Self-lubricating Copper Composites for Vacuum and Space

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SUMMARY

Self-lubricating Cu-MMCs for use in mechanical systems under vacuum or space are not commercially available till now, and usually, published papers on frictional behaviour of such Cu-MMCs report friction coefficients higher than 0,3. In order to improve the performances of the promising Cu-MMCs not only in space applications but also in vacuum systems on ground, a PM-process was optimised to produce high quality composites with solid lubricants by avoiding reaction between copper and MoS_2 particulates. Two routes were followed: a hot compaction of "conventionally mixed" powders and a hot compaction of "coated particles", i.e. the particles were coated with copper before compaction. Cu-MMCs with two kinds of lubricant particles (MoS_2 and short carbon fibres) and contents up to 40v% were also produced. Compression tests at RT revealed that strength and modulus are higher for the Cu-MMCs based on coated particles. Pin-On-Disc tests confirmed friction coefficients under vacuum less than 0,1 at RT, and less than 0,2 at 300°C.

1 INTRODUCTION

In space mechanisms, excellent tribological properties of the moving surfaces in contact constitute a prerequisite for a successful operation in orbit, and have to be maintained during all the life time of the components due to the impossibility of a reasonable maintenance (re-lubrication). However, in an increasing number of applications under medium or high temperatures, liquid lubrication has to be avoided. Herein, 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). Unfortunately, there is no recommended material at the moment for medium temperatures in space. The best example for requiring new materials in this range is the BepiColombo-Mission going to mercury, where temperatures higher than 200°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). Two possible solutions for this gap were studied recently: a polyimide composite [1], which appeared to be a very good candidate [2],[3],[4], and promising Cu-MMCs with solid lubricants largely described in literature ([5], [6]). In complement to the good tribological properties, these two solutions have to fulfil specific requirements like electrical conductivity, thermal conductivity and resistance to radiation, which gives advantage to Cu-MMC in space application.

Furthermore, this interest for good tribological properties under vacuum is strengthened by the need of mechanism under vacuum for elaboration of advanced materials (nano layers, vapour deposition ...). Two developments are supporting this tendency: needs for thin layers usually done under vacuum by vapour deposition and environmental cleanliness with vacuum purity. For the first case of vapour deposition, support lines for feeding the substrates into the vacuum chambers have be designed with high reliability. The requirements for materials used in plain bearings or linear guides are also similar to that for space, excepted the behaviour under radiations or the possibility of replacing broken parts. However, solid lubricants with low evaporation rate, high reliability and life time are recommended for the performance of these expensive vacuum systems.

Hence, the present paper reviews the findings of the development of a self-lubricating Cu-MMC applicable for use in space or under vacuum. Selection of fillers (MoS_2) is driven by application under vacuum. Additionally, carbon fibres were considered for functionality in air. This actual publication focuses on mechanical (compression) and tribological properties.

2 ENVIRONMENTAL REQUIREMENTS - Friction under vacuum

The frictional behaviour under space or vacuum differs strongly from terrestrial environment. Due to lack of oxygen, protecting surface layers (oxides) are scratched away, which is followed by strongly increased adhesive wear due to metal-metal contact [7]. Lubrication by oils and greases exhibits highest risk, since they may evaporate and re-deposit on other critical surface areas, like optical components, solar arrays. In order to minimise these risks solid lubrication is recommended, considering the limitation of low speeds. 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, this effect is driven by the presence of water vapour: it reduces friction of graphite, but degrades MoS_2. Vice versa, MoS_2 is well known for low friction in vacuum environment in a wide temperature and load range. However, its degradation due to humidity is inherent, but also well documented [7]. Polymers, e.g. PTFE, can also act as solid lubricants. However, viscoelastic behaviour, heterogeneity and the temperature dependent microstructure may cause complex frictional behaviour.

Application of solid lubricants is commonly done as a coating or composite material. In roller bearings, often both variants are combined: MoS_2 coating on races of bearings and as composites in cage (e.g. Duroid). MoS_2 –coatings enable low torque noise, but show a certain medium life time and they are susceptible to degradation by humidity. Using a composite, a film is created by transfer of the MoS_2 onto the sliding/rolling surfaces. This means, after degradation of the actual MoS_2 film in air, a new fresh film can be set up under vacuum. For use of materials in space, the European Cooperation for Space Standardisation (ECSS) has defined a check-list [8]. In the framework of an ESA-Project [9], this general check-list was adopted to the application of Cu-MMCS in a plain bearing.

