LINEAR SLIDING WEAR BEHAVIOR OF ALUMINIUM MATRIX COMPOSITES REINFORCED BY PARTICULATES

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ABSTRACT
This paper studies the linear sliding wear behavior observed when rubbing metal matrix composites reinforced by particulates against a steel cable. Different types of composites were tested: Three different techniques for incorporating particulates were used: two foundry techniques by mechanical mixing, and/ thermal projection. The composites techniques have different volume fractions as well as different particulate sizes. The results show that the lubrication has a strong effect on the wear rate. The composites did not wear when tested under oil lubrication conditions, while the cable wore rapidly. The opposite phenomena occurred when dry tests were performed: the cable was protected while the specimen wore quickly. Finally, it was observed that the wear rate of the composite is the lowest for composites reinforced by a low percentage of particulates. A mechanical model describes the behavior of both partners (cable and MMC).
KEYWORDS: Friction and wear; Metal matrix composites; Sliding dry, and Mechanism of friction lubrication

1. INTRODUCTION

Metal matrix composites offer superior properties such as good mechanical strength at high temperatures; enhanced resistance to erosion, to abrasion and, generally speaking, to friction and wear (1). On the other hand, the presence of particulates makes machining very difficult. Reinforcement particulates, such as silicon carbide, are harder than conventional tungsten carbide tools. With hard reinforcing particulates, diamond tools or diamond-coated tools can be successfully used (2). These new types of tools are more expensive, and require the use of special manufacturing machining tools, which are mostly stiffer than classical ones. Consequently, it is often easier to produce parts at near net shape in order to avoid or minimize machining (3). However these new materials have poor toughness and ductility, limiting their use. Several technologies are available for coating, including by projection, by atomization, by plasma, or with the help of an arc, in a flame, etc. Introducing WC particles on the metal matrix increases hardness of pure copper coating and the wear resistance of dispersion hardened Cu-WC composite coating was found slightly higher than that of pure copper (9). The lack of knowledge of some mechanical properties is one of the important factors limiting the wider use of MMCp. Each application is based on specific test for characterizing the material for this specific application as block-on-ring (10), pin-on-disc (11), or plan-on-plan (12). This work wishes to focus on the behavior of MMCp during sliding, at low speed, with linear contact. Linear sliding tests are not often studied even though they simplify the sliding phenomenon as well as the interpretation, since the third body coming from the two surfaces, are continually evacuated away from the friction. This test was defined for a rapid classification of surfaces submitted to localized stress. For many applications, the coating must also resist to corrosion caused by a saline environment, or by pollution generated by oil or grease. The purpose of this work is to compare the behavior in a linear alternative (reciprocal) wear of different aluminum matrix composites obtained by spray coating or by casting in bulk form for different environments. A model has been proposed describing the degradation of these materials.

2. MATERIALS AND TESTING

2.1. Experiments

For some applications, it is interesting to simulate the sliding action under linear contacts that have been contaminated with oil or water, in order to reproduce real life situations. Several methods are available (14-16) for simulating the sliding action and for classifying materials according to their sliding behavior. The military norm MIL-23003A was developed to simulate the action of a metallic cable moving over a metallic surface (Figure 1). A eutectoid steel cable was used as a counterpart. The military norm MIL-23003A was developed to simulate the action of a metallic cable moving over a metallic surface (Figure 1). A eutectoid steel cable was used as a counterpart. This test has the advantage of being inexpensive to implement. A robot was used to generate the reciprocal movement with a constant speed, which is not the case with the most classical set-up, where an electrical motor generating a sinusoidal movement.

The amplitude of the oscillatory movement is 15cm, with a frequency of 0.3 hertz. The metal surface temperature is measured with a thermocouple. Cable wear is measured, on-line by the variation of its diameter and the specimen wear by the variation of its thickness. The transferred layer, the presence of debris on the surface of the plate makes difficult to interpret the weight measurement. The tests were carried out under a standard laboratory atmosphere (22 C and 40% R.H.). Petroleum-based oil (10W 40) and city water were used as contaminants. All tests were carried out with a constant linear load of 5 pounds per inch (8.8 10-2 N/m).

