Aspects regarding wearing behaviour in case of aluminium composite materials reinforced with carbon fibers

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Abstract. This paper presents a study regarding wear comportment of sintered composite materials obtained by mixture of aluminium with short carbon fibers. The necessity to satisfying more and more the specific functions during design of high performance structures leads to perform multi-materials such as reinforced composite parts. The wear tests were made on three different orientations of fibers on a standard machine of tribology, pin disk type. Counter-disk was made of cast iron with a superficial hardness of 92 HB. The wear rate and friction coefficient decreased exponentially with time of friction and reached a stationary value. This behaviour was attributed to the development of a lubricating film on the friction surface. To conduct this work was performed measurements on samples from the Al matrix composites and carbon fiber 43%, wear mechanism was investigated by scanning electron microscopy. In addition to fiber orientation, the tribological behaviour of metal matrix composites reinforced with fiber is influenced by the interfacial reaction of fiber-matrix. The characteristics and the dimensions of the interface depend on the cycle of temperature and time at which the material has been subjected during the manufacturing process and thereafter.

1. Introduction

Aluminium alloys are used for industry in composite materials reinforced with carbon fibers because those types of material have high strength, low density, durability, machinability, availability and cost is very attractive compared to competing materials. The aluminium matrix composites can be differentiating from aluminium alloys, which are achieved via control of naturally occurring phase transformations during solidification or thermomechanical processing [1, 2].

Generally, composite materials technologies offer a unique opportunity to adapt to the properties of aluminium. Through by use of aluminium into composite is increased the strength, is decreased the weight, is achieved a higher service temperature, is improved the wear resistance, has a higher elastic modulus and can be controlled the coefficient of thermal expansion to be improved the fatigue properties, etc [3-5].

For the used samples with parallel fiber to the sliding direction, it developed a model of wearing, which includes three dominant wear mechanisms: the matrix removals by delamination, fiber wear the striation and fiber pulling out [6].

The model was evaluated numerically that offered a substantial agreement with experimental data. Thus, it is established that the fiber extraction is a mechanism that contributes to the wear, the speed of the wear is an exponential function of normal load. Conversely, lack of the extraction of the fiber, the speed of wear that presents the components is strictly proportional to the normal load.

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Is difficult to predict accurately the strength and ductility of the aluminium composite materials reinforced with carbon fibers by simple mathematical expressions, that's are determined by the matrix alloys, the reinforcement and the processing technology. In terms of the yield, stress is improved with matrix strengthening effects and residual thermal stresses, due to differential contraction of reinforcement and matrix and the fatigue properties of aluminium composites are normally better than the unreinforced equivalent alloys [7, 8].

The wear resistance of composite materials depends on the particular wear conditions, but there are many circumstances where Al-based composites have excellent wear resistance, composites form by carbon fiber and aluminium the thermal conductivity can also be enhanced. The combination of low thermal expansion and high thermal conductivity makes them very attractive for electronic packaging. Compared to the metal itself, a carbon fiber-aluminium composite is characterized by a higher strength-to-density ratio, a higher modulus-to-density ratio, better fatigue resistance, better high-temperature mechanical properties and better wear resistance [9-11].

The wear rates of the composites were lower than that of the matrix alloy and further decreased with the increase in reinforcement material. However, in both unreinforced alloy and reinforced composites, the wear rates increased with the increase in load and the sliding speed. The wear rates increases with load increasing, but it varies from linear to rapid increase for all the test materials. Similarly, with the increase of sliding velocity, the wear rate increases as well. With the increase of sliding velocity, the surface temperature of the materials increase, which leads to the rise of plastic flow of surface and subsurface, and therefore the wear rate increases [12].

2. Experimental aspects

The behaviours that have the Al-fibre carbon composites to the friction and wear was examined by means of interfacial reaction area. The wear tests were made on three different orientations of fibers on a standard machine of tribology, pin disk type. Counter-disk was made of cast iron with a superficial hardness of 92 HB. The wear rate and friction coefficient decreased exponentially with time of friction and reached a stationary value.

This behaviour was attributed to the development of a lubricating film on the friction surface. Wear mechanism was investigated by scanning electron microscopy. For the used samples with parallel fiber to the sliding direction, it developed a model of wearing, which includes three dominant wear mechanisms: the matrix removals by delamination, fiber wear the striation and fiber pulling out [13].

