THE PERFORMANCE OF PTFE, LEAD AND MoS_2 AS LUBRICANT FILMS FOR BALL BEARINGS OPERATING IN VACUUM AT 20K

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ABSTRACT

The performance of dry-lubricated, angular contact ball bearings in vacuum at a temperature of 20K has been investigated, and is compared with the in-vacuo performance at room temperature. Comparative tests were performed on the three dry lubricants most commonly used in space applications; namely MoS_2, lead and PTFE. The torque performance of the MoS_2 and lead lubrication at cryogenic temperatures was indistinguishable from that at room temperature, whereas for the PTFE lubrication both the torque and torque noise increased substantially on cooldown. The torque performance of combined MoS_2/PTFE lubrication also deteriorated on cooldown.

Keywords: Cryogenics, Tribology, Ball bearings, Solid lubrication.

1. INTRODUCTION

Several satellites which utilize instruments requiring cryogenic cooling are planned. These include the Infrared Space Observatory (ISO), the Far Infrared Space Telescope (FIRST), and the Upper Atmosphere Research Satellite (UARS). Depending on their particular application, the low temperature devices employed in these satellites {1,2} contain moving mechanical parts in which contacts can be pure sliding (as in screw threads) or rolling-with-sliding (as in ball bearings). These components must be lubricated to ensure their proper operation, thereby creating a requirement for efficient lubrication in vacuum at cryogenic temperatures.

Only solid lubrication is practicable under these conditions, as oils and greases solidify at temperatures well above the cryogenic range. However, whilst it is known that molybdenum disulphide (MoS_2), polytetrafluoroethylene (PTFE), and lead are effective lubricants in vacuum at or near room temperature, their frictional properties in vacuum at very low temperatures have been little studied.

The research described in this paper is believed to be the first systematic investigation of the performance of lubricants for ball bearings operating in vacuum at temperatures below 20K. It was conducted in order to assess the performance at cryogenic temperatures of the three main types of solid lubricant, with a view to applying them to cryogenically-cooled spacecraft instruments.

2. LUBRICANTS TESTED

There are three classes of solid lubricant: soft metals, laminar solids, and polymers. The most commonly used space lubricants of each of these classes are lead, MoS_2, and PTFE respectively. Each of these lubricants has been tested in 20mm bore ball bearings operating in vacuum at temperatures below 20K. The methods used to apply each lubricant are now discussed.

2.1 PTFE

PTFE lubrication was effected by rubbing-transfer from a self-lubricating cage constructed from a PTFE/chopped glass-fibre/MoS_2 composite (tradename 'Duroid'). On rubbing against bearing surfaces, this cage produces, and replenishes, a thin transfer film of PTFE. Those surfaces which are not in direct contact with the cage are lubricated by means of film transfer via the balls. Thus, in the first instance the bearing is effectively unlubricated and a run-in is required before an effective transfer film is established.

2.2 Lead

Lead films of approximate thickness 0.5 microns were deposited onto the raceways of the test ball bearings by the technique of ion plating. The balls were not coated. Each bearing was fitted with a cage manufactured from leaded bronze, the lead within the cage serving to supplement the lead film applied to the raceways.

2.3 MoS_2

MoS_2 films of approximate thickness 0.5 microns were applied to ball bearings by the technique of magnetron sputtering. The torque behaviour and endurance of ball bearings treated with sputtered MoS_2 are dependent on both the cage material and whether the balls, as well as the raceways, are coated with the lubricant film {3}. It is observed that when only the raceways are lubricated, low torques and relatively short lifetimes (approximately 1 million revolutions) are obtained. However, on coating both the balls and the raceways, the lifetime is increased by a factor of approximately three at the expense of a twofold increase in mean torque {3}. With regard to cage material, it is observed that bearings lubricated with MoS_2 and fitted with PTFE composite cages exhibit endurances an order of magnitude larger than the endurance of bearings fitted with MoS_2-coated steel cages {3} or cages manufactured from a composite of MoS_2 and polyimide {4}.

For the purpose of this research, two forms of MoS_2 lubrication were tested: MoS_2-coated raceways in conjunction with a PTFE-composite cage, and MoS_2-coated raceways, balls and (steel) cage. Hereafter, these are referred to as 'MoS_2/PTFE' and 'all-MoS_2' respectively.

