THE PERFORMANCE OF THIN SOLID FILMS FOR SATELLITE GEARS

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ABSTRACT

This paper describes an investigation into the use of thin solid films on spur gears for satellite mechanisms. To reduce gear wear, the use of physical vapour deposited (PVD) films of titanium nitride (TiN) was examined. To improve overall gear efficiency, the performance of solid lubricating films of ion-plated lead and magnetron-sputtered MoS_2 were evaluated. On steel gear substrates, current commercial TiN films were found to give short lives because of poor adhesion to the tooth flanks. For maximum lubricant film life, the optimum thickness of the as-deposited lead was found to be approximately 1 micron. Testing indicated that for the reported experimental conditions, magnetron-sputtered MoS_2 films give a shorter life on steel gears than ion-plated lead.

Keywords: Gears, Lubricants, Lead, Molybdenum Disulphide, Thin Solid Films, Vacuum.

1. INTRODUCTION

Critical functions of European space satellites (both in orbit and under construction) rely on geared drives and transmissions. Because of the onerous specifications now demanded for such transmissions, eg. reduced mass, lower backlash, wider operational temperature range and longer life (up to 15 years, or longer in the case of COLUMBUS), recent attention at the European Space Tribology Laboratory (ESTL) has been directed at the reduction in wear of steel gears by using ceramic coatings and at the use of solid lubrication of gear contacts.

Existing solutions for reducing spur gear wear in vacuum (Refs. 1-4) have limitations arising from manufacture and heat treatment, while the mechanism designer is largely devoid of information on the solid film lubrication of gears. To achieve low gear wear the use of physical vapour deposited (PVD) coatings of TiN has been examined. The application of TiN coatings, in particular onto high speed steel tooling, is well established in the metal cutting and forming industries.

PVD coatings of TiN are extremely hard (>3000HV), wear resistant, and have a low coefficient of friction in air. The PVD processes has a low deposition temperature which allows a range of gear substrates to be coated with minimal distortion or tempering, whilst largely retaining existing surface topography (Refs. 5 & 6). The process is claimed, for tooling applications, to give uniform coverage and, above all, good coating-to-substrate adhesion.

The dry lubrication of space gears offers a number of significant advantages over liquids (greases). These include: friction that is insensitive to temperature and speed, no threat of contamination, seals can be avoided and accelerated life testing is valid. For these reasons films of ion-plated lead and sputtered MoS_2 are increasingly used on geared satellite mechanisms (Refs. 7 & 8). However there has been little attempt at optimising the life of these films as gear lubricants. Ion-plating is used because of the adherent films that are produced, while lead has the added advantage that its mode of lubrication is essentially insensitive to the Hertzian contact stress (Ref. 9). Magnetron-sputtered films of MoS_2 exhibit, in vacuum, high durability in sliding tests (superior to ion-plated lead) and high lubricity (friction coefficient in the order 0.01, compared to 0.1 for ion-plated lead, Ref. 11)

This paper describes the results of tests designed to assess the role of coating type, initial film thickness, substrate type and surface roughness on the vacuum durability of solid films on gears.

2. GEAR MATERIALS AND THIN FILMS

2.1 Gear materials

Involute gears were manufactured from maraging steel (DTD 5212, composition 18%Ni, 9%Co, 5% Mo), nitriding steel (722M24, equivalent to En40B) and 440C stainless steel. DTD 5212 was chosen because the material will marage (harden) during TiN deposition without inducing distortion; 722M24 was selected as it could be plasma nitrided to provide a hard substrate to support the TiN coating. Both DTD 5212 and 722M24 steel gears were manufactured by hobbing, with the base material in an annealed or quenched and tempered condition. Through-hardened 440C steel gears (700 HV) were employed because of their availability at ESTL; the tooth profile was generated by form grinding.