The model was numerically evaluated, ascertaining the perfect concordant with the experimental data. Thus, it appears that the fiber extraction is a mechanism that contributes to the wear; the wear rate is an exponential function of normal load. Instead, in the absence of the phenomenon of fiber extraction, the wear speed of parts is strictly proportional to the normal load.

The properties of metallic materials, such as density, modulus of elasticity and thermal expansion, can be substantially modified by their reinforcing particles or fibers. Besides good thermal properties, their low density makes them particularly desirable for aerospace electronics and orbiting space structures.

Currently the composites are widely used for a variety of applications, such as gaskets, electric brushes or materials camps. Although, at present, the composite materials are known as performance and the application areas, the information on the wear behaviour and the applicable models of wear mechanisms presents a limited development [14].

The composites Al-particles SiC haven't shown the improvements in the wear resistance domain at low loads, showing only a relatively improvement at higher loads. Theoretically, this kind of composite would have to present a special wear-resistant due to the large hardness of SiC particles. It considers that removing of the SiC particles it's that who generates these high speeds of the wear. The phenomenon is caused by the formation of cracks in the particle-matrix interface due to weak links created between matrix and reinforcement material. At higher loads, wear particles are buried and offers greater resistance than the application of the smaller loads.

A special importance from this point of view it has the percentage of reinforcement material used. The use of small additions of graphite (2%), leading to the improvement of the wear characteristics. Increasing the percentage of reinforcement material to about 8%, resulting in reducing of these performances, causing the appearance of a significant softening and hence an increase in the rate of the wear. Improvement of resistance recorded at low percentages of reinforcing material is attributed to the lubricant effect which it has the graphite or carbon fiber, that results in reducing the friction coefficient with the increasing of temperature. However, the lubricating qualities may be lost during the sliding wear. Thus, was found that the graphite is losing the lubricating ability at the temperatures higher than 50°C, in experimental conditions. As a consequence, it showed a significant transfer of metal and was obtained a high speed of the wear.

Were made the experiments on the composite with carbon fiber and epoxy resin, observing that, if the fibers are oriented longitudinally or transversely to the direction of sliding on the surface, increases the speed of the wear, due to the fact that some fibers are pulled out from the matrix by asperities of the friction counter-disk. At the same time, it has been reported lack of significant effect of fiber orientation on the tribological properties of the metal matrix composites.

Were made velocity measurements of the carbon-polymer fiber composites wear sliding on mild steel. Was been hypothesized that, if carbon fibers are those that support the load preferentially, the speed of the wear must be independent of the matrix and it is characteristic for the carbon mass. The fibers can detach from the surface layer, if the matrix has a higher intrinsic speed of the wear or if the interfacial bonding between fiber and the matrix is relatively weak.

Wear mechanism is based on the fact that, while the adhesion between graphite and iron is relatively weak, the aluminum will be transferred to the disk by adhesion. This action leaves fibers without the support of matrix and thus will break easily. It is obvious that, in the case of the reinforced matrix with fiber oriented, wear mechanisms will be different for the three extreme cases, namely:

- the reinforcing fiber axis is perpendicular to the sliding plane and the sliding direction;
- the fibers are parallel to the sliding plane and the sliding direction;
- the fibers are parallel to the sliding plane and perpendicular to the direction of sliding.

In addition to fiber orientation, the tribological behavior of metal matrix composites reinforced with fiber is influenced by the zone of the interfacial reaction fiber-matrix. Characteristics and the interface dimensions depend on the cycle of temperature and the time at which the material has been subjected during the manufacturing process and thereafter.

They have proposed several mechanisms of the wear, each of which applies to certain conditions.

For homogeneous materials, the adhesion theory correlates the volume of wear, V, with the normal load L, the distance of sliding S, the material hardness, H, and the wear coefficient K by the equation (1):

$$V = KLS/H \tag{1}$$

For materials with hard constituent particles, between the friction surfaces in contact or when the hard material, having a rough surface, slides on a soft material, the wear speed is described by an abrasion mechanism.

The volume removed by friction, equation (2):

$$V = LS\ tg(\theta/\pi H) \tag{2}$$

where L is the normal load, S is the crossed distance, [Symbol] is the average angle of friction, and H is the softer material hardness.

