RECENT OBSERVATIONS ON THE PERFORMANCE OF HYBRID CERAMIC TRIBO-CONTACTS

M. Buttery [(1)], M. Cropper [(1)], B. Wardzinski [(1)], S. Lewis [(1)], S. McLaren [(2)], J. Kreuser [(3)],

[(1)] ESTL, ESR Technology (a Hyder Consulting Group company), 202 Cavendish Place, Birchwood Park, WA3 6WU, UK, Email: michael.buttery@esrtechnology.com
[(2)] SURREY SATELLITE TECHNOLOGY LTD., Tycho House, 20 Stephenson Road, Surrey Research Park, Guildford, GU2 7YE, Email: s.mclaren@sstl.co.uk
[(3)] CEROBEAR GmbH, Kaiserstrasse 100, 52134 Herzogenrath, Germany, Email: johannes.kreuser@cerobear.de

ABSTRACT

Hybrid ceramic ball bearings offer great promise in space applications but have not been rapidly adopted by industry perhaps partly due to the relatively low amount of published data on specific in-vacuum performance. Such bearings, having, typically, silicon nitride balls and 440C or high nitrogen steel (e.g. X30) raceways offer the potential for long life and low torque noise due a combination of chemical inertness, high hardness and the extremely smooth surfaces produced in ceramic balls. Though initial benefits were foreseen for high speed applications, the potential for reduced adhesive forces and wear in conditions of marginal lubrication, and for improvements in lubricant lifetime in long life applications limited by oil tribo-degradation render hybrid ceramic bearings more generally attractive.

This paper draws together a number of experimental studies carried out at Pin-on-Disc (POD), Spiral Orbit Tribometer (SOT) and bearing-level recently at ESTL.

1. BACKGROUND

Hybrid ceramic bearings are ball bearings comprising steel races and ceramic balls. Commercially available hybrid bearings have races which are made from either 440C stainless steel or high-nitrogen steels (such as X30 and X40). Conventionally the balls are made from silicon nitride (Si_3N_4). Zirconia (ZrO_2) balls are also available but are less well established than Si_3N_4 balls.

It is claimed that the use of ceramic (silicon nitride) balls in place of steel balls can significantly improve bearing performance. As ceramic balls are 60% lighter than steel balls (Tab. 1), and as their surface finish is superior to that of steel balls, they exhibit vibration levels which are appreciably lower than conventional (steel rings/steel balls) ball bearings. In this respect they would appear particularly attractive for high-speed applications.

There is also interest in their use in lower-speed space applications. This interest arises principally from the belief that adhesion between ceramics and steels is weak such that the likelihood of cold welding is reduced. In turn this minimises adhesive wear. This makes hybrid bearings attractive for situations where lubricant starvation might occur (allowing 'emergency' running) or in applications where no lubricant debris can be tolerated.

Additionally, hybrid bearings comprising ceramic rolling elements and Cronidur X30 steel races are capable of operation at elevated temperature (up to ~400ºC) as both ball and race materials have high hot-hardness. This material combination also offers greater corrosion resistance than conventional all-steel bearings. This is beneficial as corrosion products are abrasive and when released as debris will cause bearing damage. Furthermore, the presence of corrosion may inhibit the adhesion of solid lubricant coatings.

Table 1. Material properties of ceramics in comparison to 52100 steel

Properties	Silicon nitride	Zirconia	52100 steel
Density	3.2g/cm^3	6.1g/cm^3	7.8g/cm^3
Coeff. heat expansion	2.8 x 10^{-6}K	9.6 x 10^{-6}K	11.9 x 10^{-6}K
Thermal conductivity	30W/m.K	2W/m.K	47W/m.K
Elasticity modulus	320GPa	200GPa	200GPa
Poisson ratio	0.27	0.30	0.30

1.1. Activities

Testing activities described within this paper can be separated into four complementary phases, and shall be described separately below.

- Phase one – Unlubricated material characterisation
- Phase two – Spiral orbit tribometer testing
- Phase three – Starved regime bearing tests
- Phase four – Fully lubricated bearing tests

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2. PHASE ONE – UNLUBRICATED MATERIAL CHARACTERISATION

2.1. Phase one test plan

This initial phase of testing comprises of a series of pin-on-disc tribometer tests on unlubricated material pairings.

