THE TRIBOLOGICAL BEHAVIOURS OF NEW AND EXISTING SELF-LUBRICATING MATERIALS FOR SPACE

M. Buttery, A. Wade, A. Kent, A. Vortselas & A. Soutar

ESTL, ESR Technology, 202 Cavendish Place, Birchwood Park, WA3 6WU, (UK)
Email: michael.buttery@esrtechnology.com

ABSTRACT

Self-Lubricating Materials (SLMs) are a highly attractive and cost effective tribological solution for some medium-to-low precision applications in spacecraft mechanisms. Given the range of potential materials available to the mechanism engineer, and the dependence of their tribological properties on their operating conditions, accurate and representative characterisation of SLMs is incredibly important. However existing tribological characterisation methodologies (based upon traditional Pin-on-Disc wear testing) are flawed when considering materials for use in angular contact bearing cages, due to fundamental differences in the contact kinematics.

We present a new methodology for the characterisation of SLM tribological behaviour, utilising the Spiral Orbit Tribometer in a novel arrangement to simulate the double-transfer mechanisms of SLMs within angular contact bearings. The methodology has been used to compare the performance of several SLMs, highlighting the new material TSE8591 as a highly encouraging material.

Verification of the favourable performance of this material (in comparison to the popular PGM-HT material) has been achieved using the Advanced Bearing Test Rig, where results showed evidence of the formation of a low-torque noise transfer film during extended operation under vacuum.

AN INTRODUCTION TO SLMs

Self-Lubricating Materials (SLMs) are commonly employed in a range of spacecraft mechanism applications. Such materials include filled and unfilled polymers (thermoset and thermoplastic), metallic composites with non-alloyed free pockets of lubricant, and composites.

These materials lubricate via sacrificial wear and formation of a transfer film onto a hard counterface (Figure 1). This transfer film is generally considered to be “inferior” to those deposited by more direct means (for example through physical vapour deposition), and are typically weakly adhered, discontinuous, non-uniform, and display higher frictional noise. The tribological performance of these materials can be highly dependent upon their operating conditions (including load, sliding speed, and environmental moisture content), as well as the topography of the counterface. Selection and characterisation of an appropriate material for a given application is therefore of significant importance, and one must take great care if assumptions are to be drawn from dis-similar applications.

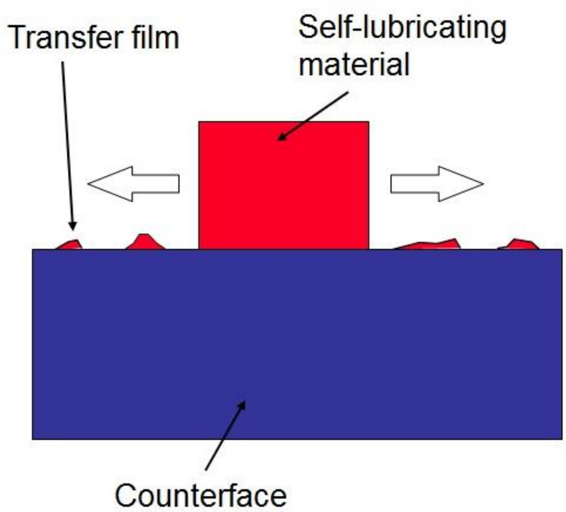

Figure 1. Sacrificial wear and transfer film production for a SLM

Despite this, SLMs provide an attractive tribological solution for some applications, generally being low cost, simple, and effectively infinite in supply. They are commonly used in applications such as bushes, sliding interfaces, guides, plain bearings, slip rings, motor brushes, gears, and ball bearing cages.

SLMs in Bearing Applications

For bearing applications requiring a separating cage, the traditional logic is to manufacture the cage of an appropriate complementary material to the deposited solid lubricant applied to the bearing raceways.

