INFLUENCE OF THE FIBER DIRECTION ON THE TRIBOLOGICAL BEHAVIOR OF CARBON-FIBER REINFORCED EPOXY COMPOSITES MANUFACTURED BY PREPEG LAMINATES.

J. Coello [1,2(*)], A. Martínez[1], A. Castillo[2], N. Medina[2] and V. Miguel[1,2]
[1] Regional Development Institute, University of Castilla-La Mancha, Campus Universitario 02006 Albacete (Spain)
[2] Industrial Engineers School, University of Castilla-La Mancha, Campus Universitario 02006 Albacete (Spain)

ABSTRACT
In this work, friction behavior of different carbon fiber-epoxy composites is evaluated. Linear friction tests are carried out and wear behaviour has been established from several parameters as wear depth, wear band width and macrostructural observation. The experimental variables considered were load (10-40N) and the fiber orientation with respect to the sliding direction (0°, 90° and multidirectional). Layers with the fiber oriented in the sliding direction showed larger wear due to cracks existing in the fiber-matrix interface once the wear depth reached the fibers. The best results were obtained in those cases in which no influence of the resin matrix existed.
KEY WORDS: friction, wear, carbon fiber, composites.

1.- INTRODUCTION.
Nowadays, fiber reinforced polymers composites are often used in variety of industrial applications such as bearings, rollers, gears and transmission belts. In these applications it is necessary high strength and stiffness, great thermal and dynamic mechanical stability and good tribological properties. Therefore, glass and carbon fiber/epoxy composites are frequently used for reinforcement in those uses.
In tribological applications, these composite materials can suffer different surface damages and the interface between the reinforcement fibers and the matrix plays a crucial role in the failure of reinforced composites [1]. Different works have been developed to study the effect of the interface on the mechanical properties and friction and wear properties [2-4]. Ozcan et al. [4] studied the friction and wear carbon fiber reinforced composite under different environmental and experimental conditions. Those authors shown that a higher abrasive wear was reported with larger difference between the hardness of the carbon fiber and the matrix. Krkoska [5] studied the effect of relative humidity on frictional performance of C/C composite materials.
There are numerous works that study the friction and wear characteristics of polymers and fiber reinforced composite and the effect process parameters (normal load, sliding speed), composite surface features (roughness, grooves) [6-8]. Ley Yan et al. [8] have been researched the influence of the applied load and velocity on carbon nanotubes reinforced epoxy composites under water lubricated condition. They show the wear rates and the friction coefficients of composites decreased with increasing sliding velocity, and the wear mechanism was slightly abrasive.
The objective of the present work is to evaluate the friction and wear behavior of different carbon fiber reinforced epoxy composites laminates under different load and

sliding velocity. The influence of fiber direction was studied too. Assays were carried out in a tribometer pin on disk

2. EXPERIMENTAL PROCEDURE.

2.1.-Materials.

For carrying out this work it has been used a commercial prepeg ACG MTM 57 manufactured by Advanced Composites Group Ltd. This prepeg is made up of 60% volume of unidirectional carbon fiber in epoxy matrix. This material has a thickness of 0.4 mm and is cured at 100ºC during 3 hours.

2.2.-Friction tests.

The friction and wear tests were executed on a tribometer, trademark Microtest®, with linear displacement.

All tests were performed using a flat pin of a diameter of 6 mm made out of Ti6Al4V alloy with a hardness of 36 HRC. Before each test, the pin surface was polished with 220 grit paper up to an average roughness of 0.15–0.2 μm and after that, cleaned with ethanol. This way, the values of hardness and roughness were considered to be fixed as reference values for performing all tests.

The experimental variables considered were load (10-40N) and the fiber orientation with respect to the sliding direction (0°, 90° and multidirectional). The sliding distance for all tests was 200 m.

The linear sliding mechanism was actioned by a crank-connecting rod system in which 1rps angular speed of the crank was fixed in all cases. As the length of the linear path was ± 30mm, it was applied a continuous range of linear velocities in each test between 0 and 3600 mm/min.

