NEW SELF LUBRICATING POLYMER MATRIX COMPOSITES FOR JOURNAL AND BALL BEARING APPLICATIONS IN SPACE (SLPMC2)

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ABSTRACT

The paper is reporting the interim results of the ESA-project "SLPMC2" covering the second phase of the development of a self-lubricating polymer composite based on PTFE for use in roller bearings. The promising results of the first project "SLPMC" were torque levels in ball bearings being comparable and partly even lower than current commercial materials.

The three targets of this project are to improve the understanding of lubrication mechanisms in PTFE-based composites under tribological conditions relevant to space applications (air, dry nitrogen, vacuum). Secondly, to sort out the most promising materials to fulfil future needs by space applications. Finally, to put emphasis on European non-dependence. Hence, in the frame of this project several new composites based on PTFE-matrix with different kind of fillers were defined, manufactured and tested on material level. From the most promising variants cages for ball bearings were machined. First ball bearing tests were done in high vacuum up to 60 million revolutions.

This paper overviews the current results from the second phase on material level focusing on tribological results derived by pin-on-disc tests. The influences of parameters like load, speed, atmosphere and temperature are discussed and compared to other already known materials. The paper also reports the findings from the first ball bearing tests.

1. INTRODUCTION

In space mechanisms, solid lubrication has certain advantages compared to liquid lubrication. Basically, the solid lubricant can be provided as a coating on the tribological surface or inside a composite material. For ball bearings, often a combination is used: to start immediately with good lubrication a coating is applied to the races (and balls). Secondly, in order to enhance life time, the cage is made of a composite containing similar lubricant. This lubricant is then transferred via the balls onto the races of the bearing, thereby enlarging the lifetime. In space mechanisms, such composites based on polymers are well known, as e.g Duroid 5813, PGM-HT (both based on PTFE), and also - based on polyimide - like Vespel-SP3 and Sintimid(Tecasint).

The above mentioned filled polymers, shall be referred to "Self Lubricating Polymer Matrix Composite (SLPMC)" as they consist of a polymeric matrix and fillers of two kinds: at first, hard fillers like short fibres made of glass or minerals and then solid lubricating particles (MoS_2).

However, Duroid 5813 production has been ceased many years ago and PGM-HT has been selected for replacing. In the last years, some questions on the PGM-HT performance were raised. This project aims at investigating on one hand the tribological mechanisms acting in such composites based on PTFE (under consideration of their general properties), but also on development of new compositions to improve their performance (long term stability in ball bearings). Hence, the actual project was aiming also in understanding of the wear and lubrication mechanisms.

2. ENVIRONMENTAL REQUIREMENTS

2.1 Friction and (solid) lubrication under vacuum

Frictional behaviour under space (vacuum) differs strongly from terrestrial environment. Lubrication by oils and greases exhibits higher risk, since they may evaporate and re-deposit on other critical surface areas, like optical components, solar arrays and shall preferably only be used under normal conditions of temperature (-40°C to 70°C). In order to minimise these risks solid lubrication is recommended, under the assumption that it is compliant with the application (e.g. low loads). In the present case, these requirements are even strengthened by the occurrence of medium temperatures.
The behaviour of solid lubricants based on lamellar structure, e.g. graphite, MoS_2, WS_2 is well known. However, the lubricant performance is driven by the presence of water vapour which reduces friction of graphite, but degrades MoS_2; this latter is well known for low friction in vacuum environment in a wide temperature and load range. However, MoS_2 degradation

due to humidity is inherent, but also well documented [1]. Polymers, e.g. PTFE, can also act as solid lubricants. However, viscoelastic behaviour, local heterogeneities and the temperature dependent microstructure may result in complex frictional behaviour.

2.2 Rationale for selection of fillers

Main objective of this second phase development is to further optimise the composition, i.e. the type and content of the fillers towards a stable friction and wear. Secondly, to replace current raw materials supplied by US-companies by European variants / suppliers.

The target in PTFE-composites is to optimise the wear of the PTFE itself towards low but steady value while keeping low friction. "Low" means that a certain wear is needed to enable the formation of a transfer film on the races in a ball bearing. This enables the low torque. Using pure PTFE would lead to the lowest friction but also to excessive wear, resulting in unacceptable lifetime of space applications. A second aspect is the appearance of the transfer film. There is still an ongoing discussion on the optimum characteristics of such a transfer film.

