SELF LUBRICATING COPPER COMPOSITES FOR TRIBOLOGICAL APPLICATIONS AT MEDIUM TEMPERATURES IN SPACE

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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 ARC together with MoS_2. This enables 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 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. This CuMMC could be envisaged for components like bushes for plain bearings, cages for roller bearings or tracks for slip-rings could be seen as applications. First test show promising tribological and electrical performances.

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). 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 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.

Besides space applications, good tribological properties under vacuum are needed in manufacturing processes, e.g. for automated vapour 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 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 occuri.e. the solid lubricant particles are destroyed. Some published papers on frictional behavior of copper composites including MoS_2 report friction coefficients higher than 0,3. This indicates that the manufacturing process was not optimised, and the MoS_2 is not existing anymore. 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. The present paper reviews the findings of the development of new process for a self-lubricating metal matrix composite based on copper (CuMMC). It is 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.

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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. To find the optimum process for composites with MoS_2 a set of different compositions and processing methods were done. The **selected MMC compositions** are shown in table 1. The main requirement was low friction in all environments. Besides that, high strength was targeted. The MMCs were produced in "three" methods, with the main differences in the "powder preparation":

- cp (coated particles, ARC-process): the filler particles or short fibres were coated with copper
- hp (hot pressing, as reference): bronze powder (Cu11Sn) was mixed with the filler particles
- hpm (hot pressing 2, as reference): powders of Cu and Sn were mixed together with filler particles

After blending (mixing), all powders mixtures were compacted in the same way: cold compaction followed by hot compaction using a uni-axial hot press. Disc like raw plates with a diameter of 65mm were prepared.

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
Cu12Sn-25M15CfP	Cp	25 v% MoS_2 15 v% CF
Cu11Sn	Hp	--
Cu11Sn-25M	Hp	25 v% MoS_2

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

3.2. Testing

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. 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 9mm. The loads were calculated from the measured 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-MMC. The resulting loads were between 3 and 10N. 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", hardness>58 HRC at 300°C). It is capable to withstand service temperatures > 300°C. Disc were grinded before friction testing to Ra<0,1µm. All samples were ultrasonically cleaned before testing.

CuMMC-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-12M15Cf	Cp	5	3
Cu12Sn-25M15Cf	Cp	5	5
Cu11Sn	Hp	5	5
Cu11Sn-25M	Hp	5	5

Table 2 : Parameters for Pin-On-Disc-tests: Load [N] used at test temperatures.

In order to evaluate the usability of CuMMC as tracks for **slip-rings**, the vacuum tribometer was re-configured. Instead of a disc a ring with v-grooves (on the circumference) was machined. Instead of a pin (loaded on the face), an adapter was manufactured which enables a contact between brush wire and v-grooved ring on its circumference (fig.1). The setup enabled measurement of friction and contact resistance. As contact forces 50 or 100mN were used. This necessary loading distance was determined by a separate "bending test". Measurement of contact resistance were taken with a current of 0.325 to 1.625 A/mm². The speed was 0.028 m/s with oscillating motion. Tests were done in ambient and vacuum from RT up to +300 °C.

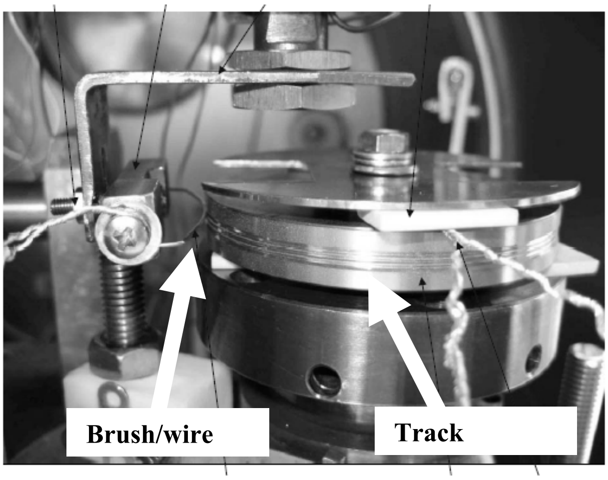

Figure 1: Slip-Ring test setup in vacuum tribometer (with temperature stage to +300°C)

4. RESULTS

4.1. Microstructure

Manufacturing with the new "ARC-cp-route" led to plates which can be regarded as "full dense". Here, the highest porosities was found to be 2-3%. They belonged to 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%.