Table 2. Material combinations for phase one

Test ID	Pin	Disc
1.1	440C	440C
1.2	52100	52100
1.3	Cronidur X30	Cronidur X30
1.4	Si_3N_4	Si_3N_4
1.5	Si_3N_4	440C
1.6	Si_3N_4	Cronidur X30

Tests were performed at room temperature, high vacuum (<10^{-6} mbar), $0.01 ms^{-1}$, over a 50m sliding distance, 750 MPa peak contact stress. Three tests were performed of each combination.

2.2. Phase one test apparatus

The pin-on-disc tribometer is shown below, and consists of a pin mounted on a balanced arm, and loaded against the disc by a deadweight. The disc is rotated by a motor positioned outside the vacuum chamber. The frictional force is measured via the deflection of the arm, and recorded using a PC-based data acquisition system. Calibration was checked using a pulley system to apply known loads to the tribometer arm.

Figure 1. Vacuum pin-on-disc tribometer

All pins and discs were manufactured to $R_a \leq 0.05 \mu m$.

2.3. Phase one results

In all instances the friction coefficient behaviours of these unlubricated contacts were high, with significant noise and friction fluctuations during the 50m sliding distances. The data can be summarised according to Tab. 3.

Table 3. Friction coefficient values for unlubricated material pairings

Test ID	Pin	Disc	Friction coefficient		
			Start-up	Mean	Peak
1.1	440C	440C	0.11	0.46	0.83
1.2	52100	52100	0.23	1.02	1.51
1.3	Cronidur X30	Cronidur X30	0.24	0.91	1.20
1.4	Si_3N_4	Si_3N_4	0.47	0.56	0.73
1.5	Si_3N_4	440C	0.13	0.70	0.84
1.6	Si_3N_4	Cronidur X30	0.19	0.50	0.75

Although from these observations it can perhaps be argued that hybrid ceramic (i.e. ceramic on steel) contacts give lower mean and peak friction values than traditional steel-on-steel, the friction itself is still restrictively high. These results demonstrate the need for lubrication for hybrid ceramic contacts.

3. PHASE TWO – SPIRAL ORBIT TRIBOMETER TESTING

3.1. Phase two test plan

A series of SOT tests were performed, of both Si_3N_4 and ZrO_2, rolling on both 440C steel and Cronidur X30. A range of popular space lubricants were employed.

Table 4. Test conditions matrix for phase two

Test ID	Ball material	Plate material	Lubricant
2.1	Si_3N_4	440C	None
2.2	ZrO_2	440C	None
2.3	Si_3N_4	440C	Fomblin Z25
2.4	ZrO_2	440C	Fomblin Z25
2.5	Si_3N_4	440C	Nye 2001a
2.6	ZrO_2	440C	Nye 2001a
2.7	Si_3N_4	440C	Sputtered MoS_2
2.8	ZrO_2	440C	Sputtered MoS_2
2.9	Si_3N_4	Cronidur X30	None
2.10	ZrO_2	Cronidur X30	None
2.11	Si_3N_4	Cronidur X30	Fomblin Z25
2.12	ZrO_2	Cronidur X30	Fomblin Z25
2.13	Si_3N_4	Cronidur X30	Nye 2001a
2.14	ZrO_2	Cronidur X30	Nye 2001a
2.15	Si_3N_4	Cronidur X30	Sputtered MoS_2
2.16	ZrO_2	Cronidur X30	Sputtered MoS_2

Tests were performed at room temperature, high vacuum (<1.3 x 10^{-6} mbar), 100RPM, 2.25GPa peak contact stress. Lubricated tests were run until the friction coefficient was measured to be above $\mu \geq 0.3$, with unlubricated tests running for 1000 ball orbits.

3.2. Phase two test apparatus

The Spiral Orbit Tribometer (SOT) is essentially a thrust bearing, with an individual ball held between two interchangeable flat plates, located within a vacuum chamber. A load is applied to the top plate via a spring-loaded linear translator. The lower plate rotates via a motor located outside the chamber, causing the ball to move in a spiral path with a radius ~21mm.