3. EXPERIMENTAL TECHNIQUE

The cryogenic test facility and the ball bearing test apparatus are described in detail in reference 5. Pairs of 20mm bore angular contact ball bearings were preloaded to 38N by means of a deadweight, and run at a rotation rate of 100rpm. The bearing torque and torque noise were measured directly by a torque transducer operating at room temperature. The output of the torque transducer was recorded on a chart recorder and measured by a programmable voltmeter. The torque noise was taken to be +/- 3 standard deviations ('3-sigma') as measured by the voltmeter.

In order to obtain more sensitive measurements of torque noise, torque measurements were made at a rotation rate of 0.5rpm. This also eliminated the effect of shaft run-out which, at 100rpm, significantly increased the measured torque noise while leaving the mean torque unaffected.

For the PTFE, lead, and MoS_2/PTFE lubrication, one pair of bearings was run in vacuum at room temperature for 1.0 million revolutions; the bearing housing was then cooled to below 20K and the bearings were run for a further 2.0 million revolutions. The all-MoS_2 lubricated bearings were run for only 30,000 revolutions at room temperature because of their limited endurance {3}.

For all four lubricants, a second pair of bearings was then tested under only the low temperature condition. The bearings lubricated with MoS_2/PTFE, lead and PTFE were tested without an initial run-in at room temperature, the all-MoS_2 bearings were run for 30,000 revolutions before cooldown as part of the quality check for the MoS_2.

4. RESULTS

The torque performances of the four lubricants are summarized in Figures 1 to 4. Figures 1 and 2 compare, respectively, the mean torque and torque noise measured for each lubricant at room temperature with that obtained at 18K. Similarly, Figures 3 and 4 compare, respectively, the mean torque and torque noise measured with the lubricants operating at only the cryogenic temperature.

The results obtained for each lubricant are now discussed.

4.1 PTFE-composite cage

The torque performance of bearings lubricated with PTFE operating at room temperature and at 18K is compared in Figures 1 and 2. At room temperature, the mean torque initially increased from $1.2x10^{-3}$Nm to a maximum of $3.3x10^{-3}$Nm. It then decreased progressively to $5x10^{-4}$Nm, and the bearings were fully run-in after approximately 0.5 million revolutions. The mean torque then remained at this level for the remainder of the room temperature measurements. The torque noise at room temperature was typically $5x10^{-4}$Nm.

On cooldown (at 1.0 million revolutions), the mean torque immediately increased by a factor of three. It remained at this level for the next 1.5 million revolutions, at which time both the mean torque and the torque noise increased substantially. During the final 0.5 million rotations, the mean torque was typically $2.5x10^{-3}$Nm with a torque noise of $1.7x10^{-3}$Nm. Despite the increase in noise towards the end of the run, the torque noise was one of the lowest observed and, for most of the run, was less than $1x10^{-3}$Nm.

The torque performance of PTFE-lubricated bearings operating at 18K, without being run-in at room temperature, is shown in Figures 3 and 4. In a similar manner to the room temperature results, the mean torque went through a maximum which probably corresponds to the run-in. However this maximum was appreciably higher ($5.8x10^{-3}$Nm) than that observed at room temperature. In addition, whereas the room temperature run-in was complete within 0.5 million revolutions, the low temperature run-in required 1.5 million revolutions. In contrast to the room temperature results, the torque noise also went through a maximum - peaking at $4.3x10^{-3}$Nm. The maximum occurred after approximately the same number of revolutions (0.6 million) for both quantities.

Throughout the low temperature run, the mean torque was greater than $2.0x10^{-3}$Nm. Despite an initial period of low noise, the torque noise was also greater than $2.0x10^{-3}$Nm for most of the run. However, once the run-in was achieved, the performance was the same as for the bearings which were run-in at room temperature before cooldown.

4.2 Lead film/lead-bronze cage

The torque performance of lead-lubricated bearings operating at room temperature and at 18K is shown in Figures 1 and 2. Both the mean torque and the torque noise were unchanged on cooldown, the torque performance at 18K being the same as that at room temperature. Throughout the run, the mean torque was typically $2x10^{-3}$Nm with a torque noise of $3x10^{-3}$Nm. Although the torque noise was the largest observed for the bearings which were run-in prior to cooldown, this level of noise is as expected from previous experience {5}.

The torque performance of lead-lubricated bearings operated at 18K without a room temperature run-in is shown in Figures 3 and 4. While the mean torque was consistent with that obtained for the bearings which were run-in before cooldown, the torque noise was appreciably lower; the maximum noise was $2.6x10^{-3}$Nm, but for most of the run the noise was less than $1.0x10^{-3}$Nm.

