TOWARDS THE EFFECTIVE SOLID LUBRICATION OF BALL BEARINGS OPERATING AT HIGH TEMPERATURE

Matthew R. Hampson, Emyr W. Roberts, Matthew D. Cropper, Richard B. Watters, Dave J. Forster

ESTL, ESR Technology Ltd, Whittle House, 410 The Quadrant, Birchwood Park, Warrington, WA3 6FW, United Kingdom, Email: matthew.hampson@esrtechnology.com

ABSTRACT

Several research projects have been completed as part of an ongoing program of work into solid lubricated bearings for high temperature operation.

Testing of bearings indicated that MoS_2 lubrication is effective at high temperature, but highlighted a potential problem with the commonly-used material PGM-HT - that it can shrink permanently during initial heating, leading to loss of clearances and high torques. This effect was subsequently measured quantitatively – components have been shown to contract by ~1.5 % on heating to 250 °C. A thermal conditioning regime was devised to avoid the problems of shrinkage.

A number of alternatives to conventional cages were also designed, manufactured and tested. Hybrid cages, with a metal body and inserts made of self-lubricating materials, were identified to be an effective option, which avoids problems with conventional cage designs.

1. BACKGROUND

Forthcoming activities with high operating temperatures, such as the BepiColombo mission to Mercury, place unusual demands on bearing technologies,. A series of preliminary test activities to study the behaviour of solid-lubricated bearings at high temperature was therefore considered essential.

Operating across a wide temperature range presents a number of challenges for ball bearing design. An effective lubricant must be found, and the bearings must be designed to minimize any untoward effects of thermal expansion.

Fluid lubrication of bearings is generally unsuitable for high operating temperatures due to the rate of evaporation of oils. A suitable solid lubricant must therefore be found. Solid lubricated bearings usually employ self lubricating cages, to provide additional lubrication. However, cage materials such as self-lubricating polymers often have much greater thermal expansivities than bearing steels (as shown in Fig. 1).

The difference in thermal expansivity between bearing races and cages can lead to problems with conventional cage designs. A bearing cage designed for operation at room temperature will often have unacceptable clearances at high temperature, or vice versa. Alternative cage designs must therefore be investigated for any bearings with wide ranges of operating temperatures.

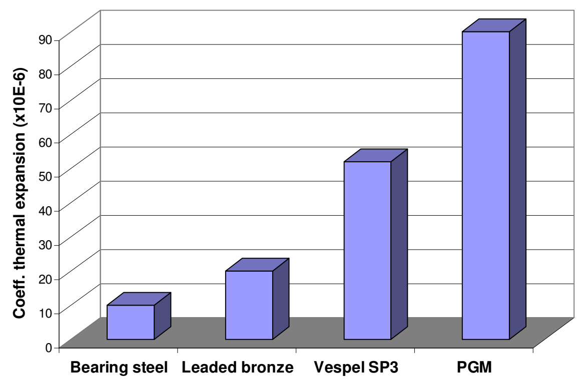


Figure 1 Thermal expansion coefficients of self lubricating bearing cage materials.

The work described in this paper comprises three separate projects:

a) An assessment of the high temperature performance of bearings lubricated with lead and molybdenum disulphide (MoS_2).
b) A study of the thermal stability of two commonly used polymer-based self lubricating materials.
c) Tests of ball separators designed to overcome problems of thermal expansion.

2. CHOICE OF LUBRICANT

The two most promising lubricants for bearings operating at high temperature were identified as being lead and MoS_2. In each case, the solid lubricant should be used in conjunction with a self lubricating bearing cage to provide additional lubrication. The recommended configurations are listed in Tab. 1.

Proc. '12th Euro. Space Mechanisms & Tribology Symp. (ESMATS)', Liverpool, UK, 19–21 September 2007 (ESA SP-653, August 2007)

Table 1 Two proposed lubrication configurations for cages operating at high temperature

Lubricant	Bearing race lubrication	Bearing balls	Cage material
MoS_2	Sputtered MoS_2	Sputtered MoS_2	PGM-HT
Lead	Lead	None	Leaded bronze

Bearing tests were conducted for both of these lubrication configurations. The self-lubricating materials relevant to the work described in this article are listed in Tab. 2.

