EROSION RESISTANCE OF METAL MATRIX COMPOSITES

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Metal matrix composites (MMC) are useful materials to resist wear. This paper deals especially with the erosion resistance of two types of MMC: those made with preforms of random oriented fibers and those with woven fibers. It is shown that the presence of fibers improves the wear protection of aluminum alloys. The role of mixtures can be applied to explain the results. It is also shown that the interface is very important; a thick interface is detrimental.

INTRODUCTION

A new class of material has emerged during the last three or four decades. In order to take advantage of the best properties of the two classes of materials (ceramics and metals) metal matrix composites (MMC) have been developed. Three classes of MMC can be identified depending on the shape of the reinforcing elements: particles, short fibers and long fibers. Two types of long fibers have been studied: randomly oriented fibers in a preform and fabric materials where the fibers have mainly two orientations at 90° from each other.

The properties of long fibers require more fundamental studies for a better knowledge of their behavior. The main goal of this study is to evaluate the erosion resistance. It is generally accepted that ceramic particles improve the wear

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resistance of metals (Harrigan et al. (1). A schematic representation of the erosion protection of the matrix is shown in Figure 1 (Masounave (2). This simple model shows that the hardness of fibers is higher than that of the matrix and of the same order of magnitude as that of the abrasive particles. Also it indicates the main parameters controlling the erosion: incidence angle, speed of abrasive particles, size of second phase (i.e. fibers), etc.

The fabrication of MMC is often a problem. In order to introduce ceramic particles or short fibers into the matrix, expensive techniques are usually used, such as rheocasting or vacuum casting. In order to decrease the fabrication cost, two types of non-expensive fibers were used in the present investigation: preforms of Kaowool fibers and fabrics of alumina-silica fibers designed for thermal insulation.

The ductility of the MMC is drastically affected and lowered to less than 3%. This can be explained in two ways: ceramics are very brittle materials, and some porosity is introduced in the matrix during the processing. In order to overcome this last difficulty, casting under pressure can be utilized (squeeze casting). To insure that infiltration was good, without porosity, a high pressure was applied. However the minimum required pressure has not been determined.

The abrasive slurry used is a very common one found in the testing of materials in the realm of transport by pipeline, pumping of slurry and so on. Ottawa 50-70 sand was used. This sand is commonly used in foundries. It is a cheap raw material, mainly used in abrasion testing (rubber and steel wheel).

EXPERIMENTAL PROCEDURE

Fabrication of MMC

Discs of 38.1 mm in diameter were produced by squeeze casting (Fig. 2). 25.4 diameter preforms or layers of fabric were placed in the casting chamber. The preforms consisted of Kaowool fibers (47% Al_2O_3 - 53% SiO_3) randomly oriented in a plane perpendicular to the disc axis. Three different preforms were used: 10, 15 and 20% of fibers. Some shots are seen in the optical micrographs (Fig. 3). Their effect will be neglected for the interpretation of the results.

The density of the alloy and fibers is almost the same: 2.64 and 2.6 g/cm^3 respectively. The same observation about density applies for the woven fibers. The woven materials were made of the same kind of Kaowool fibers in bundles.

The die was preheated to 300°C. The aluminum alloy (5083) contains 4% of magnesium which is well known to facilitate the interaction between fibers and liquid aluminum. The magnesium reduced the fiber and formed an interface which is probably a spinel. A post casting heat treatment can control the thickness and the composition of this interface. It will be shown that the wear resistance is largely a function of the quality of the interface. When not specified, the specimen was tested as squeeze cast.

After being melted, the specimens were superheated at 810°C and poured into the die over the fibers. A ram was plunged down into the die to obtain a maximum pressure of 80 MPa within 0.5 s. The load was maintained for 10 seconds in order to complete the solidification process and, therefore, avoid porosity due to shrinkage.