From literature and first results, hard fillers are necessary to steer this wear process in terms of transfer film shape and of its amount. According to literature [2], hard fillers reduce sub-surface deformation and "crack propagation". [3] reports that the shape of fillers steer the shape of the transfer film. Round fillers are reported to allow a thicker transfer film accompanied by too high wear. Long fillers like glass fibres are preferred for thin transfer films. However, they may lead to scratching of the counterpart. In order to overcome this risk, a solid lubricant maybe added (MoS_2). In materials like Duroid5813 and PGM-HT, glass fibres are used in combination with MoS_2. However, studies have also tackled other mineral fillers like particles or whiskers.

During first phase the most promising findings were:

- Composite material (C02) with PTFE/ Glass fibres/ MoS_2 with medium amount of glass fibres shows similar friction and wear rate as references. C01 with higher amount showed slightly higher wear.
- Composite material (C09) with PTFE/MoS_2 and with mineral fibres of much smaller diameter, shows similar friction and wear rate than references, but even closer to Duroid5813.

Conclusion on Ball bearing level
(10 million revolutions, uncoated races, full AISI440C)

- Selected composites C01 (glass fibres) and C09/C29/C39 (mineral fibres) showed good machining of cages
- All materials displayed good torque and torque-noise behaviour during running, with material C29 performing significantly better than the others. Post investigation might indicate that the MoS_2 amount has influence on the transfer layer.
- Torque of composites (C01, C09 and C39) was found to be as low as for reference materials like PGM-HT, but it was significantly lower for C29.
- No remarkable wear was seen until 10 million revolutions
- Tested composites are already good candidates for bearing applications!

Summarising all results, it can be concluded that **promising alternatives to current commercial PTFE-**based materials could be successfully manufactured. Moreover, candidates may allow a composition closer to Duroid than the current commercial materials enabling **even lower torque in first ball bearings tests**.

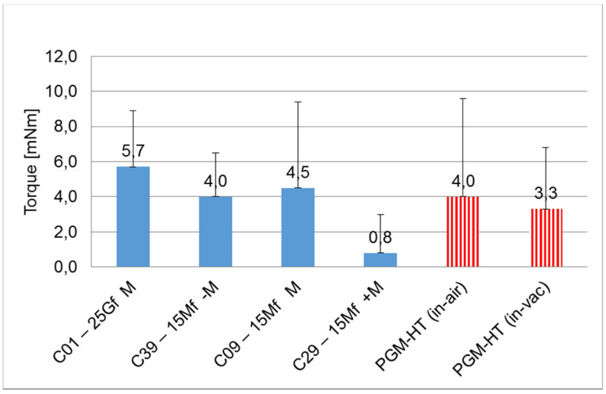

Figure 1: Ball bearing tests: torque in high vacuum, compared to literature (for PGM-HT) [4]

Following this first phase, the filler types were re-selected as most promising for the composites in this study:

- Glass fibres only as reference
- Mineral fibres with smaller diameter & varying length (European variants)
- Soft fibres (Aramid)
- MoS_2 is kept in addition to hard fillers

2.3 Requirements for use of polymers in space

For use of materials in space, the European Cooperation for Space Standardisation (ECSS) has defined a check-list [5]. However, in the framework of this ESA-Project, as different filler combinations shall be studied, only "core-properties" were investigated out of [6]i.e.:

- Density and Microstructure
- Outgassing according to ECSS-Q-70-02
- Tensile properties and hardness (ShoreD)
- Thermal expansion
- Friction and wear (by Pin-on-Disc)
- Ball bearing tests

Although all these properties were measured, this paper focuses on friction, wear and ball bearing tests.

3 EXPERIMENTAL

3.1 Materials and manufacturing

There is a large number of international manufacturers of PTFE-based composites. Most of the PTFE-based composites are usually produced by Free-Form-Sintering (FFS): the PTFE powder is cold pressed in a mould and afterwards free-form-sintered in an oven. The sintering-process is necessary for the composites to achieve the final strength of the semi-finished or finished parts.
Another process for the production of PTFE-based composites is called HCM, Hot Compression Moulding. This high-pressure sintering method is similar to the methods used in powder metallurgy, using a press and heating moulding dies. The applied pressure and temperature profile has to be adapted to the material processed and to the dimensions of the die, since a uniform heat penetration and compaction of the material (composite) is important. This HCM method can produce plates with dimensions of for example 1000 mm x 300 mm and thickness of up to 100 mm. The HCM process was selected as it enables higher strength.