2.2 Thin solid films

2.2.1. Titanium nitride

TiN coatings, applied by reactive sputtering and arc-evaporation by various UK commercial coaters, were deposited on DTD 5212 and plasma nitrided 772M24 steel gears. While plasma processing should, in theory, ensure that no friable white layer is formed at the gear surface, it was found that the gears required vapour washing before TiN deposition. The properties of the TiN coatings and resulting gear hardnesses are summarised in Table 1. The coating thickness was measured on the side of the gear, adjacent to the tooth flanks by X-ray fluorescence. As the arc-evaporative process tends to increase the surface roughness (particularly the skewness, R_{sk}) because of 'spatter' particles arriving directly from the target, a period of running-in has previously been found to be beneficial (Ref. 6). Therefore one set of TiN coated DTD 5212 gears were also lubricated with spray-bonded PTFE (Emralon, to a depth of approximately 20 microns and tested. All other tests with TiN coated gears were run unlubricated.

Table 1. TiN coating and substrate properties

TiN Coating Type	Substrate Material	Substrate Hardness (HV)	TiN Thickness (microns)
Sputter 1	DTD 5212	650	0.2-0.7
Sputter 2	DTD 5212	550	0.6-1.8
Arc Evap 1	DTD 5212	550	1.4-1.6
Arc Evap 2	DTD 5212	510	4.8-5.0
Arc Evap 2	722M24*	1040	2.7-2.8
Arc Evap 2	722M24*	780	3.7-5.3

* plasma nitrided

2.2.2 Lead

The lead films were deposited by ion-plating at ESTL, using ESA approved procedure ESTL/TP/055. The lead was deposited on 440C, DTD 5212 and 722M24 steel gears, to thicknesses in the range 0.25 to 4 microns. The thicker films (>1 micron) were obtained using multiple lead evaporations.

2.2.3 Molybdenum disulphide

Magnetron-sputtered films of MoS_2 were deposited at ESTL, also following an ESA-approved procedure (ESTL/TP/061) on 440C & 722M24 gears. Film thicknesses of 0.7 microns were obtained on the pinions and 0.3 microns on the wheels. Only limited testing was performed on the MoS_2 films.

3. EXPERIMENTAL

3.1 Gear test rig

The ESTL gear test rig consists of a "four square" arrangement inside a vacuum chamber (Fig. 1), with the pinion shaft being driven by an external motor via a rotary ferrofluidic feedthrough. A digital counter, with a magnetic sensing head attached to the drive shaft, records the number of pinion revolutions performed. The chamber is evacuated using a turbo-molecular pump and ion pump.

The gear loading is applied by "winding-up" the torsional spring wire (positioned below the lower wheel) to a specified torque before clamping the remaining gears to the shafts. The lower wheel is mounted on bearings and is free to rotate. The reactive torque, due to the frictional losses during gear mesh, causes the gear assembly to rotate backwards around the drive shaft. The motion is restrained by a load transducer at a fixed radius, the output from which is used to monitor the torque and hence, in these tests, solid film failure by the rapid rise in torque levels which follow the onset of adhesion (ie. friction coefficients > 0.2).

3.2 Test-gears

The details of the ESTL gears are as follows:

Pinions: 41 teeth, 10 mm face width
Wheels: 120 teeth, 3 mm face width

The gears were manufactured to BS 978 Part 1 (1969) - Class C (approximately equivalent to AGMA 9 quality). The gear module (tooth size) is 0.75 mm.

The measured gear surface roughnesses (R_a) **along the flanks** were in the range 0.25 - 0.4 microns for DTD 5212 & 722M24 gears, 0.1 micron for the 440C gears. It was not possible to measure the surface roughness down the flanks because of the low module size.

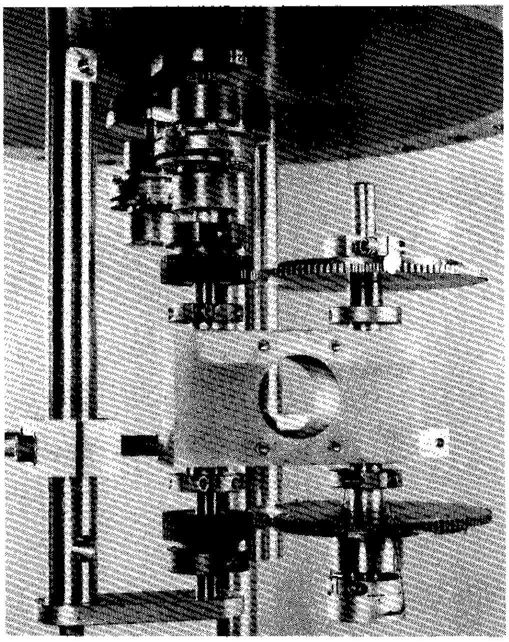

Figure 1. ESTL vacuum gear rig

3.3 Test conditions

Pinion speed	50 RPM
Tooth load	7 & 14 N/mm (equivalent to Hertzian contact pressures, p_o, at the PCD of 187 & 266 N/mm^2)
Temperature	20^o C (laboratory ambient)
Vacuum	<10^{-7} mbar

Each pinion was run against a similarly treated wheel.

