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INFLUENCE OF THE SOLID LUBRICANT PARTICLES REINFORCEMENT ON COMPOSITES TRIBOLOGICAL PROPERTIES

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Abstract: *Because of their favourable properties composite materials with reinforcements are used in many industries. With the aim to additionaly improve some of their properties, especialy their tribological properties several solid lubricants are used in the process of composite production. Many authors have analysed an influence of different reinforcements on mechanical, thermal and tribological properties of metal matrix composites (MMCs). This paper gives an overview of investigations and possibilities of solid lubricant particles (such as graphite) applying as composite reinforcements mainly for aluminium base omposites that are nowdays common in use in automotive and aeronautics industry. Based on presented experimental results of tribological properties one can find some remarks and conclusions that could be useful for further investigation of solid lubricants applying in MMCs production.*

Keywords: *composites, solid lubricants, reinforcements, graphite, tribological properties.*

1. INTRODUCTION

The term "composite" refers to a material system which is composed of a discrete constituent (the reinforcement) distributed in a continuous phase (the matrix), and which derives its distinguishing characteristics from the properties of its constituents, from the geometry and architecture of the constituents, and from the properties of the boundaries (interfaces) between different constituents. Composite materials are usually classified on the basis of the physical or chemical nature of the matrix phase, e.g., polymer matrix, metal matrix and ceramic matrix composites.

Here we are focused on metal matrix composites (MMCs) and more specifically on the aluminium matrix composites (AMCs). In this kind of composites the reinforcements are usually non-metallic such as SiC and Al_2O_3, but it is also possible to use boron or solid lubricants in form of graphite particles.

Reinforcements are usually fibres or particles of different orientation and shape. The arrangement of the particles can be random, in most cases, or preferred, in the shape of sphere, cube or any close-to-regular geometrical form. A fibrous reinforcements are characterized by its length and diameter so we distinguish, long (continuous) fibres and short (discontinuous) fibres – whiskers. Arrangement can be, as well, preferred and random.

The major advantages of AMCs compared to unreinforced materials are: greater strength; reduced density (weight); improved stiffness and damping capabilities; thermal/heat management; enhanced electrical performances and improved wear resistance.

AMCs can be classified into four types depending on the type of reinforcement [1]:

- particle reinforced AMCs,
- whisker reinforced AMCs,
- continuous fibre reinforced AMCs and
- mono filament fibre reinforced AMCs.

In addition to these four types of AMCs another variant of AMCs known as hybrid AMCs have been developed and are in use to some extent. Hybrid AMCs essentially contain more than one type of reinforcement. For example it could be mixture of two fibre types, or mixture of fibre and particle or mixture of hard and soft reinforcements. Aluminium matrix composite containing mixture of carbon fibre and Al_2O_3 particles used in cylindrical liner applications is an example of hybrid composite. Figure 1 shows microstructure of hybrid AMC having both hard SiC and soft graphite particles as reinforcement.

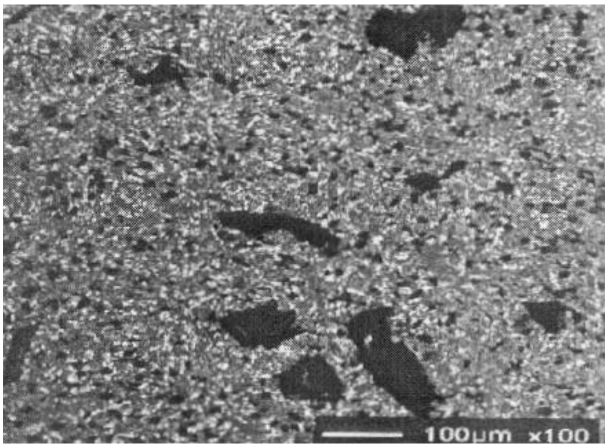

Figure 1. Hybrid composite containing 10 % SiC and 4 % graphite particles [1]

2. ALUMINIUM MATRIX COMPOSITES CONTAINING GRAPHITE PARTICLES

The aluminium matrix composites with graphite particles are fabricated usually by one of the following techniques:

- powder metallurgy,
- compocasting,
- squeeze casting,
- UPAL method and
- pellet method.

