TRIBO-COMPONENT TESTING OF SELF LUBRICATING COPPER COMPOSITES AT MEDIUM TEMPERATURES IN SPACE

A. Merstallinger [(1)], M.Fink [(1)], E. Neubauer [(1)], L. Gaillard [(2)], L. Pambaguian [(2)] , M. Anderson [(3)], E. Roberts [(3)]

[(1)] AIT Austrian Institute of Technology GmbH, A-2444 Seibersdorf, andreas.merstallinger@ait.ac.at[1]
[(2)] ESTEC, Noordwijk, [(3)] ESTL, ESR Technology.

ABSTRACT

A new type of self-lubricating metallic material for use in tribological sliding contacts up to medium temperatures under vacuum is presented. It is based on copper matrix with inclusions of solid-lubricant particles, which is referred to as "Metal-Matrix-Composite" (MMC). The main step forward was the development of an appropriate manufacturing process by AIT together with MoS_2. Previous papers have proven low friction in several environments (from humid air to space at temperatures up to around 300°C), but also electrical conductivity and thermal expansion close to steels.

This paper summarises new results based on CuMMC compositions with even higher filler contents up to 60v%. Further, components like bushes for plain bearings and cages for roller bearings were manufactured and tested showing promising tribological performances. This material could be a major contribution to forthcoming missions into the inner solar system, as. e.g. Bepi-Colombo. Here, temperatures in the range of 300°C are expected.

1. INTRODUCTION

An increasing number of tribological applications is operated under medium or high temperatures. Since liquid lubrication has to be avoided, solid lubrication is usually selected and the use of composite materials comes into interest. For example, journal bearings or roller bearing cages are often made from polymer composite (e.g. PTFE/MoS_2/Glass fibres like PGM). Unfortunately, there is no recommended material at the moment for medium temperatures in space. BepiColombo-Mission going to mercury, is an actual example, where temperatures close to 300°C are expected for the roller bearings of the antennas.

The main technical step forward is also to fill the gap between those "ambient" temperature materials (up to ~70°C) and high temperature materials (starting at 400°C). The new process enables Cu-MMCs with solid lubricants up to 50v%. As shown previously [1], good tribological properties are combined with good mechanical properties.

Besides space applications, good tribological properties under vacuum are needed in manufacturing processes, e.g. for automated vapor deposition devices, where support lines for feeding the substrates into the vacuum chambers have be designed with high reliability. However, solid lubricants with low evaporation rate, high reliability and life time are recommended for the performance of these expensive vacuum systems.

2. NEED FOR NEW METALLIC COMPOSITE

Metal matrix composites with embedded solid lubricating particles are only for ground applications commercially available. They are based on bronze or brass with graphite. One product was identified with WS_2. However, it is very brittle. This is based on the restrictions for the manufacturing process arising from the need for sulfides: at the high pressing temperatures reactions between sulfides and the copper occur, i.e. the solid lubricant particles are destroyed. Other papers report only poor lubrication performance [2],[3]. Therefore, commercial available products are based only on copper and graphite (only). These are not suitable for space applications.

The need of MoS_2 inside a metal matrix for low friction in space needs a special manufacturing process considering following restrictions:

1. MoS_2 particles must not react with the copper (bronze) matrix
2. High amounts of fillers must not lead to brittleness

The AIT-manufacturing process fulfils restriction 1 by appropriate process parameters and point 2, by the so called "coated-particle" method. Based on that, selection of fillers (MoS_2) can be done on need of application under vacuum. E.g., carbon fibres were added for functionality in air. This actual publication focuses on new compositions with high filler amounts up to 55v% and tribological application testing (journal bearings and ball bearings).

[1] AIT Austrian Research Centers GmbH has changed its name to AIT Austrian Institute of Technology by June2009

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3. EXPERIMENTAL

3.1. Manufacturing

Typically, manufacturing by "powder technology" consists of mixing of the metallic and filler powders followed by compaction, e.g. hot pressing. As mentioned above, the need for higher filler contents can be fulfilled by use of an AIT-internal process called "coated-particle": the filler particles or short fibres were coated with copper before hot pressing. Comparison to conventional hot processing showed superior mechanical performance [1].

Actually, new compositions with even higher filler amounts were processed. The **selected MMC compositions** are shown in table 1. The main requirement was low friction in all environments, combined with good mechanical and machining performance.
Semi finished parts (plates or cylinders) were produced for excerption of specimen for basic tests (Pin-on-Disc, compression, CTE) as well as for cages and bushes.

