena Obrecht (2), Sebastian Rieger (2) & Ewelina Ryszawa (3)

(1) ESTL, ESR Technology, 202 Cavendish Place, Birchwood Park, WA3 6WU, (UK),
michael.buttery@esrtechnology.com
(2) Airbus Defence and Space GmbH, Claude-Dornier-Straße, 88090 Immenstaad, (Germany),
manuela.talbot@airbus.com
(3) ESA, ESTEC, Keplerlaan 1, PO Box 299, NL-2200 AG, (The Netherlands), ewelina.ryszawa@esa.int

ABSTRACT

Tribological lifetime is frequently the main factor limiting the useful life of spacecraft mechanisms, including on-board instruments and ultimately in some cases the entire spacecraft/mission duration. Frictional losses may drive overall power requirements, and variations in tribological behaviour (instability of cages/ torque noise etc.) can severely limit the performance of mechanisms and ultimately even impact the main goals of a spacecraft through increased micro-vibration levels. Given this, the maximisation of lubricant life and functionality are frequent concerns for the spacecraft mechanism engineer.

This paper presents the conclusions of a recently completed developmental project, performed as a collaboration between ESR Technology/ESTL (UK) and Airbus Defence and Space (DE) (plus other partners) into the use of Surface Functionalization (SF) techniques as means to enhance lubricant performance for various spacecraft mechanism applications.

1 BACKGROUND

The function of a lubricant is to minimise friction and maintain as far as possible tribo-contact separation (supporting load) whilst minimising wear in contacts under relative motion. Whilst a selected lubricant may have an inherent load-supporting capability and resistance to chemical or physical degradation within the demanding local environment of tribological contacts, it will only prevent wear if supplied/re-supplied to and retained appropriately within the contacts. The maintenance of low friction is dependent on effective lubricant function, optimisation of the local quantity of lubricant available and on the management of lubricant loss (whether through creep or evaporation) and wear debris. Therefore, technologies which have the potential to improve lubricant performance (inherent lifetime), supply and retention within the tribo-contacts and so achieve these broad goals are of considerable interest.

The range of emerging Surface Functionalisation (SF) techniques which can locally modify surface wear properties or provide physical lubricant performance enhancement, lubricant retention and supply features within and adjacent to tribo-contacts offer great promise in this respect.

1.1 Project Structure

The structure of the activity is summarised below. Following each stage, a review was held, and only the most promising technology applications were progressed.

- **A literature study phase** to identify the state-of-the-art in SF technologies, conceptual designs of appropriate SF features, and the corresponding potential tribological benefits in each case together with the risks and limitations of the application of the corresponding candidate SF technologies.
- **Production of a development and procurement plan**, defining the SF processes and facility requirements applicable to the surface features selected.
- **First application trials of SF technologies**, performed iteratively upon simple, planar specimens, and trials carried out to assess SF technology efficacy.
- **Tribological assessments under representative vacuum environments**, compared against pre-existing tribometer benchmark data. SF technologies were also applied to bespoke and appropriately complex geometric specimens, representative of the previously highlighted application domains.
- **Component level tests of SF technologies** applied to tribo-components (i.e., angular contact ball bearings), monitoring key parameters such as torque and fluid film thickness.

Full and comprehensive descriptions of these phases can be found within the specific project documentation, or upon request to the authors.

2 SF TECHNOLOGIES

2.1 Overview and State-of-the-Art

As a literature study, a full and comprehensive review of surface functionalisation technologies was performed, including:

- Laser-based technologies, including Laser Surface Texturing (LST), Direct Laser Interference Patterning (DLIP), Laser Surface Modification (LSM), texturing through re-melting, micro-drilling, Galvo scanning, Laser Peen Texturing (LPT), and Laser Shock Peening (LSP)
- Ultrasonic Nanocrystalline Surface Modification (UNSM).
- Micro-Ball End Milling
- Micro-casting
- Electrical Discharge Machining (EDM)
- Etching Processes
- Deposition technologies, including Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD)
- Heat Treatments (Hardening)
- Surface Cleanliness and Contamination effects

For each of the above a detailed review was performed, include the application technology itself, as well as known and published lubricant behaviour modification from terrestrial applications.