3 EXPERIMENTAL

The **selected Cu-MMC compositions** are shown in table 3. Beside the main requirement of low friction and wear under vacuum, also a low friction in air would be “targeted”. (This would enable functional testing of mechanisms also in air.) The Cu-MMCs were produced in “three” methods, with the main differences in the “powder preparation”:

cp (coated particles = standard): the particulates/fibres were coated with copper, then they were blended with additional Cu- and Sn-powder

hp (hot pressing, as reference): bronze powder (Cu11Sn) was mixed with MoS_2
hpm (hot pressing 2, as reference): powders of Cu and Sn were mixed together with MoS_2

After blending, all mixtures of powders were compacted in the same way. Samples with a diameter of 65 mm and a height of approx.15 mm were prepared by using a graphite die and graphite foils for preventing reaction of CuSn with the die material. The mixed powders were filled into the die (three or four per run) and separated by graphite plates. Cold compaction was followed by a hot compaction using a uni-axial hot press.

Designation	**Type**	**Composition Fillers in v%**
Cu12Sn	HPm	--
Cu12Sn-25M	HPm	25 v% MoS_2
Cu12Sn-5M	Cp	5 v% MoS_2
Cu12Sn-25M	Cp	25 v% MoS_2
Cu12Sn-12M15CfP	Cp	12 v% MoS_2 15 v% CF-Pitch
Cu12Sn-25M15CfP	Cp	25 v% MoS_2 15 v% CF-Pitch
Cu11Sn	Hp	--
Cu11Sn-25M	Hp	25 v% MoS_2

Abbrev-iation	**Description**	**Trade name**	**Size**	**Density (g/cm^3)**
Cu	Copper	Norddeutsche Affinerie "FM"	< 40 µm	8,94
Sn	Tin	Norddeutsche Affinerie "NA"	< 63 µm	7,28
M	MoS_2	MOLYFORM ® M50X	< 50 µm	5,0
Cf-Pitch	Carbon fibres – PITCH	K13A10 (Mitsubishi)	550µm	2,15
Cu11Sn	Bronze			

Table 1: Cu-MMCs procured and tested (left), raw powders used (right).

Compression tests were done acc. to DIN 50106. Specimen were cylinders of L=20 mm versus diameter of 10 mm. For determination of Young's modulus and Poisson's ratio, a video extensometer was used. Tests were done at RT and 300°C.

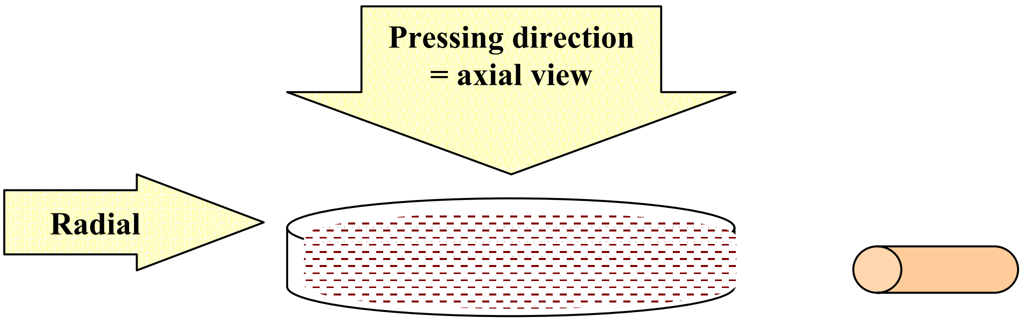

Fig. 1 Explanation of directions for subsequent testing: Pins for compression and friction tests were machined in horizontal direction, as indicated by the pin on right side.

For testing of **friction and wear** a High Vacuum Tribometer was used (Fig.2). The vacuum tribometer is based on a Pin-On-Disc configuration, similar e.g. to ASTM-G99 [10]. Turbomolecular pumping system enabled a base pressure $<10^{-5}$ mbar. A heating/cooling system enabled also to test from –100 to +300°C. Both pin and disc were directly heated. The temperature of the rotating disc was measured and transferred to the controller by a telemetry system. A recently developed control and data acquisition software enables full control of the test as well as several motion types, like unidirectional or oscillating. Pins were machined with a spherical tip, radius 9 mm. The loads were calculated from mechanical data, in order to achieve a mean Hertzian contact pressure (Pm) at beginning of the test of ~70% of the yield strength (Ys) of the softer material, i.e. the Cu matrix. The table 2 shows these loads. Further parameters were: 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", composition Fe-0.31C-0.38N-0.55Si-15.2Cr-1.02Mo, hardness>58 HRC at 300°C). It is capable to withstand service temperatures greater than 300°C. Disc were grinded before friction testing to Ra<0,1µm. All samples were ultrasonically cleaned before testing.

