ADVANCES IN SOLID LUBRICANT COATING TECHNOLOGY

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ABSTRACT

This paper describes a process optimisation exercise which was undertaken on a Plasmag sputter deposition system to develop lubricating lead films of a quality comparable to those produced by the well-established ion-plating process. The intention of this work was to transfer the lead coating technology to a batch processing system and thereby reduce the unit cost of coating. The methodology and overall results of the exercise leading to optimisation of the Plasmag process are presented. The subsequent validation of optimised lead films for use in space, by application of coatings to ball bearings and their subsequent torque testing in vacuum, is described.

INTRODUCTION

Thin-film lead lubrication was developed by ESTL in the 1970's using the technique of ion-plating. Subsequently, ESTL pioneered the use of this lubricant in space and since then it has, arguably, been the most commonly used thin-film solid lubricant in European spacecraft mechanisms. In recent years it has been demonstrated that ion-plated lead confers other benefits when applied to tribological components. First, its presence on bearing steel components inhibits corrosion and secondly, it can defer the onset of degradation of certain space oils (PFPEs - perfluoroalkylpolyethers) thus prolonging significantly their useful life.

Whilst the benefits of ion-plated lead are universally acknowledged, there have been two concerns for end-users, namely the relatively high production cost and the inability to coat large components. These concerns arise because the ion-plating technology currently used is, by its nature, restricted to a small working volume in which only a small number of modestly-sized components can be accommodated. With the increasing need to manufacture mechanisms quickly and cost effectively, there is a clear need to produce coatings at reduced cost whilst maintaining film quality. In order to meet this demand we have carried out a development programme aimed at transferring the lead-coating technology to a sputter deposition system (the so-called Plasmag facility) which has a large working volume and is custom built to handle relatively large numbers of components.

APPROACH

The first phase of the work was concerned with optimising the Plasmag coating parameters so that films of the required quality were produced. For tribological purposes the films should be well adhered to the substrate, be as dense as possible (to minimise porosity and maximise durability) and be of high purity (so that its low shear, lubricating properties are maintained). Since the microstructure (and hence density) of the films is influenced by ion bombardment of the film during growth it was decided to produce films at various levels of substrate bias voltage. Film microstructure is also dependent on deposition rate which, in turn, is a function of target current (sputtering is based on the ion bombardment of target material, the resulting ion current is referred to as the target current). Since film purity was also expected to be a function of deposition rate (and hence target current), we examined the effects of target current on film quality. We therefore deposited films under different combinations of bias voltage and target current and, by analysing film structure and composition, aimed to identify the combination(s) that yield films having the desired properties. Such films were then deposited on bearing steel substrates and their friction and wear properties evaluated.

The second phase of this work involved the validation of the optimised coating process. This involved the torque testing (under vacuum) of ball bearings lubricated with lead films produced under the optimised sputtering condition.

OPTIMISATION OF PLASMAG LEAD FILMS

Lead depositions were carried out onto 52100 steel substrates at nine combinations of lead target current and substrate bias. These conditions corresponded to bias voltages in the range –50V to –200V and target currents in the range 0.3A to 0.9 A. The initial intention was to determine the lead deposition rate for each sputtering condition.

The following trends emerged:

- For a given substrate bias voltage, the deposition rate increased with increasing target current. This was as expected since the target current is simply a measure of the rate of bombardment of the target with argon ions: thus the higher the target current, the higher the bombardment rate and the greater the deposition rate.

- For a given target current, the deposition rate decreased with increasing bias voltage. This effect arises as follows: biasing the substrate promotes argon ion bombardment of the substrate at an energy equivalent to the bias voltage e.g. at a bias voltage of –50V the bombarding Ar ions would have an energy of 50eV. Argon ions having energies in the range 50eV to 200 eV are sufficiently energetic to remove by sputtering some of the deposited lead atoms. Since the rate of sputtering increases with increasing argon ion energy the net deposition rate, at a given target current, will decrease as the bias voltage is increased.