For deposited lead this is typically a cast lead-bronze eutectoid matrix featuring ~9% of bronze in non-alloyed free pockets within the bronze matrix, with the general principle that material from the cage is transferred to the raceways during operation. In ball bearings using MoS_2 the usual separator solution is the adoption of an MoS_2 containing polymer composite cage. The current heritage material for this is the US material PGM-HT, a PTFE, glass fibre/MoS_2 composite material. However in recent years questions have been asked regarding the tribological consistency of PGM-HT and this (together with its non-European manufacture) has driven the need to identify an appropriate replacement material.

Regardless of the material used, the torque behaviour of an angular contact bearing lubricated with a solid lubricant (e.g. MoS_2) and fitted with an appropriate complementary cage (e.g. PGM-HT) will follow the same general behaviour under vacuum. Following an appropriate run-in period (ensuring that the operational environment is appropriate for the lubricant selection) a well-behaved bearing will typically display low mean torque and low torque noise. After some operational period (typically millions of revolutions but dependent upon the operating conditions, including contact stress) a transition will occur whereby the mean torque and torque noise will rapidly increase. This is interpreted as the transition between preodominently-MoS_2 lubricated operation, and predominantly-PGM-HT lubricated operation within the bearing. Following this transition the cage can continue to provide lubrication to the bearing for several 10s-to-100s of million revolutions.

Given that the behaviour of the SLM cage is considered fundamental to the behaviour of the bearing following this transition (i.e. long-to-medium life applications), it is therefore vital that as new materials are developed we characterise their behaviour using representative and appropriate means.

TRADITIONAL ASSESSMENT METHODS

Traditionally the assessment of SLMs for space have been performed via Pin-on-Disc (PoD) tribometery (Figure 2). This well-established method for assessment of friction and wear involves the loading of a bulk SLM against a substrate and sliding under some controlled conditions.

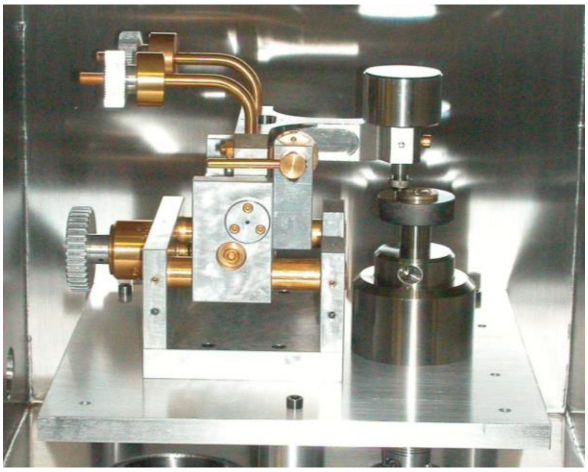

Figure 2. Pin-on-Disc (PoD) tribometer typically used for tribological assessments of SLMs

However, this technique suffers a limitation in that it measures only the physical rate of wear of the SLM itself. It does not measure the ability of the material to produce a transfer film onto the counter-face (only the bulk wear of the material), and the friction measured is a product of the sliding force between the bulk SLM and the counterface itself. Furthermore, PoD testing does not provide any direct understanding of the ability of an SLM to re-lubricate from this transfer film (herein referred to as the double-transfer method).

Whilst this may be an acceptable method of assessment for some applications of SLMs (e.g. bushes), double-transfer is a required property for a cage material within a bearing which relies upon transfer of material from the cage to the raceways, via the balls (Figure 3). Typically (for solid lubricated bearings) the torque obtained is a product of the Coulombic rolling friction of the balls on the raceways, and so the production of a transfer film is essential.