2.2 Key Application Domains

Application domains for spacecraft mechanisms were reviewed, considering the following means by which SF technologies may facilitate life extension in tribological components (or otherwise improve performance, such as to provide a graceful decline failure mode rather than a rapid and critical increase in friction and wear when the lubricant becomes even very locally depleted or degraded within the component contacts):

- **Improving the adhesion and durability of solid lubricant coatings** applied directly to component surfaces (for example spur gear teeth, cup-cone interfaces in hold-down and release mechanisms, or the contacting surfaces of rolling element bearings).
- **Improving wettability and fluid retention properties** of surfaces lubricated by fluids (oleophilic surfaces) perhaps including bearing balls, raceways, lands, cage pockets, gear teeth etc.
- **Promoting transition to EHL** in conditions which might otherwise favour boundary or mixed lubrication by fluids.
- **Reducing the propensity of fluid lubricants to creep** away from the contact zones, for example by producing local oleophobic zones where creep is inhibited or even functional surfaces which encourage flow back into the contacts by means of surface energetics or geometric features.
- **Promote and encourage local lubricant resupply and recirculation** via specific local features on the surface close to the contact zone.
- **Improving the durability of the underlying substrate** (hardness/wear resistance/surface texture) either in the context of a fully functional lubricant operating in the boundary regime where some degree of asperity contact takes place (e.g. spur gears, specific contacts within harmonic drive gears (wave-generator/flex-spline interfaces and tooth contacts)) or when incipient lubricant failure is underway (for example in local edge contacts frequently found due to elastic strains in conventional anti-back-lash gear systems or local stress concentrations).

2.3 Areas of Tribological Focus

Following the review of the state-of-the-art for SF technologies and the discussion of the key application domains, a justification was presented for the areas of focus for the remainder of the project. These areas for consideration were as follows:

- SF processes applied to the raceways of fluid lubricated bearings for the extension of life (without compromise of the friction coefficient or torque)
- Fluid lubricant reservoirs
- Passive displacement of fluid into the ball-race contact for fluid lubricants
- Oleophobic surfaces to replace creep barriers for bearing applications
- SF processes to improve the coating adhesion of sputtered MoS_2, or to better retain the 3rd body debris within the contact zone

2.4 Down-Selection

For each tribological region the pros and cons were identified and the relevance of each SF technology to achieve the desired tribological improvement were considered. This provided input into a weighted down-selection to identify the areas of focus for the remainder of the activity (summarised in Tab. 1). This down-selection highlighted two technologies for future consideration.

- **Laser Surface Texturing** (which has the flexibility and control necessary to apply a wide variety of controlled features to different substrate types). LST features away from the contact zones could be produced by Airbus (due to their larger feature dimensions), but those within the contact zones themselves were considered only to be possible to be achieved by MTC (through their contacts and partners).

- **High Power Ion Etch** (which will essentially modify global surface roughness and/or ensure chemically clean substrate). This process was selected to be produced/performed by ESR Technology going forward into the activity.

Table 1. SF processes and tribological areas of focus throughout programme

ID	SF process	Area of focus
ID-01	LST	Extension of fluid life in bearings without compromise of friction
ID-02	LST	Fluid lubricant reservoirs in bearing application
ID-03	LST	Passive displacement of fluids into the ball-raceway contact zones
ID-04	LST	Oleophobic surfaces
ID-05	Ion-etching	Oleophobic surfaces
ID-06	LST	Solid lubricant adhesion
ID-07	LST	3rd body MoS_2 lubricant retention
ID-08	Ion-etching	Solid lubricant adhesion
ID-09	LST	Oleophilic surfaces

The technical performance and applicability of the above SF processes to space mechanism applications shall now be presented.

3 UNSUCESSFUL TECHNOLOGY APPLICAIONS

During the R&D activity led by ESTL, several of the above technologies were not progressed through the full programme due to poor performance (as part of the down-selection structure). For brevity, SF technologies which did not complete the full testing campaign are first presented. For more detailed information on the performance of these SF technologies, please contact the authors.