4.3 MoS_2 film/PTFE-composite cage

During the room temperature part of the test on the MoS_2/PTFE-lubricated bearings (Figures 1 and 2), the mean torque was typically $4x10^{-4}$Nm with a torque noise of $8x10^{-4}$Nm. This is as expected from previous experience {3}. Immediately after cooldown, both quantities were unchanged. However, after $7x10^4$ 'cold' rotations the mean torque had increased by an order of magnitude and the noise had doubled. Both quantities maximised at approximately 1.2 million revolutions, the mean torque subsequently decreasing to approximately $3x10^{-3}$Nm and the torque noise subsequently going through a minimum of 1.1 $x10^{-3}$Nm.

During the repeat measurement at cryogenic temperature (Figures 3 and 4), the initial invariance of the mean torque and torque noise, followed by a dramatic increase in mean torque, was reproduced. However, an equally dramatic reduction in mean torque, to typically $1x10^{-3}$Nm, occurred after 0.6 million revolutions and the torque remained at a low level for the remainder of the run. In addition, the torque noise remained at a low level, typically $1x10^{-3}$Nm, throughout the test.

4.4 All-MoS_2

Two tests were made on all-MoS_2 lubricated bearings, these being denoted by MoS_2-A and MoS_2-B in Figures 3 and 4. The data for MoS_2-A, that is the better of the two tests, is also included in Figures 1 and 2 for reference. The lowest torque performance observed was obtained for MoS_2-A. In this test, the mean torque was typically $7x10^{-4}$Nm with a torque noise of typically $1x10^{-3}$Nm. In the second test, MoS_2-B, the mean torque was generally twice as large and was more variable. The torque noise of MoS_2-B was also typically twice that of MoS_2-A ($2x10^{-4}$Nm) and was on an upward trend. Consequently, bearings MoS_2-B gave one of the noisiest performances observed.

Before bearings lubricated with MoS_2 films were cooled to cryogenic temperatures, they were run in vacuum at room temperature for 30,000 revolutions in order to check the film quality. These measurements are indicated by the broken lines in Figure 3. The evidence suggests that the torque performance of the all-MoS_2 lubricated bearings is unchanged on cooldown. In addition, the performance subsequently obtained at cryogenic temperature is consistent with that expected at room temperature {3}.

5. DISCUSSION

5.1 PTFE-composite cage

Bearings lubricated by means of a PTFE-based, self lubricating cage exhibited higher torque and torque noise during operation at cryogenic temperature. However, both quantities were dramatically reduced by running-in the bearings prior to cooldown. PTFE-lubricated bearings which were run-in prior to cooldown gave the second best torque performance observed. However, it should be remembered that, at room temperature, PTFE lubrication can give rise to a wide range of results {5}. In addition, the results obtained at room temperature during this study were exceptionally low.

The increase in mean torque that occurs on cooldown can probably be attributed to the manner in which the shear strength of PTFE increases with decreasing temperature. Whilst the shear strength of PTFE is not known to the authors, it is reported {6} that its value at 200K is twice that at 300K. As has been discussed elsewhere {7}, the torque is expected to increase proportionately with shear strength.

5.2 Lead film/lead-bronze cage

The torque behaviour of lead-lubricated bearings is the same at 18K as it is at room temperature. In addition, the bearings do not have to be run-in prior to cooldown. Indeed, the evidence indicates that a room temperature run-in may be detrimental to the subsequent performance at cryogenic temperature.

The temperature independence of the torque and torque noise is unexpected as the shear strength of lead increases by a factor of 4 on cooling to 20K {8}. At present these observations have not been explained, but one possibility is that the frictional heat generated in the region of the contact area in which micro-slip occurs is sufficient to increase the local temperature of the lead to a level at which its shear strength is lower than expected. Another possibility is that the temperature dependence of the shear strength of thin lead films may differ from that of bulk lead.

5.3 MoS_2/PTFE-composite cage

The cooling to cryogenic temperatures of bearings lubricated by MoS_2/PTFE caused dramatic changes in the mean torque. In both tests, the torque behaviour was unchanged immediately after cooldown, but shortly afterwards the mean torque increased to 5.7×10^{-3}Nm. It then went through a minimum and, in the case of the bearings which were not run-in at room temperature, subsequently fully recovered. This behaviour is not yet understood, but a preliminary examination of the bearings which were run-in before cooldown indicates that the MoS_2 film was removed from the running tracks of the raceways and replaced by a brown-coloured transfer film. The condition of the bearings was consistent with that obtained for PTFE-lubricated bearings.