Once the deposition rates were established at the nine sputtering conditions used, lead coatings of thickness ~1μm were applied to 52100 steel discs. In each deposition, two such discs were coated. These were then subjected to adhesion tests, elemental analysis, SEM examination and tribometer testing. These tests indicated the following:

- tape tests carried out on all the coatings produced (under all nine sputtering conditions) were successful with no lead adhering to the tape.
- tribometer tests (pin-on-disc under dry nitrogen) showed the frictional properties and shear strength of the sputtered films to be similar to those of ion-plated lead.
- analyses of the Pb coatings showed the principal contaminant to be oxygen, this being present at low levels with concentrations of between 1.3 and 1.8 wt%.
- under selected deposition conditions, the morphology (porosity, uniformity) of sputtered Pb were comparable to that of ion-plated lead.

By comparing the properties of the sputtered Pb films produced under different conditions we were able to identify the optimised sputtering conditions that yielded films of comparable quality to ion-plated lead. Below we present a comparison of the properties of the optimised sputtered films with ion-plated Pb films.

Table 1 Comparison of optimised Plasmag Pb films with ion-plated Pb.

Parameter	**Ion-plated lead**	**Optimised Plasmag lead**
Adhesion	Good	Good
Shear strength	110 MPa	115 MPa
Porosity	Low	Low
Uniformity	Good	Good
Purity (O_2 content, wt%)	2.13	1.71

VALIDATION TESTING OF OPTIMSED SPUTTERED Pb COATINGS

Having completed the above study it then became necessary to formally validate the optimised coating. The purpose of such validation testing is to demonstrate acceptable reproducibility of the lubricant process under standardised ball bearing conditions. The method involves coating three pairs of angular contact ball bearings in three separate deposition runs and torque testing each pair over a defined running period. The process is deemed validated if all three bearing pairs generate torque levels (mean, peak and standard deviation) which are within specified limits.

Validation tests were performed using three pairs of SNFA ED20 angular contact ball bearings in accordance with ESTL/WI/16 "*Validation Method for Solid-Lubrication Processes Applied to Ball Bearings in Space Mechanisms*". In outline, the procedure requires three pairs of lead-lubricated bearings (coated in separate runs), fitted with leaded bronze cages, to complete 2 million revolutions in high vacuum whilst maintaining the following torques:

- steady-state mean torques of less than 30×10^{-4} Nm
- peak torque less than 150×10^{-4} Nm
- torque noise (hashwidth) less than 100×10^{-4} Nm

The operating conditions specified are:

- axial load (flexible): 40±5 N
- rotation rate: nominally 100pm; periodic torque measurements to be taken at the slower speed of 2 rpm.

Procedure undertaken

The races of three pairs of ED20 bearings were coated with optimised Plasmag lead films to thicknesses in the range 0.2 to 0.5 µm. Adhesion checks made on test coupons coated simultaneously with the bearings demonstrated the adhesion of the lead to be satisfactory.

The coated bearings were inspected using an optical microscope (x40) and assembled with the leaded bronze cages. Each bearing pair was then placed in an aluminium housing in a back-to-back configuration at an axial spring pre-load of 40 ± 5N (equivalent to 600MPa mean stress on inner ring). All tests were conducted in vacuum at a base pressure $<10^{-6}$ torr and an ambient temperature of 20 ± 2 deg.C. A 25,000 step per revolution stepper motor was used to rotate the bearings at 100rpm. A Teldix DG1.3 inductive transducer was used to measure the bearing torque. The bearings were initially run-in under vacuum for 10,000 revs., removed from the chamber and any loose debris rinsed out with Arklone solvent. This is standard ESTL practice for lead-lubricated bearings. The bearings were then returned to the test chamber for validation torque testing. During this testing, the direction of motion was reversed periodically in order to locate the zero torque level. At each reversal of motion the torque level (mean and peak) was measured with the speed of rotation reduced to 2 rpm.

Results

Plots of mean and peak torque values obtained during the low speed measurements showed that in all cases, the bearings successfully completed the required 2 million revolutions with the maximum torque values measured at 2 rpm being as tabulated below.

