Tribology of spacecraft mechanisms: current solutions and future challenges

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1. Introduction

The management of friction and wear processes in spacecraft mechanisms through effective lubrication presents unique challenges. These challenges arise principally as a result of the vacuum environment of space which promotes rapid evaporative loss of fluid lubricants and, in their absence, encourages strong adhesion and high friction in metal contacts. Additionally, the thermal environment in which mechanisms operate can be one of extremes: from cryogenic temperatures (for deep space missions and those involving cooled infra-red devices) to elevated temperatures (e.g. 250 °C for Mercury-orbiting spacecraft). At these temperature extremes the use of fluid lubricants is precluded such that only solid lubrication is feasible.

Prior to their operation in space, spacecraft mechanisms must first survive the rigours of rocket launch, during which transient loads are created and sound pressure waves produced that cause structures to vibrate randomly. These loads and vibrations are transmitted to the payload and pose a threat to the mechanical integrity of its mechanisms and their tribological components as well as the lubricants applied to them.

Meeting the tribological challenges posed by the launch and space environments has been, and remains, the goal of the European Space Tribology Laboratory (ESTL), an ESA-supported centre of excellence located near Warrington in the North-West of England. The laboratory was established in 1972 and emerged as a consequence of ESA's realisation that the long term reliability of satellites depended critically on the reliability of their mechanisms, most of which represented single point failures. In turn this reliability depended upon the integrity of tribological components such as bearings, slip-rings and gears. At ESTL the integrity of such components, that of the mechanisms themselves, and the lubrication processes applied, is assessed under closely controlled simulated space conditions.

This paper addresses how space tribology has developed to the point where today we have sophisticated solutions that meet current requirements and looks ahead to the challenges posed by future programmes. It explains how low-friction solid lubricant coatings are already base-lined for the lubrication of mechanisms on major space programmes such as the James Webb Space Telescope and the BepiColombo mission to Mercury of which are destined for launch in 2014 Beyond that, missions are expected to become increasingly longer and this tendency will place yet further demands on space lubricants. The paper concludes by considering how this challenge, and other related issues, might be addressed.

2. Lubrication of spacecraft mechanisms

2.1 Fluid lubrication

Oil loss

The use of oils in spacecraft mechanisms is in general limited to those that exhibit exceedingly low volatility such as perfluoropolyethers (PFPEs), multiply alkylated cyclopentanes (MACs) and polyalphaolefins (PAOs). Such oils (and greases based upon them) evaporate at relatively low rates at (and below) room temperature. However, at higher temperatures, the depletion of oil by evaporation may be such as to prevent it meeting a mechanism's operational life. Evaporation also carries the threat of contamination of sensitive surfaces by condensing oil molecules and for this reason oils are often precluded in mechanisms that incorporate optical devices. Below room temperature, as the pour point of the oil is approached, increases in viscosity lead to prohibitively high frictional losses. For these reasons fluid lubricants are rarely used below -40 °C and above +100 °C.

As loss of oil by evaporation defines the useful lifetime of a fluid-lubricated component in an open (unsealed) system it is informative to compare the volatility of 'space' oils. The evaporation rate can be calculated by substituting values of the oil's vapour pressure and molecular weight into the Langmuir equation [1]. Two of the most commonly used oils are Fomblin Z25 (a type of PFPE) and Nye 2001a (a type of MAC). Fomblin Z25 oil has a much lower evaporation rate than Nye2001a and so remains in its liquid state for considerably longer (see Fig.1).

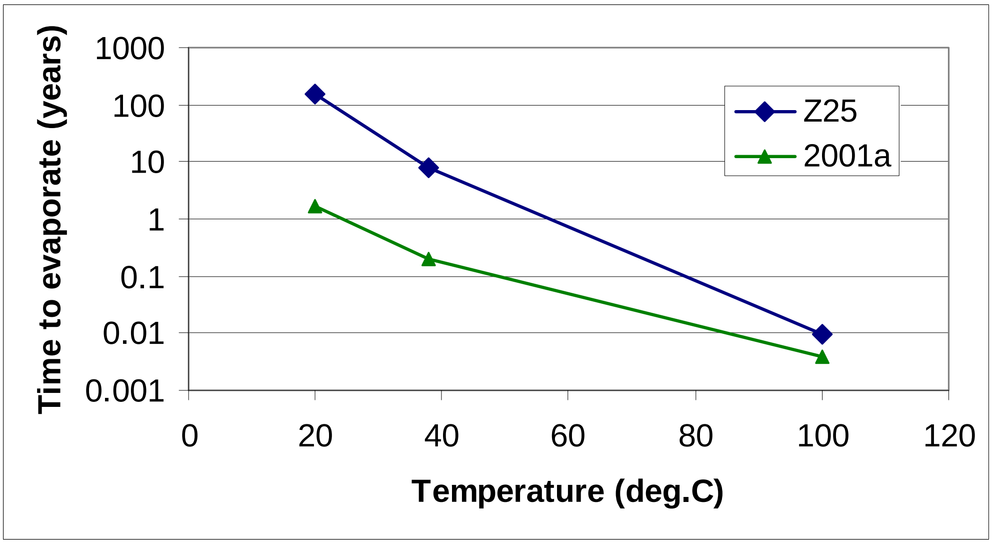


Fig. 1 Showing the time taken to lose all oil by evaporation from a medium sized ball bearing (ID 25mm; OD 42mm) lubricated with 50µl of oil

