Thin solid lubricant films in space

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Solid lubricant films of thickness one micrometre or less are to an increasing extent being employed in spacecraft applications. This is particularly so where conditions dictate the use of solid lubricants (as opposed to fluids) and where the component to be lubricated is of a precision that precludes the use of thick films. A further advantage is that the thinness of such lubricants actually promotes low friction when the substrates involved are of high hardness.

This paper reviews the tribological properties of thin, solid film lubricants as determined in vacua typical of those encountered in spacecraft environments. Further, it attempts to describe or predict (where no data exist) the performance of such films under specific spacecraft conditions whose effects on thin, solid film lubricants have, until recently, been unknown to the space tribologist. Such conditions include *in vacuo* cryogenic environments of spaceborne infrared telescope mechanisms and high flux, atomic oxygen environments of low earth orbits.

Keywords: *space tribology, solid lubricants, thin films*

Introduction

The environmental conditions experienced by spacecraft mechanisms encompass temperatures which range from cryogenic to several hundred Kelvin and pressures which range from atmospheric to ultra-high vacuum. Such conditions dictate that in many instances the only practicable means of lubrication is by the use of solids. Increasingly this requirement is being met using solid lubricants in the form of thin films.

Solid film lubrication can be effected by essentially one of two ways It can be transferred by rubbing from a solid made from, or containing, the dry lubricant—as, for example, with self-lubricating cages in ball bearings. Alternatively it can be applied to one counterface in the form of a film, as with techniques such as sputter deposition.

The former method gives rise to a transfer film which is discontinuous, uneven in its thickness and poorly adherent. The lubrication it provides is in consequence characterized by appreciable variations in friction coefficient (thus, for example, ball bearings so lubricated exhibit a noisy torque). An advantage, however, is that this method of lubrication makes available a relatively plentiful supply of lubricant which, in turn, renders it suitable for applications of long duration and high duty.

The second method, in contrast, yields a thin, continuous lubricant film of uniform thickness which, if correctly applied, is well adhered to the substrate. Such films are used in spacecraft mechanisms because:

- Low shear strength materials confer their lowest friction when present as films of thickness in the order 1 μm. Such low-friction films (and those of low frictional noise) are necessitated in applications which call for low power dissipation and low torque noise, such as in cryogenic devices and precision pointing mechanisms respectively.
- Because of their thinness they can be applied to the most finely machined tribo-components without detracting from the components' precision.

A disadvantage is that the durability of such films is relatively short, and once the films are worn through they cannot be replenished. The useful lifetime of the tribological component to which such films are applied is thus limited by the lifetime of the lubricant film itself. The type of spacecraft mechanism that can be lubricated *solely* by means of thin solid films is thus limited to those of short-to-medium term duration or those of low duty. To a degree this limitation can be overcome by combining both the lubrication methods described above. Thus, for example, the balls and races of a ball bearing may be lubricated with solid lubricant films and the bearing fitted with a self-lubricating cage.

In this paper we will principally be concerned with the tribological properties of thin, continuous films of dry lubricants as they relate to space applications and environments. We shall define a thin film as one whose thickness is in the order 1 μm.

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Space-compatible solid lubricants

Solid lubricants fall into one of three generally recognized categories. These are: lamellar solids, soft metals and polymers. Not all solid lubricants are effective in vacuum, the classic example being graphite, whose low friction properties appear in the presence only of water vapour[1] and other condensable gases. Table 1 identifies examples of solids which are effective lubricants in vacuum. The tribological properties of some of these lubricants, such as MoS_2[2] and certain polyimides[3] are, unlike graphite, appreciably superior in the absence of water vapour and are therefore more effective under vacuum than in air.

Thin-film friction

The friction arising between solid-lubricated bodies is described by the equation[4]

$$\text{Friction coefficient} = \frac{sA}{W} \quad (1)$$

where s is the shear strength of the lubricant film, A the true contact area and W the normal contact load.

Thus low friction (at a given load) requires that the contact area be small and the lubricant film be of low shear strength.

Small contact areas can be achieved by ensuring that the lubricant is applied in the form of thin (in the order 1 μm) films onto substrates of high elastic modulus and hardness. Under these conditions the contact load will largely be supported by the hard contact materials (rather than the film) and the true contact area will, in consequence, be small. For a smooth sphere sliding under elastically loaded (hertzian) conditions against a smooth, flat substrate coated with a thin film we have[5]

$$\text{Friction coefficient} = \frac{s}{W^{1/3}}\left[\frac{3R}{4E^*}\right]^{2/3} \quad (2)$$

where R is the radius of the sphere and E^* is the effective (reduced) elastic modulus of the contact materials. Thus for a given contact geometry Eq (2) shows that:

Table 1 Space compatible solid lubricants

Lamellar solids	Dichalcogenides	MoS_2, $NbSe_2$, WS_2
	Intercalated graphite	
Soft metals	Gold, Silver, Lead, Indium	
Polymers	PTFE, Phenolic and epoxy resins, Polyimides	

a) friction varies linearly with film shear strength
b) friction decreases with increasing contact load
c) friction is determined by the substrate material to which the film is applied such that the higher the elastic modulus of the substrate materials the lower the friction.

The behaviour of many space lubricants is observed to be in accordance with the above predictions. Thus it has been demonstrated that the initial friction coefficients obtained with thin films of lead, indium and silver are in proportion to their respective shear strengths[6]. Further, it is known that the friction of soft metal films[6] and sputtered MoS_2[2] decreases with increasing contact load. More recently it has been established[7] that molybdenum disulphide films, when applied to a range of substrate materials of different elastic modulus, exhibit frictional properties in line with (c).

Methods of applying thin films

There are several methods of applying solid lubricants in the form of thin films to substrates. The simplest method is to burnish, i.e. rub dry lubricant powders onto the surface to be lubricated. This can be done by hand using a burnishing cloth but the technique is crude and it is difficult to obtain films of the required thickness reproducibly. More refined methods have been devised in which the lubricant is applied in a controlled manner by mechanical means[8].