The properties of aluminium alloy composites with graphite have been studied extensively. In these composites, graphite is presumed to improve tribological properties by forming a graphite-rich lubricant film between the sliding surfaces. These materials could also have improved seizure resistance features and that is a reason why they find application in automotive industry as piston and cylinder liner materials. Owing to the lubricate effect of graphite, these alloys exhibit a lower friction coefficient values and wear rate compared with that of the aluminium matrix reinforced with ceramic particles [2].

Liu et al. [3] studied friction and wear behaviour of Al-Si alloy (2014) matrix composites with graphite particles. They found that the controlling factor was the graphite film formation between the rubbing surfaces. The coefficients of friction and wear were significantly lower in the composites, as compared to those in the matrix alloy. The transition to severe wear took place at a higher load and sliding velocity as compared to the base alloy, as well. This behaviour has been explained on the basis of subsurface deformation, leading to transfer of graphite to the surfaces, and the plastic flow of matrix alloy, resulting in covering of the embedded graphite by the matrix alloy. In low graphite content composites wear rate decreases with sliding speed as the graphite film thickness and extension increases with sliding velocity. In larger graphite volume fractions, wear rate is very low and becomes in fact independent of sliding velocity due to graphite film stability [4]. For even higher graphite contents (higher than 20 vol.%) the graphite film grows thicker, resulting in its delaminating without affecting the overall wear resistance of composites.

In very interesting research of Yang et al. [5], the compocasting method has been utilized to make A356.2 aluminium/graphite particle composites, which have been developed for cylinder linear applications in cast aluminium engine blocks. The mean diameter of graphite particles was about 15 μm with irregular shape. Four different amounts of graphite were used namely: 2, 4, 6 and 8 wt.%.

The tribological behaviour of composites has been characterized relative to normal loadings and sliding speeds. Wear tests were carried out under dry sliding condition under a normal load of 0.2, 0.3 and 0.4 MPa, and reciprocating sliding speeds of 0.13, 0.16 and 0.20 m/s. A fixed sliding distance of 60 m was used in all tests, and for each test condition.

The authors first found that poor wetability results in inadequate interface bonding between aluminium matrix and graphite particles, and that it is not easy to add graphite particle directly into molten aluminium. For this purpose the surface of graphite particles was coated with copper, nickel, magnesium or silicon.

The variation of the friction coefficient with the quantity of the graphite particle for the matrix alloy and the composites is shown in Table 1.

Table 1. Friction coefficient for different graphite particle wt.% under different loads and sliding speeds

Normal load [MPa]	Sliding speed [m/s]	Graphite particle content [wt.%]				
		0	2	4	6	8
0.2	0.13	0.44	0.49	0.41	0.39	0.41
	0.16	0.46	0.46	0.40	0.39	0.39
	0.20	0.43	0.48	0.42	0.40	0.40
0.3	0.13	0.42	0.46	0.39	0.38	0.40
	0.16	0.44	0.51	0.38	0.38	0.41
	0.20	0.45	0.50	0.39	0.40	0.39
0.4	0.13	0.45	0.51	0.40	0.40	0.43

	0.16	0.45	0.54	0.41	0.39	0.42
	0.20	0.48	0.56	0.40	0.42	0.44

For composite with 2 wt.% the graphite was in small content and the formed lubricant film could not effectively decrease the friction coefficient. This composite showed the highest values of the friction coefficient, even higher than the matrix alloy. Both the matrix alloy and the composite with 2 wt.% had no or not enough graphite lubricant film to prevent direct contact of two surfaces, thus the friction coefficient increases with increasing normal load. Composites with 4 and 6 wt.% had the smallest friction coefficient values under the same condition. At Figure 2, it is shown that the worn surface of composite with 4 wt.% has been covered more uniformly by the graphite film, which can avoid direct contact of the rubbing surfaces, thus reducing the shear stress transferred to the sliding surface, and decreasing the friction coefficient.

