THE FRICTION AND WEAR PROPERTIES OF THERMALLY CONDITIONED PGM-HT

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ABSTRACT

The composite PGM-HT (PTFE, Glass Fibre and Molybdenum Disulphide) is often used within the space industry as a self-lubricating cage material, and it has become accepted in recent years as a replacement to ‘Duroid’. However previous investigations at ESTL have demonstrated that the PGM-HT material shrinks when returning to room temperature from a period at elevated temperature (typically a cycle of 24hours at ~250°C) under vacuum. Thermal preconditioning the material inhibits this shrinkage. However, it is not known if the tribological properties are affected by preconditioning: a test program was therefore carried out to determine whether pre-conditioning affects the tribological behaviour of PGM-HT.

This paper details the results of the test program, and provides conclusions into the performance of thermally conditioned PGM-HT.

1. BACKGROUND

PGM-HT is a composite, self-lubricating material comprising of PTFE, glass fibre and molybdenum disulphide. It has become accepted in recent years as a replacement to ‘Duroid’ (specifically RT/Duroid 5813) which has a similar composition but which is no longer manufactured. Following the discontinuation of Duroid, PGM-HT was qualified as a replacement material for self-lubricating ball bearing applications [1]. PGM-HT is used primarily as a ball-bearing cage material – either as a single source of lubricant within a bearing or in conjunction with thin MoS_2 coatings applied to the bearing races and balls.

Previous tests at ESTL [2, 3] in which such bearings have been operated at high temperature (up to 300°C in vacuum) have shown that the PGM-HT material shrinks upon returning to room temperature. The effect was of such a magnitude that it led to shrinkage of the cage onto the guiding land and strongly inhibited bearing motion (effectively the PGM-HT acted as a brake).

However, at elevated temperature the combination of PGM-HT cage and MoS_2 coatings performed effectively and as such could be considered for high-temperature applications such as on BepiColombo provided the shrinkage issue could be resolved.

Further work at ESTL quantified the amount of shrinkage with temperature [4]. This was done by subjecting dummy PGM-HT cages of various sizes to incrementally higher temperatures, each time returning to ambient to measure the shrinkage. The outcome is summarised in Fig. 1 which also shows the corresponding behaviour of SINTIMID (a polyimide material containing MoS_2).

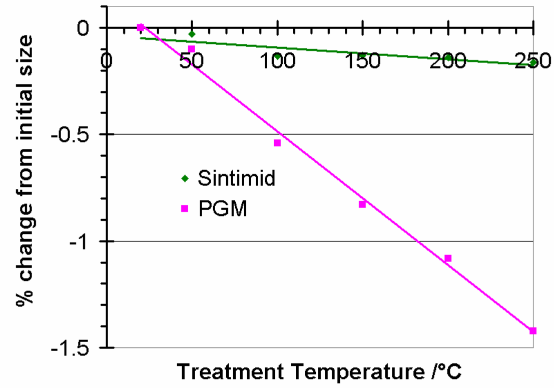

Figure 1. Percentage shrinkage of PGM-HT and Sintimid as a function of temperature (heating undertaken in high vacuum) [4]

Fig. 1 shows that the shrinkage of PGM-HT increases linearly with increasing temperature and approaches 1.5 % at the highest temperature examined (250°C).

The effect of repeated thermal cycling was then investigated by performing measurements on a new set of dummy cages identical to those used 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. 2.

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 might be possible to thermally pre-condition the raw PGM-HT to obtain a dimensionally stable material.

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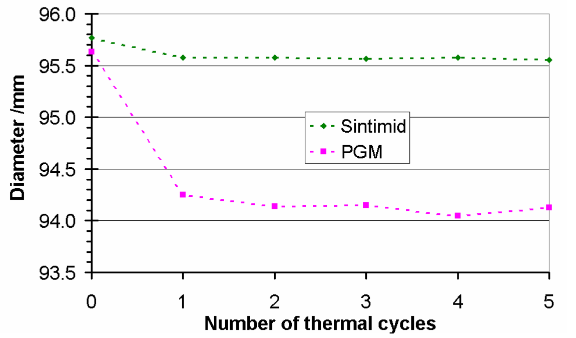

Figure 2. Dimensional change of dummy cage after heating to 250°C, Cage dimensions measured at room temperature after each 24 hour heating period. [4]

In light of these results, it was speculated that PGM-HT bearing cages manufactured from a thermally conditioned material would prove less susceptible to the thermal shrinkage effect. Tests were therefore carried out to determine the effectiveness of this approach.