Tests were performed on 3 types of samples designated M1, M2 and M3, Figure 2, under dry condition.

Samples M1 and M2 were manufactured in a similar way, by using 4 layers of prepreg oriented at 0º, 45º, -45º and 90º, respectively. Samples M1 were tested in the direction of the fiber, that is, on the 0º direction layer. On the other hand M2 specimens were evaluated in the perpendicular direction, that is, 90º on the face with the fiber oriented to 0º. Samples M3 were made up of 24 layers by repeating the 0º/45º/-45º/90º sequence as indicated for M1 and M2 samples. These samples were tested on the transversal section of the laminate in order to evaluate the behavior of the different transversal disposition of the carbon fiber.

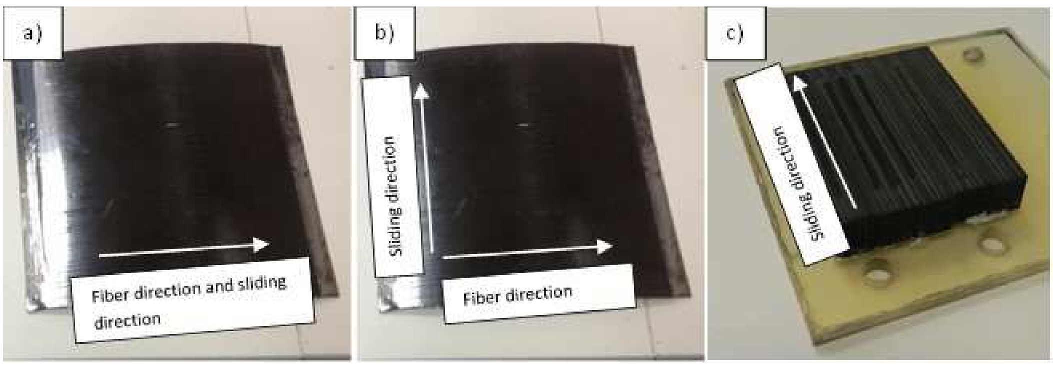

Figure 1.Types of samples configuration; a) Samples M1, b) Samples M2, c) Samples M3.

2.3. Characterization of the samples tested.

In order to assess the surface finish of the samples tested and the wear experimented, a 3D profilometry study was performed. This allowed us to determine the surface roughness of the areas tested and the depth and width of wear after every test. On the other hand, some macrostructural analysis was made in order to obtain the friction bands dimensions. The width of friction bands were evaluated by image processing by using the software PerfectImage®.

3.- RESULTS AND DISCUSION.

3.1.- Friction and wear tests.

Friction coefficient, μ, involved in every test was determined from the tangential force (F_R) and the normal force (F_N) applied in tests as it is indicated in equation (1),

$$\mu = \frac{F_R}{F_N} \qquad (1)$$

The apparent pressure, P_a, in friction tests was evaluated taking into account the width of the friction band, b_f, which was assumed to be the diameter of a circular contact section. Thus, the apparent pressure for each test was calculated according to equation (2).

$$Pa = \frac{4F_R}{\pi b_f^2} \qquad (2)$$

It was established the initial friction coefficient, μ_i, corresponding to the value obtained during the first sliding travel of the part. Moreover, values for the coefficient of friction were also measured for different sliding distances. The variation of the friction coefficient led to determine the point at which the resin layer broke and began to friction the carbon fibers. In this point an increase of the friction coefficient was observed.
Figure 2 depicts the variation of the coefficient of friction and the wear depth as a function of the sliding distance for different loads in the epoxy matrix. It can be observed that the friction coefficient increased with the load. For a load of 40N, the initial friction coefficient of 0.15 increased sharply reaching a value of 1.0 for a sliding distance of 120 m. At this distance, wear curve shows a large decreasing. This anomalous trend wear curve is due to the adhesive behavior of the epoxy resin to the flat pin. Some adhesion to the pin´s face made the distance pin-part to increase instead of reducing by wear.

