THE WEAR OF PARTICULATE CU-GRAPHITE COMPOSITE SYSTEM

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ABSTRACT

Cu-graphite composites were prepared by HIPing in the range of 0 – 50 vol. % of graphite. The same graphite powder was copper coated and composites with 30 and 50 vol. % of graphite were prepared. With increased graphite content the coefficient of friction and wear rate of composites at first decreased slightly from copper values. When percolation threshold of graphite is exceeded, the friction coefficient starts to decrease significantly. However this decrease stops after a certain critical concentration is reached. Then the friction coefficient becomes almost independent of the composition while the wear rate decreases further. Both percolation thresholds and critical concentration significantly depend on the composite structure, i.e., on the size of used graphite powder. Finally an empirical percolation model was proposed to describe this dependence.

KEYWORDS: wear, coefficient of friction, composites, copper, graphite

INTRODUCTION

Lead or tin containing copper alloys or Cu-alloy/graphite composites are widely used in sliding bearings and brush applications [1-2]. In the case of low voltage and high current densities, typical for sliding parts of welding machines, materials with a very high specific electrical conductivity, good thermal conductivity and low friction coefficient are required. Such conditions are fulfilled only by copper-graphite (Cu-graphite) composite material [3-6]. Various methods can be used to prepare Cu-graphite systems, such as infiltration, sintering, cold pressing, hot pressing or hot isostatic pressing (HIPing) [3, 7-9]. Recently the wear and coefficient of friction of Cu-graphite composites made by powder metallurgy from Cu-coated and uncoated graphite particles or mixtures of copper and graphite powders in the composition range of 0 – 50 vol.% of graphite was investigated by Moustafa et. al. and authors [10, 12]. Moustafa et. al. explained very precisely the wear mechanism in the investigated composites from the point of view of applied load. They found that both coated and uncoated Cu-graphite composites exhibited the same wear mechanisms, namely, oxidation induced delamination, high strained delamination, and sub-surface delamination.

Concerning composition dependence of sliding properties they only stated that at constant load the higher graphite content in either coated or uncoated Cu-graphite composite, the lower is the coefficient of friction. Rohatgi et. al. [2] stated that when the graphite content of metal matrix composites exceeds about 20 vol.% the friction coefficient approaches that of pure graphite and becomes independent of the matrix alloy. Therefore, the main aim of this work was to investigate carefully the effect of composition on the friction coefficient of copper-graphite composites at constant load.

EXPERIMENT

Cu-graphite composite materials were prepared by HIP-ing using pure copper (average particle size 22 μm , purity 99.9 %) and graphite (average particle size 16 μm , purity 99.9 %) powders. The powders were used to prepare particulate Cu-graphite composites in the range of 0 – 50 vol.% of graphite [3,4]. The same graphite powder was copper coated using a conventional electroless coating process at company Platingtech, Austria. The resulting volume fraction after coating is 50 vol.% of graphite [6]. SEM investigations of particles showed that there was copper coating covering whole surface of each graphite particle. The amount of coated copper corresponds to 50 vol.% of graphite in the final composite after HIP-ing. Cu-graphite coated composite with 30 vol.% of graphite was prepared by admixing of copper powder to copper coated graphite powder with 50 vol.% of graphite.

An identical powder metallurgical approach was used for the preparation of all composites: The starting powders were wet mixed at a Turbula mixer and dried afterwards. Then the mixture was cold compacted to a pellet, which was put into a steel tube, evacuated and sealed. The sample was put into hot isostatic pressing equipment and was HIP-ed at 950°C for 1.5 hour under 150 MPa.

Coefficient of friction of uncoated composites in the composition range of 0 – 40 vol.% of graphite was measured using pin-on-ring tribometer SaFM-3. The samples of 10 x 10 x 35 mm were tested. A steel ring (DIN ST 60-2) was used as a counterpart. Sliding was performed under ambient conditions (temperature 21°C, humidity 60%) in air at a sliding velocity of 0.11 m.s^{-1} and nominal load of 100N for 20 minutes twice for each composition.

Coefficient of friction and wear rate of prepared coated and uncoated composites with 30 and 50 vol.% of graphite were measured using pin-on-disc vacuum tribometer at Austrian Research Centre, Seibersdorf, Austria. The sample of various lengths and diameter of 2.4 mm were tested. A steel disk (ASTM A295) of diameter 60 mm was used as a counterpart. Sliding was performed under ambient conditions (temperature 24°C, humidity 50%) in air at a sliding velocity of 0.5 m.s^{-1} and nominal load of 30N. Track radius was 21 mm and total tested distance was 1200 m. For comparison the measuring conditions from the work of Moustafa et. al. [10] are also listed: Coefficient of friction and wear rate of prepared uncoated and coated composites in the composition range of 0 – 20 vol. % of graphite were measured using pin-on-ring tribometer. The samples with the diameter of 7.9 mm and length of 12 mm were tested. A steel ring (SAE 1045) was used as a counterpart. Sliding was performed in air at sliding velocity of 0.2 m.s^{-1} and nominal load 50 - 500N. For comparison of the results the data at nominal load of 100 N are used. Total tested distance was 2160 m.

