Friction Behaviour of Polymeric Composite Materials Mixed with Carbon Fibers Having Different Orientations Layout

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Abstract. This paper presents a study of the friction properties of polymeric composite materials reinforced with unidirectional carbon fibers having different stratified structure. So, the composites are complex and versatile materials but their behaviour in practice is not fully studied. For instance, these polymeric composite materials mixed with carbon fibers after being investigated in terms of wear, did not elucidate the effect of fiber orientation on wear properties. Is therefore necessary to investigate the effect of carbon fibers orientation on the friction-wear properties of the reinforced composite materials tested to abrasive and adhesive friction. Research work has been done with unidirectional composite materials having overlap 18 successive layers made from a polymeric resine and 60% of carbon fibers. The stratified structure was obtained by compressing multiple pre-impregnated strips, positioned manually. During this experimental work, three types of test samples were investigated: parallel, normal and anti-parallel, taking in consideration the carbon fibre orientation with respect to the sliding direction. The friction coefficient is computed function to the friction load and loading value. Also, the specific wear rate was calculated according to: the mass loss, density, the normal contact surface, the sliding distance and load rating.

1. Introduction
The importance of composite materials plays an increasing role in everyday life. Their superior combination of stiffness, strength and low density has given composite materials a competitive advantage in aerospace, automotive, civil infrastructure and wind energy industries [1-3].

Composite materials are made of a combination of two or more constituents to make one heterogeneous material. The advantage of the resultant material is that it is designed to take advantage of the beneficial properties of each constituent without being limited as much by the detrimental properties of the original constituents. Composite materials consist of a matrix and filler. The matrix usually consists of an epoxy type polymer and the filler is usually particles or fibers. Thin layers can then be stacked into a resultant called a laminate [4,5].

Although composite laminates have obvious advantages to traditional metals, the composites are much more susceptible to damage induced by impact from foreign objects [6].

The use of composite materials in aerospace, electronics and wind industries has become increasingly common and the composite components are required to carry mechanical, electrical, and thermal loads simultaneously. For instance, carbon fiber epoxy matrix composites are expected to disperse high electric currents during lightning strike events, which has sparked research interest into the electrical properties of composites [7-10].

At present, because of easy adaptability to conventional manufacturing techniques and low cost of fabrication, short fiber reinforced composites will increasingly be used in a wide range of application. So it is more important to understand short fiber reinforced composites mechanical properties, which
depend strongly on the interfacial bonding between fiber and matrix. Compare with continuous fiber reinforcement, the composites with short carbon fibers can be prepared by conventional methods and lead to the homogenous properties because of the uniform distribution of short carbon fiber in the matrix [10-13].

In this paper, the effect of carbon fiber orientation function to the sliding direction on the tribological behaviour of the resulted composites, especially the friction and wear behaviours of the composites sliding under different sliding speed and constant applied load and time, were carefully investigated in order to provide some practical guidance for the use of polymer-based composites.

The objective of this research work it was to investigate a polymeric composite material reinforced with unidirectional carbon fibers having stratified structure.

2. Experimental procedure

Investigations were carried out on unidirectional composite materials having stratified structure with 18 successive layers made from a polymeric resin and 60% of carbon fibers. The experiments have involved the realization of the composite materials reinforced with short carbon fibers. Technological flow related to preliminary experiments is shown in figure 1.

![Technological flow for obtaining the polymeric composite materials sintered with the carbon fiber.](image)

Figure 1. Technological flow for obtaining the polymeric composite materials sintered with the carbon fiber.

Depending on the type of resin used, the temperature changes of the pre-polymerization and the polymerization for the composite systems [14].

In these experiments were carried out the tests by realization of the polymer composite material reinforced with short carbon fibers, using the polymers in the solid state. The formulations used in these tests are shown in table 1.
The formulations used in the production of the composite materials with short carbon fibers and the polymer matrix.

| Tested type | Composition, % |
|-------------|----------------|
|             | Resin | Fiber | Filling material (graphite) |
| T₁(P)       | 22.62 | 61.42 | 6.56 |
| T₂(AP)      | 19.25 | 58.15 | 13.34 |
| T₃(N)       | 36.40 | 62.48 | -   |

The physic-mechanical characteristics determined for the composite materials tested are shown in table 2.

Characteristics of polymer composite materials made with short carbon fiber polymer in the solid state.

| Tested type | Characteristics |
|-------------|-----------------|
|             | Mechanical resistance (daN/mm²) | Density (g/cm³) | Porosity (%) | Expansion coefficient (1/°C) |
| T₁(P)       | 0.71 | 1.827 | 14.95 | 4.21 |
| T₂(AP)      | 0.53 | 1.757 | 10.97 | 9.68 |
| T₃(N)       | 4.52 | 1.792 | 14.88 | 10.38 |

There have been made investigations by scanning electron microscopy on the samples subject to wear, in order to elucidate the wear process.

In principle, a wear process is a phenomenon of the cracks propagation which lead to the formation of the very fine particles. Regarding to the carbon-fiber-reinforced polymers, can be detected some differences in the wear mechanism, related to the fibers behavior in the matrix.

Thus, the wear phenomenon in this case is a sum of [15]:

- matrix wear;
- sliding wear of the fibers;
- cracking wear of the fibers;
- fiber separation wear from the matrix at the interface.

