SLPMC – NEW SELF LUBRICATING POLYMER MATRIX COMPOSITES FOR JOURNAL AND BALL BEARING APPLICATIONS IN SPACE

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ABSTRACT

The paper is surveying the results of the ESA-project "SLPMC" covering the development of a self-lubricating polymer composite based on PTFE for use in bearings. The two targets of this project were to investigate lubrication mechanisms in PTFE-based composites under tribological conditions relevant to space applications (air, dry nitrogen, vacuum). And secondly, to develop a new composite to fulfil future needs by space applications. 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 bushes for journal bearings and cages for ball bearings were machined. Ball bearing tests were done in high vacuum up to 10 million revolutions.
This paper summarises the main results from the project 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 final ball bearing and plain 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, a 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 life times. In space mechanisms, such composites based on polymers are well known, as e.g Duroid 5813, PGM-HT (both based on PTFE), but also like Vespel-SP3 and Sintimid=Tecasint (based on polyimide).
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, particles and carbon nano fibres (CNF), and 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.

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2.2 Rationale for selection of fillers

Main Objective in PTFE-composites is to optimise the wear of the PTFE itself towards low wear while keeping low friction. However, a certain wear is needed to enable the formation of a transfer film on counter disc or on races in ball bearings. This is needed for low friction (and that will also lower the wear in return). Using pure PTFE would lead to lowest friction but also to excessive wear, resulting in unacceptable life-time 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 experience, the hard fillers are necessary to steer this wear process in terms of shape of transfer film and of its amount. According to literature [2] hard fillers reduce sub-surface deformation and "crack propagation". [3] report, 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 film. 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.

Following literature and experience from space applications the following filler types were selected for as most promising for the composites in this study:

- Glass/mineral fibres with varying diameter & length
- SiO_2 particles (same chemistry, but "round")
- MoS_2 in addition to hard fillers

Their respective amounts were selected to be close to the most used materials already in use in space applications (PGM-HT and Duroid5813).

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 [4]. However, in the framework of this ESA-Project, as different filler combinations shall be studied, only "core-properties" were investigated out of [5]i.e.:

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

3 EXPERIMENTAL

3.1 Materials and manufacturing

There exists 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 heatable moulding dies. The applied pressure and temperature profile has to be adapted to the material processed and to the dimension of the die, since a uniform heat penetration and compaction of the material (composite) is important. This HCM method can produce plates with dimension of for example 1000 mm x 300 mm and thickness of up to 100 mm.

The difference to the FFS process is that the part remains in the mould during the whole process. The HCM process is more complex, time- and cost-intensive and allows better mechanical properties. So this HCM method is rarely used in the manufacturing of PTFE composites. Sintimid Ensinger GmbH has the experience and the equipment for FFS and also for HCM.

About 20 years ago, it was found that PTFE composites produced with the HCM method compared to the FFS method show higher strength and lower porosity. Hence, for space applications with most demanding performance, the PTFE compounds were produced with this HCM method.

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. (Their general microstructure is not too far from C02/C03 including type of fibres and MoS_2 flakes.)

The mixing of nano-fibres to PTFE was done by AAC. HCM semi-finished discs were produced by ENSINGER. They machined also the specimen needed for material testing tensile, CTE and friction testing.

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 1*). Test atmosphere were air, vacuum and nitrogen; the tribometer is 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.

Designation of grade	Composition Fillers in w%	Comment on fillers (size)
Pure PTFE	--	--
C01-25Gf10M	25% Gf 10% MoS_2	Glass fibre ∅13µm
C02-20Gf10M	20% Gf 10% MoS_2	Glass fibre ∅13µm
C03-15Gf10M	15% Gf 10% MoS_2	Glass fibre ∅13µm
C09-15Mf10M	15% Mf 10% MoS_2	Mineral fibre ∅3µm
C10-10CNF	10% CNF	Carbon Nano Fibres ∅0,1µm
C23-15Gf +M	15%Gf / MoS_2	Increased amount of MoS_2
C33-15Gf -M	15%Gf / MoS_2	Decreased amount of MoS_2
C29-15Mf +M	15%Mf / MoS_2	Increased amount of MoS_2
C39-15Mf -M	15%Mf / MoS_2	Decreased amount of MoS_2
C49-15MfA M		European mineral 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 (C01-C49) 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)