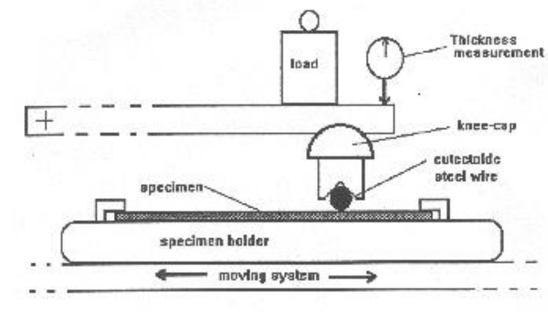


Figure 1 Scheme of the sliding test device for cable

2.2. Materials

Five types of specimens were used: (1) MMC reinforced by small silicone carbide particulates, 15 µ, produced by Alcan, under the trade name 'Duralcan'; (2) Duralcan with small volume fraction, obtained by dilution; (3) MMC reinforced by large silicone carbide particulates; silicone carbide particulates with size up to 180µ, with different volume fraction, produced by ETS; (4) Coated steel plate by sprayed layer of Duralcan, produced by Alcan; (5) Pure aluminum A1100, for comparison purpose.

3. RESULTS

Figure 2 shows, as an example, the wear rate measured by the thickness variation of the thermal spray coated steel plates (referred to as 90/10 material) relative to the number of cycles, for dry experiments. These results were obtained with the same sample, removed from the bench every 200 cycles. The diameter of the cable was then measured and the sample was set back. Between two removing specimen periods, the diameter variation is measured automatically, on-line. The results are the average of three specimens.

The variability of results is one the order of 2 %. It has already been mentioned that a mechanical system, a kneecap, allows the cable to be aligned relative to the MMCp surface. This system decreases the running-in period by a large factor. It is observed that the running-in period is short, around 50 cycles. The wear rate is calculated by taking in account this initial running-in period. For example, the wear rate is between 2 to $3*10^{-5}$ mm / cycle in dry conditions. Sometimes it was observed that, the diameter of the cable increases due to the formation of a built-up edge (BUE) on the cable. The cable surface is not affected by the sliding action, the BUE layer protects. The BUE has the same composition as the sprayed layer coating, but the microstructure was largely modified A highly mechanically mixed microstructure (mechanical alloying) is present on the cable. The BUE is formed by shearing due to the friction on the surface. This shearing action generates a lot of tiny debris coming from the specimen surface. These debris are transferred onto the cable and form the BUE.

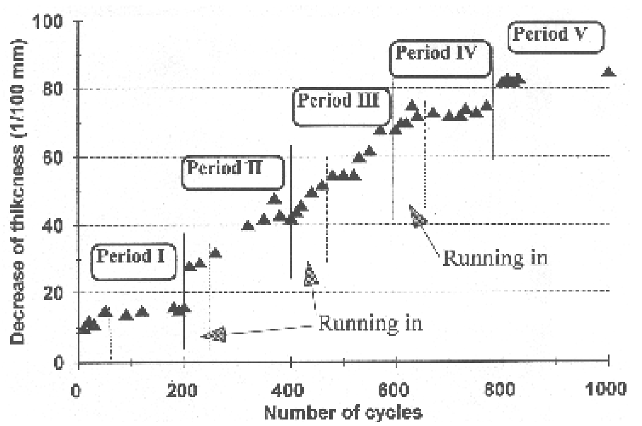


Figure 2: Wear rate of the thermal spray coated steel plates (90/10l) relative to the number of cycles, for dry experiments

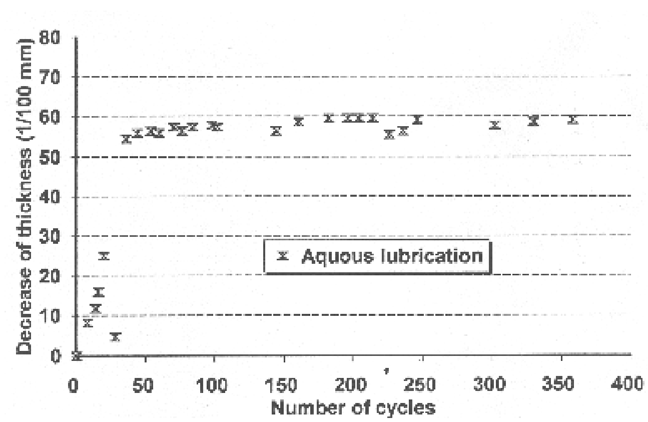


Figure 3: Variation of specimen thickness of the composite 90/10 relative to the number of cycles, in aqueous conditions

This transfer happens between a hard material, which is the case of the cable used (eutectoid steel), and the a ductile specimen, such as 1100 aluminum and the 90-10. The following micrograph shows details of the BUE formed by composite sprayed specimens. The friction surface is shown by the white doted line and the direction of the movement by the double arrow. The BUE adheres to the cable and forms a continuous layer which covers all the surface of the cable. This BUE, strongly deformed, is very hard and consequently, protect the cable. This BUE is formed in dried conditions, not in lubricated one. The presence of lubricant prevents the formation of BUE. Comparing with a BUE formed from a soft material as 1100 alloy, no real difference is observed . The material of this BUE is hard, formed with a highly deformed material. The situation is quite different when a film of oil or water covers the surfaces. It is observed that the wear rate is small. A very fine, if any, transferred layer of MMC is observed on the cable surface. The oil film protects the composite and the cable, when using composites reinforced by small particulates. Figure 3 represents the variation of specimen thickness of the sample relative to the number of cycles.