Cross sections of the CuMMC grades were prepared to investigate the microstructure (see fig.2). The SEM-image confirms well distributed MoS_2 particles inside dense metallic matrix, i.e. absence of agglomeration of particles or cracks in the metal matrix. As metneiond above, there exists the risk, that Cu and MoS_2 react to $CuMo_2S_3$. X-ray diffraction were performed, to confirm that no reaction has occurred. MoS_2 particles are still present as solid lubricant particles (dark areas in fig.2).

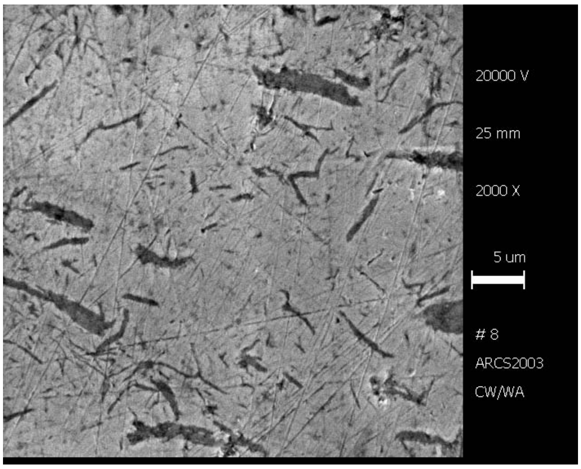

Figure 2: SEM image: dense metal matrix with well distributed MoS_2 particles(dark).

4.2. Mechanical

Compression tests were performed for all three types of manufacturing processes. Figure 3 shows the compression strength in groups: left: hpm (mixing of powders Cu+Sn+MoS_2), middle ARC-cp-route, right hp-route Cu11Sn+MoS_2).

The compressive yield strength σ_{RP02} is significant higher than the minimum required by DIN 1705 for standard alloy Cu12Sn. 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). 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%. Hence, it is visible that the CuMMC made by cp-process developed by ARC has clearly the best mechanical properties.

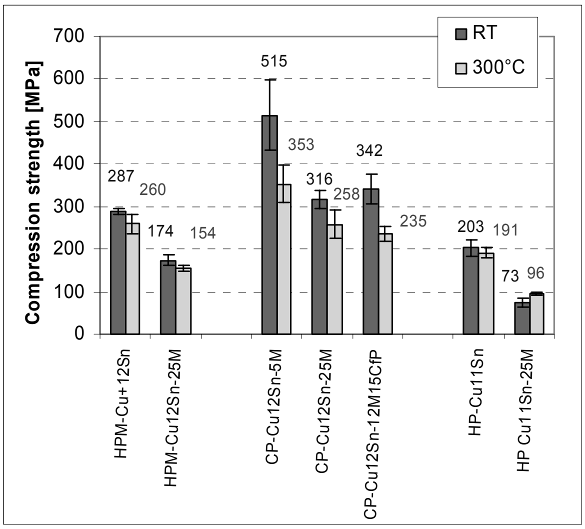

Figure 3: Compression properties of Cu-MMCs: compression strength (elastic limit) the high filled CuMMCs (~25v% fillers) by the ARC-cp-route show higher values than hp- and hpm-MMCs.

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 (right plot) and the wear rates (left plot, only A1) of different Cu-MMC grades versus Cronidur 30.

In air, the lubricating effect is due to the 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. Low reinforcement of 5-12v% MoS_2 does not enable proper solid lubrication neither in air nor under vacuum. As expected, combination of low reinforcement of 12v% MoS_2 with 15v% carbon fibres does also not enable proper lubrication under vacuum. This is reflected by high friction and wear (CuMMC-12M15Cf).

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 (Cu11Sn-25M in fig. 3 and A1).

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 4 shows that a friction coefficient below 0,2 can be achieved in all 3 environments (air, vacumm/RT and vacuum/300°C).