Designation	**Type**	**Composition Fillers in v%**
Cu12Sn-5M	Cp	5 v% MoS_2
Cu12Sn-25M	Cp	25 v% MoS_2
Cu12Sn-12M15Cf	Cp	12 v% MoS_2 15 v% CF
Cu12Sn-25M15Cf	Cp	25 v% MoS_2 15 v% CF
Cu12Sn-35M15Cf	Cp	35 v% MoS_2 15 v% CF
Cu12Sn-40M	Cp	40 v% MoS_2

Table 1: CuMMC compositions (CF=short carbon fibres)

3.2. Testing on specimen level

From raw disc-like plates, samples were cut and investigated for microstructure, mechanical and tribological properties. **Mechanical** testing covered standard compression tests at RT and 300°C. Besides that, thermal expansion was measured from -180°C to +450°C. Two cycles were done in order to shows if the material shows relaxation effects.

For **tribological** testing a Pin-On-Disc type vacuum tribometer was used. It is capable of testing from -100°C up to +300°C (under vacuum !). Pins were machined with a spherical tip radius of 9mm. Further parameters were: load of 5N, oscillating motion (angle of 70° at circular radius of 25mm), speed 0,1 m/s, air (50%rH) or high vacuum, temperature 25 and 300°C. As counter material, a stainless high carbon and high nitrogen steel was selected (trade name "Cronidur 30", hardness>58 HRC at 300°C). Disc were grinded before friction testing to Ra<0,1µm. All samples were ultrasonically cleaned before testing.

3.3. Testing on application level (bush and cage)

Following results of previously mentioned tests, for both application tests the composition Cu12Sn-35M15Cf with 35v% MoS_2 and 15v%Cf was used.

For journal bearing tests bushes were machined from CuMMC at AIT. The overall dimension were Inner diameter ID=10mm, length L=10mm, and outer diameter OD=16mm. As counter specimen a shaft made of Cronidur 30 was used. They were polished to roughness Ra~0,1µm. Tests were run in oscillating mode with angle of 50° and speed of 0,01m/s. Tests were done at 150N load (approx. 2MPa). Tests were stopped at 1000m, i.e. 110.000 cycles.

At ESTL ball bearing tests were performed using ball bearings, type 7004 which were mounted as soft-preloaded pairs. These bearings have races manufactured from Cronidur 30 steel and are fitted with silicon nitride balls. No coating was applied onto the races. Four cages were manufactured from CuMMC (35M15Cf). Two tests were done using two pairs of bearings: one at RT for 1000 revs in air and 250.000 revs in vacuum, and the second under vacuum at 300°C for 250.000 revs. (See fig.1.)

Figure 1: Images of bush (manufactured by AIT) and cage (manufactured by ESTL)

4. RESULTS

4.1. General properties for high filled compositions

Mechanical properties of CuMMC are shown in fig.2: The compressive yield strength σ_{RP02} is significant higher than the minimum required by DIN 1705 for standard alloy Cu12Sn. It decreases almost linear with increasing filler amount from up to 50v%. But even at 50v%, it is still higher than conventional manufactured composite Bronze with 25v% MoS_2 (~100 MPa) [1]. Only minor decrease due higher temperature is seen (300°C). (See fig 2a and 2b.)

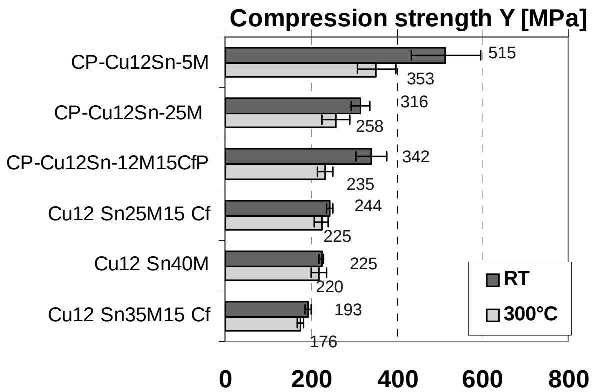

Figure 2a: Mechanical properties of CuMMC: compressive yield strength decreases linear up to 50v%. But is still higher than conventional composite Bronze-25M (~100MPa). Minor decrease due to higher temperature (300°C).