Table 2 Self-lubricating materials.

Material	Composition	Source
PTFE (polytetra-fluoroethylene)	Pure polymer	Multiple sources
Vespel SP3	Polyimide based polymer, 15% MoS_2 filler	DuPont
SINTIMID 15M-HT	Polyimide based polymer, 15% MoS_2 filler	Ensinger
PGM-HT	PTFE, chopped glass fibres and MoS_2	JPM of Mississippi Inc
Leaded bronze	Copper, tin and lead.	Multiple sources

2.1. Test rig

A test rig was designed and manufactured at ESTL to enable torque measurements of bearings operating at high temperature in vacuum.

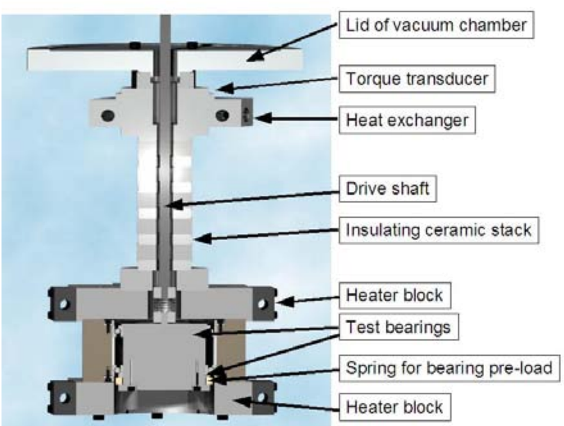


Figure 2 High temperature bearing test rig.

The rig (Fig. 2) enables heating of the bearings up to 300 °C. The test bearings are driven by a shaft connected to a stepper motor mounted external to the vacuum chamber. Electrical heaters mounted above and below the bearing housing are used to control the temperature. The reactive torque of the bearing housing is measured using a piezoelectric torque transducer. The torque transducer table is thermally isolated from the bearing housing by means of a stack of ceramic discs and cooled by a recirculating fluid bath.

2.2. Test method

The test rig described above was used to separately test the two configurations listed in Tab. 1. The bearings used for the tests were as detailed in Tab. 3. A pair of angular contact ball bearings was mounted in a back to back configuration and an axial pre-load of 65 N, (corresponding to 1000 MPa peak Hertzian contact stress at the inner ring) was applied by means of a spring.

Table 3 Details of test bearings.

Number of balls	11
Ball material	Silicon Nitride (Si_3N_4)
Ring material	Cronidur® 30
Outer diameter	42 mm
Bore	20 mm
Width	12 mm

There were two stages to the tests: an initial evaluation of the torque behaviour at elevated temperatures, and a life test at 250 C.

2.3. Test results - lead lubrication

The lead lubricated bearings showed initial torque of around 300 mN·m at room temperature, with the torque decreasing gradually with running in and increased temperature, as shown in Fig. 3.

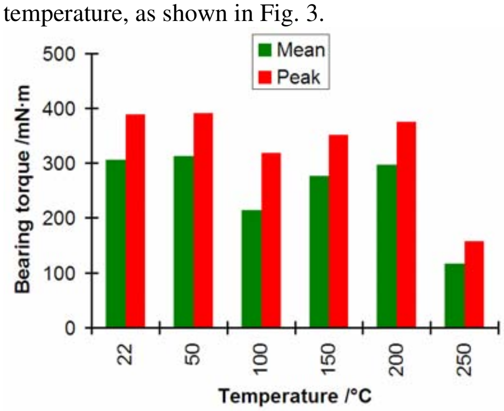


Figure 3 Results of initial tests of lead lubricated bearing with leaded bronze cages.

At the start of the life test, the torque initially remained at around 100 mNm, but gradually increased with prolonged running. A sharp increase in torque was seen at around 3.5 million revolutions, indicating a failure of the bearing.