3.4 Assessement of gear performance

Solid film life was assessed from measurements of the gear torque and visual examination (via a chamber window). The onset of failure was indicated by a rise in gear torque (reduction in efficiency). Visual observation confirmed the removal of the TiN coating or the onset of adhesion on the gear teeth contact, in the case of the solid lubricants.

3.5 Post-test examination

The gear teeth were examined by:

(a) Scanning Electron Microscopy using a Robinson back-scatter detector. Through the enhanced atomic number contrast, this revealed the location of residual lubricating films in the contact area. By varying the accelerating voltage an indication of the film thickness could also be obtained.

(b) X-ray fluorescence (XRF), using a Fischerscope XRAY 100C. This was programmed to measure the thickness of the lubricant and TiN films on the gear substrates. The instrument has a limiting depth resolution of 100 A^o, over a target area of 0.02 mm^2.

(c) 3D profilometry using a Talysurf stylus and measurement head. This mapped and measured the gear wear scar volume.

(d) Optical microscopy.

4. RESULTS

4.1 Titanium nitride coatings

The effective life of the TiN coated gears, at a tooth load of 7 N/mm, is shown in Figure 2. Without lubrication all coatings failed in less than 2 x 10^4 tooth encounters. SEM examination and hardness indentations revealed that the adhesion of the TiN to the substrate, for the sputtered and the evaporative type 1 coatings, was poor. With its better adherence, a modest improvement in life was obtained with the evaporative type 2 coating on DTD 5212. There was evidence, however, that the low substrate hardness contributed to the early failure. To ensure adequate substrate strength, a set of 722M24 gears were plasma nitrided, vapour washed and then TiN coated.

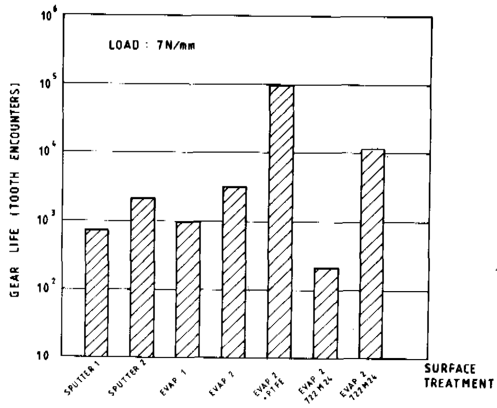

Figure 2. Life of TiN coated steel gears, load: 7 N/mm

The coating life of these gears was not improved, with the coating rapidly removed from the tooth flank. While microhardness indentations indicated excellent adhesion of the TiN on the gear sides and tooth tips, microsections of the tooth profile showed a thin white layer of iron nitride, not removed in vapour washing (Fig. 3). The friable nature of the white layer was responsible for the spalling of the TiN coating. Vapour washing procedures were modified to ensure removal of residual white from nitriding (this was confirmed by metallographic examination), and a second set of plasma nitrided 722M24 gears coated with TiN. A coating life of 2 x 10^4 was subsequently obtained.

Applying PTFE to the TiN coated DTD 5212 gears, to allow the coating to run-in, improved the coating life to a maximum of 10^5 tooth encounters at a load of 14 N/mm.