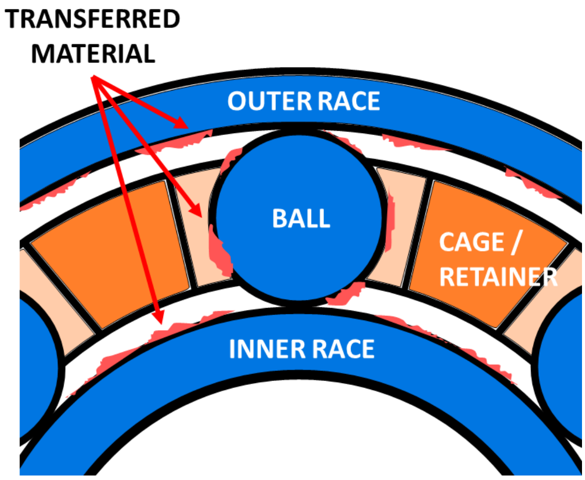

Figure 3. Double-transfer mechanism within a bearing

It is entirely plausible that the propensity of an SLM to produce an adequate transfer film is independent of the metrics measured by the PoD tribometer (e.g. friction and bulk wear of the SLM). For example, properties such as the physical matrix structure of the material, its elastic moduli, and its tensile strength may potentially affect the ability for the material to rapidly produce an effective and self-sustaining transfer film. There is therefore a desire to identify and demonstrate a method (or methods) of SLM assessment which is more representative of the kinematics of a true bearing cage application.

SLM ASSESSMENT ON THE SOT

To address this potential disparity, ESTL has developed a test methodology using a Spiral Orbit Tribometer (SOT) in which the steel guide plate is replaced by one manufactured of a SLM.

The Spiral Orbit Tribometer (SOT) is a test facility designed to reproduce the kinematics of an angular contact bearing. Essentially a thrust bearing, within the facility an individual ball is held between two interchangeable flat plates (Figure 4), located within a vacuum chamber. 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 maintain a repeatable orbit. A force transducer behind the guide plate measures the force exerted by the ball onto the guide plate, allowing measurement of the friction coefficient between the ball and the flat plates.

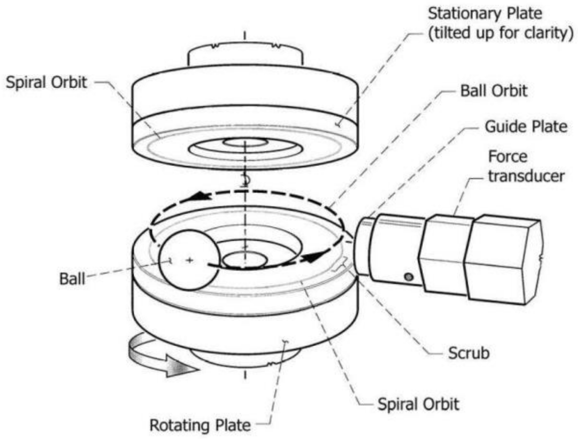

Figure 4. Internal arrangement of the SOT

In standard configuration the guide plate within the SOT is manufactured of stainless steel (typically 440C). However by replacement of the steel guide plate with one manufactured of SLM the contact between the guide plate and the ball will result in transfer of material onto the ball, and eventually onto the steel flat plates (in an analogous manner to the contact in a ball bearing between cage pocket and ball). Through the monitoring of the in-situ friction coefficient, as well as the transfer of material onto the ball and flat plates, the propensity of an SLM to produce an adequately lubricating transfer film can be assessed.

This new and unique assessment method was employed to measure the tribological behaviour of a number of SLMs of interest to the space mechanisms community.

SELECTION OF COMPOSITES

Six SLMs were selected for study on the SOT. Guide plates were manufactured of these materials.

<u>PGM-HT</u> – Composite material comprising PTFE, glass fibre and molybdenum disulphide. Following the discontinuation of the manufacture of RT/duroid 5813, PGM-HT has become accepted in recent years as its qualified replacement for use in ball-bearing cage applications primarily due to its similarity of tribological performance to that of Duroid [1]. However, recently this material has come under scrutiny for a perceived lack of tribological repeatability [2], and there is currently great interest in sourcing a more predictable composite. PGM-HT is manufactured exclusively by JPM of Mississippi, USA.

<u>RT/duroid 5813</u> – Duroid features a similar structure of PTFE, glass fibre and molybdenum disulphide, though arguably more isotropic due to smaller glass fibres than PGM-HT [3]. The material was commonly used as a ball-bearing cage material before production was discontinued in the late 1990s due to market reasons. The material was formally manufactured by Rogers Corporation, USA.