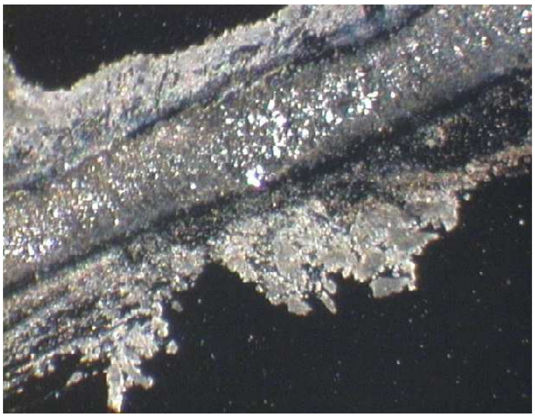
Fomblin Z60, a PFPE oil that has recently come into consideration for space applications, has an exceptionally low vapour pressure and offers a lower rate (by some 3 orders of magnitude at room temperature) of evaporative loss than Fomblin Z25. It is currently being considered for long life applications and appears to have similar tribological properties to Fomblin Z25 [2].

In practice the loss of oil by evaporation can be greatly impeded by the use of labyrinth seals [3] although these complicate the design of the bearing assembly. Oil loss also occurs by surface migration (otherwise known as 'creep'). Creep barriers arrest the migration of oils away from tribo-components and thus provide the dual function of keeping the lubricant where it is required and preventing contamination of nearby surfaces. Creep barriers prevent oil spread by virtue of their low surface energy – thus fluids tend to form droplets (beading) when present on the surface of creep barriers. The type of creep barrier used in space applications is based upon a fluorinated methacrylate polymer having surface energies in the range 11-12 mN/m which is lower than the surface tension of all existing 'space' oils. Typically, these oils have surface tensions in the range 17-33 mN/m and are thus theoretically incapable of wetting the barrier material.

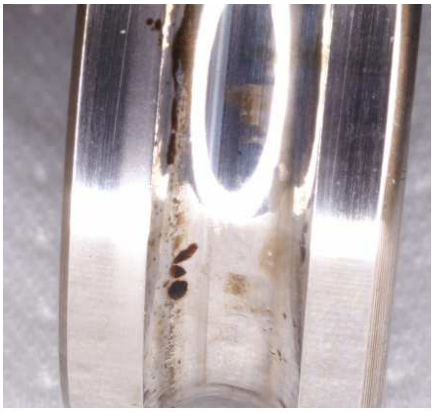
Oil lubricity and life

The function of a lubricant is to reduce friction and prevent, or minimise, wear. When a variety of oils are tested in tribometers they tend to exhibit a narrow range of friction coefficient, μ. Typically, under boundary lubricant conditions μ lies close to 0.1 regardless of the oil type [4] for bearing steel contacts operating at stresses representative of those occurring in mechanisms.

As long as lubricant is present in the contacting surfaces wear will be minimised. An oil will however eventually degrade and lose its lubricating action. Oils degrade most quickly when operating in the boundary and mixed lubrication regimes (as is the case in many space applications) where the contacts are not fully separated and interaction occurs between opposing surface asperities. The mechanism of degradation varies according to lubricant type. Thus MAC oils form friction polymers - known colloquially as 'brown sugar' due to their translucent, crystal-like qualities (Fig.2a).



a) Showing build-up of translucent friction-polymer at edge of MAC-lubricated (Nye 2001a oil) wear track



b) Showing black, degraded Z-type PFPE oil on the inner race of a life-tested ball bearing

Fig.2 Degradation products of MAC and PFPE oils

In PFPE-lubricated steel contacts fluorine is released from the oil by the action of repeated shearing under high contact stresses and reacts with iron in the steel to form iron fluoride, FeF_3. Despite being chemically inert to most materials, PFPEs suffer catalytic attack by the iron fluoride which in turn leads to a breakdown of further oil molecules and the release of yet more fluorine. The chain reaction that follows leads to rapid degradation of the oil. The product of this degradation process is black and has a viscous consistency (Fig.2b).

For both oil types (MACs and PFPEs) the act of degradation 'consumes' lubricant and eventually leads to a point where oil is no longer present (that is in the chemical state in which it was originally applied). In the absence of lubricant high friction and wear ensues.

In principle the life of MACs (and PAOs) under boundary lubrication conditions can be enhanced by the addition of anti-wear additives. Additives are insoluble in PFPEs and are therefore inapplicable but the life of PFPE oils can be enhanced through the use of coatings (e.g. Pb) to prevent direct contact of the oil with the steel substrate [5].