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

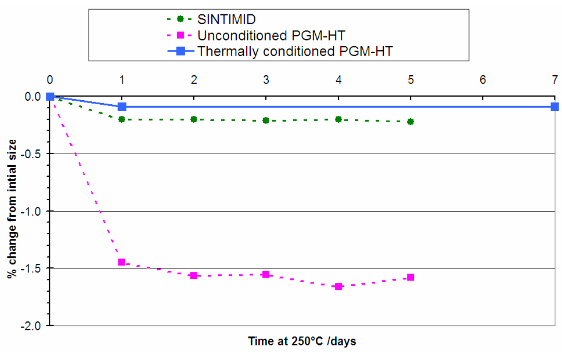

Figure 3. Dimensional change of dummy PGM-HT cages after heating to 250 °C – showing beneficial effects of pre-conditioning on PGM-HT. [4]

The results show that the pre-conditioning is indeed effective in stabilizing the material, with a contraction of only 0.1% after 1 day at 250°C and no further measurable change after 6 further days of heating.

These results lead to the need to demonstrate that the process of pre-conditioning PGM-HT does not degrade its tribological properties. ESTL examined the tribological properties and compared them with those of un-conditioned material.

2. TRIBOLOGICAL TESTING OF PRE-CONDITIONED PGM-HT

2.1. Test Details

The tests were carried out in two stages: a first stage in which the tribological behaviour of the material was characterised as a function of stress, sliding speed and environment; and a second stage where the batch-to-batch repeatability of pre-conditioned material was studied.

First stage – characterisation

The first stage of testing comprised friction and wear measurements of PGM-HT, under a variety of environments, consistent – where possible - with such measurements made previously by ESTL on un-conditioned PGM-HT. Hemispherically ended PGM-HT pins were run against 52100 steel discs of surface roughness ~0.1μm R_a. The motion was carried out over a sliding distance of 1,000m in a uni-directional movement. (Though inconsistent with previous tests, preliminary results indicated little difference between uni-directional and reciprocating in this case.) The test conditions are provided in Tab. 1.

Table 1. Test conditions for friction & wear assessment of pre-conditioned PGM-HT

Test no.	Environment	Sliding speed (m/sec)	Contact stress	MoS_2 coating on disc
1	Vacuum	0.1	S1	No
2		0.01	S1	No
3		0.1	S2	No
4		0.1	S1	Yes
5	Lab Air	0.1	S1	No
6		0.01	S1	No
7		0.1	S2	No
8		0.1	S1	Yes
9	Nitrogen	0.1	S1	No

Notes: S1 equates to a mean contact stress of 10MPa (Pin load 5N; pin radius 18mm)

S2 equates to a mean contact stress of 16.2MPa (Pin load 20N; pin radius 18mm)

0.01m/sec equates to 10RPM at a track radii of 12mm

0.1m/sec equates to 100RPM at a track radii of 12mm

1,000m equates to 13,260 revs.

The contact stress S1 is based on previous ESTL assessments of PGM-HT in which the applied normal load and the pin's radius of curvature were selected to provide an initial mean Hertzian stress approximately equal to two-thirds of the yield strength of the material. This value represents an upper limit to the ball-to-cage interaction stresses occurring in medium-sized bearings (operating at medium speeds and loads).

The higher contact stress, S2, is aimed at representing the condition when a bearing is misbehaving e.g. when hang-up occurs, and the ball-to-cage loads are higher. To be consistent with previous ESTL studies of PGM-HT, S2 equates to 16.2 MPa.

Second stage – repeatability

Hemispherically ended PGM-HT pins of an identical design to those used in stage one were manufactured from three independently pre-conditioned material blocks. Three pins were manufactured per material block, and tests performed under similar conditions as Test no. 1 from stage one (see Tab. 1); sliding against uncoated 52100 steel in a unidirectional motion at 0.1ms^{-1}, under vacuum, loaded to 5N, over 1,000m. Nine pin-on-disc tests were performed, and the friction and wear of each PGM-HT pin assessed.

2.2. Pin-on-disc methodology

Test specimens were ultrasonically cleaned in Lenium ES in a low-emission solvent cleaning plant prior to pin-on-disc tests. All pin-on-disc tests were carried out using ESTL's vacuum pin on disc tribometer. The experimental set up is shown in Fig. 4, 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 friction force is measured by the deflection of the arm and recorded using a PC-based data acquisition system. The tribometer system was calibrated using a pulley system to apply known loads to the tribometer arm.