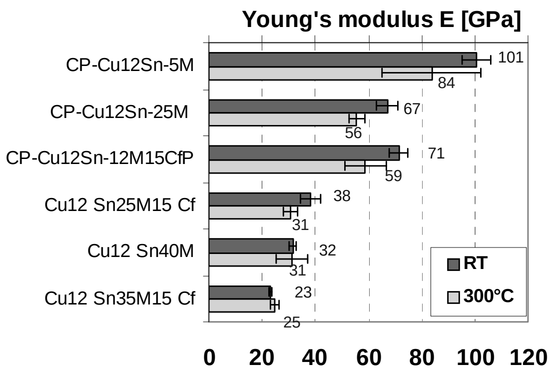

Figure 2b: Mechanical properties of CuMMC: Young' modulus similar to yield strength

4.2. Thermal properties

For components like bushes or cages which shall be used in a wide temperature range, eg BepiColombo up to 300°C, a thermal expansion coefficient (CTE) close to steel is highly appreciated. Thermal expansion tests were performed in a temperature range of -180°C to +450°C and in two cycles.

No significant difference between first and repeated cycle is found, i.e. no relaxation effects or the like were found. Secondly, the CTE is almost constant over the whole temperature region and no significant deformations of the samples were identified after testing. This means, that the CuMMC may survive even more the 400°C without dimensional failure, which is a remarkable "safety margin" compared to other (polymeric) materials. Finally, the average CTE is compared in fig.3b. For composition 35M15Cf, a CTE of 13.10^{-6} K^{-1} is found, which is almost similar to steel.

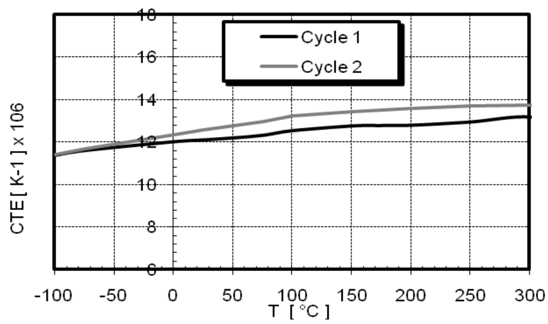

Figure 3a: Thermal expansion test on CuMMC with 35M15Cf: almost constant expansion, with insignificant deviations between cycle 1 and 2. Dimensional stability up to >400°C.

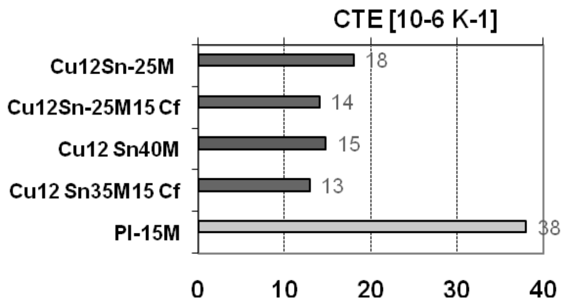

Figure 3b: CTE of CuMMC compared to Polymimde: CTE of CuMMC is close to steel..Slight reduction with higher contents of fillers

4.3. Tribology (Pin-On-Disc-Tests)

Pin-On-disc tests were performed in air, vacuum and vacuum at 300°C. The records of the friction tests were evaluated for the mean value of the friction coefficient after running. Wear volumes were measured by means of an optical profiler, the wear rate is calculated by dividing the volume by the total test distance and the load.

Figure A1 in Annex surveys the friction coefficient (left plot) and the wear rates (right plot) of the highly filled

Cu-MMC compositions versus Cronidur 30. In air, friction coefficients from 0,17 to 0,25 are found, showing no significant difference. Under vacuum at RT, compositions with 35v% MoS_2 and more show lowest friction. In vacuum at 300°C again no significant tendency is visible. Regarding wear, it is clearly visible that compositions 35M15Cf and 40M15Cf show lowest wear rates. Therefore, composition 35M15Cf was selected for ball bearing and journal bearing tests.

In addition to these new tests, all results obtained from pin-on-disc tests on CuMMCs , a load dependence was found: a certain (mean) contact pressure is needed to enable a proper solid lubrication. Friction coefficients of tests (Vac-RT) and all wear rates were plotted against the mean contact pressure at the end of the test (fig.4). It can be seen that reducing the contact pressure leads tin increase of friction and wear. Hence, in design a contact pressure of at least 2MPa has to be ensured, e.g. the bushes shall be as small as possible. This is an advantage, since it reduces the mass.