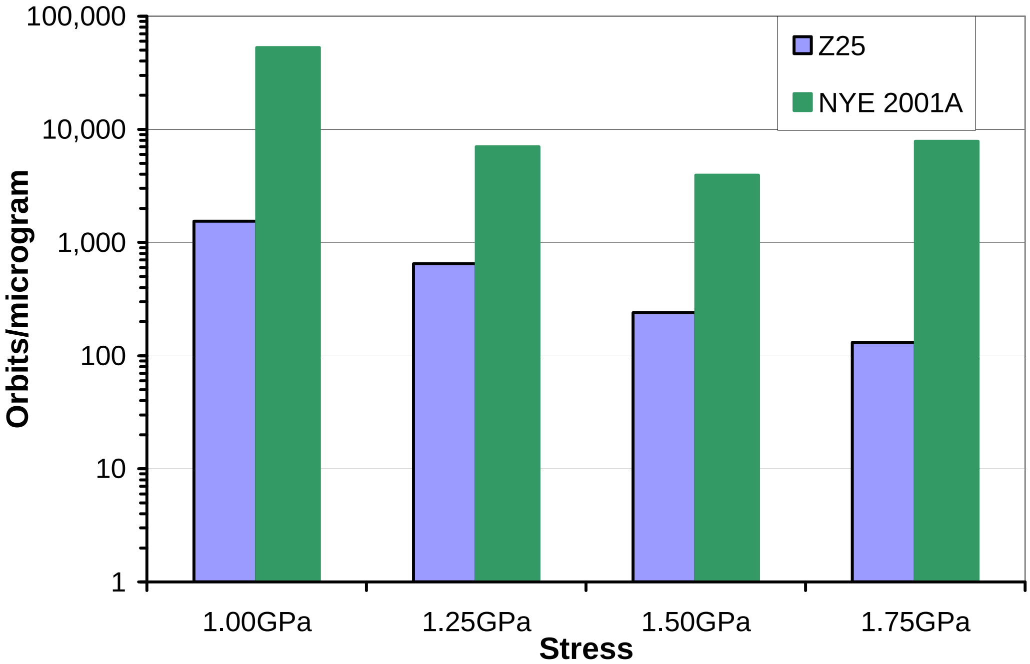


Fig.3 Lifetimes of oils applied to bearing steel [6] as measured in vacuum using a spiral orbit tribometer (under boundary lubrication conditions at room temperature)

Degradation within PFPE oils occurs appreciably quicker than in MAC oils and typically, bearings lubricated with MAC oils show a tenfold (or more) increase in life over the same components lubricated with PFPEs (Fig.3) [6, 7]. Fig.3 also demonstrates that the degradation of these oils is promoted by contact stress such that the higher the stress the shorter the life.

Greases

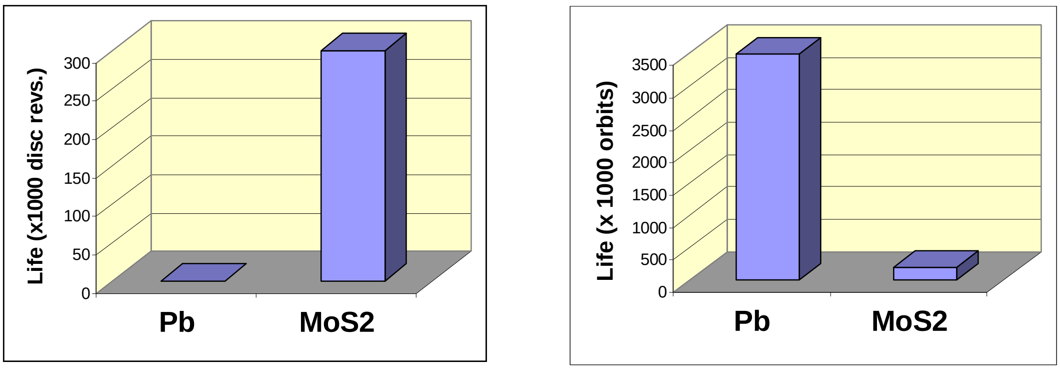
Unsurprisingly the most commonly used greases in spacecraft mechanisms are those based on the most commonly used oils i.e. PFPEs and MACs. The life behaviour of these greases mirrors that of their base oils in that, under boundary lubrication conditions, the MAC-based greases yield longer lifetimes than those which are PFPE-based.

2.2 Solid lubrication

Where temperature and contamination issues preclude the use of fluid lubricants, solid lubrication should be used. Solid lubrication is broadly implemented by two routes, namely: a) through the application of thin lubricant coatings and b) through the use of self-lubricating materials (such as cages in ball bearings).

Thin solid film lubricants

Thin (≤1μm) solid lubricant coatings are produced by physical vapour deposition (PVD) techniques such as sputtering and ion-plating [8]. They are used predominantly to lubricate precision bearings, gears and screws. As with the 'space' oils, there are two commonly used solid lubricants in space namely sputtered molybdenum disulphide (MoS_2) and ion-plated (or sputtered) lead (Pb). The former (MoS_2) yields exceptionally low friction under vacuum (μ in the range 0.01 to 0.05, depending on contact stress and bearing material) whilst the latter gives correspondingly higher friction (μ typically in the range 0.1 to 0.2).