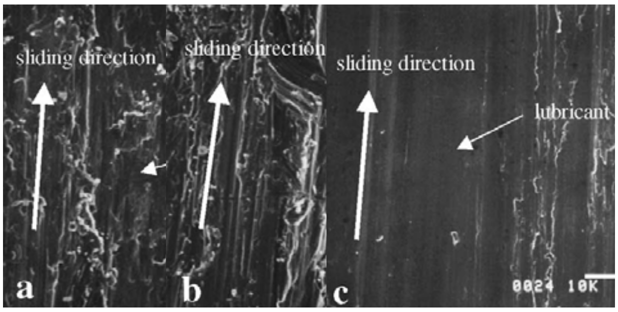

Figure 2. SEM photograph of worn surface: a) matrix alloy, b) composite with 2 wt.% of graphite and c) composite with 4 wt.% of graphite

As for the composite with 8 wt.%, even if the graphite lubricant film can readily form on the worn surface, the high content of the graphite particles will cause easy clustering of graphite, thus aiding crack nucleation within the graphite particles which slightly increases the coefficient of friction. From Table 1, it could be noticed that the sliding speed has little effect on the friction coefficient. Also for composites with 4 and 6 wt.% the normal load has little effect on the friction coefficient, because the graphite lubricant films are able to decrease plastic deformation on worn surface.

The wear debris for the matrix alloy was quite large, and the wear debris becomes smaller as graphite particle content increases. This decrease in the size of the wear debris was mainly a result of the decreased probabilities of direct contacts of two worn surfaces at high graphite content which decrease the severity of ploughing and micro cutting effects.

The formation of a graphite lubricating film on the surface is considered to be the major cause for the low friction and wear rate of composites. However, composites with 4 or 6 wt.% graphite particles gave a significantly lower wear rate than the other specimens, Table 2. This appropriate amount of graphite particle would be squeezed onto the sliding surface, and easily cover the surface of the aluminium matrix. It is obvious that there exists a range of optimal value of graphite particle content to produce such a good lubricating film and avoid severe wear.

Table 2. Wear rate [mm^3/m] x 10^{-4} for different graphite particle wt.% under different normal load and sliding speeds

Normal load [MPa]	Sliding speed [m/s]	Graphite particle content [wt.%]				
		0	2	4	6	8
0.2	0.13	0.24	0.34	0.01	0.01	1.72
	0.16	0.32	0.38	0.03	0.04	0.90
	0.20	0.23	0.40	0.02	0.01	0.65
0.3	0.13	0.21	0.37	0.02	0.03	1.12
	0.16	0.24	0.40	0.01	0.01	0.90
	0.20	0.22	0.37	0.03	0.04	1.10
0.4	0.13	0.33	0.41	0.02	0.01	0.56
	0.16	0.34	0.47	0.01	0.03	0.82
	0.20	0.31	0.42	0.01	0.04	0.74

Gomez-Garcia et al. [6] investigated the effect of graphite particles distribution on wear behaviour of aluminium composites with graphite particles. It was observed that the graphite particles were placed at different regions of the aluminium matrix as they were cooled under three different cooling rate during solidification, maintaining 4.5 wt.% of graphite content. Smaller content of graphite particles were found in regions where the cooling rate was higher, while higher content were located in regions where the cooling rate was lower. They also found that this phenomenon could improve the wear resistance in composites containing smaller graphite particles.