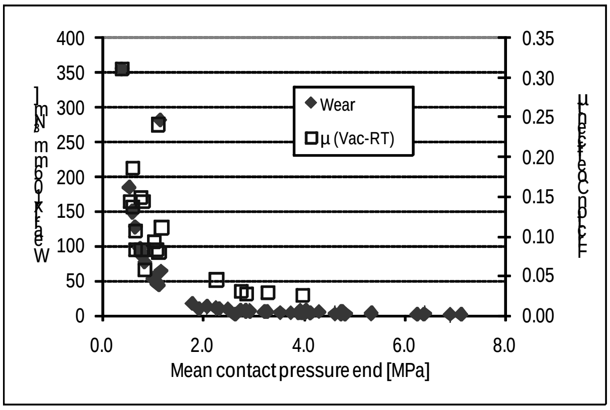

Figure 4: Load dependence analysis for CuMMC: to enable proper solid lubrication a minimum contact pressure of ~2 MPa has to be achieved.

4.4. Journal bearing tests (CuMMC as bush)

Six Journal bearing test were performed in air, vacuum and vacuum at 300°C (2 parallel tests at each environment). From these plots done in oscillating motion, average torque values were derived. They are compared in fig.5a: in air an average torque of ~0,2Nm is seen, in vacuum at RT ~0,05Nm and in vacuum at 300°C ~0,1Nm. This is in good correlation to Pin-on-disc tests.

Additionally, one long term tests was run at vacuum at 300°C. Fig.5b shows the plot of the torque (the lower plot is the average value of each cycle, the upper is the peak.) This test was run for the planned 200.000 cycles in unidirectional motion to achieve a high number of revs. It can be seen that the torque did not change significantly. Also the noise is low (the upper plot of the peak values is close to the average plot.)

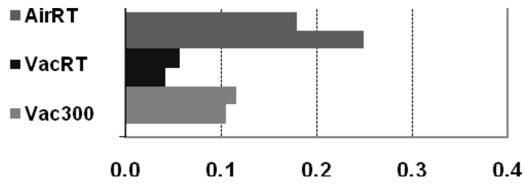

Figure 5a: Torque (average from each test) compared for 35M15Cf.

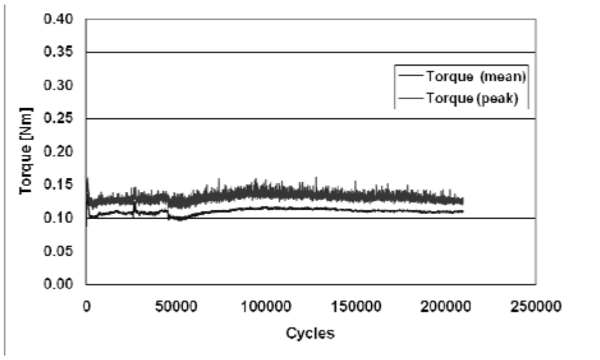

Figure 5b: Long term test of a bush (35M15Cf): no increase of torque or noise.

4.5. Bearing tests (CuMMC as cages)

The two bearing tests were run successfully until planned end at 250.000 revs, i.e. no early failure was reported. In order to show, if CuMMC cages can initiate the transfer of MoS_2 onto the race, no coating was on the races.

Fig. 6a shows the torque measured at RT. During the first 1000 revs in air, a mean torque of ~21 gcm (2,1mNm) is reported and in the following vacuum phase, the torque varies between 20 and 40 gcm (2-4 mNm). Certain peaks are visible.

At 300 deg C under vacuum, the mean torque ranged to approx. 20gcm (2mNm). Close to the start of the test (15,100 revs), some high peak torques are found for approximately 300 revs, i.e during running-in (Fig.6b).

After the high temperature test, one bearing was post-investigated by SEM and EDX in order to prove that the transfer mechanism "MoS_2 from cage to races" had occurred. Fig.7 shows a SEM image in "back-scattered-mode" from the inner race. In this SEM-mode materials with different density are displayed in different grey-tones. A transfer layer is clearly visible on the inner race (bright track). Additional EDX-analysis shows that the transfer layer consists Mo, S with partly Cu and Sn. This confirms that a solid lubricant transfer had occurred.