<u>C59/TSE8591</u> – A self-lubricating polymer matrix composite (SLPMC) composite of ~15% "EU sourced mineral fibre" (of dia ~3micron), PTFE and a slightly higher MoS_2 content than PGM-HT. It is understood that this material is similar to PGM-HT but designed to be more homogeneous to provide more consistent tribological performance. This material was deemed as the best performing candidate from the recent SLPMC investigation performed by AAC [4] and has been formally given the designation TSE8591 by the manufacturer Ensinger Sintimid, Austria.

<u>C79</u> – Similar material to C59 but displayed slightly less favourable tribological properties when used as a cage material during bearing tests performed at ESTL for a commercial client.

<u>Vespel SP3</u> – Vespel SP3 is a trademarked polyimide/MoS_2 composite manufactured by DuPont, USA, which is occasionally used as a ball bearing cage and bush material in vacuum applications [5]. However, as a polyimide, the tribological properties of this material are known to be highly dependent upon environment, with friction coefficients significantly higher in moist air (and under initial operation in vacuum) due to adsorbed moisture at the surface of the material [6]. The European equivalent of this material is Tecasint 1391, which is no longer commercially available.

<u>Tecasint 2391</u> – This polyimide/MoS_2 composite is offered by Ensinger Sintimid as a replacement to the discontinued product TSE1391. The manufacturer states that this new material provides lower friction than TSE1391 for vacuum applications, with the base material modified to provide better toughness, machining characteristics, thermal properties, outgassing characteristics, and wear resistance [7].

SOT Test Conditions

SOT tests were performed under identical conditions for all materials:

- Substrate material – 440C steel
- Ball diameter – 12.7mm
- Peak Hertzian contact stress – 1GPa (between the ball and the steel plates)
- Environment – Vacuum (<1.3 x 10^{-6} mbar)
- Temperature – RT (22 ± 3°C)
- Ball rotation speed – (100rpm)
- Duration – 10^{6} ball orbits (~1 week per test)

Three identical SOT tests were performed for each material. Following completion of each SOT test, the samples were inspected via a combination of optical, XRF, and profilometer techniques to further understand the material transfer process.

SOT TEST CAMPAIGN

Friction Progression

A summary of the friction behaviour of each material during the SOT test campaign is presented below (Table 1). Full data, including friction traces, are available elsewhere [8].

Table 1. Summary of SLM friction behaviours during SOT testing

Material	Mean CoF	CoV
PGM-HT	0.187	53.6%
Duroid	0.270	41.5%
TSE8591	0.211	55.2%
C79	0.301	26.5%
Vespel SP3	0.498	26.8%
Tecasint 2391	0.561	23.3%

As evidenced by the large Coefficient of Variance (CoV), the majority of tests displayed non-stable friction coefficients during SOT testing. Although there are examples of the achievement of “steady-state” in some individual tests these do not occur consistently for any given material.

PGM-HT and TSE8591 provide similar frictional behaviour, with the lowest mean CoF and comparable levels of variance. Vespel SP3 and Tecasint 2391 provided the highest friction, suggesting either that the transfer behaviour of these polyimide-based materials is inadequate to prevent steel-on-steel contact (under these test conditions at least), or that the material itself provides a higher CoF than the other SLMs.

SLM Wear

A crude assessment of SLM material wear was performed by weighing the guide plate before and after each test and is presented below (Table 2).

C79 showed the lowest mass loss, with PGM-HT and TSE8591 being reasonably consistent. The mass loss of RT/duroid 5813 was slightly higher, which corresponds well with direct measurements of wear rate from prior PoD test campaigns [1]. The material loss of Vespel SP3 and Tecasint 2391 are proportionally much higher than the other tested materials, potentially due either to the elevated mean CoF (although an increase in CoF does not necessarily correlate directly to increased wear rate), or the polyimide nature of these materials themselves (which has been observed in the past [6].