A widely used method for the lubrication of, in particular, non-precision components involves the application of bonded lubricants. These are films in which the lubricant powder is attached to the substrate by means of binder materials. In general, the binding agent and lubricant powder are suspended in a solvent, the dispersion then being applied by spraying, painting or dipping. Resin-bonded lubricants require curing following application. Whereas films utilizing cellulosic and acrylic resins are air-cured, those containing thermosetting resins call for heat-curing. Resins which come into this latter category include epoxies, phenolics, polyimides, alkyds, silicones and polyphenyl sulphide. Because bonded lubricant films tend, in general, to be applied to thicknesses which exceed 10 μm they lie outside the scope of the present paper. Details of commercially available resin-bonded lubricants that are suited to spacecraft applications can be found in Reference 9.

Finally there are the techniques of physical vapour deposition in which films are formed by deposition from a physically generated vapour. These are superior to the techniques already described in two ways: first, they give improved film-to-substrate bonding and secondly, film thicknesses can be controlled very accurately such that very thin films (sub-micrometre) can be readily produced. The most widely employed techniques are thermal or electron beam evaporation, sputtering and ion-plating.

Ion-plating[10] is preferred for the deposition of soft metals as it gives rise to strongly adherent films. In this technique atoms of the chosen soft metal are thermally evaporated into an argon ion plasma where some become ionized. These ions are then accelerated towards a negatively biased substrate where film growth occurs. The substrate bias also ensures that during its growth the film is continuously bombarded by argon ions which help keep the developing film free of contamination.

In sputtering[11], the vapour is created by ion-bombardment of the source material. There are essentially two modes of sputtering, DC and RF: so called because of the manner in which bias is formed on the target (and occasionally the substrate). RF sputtering is the more versatile of the two in that it allows deposition of electrically insulating materials. Higher deposition rates can be effected by the use of magnetron sources. Sputtering is commonly employed for the deposition of molybdenum disulphide and other metal dichalcogenides.

In both ion-plating and sputtering, film adhesion can be improved by ion-cleaning the substrate prior to film deposition.

Tribological properties of thin solid films

Soft metal films produced by PVD

The frictional properties of soft metal films in vacuum change with film thickness, load (contact stress), sliding speed and surface roughness. Optimum lubrication is obtained at thicknesses of about 1 μm. In general we observe that the friction coefficient decreases with load[6] and surface roughness, but increases at very low sliding speed. These trends are observed with ion-plated lead films as shown in Fig 1, the data of these curves having been obtained by means of a pin-on-disc apparatus operating under high vacuum. The effects of load (Fig 2) and surface roughness persist in air, as demonstrated elsewhere[6, 12]. At sliding speeds two orders of magnitude higher than those of Fig 1, the friction coefficient increases with increasing sliding speed[13]. However, it should be noted that the sliding speeds of Fig 2 represent more closely those speeds occurring in the microslip areas of ball bearings[14] in spacecraft applications and are thus more pertinent to the theme of this paper.

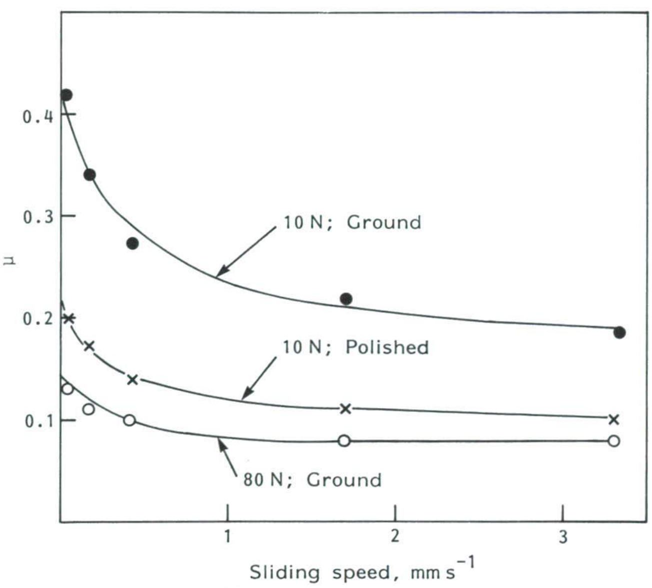

Fig 1 Friction coefficient of lead films, in vacuum, as a function of sliding speed (substrate: 52100 steel)

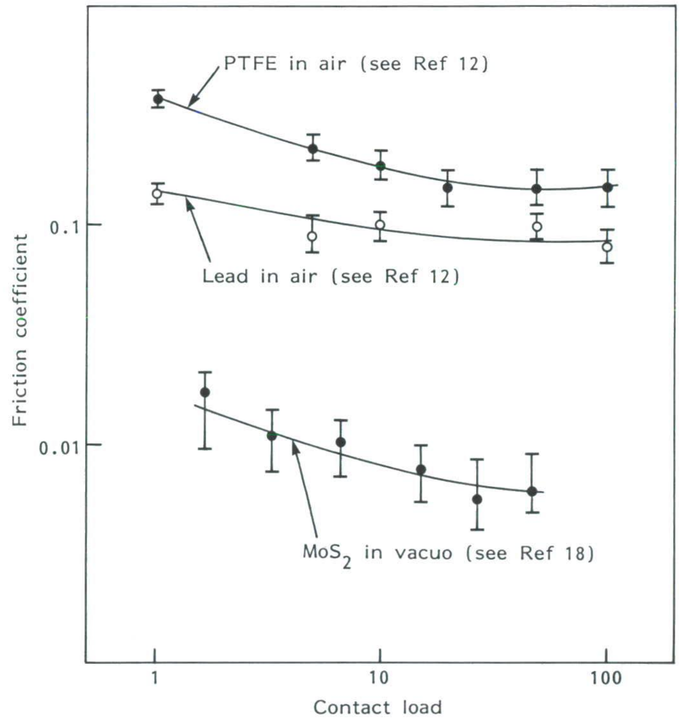

Fig 2 Friction coefficient as a function of load for thin films of three commonly employed space lubricants (steel substrates)

Whilst the melting point of lead places an upper limit on its temperature range of operation there is evidence to suggest that lead films retain their lubricating properties down to very low temperatures. This has been demonstrated at the European Space Tribology Laboratory (ESTL) where it has been shown that lead-lubricated bearings operate equally well in vacuum at cryogenic temperatures (20 K) as at room temperature (see section on *in vacuo* cryogenic environment).