The compositions selected for the study are shown in *Table 1*. All composites labelled "Cxx" were produced by the HCM-method by ENSINGER SINTIMID GmbH. Reference materials were provided by suppliers from Europe (F1) and US (P2) but without detailed information on the composition. ENSINGER also machined the specimen needed for material testing tensile, CTE and friction testing.

Designation of grade	**Fillers types**	**Comment on fillers (amount, size)**
Pure PTFE	--	--
C01-25Gf10M	25% Gf / MoS_2	Glass fibre ∅13µm
C02-20Gf10M	20% Gf / MoS_2	Glass fibre ∅13µm
C03-15Gf10M	15% Gf / MoS_2	Glass fibre ∅13µm
C09-15Mf10M	15% Mf / MoS_2	Mineral fibre ∅3µm (US)
C10-10CNF	10% CNF	Carbon Nano Fibres ∅0,1µm
C23-15Gf +M	Gf / + MoS_2	Increased amount of MoS_2
C33-15Gf -M	Gf / - MoS_2	Decreased amount of MoS_2
C29-15Mf +M	Mf / +MoS_2	Increased amount of MoS_2
C39-15Mf -M	Mf / -MoS_2	Decreased amount of MoS_2
C49-MfA M	MFa / MoS_2	Similar to C09 but with Mineral fibres from EU
C59-MfA +M	MFa / +MoS_2	Similar to C09 but with Mineral fibres from EU with increased amount of MoS_2
C71- 15Af M	Af / +MoS_2	Composition as C09, aramid fibres, with MoS_2
Ref-P2	Gf & MoS_2	Glass fibre ∅>25µm
Ref-F1	Gf & MoS_2	Glass fibre ∅15-25µm
Ref-duroid5813	Gf & MoS_2	Glass fibre ∅<10µm

Table 1: Compositions manufactured by ENSINGER and selected for testing. Reference materials P2, F1 and Duroid5813 (all Matrix: PTFE, composition for Ref-materials not known, fibre size derived from cross sections)

3.2 Tribological test devices and parameters

For testing of friction and wear a **High Vacuum Tribometer** based on a Pin-On-Disc configuration was used (*Figure 2*). Test atmosphere were air, vacuum and nitrogen; the tribometer is also capable of running under Martian atmosphere (6mbar of CO_2). A heating/cooling system enables testing between -100°C and +300°C. Friction forces could be resolved by +/- 0.02N. The software enables full control of the test as well as several motion types, like unidirectional or oscillating.

Pins were machined from all materials with spherical tips of curvature 18 mm. Two loads were applied: 1N and 5N. The lower load was selected to achieve a mean Hertzian contact pressure at beginning of the test of 2/3 of the yield strength of the polymer [7]. From this requirement and the curvature radius of 18 mm, the calculated loads were 1-2 N for low load. To compare with references tests, 5N loading was also applied (Testing in [8] was done at 5,5N at radius of 18mm for PGM-HT, Duroid). Further parameters for friction tests were: oscillating motion (stroke approx. 20mm), speed 0.1 m/s, environment (air with 50%rH, vacuum 10^{-6} mbar, nitrogen), temperatures (-80, 20 and +80°C). As counter material, a stainless high carbon steel (AISI440C) was selected. The discs were grinded before friction testing to Ra~0.1µm. All samples were ultrasonically cleaned before testing.

Text case	Environment	Temp. [°C]	Load [N]	Speed [m/s]
X0	Air (50%rH)	20	5	0,1
X1	High vacuum	20	1	0,1
X3	Dry N2	20	5	0,1
X4	High vacuum	20	5	0,1
X5	High vacuum	20	5	0,05
X6	High vacuum	+80	5	0,1
X7	High vacuum	+80	1	0,1
X9	High vacuum	-80	5	0,1