Figure 4. Vacuum pin on disc tribometer

2.3 Test Results - characterisation

Two examples of typical plots of friction coefficient as a function of disc revolutions are presented in Figs. 5 and 6. See Tab. 2 for test data.

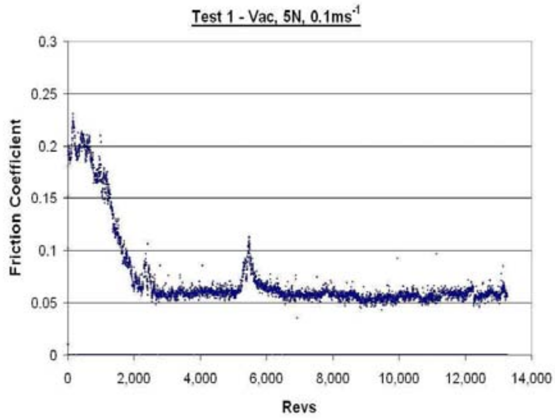

Figure 5. Test 1 – Vacuum, 5N, 0.1ms^{-1}

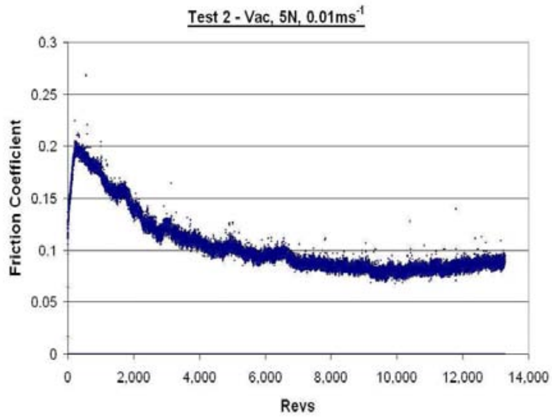

Figure 6. Test 2 – Vacuum, 5N, 0.01ms^{-1}

Specific wear rates are found by measuring the wear scar on pin after completion of the test. They are given as wear volume per unit load per unit distance (m^3/Nm) and are provided in Fig. 7. See Tab. 3 for test data.

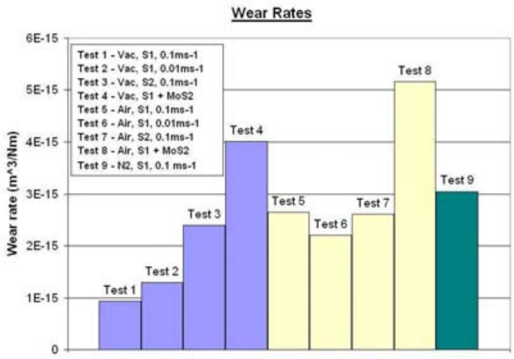

Figure 7. Wear rates of PGM-HT pins

From the tests of PGM-HT sliding against uncoated 52100 steel we can see a significant difference between the run-in friction coefficients found in air (0.20 – 0.24) and those in vacuum (0.05 – 0.1). This is in contrast to previous tribological tests performed on un-conditioned PGM-HT, which found (Table 2) values in the range 0.2 to 0.32 over all test conditions [5]. In particular, we find significantly lower friction values in vacuum than previously measured.

The presence of a thin coating of sputtered MoS_2 on the disc quickly yielded low friction in vacuum and relatively high friction in air. This is in line with the environmentally-sensitive nature of MoS_2 but at odds with tests on un-conditioned PGM-HT which exhibited higher friction in vacuum (Table 3).

Start-up friction values for all tests was ~0.20, with the exception of tests performed at $0.01 ms^{-1}$, which displayed values of 0.15. No other differences were apparent from varying the sliding speed. Tests performed under nitrogen conditions proved consistent with previous results.