Although ion-plating gives rise to a well-adhered film the *in vacuo* endurance of such films under pure sliding conditions is still poor in relation to films of molybdenum disulphide produced by sputtering (see below). Gerkema[15] has studied this problem and has brought about improvements in the life of lead films through the introduction of metallic interlayers and dopants. Lead films were deposited (using the techniques of sputtering or electroplating) on steel substrates which had been previously coated with thin (0.1 μm) films of metal (Ag, Cu, Ta, W, Mo). Most of the metallic interlayers produced little or no improvement. However, the use of copper effected a five-fold increase in endurance. This enhancement is thought to arise because the soft copper interlayer decreases the likelihood of steel-to-steel asperity contacts, thereby delaying the onset of film failure.

Lamellar solids—sputtered molybdenum disulphide

Sputtering is the preferred method of applying MoS_2[16] as it gives rise to film durabilities longer than those achieved with films produced by burnishing and resin-bonding[7]. The tribological properties of sputtered MoS_2 are dependent on its composition, structure and morphology: and these in turn are observed to be critically dependent on the sputtering conditions.

A study of films produced by magnetron sputtering[17, 18] has shown that film composition in terms of the ratio of sulphur to molybdenum atoms varies with deposition rate. At low deposition rates (<150 A min^{-1}) the films were found to be sulphur-deficient whilst higher deposition rates (>450 A min^{-1}) produced either stoichiometric or sulphur-rich films. The latter films proved tribologically superior when tested under vacuum. These observations are consistent with those of Buck[19, 20] who demonstrated that the purity of MoS_2 films is dependent upon the relative deposition rates of MoS_2 and the gaseous contaminants (particularly water vapour) present in the deposition chamber. The findings imply that at high MoS_2 deposition rates and low partial pressures of water vapour stoichiometric films are obtained, whereas when the deposition rate is low and the H_2O partial pressure is high the films are sulphur-deficient and contaminated with oxygen. Again it was observed that sulphur-deficient films are tribologically inferior to those that are stoichiometric.

Most sputtered MoS_2 films exhibit a characteristic columnar structure corresponding to crystallite growth in which the 0001 basal planes are aligned perpendicular to the substrate surface. From a tribological viewpoint this is not ideal since the preferred orientation would be with the easy-shear, 0001 planes arranged parallel to the substrate surface. It is reported[21] that 0001-orientated films can be fabricated by sputtering, although there is some uncertainty regarding the conditions under which this occurs. An advantage of growing films oriented in this manner, in addition to that gained tribologically, is that the 0001 surface is much less reactive than the edge sites which are exposed by the 'columnar' films[22] and which oxidize readily in air, thereby degrading the film's lubricating qualities.

As with lead films it is found that the behaviour of sputtered MoS_2 films varies with contact load, substrate surface roughness and sliding speed. In general, however, much lower friction coefficients (in the order 0.01) are obtained with MoS_2 *in vacuo*.

The effects of load (Fig 2) and sliding speed are qualitatively similar to those observed with lead films in that the friction coefficient decreases with load and increases at low sliding speeds[2]. However, the influence of the surface roughness of the substrate is quite unlike that applying in the case of lead films in that for substrate surface roughnesses up to 0.15 μm cla, the friction coefficient decreases with increasing surface roughness. The friction coefficient of 0.01 seen in Fig 2 at loads of about 10 N was obtained for MoS_2 films sputtered onto 52100 steel substrates having a surface roughness of 0.10–0.15 μm cla. When applied to smoother steel surfaces (0.04 μmicron cla) the run-in friction coefficient approximately doubles, to about 0.02, given the same conditions of load, sliding speed and vacuum level. More recent evidence suggests that for a 1 μm thick film there exists an optimum level of substrate surface roughness at which friction is minimized and film endurance maximized[23].

The tribological properties of molybdenum disulphide further differ from those of lead films in that the lubricity of MoS_2 is highly sensitive to the presence of water vapour. This is most pronounced when MoS_2 is operated in humid air, whereupon friction coefficients of between 0.15 and 0.30 are observed[17]. The effects of water adsorption persist, albeit to a lesser extent, under vacuum conditions. Thus, for example, it is observed that when molybdenum disulphide films are allowed to dwell (that is, not subjected to sliding for a defined period) the friction coefficient is higher on the recommencement of sliding (Fig 3). The increase in friction is thought to result from the adsorption of sub-monolayer quantities of water molecules[18]. With continued sliding these are removed (probably by desorption induced by frictional heating) and the friction coefficient decreases. The recovery time is also observed to be a function of the dwell period (Fig 3).

The tribological properties described above relate to MoS_2 applied by sputtering to steel (52100) substrates. Recent work has shown that the friction and wear properties of sputtered MoS_2 films are strongly dependent on the substrate materials to which they are applied[7]. Films were applied to substrates made of titanium alloy, steel (440C and 52100) and ceramic (silicon nitride). *In vacuo* friction coefficients varied in a manner that was consistent with Eq (2) in that the lowest friction occurred with films applied to the highest modulus substrate (silicon nitride) whereas the highest friction was observed with films applied to the substrate of lowest modulus (titanium alloy). This study also demonstrated that magnetron-sputtered MoS_2 when applied to silicon nitride gives rise not only to low friction, but also high endurance.