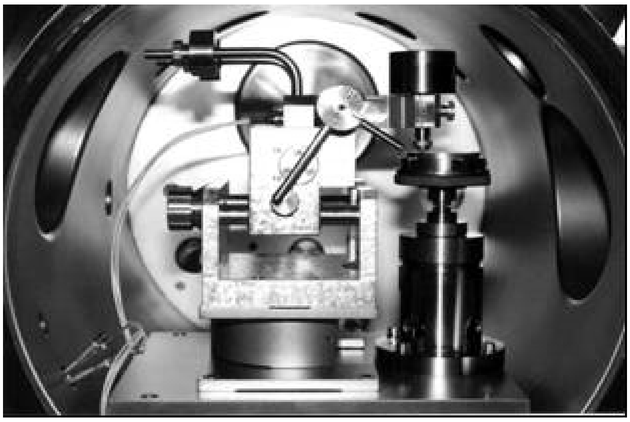

Figure 1: High Vacuum Tribometer (Inside view). Pin and disc holding, heating system not shown.

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 (Pm) at beginning of the test of 2/3 of the yield strength (Ys) of the polymer [6]. 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 a load of 5N was added (Testing in [7] 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, air with 50%rH, vacuum 10^{-6} mbar, nitrogen), temperatures 25 and 80°C. As counter material, a stainless high carbon steel (AISI440C) was selected. Disc were grinded before friction testing to Ra~0.1µm. All samples were ultrasonically cleaned before testing.

4 RESULTS on MATERIAL LEVEL

4.1 Tribological Screening of composites (PoD)

In the following images (*Figure 2* to *Figure 5*), plots of the friction coefficient as function of cumulated sliding distance are shown for each tested composition. Each plot covers all tests done. Such representation allows performing an assessment of the dependence between friction and testing parameters. Hence, no details on each test are given, but just deviations are highlighted.

As overall behaviour a slight running-in with increase of friction until approximately 200m sliding distance is seen. After that in most cases 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%rR) and vacuum.

However, for certain compositions related to low load/high speed or high load/low speed, a "super-low-friction" regime appears. Neither the starting point for super-low friction, nor the appearance itself is not fully reproducible.

The compositions (C01-C03) are based on a variation of content of short glass fibres. It can be seen that for certain parameters a "super-low-friction" regime is found, which appears at unpredictable times of sliding. This is in most cases related to tests at low load and or lower speed. This effect seems to emerge with higher glass fibres content (>20% C01 and C02 (*Figure 2*)). With C03 (15w%Gf) this effect was not seen (*Figure 3*).

Concerning its microstructure Ref-Material-P2 seems to be close to C01-C02 regarding size of hard fillers and the addition of MoS_2. Its behaviour is quite similar to C02: super-low friction emerging for low load or low speed (*Figure 4*).

A second reference materials "F1" was tested. It is also based on PTFE filled with glass fibres and MoS_2. The exact composition was not communicated by the supplier. Microstructural investigation shows the size of glass fibres being approximately similar to Reference material P2 and composites C01-C03. It shows in principal similar behaviour with super-low-friction at RT (low load). The only exception is an increase of friction when testing in N2 after some test times (*Figure*

5). A similar behaviour was seen in composite C05, where a modified PTFE-polymer was used as matrix.

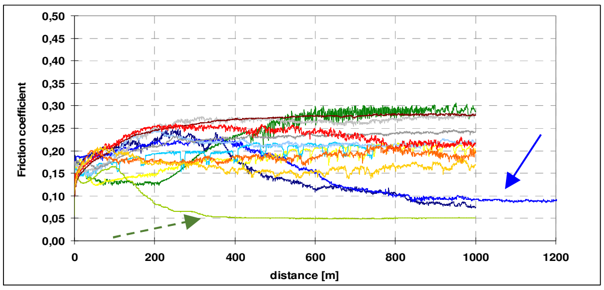

Figure 2: Composition C02 (..20GF..): Friction as function of test duration, partly super-low-friction for low load (→) and high load/low speed (- ->) (all at RT).