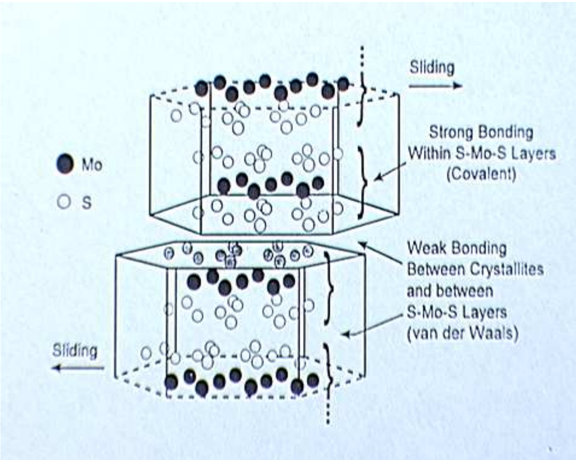
a) Pin-on-disc 'sliding' life b) Spiral orbit tribometer 'rolling' life.

Fig. 4 Illustrating the effect of motion type on the relative wear lives of PVD coatings of MoS_2 and Pb [6].

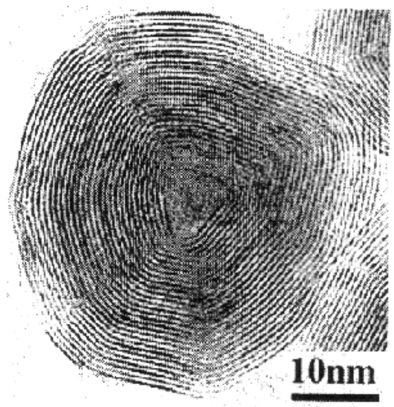
The wear lives of these coatings differ greatly according to the type of motion to which they are subjected. Thus under pure sliding (in vacuum) the life of sputtered MoS_2 is far superior to that of lead (Fig.4a), whereas under rolling motion - of the type encountered in ball bearings - the converse is true (Fig.4b) [6]. The difference in behaviour is attributable to the structure and ductility of the respective materials. Molybdenum disulphide has a lamellar structure whose low-shear planes (lamellae) align under sliding motion to give low-friction films of relatively long life. By contrast, lead is soft and easily displaced from the wear track in a pin-on-disc 'sliding' tribometer. In ball bearings however the ductility of lead promotes transfer between contact surfaces – the lead continuously re-distributing itself by adhesive transfer between races and balls - whereas MoS_2, being of a more friable nature, does not transfer easily and is worn away more quickly to form fine particulate debris that is dispersed from the contact areas.

Although both lubricants are well established for space applications a major inconvenience is that their tribological performance falls off in air. For MoS_2, the effect is particularly severe and greatly restricts in-air ground testing. In these circumstances the presence of adsorbed water molecules increases the shear strength of the MoS_2 lamellae and causes higher friction which, with continued operation promotes oxidation of the lubricant. The resulting oxide wears at a much higher rate than (unoxidised) MoS_2 under vacuum [9, 10]. Numerous attempts have been made to improve MoS_2 lubricity in air through co-deposition with other elements such as titanium and gold [11, 12, 13] but none has been entirely convincing and certainly no one has succeeded in replicating in air the friction and wear characteristics seen under vacuum.

Oxidation of MoS_2 occurs at the exposed edge sites of the lamellae (Fig.5a). When it was demonstrated that fullerene-structured metal dichalogenides [14, 15] could be synthesised there was speculation that their closed, onion-like structures (which have no exposed edge sites - Fig.5b) would prove much less reactive with water vapour and oxygen. Disappointingly, experiments have shown that the friction of films produced from nano-fullerene particles of tungsten disulphide (tribologically and structurally similar to MoS_2) display the same sensitivity to operation in air [16].



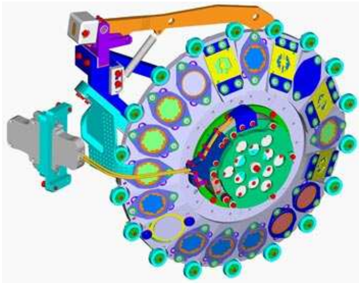
a) Lamellar structure of MoS_2



b) Electron microscope image showing nested (onion-like) structure of a nano-fullerene particle

Fig. 5 Showing (a) lamellar structure of naturally occurring MoS_2 and (b) fullerene structure of synthesised material

The low-friction properties of sputtered MoS_2 in vacuum are maintained over an impressively wide temperature range. Ball bearings so lubricated produce similar torque behaviour at temperatures as low as ~10K [17] and at temperatures as high as 300°C [18]. It is for this reason that sputtered MoS_2 is base-lined for instrument mechanisms that will operate at 30K on the James Webb Space Telescope (JWST) and for mechanisms on board the BepiColombo spacecraft which, when orbiting Mercury, will see temperatures of around 250°C.



a) NIRSpec filter wheel

b) MoS_2 coated inner race shaft

c) MoS_2 coated duplex outer race

d) MoS_2 coated inner race

Fig. 6 Showing MoS_2-coated main bearing components of the NIRSpec (near infrared spectrograph) filter wheel on the James Webb Space Telescope.