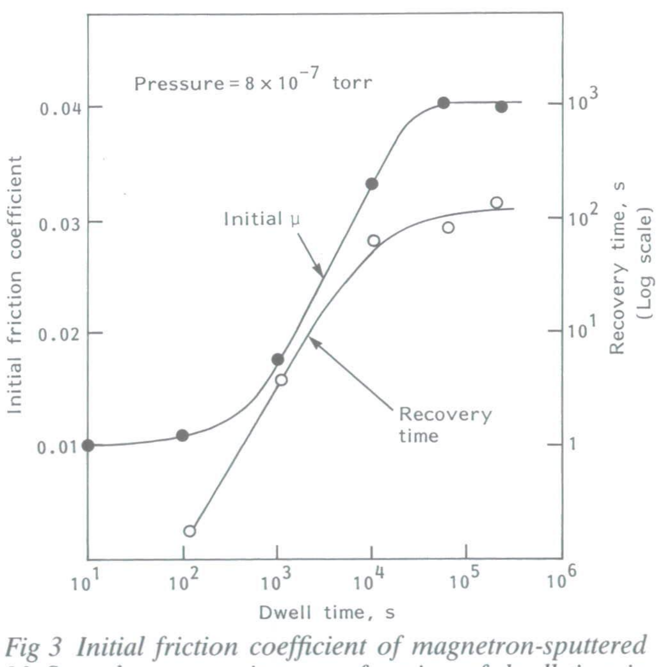

Fig 3 Initial friction coefficient of magnetron-sputtered MoS_2 and recovery time as a function of dwell time in high vacuum[18]

The low durability of MoS_2 on titanium alloys was attributed to poor adhesion, as occurs with some other metal substrates. For example, it has been known for some time that the sputtering of MoS_2 onto metals that readily form sulphides (copper, silver etc.) yields poorly adherent films of negligible durability. In such cases the use of interlayers can prove remedial[24].

Co-deposited and multi-layered films

The tribological properties of sputtered MoS_2 can be enhanced by either co-deposition with other materials or through the use of thin, hard interlayers.

Adding small amounts of metals to MoS_2 films has been shown to lengthen their durabilities and effect lower and more stable friction. Stupp[25] has shown that these improvements are brought about when the concentration of the metal component is between 5% and 7%. The most favourable results were obtained with the addition of the metals nickel and titanium. Elsewhere it has been shown that films produced by co-sputtering MoS_2 and PTFE perform better in moist air than do films of pure MoS_2[26]. The inclusion of PTFE, a water repellant, is believed to make the film less sensitive to moisture. In air the PTFE-containing films gave a friction coefficient of 0.1 as opposed to 0.2–0.3 obtained with pure MoS_2 films. Film durability was increased by at least a factor five.

The use of hard interlayers to prolong the life of sputtered MoS_2 films was demonstrated initially by Spalvins[27]. Since then it has been shown that dual layers of TiC and MoS_2 applied to 440C balls increases the low-torque lifetime of ball bearings[28] over and above that achieved with single-layer MoS_2 lubrication. More recently ion-beam assisted deposition (IBAD) and fast-atom techniques have been used to produce multilayer films[29] comprising a hard interlayer (such as TiB_2 and BN) and MoS_2. Such films are of interest since they apparently display low friction in air.

Polymers

There is practically no published information on PTFE or other polymeric films produced by PVD techniques such as sputtering. There is evidence[30] that sputtered films of PTFE have been used in Japanese space mechanisms and PTFE films prepared by sputtering were reported by NASA[31]. Also, as reported above, PTFE has been successfully co-sputtered with MoS_2[28]. However, there appears to have been little systematic study of the *in vacuo*, tribo-properties of sputtered PTFE.

Some data exist, however, on the tribological properties of polymeric films produced by rubbing transfer. Fig 2 shows how the friction coefficient of PTFE films applied to steel substrates changes with contact load[12]. As with other dry lubricants friction is seen to decrease with increasing load. PTFE has the advantage that its lubricating properties are similar in both air and vacuum. A disadvantage is that PTFE's load-carrying capacity is low such that it should not be employed in applications where contact stresses exceed 1200 MPa.

Certain polyimide films exhibit considerably lower friction in vacuum than in air[3]. Such films gave rise to run-in friction coefficients of 0.04 (load and stress conditions unspecified) and exhibited appreciably longer lifetimes in vacuum than in air. The higher friction observed in air is attributed to water adsorption and its retention on those polyimide sites that offer free hydrogen bonds. It is postulated that on removal of the water molecules by desorption (under vacuum) the polymer's shear strength is reduced and friction therefore decreases.

Performance of spacecraft components lubricated with thin, solid films

Ball bearings

Ion-plated lead is probably the solid lubricant most commonly employed on precision spacecraft components. The use of such films for the lubrication of ball bearings is extensive (particularly in Europe). Their employment in ball bearings is usually undertaken in conjunction with leaded bronze cages which provide supplementary sources of lead. In Europe this combination has been extensively applied, as for example in the despin bearings of GIOTTO[32] and the bearings of the solar array drive mechanism on OLYMPUS 1[33].

Increasingly, bearing lubrication with sputtered MoS_2 is being considered for space applications, in particular where there exists a need for low torque and low torque noise. The torque performance, however, is related to the number of bearing parts lubricated[17]. Thus it is observed that the lowest torques are obtained when only the bearing races are coated (i.e. no coatings on the balls). When in addition the balls are coated the torque is increased (though still remaining low compared to that obtained with other solid lubricants). This torque increase is compensated to a degree by a five-fold increase in bearing lifetime.