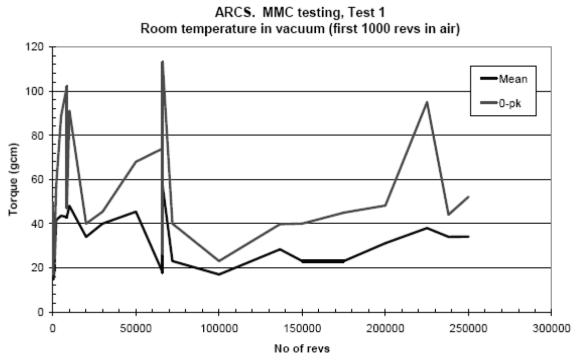

Figure 6a: Torque measured in ball bearings with CuMMC cages at RT in air (up to 1000 cycles) and vacuum.

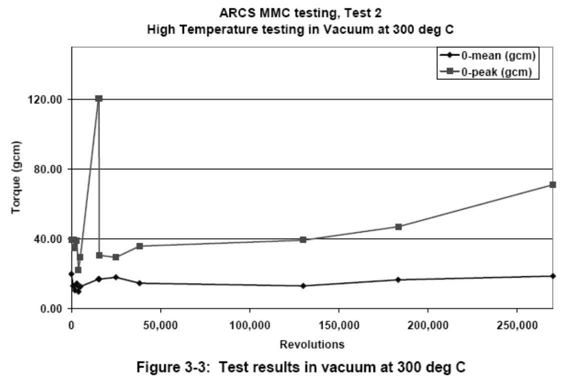

Figure 6b: Torque measured in ball bearings with CuMMC cages at 300°C in vacuum.

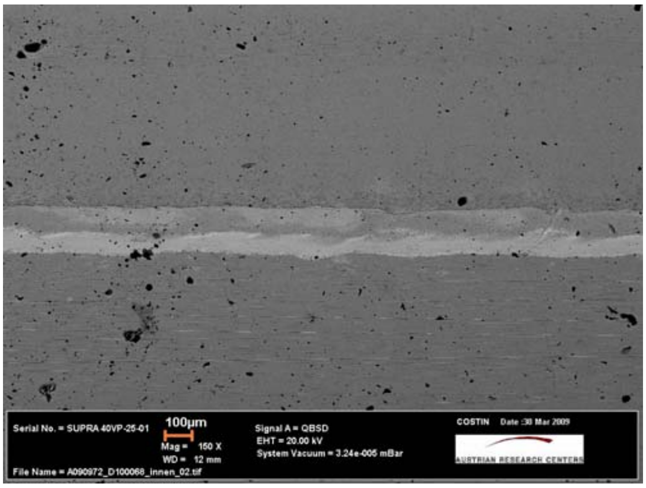

Figure 7: SEM-image (Back-scattered mode): Inner race with transfer layer taken from bearing run at vacuum 300°C (bright track in middle).

Fig. 8 shows a SEM- image of the cage pocket with the grooves from manufacturing (bottom and top) and the wear groove resulting from the ball (middle). The dark spots inside the track clearly visualize the solid lubricant fillers, which is also confirmed by EDX. It was reported that the ball was not worn. From the width of the track and the know radius of the ball, therefore the depth of the track can be calculated to ~10-20µm.

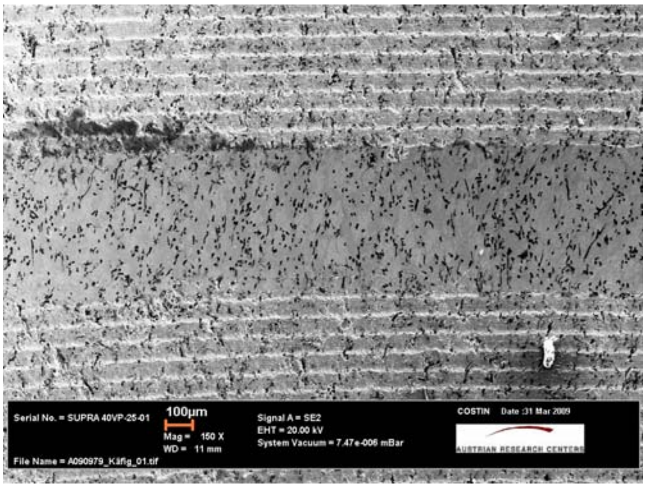

Figure 8: SEM-image: cage pocket with the grooves from manufacturing (bottom and top) and the track created by the balls.