Stratification theory correlates the wear speed with the nucleation of under-superficial cracks and propagation of the material deformation by shearing. Under-superficial cracks propagate on the surface forming layers of the wear, gradually falling off the surface. Wear volume, V, is given by equation (3):

$$V = S/S_o \times N_S A_S h \tag{3}$$

where S is the distance of sliding, S_o is the distance of sliding required for complete removal of a one surface layer, N_S is the number of layers of the wear/layer exfoliated, h is the thickness of the wear layer, which is equal to the thickness of the deformed area with low density and A_S is the average area of each layer of the wear.

None of these models do not take into consideration the relationship between fiber and the sliding direction, very different mechanical properties of the matrix and fiber or bond strength between fiber and matrix, that correlations have to be determined through experimentation.

3. Results and discussion

Were performed determinations on the test specimens from the composites materials with Al matrix and 43% carbon fiber. Table 1 shows the properties that it has the fiber and the matrix. The material was fabricated by bonding technology trough diffusion.

Table 1. The specific properties of the fiber and metal matrix.

Characteristic	Thornel Fiber P-55	Matrices 201 Al
Diameter	11 µm	-
Tensile strength	1720 MPa	190 MPa
Tensile modulus	380 GPa	71 GPa
Elongation	0.5 %	20 %
Density	2.0 mg/m^3	2.77 mg/m^3

Studies by electron microscopy with streaks and electron diffraction showed the presence of the reaction zone from the fiber-matrix interface. Reaction zones, in case of material found out in receiving state, include the present compounds Al_4O_4C, in the case of heat-treated material the intermetallic compounds Al_4C_3. The thickness of the reaction areas increased with increasing of time and temperature of thermal treatment, leading to improve of the mechanical properties.

Simultaneously with increasing the thickness of the reaction zone, the bonding resistance increased between the matrix and the reaction zone and decreased between the reaction zone and the fiber. The effect that it has the heat treatment of the matrix micro-hardness and the resistance whom it has the composites to the tensile strength are shown in table 2.

Table 2. The micro-hardness and resistance to longitudinal traction.

Material	Hardness (kgf/mm^2)	Tensile strength (MPa)
In reception status	78.8	735
450°C, 24 h	62.0	615
500°C, 24 h	55.0	580
545°C, 24 h	68.2	405
545°C, 258 h	64.6	420

The wear samples were prepared mounting them initially in epoxy resin, then wet sandblasting them (with SiC, graining 600) and polishing them with Al_2O_3 (1 and 0.5 µm) in kerosene. After preparation, the epoxy resin was removed with acetone, and the profiles were measured with surface profile-graph.

Typical surface profiles of the polished samples are shown in figure 1.

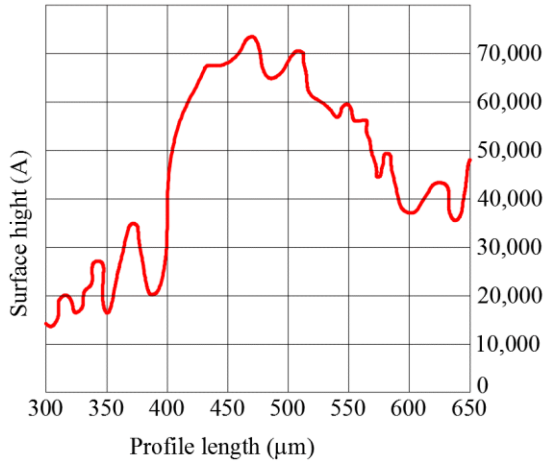

Figure 1. The surface profile of Al-fiber carbon composite in status reception.

The speed of sliding used in the wear tests was 1 m/s. Mass losses were evaluated after 3, 6, 9, 12, 15, 30, 45 and 60 minutes from the total time of the wear.

Figure 2 shows a typical curve for the speed of the wear as a function of the fiber orientation and sliding time; relative orientations are marked with:

- N - fibers perpendicular to the plane and the sliding direction;
- PL - fibers parallel to the sliding direction;
- PD - fibers perpendicular to the sliding direction.