Fig 4 compares the torque behaviour of three bearing pairs (20 mm bore, angular contact) operated under high vacuum at an axial loading of 40 N. Lubrication was by means of three types of thin solid film: ion-plated lead[34]; ion-plated gold[34]; and sputtered MoS_2 (races only)[17]. The mean torques observed on ball bearings lubricated by soft metals (Pb and Au) show similar behaviour, whilst that of the MoS_2-coated bearings is appreciably lower. Even greater variations in performance can be discerned from the plots of torque noise, which show that MoS_2 confers exceptionally low torque noise properties. The highest torque noise, which is observed on gold-plated bearings, probably reflects the generation of gold wear debris in which case the presence of gold particles, together with their tendency to work harden, would account for the observed torque perturbations.

Torque generation within a solid-lubricated ball bearing, the Coulombic torque, can be predicted with reasonable accuracy given applicable values of friction coefficient. Data on the friction of thin solid films under a variety of operating conditions are now available (as we have seen above) thus allowing ball bearing software to be used with greater confidence. Such computations[35] allow the prediction of Coulombic torque in steady-state motion and non-steady-state

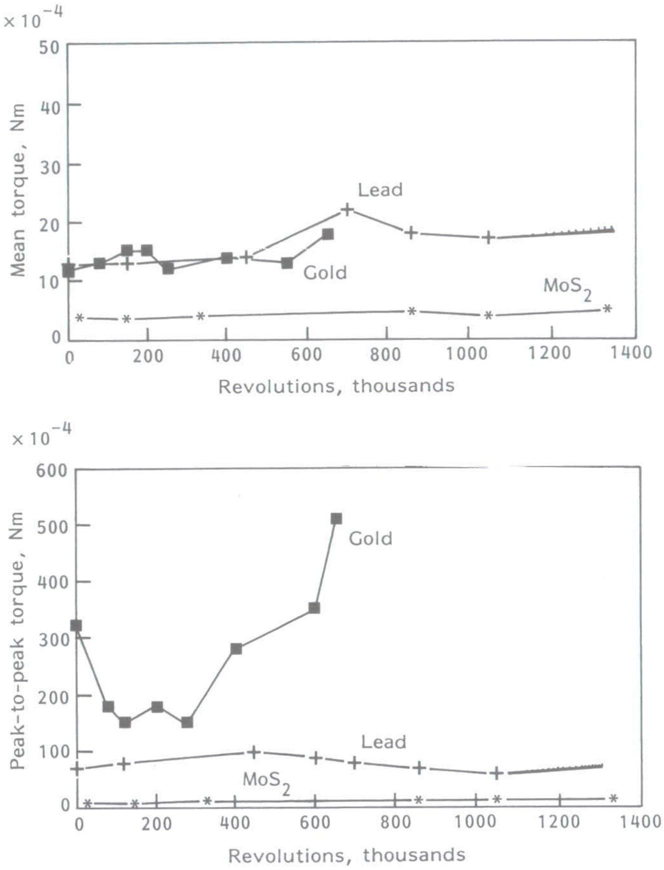

Fig 4 Comparison of mean and peak-to-peak torques of ball bearings lubricated with thin films of lead, gold and MoS_2 (in vacuum)

motion, such as the torque hysteresis encountered during small-angle oscillation of bearings.

Gears

The use and tribological behaviour of thin, solid lubricant films on satellite gears is not well documented. It is known, however, that thin films of lead and molybdenum disulphide produced by PVD have been employed in several space applications[36, 37].

In a study[38] of the *in vacuo*, tribo-behaviour of lead-coated steel satellite gears it was shown that a film thickness of 1 μm gave the longest durability (range examined: 0.25 to 4 μm). Examination of gear teeth prior to film failure indicated that the lead coating had been squeezed under the combined actions of sliding and rolling to form an ultra-thin film of thickness approximately 10 nm. Evidently the film, even at this thickness, was still providing effective lubrication. In the same study it was shown that sputtered MoS_2 films gave rise to improved gear transmission efficiencies (gear torque about half that obtained with lead films) but with a slightly reduced lifetime.

Screws, cams, collars, journal bearings and slides

These are components whose tribological surfaces are subjected to purely sliding motion (that is, there is no rolling motion). Where precision requirements or other factors dictate the use of thin solid lubricants the preference is for MoS_2 as its durability under pure sliding is far greater than that of soft metal films.

Environmental influences on solid lubricant film behaviour

The environmental conditions (vacuum level, composition of vacuum gases, temperature, etc.) to which a spacecraft component is exposed vary according to many factors. These include: orbital height; the location and role of the component; and whether the component is sealed, partially enclosed or fully exposed to space.

We examine below how exposure to these various space environments, and indeed that encountered during ground testing, affect the performance of solid lubricant films.

Earth-orbit environments

The vacuum level at geostationary orbital height is in the order 10^{-13} torr. However, a geostationary spacecraft and its mechanisms will experience vacuum pressures that are appreciably higher than this. These higher pressures—about 10^{-10} torr close to the spacecraft's exterior surfaces and between 10^{-6} torr and 10^{-8} torr within partially sealed mechanisms located inside the spacecraft—arise as a result of the outgassing of materials that emit gases such as water vapour and carbon monoxide[39].

Components located on the exterior of the spacecraft will be subjected to proton and electron bombardment. The latter may damage some polymers, including PTFE, and careful consideration should be given to their use in long-term missions.

There are two environments that are peculiar to mechanisms of spacecraft in earth orbit and these call for special attention. These are firstly, *in vacuo* cryogenic environments and secondly, atomic oxygen environments.