TABLE 1 Wear rates of the sprayed composite

Experimental condition	Cable wear rate mm/cycle	Composite 90/10 wear rate, mm/cycle
Dry	0	1 to $7*10^{-5}$
Water	$2*10^{-4}$	1 to $6*10^{-6}$
Oil	$2*10^{-4}$	$1.3*10^{-5}$

TABLE 2 Wear rate of the unreinforced alloy A1100

Experimental conditions	Cable wear rate, mm/cycle	Alloy 1100 wear rate, mm/cycle
Dry	0	2 to $4*10^{-5}$
Aqueous	0	.8 to $1.5*10^{-5}$
Oiled	0	$2*10^{-7}$

This table 1 summarizes the average wear rate of the three tests of the sprayed specimens. These results underline the effect of the environment. When experiments were carried out unlubricated, cables did not wear. This surprising effect was verified for all types of specimens (sprayed or massive MMC'). When the partner is a composite, the lubricant did not protect the cable as is the case in dry conditions, where the BUE protects the cable. Metallic debris formed by mechanical alloyed material and debris from reinforcing particulates act as small tools and wear the cable (see discussion). As already mentioned, the cable is protected by the BUE, but not in the lubricated conditions, where it doesn't formed. Figure 4 shows the variation of the thickness of this bulk material versus the number of cycles.

Table 2 summarizes these results. Oil is a better lubricant than water, as it can be expected even for this configuration of linear friction. With the 10% Duralcan material the cable does not wear, irrespectively of the experimental conditions. The steel cable is harder than the A 1100 alloy. The softer material forms a transfer layer which protects the steel cable. The behavior of massive composites was also tackled. This class of material is produced by foundry either by Duralcan or by ÉTS, as already mentioned. Tables 3-4 summarize the results obtained with these massive composites.

Some obvious observations can also be raised from these results. Oil or water have the same general effect and decrease the wear rate of the specimen but, generally, increase the one of the cable. In other words, the reinforcing particulates of the composites increase the wear rate of the cable when the test is lubricated. The BUE doesn't form and reinforcing particulates act as micro tools for the steel cable. The debris produced are small because they come from the micro machining action of the silicone carbide reinforcing particulates.

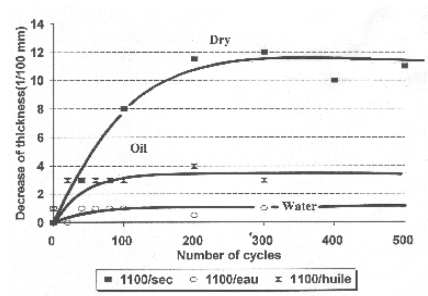


Figure 4: Influence of lubrication on wear of the unreinforced material A1100

TABLE 3 Effect of the volume fraction of MMC' reinforced by small particulates on the wear rate

Volume fraction	Cable wear rate, mm/cycle	Composite wear rate, mm/c
0%	0	$4*10^{-5}$
2.5%	0	$3.5*10^{-5}$
5%	0	$9*10^{-6}$
10%	0	$2.5*10^{-6}$
20%	0	$1.5*10^{-6}$

TABLE 4 Effect of the volume fraction for MMC' reinforced by large reinforcing particulates

Materials	Cable diameter variation in mm/cycle	Specimen thickness variation in mm/cycle
ÉTS, 10%, SiC-120 µm, dry	0	$2.5*10^{-5}$
ÉTS, 10%, 120 µm, water	$1*10^{-6}$	0
ÉTS, 10%, 120 µm, oil	$1*10^{-6}$	0
ÉTS, 35%, 120 µm, water	ND	$5*10^{-6}$
ÉTS, 35%, 120 µm, oil	0	$5*10^{-6}$
ÉTS, 35%, 120 µm, dry	$1*10^{-6}$	$1*10^{-5}$

4. DISCUSSIONS

4.1. Influence of lubrication

As already mentioned, lubrication plays a fundamental role in the friction behavior for all studied composites. As it is expected the presence of lubricant decreases the shearing effort. The surfaces are protected by the layer of lubricant and the wear rate of the two partners is very small. This situation is true for all experiments, except for composites reinforced by coarse particulates. This micrograph illustrated the generated effect of micro-machining by coarse particulates. When using a lubricant, no adhesion is possible.