This configuration causes the ball to spiral outwards, and a fixed guide plate is positioned to keep the ball within the flat plates and to produce a repeatable orbit. A force transducer behind the guide plate measures the force exerted by the ball onto the guide plate. From this a friction coefficient value is found, once per orbit. The SOT is controlled using a LabVIEW-based data acquisition program.

The arrangement of the SOT allows the ball to experience rolling, sliding and pivoting – all motions experienced by a ball in an angular contact bearing. This allows for a more representative testing of a lubricant than conventional pin-on-disc testing, which only recreates sliding motion.

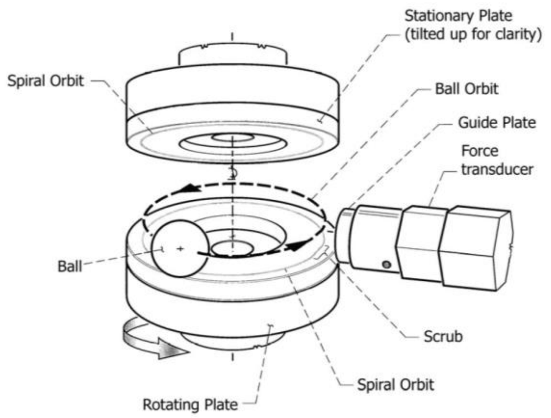


Figure 2. Internal arrangement of SOT

Lifetimes are given in units of orbits/micrograms, allowing for normalization of results should varying lubricant amounts be used.

SOT flat samples were manufactured from non-passivated 440C steel and Cronidur X30, polished to a roughness of R_a<0.05 micron. Balls used for tests were either 1/2” (12.7mm) or 3/8” (9.525mm) diameter, manufactured from Si_3N_4 and ZrO_2 respectively, supplied by Cerobear.

Solid lubrication (MoS_2) was provided using ESTL’s sputtered coating rig. Coatings were applied to the balls only with a target thickness 0.5 micron for balls, this being the typical thickness of MoS_2 in an application.

SOT fluid lubrication was achieved through the preparation of a solution of lubricant diluted in an appropriate solvent to give a known concentration. This solution was applied directly to a rotating ball. The solvent was allowed to evaporate from the ball’s surface, leaving the desired lubricant amount.

This method of lubrication allows for the application of very small lubricant amounts, typically 50µg. This minuscule amount of oil allows for reduced test times, and ensures all tests take place under boundary conditions.

3.3. Phase two results

All unlubricated tests gave high friction and high frictional noise, with µ > 0.4 achieved within 100-200 ball orbits and maintained thereafter. Evidence of wear of the steel plates was also observed, perhaps a surprising observation given the low rolling duration of the unlubricated tests (no steel wear of the SOT plates is observed during typically lubricated operation). This again reinforces the above statement that lubrication is necessary for hybrid ceramic material combinations.

Tests on Z25 oil displayed extended periods of low friction in comparison to the unlubricated tests, demonstrating that hybrid ceramic contacts such as these can be successfully lubricated with PFPE oils. However all lubricant lifetimes were shorter for the hybrid contacts than for steel-on-steel contacts (Fig. 3).

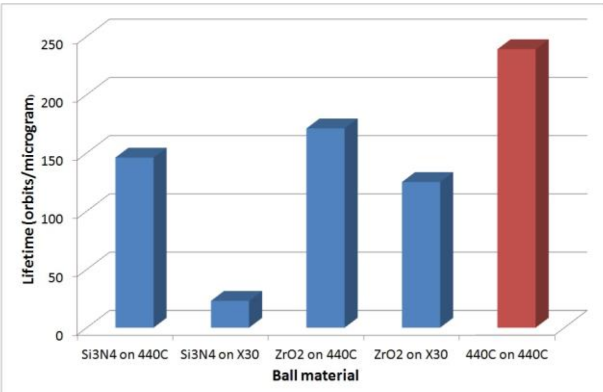


Figure 3. Normalised lifetimes of Z25 lubricated ceramic balls, in comparison to steel-on-steel [1]

In addition, on multiple tests under the same conditions the repeatability of Z25 lubricated Si_3N_4 was measured to be ~3x poorer than for steel-on-steel contacts. The cause of this is not clear.