In vacuo *cryogenic environment*

The development of spaceborne infrared telescopes as used for example on the Infrared Space Observatory (ISO), the Far Infrared Space Telescope (FIRST) and the Space Infrared Telescope Facility (SIRTF) has led to a requirement for lubrication at cryogenic temperatures in vacuum. This requirement has arisen because infrared astronomy calls for the cooling of solid-state detectors to cryogenic temperatures to achieve an acceptable level of signal-to-noise ratio. Infrared detection systems employ devices such as interchange wheels (to position filters, mirrors, polarizers etc.), cameras and interferometers (Fig 5), all of which are mechanical assemblies that contain tribological components. These assemblies, by virtue of their proximity to the detectors, are required to operate at very low temperatures. It follows that there is a need for lubrication at cryogenic temperatures under conditions of high vacuum. Indeed the vacuum conditions are more likely to be akin to UHV since cooled surfaces act as cryo-pumps and are thus capable of reducing the pressure of the local environment.

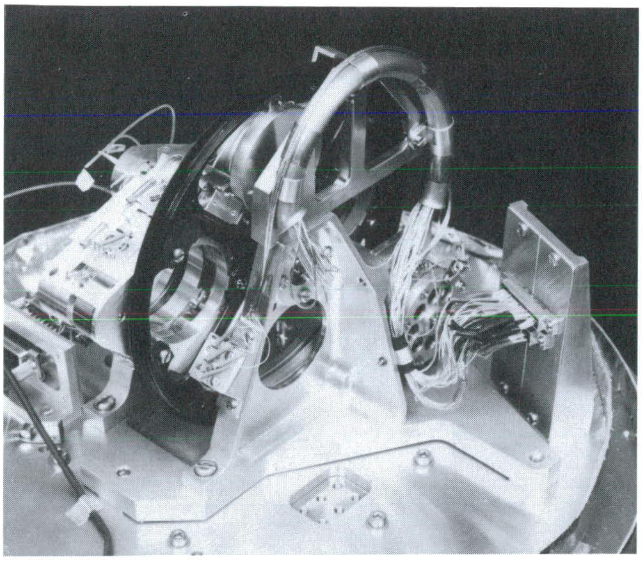

Fig 5 Fabry–Perot interchange mechanism for ISO's Long Wavelength Spectrometer. Ball bearings within the motor and supporting the interchange wheel are lubricated with sputtered MoS_2. The teeth on the interchange gear wheel are also coated with sputtered MoS_2 (photo courtesy of Tom Patrick, Mullard Space Science Lab.)

Lubrication is needed not only to minimize wear and prevent seizure of moving parts but also to minimize the generation of frictional heat, since any heat generated within the spacecraft promotes evaporative loss of liquid helium upon which most spacecraft IR detectors rely for cooling.

Lubrication under *in vacuo*, cryogenic conditions is only practicable using solid lubricants. Fluid lubricants cannot be used because they solidify and become glass-like at temperatures well above the cryogenic range. Furthermore liquid cryogens cannot be employed for hydrodynamic lubrication since they are not sufficiently viscous to generate the necessary load carrying capability.

For these reasons solid lubricants and, in particular, thin solid film lubricants have been examined as potential means of bringing about effective lubrication in spaceborne IR telescopes. To this end ball bearings lubricated with ion-plated lead and sputtered MoS_2 have been torque tested in vacuum at temperatures as low as 20 K[40, 41]. The bearings in question were of type ED20 (bore 20 mm) and made from 52100 steel. Torque measurements were made on pairs of bearings of this type. Lubrication of the bearings was as follows:

a) films of sputtered MoS_2 (0.5 μm in thickness) applied to raceways, balls and steel cage.
b) 0.5 μm thick films of lead deposited by ion-plating onto raceways only; balls uncoated; cage made from leaded bronze.
c) films of sputtered MoS_2 (0.5 μm in thickness) applied to balls and raceways. Cage made from PTFE/MoS_2/glass fibre composite.

Each ball bearing pair, with the exception of pair (a), was run in vacuum for 1 million revolutions at room temperature. The temperature was then decreased to achieve a bearing housing temperature of 18 K and the bearings rotated over a further 2 million revolutions. Bearings (a) were operated at cryogenic temperature only. The results of these tests are shown in Fig 6.

These results indicate that:

- Bearings lubricated solely by sputtered MoS_2 maintain their low torque performance at cryogenic temperatures.
- The torque of bearings lubricated with ion-plated lead is essentially unchanged at 20 K.
- MoS_2-coated bearings fitted with PTFE composite cages gave low torques at room temperature but significantly higher torques at cryogenic temperatures.

It is encouraging to note that all lubrication systems tested were effective, albeit to different degrees, in providing lubrication over the full 2 million revolutions undertaken at cryogenic temperature.

It is planned that sputtered MoS_2 be used to lubricate tribological components on a number of mechanisms on ESA's Infrared Space Observatory (ISO), including an interchange mechanism[42] (Fig 5), and a camera mechanism[43]. Previously, in possibly the first recorded use of thin solid film lubrication for an *in vacuo* cryo-application, it had been demonstrated that ion-plated lead films (300 nm thickness) act as an effective bearing lubricant in a movable stop mechanism intended for the Space Infrared Experiment[44].

Atomic oxygen environment in low earth orbit

Atomic oxygen is the principal gaseous species present in low earth orbit. Whilst the pressure of the atomic oxygen is not high (less than 10^{-7} torr) the flux incident upon an exposed and forward-facing surface can, as a result of the spacecraft's high velocity, be significant (about 1 monolayer s^{-1}). As a result of the spacecraft's speed the relative velocity of atomic O at impact with the spacecraft is high and is equivalent to the bombardment of a stationary surface with particles of approximate energy 5 eV[45].

Interactions of atomic O with solids under these conditions can cause chemical degradation leading to erosion of exposed material. Degradation can occur through oxidation, and erosion by sputtering or loss, through evaporation, of volatile oxides. Clearly, solid lubricants are at risk, particularly when in the form of thin films, since even a low erosion rate would cause their removal in a comparatively short time. The susceptibility of solid lubricants to attack by atomic O has been addressed by Leger and Dufrane[45]. Table 2 summarizes the reaction efficiencies, in terms of volume of material lost per incident oxygen atom, of some selected tribo-materials.