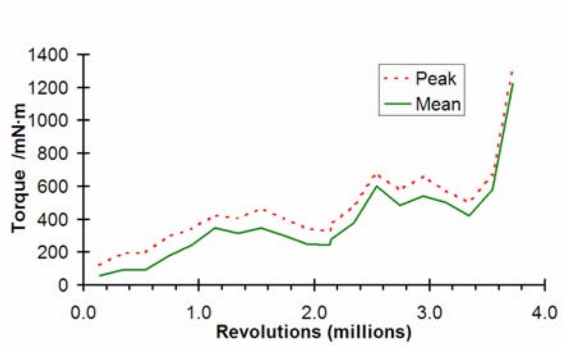


Figure 4 Results of life tests of lead lubricated bearing with leaded bronze cages.

A post test inspection showed an unusually large amount of bronze debris flakes generated by excessive transfer of material from the cage.

2.4. Test results - MoS_2 lubrication

The initial tests of the MoS_2 lubricated bearings (Fig. 5) showed a torque level of around 200 mN·m, slightly lower than the lead lubricated bearings. However, at high temperature, the mean torque was exceptionally low, becoming immeasurable at 300 °C, prompting suspicion that there had been a loss of bearing pre-load. The test was stopped at this stage to enable an inspection of the bearings, which showed no problem with the pre-load application. However, as the bearings were cooled to room temperature for the inspection, an unexpected problem was observed. On decreasing the temperature, the reactive torque became extremely high, with the bearings effectively seized.

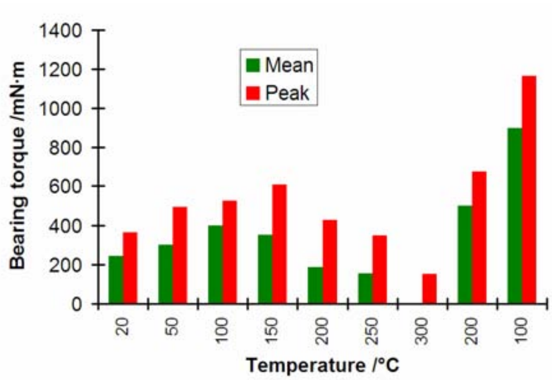


Figure 5 Results of Initial tests of MoS_2 lubricated bearing with PGM-HT cages.

The bearings were inspected, and the cages were seen to have contracted considerably, resulting in contact between the cage and the bearing inner ring. This demonstrates a problem with serious potential consequences – that PGM-HT components can permanently contract after heating.

In order to complete the tests, a temporary solution was devised. A cut was made in the bearing cage, enabling it to bend slightly, so that it was no longer seized around the inner ring. The initial tests were then repeated as shown in Fig. 6.

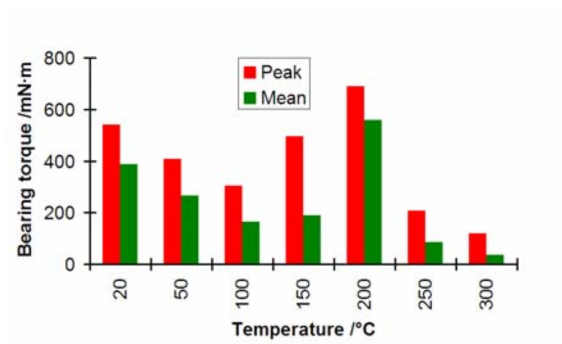


Figure 6 Repeat tests of MoS_2 lubricated bearing with PGM-HT cages with cut - torque measurements at various temperatures.

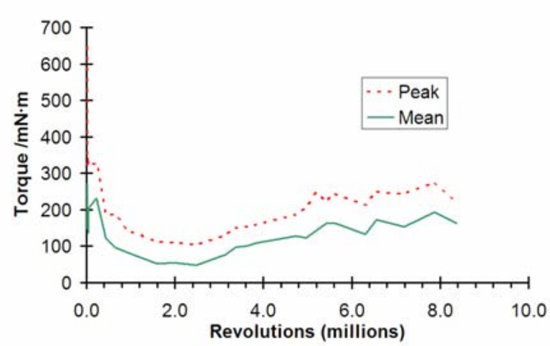


Figure 7 Life test of MoS_2 lubricated bearing with PGM-HT cages with cuts.