5.4 All-MoS_2

The best torque performance was obtained during one of the two all-MoS_2 tests. During this test, the mean torque was typically 7×10^{-4}Nm with a torque noise below 1×10^{-3}Nm. In addition, the torque performance at cryogenic temperature was similar to that expected at room temperature. However, during the second test, although the mean torque was comparable, the torque noise was typically twice as large and was one of the worst performances measured.

6. CONCLUSIONS

Although the work described in this paper is at an interim stage, many interesting observations have been made. However, a more detailed interpretation of the results cannot be made until the test bearings have been thoroughly examined and further measurements made. The following, preliminary, conclusions are drawn:

1. Whilst all the dry-lubricated bearings tested at 20K survived 2 million revolutions, the best performance was obtained for bearings lubricated with MoS_2 coatings on the raceways, balls and (steel) cages. The torque performance of these bearings at cryogenic temperature was the same as that expected at room temperature. However, two such pairs of bearings were tested and the torque of the second pair was appreciably noisier.

2. Bearings lubricated with MoS_2 films on the raceways and fitted with PTFE-composite cages showed appreciable increases in torque soon after cooldown. However, the bearings which were not run-in at room temperature subsequently staged a complete recovery.

3. Bearings lubricated with thin lead films and fitted with a lead/bronze cage showed no torque deterioration on reducing the temperature from 300K to 20K.

4. Bearings fitted with PTFE-composite cages showed increased torque and torque noise at 20K. The torque performance of bearings lubricated in this manner was improved by running-in the bearings prior to cooldown.

7. ACKNOWLEDGEMENT

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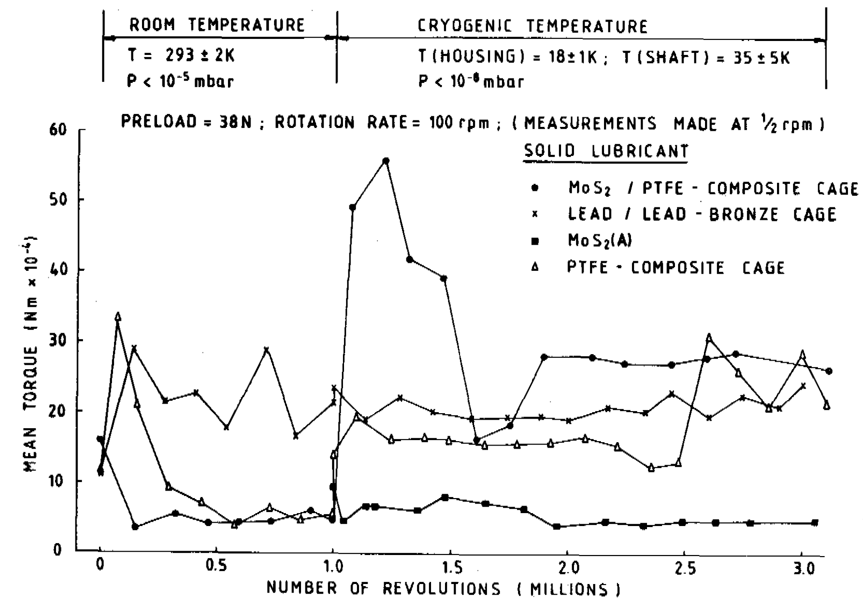

Figure 1. The mean torque of solid-lubricated ball bearings operating at room temperature and at cryogenic temperature.