3.1 Extension of Fluid Lubricant Life via LST

Multiple trials of fluid lubricant life extensions were performed utilising Direct Laser Interference Patterning (DLIP), facilitated by The Manufacturing Technology Centre (MTC). This included an investigation into the form of the applied textures, with dimples, parallel groves, and nested wavy grooves being produced with varying parameter sets. Analysis was performed on the substrates including detailed profiling of the texture regions, and fluid mobility, for which the parallel textures performed the best.

Whilst technologically feasible, issues were encountered with the cost and availability of the hardware used to produce the textures. Given that no improvement in performance was observed compared with the other, lower cost, LST techniques employed within this project, the specific use of DLIP was not continued. However, the lessons learned on the form and structure of the textures were implemented into the other SF technologies within the project (see Section 5).

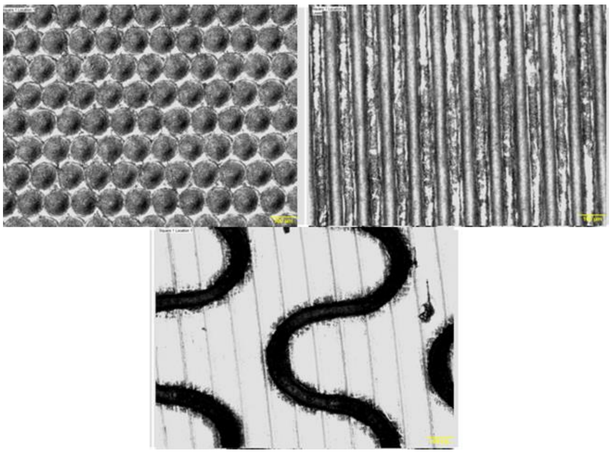

Figure 1. Surface texture grooves produced via DLIP

3.2 Oleophobic Surfaces

Oleophobic textures were produced on various substrates via a laser marking system, with many parameter sets investigated (including power levels, intensity, frequency, microstructure density, and texture formation). The success of these parameter sets was assessed principally through surface energy measurements performed via contact angle and fluid mobility trials (including against gravity).

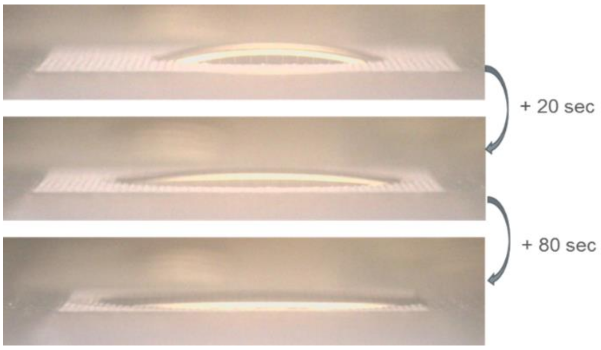

Figure 2. Lubricant mobility trials of cross-hatch LTS microstructures

Results were successful, although not in the manner anticipated. In general, no LST parameter set was seen to display true and uniform oleophobic behaviour. However, the textured surfaces showed highly directional favoured flow and lubricant penetration (Fig. 2), akin to oleophilic behaviour in one direction, and oleophobic behaviour perpendicular to this. Lessons learnt from this behaviour was implemented into the oleophilic surfaces (SF ID-09), described in more detail in Section 5 below.

Creation of oleophobic surfaces via etching was unsuccessful, with no modification of the surface energy observed for any assessed parameter set.

3.3 Improved Solid Lubricant Adhesion via LST

An iterative development campaign was performed, focusing upon refinement of the LST paramaters for optimised solid lubricant adhesion. Varied paramaters included laser power, frequency, and texture distributions, with surface assessments made of homogeneity, surface hardness, isotropy, and surface topography. A total of 96 parameter sets were assessed during the programme, with surface analysis down-selecting this to the most encouraging 4 sets.