The life test of the bearings showed mean torque level in the range 50-200 mNm, and the torque was still low when the test was stopped after 8 million revolutions. These tests therefore suggest that MoS_2 lubrication is better suited to high temperature bearing operation.

3. THERMAL STABILITY OF CAGE MATERIALS

The stability of self lubricating materials was investigated, in order to gain an understanding of the unexpected contraction of PGM-HT cages in the previous tests. Tests were undertaken to quantitatively assess the dimensional stability of PGM-HT. For comparison, another self lubricating polymer material SINTIMID 15M-HT, was also studied.

3.1. Effect of heating

A series of tests was performed to monitor the effect of heating components made from the two materials. Tests were performed using "dummy cages" - rings with basic dimensions identical to actual cages, but without ball pockets. Three sizes of dummy cage were used, with outer diameters in the range 10-100 mm. The components were heated in vacuum (pressure $<10^{-5}$ mbar) to temperatures of up to 250 °C, and their dimensions measured at room temperature before and after heating using a coordinate measuring machine (CMM).

In the first stage of testing, a set of cages made from each material was heated, for 24 hours at each of the following temperatures: 50, 100, 150, 200 and 250 °C, with the dimensions measured after each step.

All the dummy cages were found to contract during heating, as shown in Fig. 8. The magnitude of the contraction appears to be dependent on the treatment temperature, with maximum values of 0.2 % and 1.4 % for SINTIMID 15M-HT and PGM-HT respectively. The proportional change in diameter after heating was found to be consistent for the three cage sizes.

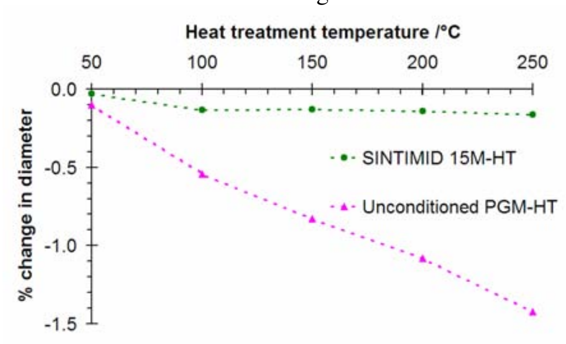


Figure 8 Size variation of PGM-HT and SINTIMID 15M-HT "dummy cages" after heating to a range of temperatures.

The effect of repeated thermal cycling was then investigated by performing measurements on a new set of dummy cages identical to those described previously. The cages were heated to 250 °C for 24 hours at a time, and measured at room temperature after each heating period. These results are shown in Fig. 9.

The magnitude of contraction on the first heating cycle confirmed the result of the previous test (1.5 % for PGM-HT and 0.2 % for SINTIMID 15M-HT). The contraction was much smaller on subsequent thermal cycles., suggesting that it may be possible to thermally pre-condition the raw PGM-HT to obtain a dimensionally stable material.

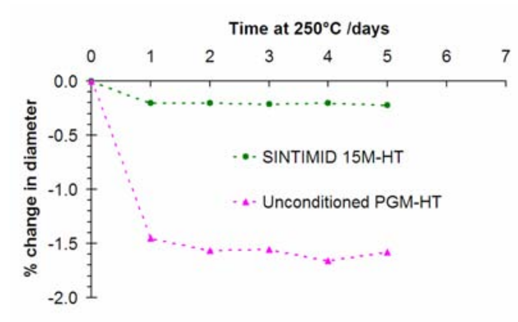


Figure 9 Dimensional change of dummy cages after heating to 250 °C. Cages measured at room temperature after each 24 hour heating period.

3.2. Thermal conditioning of PGM-HT

In the light of the results described above, it was hoped that bearing cages manufactured from a thermally conditioned material would be insusceptible to the thermal shrinkage effect. Tests were then carried out to determined the effectiveness of this approach.