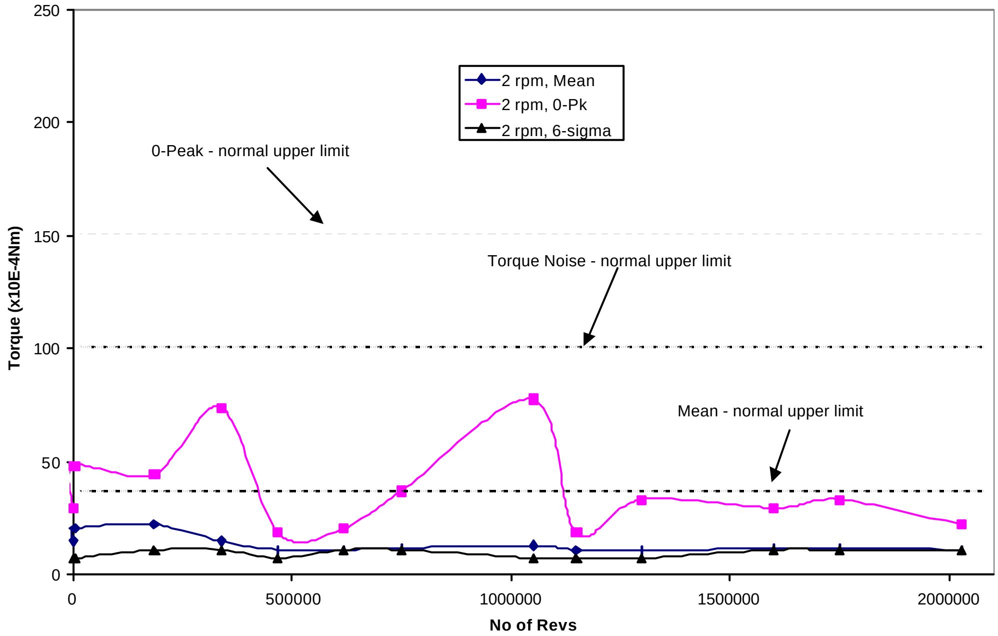
Table 2 Maximum values of measured torques ($x10^{-4}$ Nm) at 2 rpm

	Max. Values		
Test No.	**Mean Torque**	**Hash-width**	**Zero-peak**
1	20.4	26	132
2	18.5	18.5	46
3	22.2	11.1	78
Validation spec. (normal range)	**<30**	**<100**	**<150**

It can be seen that all values lie within the value specified for the “normal” range as required for successful validation.

An example torque trace is shown in Fig.1.

Fig. 1 PLASMAG LEAD TESTING
ED20 bearing pair, 40N preload, 20 rpm, vacuum
Test 3



Post-test examination of bearings

All six bearings were dismantled after testing and their condition examined by optical microscopy. The following observations were made:

- All bearings were in a satisfactory condition with little variation in appearance from one test to the next.
- Wear tracks on inner races were characterised by a transfer layer of leaded bronze of uniform, polished appearance
- The outer races exhibited similar wear tracks i.e. a transfer layer of leaded bronze in polished condition. Adhered leaded-bronze wear debris was present on that edge of the wear track closest to the unrelieved land of the outer race. Outside the wear tracks there remained adherent films of sputtered lead.
- In general, the balls had a uniformly grey appearance. There was little evidence of transferred leaded bronze or other forms of debris on any of the balls.
- All cages had characteristic wear marks in the pockets where ball-cage interactions had taken place. Additionally there were light wear marks on the outer surface of each cage where there had been contact with the non-relieved land of the outer race.

CONCLUSIONS

The following conclusions are drawn:

- The sputtering conditions necessary to yield lubricating coatings of lead of comparable quality to those produced by ion-plating have been identified.
- Tests have demonstrated that adherent lead coatings of the required thickness and uniformity can be applied to bearing raceways using the Plasmag deposition system.
- Bearings coated with Plasmag lead and fitted with leaded bronze cages have been subjected to validation testing and have met the validation criteria.

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