Table 2. Guide plate mass changes during SOT tests (mean for each material)

Material	Guide plate material loss (mg)
PGM-HT	0.382
Duroid	1.093
TSE8591	0.305
C79	0.149
Vespel SP3	8.290
Tecasint 2391	1.981

Indirect wear measurements were also taken by performing profilometer analysis on the guide plate wear scars (to determine the material loss), with the observations from these measurements being consistent with the statements above.

Transfer Film and Substrate Wear

An assessment of the transfer film formation onto the balls and races was performed via multiple techniques. Firstly the balls were measured for molybdenum thickness using an XRF system. Whilst it is recognised that the material transfer onto the ball will not exclusively be molybdenum, and the molybdenum content of the bulk SLMs (and therefore presumably their transfer films) are not necessarily consistent, the XRF can be used to give an indicative and comparative value of this transfer film (Table 3).

Table 3. Post-test molybdenum thickness on ball via XRF

Material	Mo thickness on ball (µm)
PGM-HT	0.359
Duroid	0.362
TSE8591	0.353
C79	0.356
Vespel SP3	0.383
Tecasint 2391	0.368

The consistency of these results suggests an approximately stable transfer film produced during the 1 million ball orbits in all cases, with little difference between the materials.

Microscopy inspections of the flat steel SOT plates revealed evidence of successful formation of a double-transferred film for all assessed SLMs, but this film differed significantly between the materials. TSE8591 were observed to produce the more uniformed and homogenic films (considered to be beneficial to the tribological properties of the film), with other material films being lumpier and more discontinuous.

Profilometer measurements of the double-transfer films agreed with these observations, with TSE8591 and Duroid providing the most uniform coatings with relatively few peaks and consistent films of 1-2µm, in comparison to PGM-HT which displayed high variability and inconsistent amalgamation of deposited material up to 3µm in diameter. The polyimide materials also showed highly inconsistent transfer films, as well as evidence of steel wear.

Discussion of Summary of Tribometer Testing

The test methodologies described above were successful and verify the ability of the SOT to be used to identify and compare the transfer films produced by self-lubricating materials. In some instances, the friction coefficient had still not achieved steady-state after 1 million ball orbits, and so it could be argued that in future activities the tests should be operated for even longer durations.

From the investigations performed it can be reasonably stated that C59/TSE8591 is the best performing SLM assessed, providing low and reasonably consistent behaviour with a uniform transfer film and low material wear. C79, PGM-HT and RT/duroid 5813 provide reasonable behaviour, with the transfer films being generally less uniform but still providing low friction. Vespel SP3 and Tecasint 2391 were hindered by large volumes or wear debris resulting in elevated friction and noise. Full details of the SOT test campaign are provided within the relevant technical memorandum [8].

SLM BEHAVIOUR IN BEARINGS

As a follow-on to the above detailed SOT activity, ESTL has performed a study to assess the transfer film behaviour of TSE8591 compared with PGM-HT in bearing tests in using the Advanced Bearing Test Rig.

Advanced Bearing Test Rig (ABTR)

The ABTR (Figure 5) is a unique test facility at ESTL which has been designed to provide high resolution, detailed and more complete information compared to a standard bearing test facility. A pair of angular contact bearings are preloaded using a spring on the inner race such that a back-to-back configuration is achieved.

Bearing torque is measured along with preload variation and electrical conductivity through the beating. The addition of a capacitive sensor to measure axial shaft displacement gives us the ability to measure the formation of films in fluid lubricated bearings. However, this measurement can also be used to monitor the formation of transfer films and the onset of raceway wear in a solid lubricated bearing. This provides much needed context to the bearing torque measurements obtained in standard test facilities.