Table 2: Test cases for PoD-Tests in vacuum tribometer

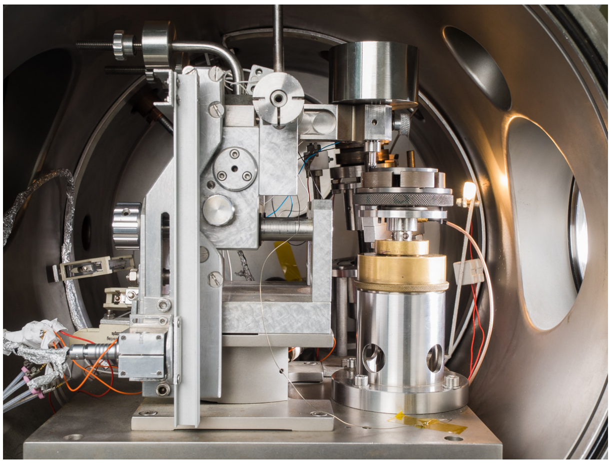

Figure 2: High Vacuum Tribometer (Inside view). Pin and disc holding, heating system not shown.

4 RESULTS on MATERIAL LEVEL

4.1 Tribological Screening of composites (PoD)

Friction coefficient as function of test duration was found to be similar to previous tests [4]: as overall behaviour a slight running-in with increase of friction until approximately 200m sliding distance is seen. After that, in most cases, the friction coefficient stabilises in a range of 0.2-0.3. The “steady-state” friction level is generally very similar between the environments humid air (50%rH) and vacuum.

Tests were done in all relevant environments (humid air, high vacuum and dry N_2). In high vacuum also temperature was varied from -80°C to room temperature and up to +80°C. From these plots of friction coefficient, an average was calculated for the steady state phase. In Figure 3 these average friction coefficients are shown for each tested composition in all test cases. In several cases multiple parallel tests were done to proof reproducibility. Such representation allows performing an assessment of the dependence between friction coefficients and testing parameters. Due to the high number of tests, no details on each test are given, but just deviations are highlighted: a material must be useable in all environments.

The friction coefficient for the new composites with European mineral fibres (C49, C59) shows fairly the same behaviour as the reference materials from the previous project: scattering between 0,18-0,30. There is no clear dependence on environment, temperature or load (1 and 5N) visible. This means that the new composites based on European mineral fibres or even with aramid fibres are promising from view of friction coefficient. Figure 3 and Figure 4 show also the values for composites C03 (glass fibres/MoS_2) and C09 (mineral fibres/MoS_2) as reference [4].

In addition to previous test campaigns, also friction at low temperature (-80°C) was measured: values for all tested variants were in the known range (0,2-0,3).

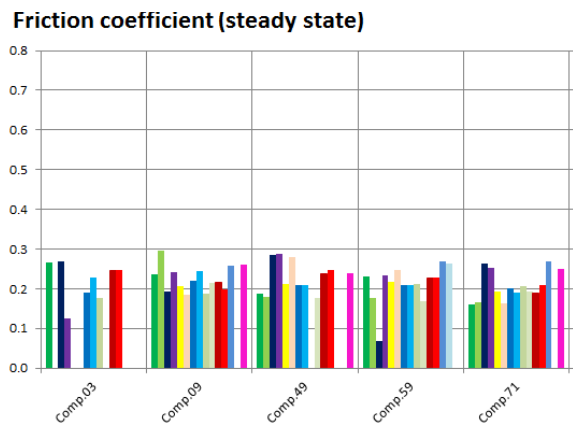

Figure 3: Friction coefficient for new composites based on European mineral fillers (C49, C59) and aramid fibres (C71) compared to US based mineral fibres (C09) and glass fibres (C03): Friction in all test cases in range 0,18-0,30.

In two cases (C03 and C59) a very low friction coefficient was found. This effect was discussed as “super-low-friction” regime [4]. It appears at unpredictable times of sliding. A clear relation to composition or test parameters could not yet be established. The super-low-friction regime is found preferably at low loads (1-2N) with friction coefficients in range of 0.07-0.12. It has to be said, that this super-low-friction regime was not reproducible. This friction coefficient is close to that of pure PTFE or pure MoS_2. This effect is not reported in literature [9] on Duroid5813 or PGM-HT. However, testing in [9] was done at higher loads.

4.3 Wear

Figure 4 shows the wear rates for the investigated composites. The wear rates were determined by measuring the diameter of the contact areas on the pins after testing. From that the lost volume was calculated. Generally, all compositions show reasonable low wear rates in range of 1 to 20x10^{-6} mm³/Nm which is rather low compared to pure PTFE (>>10^{-4} mm³/Nm). (For details please refer to [4].)