Fig.6 illustrates some bearing parts for JWST coated with sputtered MoS_2 [19]. The high precision of the main bearing calls for a highly uniform MoS_2 coating of thickness 0.5 μm. The application of such thin films of the required uniformity is only possible using PVD techniques.

Lead (Pb) also maintains its lubricating action under cryogenic-vacuum conditions but its relatively low melting point restricts its upper limit of operation to moderate temperatures.

Other thin solid films that give low friction (comparable to MoS_2) in vacuum are tungsten disulphide coatings formed by particle impingement processes. Coatings such as these (e.g. Dicronite) are appropriate for low-duty applications only [20]. Diamond-like carbon (DLC) in its hydrogenated form also yields very low friction in vacuum but, like MoS_2, develops higher friction in air [21]. Currently it has little or no space heritage.

Self-lubricating materials

Self-lubricating materials play an important role in bearings (as cages and bushes) and as lightweight gears. The materials used are mostly polymeric with polyimides and PTFE being by far the most popular. PTFE has the advantage that it can produce low friction in both air and vacuum but because of its low tensile strength has to be reinforced with glass fibre. PTFE is commonly used as a cage material in the form of a PTFE/glass fibre/MoS_2 (PGM) composite in otherwise unlubricated ball bearings or those coated with sputtered MoS_2. Polyimides are sufficiently strong not to need reinforcement and are used either in their pure form or with some (typically 15%)

MoS_2 as filler (such as Vespel SP3, Sintimid 15M/Tecasint1391). These polyimide composites are an alternative bearing cage material to PGM.

Polymeric materials (such as PTFE and polyimide) have high thermal expansivities in comparison to bearing steel. This has to be taken into account when designing polymeric cages for steel bearings that will be required to operate at temperatures other than at room temperature. Such cages are usually land-guided where it is important to maintain the optimum clearance between cage and land. This can be problematic if bearings have to operate over a wide temperature range. A potential solution is to have hybrid cages in which the structure of the cage is made from a material of similar expansivity to steel (such as titanium) and fit the cage pockets with self-lubricating polymeric inserts. This approach has been tested and shown to be feasible [18].

A further issue with some PTFE composites is their propensity to shrink when subjected to thermal cycling. This effect can be minimised by thermally conditioning the base material under vacuum prior to machining of the cages [18, 22].

Other than the above polymeric materials, the only other widely employed self-lubricating cage material is leaded bronze. This is used routinely in PVD lead–coated bearings and ensures a supply of lead lubricant long after the PVD coatings have become depleted [8, 23]. These cages (Fig.7a) are designed to be guided by either the inner or outer lands of the bearing races. This interaction inevitably induces cage wear but since cage-to-land loads are generally low this is not of major concern. An

a) Conventional leaded bronze cages

b) Lightweight hybrid cage: leaded bronze inserts in Vespel SP3 cage

Fig. 7 Showing a) conventional leaded bronze cages and b) hybrid polymeric cage with leaded bronze inserts

exception arises if the bearings experience high g forces as was the case on the GERB de-scan mirror mechanism on an MSG satellite [24]. The spacecraft, being spin-stabilised, creates 16g of acceleration on the mirror mechanism that is located on the periphery of the satellite. Under simulation, it was found that the combination of high g and the relatively high mass of leaded bronze cages created cage-to-land forces that produced unacceptably high cage wear. The problem was solved by using lightweight hybrid cages having a Vespel SP3 cage structure fitted with leaded bronze inserts (Fig. 7b).

3. Tribo-components

Ball bearings, gears, ball screws and slip-rings are considered the critical building blocks of spacecraft mechanisms. With the exception of slip-rings, redundancy is either impossible or impracticable to achieve and as such these components are deemed potentially to be single point failures. In consequence the functionality of a mechanism - and often that of the spacecraft itself – is entirely dependent on the reliability of tribological components.

It is understandable therefore that attempts are made to eliminate any potentially troublesome tribological contacts. Foremost in this respect is the development of magnetic bearings for reaction and momentum wheels – which offer not only increased reliability but also reduced micro-vibration. Aerospatiale (now Thales Alenia Space) have been developing such wheels for over 35 years – and have gained flight heritage on satellites such as SPOT and ERS [25]. But in the main their use has been restricted to demanding, high-end missions [26] and the mature technology of wheels fitted with conventional bearings still predominates. Developments have also taken place in contactless electrical transmission using rotary transformers and capacitive transfer techniques [27, 28] but again their use on spacecraft (an example being on NASA's Galileo spacecraft [29]) has been sporadic and conventional slip-rings with their somewhat uncomplicated designs are nearly always preferred.