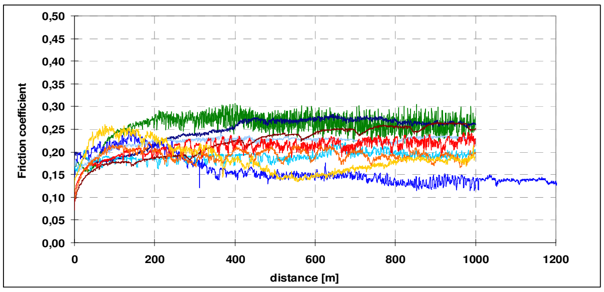

Figure 3: Composition C03 (..15GF..): Friction as function of test duration, super-low-friction not clearly identified (low load at RT).

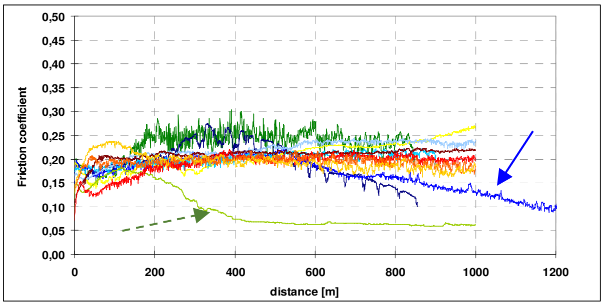

Figure 4: Ref-Material-P2: Friction as function of test duration, partly super-low-friction for low load/high speed and high load/low speed (all at RT), similar to C02.

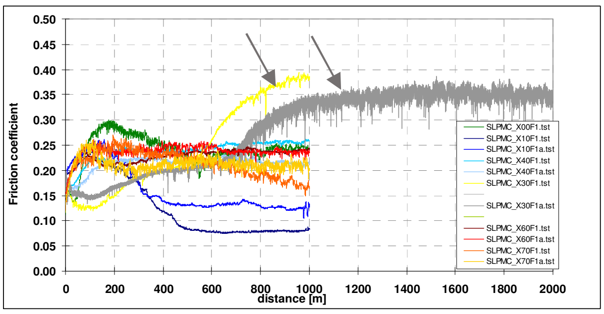

Figure 5: Ref-Material-F1: Friction as function of test duration, high friction in N2for F1 (→).

Following these findings, and the fact that Duroid5813 was based on definitely smaller fibres, some composites were manufactured with smaller fibres (mineral fibres and CNFs).

C09 was filled with a mineral fibre being thinner than the glass fibres mentioned above and MoS_2. This mixture leads to constant friction being almost independent of all test parameters within 0.17-0.27. No super-low-friction regime was seen.

Composite C10 was filled only with carbon nano fibres (CNF) and no MoS_2. Even without any MoS_2 constant friction is seen combined with low wear. Average friction is slightly higher (0.25-0.33) than for the C09 but also independent from all test parameters and environments.

4.2 Mean friction

Each test was assessed defining the “steady state phase” from its end. It means in case of the super low friction regimes, the “steady state phase” represents this regime. From this whole “steady state phase” an average value and the peak value were calculated. Details are shown in [8]. Overall trends are summarised as follows.
The chosen compositions revealed almost similar mean friction being close to 0.2. Composites with large glass fibres (C01, C02, C03, P2 and F2) combined with MoS_2 show the appearance of super-low-friction regimes. Also composites with combination of SiO_2–particles and MoS_2 (C06, C07) seem to promote this super-low friction. Composites with smaller mineral fibres (C09) or CNF only (C10, C11) do not show this regime.

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

Wear factors were determined by measuring the diameter of the contact areas on the pins after testing. Generally, all compositions show reasonable low wear factors in range of 10^{-5} to 10^{-6} mm³/Nm compared to pure PTFE (>>10^{-4} mm³/Nm). (For details please refer to [8].)
As discussed in literature the shape of wear tracks is of interest. A selection of wear tracks were investigated by optical microscopy. At first glance, during start of testing grooves on the steel discs are filled with transfer particles. In case of longer testing and/or higher loads

the transferred amount increases. In general, the tracks show dark brown appearance (except for a track with pure PTFE where gross amounts of flakes are attached).