Post-test inspections show evidence of ‘brown sugar’, a product of PFPE degradation, on both the balls and the flat plates, similar in appearance to that previously observed for steel-on-steel contacts [1]. This suggests that the degradation of the Z25 is occurring via a similar process.

In all instances when testing Nye 2001a lubricated hybrid contacts the tests were stopped prior to failure, while still giving low friction of $\mu < 0.1$, and having displayed normalized lifetimes some 10x greater than comparative steel-on-steel contacts (Fig. 4). In one case (Test ID 2.5) the test was allowed to run until a 20x lifetime had been achieved, still with no increase in friction over this period (6-million ball orbits).

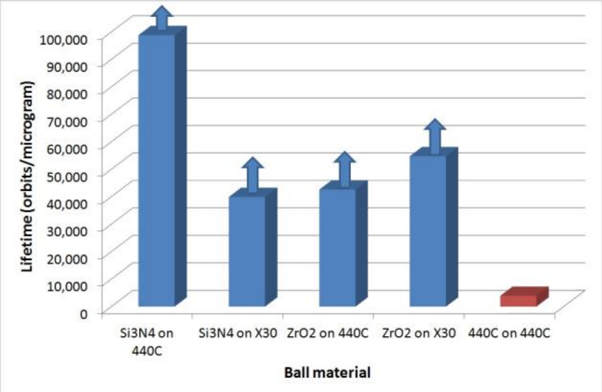


Figure 4. Normalised lifetimes of 2001a lubricated ceramic balls, in comparison to steel-on-steel [1]

Inspection of the samples post-test showed small amounts of dark material pushed aside from the ball track on the flat plates. In addition, a build-up of friction polymer was found on the guide plate, of a similar appearance to that seen with the steel-on-steel contacts [1]. This suggests that the 2001a oil is degrading and, despite running with low friction for 6-million orbits, the oil would not have lubricated indefinitely. However the true lifetime of the lubricant cannot be inferred from this information, especially given that virgin oil was also found on the flat plates.

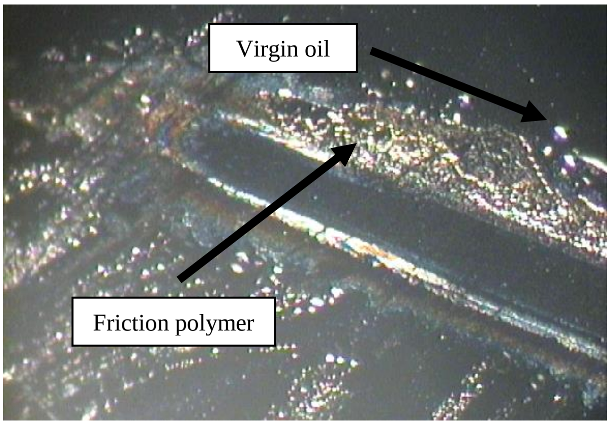


Figure 5. Guide plate from Test ID 2.5, showing polymer and virgin oil

Lifetimes of MoS_2 coated ceramic balls were found to be fairly comparable with MoS_2 coated steel balls, demonstrating that such ceramic materials can be successfully lubricated with sputtered MoS_2.

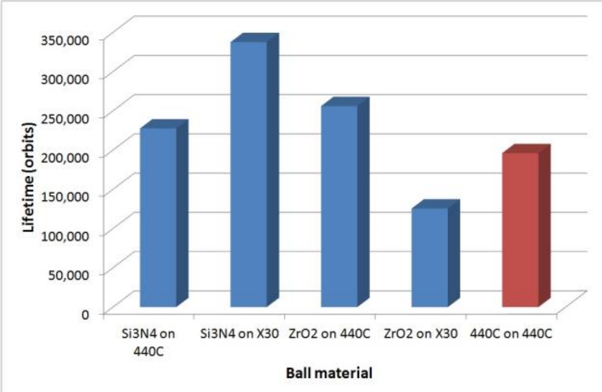


Figure 6. Normalised lifetimes of MoS_2 lubricated ceramic balls, in comparison to steel-on-steel [1]

Inspecting the samples post-test finds the vast majority of the MoS_2 removed from the surface of the balls and loose, friable, debris thrown away from the ball track on the plates. Observations of this sort are very common amongst MoS_2 tests, and indicate that the lubricant has failed in a very similar way to previous tests.