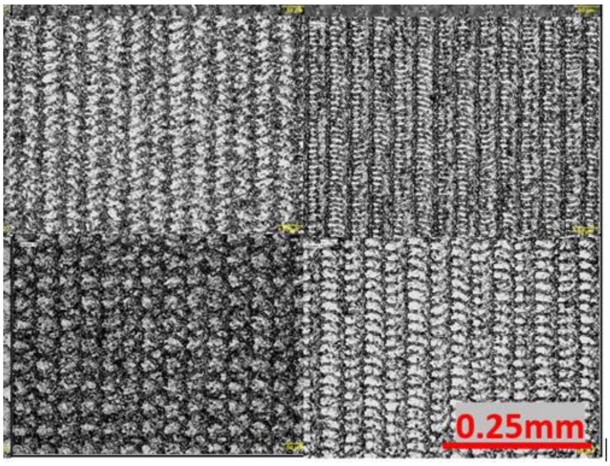

Figure 3. Example surface textures for solid lubricant adhesion via LST

Down-selected parameter sets were then assessed via a Pin-on-Disc (PoD) tribometer using MoS_2. Results showed no evidence of a repeatable improvement in lubricant lifetime, but some evidence of the LST introducing a more graceful degradation behaviour of the lubricant (as opposed to the usual rapid and catastrophic failure behaviour observed on the PoD).

3.4 3rd-Body Lubricant Retention via LST

Trials were performed to identify surface texturing techniques to allow for favourable 3rd body debris retention for wearing lubricants (e.g., MoS_2), with the technique applied post-deposition.

The initial challenge of this SF technology lay in the identification of the appropriate laser power; if this was too high it compromised the tribological properties of the coating through the formation of MoO_3 and substrate texturing, but if the power was too low no retention of lubricant debris was achieved. In total 34 texture combinations were produced and assessed during the first application trials, with these parameter sets assessed using surface analysis, optical inspections, chemical analysis, and coating adhesion measurements. As previously a trade-off and down-selection exercise was performed to identify the most promising candidates for tribological assessment.

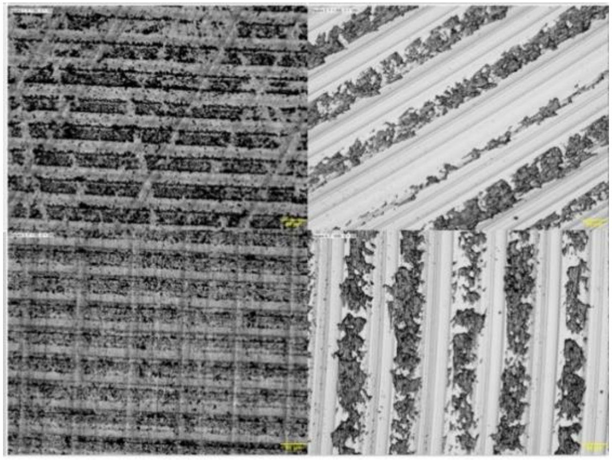

Figure 4. Example 3rd body MoS_2 debris retention achieved via LST

Tribological assessments were generally unsuccessful. Although evidence of lubricant debris capture (rather than bulk expulsion from the contact) could be seen, this did not translate into a repeatable improvement of lubricant life. Therefore, this SF technology was not progressed further into the project.

4 LUBRICANT RESERVOIRS AND PASSIVE DISPLACEMENT

Numerous iterative studies were performed to identify the preferred conditions for lubricant flow and passive transport, with highest powers generally avoided to prevent unwanted plastic deformation. These iterations were first performed on non-representative 1.4544 Stainless steel, before the parameters were translated to 52100 steel, though little influence of substrate was observed, with channel and lubricant behaviours being broadly independent of substrate. Considering power, a relationship was identified between pulse diameter and power percentage, and pulse diameter and pulse frequency, suggesting that higher powers are preferred for the production of lubricant channels, as long as significant material ablation can be avoided.

Considering repetitions of the laser path to produce the channels, a study was performed identifying a dependence in the form of the channel with the number of passes. If the number of repetitions is too high a material build-up in the whole area of the laser pulses can be observed, caused by the build-up of ablated material within the channel itself which cannot escape the target area before the next pulse arrives. Therefore, a practical limit exists on the maximum depth a channel can be, for a given width.

The influence of channel geometry on lubricant flow was next studied, with relationships between both channel width (Fig. 5) and depth with lubricant flow being observed. From these studies the optimised parameters were identified for implementation at bearing level. However even under these conditions there exists some degree of "lips" at the edges of the channels which may preclude the use of these techniques within the ball track.