Investigations of Akhlaghiand and Zare-Bidaki [7] was aimed to evaluate the effect of graphite content on the tribological behaviour of aluminium matrix (2024) composite, made by *in situ* powder metallurgy method under dry and lubricated (oil impregnated) sliding conditions. It is well known that the production method has a strong influence on the mechanical and tribological properties of such composites via its effects on the matrix grain size, porosity, the distribution of graphite particles and the interfacial properties of the Al/Gr couple. The percentage of flake graphite particles was 5 – 10 wt.%, and the average size of the particles varies from 55 μm to 160 μm. Tribological tests were undertaken under the normal load of 50 N (resulting in a normal pressure of 1 MPa), the sliding velocity of 0.5 m/s and the total sliding distance of 1000 m.

Results of bending tests indicated that the bending strength decreased as the graphite content increase. Addition of graphite addition to aluminium alloys is known to decrease the strength, fracture energy, ductility and hardness of the material.

The variation in the measured wear rate and coefficient of friction with the wt.% of graphite in the composites for both dry sliding and oil impregnated sliding are shown in Figures 3 and 4, respectively. It can be seen that the dry sliding wear rate of composite with 5 wt.% graphite is about 10 times lower than that for the matrix alloy. However, for composites with 10 wt.% or more graphite particles addition, the wear rate increases.

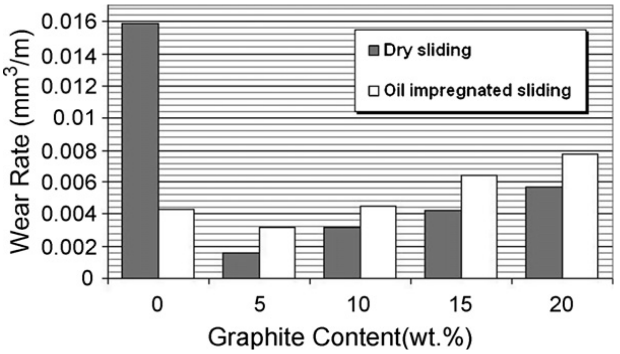

Figure 3. The wear rate variation with the wt.% of graphite in composites

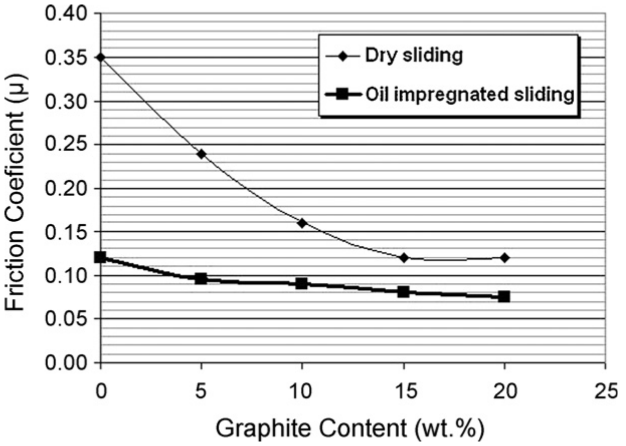

Figure 4. The coefficient of friction variation with the wt.% of graphite in composites

As shown in Figure 4, for dry sliding, the friction coefficients starts at 0.35 for the matrix alloy and decreases with increased graphite content reaching to a final value of about 0.12 for composites containing 15 wt.% graphite which is about one-third that of the matrix alloy. It is to note that there is no significant difference in friction coefficient between composites with 15 wt.% and more graphite addition.

It is evident from Figures 3 and 4 that the wear rate and friction coefficient of the oil impregnated base alloy are considerably lower than those of the dry sliding. The wear rate of the oil impregnated matrix alloy is approximately four times lower than that for the dry sliding. These results are expected from the oil impregnated sliding and can be attributed to formation of an oil film between the two contacting surfaces.

It is interesting to note that except for the matrix alloy, the wear rates of Al/Gr composites containing different amounts of graphite are always higher for oil impregnated sliding as compared with dry sliding.