A block of raw PGM-HT material was pre-treated by heating it in vacuum (pressure $< 10^{-3}$ mbar) to a temperature of 240 (+10, -0) °C and maintained at this temperature for 24 hours. The block was then allowed to cool under vacuum. A new set of dummy cages with dimensions identical to those used for the previous tests was manufactured from the pre-conditioned material. These cages were measured before heating and then after heating at 250 °C for 1 day and then a further 6 days. The dimensional change for the pre-conditioned material is compared to the previous results in Fig. 10.

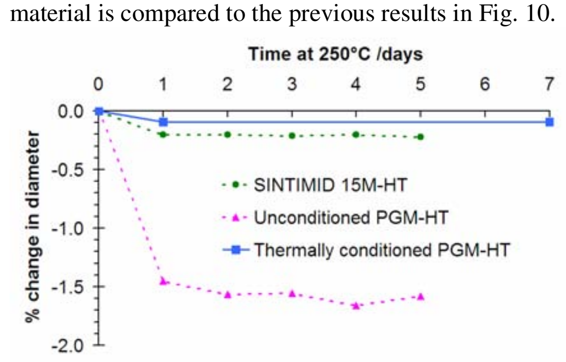


Figure 10 Dimensional change of "dummy cages" after heating to 250 °C.

The results show that the pre-conditioning has indeed been effective in stabilizing the material, with a contraction of 0.1% after 1 day and no further measurable change after 6 further days of heating.

4. ALTERNATIVE CAGE/BALL SEPARATOR DESIGNS

Bearing cages are usually made from self-lubricating materials, the thermal expansivity of which is typically much greater than that of bearing steels, as mentioned in the introduction. This presents a number of problems for the design of cages for bearings to be used at high temperature.

The design of conventional cages must allow for significant changes in the clearances between the bearing components. If the clearances between bearing components is insufficient, cage to land interactions may become significant. Thermal expansion effects can also lead to cage instabilities as bearing cages undergo a transition between inner-race riding to outer-race riding.

It may be possible to avoid these problems by using alternative ball separator designs. Three distinct design concepts were devised:

- a conventional cage made of metal
- hybrid cages with a metal body and self lubricating inserts in the ball pockets
- toroidal ball separators.

A range of ball separators were designed manufactured and tested, and their performance was investigated in high temperature bearing tests.

4.1. Bearing ball separator designs

The simplest of the tested solutions was a one-piece conventional cage. Rather than a self-lubricating material, the cage was made of a titanium alloy, which has a thermal expansivity similar to typical bearing steels. The cage was coated with sputtered MoS_2 to provide some, albeit limited, lubrication similar to self-lubricating cages, and tested with bearings with MoS_2 coated balls and races.

Hybrid cages, a concept pioneered by ESTL, consist of a cage body with expansivity compatible with the races (in this case a Ti alloy as above), but fitted with self-lubricating inserts in the cage pockets to provide a source of lubrication. The inserts were held in place using a ceramic adhesive.

The final concept dispenses with a traditional cage entirely. Instead, toroidal (doughnut shaped) separators are placed around alternate balls. This approach is potentially suitable for high temperature as thermal expansion of the toroids will not significantly affect the clearances since the dimensions of the individual ball separators are small in comparison to the race diameters.

The same bearing type as used in the previous tests (Tab. 3) was used to test a range of configurations, which is summarized in Tab. 4.

Table 4 Summary of bearing configurations for tests of alterative ball separators.

Design type	Material(s)	Lubrication
Full cage	Titanium alloy cage	Sputtered MoS_2 on cage, races and balls
Hybrid cage	Titanium alloy cage body, PGM-HT inserts	Sputtered MoS_2 on races and balls. Transfer from PGM-HT inserts.
Hybrid cage	Titanium alloy cage body, PGM-HT inserts	Transfer from PGM-HT inserts only.
Hybrid cage	Titanium alloy cage body, SINTIMID 15M-HT inserts	Sputtered MoS_2 on races and balls. Transfer from SINTIMID 15M-HT inserts.
Hybrid cage	Titanium alloy cage body, SINTIMID 15M-HT inserts	Transfer from SINTIMID 15M-HT inserts only.
Toroidal separators	PGM-HT separators	Sputtered MoS_2 on races and balls.
Toroidal separators	PTFE separators	Sputtered MoS_2 on races and balls.