Whilst the data available hitherto on solid lubricants are limited, it is clear from Table 2 that perfluorinated polymer lubricants, some soft metals, and epoxy-bonded lubricants will be affected.

Leger and Dufrane[45] have calculated the expected lifetimes of epoxy-based bonded solid lubricant films when exposed to a low earth orbit (LEO) environment. Assuming a reaction rate of 1.7×10^{-24} cm^3 $atom^{-1}$,

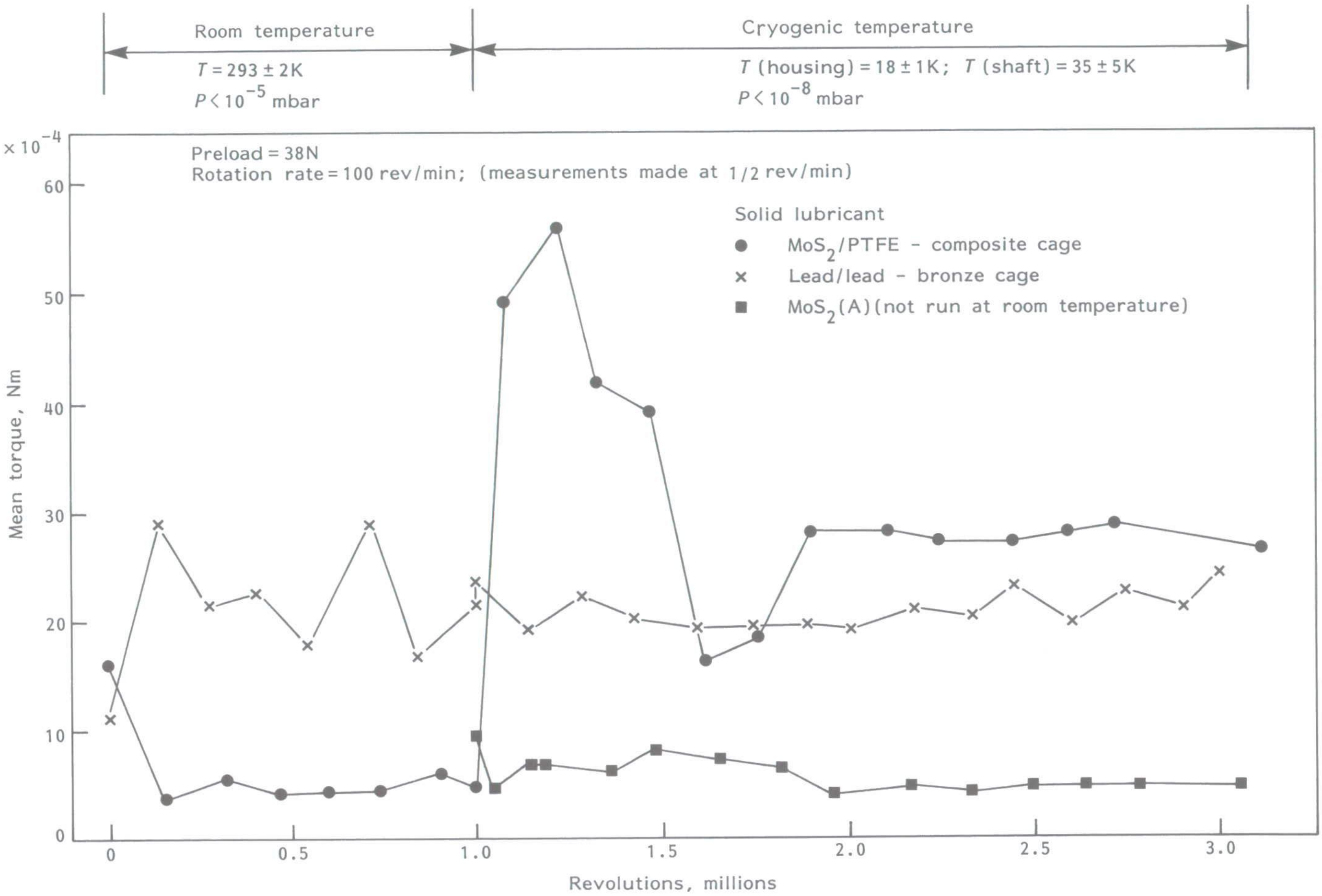

Fig 6 Mean torque of solid lubricated ball bearings operating at room temperature and at cryogenic temperature (in vacuo)

Table 2 Reaction efficiencies of tribo-materials with atomic oxygen in low earth orbit (selected from Reference 45)

Material	Reaction efficiencies ($\times 10^{-24}$ cm^3 $atom^{-1}$)
Polysulphone	2.4
Epoxy	1.7
Carbon (various forms)	0.9–1.7
Perfluorinated polymers (Teflon TFE, FEP)	< 0.5
Silver	heavily attacked

an O-atom fluence of 1.5×10^{23} atoms cm^{-2} (on a forward-facing surface) and a film thickness of 2.5 μm, they predict that the lubricant film would be either eroded away completely or rendered ineffective within 10 days.

To date, the most extensive study of atomic O effects on solid lubricants has been carried out on molybdenum disulphide[46, 47]. In these laboratory tests films of MoS_2 produced by sputtering were exposed to a 1.5 eV source of atomic oxygen at a flux of 10^{17} O-atoms s^{-1} cm^{-2}. Such exposure led to the formation of molybdenum oxides and the release of sulphur dioxide. The oxides comprised MoO_3 and, to a lesser extent, MoO_2 and were restricted to a surface layer of 10 nm in thickness. It was further shown, by exposing MoS_2 samples to atomic O of low (thermal) energy, that the ready growth of surface oxide was not a consequence of the high energy of the oxygen species but, rather, arose as a consequence of its atomic state.