4. PHASE THREE – STARVED REGIME

4.1. Phase three test plan

As evidenced by the above results, the lifetime of Nye 2001a under boundary conditions is significantly extended on ceramic materials. This suggests the potential for hybrid ceramic bearings to be employed in conditions of poor lubrication, or starved conditions.

To investigate, bearing pairs were run at ESTL with lubrication provided by an oil-impregnated cage only (no additional lubricant on the raceway or the balls). This can be considered a simulation of the 'end of life' running of a bearing, in which the oil that would normally be present has been tribologically consumed.

Hybrid ceramic bearings (Si_3N_4 balls, 440C steel raceways) were provided by SSTL. The details of these bearings are proprietary to SSTL. Cotton phenolic cages were impregnated with Nye 2001a by SSTL prior to assembly.

Test ID	Lubricant	Preload	Duration
3.1	2001a cage impregnated only	1650 MPa	7.5 x 10^6 revs
3.2	2001a cage impregnated only	825 MPa	5 x 10^6 revs

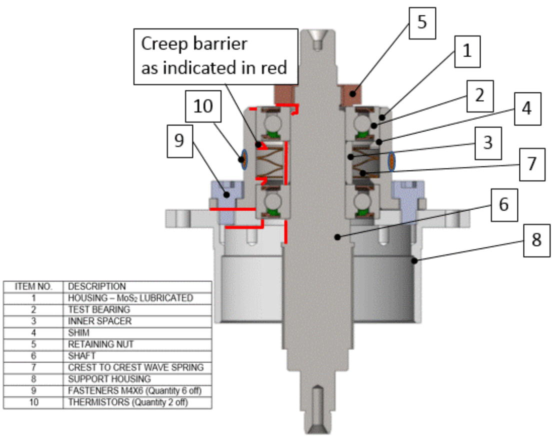
Bearings were rotated at 1250RPM under vacuum, at room temperature following a 4,000 revolution running-in period performed under vacuum. Periodic torque measurements were made via reversals performed at

2RPM & 1250RPM.

4.2. Phase three test apparatus

The test facility used for this program was a vacuum torque and temperature measurement facility.

The bearings were assembled into the test housing, mounted onto a piezoelectric torque transducer (Kistler). Thermistors were mounted on the side of the test housing to monitor frictional heating during testing. A servo motor and controller was used to rotate the bearings both CW and CCW at speeds between 2rpm and 1250rpm and the Kistler transducer was used to measure the bearing torque. The output voltage from the transducer was calibrated, filtered and output to a data processing system (LabVIEW). The test rig was mounted in a vacuum chamber and evacuated via a turbo-molecular pump. The vacuum pressure was monitored using a cold cathode vacuum gauge.



ITEM NO.	DESCRIPTION
1	HOUSING – MoS_2 LUBRICATED
2	TEST BEARING
3	INNER SPACER
4	SHIM
5	RETAINING NUT
6	SHAFT
7	CREST TO CREST WAVE SPRING
8	SUPPORT HOUSING
9	FASTENERS M4X6 (Quantity 6 off)
10	THERMISTORS (Quantity 2 off)

Figure 7. Schematic of test housing, showing location of creep barrier

4.3. Phase three results

Life-tests of both bearings performed well, with mean torque values of 1.5 and 0.3 mNm respectively, and no evidence of failure during the full duration. Cage hang-up (a form of cage instability) was observed, but not to a level of significant concern, and did not lead to a degradation of the performance of the bearings.