For successful in-orbit operation tribological components must first survive the launch environment. Rocket launches generate high transient loads and vibration-induced fretting motion within mechanical contacts and both effects can potentially harm components and the lubricants applied. High preloads can prevent gapping and damage within ball bearings but bring the penalties of high torque and reduced lubricant life. Alternatively, off-load devices can be employed to provide high preload during launch, the load being subsequently relieved upon the spacecraft attaining orbital height. Sophisticated devices, such as ESTL's bearing-active-preload-system (BAPS) that forms an integral part of the bearing assembly, are now being developed and offer on-demand control of the bearing preload [30].

The type of lubricant applied to bearings and ball screws depends on application, duty and operational conditions. Fluid lubricants offer low torque noise and long life (especially in EHD mode) but, as discussed, are useful over a limited temperature range only. Accelerated testing by increasing speed is also problematic and may only be valid if the lubrication regime is unchanged. Solid lubricated bearings can, depending on the lubricant, operate at temperature extremes and, advantageously, accelerated testing is often valid. However, torque noise is generally higher - especially so at low preloads [31] – and contributions to noise from cage interactions can vary from mild to the unacceptable (e.g. when cage hang-up causes appreciable perturbations in torque [32]).

Gears (unless made from self-lubricating materials) are lubricated with either greases or solid lubricant coatings. Greases afford longer lives and, if operating conditions allow, are preferred to solid coatings. The latter typically yield lifetimes on spur gears of around 500,000 tooth encounters [33]. Whilst spur and planetary gears are the most commonly employed gearboxes there is increasingly a tendency to use harmonic drives. These are attractive because they offer a high ratio, compact, gear set (ratios up to 160:1) with minimal moment of inertia and low mass. A harmonic drive comprises three main parts (Fig.8): an elliptically shaped radial bearing known as the wavegenerator (WG); a thin cylindrical cup with external gears referred to as the flexspline (FS); and a circular spline (CS), which is a solid cylindrical ring with internal gears.

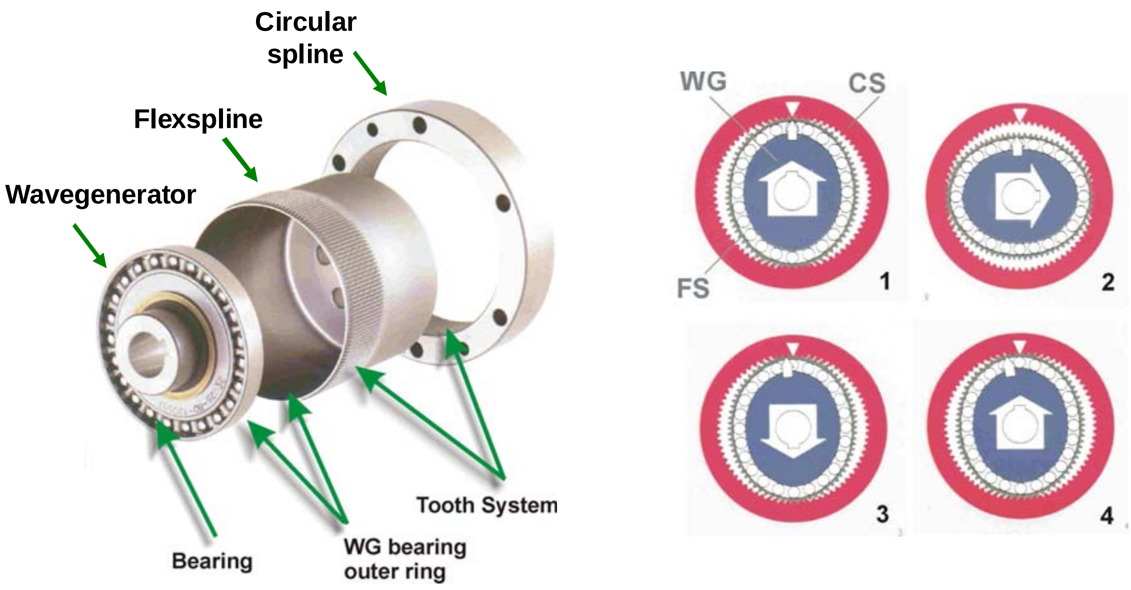


Fig. 8 Showing component parts of a harmonic drive [34]

Various studies [34, 35] have shown that, in vacuum, the WG/FS interface is the most difficult at which to maintain effective lubrication. Grease in this area tends to be pushed out by the squeezing action of the flexspline. In air, displaced grease is sucked back in and lubrication is sustained. In vacuum this cannot happen and the life of the gearbox is much reduced. Current studies are aimed prolonging the in-vacuum life by improving the lubrication at this interface.