As target, the range of wear rate for Duroid 5813 was taken (10-20x10^{-6} mm³/Nm). It can be seen, that the measured wear rates are mostly slightly less than the targeted range of 10-20x10^{-6} mm³/Nm. Overviewing the results, composite C59 shows slightly higher wear rates than C49 or C09. On the other hand, wear of C71 (aramid fibres) was found to be too high.

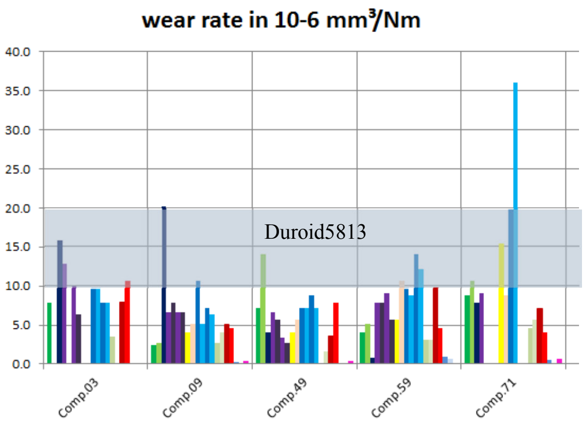

Figure 4: Wear rates for new composites based on European mineral fillers (C49, C59) and aramid fibres (C71) compared to US based mineral fibres (C09) and glass fibres (C03).

5. BEARING TESTS

5.1 Ball bearings

First ball bearing tests were done by ESTL during previous project on C01 (glass fibres and MoS_2), C09 (mineral fibres and MoS_2) and two variants with higher (C29) and lower MoS_2 content (C39). Cages were manufactured from the composites and full steel bearings (AISI440C type 7004) with races and balls were assembled. Neither races nor balls were coated with MoS_2. No special running in was performed.

Test duration comprised 1000 revolutions in air followed by 10 million revolutions in high vacuum at RT. The bearings were loaded axially with 40N (850MPa on balls). Motion was unidirectional running at 150 rpm for the first part of the test and 300 rpm for the second part. Bearings were mounted in a back-to-back configuration, and test was started with 1,000 revolutions running in air prior to in-vacuum testing. Torque was measured at certain times over a few slow-speed (2rpm) reversals according to standard procedure. Each data point refers to the average value of this torque record.

Figure 5 and *Figure 6* show the torque plots during vacuum testing. After around 300.000 revs, the composition C29 with higher MoS_2 content shows the lowest torque (*Figure 5*). The two other mineral fibres based composites (C09, C39 with less MoS_2 content) might still be slightly lower than the C01 with glass fibres.

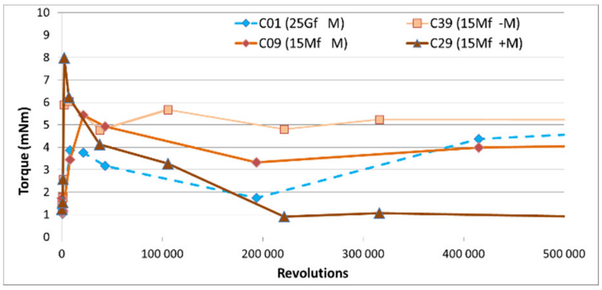

Figure 5: Ball bearing tests: torque in high vacuum (detail showing start) [4]

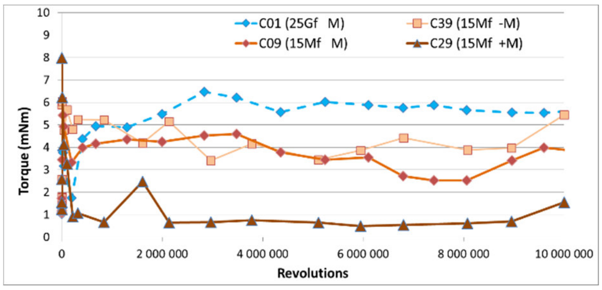

Figure 6: Ball bearing tests: torque in high vacuum (full test duration), C29 with higher MoS_2 shows definitely lowest torque. [4]

Following these first findings, the question on the development of the torque over longer testing durations was risen. The bearings with cages made of C29 and C39 were available in disassembled state after the post-test inspection. These bearings were re-assembled at AAC and re-loaded with 40N. With the AAC-ball bearing test device the test was continued under vacuum with 600rpm. Measurements of torque were done similarly to previous tests at 2rpm over 2 revs. *Figure 7* shows the evolution of the average torque for the two mineral based composite cages: for both composites the average torque measured at ESTL was found during continuation of test at AAC, composite C39 (less MoS_2) keeping the value closer to PGM-HT, and C29 (higher MoS_2) keeping the lower value. The test on C39 was continued up to 60 million revs without changing shape of torque.