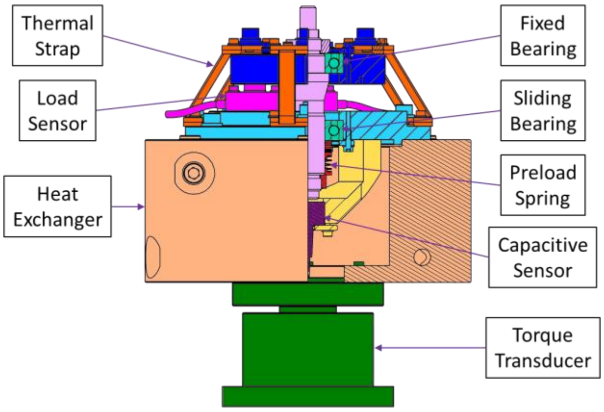

Figure 5. Internal arrangement of the ABTR

The capacitive sensor has been used in recent solid lubrication studies to justify the validity of accelerated testing, monitor the formation of PTFE transfer films in bearings operated in air and comparing the performance of new SLM materials.

Bearing Test Conditions

Results from several ABTR test campaigns under identical conditions have been brought together for this paper to compare the performance of PGM-HT to TSE8591. The test conditions are detailed in Table 4. The full details of the PGM-HT lubrication study including results at additional bearing speeds performed by ESTL can be found in ESA-ESTL-TM-0223 01- [9]. The follow-on study using TSE8591 lubricated bearings and the same test speeds can be found in ESA-ESTL-TM-0297 01- [10].

Table 4. Comparison of test parameters for different ABTR solid lubrication tests

Parameter	**Unit**	**PGM-HT**	**TSE8591**
Speed	rpm	3500	3500
Bearings	-	FAG B7004C	FAG B7004
Preload	N	48	48
Contact Stress (Peak)	MPa	820 (IR)/ 710 (OR)	820 (IR)/ 710 (OR)
Temperature	Celsius	22	22
Vacuum	mbar	$<1 \times 10^{-5}$	$<1 \times 10^{-5}$
Duration	Revolutions	6×10^{7}	6×10^{7}

A unique bearing pair for each test speed was coated (balls and raceways) with MoS_2 at ESTL and assembled with cages (inner race riding) with identical dimensions made from the appropriate material.

The 60 million revolution life test was performed at 3500rpm which represents a "worst case" for operation. Torque reversals in order to measure mean torques were performed at set duration intervals based on revolutions. All reversals were performed at 5rpm and are comparable between tests. A speed ramp up to 3800rpm was performed at 500,000 revolutions and then at increasing intervals to assess cage dynamics.

Bearing Test Results

The ABTR is capable of measuring axial shaft displacement which can be used to determine the average contact separation in solid lubricated bearings. This contact depth is adjusted such that 0μm is the position of the contact during the stable MoS_2 dominated regime. Positive contact depth exists before the bearing is run in and is indicative of transfer of material from the cage (via the double-transfer mechanism). Negative contact depth represents wear of the coating from the stable regime or underlying metallic wear of the raceway.

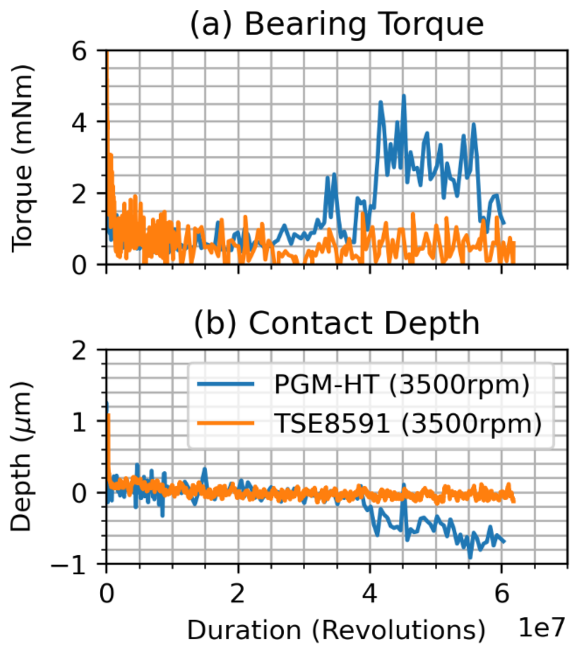

Figure 6. Comparison of (a) mean bearing torque and (b) contact depth measured in ABTR for two different SLMs

Figure 6 contains results from the 3500rpm life test performed for both cage materials. The mean bearing torque for both materials decreases rapidly as the bearings are run in over the first 1-2 million revolutions. The bearing torque then remains below 1mNm until 20 million revolutions for both materials.