Designation	**Type**	**Load at 25 °C [N]**	**Load at 300°C [N]**
Cu12Sn	HPm	5	5
Cu12Sn-25M	HPm	--	--
Cu12Sn-5M	Cp	10	--
Cu12Sn-25M	Cp	4	5
Cu12Sn-12M15CfP	Cp	5	3
Cu12Sn-25M15CfP	Cp	5	5
Cu11Sn	Hp	5	5
Cu11Sn-25M	Hp	5	5

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

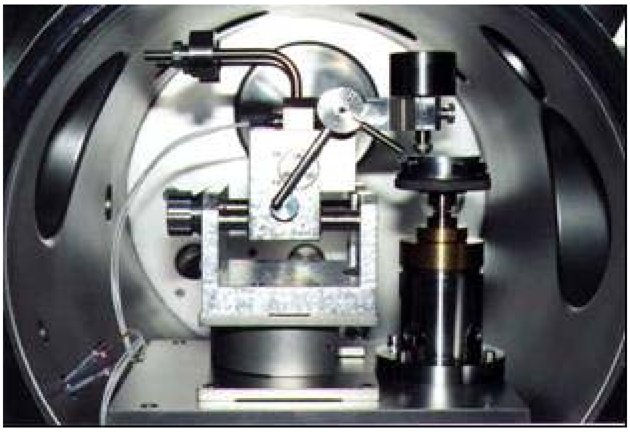

Fig. 2: Vacuum Tribometer (Inside view): heating system not shown

4 RESULTS

The porosity was calculated as difference between measured and theoretical density. All samples of the "cp-route" can be regarded as "full dense". The highest porosities (2-3%) were measured for the samples with the highest filler amount, e.g. Cu12Sn-25M or Cu12Sn-12M15Cf. The hp-grades showed porosities of 5-8%, the hpm-grade Cu12Sn-25M even 15%.

Microstructure of the Cu-MMC grades was investigated by cross sections, done in "both" directions (see also fig.3): left image: axial (view in pressing direction, "top view of plate"), right image: radial (view perpendicular to pressing, "side view of plate", fig.1). Both images confirm a dense metal matrix with well distributed MoS_2 particles, i.e. absence of agglomeration of particles or cracks in the metal matrix. However, the right image shows that MoS_2 particles are more densified in pressing direction. This (right) view refers to the surface which was in frictional contact. In general, Cu and MoS_2 react to give $CuMo_2S_3$. X-ray diffraction was done to confirm that no reaction has occurred (MoS_2 particles are still present).