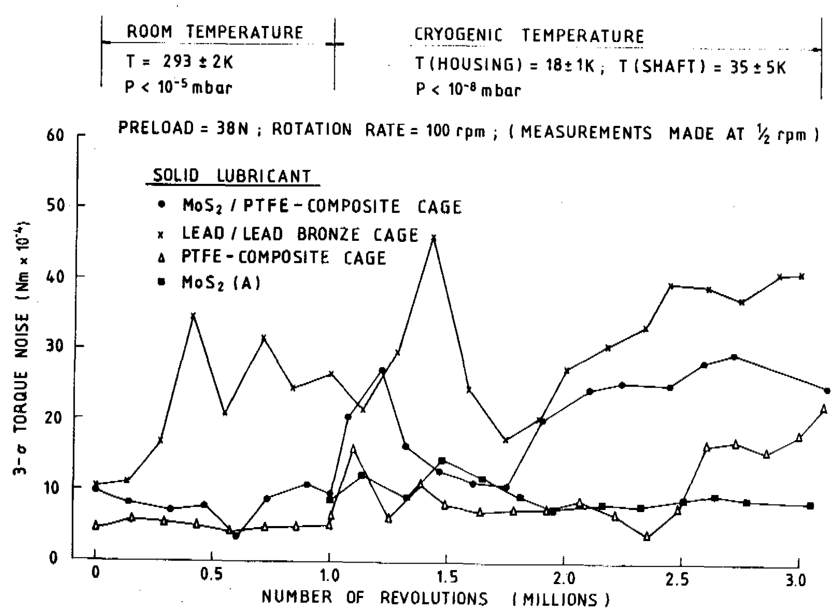

Figure 2. The torque noise of solid-lubricated ball bearings operating at room temperature and at cryogenic temperature.

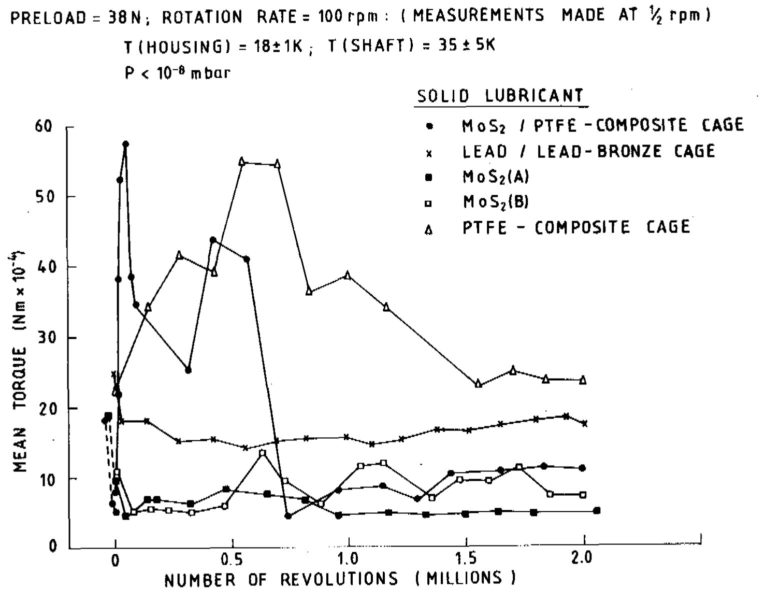

Figure 3. The mean torque of solid-lubricated ball bearings operating at cryogenic temperature.

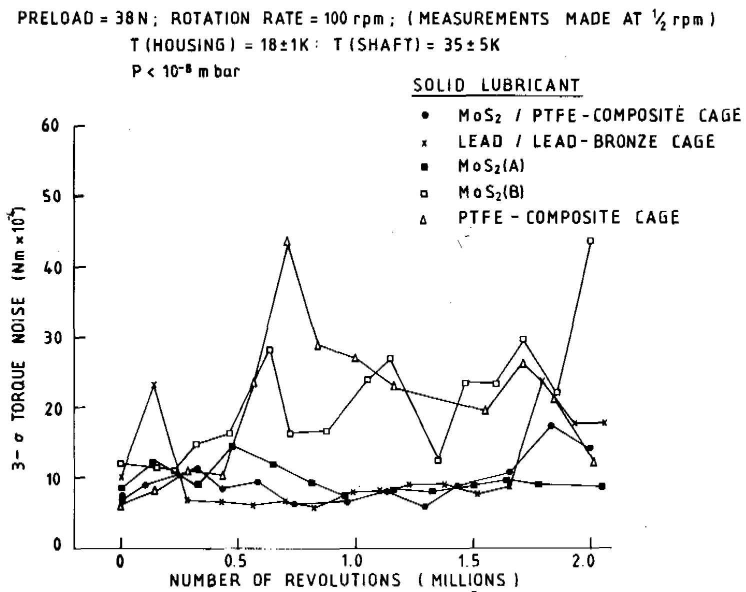

Figure 4. The torque noise of solid-lubricated ball bearings operating at cryogenic temperature.