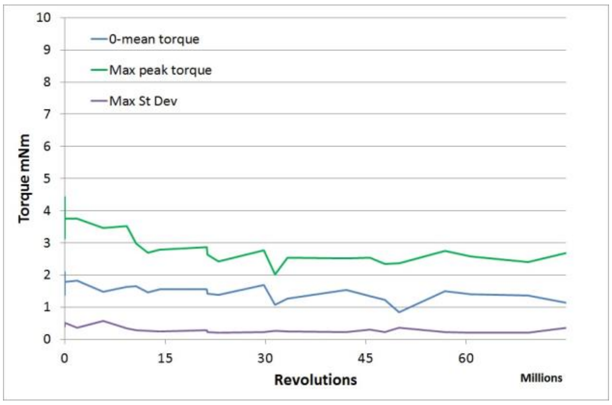


Figure 8. Test ID 3.1 torque progression (based on 2RPM reversals)

To predict the expected torque values for these life-tests the bearing analysis software CABARET was employed. Based on these predictions we find that the above running torques equate to friction coefficient values of ~0.1. Clearly this value is much lower than the unlubricated friction value for Si_3N_4 on 440C (Tab. 3), and close to the reverse calculated friction coefficient from normally lubricated bearings [2], suggesting that the bearings are being sufficiently lubricated by oil transfer from the cage. Running under these 'starved' conditions is therefore analogous to the SOT testing of phase two, which also displayed extended lifetimes of minimal amounts of Nye 2001a oil on ceramic balls.

It appears that hybrid ceramic bearings can provide longer end-of-life running than conventional stainless-steel bearings, but perhaps not for the previously perceived reason (see Section 1).

Both bearing pairs were exposed to a variable speed test both before and on completion of the lifetime. These results showed a relationship between rotation speed and torque. No significant difference was observed between the pre and post-test measurements, again contributing to the theory that the oil had not significantly degraded during the life-tests.

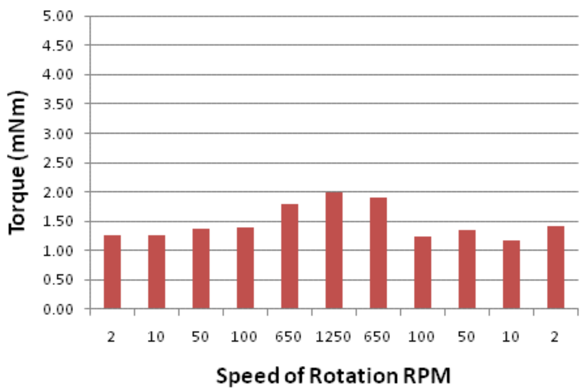


Figure 9. Pre-test variable speed testing for Test ID 3.1 bearing pair

Given the minimal amount of oil present it is surprising that the torque increases with increasing speed as such behaviour is normally attributed to increasing viscous losses. In fact the torque-speed behaviour is very much in line with that of ball bearings lubricated with conventional quantities of oil. However, as this behaviour is not expected to be related to the hybrid ceramic materials (as opposed to traditional steel-on-steel), a comparison and full explanation is beyond the scope of this paper, but has been discussed elsewhere [3].

Test 3.2 only was inspected at ESTL with aid from SSTL. Inspection revealed no evidence of debris, with both bearings in good condition. Preload was checked and found to be still present and within 10% of the pre-test value. There was no visible discolouration of the oil and the races, balls and cages were all in good condition. A running track could be seen on each of the bearing rings, lubricated by a thin layer of oil transferred from the cage via the balls (Fig. 10). There was no evidence of egress of oil from the bearings.

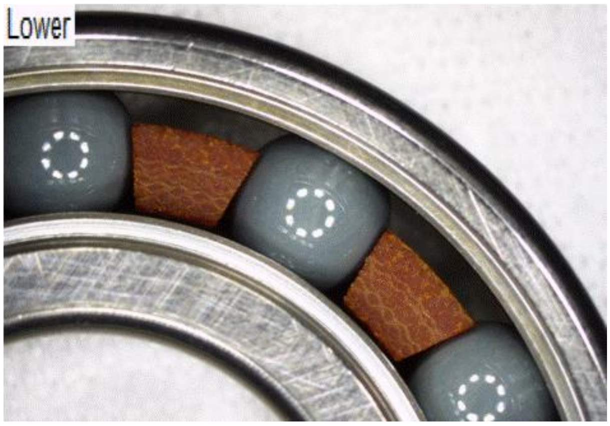


Figure 10. Test ID 3.2 lower bearing. Good condition, little sign of wear, oil transferred from cage to balls and races

5. PHASE FOUR – BEARING LEVEL

5.1. Phase four test plan

The final phase of testing comprises of a number of angular contact bearing pairs, designation B7004, Si_3N_4 balls with Cronidur X30 raceways, lubricated according to standard procedure. Details are shown below.