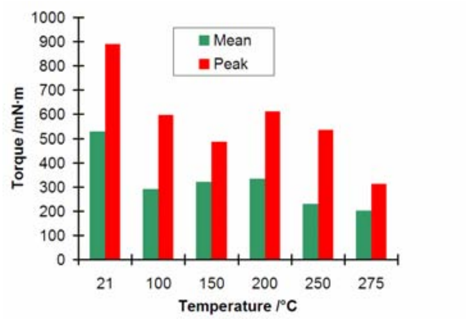
4.2. Test method

Bearing tests were conducted using the test rig as described in Section 2.1. Each bearing was fitted with only 10 balls rather than 11 as in the previous tests. The pre-load was set to 90 N in all cases, and measured from a load-displacement curve before and after testing.

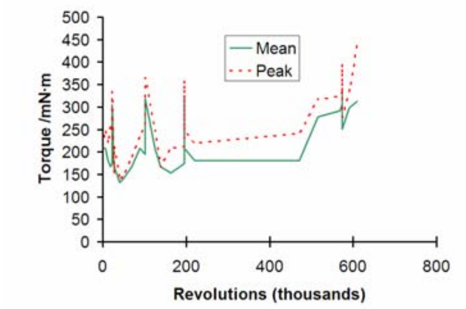
As with the tests of conventional cages, the tests consisted of two parts: an evaluation of the change in bearing torque with temperature (up to 275 °C) and a life test. The life test was performed at a rotation speed of 200 rpm and continued until 500,000 revolutions were completed or to the point of bearing failure. The bearings were characterized by measuring the torque during low speed direction reversals at periodic intervals. The torque was also logged continuously throughout the tests to record any change in behaviour.

4.3. Test results - full cage design

The test of the full titanium cage (Fig. 11) showed a gradual decrease in mean torque on increasing temperature, with the torque remaining at around 150-300 mN·m until the life test was stopped after 600 thousand revolutions.



(a) Initial torque variation with temperature

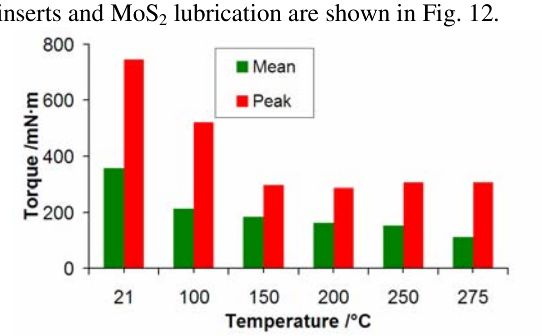


(b) Life test at 200 RPM

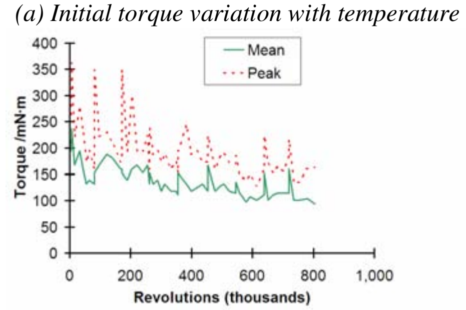
Figure 11 Results from test of full titanium cage.

4.4. Test results - Hybrid cage design

The results for hybrid cages with SINTIMID 15M-HT inserts and MoS_2 lubrication are shown in Fig. 12.



(a) Initial torque variation with temperature



(b) Life test at 200 RPM

Figure 12 Results from test of hybrid cage with SINTIMID 15M-HT inserts, with MoS_2 coating on balls and races.

The mean torque decreased steadily with increasing temperature, and remained at around 100-200 mN·m until the test was stopped after 800,000 revolutions.

The tests of the same type of cage without MoS_2 lubrication showed slightly higher mean torque, in the range 200-600 mN·m, as shown in Fig. 13. The torques peaks were significantly higher.