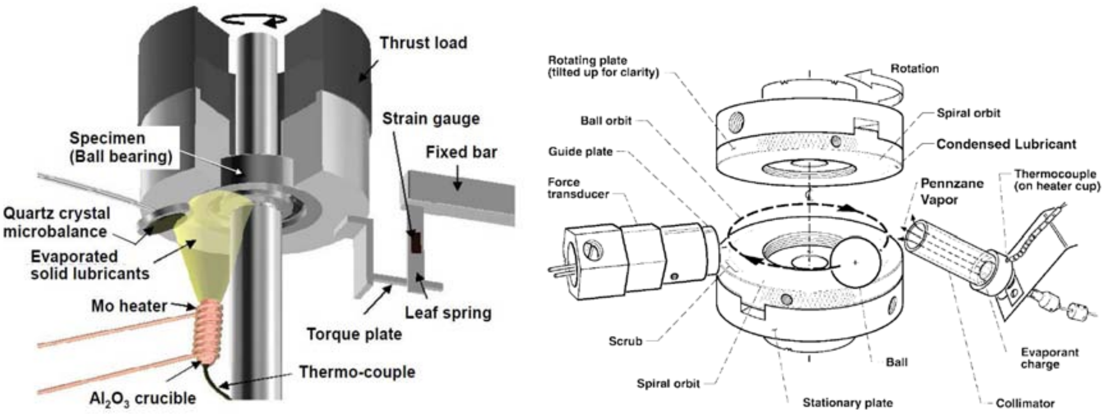
4. Future directions

Changes in lubrication approach will be driven by increasing mission lives, technological advances in mechanism and component design and the need to replace environmentally unfriendly substances. The manner in which these changes might be met are addressed below.

Lubricant replenishment for prolonged life

The need for longer-life spacecraft missions and the requirement for mechanisms to undergo more complex motion profiles are pushing existing space lubricants to their limits. With the exception of those on the Hubble Space Telescope and the International Space Station all spacecraft mechanisms once lubricated are lubricated for life (as they become inaccessible after launch). Unless longer lifetime lubricants are developed (and it is unclear how such improvements might be effected) enhanced life will only be possible through techniques that allow *in situ* lubricant replenishment.

Each thin solid film lubricant has a finite lifetime and once the film is depleted lubrication ceases. It follows that if such coatings could be restored (replenished) *in situ* then lubricant life could be extended indefinitely. As discussed above thin solid films are created by condensation from a vapour (physical vapour deposition – PVD). The simplest way to create such a vapour is by thermal evaporation and in Japan experiments have been undertaken to look at the feasibility of using this technique to replenish lubricant coatings *in situ* on ball bearings [37]. A range of soft metals (Pb, Ag, Au, In) were studied and indium was found to be best suited to the technique. The concept is illustrated in Fig. 9(a).



a) In-situ evaporation of indium into ball bearing [37]

b) In-situ evaporation of oil [38]

Fig. 9 Illustrating concepts for in-situ evaporation of lubricants (solid & liquid) to prolong bearing life

Studies have also examined the possibility of replenishing fluid lubricated contacts by condensation of oil molecules from a vapour created by heating an oil reservoir [38]. The feasibility of this concept was assessed using a vacuum spiral orbit tribometer in which MAC oil (Nye 2001a) was evaporated from a heater cup and collimator (Fig.9b) .These tests were successful and demonstrated the feasibility of extending life using *in situ* techniques.

In order to realise this technology in space applications it will be necessary to minimise power consumption and miniaturise designs so that they can be made an integral part of the bearing assembly. In the technology’s favour, only minute amounts of lubricant (solid or liquid) are required to maintain effective lubrication (e.g. tests at ESTL have shown that lead coatings of thickness <100nm survive millions of revolutions in a tests using a spiral orbit tribometer) and therefore, in principle, reservoirs can be made small and will require only the occasional activation.

Environmentally friendly replacement for lead lubrication.

The need to improve the quality of the environment has resulted in the banning of various substances previously used in the space industry. This has already had an impact on fluid lubricants in that alternative, environmentally friendly solvents have replaced CFCs in the production of greases – hence the ubiquitous EF suffix on several grease designations. Needless to say, with every change comes the need for re-qualification.

Lead (Pb), arguably, is the most commonly used solid lubricant on precision bearings in European spacecraft mechanisms – yet this too is at risk as it is a toxic material. We envisage that the use of lead-based lubricants - which ironically poses no threat to the Earth's environment when present on in-flight spacecraft - will eventually be banned. In the UK lead is no longer permitted in paint and petrol and elsewhere there are concerns on the use of lead for hunting (e.g. lead weights in angling and lead shot in shooting). In 2006 the European Union (EU) introduced a ban on the use of lead in electronics equipment. This so-called EU Restriction on the Use of Hazardous Substances (RoHS) law prohibits any electronics equipment that contains lead from being sold in Europe. The current legislation as applied to lead-lubricated bearings is ambiguous. Whilst there would appear to be no immediate threat to the use of lead-lubricated bearings for space (and other) applications it is presumably only a matter of time before the legislation encompasses this area. In the meantime, given the strength and influence of the environmental lobby, it would not be surprising if suppliers encountered some reluctance by end-users to handle lead-coated parts.