Test ID	Lubricant	Cage	Duration
4.1	None	PEEK	10^6 revs
4.2	None	PGM-HT	10^6 revs
4.3	None	Tecasint 1391	10^6 revs
4.4	2001a	Cotton phenolic	Failure
4.5	Z25	Cotton phenolic	Failure
4.6	MoS_2	PGM-HT	Failure

For Tests 4.4 & 4.5 cotton phenolic cages were impregnated by ESTL in accordance with standard procedure to prevent removal of the free oil in the bearings. For Test ID 4.6 the balls and races were coated with sputtered MoS_2 by ESTL.

Test bearings were provided by Cerobear. In addition, a ‘control’ test under identical conditions to Test ID 4.5 was run, with conventional steel-on-steel contacts.

Preload was applied to bearing in back-to-back pairs via a spring system, loaded to 65N (1.28 GPa peak stress on the inner raceway). Bearing were rotated at 200RPM under vacuum, at room temperature, with no in-air running-in period. Periodic torque measurements were made via reversals performed at 2RPM.

5.2. Phase four test apparatus

Phase four was performed using ESTL’s three turret rig, allowing for multiple bearing pairs to be tested in parallel, ensuring that all conditions were identical between tests.

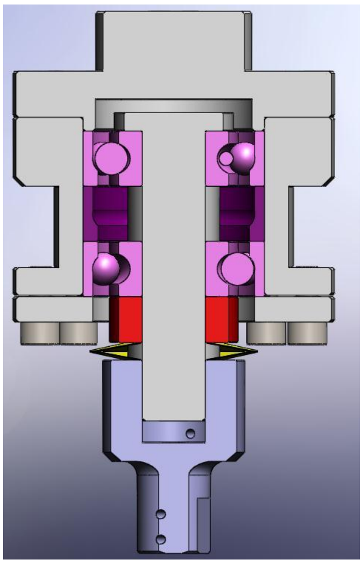


Figure 11. Bearing housing for B7004 bearing pairs, used during phase four

Each bearing pair is mounted on a shaft and installed in a housing, both of which are manufactured from stainless steel. The housing is fixed to a Teldix DG1.3 torque measuring system. Rotation is accomplished by means of a pair of motor gearboxes located externally to the vacuum chamber, controlled by a single control unit. A ferro-fluidic feed-through connects each bearing drive shaft to the motor gearbox. Torsionally stiff couplings are used to ensure that backlash and stick-slip are eliminated from the drive system.

5.3. Phase four results

Considering the unlubricated bearing tests, all materials displayed high torque and torque noise during the 10^6 revolutions, with the PGM-HT performing significantly better than the alternative materials, though the Tecasint material did appear to be showing recovery in the latter stages of running. In addition, both the PEEK and the Tecasint 1391-caged bearings showed evidence of cage hang-up, whilst the PGM-HT did not.

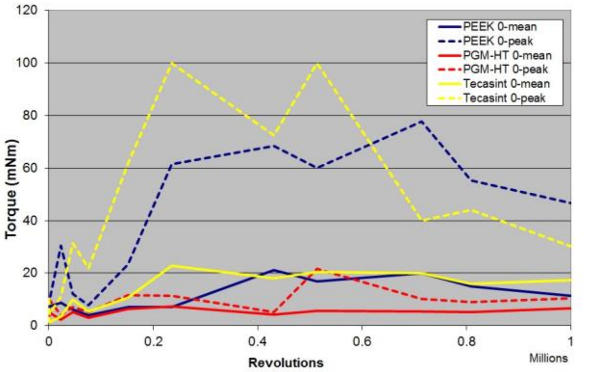


Figure 12. Torque progression of unlubricated ceramic bearings. Extremely high torques for PEEK and Tecasint 1391 were observed

Immediately upon opening the chamber it was noticed that a large amount of loose black debris had been deposited below the bearing housings for both the PEEK and Tecasint bearing pairs (Fig. 13). Analysis showed these particles to be 0.1 – 0.01mm diameter, and to contain both worn cage material and steel wear from the bearing raceways.