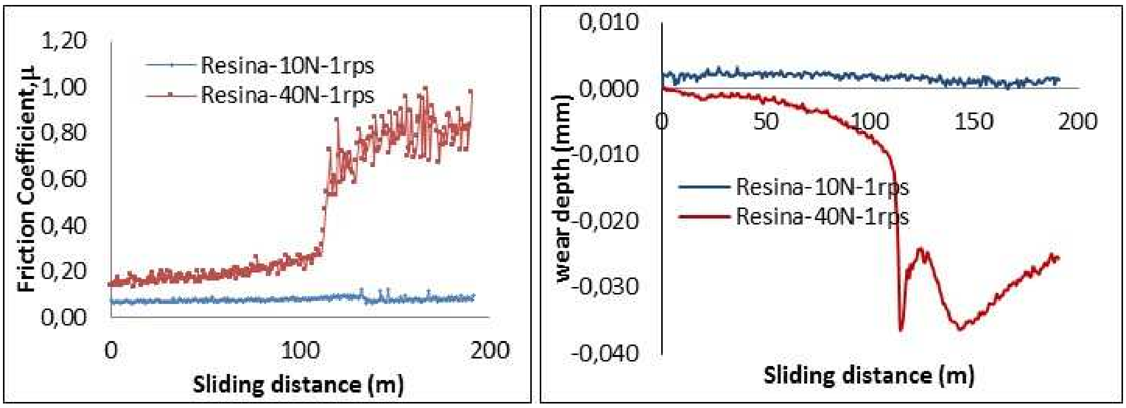

Figure 2. Variation of friction coefficient and wear depth with sliding distance and load for the epoxy resin.

The variation of friction coefficient and wear depth as a function of sliding distance for different loads and different samples is shown in Figure 3.