4.4 Influence of MoS_2 content on friction (PoD)

During first part of the project a fixed content of 10w% of MoS_2 was combined with different types of hard fillers (glass and mineral fibres, SiO2-particles). Only Nanofibers were embedded without MoS_2. Results were presented in [8] and summarised above. In the second part of the project, on two composites (C03 with glass fibres and C09 with mineral fibres) the MoS_2 content was varied to a lower "-M" and a higher "+M" content. After successful manufacturing, mechanical and tribological tests at room temperature were performed. Between 2 and 4 PoD-tests per composite were done on loads of 1, 5 and 10N and compared to results from previous testing. The mean friction coefficients from the steady state of each test were averaged. This average is plotted as bar together with the minimum and maximum values found (reflected by the error bar).

A slight influence of MoS_2 content on friction can be seen: less amount of MoS_2 (C33) shows more stable friction (*Figure 6*). Also for composite with higher amount of glass fibres no low friction is seen (C01 right on the side). Spoken in the other way: increase of MoS_2 may promote the super low friction effect. This effect is still not understood (on the other hand it is not sure if there is any influence on bearing level). It shall be noted, that for certain Gf-base composites even the average at low load is low, meaning that this effect is reproducible.
Increase of load (>5N) steers friction towards PTFE (~0.2), and decreases scattering (no super-low-friction occurring by chance in single tests).

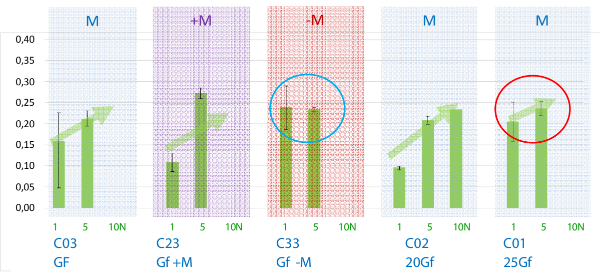

Figure 6: Pin-on-disc-tests: survey of friction coefficients for glass fibres based composites

In contrast to glass fibres, the average friction is more stable when using mineral fibres (*Figure 7*). However, also here scattering to low values was found. It seems that the medium MoS_2 content used in C09 shows most stable friction. Composite C49 uses an alternative European mineral fibre. First screening shows similar performance as for the US-based fibres used in C09.

Using nanofibers leads to almost stable friction at level of PTFE (*Figure 7*). They enable to stabilize wear properly without need of additional MoS_2. (Literature reports that glass fillers without MoS_2 exhibit higher wear combined with risk of scratching the counterpart.)

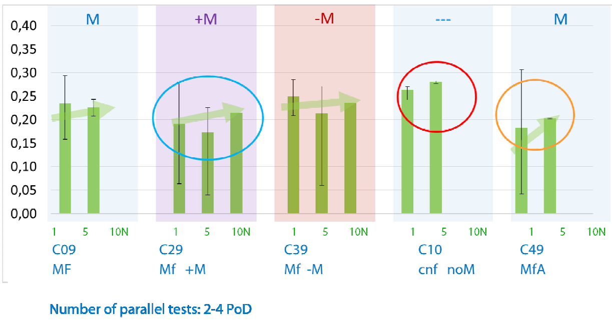

Figure 7: Pin-ON-Disc-tests: overview on friction coefficient with CNF and mineral fibres (US-fibres in C09,C29,C39, European supplier in C49).

4.5 Overview - Influence of parameters

Contact pressure / Load: there is an influence of load on friction visible, sometimes. At beginning it was dominated for composites with glass fibres of larger diameter (C01-C03, P2, F1). Following the latest results, a low friction regime may occur after some running time for all kind of fillers when combined with MoS_2. It might be more likely when using glass fillers and higher amounts of MoS_2. It is also more likely when testing at low loads (so far not done in literature, e.g. [7]). However, in some cases after longer testing times it also occurred at medium loads (5N). The effect was also visible in particle filled composites (C06/C07), but there it was combined with definitely higher wear.