It is also worth of mentioning investigation of Jha et al. [8]. They investigated wear properties of the two Al-Si alloys (LM 13 and LM 6) and corresponding composites which were obtained by adding talk powder (with the average size of 50 – 150 μm) to the appropriate matrix alloy. Composites containing 2.8 wt % talc in LM 13 and 2 wt % talc in LM 6 have been prepared with the liquid metallurgy technique. Wear rates of these composites, with talc as solid lubricant, were found to be 22 to 30 % less than the wear rates of corresponding base alloys without any dispersion.

3. HYBRID COMPOSITES FORMED WITH SOLID LUBRICANTS

Hybrid composites represent the merging of two philosophies in tribological material design: hard particle reinforcement, for example by carbide particles, and soft particle reinforcement (and consequent lubrication), for example by graphite powder.

The tribological behaviour of self-lubricated aluminium/SiC/graphite hybrid composites with various amount of graphite addition synthesized by the semi-solid powder densification method has been studied by Ted Guo and Tsao [9]. Mixtures of 6061 aluminium powder (average powder size: 30 mm), SiC powder (average powder size: 45 mm) of 10 vol.%, and graphite powder (average powder size: 8 mm) of 2, 5 and 8 vol.% were investigated. Mechanical characteristics (hardness, coefficient of thermal expansion and fracture toughness) of tested materials decreased with the increase of graphite content.

The tribological tests lasts for 5 min under dry sliding condition, constant of 0.094 MPa and sliding speed of 1.09 m/s. The authors found that the seizure phenomenon which occurred with a monolithic aluminium alloy did not occur with the hybrid composites. The amount of graphite released on the wear surface increases as the graphite content increases, which reduces the friction coefficient, Fig. 5.

Authors also concluded that wear becomes more stable, and wear debris particles become smaller as the graphite content increases, Fig. 6.

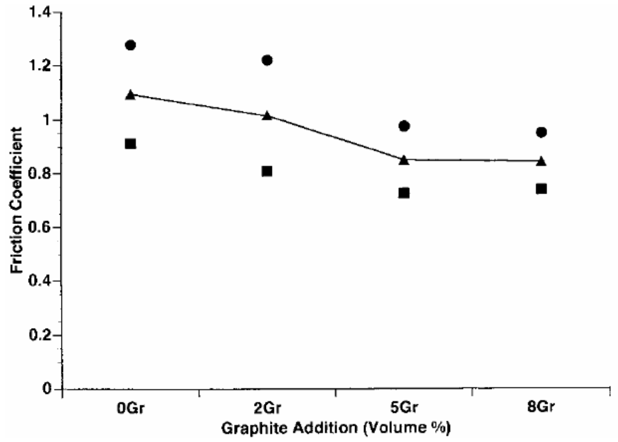

Figure 5. Variations of friction coefficient with the percentage of graphite addition

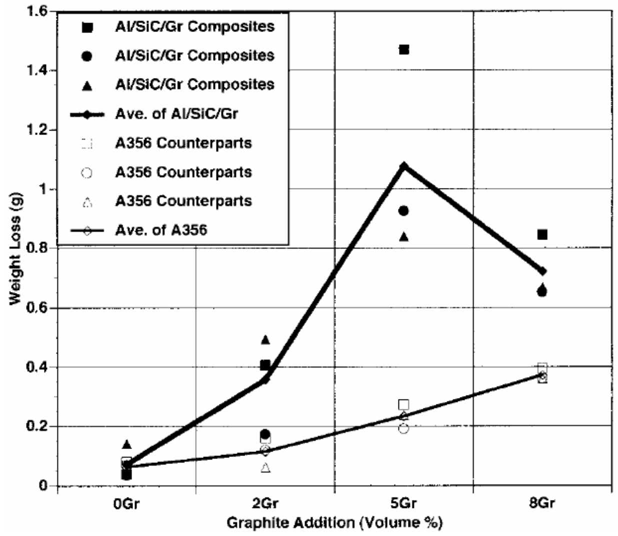

Figure 6. Weight loss of the composites and the counterparts for various graphite additions

Basavarajappa et al. [10] investigated dry sliding wear behaviour of as cast aluminium alloy 2219, composite with SiC particles and composite with SiC particles and graphite. The composites were produced using the liquid metallurgy technique. SiC reinforcement content was 10 wt.% and average particle size of 25 μm for both composites, while the graphite content in the second composite was 3 wt.% and the average particle size of 45 μm.