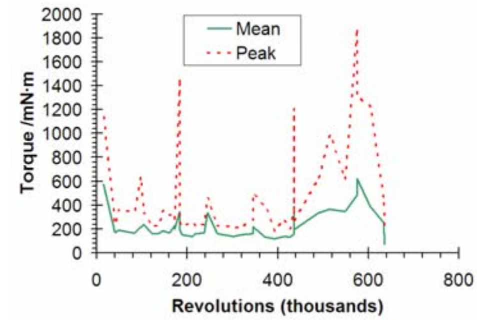
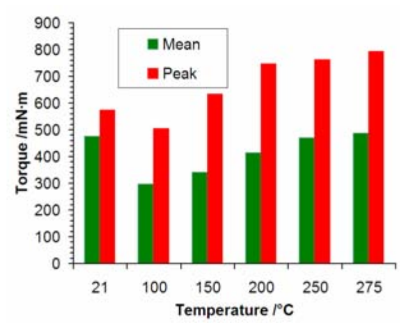
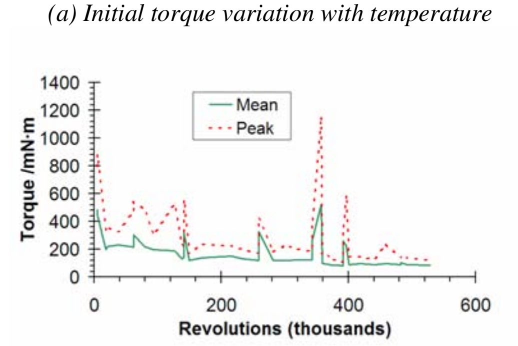


Figure 13 Results from life test of hybrid cage with SINTIMID 15M-HT inserts, without lubricant coating on balls and races.

The test of hybrid cages with PGM-HT pocket inserts and MoS_2 lubrication are shown in Fig. 14.



(a) Initial torque variation with temperature



(b) Life test at 200 RPM

Figure 14 Results from test of hybrid cage with PGM-HT inserts, with MoS_2 coating on balls and races.

The mean torque was initially high (~500 mN·m), but decreased as the test progressed as MoS_2 was transferred form the cages to the balls. The test of PGM-

HT inserts without additional MoS_2 lubrication (Fig. 15) showed similar behaviour, with a longer run-in period.

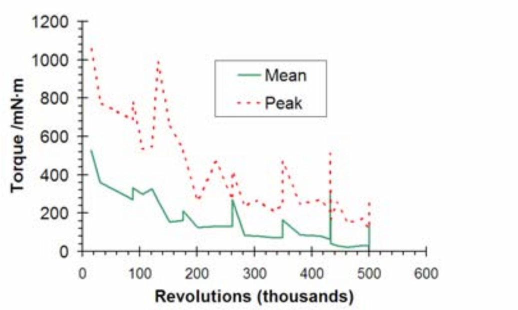
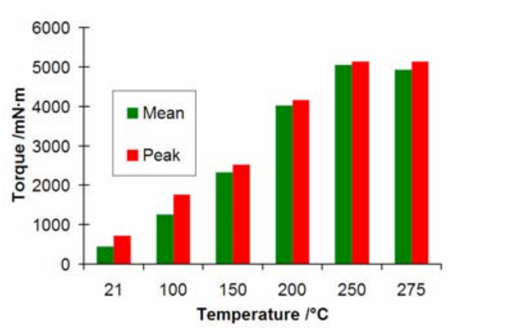


Figure 15 Results from life test of hybrid cage with PGM-HT inserts, without lubricant coating on balls and races.

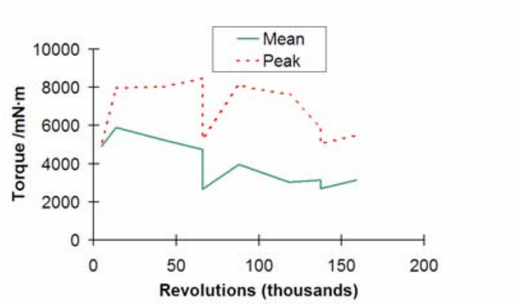
After the tests of hybrid cages, the inserts were found to have become loose, although still in place. Although this does not seem to have adversely affected their performance, a more effective adhesive should be identified before we can recommend this approach for high temperature operations.