Reversible effect by load: It is worthwhile to mention that this super-low-friction appears after some time of sliding, i.e. after some wear. This leads to the assumption that this decrease of friction is related to the contact pressure falling under a certain critical value. At first glance, the important question is if this effect is reversible: it vanishes when load is increased [8].

Speed: only selected composites were tested under high load at lower speed (0.01m/s). There is again an influence between larger fibres and low speed visible: composites with glass fibres of larger diameter (C02, P2, F1) show definite super-low friction, whereas small fibres (C09) do not.

Temperature (+80°C): in general, the typical friction coefficient, in range of 0.2, is observed in almost all conditions and composites. Only for C01 at low loads (25%GF) and for SiO_2 filled composites at all loads super-low-friction is seen. No significant change of wear is seen when increasing temperature. The average friction coefficients are lower than reported for Duroid @60° by [5] being ~0.38.

4.6 Mechanical properties

For tribological applications, the calculation of Hertzian pressures needs the yield stress. All composites and the reference materials F1 and P (in both thermal treatments, P2 being a vacuum based one) were subjected to tensile tests. Only for Duroid5813, not enough material was available and the literature only provides ultimate tensile strength between 6.9 and 17.3MPa [9].

The yield strength for the new composites are close to the reference material P2 ranging from ~7 to ~10MPa (*Figure 8*). The values for the Young's modulus range from 1.5 to 2.5 GPa. Composites based on mineral fibres (MF_M, C09) are slightly higher than the GF-based ones. Tensile strength seems to correlate to the share of the PTFE-matrix. Also, the Young's modulus correlates with the ratio of the PTFE-matrix. The yield strength seems to be inverse proportional to the PTFE-matrix, i.e. the fillers improve the elastic behavior.

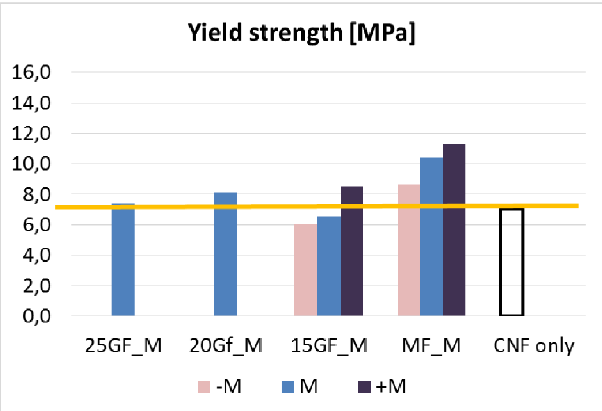

Figure 8: Yield strength of most promising composites: (Line=Reference PGM-HT (vacuum tempered), for Duroid only UTS given >6.9 MPa)

4.7 Thermal expansion

Thermal expansion was measured on selected composites by a dilatometer from -180°C up to +300°C in one full cycle: RT – highT – lowT - RT. In the *Figure 9* the average of 2 parallel specimen are plotted. It can be seen that the CTE is fairly constant and similar for the ENSINGER composites C03 and C09 and Ref F1, especially in the temperature range from RT to +80°C. The drop of CTE is for F1 higher than for the composites C03 (GF/M) and C09 (MF/M).

For the material P in both tempering states, a drop in CTE is visible between +20°C and +80°C. This anomaly vanished after an additional tempering by AAC (indicated by shortly dashed lines, P01T and P02T).

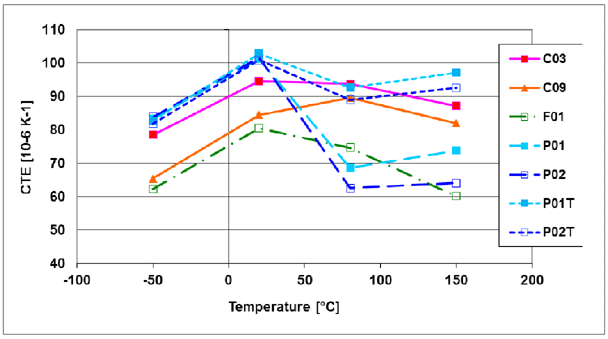

Figure 9: Coefficient of Thermal Expansion: Materials P1 and P2 had to be re-tempered to avoid shrinkage.