The tribological tests were conducted with the load ranging from 10 to 40 N at a sliding speed of 1.53, 3, 4.6 and 6.1 m/s with a constant sliding distance of 5000 m.

It was found that the addition of SiC particles increases the wear resistance of the composites comparing to the matrix alloy. The wear resistance increase further with the composite containing SiC particles and graphite. The wear rate of the tested materials increased with increase of the sliding speed but for the both composite that increase was not as drastic as for matrix alloy, and yet the composite containing SiC and graphite showed the lowest increase, Fig. 7.

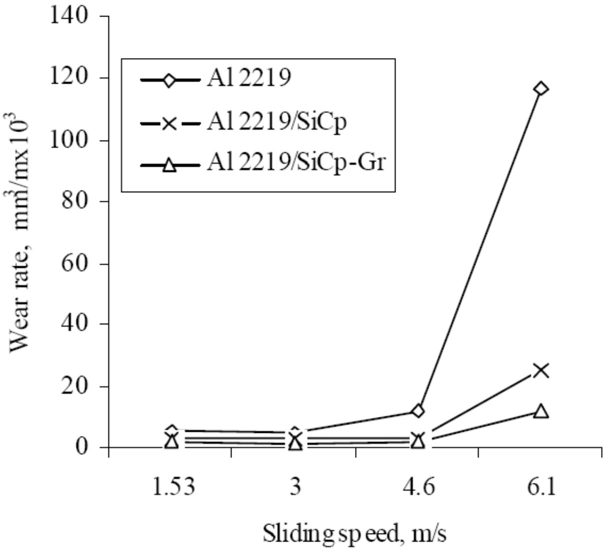

Figure 7. The wear rate variation with sliding speed for both composites and its matrix alloy

4. CONCLUSION

Based on presented experimental results the following conclusions, which could be useful for further investigation of solid lubricants applying in AMCs production and used in dry sliding condition, could be pointed out:

- First problem that occurs with the production of the AMCs is a poor wetability of the solid lubricant (which is usually graphite) into the matrix alloy. The solution of this problem differs from one production technique to another;
- There is more than one production technique of the AMSc but generally the powder production one gives the most preferable distribution of the reinforcement phase and wetability solutions. On the other hand this technique is usually the most expensive;
- Increase of the graphite addition, as a solid lubricant, decrease the coefficient of friction, but it seem that the amount greater than 4 to 6 wt.% does not show further significant improvements of the coefficient of friction;
- Wear rate of the AMSc containing graphite also decrease with the increase of the

graphite content up to some value. Above 4 to 6 wt.% of graphite content tends to increase the wear rate of composite;

- Appropriate value of the graphite content must be determined for any particular case taking in account not only the tribological properties. The mechanical properties of the obtained composite must be considered also, since the higher content of graphite tends to decrease them;
- The mechanical properties decay of the AMCs containing graphite could be solved with addition of the hard reinforcing phase, for example SiC or Al_2O_3. and thus obtaining a hybrid AMC;
- In contrast to the dry sliding condition in lubricated sliding condition coefficient of friction for the AMSc was lower (as expected) but the wear rates were higher. These higher wear rates were attributed to prohibited formation and retention of the graphite lubricating film at the presence of oil in the contact area due to displacement and pushing of the suspended graphite particles on the sliding surface.

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