Beyond this point, after 20 million revolutions the PGM-HT begins to show differences in performance with increasing levels of torque noise. At 40 million revolutions there is a drastic change in the level of torque noise. The advantage of the ABTR over a standard bearing test is that we can see this transition is accompanied by a negative change in the contact depth. The negative contact depth change is likely due to typical metallic micro-wear of ball and raceway surfaces that occurs as a stable transfer film is formed. This micro-wear is common for bearing systems equipped with a SLM cages and is presented in more detail in [8].

The TSE8591 by comparison has a mean bearing torque and contact depth that remains stable until the completion of the 60 million revolutions. In fact, it is not fully clear if the TSE8591 is extending the life of the originally deposited MoS_2 or producing a transfer film which itself displays low friction/torque rendering it indistinguishable from the MoS_2. Whilst it is not possible to distinguish between these two models given the current data (and it is of course entirely plausibly that both are occurring to some degree), it has previously been noted by ESTL during studies for a commercial client that the transfer film produced by TSE8591 (with no additional MoS_2 applied to the bearing) displays an extremely low friction coefficient under vacuum, significantly lower than that of PGM-HT. Future long duration ABTR tests are planned at ESTL to further characterise the positive interaction between the deposited MoS_2 and the transition behaviour for TSE8591, and so to provide a more detailed comparison to PGM-HT.

Figure 7. Post-test TSE8591 cage pocket wear

Post-test inspections of the bearings showed evidence of transferred material within the running track of the raceways, with limited loose debris. Some evidence of wear was observed within the cage pockets (Figure 7), this being usual and indicative of material transferred from cage to ball, and from ball to raceway. These observations are typical for angular contact bearings lubricated in this manner, and no significant differences were observed between the PGM-HT and TSE8591 materials.

DISCUSSION OF ABTR STUDY

The results from this study have highlighted a significant difference in tribological performance at bearing level between PGM-HT and TSE8591 cages.

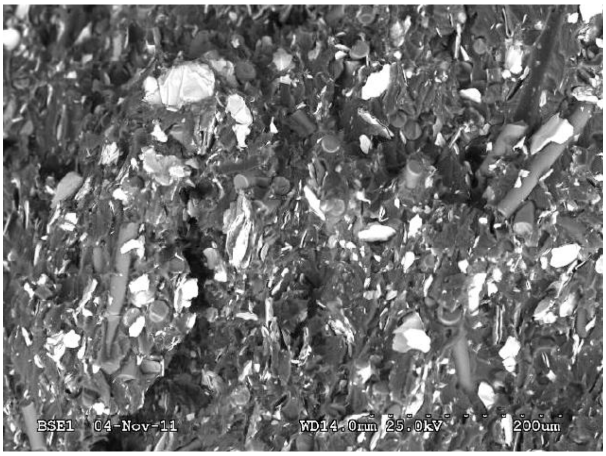

Figure 8. SEM micrograph of PGM-HT material cross-section [11]

Figure 8 contains a SEM micrograph of a cross section through bulk PGM-HT material which shows the non-homogenous nature of the material. The glass fibres are easily distinguished by their cylindrical shape.