4.5. Test results - Toroids

The PGM-HT toroidal ball separators showed relatively high torque, increasing to 5000 mN·m (Fig. 16).



(a) Initial torque variation with temperature

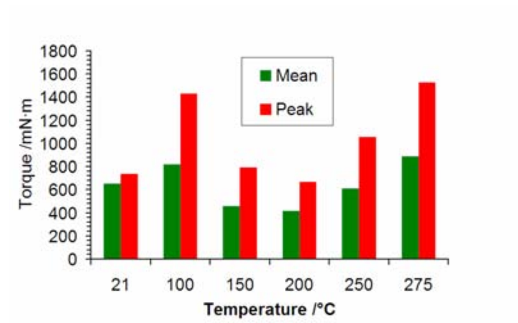


(b) Life test at 200 RPM

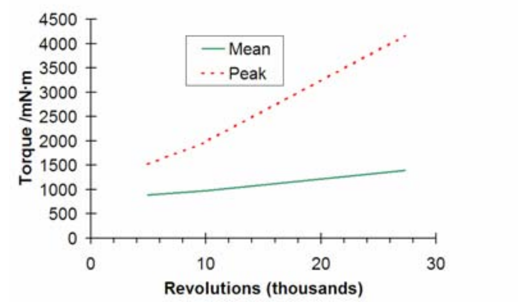
Figure 16 Results from test of PGM-HT toroids, with MoS_2 coating on balls and races.

The torque decreased slightly during the life test, but remained much higher than any of the other tested solutions and the test was aborted after 160,000 revolutions.

The PTFE toroids showed initially lower torque than the PGM-HT toroids (Fig. 17).



(a) Initial torque variation with temperature



(b) Life test at 200 RPM

Figure 17 Results from test of PTFE toroids, with MoS_2 coating on balls and races.

However, a dramatic failure occurred after only 27,000 revolutions. An examination of the bearings showed that the toroids had actually melted. A possible explanation for this failure is that the toroids, although operating below the melting point of PTFE, deformed slightly during high temperature operation, which resulted in increased friction. The heating caused by the friction could then have further exacerbated the problem, leading to a catastrophic and sudden failure.

5. CONCLUSIONS

Bearing tests have been performed which indicated that the combination of MoS_2 and PGM-HT cages is more suitable for high temperature operation than lead lubrication with leaded bronze cages. The torque was lower and the life time longer in the case of MoS_2 lubrication.

However, the bearing tests also revealed an unexpected problem with the commonly used self-lubricating material PGM-HT - that it can permanently contract after heating. This effect was subsequently investigated by a quantitative study of the dimensional stability of PGM-HT.

PGM-HT was shown to contract by up to 1.5 % after heating to 250 °C. SINTIMID 15M-HT, an alternative self lubricating material, was also found to undergo a slight shrinkage after heating, although the magnitude of the effect was much smaller.

PGM-HT is already in use in a wide variety of applications throughout the space industry, and knowledge of this problem could have important consequences. Whilst the physical origin of the shrinkage is not yet fully understood, our tests have shown that the material may be stabilized by thermal pre-treatment. Further studies into the properties of thermally pre-conditioned PGM-HT are ongoing.

A variety of alterative ball separators for high temperature applications were designed, manufactured and tested, with the aim of avoiding problems due to thermal expansion.

The full metal cages performed well, with relatively low torque levels. However, in this design, the cage lubrication effect is limited. The hybrid cages offer an improvement in torque and lifetime, and the tests have confirmed that the design philosophy is sound. Some further work is required to optimize the design and determine a more reliable adhesive.

The toroidal ball separators did not prove successful in these tests, with extremely high torque for the PGM-HT toroids and a total failure for the PTFE toroids. The toroids appear to be sensitive to misalignment, and further work may allow the design to be optimized.

In conclusion, our test programs have identified appropriate lubricant and bearing cage solutions for operating temperatures of up to 275 °C.

ACKNOWLEDGMENTS

The work described was performed under contract for the European Space Agency. JPM of Mississippi supplied the dummy PGM-HT cages for the thermal stability tests.