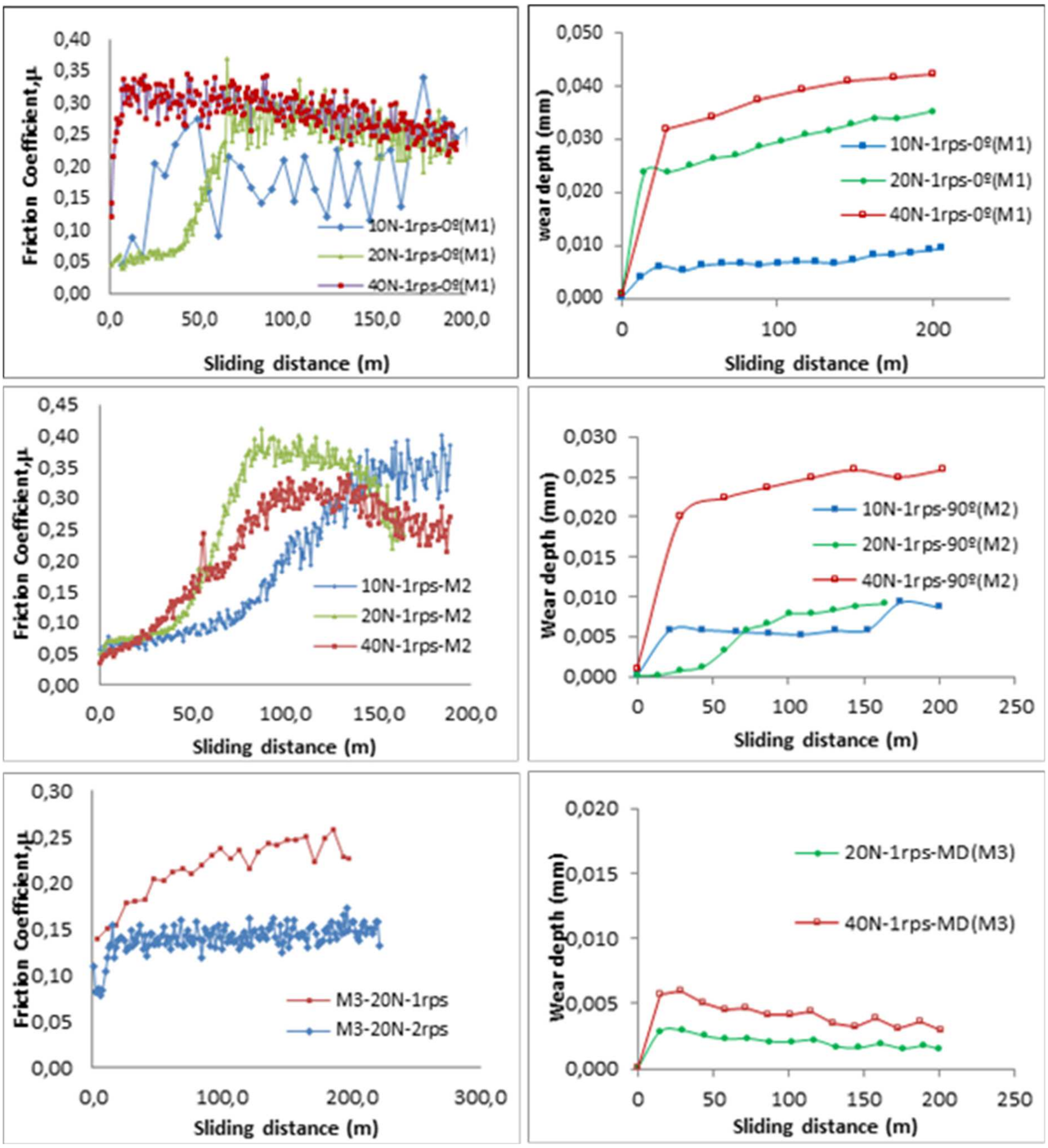

Figure 3 Variation of the friction coefficient and wear depth with sliding distance and load for the three samples of composites experimented.

Samples M1 and M2 present an initial friction coefficient of 0.05. In both samples the friction coefficient remains constant during some distance and after that increases sharply, reaching maximum values of 0,4. This fact may be justified by the breakage of the epoxy surface layer. Furthermore, it is observed that this distance decreases with load and it is lower for sample M1.

Samples M3 present a highest inicial friction coefficient, 0.15, but this value remains almost constant with distance.

As it can be seen, all wear curves present the same pattern. There is a first stage with linear variation of wear depth as function of sliding distance considered as run-in period and a second stage, where slight variation of wear is observed and in which the wear value reaches a maximum. Adhesions of resin on the pin´s face may establish light decreasing trends in wear as it was mentioned before.

On the other hand, the comparison of wear corresponding to the different configuration of samples reveals that the samples type M3 present a better wear resistance. The higher resistance of this composite is due to the direct friction of the carbon fibers in the transversal section with the flat surface of pin. In this surface there is not any layer of resin matrix and carbon fiber has a high specific strength modulus and a self-autolubricated nature. No significant differences were registered for the different fiber position. The samples M1 and M2 showed a larger wear behavior and it reaches a maximum value of 30 µm.

Table 2. Maximum wear Depth and run in-distance for different loads and for the three sample configurations

Samples	Maximum wear Depth (mm)	Run in distance (m)
10N-1rps-M1	0,00951	24,36
20N-1rps-M1	0,03531	29,12
40N-1rps-M1	0,03745	29,60
10N-1rps-M2	0,00926	43,62
20N-1rps-M2	0,00913	14,44
40N-1rps-M2	0,02588	14,61
20N-1rps-M3	0,00296	14,66
40N-1rps-M3	0,00593	14,42

3.2. Characterizations of tested samples.

3.2.1. 3D perfilometry

Figure 4 shows 3D surface maps corresponding to the different samples tested with a load of 40 N and a velocity of 1rps. It can be clearly observed that the wear depth is greatest for samples M1 and lowest for samples M3. As expected, this effect was more severe for higher apparent pressures.