RESULTS AND DISCUSSION

During sliding, materials from the pin transfers to the counterpart and vice versa. This influences tribological properties due to change in the metal to metal contact area, including friction coefficient and wear loss of the pins and the counterpart. The predominant wear mechanisms in the pin composite materials were already identified [10]: The involved wear mechanisms of pure copper at low, mild and severe wear rate regimes could be oxidative-dominated delamination and seizure wear mechanisms, respectively. Both coated and uncoated Cu-graphite composites exhibited the same wear mechanisms, namely, oxidation induced delamination, high strained delamination and sub-surface delamination.

In comparison to pure copper the situation is different for Cu-graphite composites due to the presence of graphite: At low wear rate regime very little deformation occurs at sub-surface, but the surface itself is covered not only with a thin copper oxide layer, but also graphite particles are present on the surface. Very few debris are generated consisting of fine equiaxed particles for both

coated and uncoated composites. At mild wear rate regime, high deformed layer appears beneath the wear surface, whereas the surface is covered with a smeared graphite layer of thickness of 40–200 μm [10], which is formed due to the extrusion of graphite from the deformed layer into the surface. There compacted particle-like copper and cracked-shaped graphite wear debris are formed for both coated and uncoated composites. Severe wear rate regime produces considerable deformation and fragmentation in the contacting surface and at the sub-surface, forming several grooves at the surface and subsurface. There predominantly large and sharp-edged debris are generated in both cases of coated and uncoated composites.

What happens when graphite volume fraction at constant applied load varies? A tribolayer is usually found to cover the worn surface continuously. Since it consists of mixtures of materials from the composite and the counterpart as well as environment, it is denoted as a “mechanically mixed layer” (MML) [11]. Initially during sliding, the film of graphite is not present but it forms as a result of surface and subsurface deformation resulting in transfer of graphite to the tribosurface. Because of the softness and lamellar structure of graphite, the subsurface cavities containing graphite particles tend to deform with the subsurface matrix, squeezing out the graphite to the wearing surface during the sliding friction process. The graphite will then smear on the wearing surface layer by layer and mix with the other debris detached from the pin and disk/ring. A mechanical mixing process between the contacting surface results in the formation of a graphite-rich MML. The presence of the MML decreases the direct contacting area between the composite and the counterpart, therefore improving the wear resistance of the composites. A large quantity of graphite in the MML decreases the shear strength of the near-surface region, so reducing the coefficient of friction. With increasing vol.% of graphite within copper matrix the amount of graphite in MML increases thus enhancing its effect on wear and friction of composite. Fig. 1 indicates that this squeezing out and smearing of graphite particles into MML as described above takes place for both uncoated and coated Cu-graphite composites. The key factor that affects the coefficient of friction composition dependence is the homogeneity of spatial distribution of graphite within the composite. At low graphite concentrations, coefficient of friction for composites made from graphite powders with diameter of approximately 25 - 40 μm [10] is significantly higher than coefficient of friction for composites prepared from graphite powders with diameter of 16 μm (Fig. 1). Besides obvious clustering of graphite particles it is evident that finer powder gives better sliding properties. To avoid clustering the copper coating of graphite powder can be used. In this case the coefficient of friction of coated composites made from copper coated graphite powders is comparable to the coefficient of friction of composites made from fine graphite powders.

Fig. 1 Composition dependence of friction coefficient of uncoated (left) and coated (right) Cu-graphite composites at 100N.

However, above a certain graphite volume fraction within composite the graphite debris within MML reach their maximal concentration. Such graphite saturated MML then prevents further significant deformations of subsurface areas thus keeping the shear strength of the near-surface region almost constant and also the coefficient of friction [2]. The wear of composite still takes place as there is dynamic flow of the material into and from the tribosurface. It indicates that there exists certain concentration threshold above which the other particles within MML become uncorrelated and the properties of MML are fully determined by the graphite debris, especially from the point of view of the coefficient of friction.

It is evident that the most cost effective solution for the sliding application is to use composites in the vicinity of the concentration threshold. This concentration threshold significantly depends on the composite microstructure. Fig. 1 indicates the concentration threshold of 12 vol. % of graphite for fine uncoated composites and approximately 23 vol. % of graphite for coarse uncoated composites [10]. Surprisingly the concentration threshold is above 25 vol. % of graphite for coated composites.

The reason for this is that not only homogeneous distribution of graphite phase, but also homogeneous distribution of copper phase takes place for coated composite (Fig.2). Moreover, the thickness of both phases is significantly smaller in this case. Therefore the increased number of fine copper debris is released into the MML homogeneously from the whole composite surface. This significantly influences the properties of tribolayer: It shifts the concentration threshold to higher graphite volume fraction and increases coefficient of friction and wear rate of coated composite in comparison with uncoated one. This is more pronounced at higher graphite volume fraction within the composite as indicates wear rate and coefficient of friction of coated composite with 50 vol.% of graphite (see Table 1).