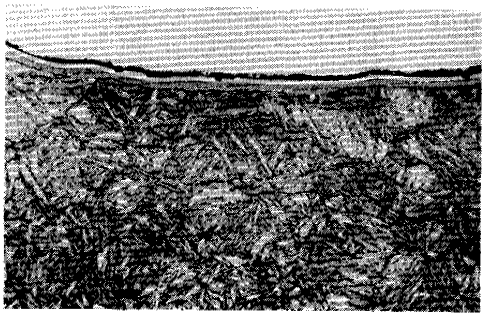

Figure 3. Microsection of tooth profile, showing white layer beneath TiN coating, x500

4.2 Lead films

Figure 4 shows the typical frictional torque behaviour of 440C gears lubricated with differing thicknesses of ion-plated lead (at a load of 7N/mm) and run in vacuum. Three general regimes can be identified. First there is an initial period, typically, 10^4 revs (tooth encounters), where the mean torque is gradually reducing. The second regime is one of low and stable torque. Finally the frictional torque increases, indicative of film failure and adhesion between the gear teeth. Despite the onset of adhesion, the lead continued to provide some measure of lubrication. The unlubricated gear torque of a 440C combination was approximately 280 Nm x 10^{-4}, some 2 to 3 times that of the lead-plated gears up to their failure.

The life of the lead film on gears (Fig. 5) showed some dependence on initial film thickness, a 1 micron film giving the longest film life. Varying the substrate and hence the gear surface roughness had minor influence on film life (only one film thickness condition examined). Doubling the contact load neither improved nor reduced film life.

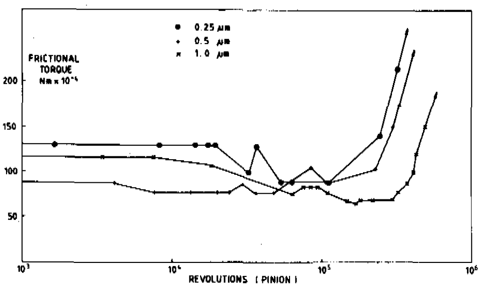

Figure 4. Typical frictional torque behaviour of 440C gears with differing thicknesses of ion-plated lead

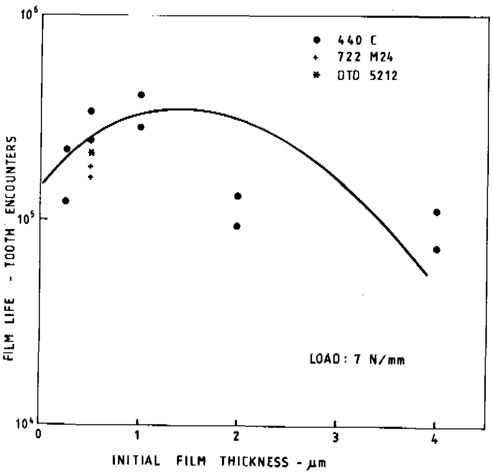

Figure 5. Effect of initial film thickness on life of ion-plated lead.

SEM examination of the gear contact zone (Fig. 6), prior to failure, revealed lead transfer and smearing at the edges of the contact area (at positions corresponding to maximum sliding). At the PCD, where rolling motion is dominant, lead was only present as a very thin film. XRF measurements indicated lead films of thickness around 100 A^{o} or less at the pitch point. The presence of lead films of thickness <100 A^{o} (ie at the resolution limit of the XRF instrument) was inferred from SEM examination where the accelerating voltage was varied and by the absence of surface damage by adhesion.

SEM inspection after film failure, in general, revealed that adhesive wear begins at or close to the pitch point, before spreading across the contact zone, rather than at the positions corresponding to high relative sliding.

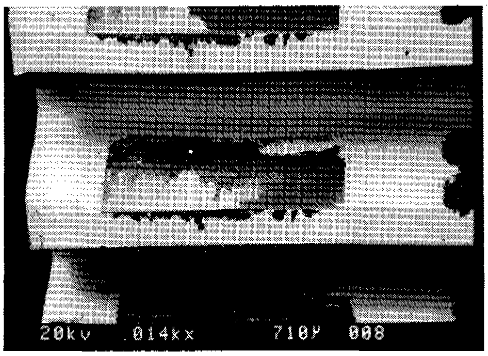

Figure 6. SEM micrograph of contact area before film failure, x14

4.3 Molybdenum disulphide

Limited tests performed at a tooth load of 7 N/mm gave film lives in the range 1.2 to 2.1 x 10^5 tooth encounters, for 440C and 722M24 gear substrates (and combinations thereof). These lives are shorter, by up to a third, than the comparable result for lead films. The frictional torque behaviour with the number of pinion revolutions was generally similar to that shown in Fig. 4, with the torque remaining at a steady value. Film failure produced a rapid and pronounced increase in gear torque. The MoS_2 film life was also independent of the initial surface roughness of the ESTL test gears.