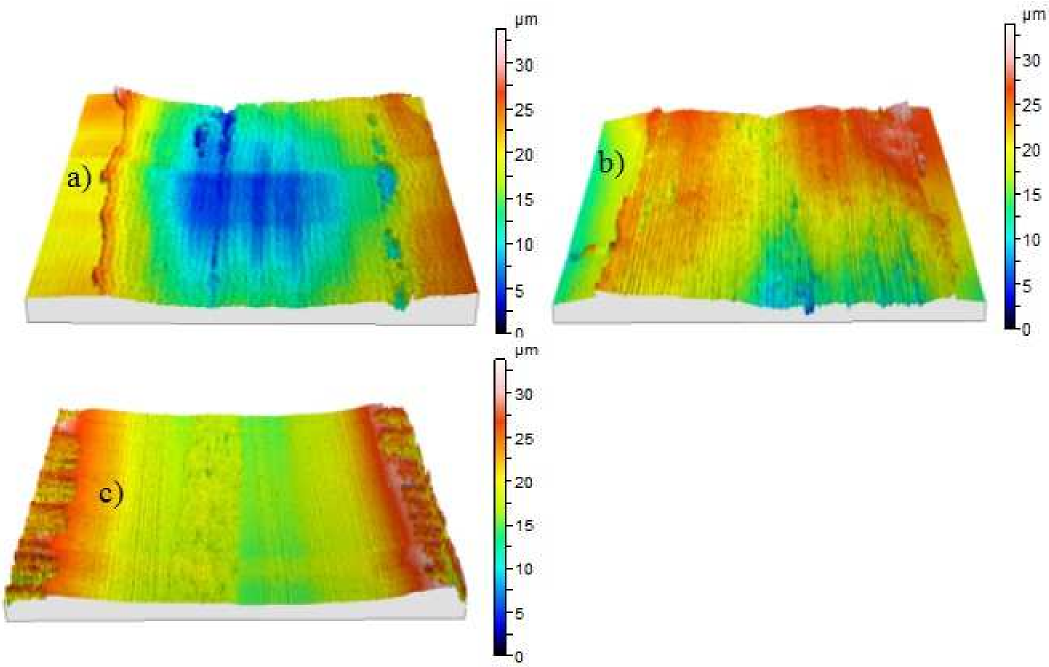

Figure 4. 3D profilometer images of sliding surfaces. a) Samples M1, b) samples M2, c) samples M3 (1rps, 40 N, 200 m).

To evaluate wear, 2D roughness profiles were obtained from transversal sections of 3D maps with a length of 2 mm, Figure 5. In each profile obtained, wear depth and width were considered.

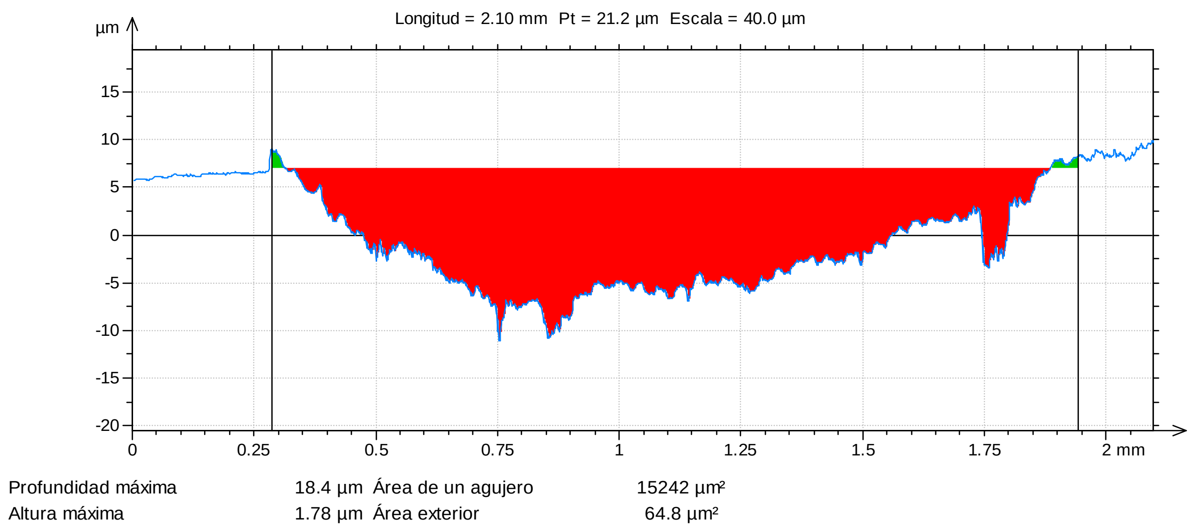

Figure 5. 2D roughness profiles M1 samples. (40N normal load, 1rps)