Erosion Testing

The tests were performed with an air-powered double-diaphragm slurry pump (Fig. 4). The slurry was pumped from a slurry tank of 7 l capacity. Two sand concentrations in the slurry were used: 10% for the specimen obtained from a preform and 5% for "woven" specimens. The AFS 50-70 Ottawa sand used shows a granulometry between 200 and 300 μm. The pumped slurry was projected against the sample and returned back to the pump. The velocity of the impacting particles was assumed to be equal to the velocity of the fluid. The high sand concentration can justify this hypothesis. The velocity of the slurry was measured by an electromagnetic flowmeter. The diameter of the jet is 4.76 mm at the nozzle. After 15 min of test, the wear rate was calculated from the mass losses of the samples after cleaning and drying. The comparison between all samples can be done on the basis of the mass loss because they have nearly the same density, as already mentioned. The erosion test duration was determined after a short study of the degradation of the sand. The wear rate should be constant. But, because the sand is recirculating, some degradation occurs. It was shown (Fig. 5 a) and b)) that, for a test duration of less than 15 min, the sand degradation is negligible. It was also verified that the sand degradation is the same, whatever the incidence angle.

Observation by Electron Scanning Microscope

As usual, a thin Au-Pd coating was deposited on the surface. After erosion testing the fibers were covered by a layer of the deformed aluminum matrix. In order to observe the damage of the fibers, the worn surface was etched. A solution of 10 ml of HF, 15 ml of HCl and 90 ml of water was used.

RESULTS

MMC with Preforms

The effect of the velocity and of the incidence angle is shown in Figure 6. The addition of fiber preforms slightly improves the wear resistance of the matrix (around 20%). The very good wear protection provided by the fibers at low impact angle and high particle speed has to be pointed out (improvement of more than 60%). The protection given by the fibers is more constant at low speed: between 25 and 35%, independent of the incidence angle.

The effect of the speed is well described by the following classical relation:

$$\dot{W} = k \cdot v^{n} \tag{1}$$

where the exponent n is equal to approximatively 4.4 (Fig. 7).

MMC Cast with Woven Fibers

A few experiments were done in order to test the effect of the interface on the wear rate. For that purpose three types of specimens were used: virgin 5083 alloy, as-squeeze-cast composites and composites squeeze cast and heat treated (680°C for 15 min). In this latter case, a thick interface is shown (Fig. 8). The following table gives the mass loss (in mg) during the erosion tests for different materials and incidence angle. Each figure is the average of two or three tests.

TABLE 1 - Mass loss during erosion tests (mg)

Incidence angle	5083	MMC-5083	MMC-5083 + heat treatment
90°	2.9	5.8	16.2
15°	4.6	3.1	3.15

The effect of the fibers is remarkable: detrimental at 90° and small effect (improvement of 32% in the wear resistance) at 15° (Fig. 6).

The wear protection given by the fibers is obvious when comparing Fig. 9, 10 and 11. At 90° the long fibers are crushed (Fig. 10). It has to be remembered that the size of the impacting particles is much larger than the size of the fibers

(200-300 µ vs 10 µ). The debris of the fibers remained on the surface and still protected it (Fig. 12). Hence, the wear rate is lower than that of the 5083 alloy. At low angle the impact effect is lower. The fibers are less crushed and so provide a more effective protection. Also, it was observed (Fig. 13) that some aluminum platelets had the tendency to cover, at least partially, the fibers.

DISCUSSION

The tests done with preform can be easily interpreted by the rule of mixture (Fig. 14). This rule is well verified (3) when there is no interaction between particles, and when the effect of residual stresses can be neglected. In general terms, a property P of a MMC can be described by:

$$P = P_M V_M + P_f V_f + P_S + P_R \qquad (2)$$

where M and f refer to matrix and fiber respectively, V is the volume fraction, P_S the part due to the variation of microstructure of the matrix caused by the presence of fibers and P_R the action of residual stresses on the property P. The relation can be rewritten neglecting the last two terms:

$$P = P_M + v_f (P_f - P_M) \qquad (3)$$

Because the fibers are well dispersed (Fig. 3) and also well separated, the interaction between fibers can be neglected and the relation (3) verified (Fig. 14).

From equation (3) it is possible to extract the effect of the fibers on the total wear rate.

$$\dot{W}_f = [\dot{W}_C - \dot{W}_M (1 - V_f)]/V_f \qquad (4)$$

The relation is verified in Table 2. This table underlines the strong effect of the incidence angle. The wear protection is better for low angle as already pointed out and for high fiber concentration and high velocity (Fig. 15).

The presence of fibers improves the wear resistance of the aluminum alloy used in this study. However the wear mechanism is not affected by the fibers because the shape of the W vs α curve remains the same. Fibers act as reinforcement of the matrix, not as a ceramic phase. In this last hypothetical case, the shape of the wear curve should change.