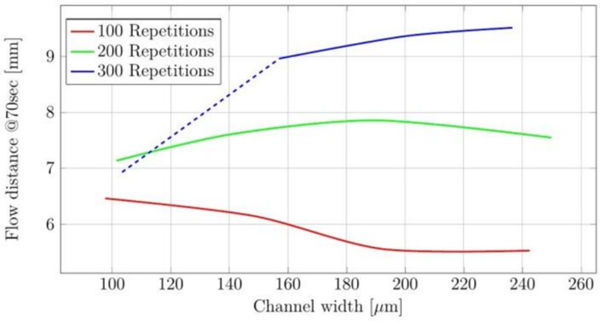

Figure 5. Lubricant flow velocity vs channel width

Application trials were performed to identify techniques for applying these passive displacement technologies onto bearing raceways, based upon the most onerous geometries for the line-of-sight hardware. Issues were encountered regarding feature mapping onto the 3D surface and required power fluctuations due to the high reflectance of the raceway surface, potentially resulting in material ablation. Nevertheless, application trials on bearing raceways were deemed successful (Fig. 6).

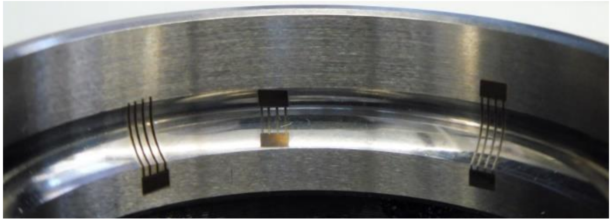

Figure 6. Lubricant reservoirs and passive displacement channels on B7004C-type bearing raceway

Lubricant retention and displacement trials were performed via vacuum bearing tests utilising the Advanced Bearing Test Rig (ABTR), combined with oleophilic features. B7004C-type angular contact bearings were lubricated with Nye 2001a and fitted with impregnated phenolic cages, and operated under a range of speeds and temperatures under vacuum to map the fluid film behaviour.

Overall results of these bearing tests will be discussed in the next section, but specifically the lubricant retention features were observed to be successful, with fluid lubricant retained and expelled during the bearing rotation.

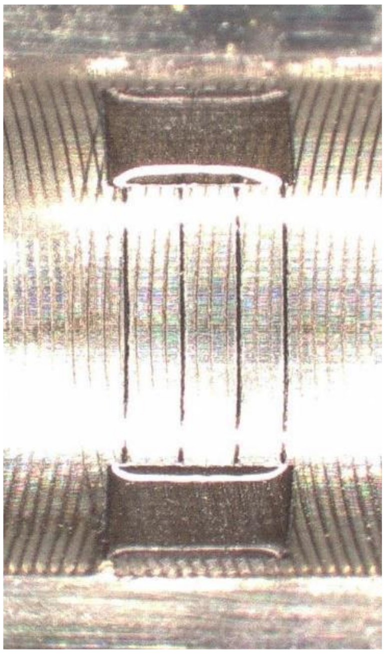

Figure 7. Fluid lubricant retention within reservoirs (on bearing raceway with perpendicular textures)

5 OLEOPHILIC SURFACES FOR FLUID LIFETIME EXTENTION

Lessons learnt from other related technologies were implemented into the development of this SF technology (texture forms and densities, laser parameters, fluid mobility, etc) to aid in optimisation. Straight textures were again selected as being the most appropriate, but fluid mobility trials could not differentiate between parallel and perpendicular (to the ball motion) as being the most favourable textural form.

Figure 8. Oleophilic textures applied to B7004C-type bearing ring in perpendicular (left) and parallel (right) directions

Vacuum tribological tests (using the Spiral Orbit Tribometer) were performed to identify the behaviour of the features within a lubricated ball contact. Results were tentatively encouraging, with decent tribological behaviours (friction and lubricant life), with no evidence of substrate wear. However, the performance of the parallel vs perpendicular textures again could not be conclusively differentiated, so both texture forms were progressed to bearing level, together with the lubricant reservoirs and passive displacement technologies presented previously (Fig. 8).