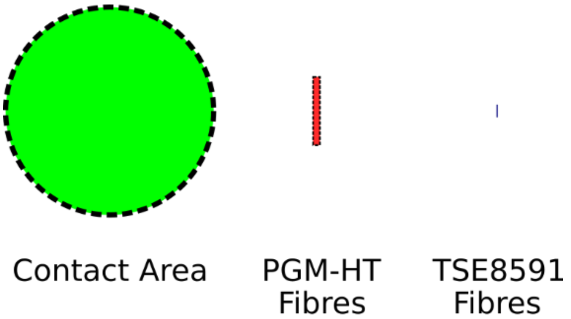

Figure 9. Size comparison of bearing contact area with different fibre sizes

The glass fibres in PGM-HT typically have a diameter around 20µm and a length of 200µm. Figure 9 provides a scaled comparison of the size of these PGM-HT glass fibres against a theoretical circular contact area of 500µm diameter (with this diameter approximately equating to the major-axis of the elliptical ball-race contact within an angular contact bearing). In contrast the fibres in TSE8591 have a significantly smaller diameter of 3µm and a length of 30µm (assuming a similar aspect ratio) [4].

In the case of PGM-HT (and it assumed also for TSE8591), these glass fibres are transferred along with the PTFE and MoS_2 onto the bearing raceway.

Figure 10 shows a SEM micrograph of PGM-HT material transferred onto a substrate (from PoD testing [11]), in which these glass fibres can clearly be seen. The same 500µm contact zone has been superimposed onto this image, and in doing so one can clearly appreciate the non-homogeneous nature of the transferred material. It is highly probable that the proportion of glass fibres to PTFE within a given contact area can vary tremendously, resulting in a non-repeatable tribological performance.

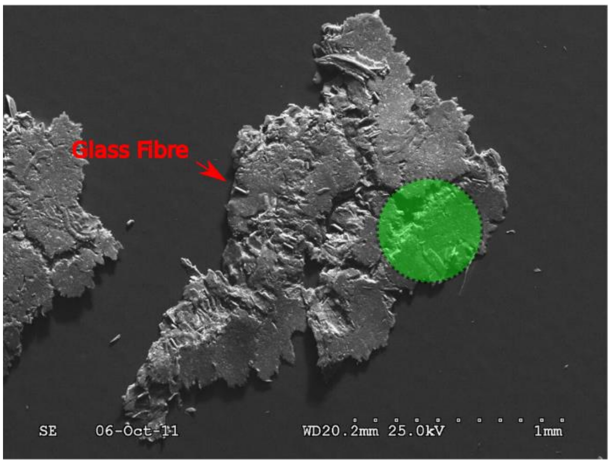

Figure 10. SEM micrograph of transferred PGM-HT material with the contact area overlaid (green circle)

In addition the presence of these hard particles is likely to increase the abrasion of the originally deposited MoS_2 coating, increase the abrasion of the PGM-HT transfer layer, contribute to the torque noise as the balls are forced to roll over these hard fibres, and potentially result in wear raceways. Given the smaller fibre particles (and the more homogeneous material structure), this may help explain why the bearing fitted with a TSE8591 cage remains stable beyond the transition point of PGM-HT.

The comparison of the ABTR results presented in this paper show how the ABTR can be used to compare the transfer film formation of different SLM materials in solid lubricated bearings, and not just for the measurement of film thicknesses in fluid lubricated bearings.

CONCLUSIONS

The Spiral Orbit Tribometer and the Advanced Bearing Test Rig are shown to be appropriate experimental testing facilities for the assessment of SLMs, able to identify and characterise the formation of transfer films of lubricating material and their subsequent tribological behaviour, in both a qualitative and quantitative manner. These assessment methods should be considered as complementary to the more traditional Pin-on-Disc and bearing testing techniques, particularly for assessments of SLMs in bearing cage applications where they provide more representative and highly detailed assessments of the materials under study.

These techniques have been used during investigations of multiple SLMs, which have demonstrated the highly encouraging performance of C59/TSE8591. In comparison to the commonly-used PGM-HT, this new material displays low bulk wear, acceptable friction, and forms a generally uniform and homogeneous transfer film with little to no evidence of substrate steel wear. In bearing tests under vacuum the torque noise is low, and material interacts positively with a deposited MoS_2 coating to maintain low torque for an extended duration.

TSE8591 appears to be a very encouraging candidate material for space applications and should be seriously considered going forward.

ACKNOWLEDEMENTS

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