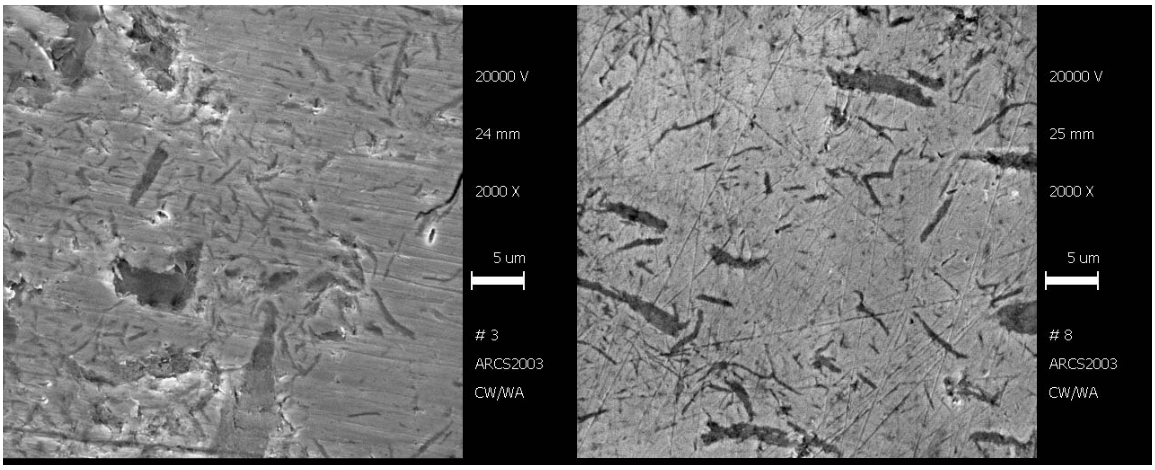

Fig. 3 SEM images show a good distribution of MoS_2 particles (dark lines). Left image: axial, right image: radial. Both images confirm a dense metal matrix with well distributed MoS_2 particles.

4.1 Mechanical properties

Results from the compression tests are compared in fig. 4. Young's modulus of Cu12Sn-5M is close to pure Cu12Sn (prepared by the hpm-route). The two other cp-grades (Cu12Sn-25M, Cu12Sn-12M15CfP) show lower values. The decrease is close to the rule of mixture, approx. 25%. The compressive yield strength σ_{RP02} is significant higher than the minimum required by DIN 1705 (Cu12Sn-lit). It even increases due to reinforcement by solid lubricant particles. Comparison the yield strength and the strength at failure shows, that the elastic regime is enlarged by the filler particles (both values become closer).

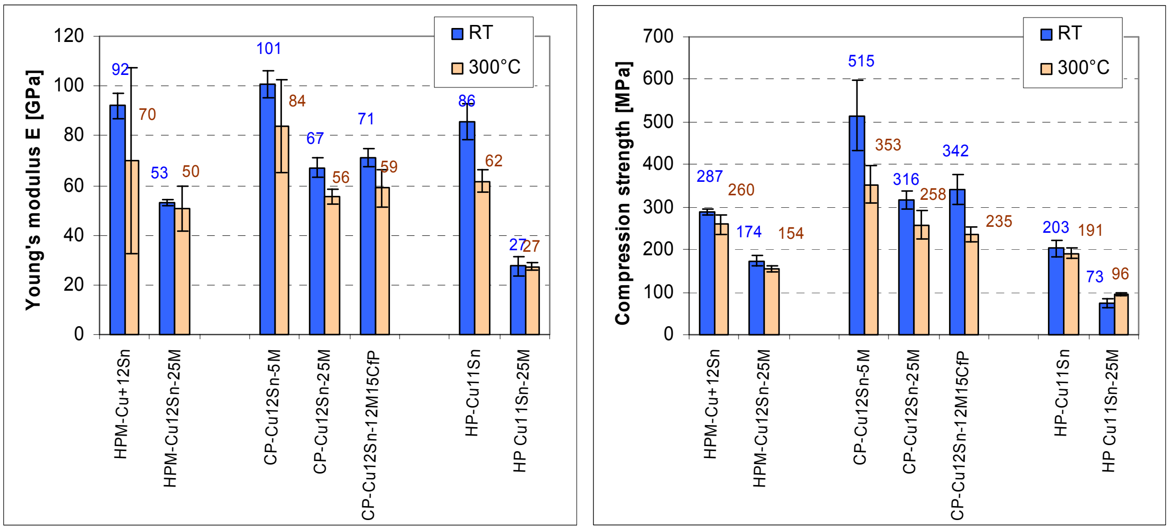

Fig. 4: Compression properties of Cu-MMCs: Left: Young's modulus: all cp-MMCs show higher values than the hp- or hpm-MMCs. Right: compression strength (elastic limit) the high filled MMCs (~25v% fillers) show higher values than hp- and hpm-MMCs.

4.2 Friction and wear

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 test distance and the load. Figure 5 surveys the friction coefficient (right plot) and the wear rates (left plot) of Cu-MMC grades versus Cronidur 30. In air, the lubricating effect is due to the pitch carbon fibers. It is visible by the lowest friction and wear rates. Under vacuum, a reinforcement of 25v% MoS_2 shows lowest friction and wear rate. Reinforcement of only 5v% MoS_2 does not enable proper solid lubrication neither in air nor under vacuum. A reinforcement of 12v% MoS_2 (in the grade 12M15Cf), is also too low for proper lubrication under vacuum. This is reflected by high friction and wear.

As reference friction of hpm-Cu11Sn was investigated at 300°C: the friction is comparable to the cp-grades with 25v% MoS_2 . However, wear is higher and the poor mechanical properties have to be considered.