5. BEARING TESTS

5.1 Journal bearings

From the 5 most promising composites bushes were manufactured and tested against hard steel shafts (440C) in air, vacuum and vacuum@80°C. They had 10mm inner diameter, and 10mm length. Load of 100N was applied in radial direction. Reciprocating movement with an angle of 50° and a speed of 0,01 m/s was selected in accordance to previous projects [10].

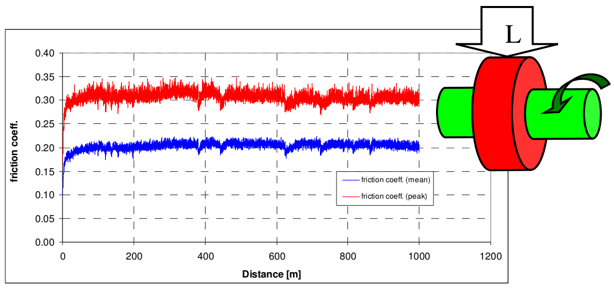

Figure 10: Example and principle for bush test: Friction is steady over the whole test

All compositions showed almost steady friction with some running in. Torque values for all composites are in range between 0,08 and 0,11Nm. There is no clear trend visible, e.g. by amount of MoS_2 or by environments. Overall, no clear favourite was identified, maybe C09 (mineral fibre) is on lower side of scattering with 0,08Nm in all environments. No measureable wear was found in all cases (all values within scattering of method).

5.1 Ball bearings

Ball bearing tests were done by ESTL in the middle and at the end of the project. First selection covered C01 (glass fibres and MoS_2) and C09 (mineral fibres and MoS_2). After refining of the compositions, the final bearing tests were done on C29 and C39 (both mineral fibres with higher and lower MoS_2 content as in C09). Cages were manufactured from the compositions 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. Hence, the plots of torque in air refer to the first motions of the new bearing (with blank steel races).

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 and 300 rpm for the second test run. Bearings were mounted in a back-to-back configuration, and were 'run-in' in air for 1,000 revolutions prior to in-vacuum testing. Torque was measured periodically through slow-speed (2rpm) reversals according to standard procedure.

Torque during first 1000 revs in air is shown in *Figure 11*. After evacuation, initial mean torque in high vacuum ranged up to 8mNm. *Figure 12* and *Figure 13* 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 12*). The two other Mf-based compositions (C09, C29 with higher MoS_2 content) might still be slightly lower than the C01 with glass fibres. However, there is the need for repeatability testing to confirm those trends.

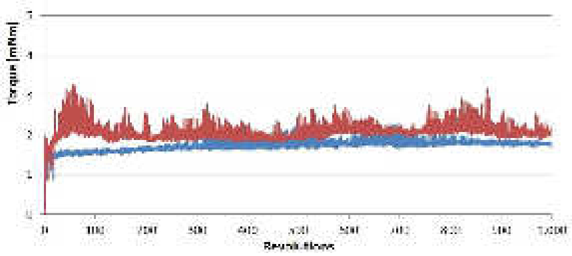

Figure 11: Ball bearing tests (C29,C39): torque in air

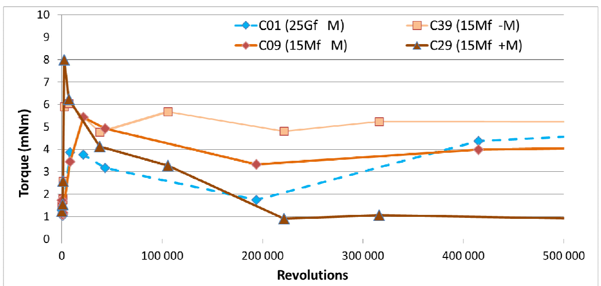

Figure 12: Ball bearing tests: torque in high vacuum (detail showing start)