Due to the anticipated extensive test duration, it was deemed impractical to perform life tests on fluid lubricated bearings featuring these textures. An alternative test methodology was proposed in which success could be identified by mapping of the fluid film thickness in-situ under vacuum during bearing operation over a range of conditions (speed, temperature, fluid fill volume). This methodology has previously been used by ESTL to explore the film-thickness behaviours of angular contact bearings using the ABTR [1], and any favourable reflow behaviours resulting from the oleophilic textures should enable film formation over a wider range of conditions (shown by the arrows in Fig. 9). Therefore, all test parameters were held to be consistent with this previous study.

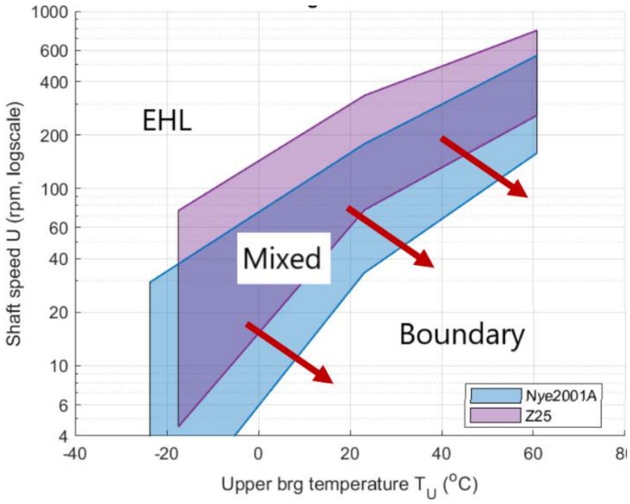

Figure 9. Demonstration lubrication transition diagram, showing desired behaviour [1]

It should be noted that for a meaningful comparison to be made between the lubrication regime of a textured and non-textured bearing (with respect to differentiating the lubricant reflow effects from the textures), all other parameters must be considered as consistent. Clearly this is not the case for lambda, as the composite surface roughness of the bearing raceways is modified at a macro level by the LST. However, as the surface roughness between the textures is considered to be unmodified (so similar at the micro-level), this assumption was deemed to be valid for the purpose of assessment during this study.

ABTR results showed only marginal improvement of the bearing lubrication mode, assigned to promotion of fluid mobility into the contact areas. Parallel textures provided the most tangible improvement over control data (non-textured bearings), though this analysis relies upon known to be false assumptions regarding constant roughness of the contact surfaces (observed during the post-test inspections, discussed below). Torque improvements were observed only at low temperatures, with torques generally elevated in comparison to control data.

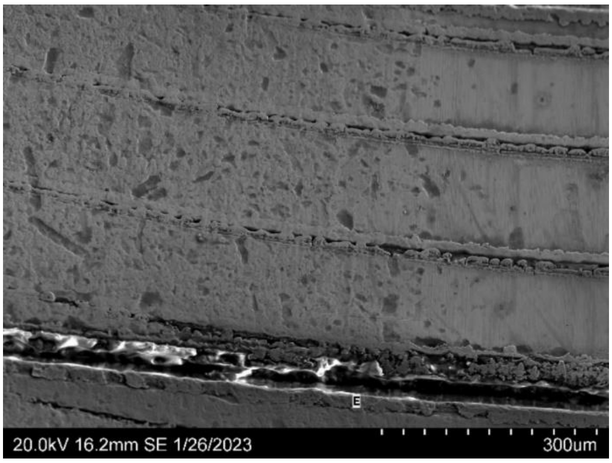

Figure 10. Surface disruption post-test (inner raceway, parallel texture, nominal fill)

Post-test all fluid-lubricated bearings showed evidence of significant plastic deformation of the contacting surfaces, attributed to hard abrasive particles originating from the LST, of a magnitude not expected for non-textured bearings subjected to the same operational duration. The origin of these hard particles is likely the channel lips themselves, which were severely worn to the point of being flattened (Fig. 10).