For coarse particulates, the presence of lubricant modified the wear mode from the formation of microchips and small debris, to an abrasive wear mode of the cable. The BUE is not formed on the both partner's composite and cable. The presence of lubricant prevents the formation of a transfer later on the two partners.

Therefore, to protect a steel part implicated in a dried linear contact, it is recommended to use a composite reinforced by small particulates, while to protect the aluminum surface, it is preferable the lubrication. In the latter case, the rate of wear of the cable is high, mainly with coarse particulates.

4.2. Effect of the volume fraction

The effect of the volume fraction is shown to Figure 5 for two types of composites, one reinforced by small particulates and the other by large one. Adding 10% induced a decrease in the wear rate by a large factor of about 20. Belong this concentration the effect of the volume fraction of reinforcing particulates is small. This observation is very useful, from a practical perspective. A specific volume around particles can explain this effect. The graph representing the wear rate vs the volume fraction can be decomposed in two ranges (fig.5), delimited by V_{pc}A simple calculation illustrates this phenomena. A critical volume fraction V_{pc} is around 10 %.

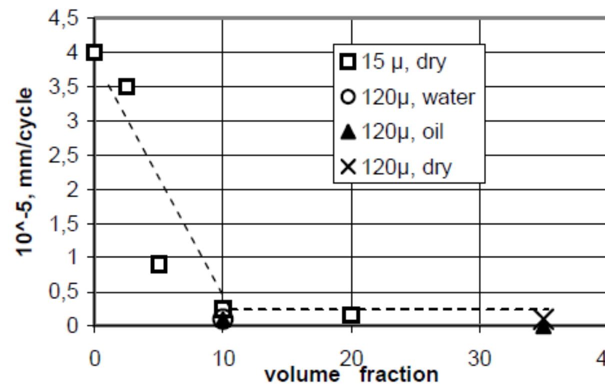
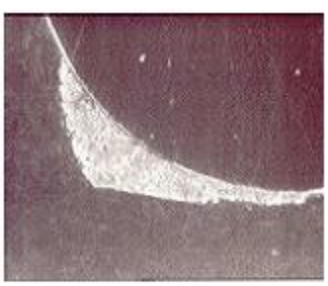


Figure 5: effect of the volume fraction of reinforcing particulates on the wear rate of composite

The presence of reinforcement particulates sharply decreases the rate of wear of the specimen mainly for dry experiments. This can be explained by the "contiguity effect". Each of them can be associated with a sphere of influence. If we assume that particulates are located as a simple cubic network, , it is possible to calculate the F_{pc}, the load carried by each particle. By assuming that the supporting surface of the cable is a straight line, F_{pp} can be approximated by: $F_{pc} = F_a / (L_c * V_p)$, where L_c stand for the length of the cable in contact with the specimen, F_a the applied load and V_p the volume fraction of particulates. For example, in the case of Duralcan, it is found that $F_{pc} = 4.5$ Kg / (cm * % particle). If the load carried by the particulates is higher than F_{pc}, the wear rate of the composites increases.

4.3. Influence of the Size of Reinforcement Particulates

The effect of reinforcing particulates strongly depends of the size of these particulates. The following scheme (fig. 6) provides a guide for the choice of the particles sizes; it summarizes knowledges in the area of friction and wear. For small particles, dislocations are pinned, and yield strength increased. This effect is important for monophased metals like aluminum. This is the domain of heat-treating and/or precipitation hardening. This is shown in photograph 1.



Photograph 1: Built up layer for a 90/10 specimen for a large number of cycles

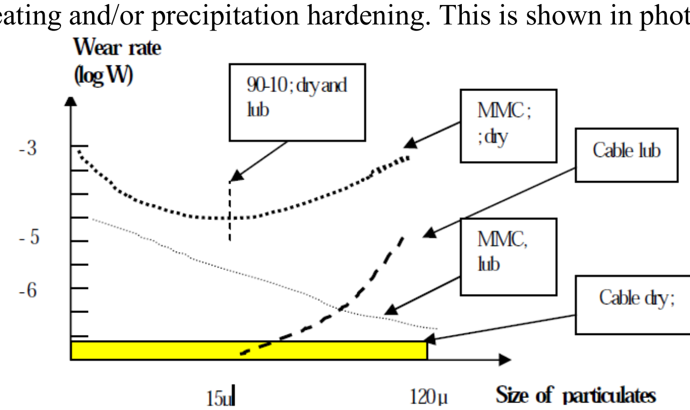
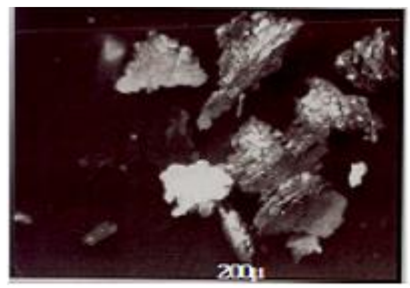