TABLE 2 - Value of the parameter $\dot{W}_f$ (mg) equation (4)

V_f α	0.1	0.15	0.2
15°	-37.5	-42.5	-73.7
30°	--	-35	9
60°	-33	-21	-18
90°	8.5	6.8	1

The effect of the interface on the wear rate is clearly shown in Figure 5. The heat treatment was done in the liquid domain at 680°C for 15 min. Therefore the fibers react very rapidly with the liquid (Fig. 8) and a spinel with Al_2O_3, MgO and possibly CuO and NiO is probably formed [4]. This new interface is very brittle and thus is strongly detrimental to the wear resistance. This decrease in wear resistance is more evident at high incidence angle. It should be remembered that the impacting particles are much larger than the fiber diameter. Consequently, the erosion test at 90° is close to an impact test for each individual fiber. Then the presence of a brittle phase around the fibers enhances the crack initiation process. On the other hand, at low angle more fibers act to resist the impacting particles and some aluminum covers the fibers by plastic deformation. This aluminum layer acts as a protection (Fig. 13).

CONCLUSION

It has been shown that:

- Randomly dispersed fibers (preformed) provide a good protection against slurry erosion.
- Protection is best for small impact angle. In this case, the fibers are better sustained by the matrix and hence, can play a better role in the erosion protection.
- A simple rule of mixtures can be used to predict the wear rate.
- The wear mechanism is still controlled by the matrix.
- A brittle interface is highly detrimental at high angle: the fibers destroyed rapidly.

ACKNOWLEDGEMENTS

I thank Babcock and Wilcox (Georgia) for supplying the preforms. I gratefully thank Dr.D. Briggs from CANMET and F.G. Hamel for helpful discussions and critical reading of the technical assistance offered by P. Thibault and R. Lavallée is acknowledged.

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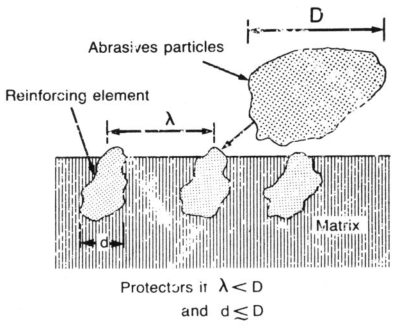

Figure 1 Schematic representation of the effect of abrasive particles during erosion wear.

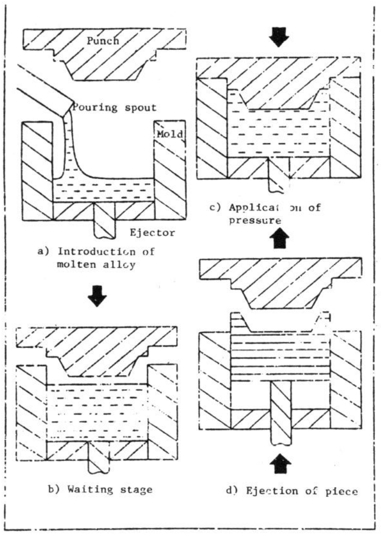

Figure 2 The four steps found in squeeze casting. To avoid porosity formation, pressure has to be applied at the appropriate time.