Figure 13. PEEK (centre) and Tecasint 1391 (left) bearing housings, displaying debris within test chamber

Bearing pairs were then disassembled and inspected in detail. This proved rather difficult for the PEEK lubricated pair, as the volume of wear debris was such that the bearings could not be separated without considerable force.

For the PEEK and Tecasint 1391 bearings considerable wear of the cages and raceways was observed. All surfaces showed a dusting of debris, believed to be acting as a brake within the bearing, and resulting in the high torques observed. For the Tecasint material in particular, it is known that polyimides can display high initial wear and friction when operating under vacuum due to adsorbed moisture [4]. It is suggested that, in the absence of an additional source of lubrication, this high friction/wear produced the large volumes of debris. The apparent partial recovery of the Tecasint material is likely to be a result of the subsequent lower friction/wear of this material with further sliding. In contrast, the PGM-HT lubricated bearings looked good, with clear evidence of double-transfer of lubricating material from the cage, through the balls, to the raceways.

These results again demonstrate that lubrication of the balls/races must be employed in hybrid ceramic bearings to avoid high torque and wear.

At the time of writing, Test IDs 4.4 & 4.5 are still running, showing no sign of failure at 60-million revolutions. 0-mean torque values are ~1.25mNm, in line with torque predictions. Full analysis and disassembly shall be performed upon completion of this life-test.

Test ID 4.6 has been completed after performing 35-million revolutions under vacuum. Torque values were initially high, before rapidly reducing to a 0-mean of ~0.23mNm, in line with predictions for MoS_2 lubricated bearings, and expected in comparison to the fluid lubricated tests.

Post-test inspection revealed a small amount of loose MoS_2 debris distributed away from the raceway (Fig. 14). Balls appeared shiny, with no obvious signs of MoS_2 remaining. No wear of the raceways was seen. A small amount of cage wear was seen within the ball pockets, indicative of material transfer from the PGM-HT cage as intentioned.

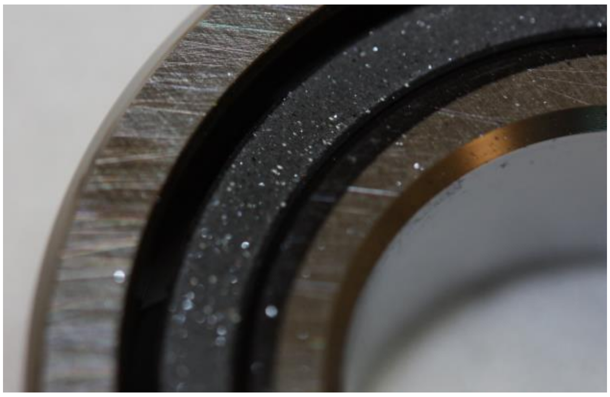


Figure 14. Dusting of MoS_2 debris visible on bearing lands and cage following 35-million revolution life-test

6. CONCLUSIONS

This paper has provided a fairly brief overview of recent testing at ESTL on hybrid ceramic material combinations and bearings. Whilst not intended as a comprehensive assessment, the main conclusions of the work presented here are:

- Fully unlubricated hybrid ceramic combinations produce restrictively high friction, and require lubrication

- SOT results suggest lubricant lifetimes of Z25 are reduced, and displayed poorer repeatability, for hybrid ceramic contacts in comparison with steel-on-steel, though failure appears to be occurring via the same process

- Lifetimes of Nye 2001a are extended by over an order of magnitude in comparison to steel-on-steel on the SOT. At bearing level, 'starved' hybrid bearings performed well for extended periods with this lubricant.

- SOT tests on MoS_2 lubricated ceramic balls gave similar lifetimes to MoS_2 lubricated steel balls. Bearing level tests were tentatively optimistic, suggesting that MoS_2 lubrication of hybrid ceramic bearings is a viable option.

6.1. Further Work

Angular contact bearing tests on fluid lubricated hybrid ceramic bearings (Test IDs 4.4 & 4.5) are continuing. It is anticipated that a lifetime comparison of this data, against existing stainless steel bearings, will provide validation of the observations provided above for hybrid ceramic bearings.

7. REFERENCES

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