Table 2. Comparison of run-in friction coefficients

Test No.	**Conditions**	**Previous results from un-conditioned PGM-HT (ESA/TM/226 [5])**	**Present results from pre-conditioned PGM-HT**
1	Vac, S1, $0.1 ms^{-1}$	0.25	0.06
2	Vac, S1, $0.01 ms^{-1}$	0.27	0.08
3	Vac, S2, $0.1 ms^{-1}$	0.20	0.05
4	Vac, S1 + MoS_2	0.36	0.06
5	Air, S1, $0.1 ms^{-1}$	0.20	0.22
6	Air, S1, $0.01 ms^{-1}$	0.32	0.20
7	Air, S2, $0.1 ms^{-1}$	0.18	0.21
8	Air, S1 + MoS_2	0.35	0.33
9	N_2, S1, $0.1 ms^{-1}$	0.30	0.20 - 0.32

A comparison of wear rates obtained in this study with those previously obtained for un-conditioned PGM-HT is presented in Tab. 3.

Table 3. Comparison of specific wear rates ($x10^{-15} m^3/N.m$)

Test No.	**Conditions**	**Previous results from un-conditioned PGM-HT (ESA/TM/226 [5])**	**Present results from pre-conditioned PGM-HT**
1	Vac, S1, $0.1 ms^{-1}$	7.0	0.9
2	Vac, S1, $0.01 ms^{-1}$	4.3	1.3
3	Vac, S2, $0.1 ms^{-1}$	1.3	2.4
4	Vac, S1 + MoS_2	1.3	4.0
5	Air, S1, $0.1 ms^{-1}$	1.7	2.7
6	Air, S1, $0.01 ms^{-1}$	2.8	2.2
7	Air, S2, $0.1 ms^{-1}$	1.3	2.6
8	Air, S1 + MoS_2	1.8	5.2
9	N_2, S1, $0.1 ms^{-1}$	1.3	3.0

For PGM-HT sliding against un-coated 52100 steel discs we found SWR's in the range 0.9 to 4.0 x $10^{-15} m^3/Nm$ in vacuum for pre-conditioned material whereas previously (for un-conditioned material) the corresponding range was 1.3 to 7.0 x $10^{-15} m^3/Nm$. The means are comparable between the two materials; 3.5 x $10^{-15} m^3/Nm$ for unconditioned, 2.2 x $10^{-15} m^3/Nm$ for pre-conditioned material.

In air, the wear rates for conditioned PGM-HT are comparable, but generally higher than for unconditioned material.

The highest wear rates (surprisingly) occurred for conditioned PGM-HT sliding against MoS_2-coated steel discs – these being a factor of ~3 higher than the wear rates observed previously for the corresponding tests with un-conditioned PGM-HT.

The wear marks varied in appearance depending upon the test condition; orange/brown debris (Fig. 8) was observed for air testing (probably oxidised MoS_2) and black debris (Fig. 9) was found for vacuum/nitrogen environments.

Figure 8. Wear scar after air test

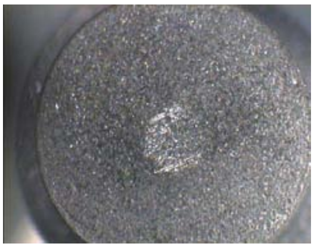

Figure 9. Wear scar after vacuum test

2.4 TEST RESULTS - REPEATABILITY

There was not much consistency, either between separately conditioned blocks of PGM-HT, nor in the blocks themselves. Run-in friction coefficients ranged from ~0.05 to 0.45, and displayed erratic profiles. Some tests did not reach a steady-state friction coefficient during the test duration. All plots display the same start up friction of ~0.20; consistent with Stage 1 tests.

Measured wear rates also varied, ranging from 2 to 18 x 10^{-15} m^3/Nm (Fig. 10). Applying simple statistics this converts to a mean of 5.6 x 10^{-15} m^3/Nm with a standard deviation of 2.6 x 10^{-15} m^3/Nm.

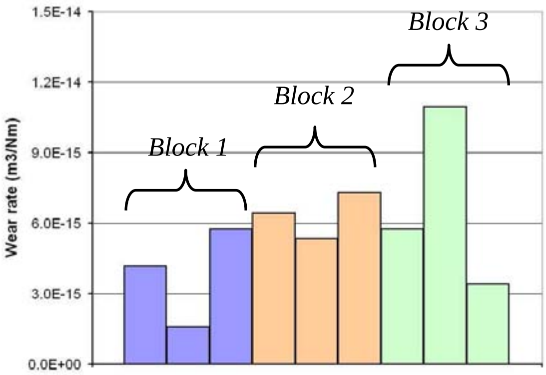

Figure 10. Wear rates, separated by PGM-HT block

If we plot mean friction (averaged over 1,000m) against wear we find a relationship, with higher friction tests generally giving higher wear rates (Fig. 11). Comparisons with previous results are also provided and the data indicate that the performance of thermally conditioned PGM-HT is similar from unconditioned material.