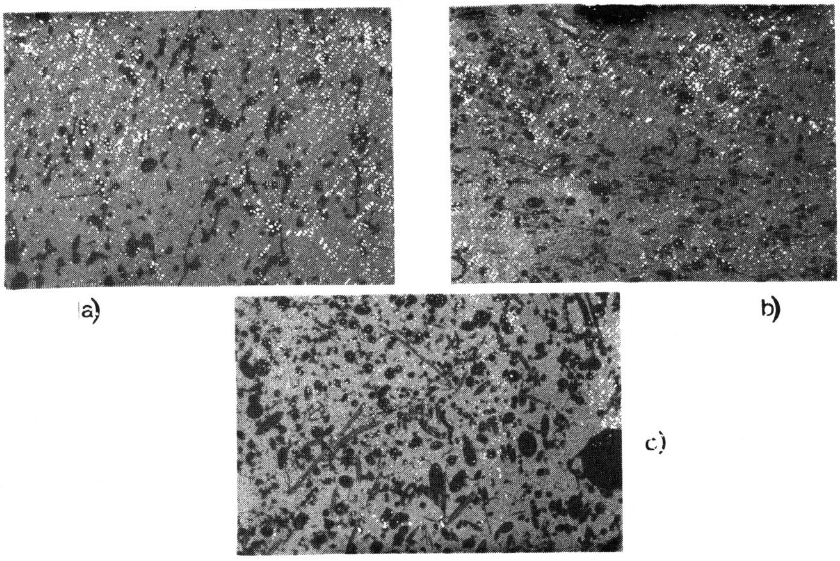

Figure 3 Microstructure of the MMC produced from a preform with a) 10%, b) 15%, c) 20% of Kaowool fibers.

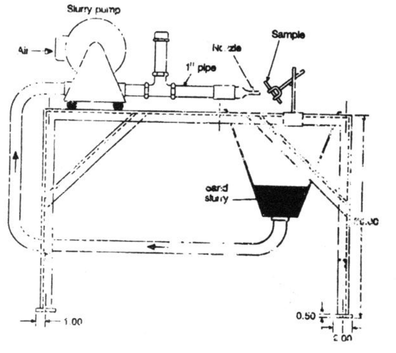

Figure 4 Schema of the set-up for erosion testing.

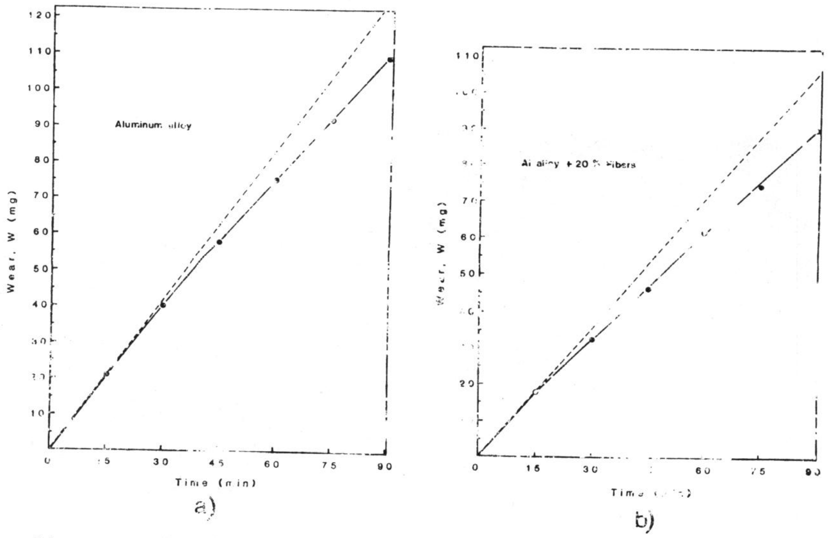

Figure 5 Erosion of wear versus time a) for the 5080 alloy, b) for the MMC with 20% of fibers.

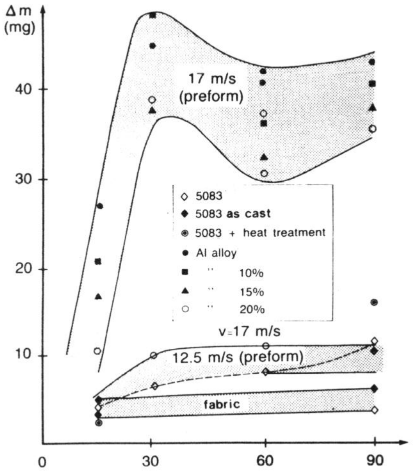

Figure 6 Effect of speed and impact angle on wear of preformed and woven MMC.

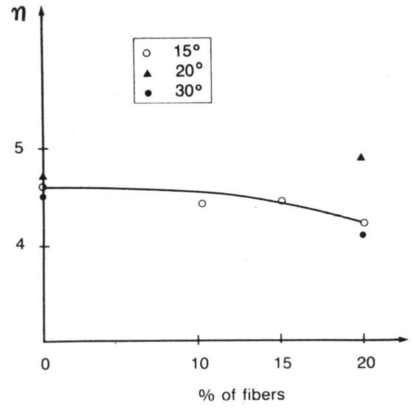

Figure 7 Variation of the exponent of the speed with the percentage of fibers $(W - k \cdot v^n)$.