Figure 6: Effect of the size of particulates

4.4. Mechanism of wear; chips formation

For two materials, 1100 aluminum and 90/10 coated steel plates (photograph 2); a significant built-up layer is created on the cable by the plastic deformation of the matrix. The cable does not participate in the formation of the built-up edge, no trace of iron was detected in this layer and micrographs don't reveal modification of the cross-section of the cable. The friction between the cable and the specimen generates a significant plastic deformation. This shearing action by the cable on the plate is responsible for the formation of debris. Some of them are accumulated on the cable and form a transfer layer, but most are ejected away from the sliding area. The cable hardness is higher than that of aluminum, and therefore, the cable acts as a tool, and chips produced are similar to those observed during machining with a negative cutting angle. Chips are short, with no defined shapes. Comparing the shape of chips produced in dry condition for composite reinforced by small and large particulates, some observations can be raised. For composites with small particulates, debris are numerous, small and mainly composed by materials coming from the plate (Si, Al). For composites reinforced by large particulates, debris are larger and composed with materials coming from the plate and the cable (Si, Al, Fe). The subsurface layer forms chips from the plate, where shearing deformation is high. The following photograph 5 is an example of the shearing action with an unreinforced composite. Debris are numerous and large.

Photograph 2: Top view of the BUE formed on a 1100 alloy



Photograph 3: Chips produced during the friction of the A1100 and 90/10 specimens, dry exp. (X100)

In the case of lubricated tests, reinforcement particulates, mainly for larger ones, act as micro tools that machine the cable. Consequently the wear rate of the cable increases when lubrication is used. From the point of view of chip formation, the thermal spray composite coating and the massive aluminum A1100 behave in the same manner. In both cases, there is chip, debris, formation as of photograph 3. The reinforcing with particulates in an A356 matrix generates a very effective protection of the matrix. It is obvious, by comparing the three last micrographs. The particulates protect the matrix. The formation of these highly deformed chips is responsible for the wear of the plate. These chips are formed by micro-extrusion or micro-rolling. This surface layer protects the composite more efficiency than for unreinforced materials. Therefore, the wear rate of composite is lower than the one of unreinforced alloys. In the case of oiled surfaces or surfaces covered by a film of water, the friction is very low, leading to a sharp decrease in the shearing effect of the cable into the sample. Some small chips - smaller than the one produced in the previous dried case- are produced. Also, the chips are in smaller quantities than for dried experiment.

The presence of oil prevents or restrains the formation of chips. Reinforcing particulates, mainly larger one, act as abrasives, and consequently, wear the cable. Very little debris are formed and the shape is not comparable to the one produced in dry experiments. The following scheme shows an illustration of phenomena involved in the different conditions.

In the first case, with a composite reinforced by small volume fraction of particulates or without reinforcement, the plastic deformation of the surface is high and chips are large and numerous. A BUE is formed on the surface of the cable. For large particulates, the matrix is protected and the cable worn.

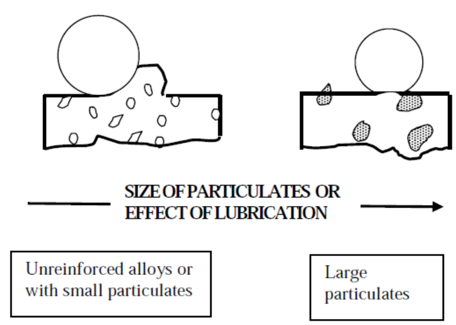


Figure 7: Scheme of the effect of the size of particulates on the wear rate

5. CONCLUSIONS

For the actual experimental conditions (a steel cable sliding with a reciprocating motion on the surface of composites made using different casting processes), it has been shown that the cable or the composites can be protected from wear depending on experimental conditions.

1. When surfaces are lubricated, the composite made of coarse particulates is protected and the cable wears rapidly.
2. In non-lubricated friction, the situation is exactly the opposite.
3. The critical volume fraction, i.e., the minimum fraction of reinforcement particulates for protecting the composites, is on the order of 10%, whatever the size of the reinforcement.
4. This minimum volume fraction does not seem to significantly depend on the size of the particulates.
5. The fabrication process don't seem to have a strong influence on the results

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