6 IMPROVEMENT OF SOLID LUBRICANT ADHESION

Under previous R&D activities (funded by ESA), ESTL has developed process improvements for MoS_2, resulting in extended lifetimes under vacuum (as assessed via PoD) without subsequent increase in friction coefficient [2]. This developmental coating is given the designation MoS_2-201 to differentiate it from the “standard” ESTL MoS_2 coating (subsequently called MoS_2-101). Other variation coatings are also available (called MoS_2-301 and MoS_2-Star), but these also include chemical changes to the lubricant film itself, whilst MoS_2-201 is a process change only.

Through the implementation of SF technologies, this process improvement was refined further under the current activity. This iterative process focused upon power distributions, frequencies, and cover gas pressures, with analyses made of substrate hardness, topography, and coating adhesion, first ensuring that the process did not adversely impact the underlying

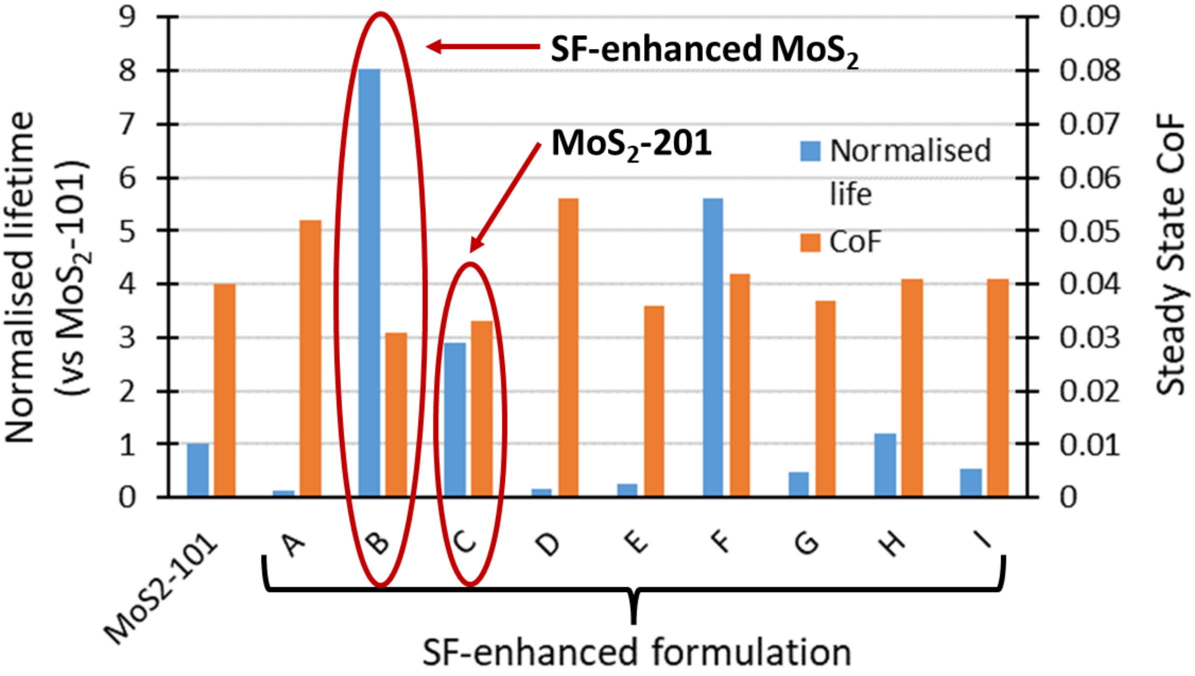

Figure 11. Vacuum tribological performances of SF-enhanced MoS_2 (via PoD)

substrate before progressing onto assessments of coating improvement.

The most promising 9 parameter sets were used to produce MoS_2 coatings onto standard PoD samples for assessment under vacuum, given the test designation of Formulation A-I. For completeness, Formulation C was identical to the previously developed MoS_2-201.

PoD results were encouraging, with several of the new formulations providing significantly longer lifetimes than standard MoS_2-101 in both vacuum and air, with no increase in friction coefficient (Fig. 11). Based upon these results the best performing coating (Formulation B) was down-selected for component level trials, performed using B7004C-type angular contact bearings on the ABTR.

Formulation B MoS_2 was applied to the balls and races of two pairs of test bearings. Two cage materials were assessed; the self-lubricating material TSE8591 to provide a meaningful comparison to typical applications and existing data, and a standard unlubricated 440C steel cage selected to remove any influence of the self-lubricating composite for comparison.