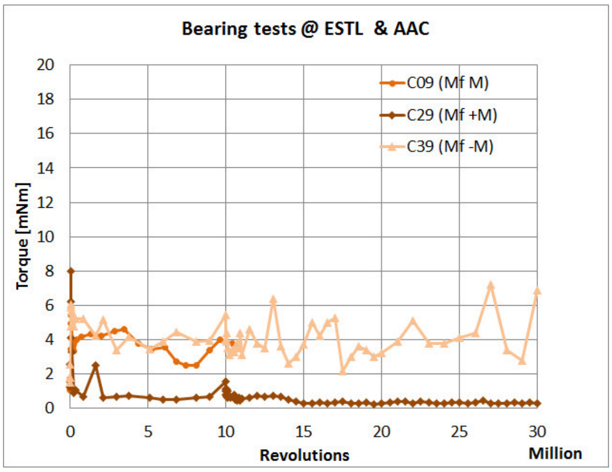

Figure 7: *Ball bearing tests in high vacuum on mineral fibre based composites: C29 with higher MoS_2 shows definitely the lowest torque. (Tests until 10mio rev done at ESTL)*

Due to time saving issues, bearings with cages based on glass fibres and varying MoS_2 content were also manufactured in the previous project, but were finally not selected for testing. Considering the results of mineral fibre filled compositions the question was risen, whether higher MoS_2 content also improves torque in glass fibres based composites.

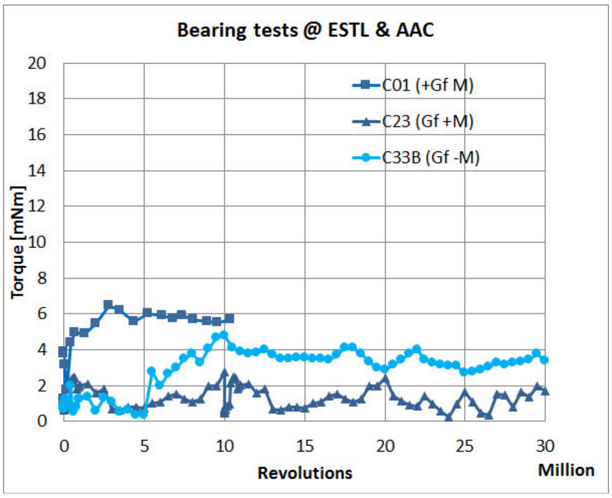

Figure 8: *Ball bearing tests in high vacuum: on glass fibres based composites: C23 with higher MoS_2 shows low torque, but more noise. (Test of C01 done at ESTL.)*

Figure 8 shows the average torque as function of revolutions for those two sets of bearings: C23 is composed of glass fibres and higher amount of MoS_2, C33 has the same glass fibres amount but less MoS_2. C01 is a reference test done by ESTL in previous project (higher glass fibres content and medium MoS_2). It can be seen, that the composites with less glass fibres (C23, C33) show lower torque. In particular, the C23 (with aeven higher amount of MoS_2) shows the lowest torque. However, the torque is still more noisy compared to C29 (same composition, but C29 is based on mineral fibres, *Figure 7*). For C33 (lower amount of MoS_2), the torque increases after some 5 million revolutions. Test on C23 was continued up to 70 million revvolutions (*Figure 9*). At the beginning, also a low torque level was seen (this composite has also a high amount of MoS_2). However, after about 30 million revs, the torque started to increase and levelled out to a value similar to C33 (less MoS_2).