Composition		Cu+50 vol.% graphite		Cu+30 vol.% graphite	
Coating		Uncoated	coated	uncoated	coated
Density	[g/cm ³]	5.32	5.43	6.83	6.72
Friction coefficient	[-]	0.15	0.18	0.15	0.13
Wear rate	[mm ³ N ⁻¹ m ⁻¹]	5.7.10 ⁻⁴	6.4.10 ⁻⁴	1.6.10 ⁻³	1.2.10 ⁻³

Tab. 1 Experimental values of wear rate and coefficient of friction of coated composites compared with uncoated ones at 30N

Fig. 2 Structural changes in Cu- graphite composites at 50 vol. % of graphite: left– coated, right– uncoated graphite (SEM).

It was also confirmed that further increase of graphite content over concentration threshold decreases further the wear rate (see Table 1). The coefficient of friction remains almost unchanged for fine graphite powder composites and is about 0.15-0.16. This is probably the corresponding value of the dynamic coefficient of friction of used graphite material.

Until now there is no rigorous approach how to model the composition dependence of friction coefficient of composite materials. It can be expected that only mechanical bonding between copper and graphite simplify the problem very significantly. Due to fact that the friction coefficient varies reciprocally to modulus of elasticity and according to the analogy with thermal and electrical conductivity composition dependence of Cu- graphite composites an empirical model was proposed to describe the observed composition dependence. it is based on percolation

$$f \frac{\sigma_{lo}^{1/t} - \sigma_{eff}^{1/t}}{\sigma_{lo}^{1/t} + g\sigma_{eff}^{1/t}} + (1-f) \frac{\sigma_{hi}^{1/t} - \sigma_{eff}^{1/t}}{\sigma_{hi}^{1/t} + g\sigma_{eff}^{1/t}} = 0 \quad (1)$$

theory and the general effective medium theory (GEM) [13, 14]. There t is characteristic exponent for the effective property - eff , f is volume fraction of lower coefficient of friction phase – lo , g is a parameter connected with percolation threshold as follows $f_c = g/(1-g)$ and σ is considered as friction coefficient. Index hi denotes high friction coefficient phase.

As can be seen from Table 2 the proposed model describes the obtained results very well. However the values of the percolation threshold are different from the critical concentration values of graphite. Critical concentration of graphite is such graphite concentration at which the properties of MML layer are fully controlled by graphite. On the other hand, percolation threshold is such graphite concentration at which starts the synergic effect of graphite phase presence within MML, i.e., it starts to influence significantly the friction coefficient of composite.

The size effect plays an important role also in the proposed model. For fine uncoated graphite powders the percolation threshold is 1.5 vol. % of graphite. Coarse graphite possesses approximately 12.8 obj. % vol. % of graphite. The model was also tested for the composite Cu – carbon nanotubes (MWCNTS) [15], in this case the percolation threshold is 3.8 vol. % of carbon nanotubes.

	g [-]	f_c [vol.%]	t [-]	Friction coefficient of graphite
Uncoated	0.03011± 0.00278	1.5	-8.98204 ± 2.07802	0.13656 ± 0.00779
Uncoated Moustafa et. al	0.14631± 0.00087	12.8	-10.28794 ± 0.47692	0.14858 ± 0.00166
Coated	0.07999± 0.01376	7.4	-23.9584 ± 725.7794	0.15373 ± 0.32184
Coated MWCNTS Tu et. al.	0.03996± 0.01168	3.8	-23.4886 ± 639.2345	0.08918 ± 0.28576

Tab. 2 *Fitting parameters according to GEM for Cu – graphite composite systems*

CONCLUSIONS

The Cu-graphite composite in the composition range of 0 – 50 vol.% of graphite were prepared by HIP-ing and their sliding properties were measured. It was confirmed that with increasing concentration of graphite the coefficient of friction and wear rate of coated and uncoated composites at first decreases until certain critical concentration threshold of graphite is reached. Then the coefficient of friction of composites becomes independent on the composition (0.15-0.16) and corresponds probably to the dynamic coefficient of friction of used graphite while the wear rate decreases further.

The decrease of the coefficient of friction is governed by the synergic effect of graphite phase sliding properties and its spatial distribution within composite microstructure. Higher is the homogeneous spatial distribution of graphite phase the lower is coefficient of friction of composite. We have found concentration threshold at 12 vol. % of graphite for uncoated composites prepared from graphite powders of size of 16 μm . For graphite powders of approximately 25 - 40 μm it is approximately 23 vol. % of graphite.

The other way to obtain homogeneous distribution of graphite is to use copper coated graphite. Copper coating prevents clustering of graphite. In this case, the coefficient of friction decreases significantly earlier as for uncoated composites. However the concentration threshold was found above 25 vol. % of graphite in this case. The reason for this is that not only homogeneous distribution of graphite phase, but also homogeneous distribution of copper phase takes place. Then at high graphite volume fraction it is much easier to squeeze out also fine copper parts into graphite rich tribolayer. This increased number of fine copper debris within MML is then responsible for the increase of the coefficient of friction and wear rate of coated composite in comparison with uncoated one.

The proposed empirical GEM model seems to describe very well composition dependence of friction coefficient for Cu – carbon composite systems.

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