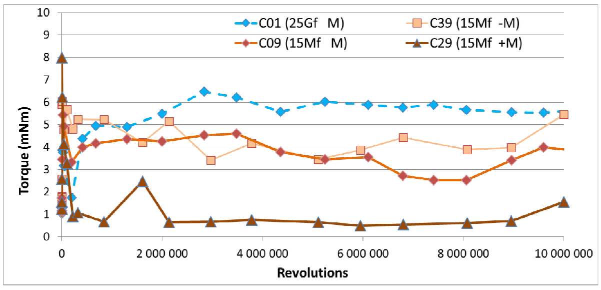

Figure 13: Ball bearing tests: torque in high vacuum (full test duration), C29 with higher MoS_2 shows definitely lowest torque.

To compare the performance from those ball bearing tests the average and peak torques were calculated and compared to reference material P2 (*Figure 14*). It can be seen that the composite C01 with glass fibres shows the highest torque 5,7Nm). The composite with mineral fibres show lower torque (4,0-4,5Nm) being closer to the torque of PGM-HT (vac tempered). The composite C29 with an increased MoS_2-content shows definitely a lower torque compared to all others including PGM-HT (vac tempered).

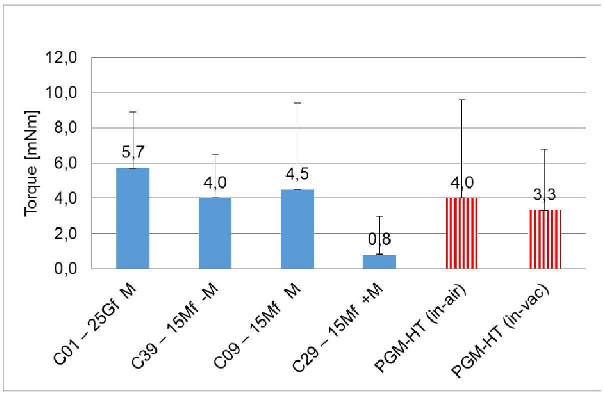

Figure 14: Ball bearing tests: torque in high vacuum, compared to literature (for PGM-HT)

6. CONCLUSION

The first main objective of this project was to define a set of compositions considering on one hand successful materials in use (Duroid5813, PGM-HT) and new materials with a wider scope on fillers considering also knowledge from literature and experience.

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

Overall, out of 16 designed composites 14 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, 4 composites cages were machined again with appropriate accuracy.

Conclusion on material level:

- The family of PTFE as matrix is proposed to be followed for the current requirements as stated in the SOW. Other matrix material like PEEK or polyimide do not offer low friction in air. Most of the properties specified in current RSD [5] are achieved.
- PTFE with modified chemical structure (C05) shows high friction after longer test duration in dry nitrogen, and is therefore not useful when testing in dry nitrogen is planned. Similar is seen for reference material F1 (no information from supplier).
- Fillers need to have an aspect ratio > 1, i.e. short fibres or at least whiskers, spherical particles are not as efficient in wear and mechanical performance.
- Mechanical behaviour of all composites is promising and comparable to existing materials.
- CTE is reproducible for all ENSINGER composites, except for reference material P2 (for both tempering states the delivered specimen showed instable CTE). After an additional tempering at AAC this vanished.
- Super low friction occurs on all parameter sets, the reason is still unclear. It is more likely with bigger glass fibres on one hand and higher amount of MoS_2 and also for mineral fibres on the other hand. Increasing the load causes the friction coefficient to approach 0.2-0.25 (PTFE –lubrication). It was also never seen with carbon nano fibres (here no MoS_2 was added to the composites).
- Composite material (C02) with PTFE/ Glass fibres/ MoS_2 with 20m% glass fibres shows similar friction and wear rate as references P2 and F1.
- Composite material (C09) with PTFE/Mineral fibres/ MoS_2 with much smaller diameter mineral fibres (C09), shows similar friction and wear rate than Duroid5813.
- Apart from standard formulations based on glass fibres, nano fibres might be an interesting option, as friction is found almost independent of environments/temperature and independent of load (~0,25-0,3 even without MoS2).

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

- Selected composites C01 (glass) and C09/C29/C39 (mineral) 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 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**.

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