Surveying these results under the main target of use at high temperatures in vacuum and low speeds, the MMC Cu12Sn-25M15Cf is regarded as best solution.

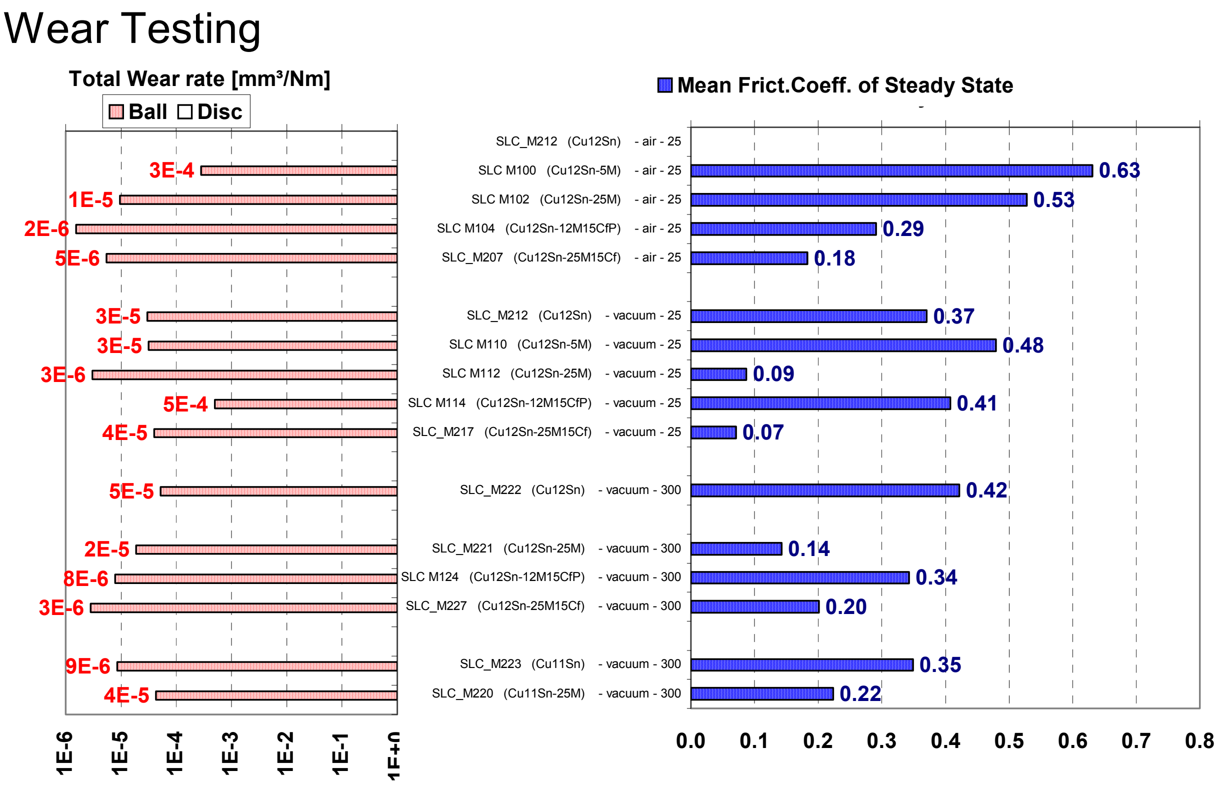

Figure 5: Friction coefficient in air (50%rH) and vacuum, applied loads achieving 2/3Ys of each Cu-MMC. Air: Lowest friction due to carbon fibres (PITCH-type). Vacuum: lowest friction for 25v% MoS_2. Combination of MoS_2 and Cf: low friction in both air and vacuum.

5 CONCLUSION

A PM-process was developed for the elaboration of high quality Cu-MMCs with MoS_2 and short carbon fibres (PITCH-type) as fillers. Optimisation of this PM-process allowed to reduce the reaction between Cu and MoS_2 with a porosity to less than 3%. Driven by intended space applications, the tribological tests focused on low loads and low speeds, combined with oscillatory motion. Surveying the results under the main target of use at high temperatures in vacuum, the compounds Cu12Sn-25M15Cf is regarded as best solution. It enables in a friction coefficient below 0,2 in air and vacuum up to 300°C.

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