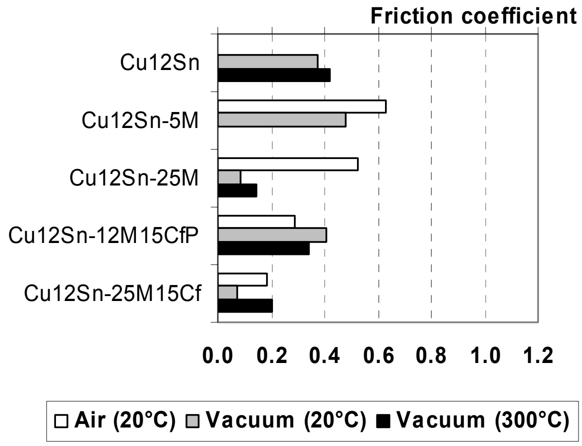

Figure 4: Friction coefficient of Cu-MMCs (cp-process) in air, vacum and Vacuum/300°C. Best composition for "all environments is Cu12Sn-25M15Cf.

4.4. Tribology (Slip-Ring)

In the following figures, first results of tests in slip-ring-configuration from the vacuum tribometer are shown. The track was made of CuMMC and it was in contact to standard gold coated brush wire. Two tracks manufactured by two different processes were compared: ARC-cp-process and a standard MMC by hpm-process.

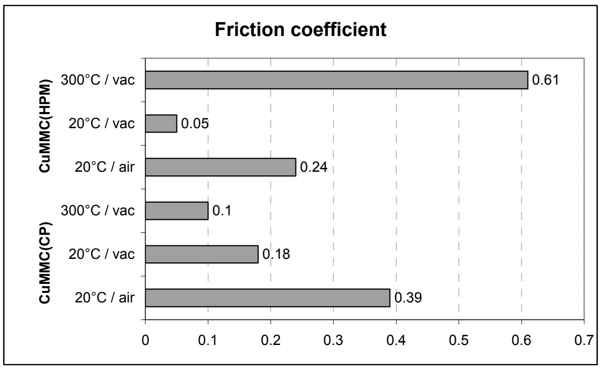

Figure 5: Friction coefficient of Cu-MMCs in air, vacuum and vacuum / 300 °C.

From point of view, of friction the ARC-cp-material shows lower values under vacuum and vacuum/300°C. This corresponds well to the standard Pin-On-Disc-tests (see fig. 5 and above). Contact resistance between gold coated wires and CuMMC are in the range of typical material combinations (50mOhm). For the hp-process-material, in some conditions a more pronounced dependence between current and contact resistance can be seen: contact resistance decrease with higher current (fig.6).

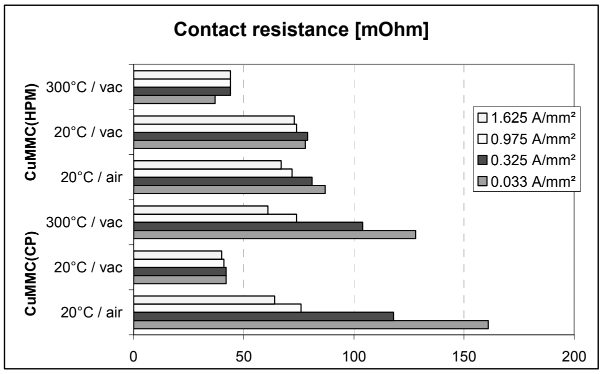

Figure 6: Contact resistance of Cu-MMCs in air, vacuum and vacuum / 300 °C.

5. CONCLUSION

ARC has developed a process which enables to achieve copper based metal composites (CuMMCs) with MoS_2 and short carbon fibres as fillers. Optimisation of process parameters enabled to avoid reaction between Cu and MoS_2 and to limit porosity to less than 3%.

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. A friction of less than 0,2 can be given for all these environments up to 300°C.

For only the ARC-cp-process this low friction is combined with high yield strength (235 MPa at 300°C). Therefore, this new CuMMC overcomes two long lasting problem: low mechanical properties for copper or bronze composites and non-availability of a spcae suitable composite with MoS_2.