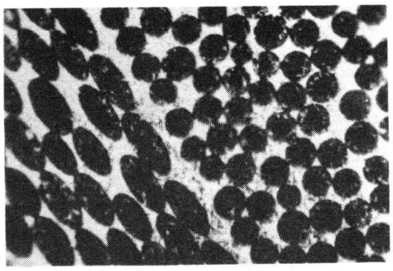

Figure 8 Micrograph of a 5083 fiber after heat-treatment (680°C for 15 min). Magnification x1250 (Keller's gent). The reaction zone is seen around a fiber core.

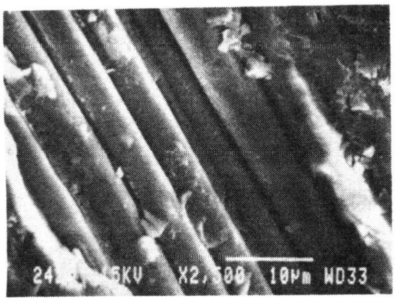

Figure 9 Micrograph of uneroded fiber in matrix.

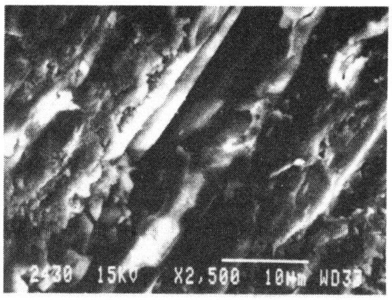

Figure 10 Micrograph of eroded fibers worn at 90°.

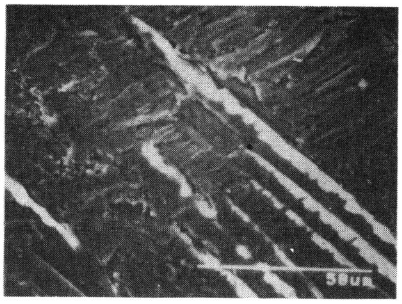

Figure 11 Micrograph of eroded fibers worn at 15° (woven fibers).

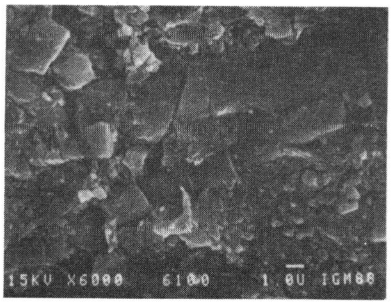

Figure 12 Worn surface of 5083-20% (preform). Impacting angle: 90°. Speed of abrasive particle: 17m/s.

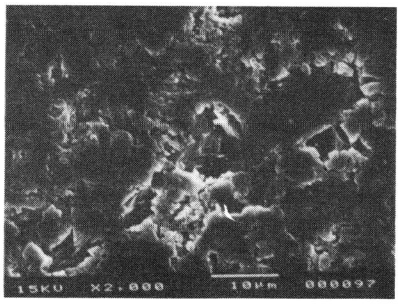

Figure 13 Worn surface of 5083-20% (preform). Impacting angle: 15°. Some platelets of aluminum tend to cover the fibers.

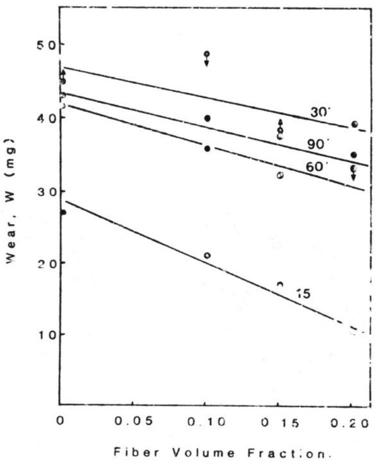

Figure 14 Erosion wear as a function of fiber volume fraction (for 17 m/s).

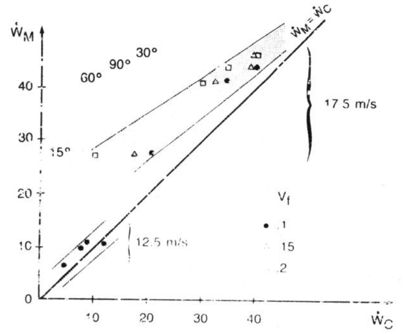

Figure 15 Erosion of the matrix as a function of the erosion of the composite.