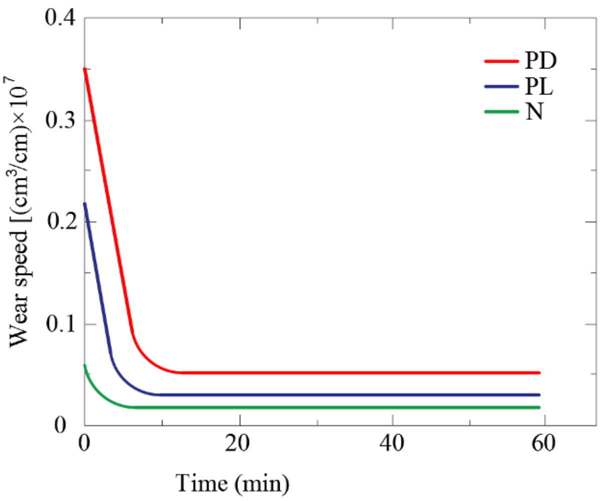

Figure 2. The wear typical speed as a function of time and fiber orientation to the disk and to direction of sliding.

The wear speeds, initially high, have decreased exponentially. All samples have arrived at a steady speed of the wear in the first 25 minutes of sliding. For all samples tested, the experimental results showing the wear speed was lowest when the fibers are oriented in the perpendicular to the disk and sliding direction. In case of the material in reception status, fiber orientation does not seem to significantly influence the size of the stationary wear.

Tables 3 ÷ 5 shows average speeds of stationary wear and standard deviations obtained from at least five experiments applied to each sample and each fiber orientation. In the case of fibers normal to the plane and the direction of sliding, the speed of the wear decreases with decreasing of the matrix hardness. The opposite trend, increasing the speed of the wear with decreasing of hardness, was observed in materials with the fibers parallel to the plane of sliding and perpendicular to the direction of sliding. If the fibers were parallel to the direction of sliding has been found a clear correlation between the speed of the wear and the thickness of the reaction zone, the speed of the wear increases with increasing of the reaction zone.

Table 3. The effects of the heat treatment on the stationary speed with the wear out of the test samples having the fibers oriented normal to the friction counter-disk.

Material	Wear speed [$(cm^3/cm)\times10^7$]	Hardness (kgf/mm^2)
500°C, 24 h	0.0052±0.0006	55.0
450°C, 24 h	0.0060±0.0007	62.0
545°C, 168 h	0.0067±0.0017	64.6
545°C, 24 h	0.0076±0.0015	68.2
Material – reception	0.0077±0.0011	78.8

Table 4. The effects of the heat treatment on stationary speed of the wear of presented by test samples having the fibers oriented parallel to the sliding direction.

Material	Wear speed [$(cm^3/cm)\times10^7$]	Hardness (kgf/mm^2)
In reception status	0.0070±0.0000	22
450°C, 24 h	0.0095±0.0003	36
545°C, 168 h	0.0141±0.0017	120
500°C, 24 h	0.0157±0.0079	104
545°C, 168 h	0.0168±0.0048	145

Table 5. The effects of the heat treatment on stationary speed of the wear of presented by test samples having the fibers oriented perpendicular to the sliding direction.

Material	Wear speed [$(cm^3/cm)\times10^7$]	Hardness (kgf/mm^2)
At reception	0.0075±0.0001	78.8
545°C, 24 h	0.0099±0.0011	68.2
545°C, 168 h	0.0123±0.0064	64.6
450°C, 24 h	0.0126±0.0034	62.0
500°C, 24 h	0.0204±0.0070	55.0

4. Conclusions

The behaviour analysis in case of aluminium composite materials reinforced with carbon fibers reveals a wear rate and friction coefficient decrease exponentially with time of friction and reached a stationary value. This kind of behaviour was attributed to the development of a lubricating film on the friction surface.

With increasing of the thickness of the reaction zone, the bonding resistance increased between the matrix and the reaction zone and decreased between the reaction zone and the fiber. The heat treatment of the matrix micro-hardness, effect that it has the and the resistance whom it has the composites to the tensile strength.

After the consulting of graph with wear typical speed as a function of time and fiber orientation to the disk and to direction of sliding, can be observed in the case of fibers normal to the plane and the direction of sliding, the speed of the wear decreases with decreasing of the matrix hardness. Can be observed an opposite trend, by increasing the speed of the wear with decreasing of hardness, in materials with the fibers parallel to the plane of sliding and perpendicular to the direction of sliding. If the fibers were parallel to the direction of sliding has been found a clear correlation between the speed of the wear and the thickness of the reaction zone, the speed of the wear increases with increasing of the reaction zone.

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