Table 2. Values of the wear depth, wear area, and wear width

Samples	Load (N)	Ra (µm)	Pa (Mpa)	wear width (mm)	wear depth (µm)	wear area (µm²)
M1	10	0.606	10.87	0.92	4.29	658
M1	20	0.512	12.12	1.65	8.53	3678
M1	40	0.466	21.98	1.82	18.4	15157
M2	10	0.064	12.35	0.81	1.39	241
M2	20	0.125	12.74	1.57	3.22	954
M2	40	0.243	18.52	2.16	7.79	6894
M3	20	0.153	19.42	1.03	2.34	857
M3	40	0.089	31.75	1.26	5.38	2546

3.2.2. Macroestructural study.

Figure 6 shows the surfaces of each kind of the three samples tested. In fig 6a and 6b the surfaces of the fibers do not show a significant wear but some broken fibers in worn areas were observed. This points to the fibers fracture as wear mechanism in these samples. As well as carbon fiber, the matrix in these areas was also remove from the part due to craks formed at the fiber-matrix interface. This fact justified that samples M1 and M2 presents higher wear than the quantified for samples M3.

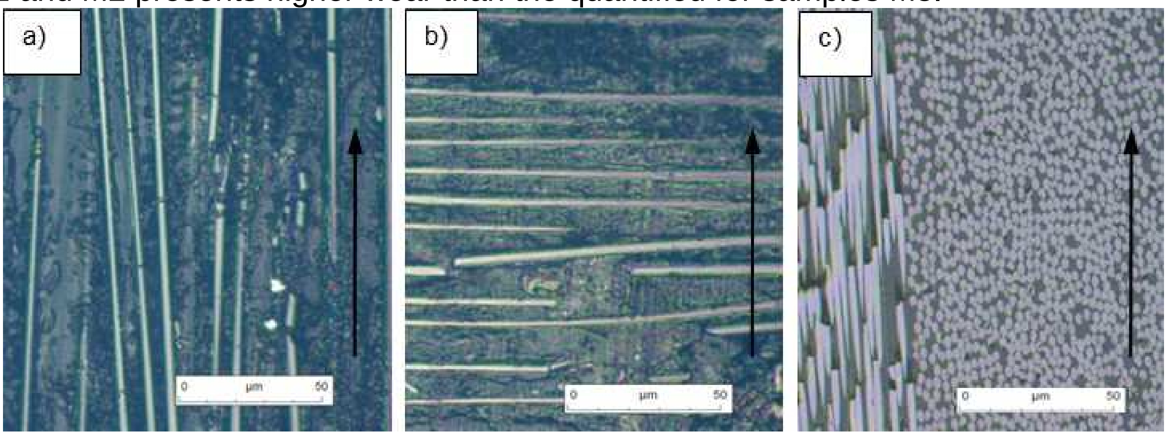

Figure 6. Macrography of the worn surface of samples at 40N and 1rps a) M1, b) M2, c) M3.

4.- CONCLUSIONS

In this work, the friction behavior of different carbon fiber-epoxy composites has been evaluated. Friction tests were made on layers with fiber located at 0º and 90º respect to the sliding direction. The influence of the load applied was similar in both cases but laminates at 90º behave better. Layers with the fiber oriented in the sliding direction showed larger wear due to cracks existing in the fiber-matrix interfase once the wear depth reached the fibers. In order to evaluate wear behavior of carbon fiber, samples made up of many prepeg layers were fractioned on the lateral or transversal face. These samples gave the best behaviour since no influence of the epoxy matrix appeared. For this last case, no cracks were observed neither in the matrix nor in fibers.

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