5. DISCUSSION

5.1 Titanium nitride

The current tests with TiN coated gears have given unacceptably short lives for satellite gear applications. Poor adhesion was rapidly identified as being the cause of failure of the sputtered and evaporated type 1 coatings. In conjunction with the UK commercial coaters, procedures were adopted to improve both pre and in-chamber cleaning operations. The arc-evaporative process was also chosen because of its good adhesion.

Despite these procedures and the use of a fully supportive substrate (plasma nitrided 722M24), the resulting films of TiN still had short lives. The adhesion **on the gear flanks**, as assessed by hardness indentations, was however equal to that found on TiN coated tool and high-speed steels. Film thickness measurements down the tooth flanks (metallographic sectioning was required) revealed that TiN coating thickness reduced from gear tip to root. Stevens and Douglas (Ref. 6) have found on re-entrant surfaces such as through or blind holes, that the coating thickness and, by inference, the ion-cleaning of surfaces, is reduced. The smaller the diameter of the hole the greater and more rapid the reduction. Hence the re-entrant tooth surfaces on a low module precision gear appear to limit TiN coating uniformity and its adhesion to the substrate.

It should be noted that plasma nitrided steel gears, **without TiN coatings**, have been found to give the lowest wear rates for in vacuum (Ref. 3). It has not been possibly to measure an effective wear rate for the TiN coatings because of their short lives. But **if adherent**, a TiN coating would give a further reduction in the wear rate of a plasma nitrided gear.

5.2 Lead

The life of an ion-plated lead film on a steel involute gear has been found to be characterised by three operating regimes. The first corresponds to the initial squeezing and deformation of the lead, to a thickness where it forms a thin elastic skin. Measurements have shown this elastic film to be of the order of 100 A°, which is close to its equivalent thickness in rolling element bearings (Ref. 10). Lead transfer, between pinion and wheel, predominates at the regions of greatest sliding in the contact area. The second regime is one of stable or equilibrium film wear. Because the film is not replenished then the substrate is eventually exposed and adhesion begins, initiating the third regime which is film failure.

Up to a critical thickness of 1 micron, the wear life of the lead increases to approximately 3 x 10^5 tooth encounters. In part this behaviour is explained by the extended period of running-in with 1 micron films, needed to establish the elastic film. Further benefit is not obtained with thicker films because the lead transfers in lumps, which may also cause some disruption to the establishment of the elastic film. It should be noted that where gear backlash is small, interference can be caused by the build-up of lead at the edges of the contact zone.

The independence of the initial surface roughness of the ESTL test gears on film life, highlights the remarkable lubricity of the lead film, in its elastic film mode.

5.3 Molybdenum disulphide

Magnetron-sputtered films of MoS_2 can exhibit very low friction (0.01) and long life under pure sliding in vacuum (ie superior to lead), at Hertzian pressures up to 10^3 N/mm^2 (Ref. 11). Despite the lower contact pressures in these tests, the latter benefit of long life is not apparent in the rolling sliding/ motion occurring in gear contacts. The reasons for this anomalous behaviour are not clear and these films are under further investigation at ESTL. Gear torques were, however, reduced (to approximately 60 Nm x 10^{-4}) because of the lower friction characteristics of the film.

Thicker films are unlikely to improve film life, as the endurance of RF sputtered MoS_2 does not increase, in sliding wear tests, above a film thickness of 0.5 microns (Ref. 12).

6. CONCLUSIONS

(a) On low module involute steel gear substrates, current commercial TiN coatings give, in unlubricated tests, short lives ($<2 \times 10^4$ tooth encounters) before removal; this is too short to be of benefit to satellite applications.

(b) In these tests, ion-plated films of lead are more endurant that sputtered MoS_2 films, for the solid lubrication of involute gears.

(c) For maximum life as a gear lubricant, the optimum as-deposited thickness of ion-plated lead is 1 micron.

(d) Solid lubricant life shows no dependence on initial gear surface roughness (in the range 0.1 to 0.4 microns R_a).

7. ACKNOWLEDGEMENTS

The work was funded under ESTEC contract no. 5615/83/NL/PP, under the technical management of Mr D Wyn-Roberts.

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