In anticipation of the outlawing of the use of lead in the ESTL process a survey of possible replacements was carried out [36]. A comparison of the properties of several alternative soft metals led to the emergence of indium as the strongest candidate. A current development programme is aimed at assessing the lubricating properties of thin indium film coatings produced by PVD techniques.

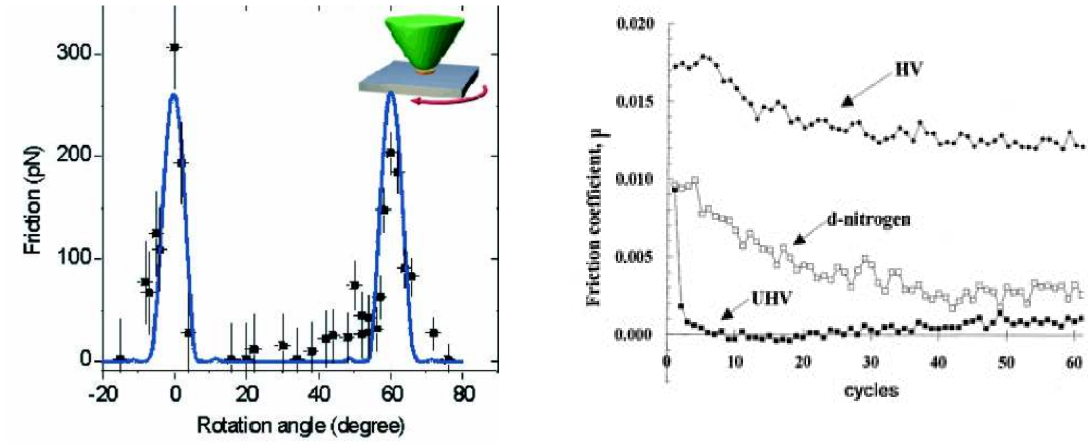
Superlubricity

Elsewhere, changes will be driven by the exploitation of technological advances. In particular nano-technology is expected to revolutionise the design of mechanisms resulting in a quantum change in miniaturisation. This will bring its own lubrication challenges, but may also create conditions that favour the phenomenon known as superlubricity.

'Superlubricity' is the name given to the occurrence of extremely low friction, such that the frictional forces can be immeasurably small. There is no clear definition of superlubricity but the consensus is that it refers to friction coefficients (μ) in the order 0.001. Conditions necessary for superlubricity appear to be:

- contacting surfaces must be incommensurate (i.e. the periodicity of their atomic structures must not match)
- surfaces must be smooth (atomically flat ideally)
- surfaces must be clean i.e. uncontaminated (a condition generally only attainable under ultra-high vacuum)

Most observations of superlubricity appear to be in nano-contacts where the applied loads are extremely low. The effect has occasionally been observed in macroscopic contacts [39, 40] and in graphite intercalated with C60 molecules [41] where the latter are reputed to act as 'molecular ball bearings'. Some examples of experimentally observed superlubricity are shown in Fig.10.



a) b)

Fig.10 Superlubricity resulting from (a) incommensurate surfaces in nano-contacts of graphite [42], (b) pure, contamination-free MoS_2 surfaces in ultra-high vacuum (UHV) [40]

Clearly, the use of super-lubricated components in spacecraft mechanisms would bring obvious benefits. However, for current (macroscopic) mechanism designs, it seems unlikely that superlubricity will be achieved either in the near future or in the medium term. For example to achieve superlubricity in MoS_2-coated contacts, the coatings have to be of high purity, applied to ultra-smooth surfaces and be operated in ultra-high-vacuum. But sputtered MoS_2 coatings are not 100% pure, the surfaces to which they are applied are far from being ultra-smooth and the environment in which they operate *within* spacecraft mechanisms is not one of ultra-high-vacuum (due to materials outgassing [43]). We are therefore some way from achieving superlubricity in conventional mechanism designs.

However, in nano-scaled devices, the ultra-light loads and miniscule, atomically flat, contact areas yield conditions which would appear to favour superlubricity. Superlubricity in such contacts is thus feasible, and it is predicted that superlubricity in space applications will, in the first instance, be realised in nano-technological devices.

5. Concluding remarks

The success of spacecraft missions depends critically on the reliability of mechanisms and, in turn, this is reliant upon the life and functionality of their component parts. The management of friction and wear processes in those parts that have a tribological element is the subject of space tribology. In practice, the choice of 'space' lubricants is limited to a small number of low-volatility oils (PFPEs, MACs and PAOs) and a few types of vacuum-compatible solid lubricant (MoS_2, lead, PTFE and polyimides). All lubricants have a finite life and their ability to meet ever increasing mission lives is being pushed to the limit. As such, changes in our approach to lubrication in space will be needed. Longer life requirements will hasten the development of lubricant replenishment systems. The miniaturisation of mechanical systems will bring further lubrication challenges, but nano-scale devices offer the prospect of operation in a super-low-friction regime.

6. Acknowledgements

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