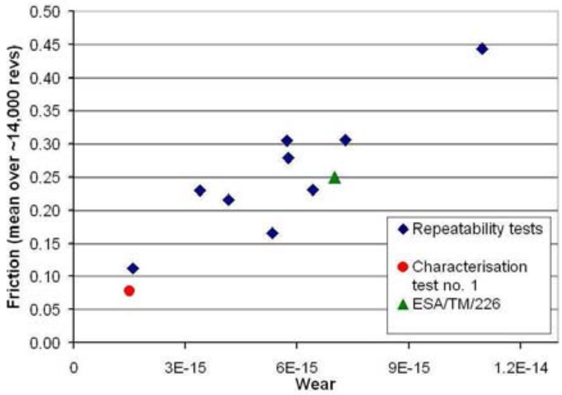

Figure 11. Wear rates (m^3/Nm)

3. BEARING TESTS

PGM-HT is used principally as a cage material in ball bearings. It is therefore appropriate to complete this activity by carrying out tests on bearings fitted with pre-conditioned PGM-HT cages. These tests represent the full range of thermal-vacuum environments over which PGM-HT caged bearings are used. These environments are:

- At or near room temperature in vacuum
- At elevated temperatures (up to 250°C) in vacuum
- At cryogenic temperature (~25K) in vacuum

In many instances the bearings that employ PGM-HT cages are coated (races & balls) with sputtered molybdenum disulphide coatings. To reflect this, PGM-HT caged bearings are being tested with and without MoS_2 coatings applied to both the races and balls. The test matrix was as follows and tests were carried out using 20mm bore ball bearings (type FAG B7004 – AISI52100 steel balls and races and XCB7004 for high temperature tests as they are fitted with ceramic balls and have Cronidur 30 raceways).

Table 4. Bearing test matrix

Test no.	Temperature	Preload	MoS_2 coating
19	RT	TBD	No
20	RT	TBD	Yes
21	250°C	TBD	No
22	250°C	TBD	Yes
23	25K	TBD	No
24	25K	TBD	Yes

At the time of writing, Test 24 has been completed and Test 22 is ongoing.

3.1 BEARING RESULTS

Test 24 – the results of test carried out under cryogenic-vacuum conditions are shown in Fig.12.

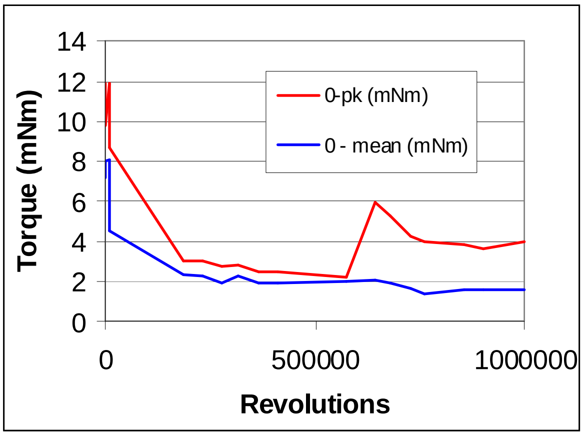

Figure 12. Test 24 results, with MoS_2-coated bearings

Following a running-in period of approximately 10,000 revs, the mean torque decreased to a steady-state regime between 16 and 20 gcm. There was no cage misbehaviour and the test was considered successful.

Test 22 – in this test, bearings are being operated under vacuum at 250 deg.C. The torque behaviour thus far has been nominal with again no cage misbehaviour. Reducing the temperature from 250°C to 25°C has shown no anomalous torque increases as seen with the un-conditioned PGM-HT cages (where shrinkage of the cages onto the bearing lands caused very high torques - ref.2).

4. CONCLUSIONS

Pin-on-disc testing of thermally conditioned PGM-HT resulted in variable friction coefficients which were generally less than those measured in previous work for non-conditioned PGM-HT.

Wear rates for non-conditioned PGM-HT were comparable, being of the same order of magnitude. Repeatability tests demonstrated that higher friction coefficients were correlated with higher wear rates.

However there is little consistency between separate blocks of material, nor indeed the individual blocks themselves. Pin-on-disc tests demonstrate erratic behaviour, often with no stability during the test duration.

5. REFERENCES

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