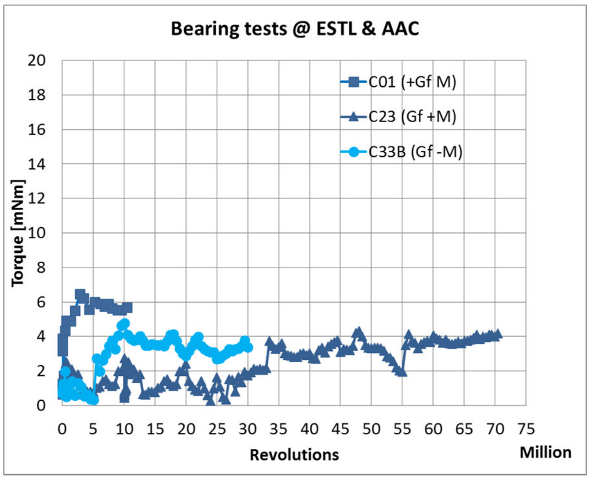

Figure 9: *Ball bearing tests in high vacuum: on glass fibres based composites: C23 with higher MoS_2 shows later an increase of torque. (Test of C01 done at ESTL.)*

To compare the performance shown in those first generation ball bearing tests, average torques can be calculated and compared to reference material P2. It can be seen that the composite C01 with glass fibres shows the highest torque 5,7mNm (*Figure 1*). The new composites show torque levels in the range of 4mNm, being close to the torque of PGM-HT (vac tempered).
Lower torque levels were found for composites with lower amount of glass fibres (C23,C33) but only for limited test durations (*Figure 8*). The torque level then increased in the range of 4mNm.
Only composite C29 with an increased MoS_2-content and mineral fibres shows definitely a lower torque with lower noise compared to all others, including PGM-HT (vac tempered).

6. CONCLUSION

The first main objective of this second development phase was to refine compositions for self lubricating materials (like e.g. Duroid5813, PGM-HT).

The new composites were designed to target low friction and appropriate wear in vacuum from -80°C to until +80°C and, as minor objective, low friction in air too.

Overall, out of 8 composites, 6 could be manufactured successfully. Out of all these materials, test specimen could be machined with proper accuracy and surface appearance. Finally, out of these materials, the most promising are based on European mineral fibres. Recently, composites cages were machined with appropriate accuracy.

Conclusion on material level:

- Following promising results of mineral fibres in the previous project, composites with European variants of mineral fibres were successfully manufactured.
- Specimen for outgassing, mechanical, thermal and tribological testing could be machined properly.
- Outgassing, mechanical and thermo-physical tests showed promising results.
- PoD tests on compositions based on mineral fibres combined with average and high amounts of MoS_2, showed good results in friction (0,2-0,3) combined with wear rates close to those reported for Duroid5813.
- Apart from formulations based on glass and mineral fibres, composites based on aramid fibres were successfully manufactured: friction was found in the expected range (0,2-0,3), but unfortunately too high wear rates were measured.

Conclusion at ball bearing level
(>10 million revs, uncoated races, full AISI440C)

- Selected composites from previous phase enabled good machining of cages: C01, C23/C33 (glass fibres) and C29/C09/C39 (mineral fibres)
- Cages based on materials C01 (glass fibres) and C29/C09/C39 (mineral fibres) were tested in phase one, but tests were continued (after re-assembly) up to 60mio revs. The torque levels seen before were found also for the extended test durations: "normal" for C39, and significantly lower for C29.
- Cages C23/C33 based on glass fibres were tested only now and showed a torque level comparable to reference materials (range of 4mNm). For a limited time since the beginning, a lower torque level was seen.

Summarising all results, it is concluded that **promising alternatives to current commercial PTFE-based materials** could be successfully manufactured. Moreover, candidates based on mineral fibres may allow a composition closer to Duroid than the current commercial materials, **enabling even lower torques in preliminary ball bearings tests.**

Considering other activities led by ESA, like the GSTP with ULG (Université de Liège) on the ball bearing cage dynamics and the TAP activity, with ESTL, on the study of the transfer film of self-lubricating materials, the present Artes activity might lead in having a fully European self-lubricating material for ball bearing cage applications and an associated model to predict the ball bearing lifetime, as the wear will depend on the number of cage | ball contacts (investigated through the GSTP) and the amount of lubricant transfer per cage | ball contact (investigated through the TAP). If this is achieved, it will be a breakthrough in mechanism and tribology science.

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ACKNOWLEDGEMENT

1) The presented results were achieved within an actual project financed by the European Space Agency (ESA): "EU Self Lubricating materials SLPMC2", Contract No. 4000115464/15/UK/ND.