In vacuo, pin/disc measurements made on MoS_2 films before and after atomic-O exposure indicated that untreated films gave rise to friction coefficients of 0.03, whereas oxidized films conferred initial coefficients of 0.25 (Fig 7). The friction of oxidized samples decreased with repeated sliding such that values approaching 0.03 were obtained after about ten cycles. Recent Japanese data[48] are consistent with this pattern of tribological behaviour exhibited by MoS_2 following irradiation with atomic oxygen.

The implications of the above observations with regard to the use of sputtered MoS_2 in low earth applications would appear to be as follows. MoS_2 films will oxidize upon exposure to a low earth orbit environment. The rate of oxidation will depend upon the location and orientation of the lubricated component relative to the spacecraft and the extent to which the lubricated surface is exposed. The highest oxidation rate will occur on forward-facing exposed surfaces, but even shielded surfaces will be prone to oxidation from scattered atomic oxygen. Tribological components enclosed in a fully sealed system will not be at risk.

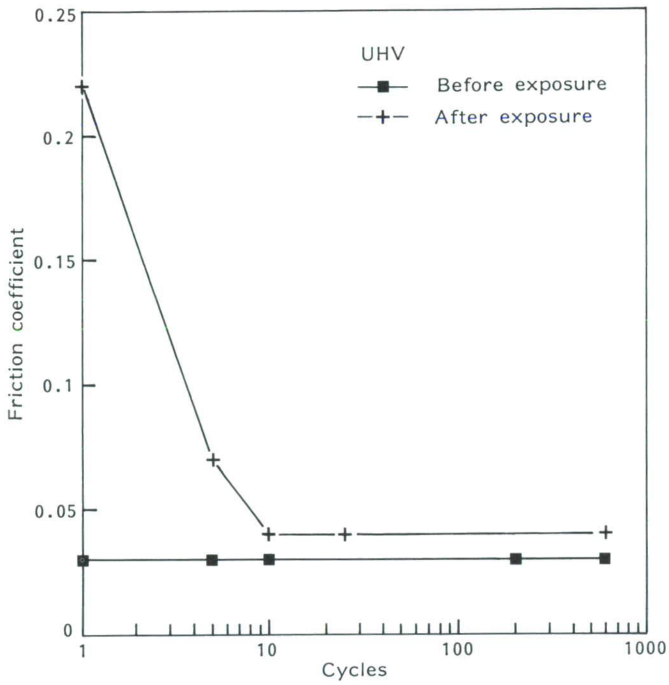

Fig 7 In vacuo *friction of sputtered MoS_2 films before and after exposure to atomic oxygen*[47]

It is known that MoS_2 films operated in humid air oxidize and that such films not only exhibit higher friction but also wear at a greater rate than occurs in vacuum[17]. Thus, for example, the rate of wear of sputtered MoS_2 in air of 50% RH increases a hundred-fold above that of the same film in high vacuum. Thus it is reasonable to assume that MoS_2 films oxidized as a result of exposure to atomic O will exhibit higher friction and a higher rate of wear than in a non-oxidizing environment. The values of friction and wear will be determined by the rate of oxidation and the duty cycle of the exposed component.

Table 2 indicates that silver, a soft metal lubricant, is heavily attacked by atomic O. Again the resulting chemical product is an oxidized metal which is then lost by flaking and spallation[45]. Indeed, any metal with a susceptibility to oxidation seems likely to suffer in similar fashion. For this reason thin films of lead would seem to be unsuitable lubricants. Gold, however, being relatively inert, is more likely to survive the hostile low earth orbit environment, and the use of thin gold films may well prove to be one of very few methods capable of providing adequate lubrication in the presence of high fluxes of atomic oxygen.

Organic compounds would appear to be particularly susceptible to atomic O-induced degradation[45]. This susceptibility may prohibit the use of those organic compounds that are used as lubricants or as binders of solid lubricants. Additionally certain polymeric lubricants (e.g FEP Teflon) show a much enhanced reactivity to atomic O when exposed simultaneously to ultraviolet radiation[49].

Clearly there is much that has to be learnt about the ability of solid lubricants to withstand LEO environments. In view of the long-term requirements (up to 30 years) of programmes such as Space Station Freedom there will inevitably be created a strong demand for information of this nature.

Deep space environments

Mechanisms on long-term missions into deep space often remain dormant for some considerable time. In such cases there is concern regarding the ability of tribo-components to function correctly after protracted periods of inactivity. Exposure of thin solid film lubrication to vacuum environments for periods of several years should lead to no appreciable chemical degradation and therefore no detrimental effects in lubricating ability should occur.

Ground testing and storage

All components and mechanisms are subjected to some ground testing prior to, and during, spacecraft integration. Often, such testing is carried out in uncontrolled environments and can lead to the irrevocable degradation of solid lubricant films.

Thus MoS_2 films will give relatively high friction and form oxides when run in moist air. Whilst the film is likely to recover its low friction properties in vacuum the durability of the film will be shortened to a degree commensurate with the amount of in-air running[18]. Components lubricated with thin films of MoS_2 and lead (which also oxidizes) should therefore be tested either under thermal–vacuum conditions or in an inert atmosphere. Storage of components thus lubricated should similarly take place in an inert atmosphere to minimize film oxidation.

Future trends

Currently, considerable attention is being paid to the development of new, thin, solid lubricating films and the improvement of existing lubricant films. Many of these developments are highly relevant to space lubrication. Foremost in this respect are: the development of carbon-based films (diamond and diamond-like carbon films[50,51]) and ion-beam mixing and compaction of thin films[52]. The application of the latter technique to films of sputtered MoS_2 has been shown to enhance film durabilities (by a factor five) without detracting from the film's low-friction properties[52]. The assessment of tribo-components lubricated with ion-modified films has yet to be carried out, but the pace and promise of these developments are such as to suggest the early insertion of this technology into forthcoming space programmes.

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