5. CONCLUSION

AIT has developed a process which enables to achieve copper based metal composites (CuMMC) with MoS_2 and short carbon fibres as fillers. The actual study shows that using this process, high filler contents of up to 55v% can be achieved.

Even at high filler contents **mechanical properties** are superior to other process types (see previous studies [1]). This can also be seen in the fact, that cages can be manufactured. **Thermal expansion** could be adjusted to that of steel and no relaxation effects were found in thermal cycling up to 450°C.

Driven by intended space applications, low friction in both environments (humid air) and vacuum was targeted. This could be achieved by a proper combination of fillers. The highest friction was found in humid air with ~0,2, under vacuum friction rises from ~0,05 (RT) to ~0,1 (300°C).

Therefore, this new CuMMC overcomes two long lasting problem: low mechanical properties for copper or bronze composites and non-availability of a space suitable composition with MoS_2.

Testing of bushes shows similar behaviour. The average torque measured in journal bearing tests fit well to the friction coefficients derived in pin-on-disc tests.

First **ball bearing tests** were run at ESTL, using CuMMC as cages. In order to show clearly that MoS_2 is transferred from the cage onto the races, no coating was applied to the races. At 300°C average torques were measured to ~20gcm (2mNm). They are reported to be in ranges of other self-lubricating materials. Certain peaks in torque were found, it is expected that they will decrease during a second test set campaign using MoS_2 coated races (This would be the standard configuration in applications).

Hence, this metal based composite material **"CuMMC" offers a new combination** of properties, presently not being available for space applications like bushes (journal bearings) or cages for roller bearings. This covers low friction in ambient and high temperature vacuum conditions. Higher mechanical strength enables smaller mass efficient design (especially for cages or bushes). The metallic nature of the composite with high amounts of fillers reveal thermal expansions close to that of steel and good thermal conductance (advantage for cages). Finally, no degradation due to radiation is given.

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6. REFERENCES

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ANNEX

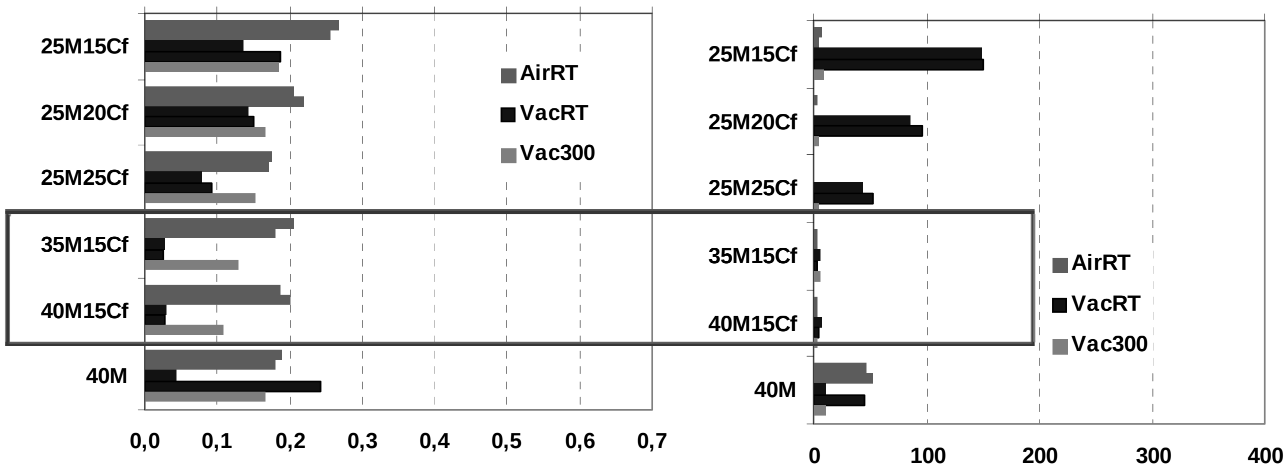

Figure A1: Survey of Friction coefficient (left) and wear rate (right) in air (50%rH,) vacuum and vacuum/300°C: Air: friction coefficient ~0,2. Vacuum: lowest friction achieved with only higher amounts of MoS_2(35-40v%). Combination of MoS_2 and carbon fibres successful: low friction in both air and vacuum. Highest filler contents show low wear too.