All parameters were selected to match the nominal values used in previous tests within the ABTR test facility [3]. All solid lubricated tests were performed at ambient temperature (22 ± 2°C), maintained using a heat exchanger and fluid bath. All testing was performed at $\leq 5 \times 10^{-5}$ mbar. Test bearings were preloaded to 48 ± 3N giving a peak Hertzian contact stress of 720MPa on the outer bearing race and 840MPa on the inner bearing race.

Approximately 80,000,000 revolutions were completed for the TSE8591 caged bearings. Mean and peak torques were initially high before stabilising to <1 and <2 mNm respectively after ~5,000,000 revolutions with no evidence of lubricant failure. Bearing shaft displacement was observed during this initial operation, attributed to a removal of ~50% of the available deposited MoS_2, consistent with previous ABTR studies. Further slow shaft displacement was observed during the remainder of the test, but without dramatic change, supporting the argument that MoS_2 was still present within the contact after 80-million revolutions, and there was no evidence of bulk material transfer from the cage.

Given the conclusion that these bearings had not failed, the test bearings were not disassembled, and no post-test inspection was performed. It is currently planned to re-insert these bearings back into vacuum test as part of a subsequent R&D activity funded by ESA (under the 2023 Frame Contract) to determine the true lifetime of this improved coating.

The bearing test featuring the 440C cage behaved similarly (including similar torque behaviour) but showed rapid and unrecoverable torque increase at 40,000,000 revolutions. Beyond this point however large torque spikes were seen, attributed to cage misbehaviour caused by an increase in friction due to the MoS_2 reaching the end of its life. Disassembly and post-test inspection of the bearing was performed, showing the presence of MoS_2 fragments and evidence of surface disruption.

Given the successful demonstration of this coating at tribological and component level, and its origin as a refinement of the process improvements identified under the previous work, this developmental lubricant is given the designation **MoS_2-202**.

7 CONCLUSIONS AND NEXT STEPS

From this activity our general conclusions on surface functionalised technologies for space mechanism applications are as follows:

- **SF-enhanced deposition processes displayed encouraging results**, with this technology being used to extend the tribological lifetime of subsequently deposited PVD MoS_2 and displaying compatibility with next-generation self-lubricating composites without compromise of friction. A roadmap for development to higher TRL has been identified, including appropriate further testing campaigns, demonstrations at mechanism level, and QA/productization considerations.

  Going forward the coating produced under this process shall be called MoS_2-202. Assuming successful completion of the developmental roadmap, a surface functionalised MoS_2-202 product would likely be welcomed by the space mechanism community, providing extended in-vacuum durability without compromise of torque, and good (and potentially cooperative) compatibility with the next generation of complimentary cage material (i.e., TSE8591).

- **Laser surface texturing for improved fluid film behaviours gave mixed results**. At flat sample level the directional-oleophilic behaviours of the textures were observed to encourage lubricant flow, but this could not be conclusively demonstrated at component level due to significant plastic deformation of the substrate as a result of raised lips to the sides of the textures. Lubricant reservoirs and passive displacement technologies were tentatively successful, but also could not be verified at component level.

  Actions have been identified to address these issues going forward. Primarily these focus upon either the mitigation of the lips through reductions in the energy-input density at the substrate, or improved planning regarding their locations to prevent them contributing negatively to the tribological performance. It is suggested that the texture occurs only within the meniscus area, the zone between a and 3a, where a is the contact ellipse semi-width in the (larger) lateral direction. This would also require consideration of the exact running track of the ball within the bearing (a property of contact angle and loading) and would increase the risk occurring from misalignment (where the running track may also deviate).

  Alternatively, if they cannot be fully avoided during production, actions must be taken to remove these lips as a post-production step. This could involve micro-polishing, grinding, or potentially etching of the bearing surface. Such actions are certainly possible but are non-trivial and may introduce higher production costs. It is likely that such development would need to take place as part of the manufacture of the bearing rings themselves, and not as a post-production texturing of procured bearing rings (as was performed during the current activity). Therefore, direct involvement from a bearing manufacturer is likely necessary to move this technology to higher TRL.

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