Testing of CuMMC in Slip-Ring-configuration using a vacuum tribometer showed both properties (friction and contact resistance) up to 300°C to be in acceptable ranges.

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

6. REFERENCES

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ANNEX

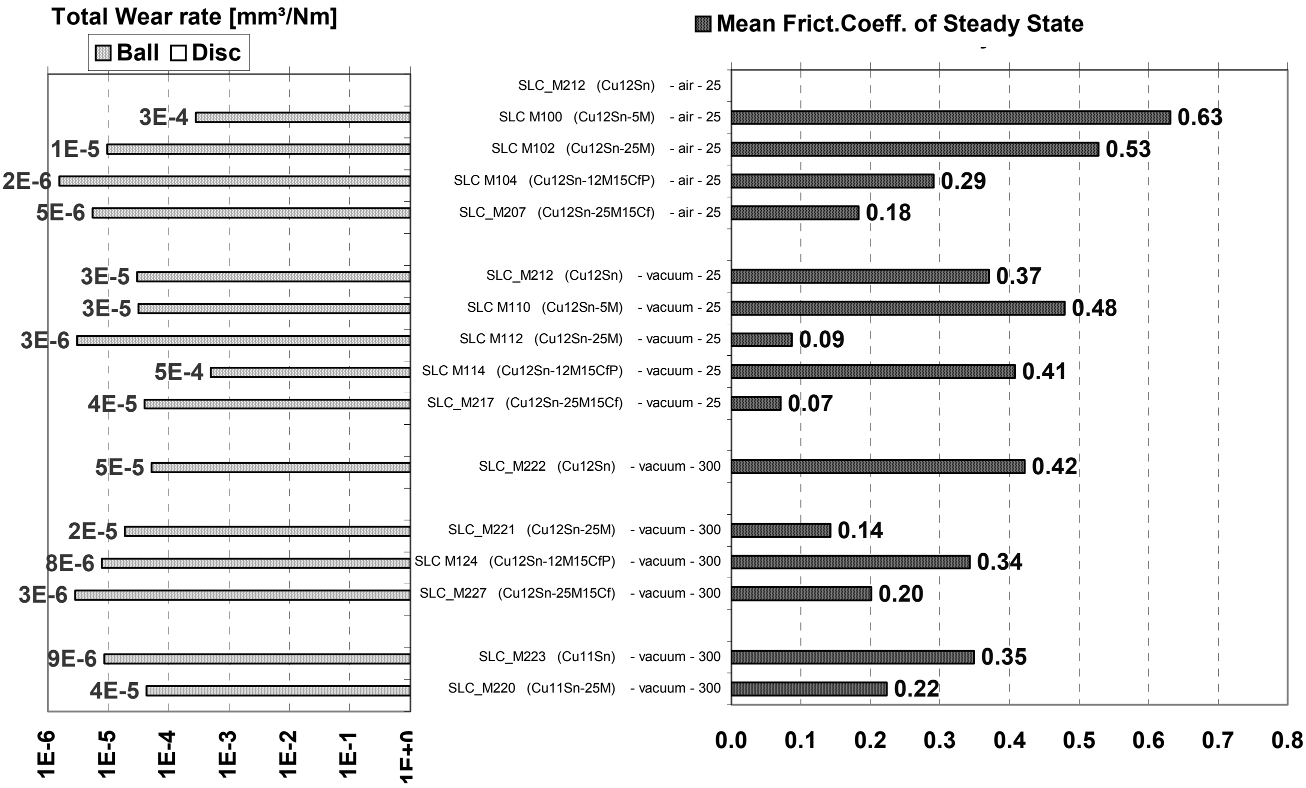

Figure A1: Survey of Friction coefficient and wear rate in air (50%rH) and vacuum: applied loads achieving 2/3Ys of each Cu-MMC. Air: Lowest friction achieved by carbon fibres. Vacuum: lowest friction achieved with only higher amounts of MoS_2(25v%). Combination of MoS_2 and carbon fibres successful: low friction in both air and vacuum (←). Reference material Cu11Sn-25M comparable reason