In case of polymer composites reinforced with short fiber, characteristic are the traces of the wear from the matrix material and spraying of the fibers. The presence of fibers tends to inhibit the formation of the large chips from the matrix material, by accumulating layers of the sheared polymer material. These mechanisms are more probable for the oriented fibers.

Characteristic values determined for the polymer composite are shown in table 3.

| Tested type | Parameters |
|-------------|------------|
|             | N = 0.25 daN | N = 0.85 daN |
|             | v = 6.5 mm/s | v = 41.5 mm/s | v = 6.5 mm/s | v = 41.5 mm/s |
|             | μ | μ | μ | μ |
| T₁(P)       | 0.65 | 0.53 | 0.66 | 0.55 |
| T₂(AP)      | 0.62 | 0.78 | 0.68 | 0.61 |
| T₃(N)       | 0.66 | 0.79 | 0.78 | 0.77 |

Investigations by electron microscopy have revealed, in this case, a particular behavior in the friction tests, generated by the presence of the short fibers, and the areas of the resin epoxy polymerized.
3. Results and discussion

The influence of the carbon fiber orientation on the friction-wear properties in the case of fiber polymer composites reinforced can be studied by using of the mechanical wear tests and the microscopy, and by using of the phenomenological models.

For the polymer composites reinforced with fiber investigated in this study from the point of view of wear, it was able to elucidate the effect of the fiber orientation on the properties of wear. Therefore, it is necessary to investigate the effect that it has the fiber configuration on the friction-wear properties presented by polymeric reinforced carbon fiber, in case of adhesive and abrasive wear [16,17].

There have been made some investigations on the uniaxial multi-layered composite with 18 layers and a percentage of 60% carbon fiber, impregnated with polymeric resin. The multi-layered was made by pressing of the sheets pre-impregnated type filed manually. There are analyzed three types of samples: normal, parallel and antiparallel (figure 2).

Specific wear rate, \( W_s \), is calculated by the following equation [18]:

\[
W_s = \frac{\Delta M \cdot P}{\rho A S} = \frac{\Delta M}{\rho S L}
\]  

(1)

where \( M \) - mass loss; \( \rho \) - density; \( A \) - nominal area of contact; \( S \) - sliding distance; \( P = L/A; N \) - normal load.

The coefficient of friction is calculated by the equation:

\[
\mu = \frac{F}{N}
\]  

(2)

where \( F \) is the friction force.

The dates corresponding to the friction coefficient are given in figures 3 and 4.

It is observed that:

- the wear rate increases in the order \( N \rightarrow AP \rightarrow P \), indifferent of the sliding speed or variation of the normal load;
- the wear rate is almost insensitive to the variation of the sliding speed, while the wear rate tends to decrease with the increase of the normal load;
- coefficient of friction under high load increases in the order \( P \rightarrow AP \rightarrow N \) with increasing of the sliding speed;
- coefficient of friction at the high speed decreases with increasing of the normal load;
- generally, the friction coefficient is insensitive to sliding speed variation under the heavy load;
- correlation between the wear rate and the friction coefficient is reduced.
Figure 3. a) The coefficient of friction according to the normal load, to the abrasive wear, for the low sliding speed (6.5 mm/s); b) coefficient of friction according to the normal load for the abrasive wear at the high sliding speed (41.5 mm/s); o-N type; Δ-P type; x-AP type.

Figure 4. a) Abrasive friction coefficient, according to the sliding speed under to the small normal load (0.25 daN); b) abrasive friction coefficient, depending on the sliding speed, under to the high normal load (daN 0.85); o-N type; Δ-P type; x-AP type.

A similar type of behavior is observed on the curve of the friction coefficient as a function of the sliding speed (figure 5). The effect of the fiber orientation is unclear both case of the friction and the wear.

Figure 5. The coefficient of friction on the sliding speed for abrasive wear of the polymer laminates reinforced with the carbon fiber; o-N type; Δ-P type; x-AP type.
As the normal load increases, the friction coefficient tends to decrease as is shown in figure 6 a, indicate an increase in the coefficient of friction, in order AP → P → N, under a constant sliding speed. This behavior has been observed with the abrasive wear. Under a very low sliding speeds, the wear rate appears to be insensitive to the normal load variation, figure 6 b.

The resulting material by the wear is formed by fracturing and deformation of the matrix. The wear particles, powders, were easily observed at very low sliding speeds, appearing to involve the abrasive wear, prevalent when the thermal effect is negligibly for the low sliding speeds.

The values of the friction coefficient can be seen in figures 3 and 4, differ by orientations N and P about 10% (µN, µP), and therefore the friction coefficient cannot explain the wear rate. Therefore, the specific wear rate seems to be under control by three factors: E, EW and IS.

![Figure 6](image_url)

Figure 6. a) The coefficient of the abrasive friction according to the normal load, for the polymeric laminates with the carbon fiber at a high sliding speed (2.5 m/s); b) the coefficient of the abrasive friction according to the normal load, for the polymeric laminates with the carbon fiber at a low sliding speed (0.025 m/s); o-N type; ∆-P type; x-AP type.

The previously made calculations for the composites with short fiber indicated that the EN is greater than EP by about 200% and that eN is greater than eP about 20%. It should be noted that in the case of a short fiber composite, the percentage of the existing fiber is 45% (weight percent), without an orientation of the fibers.

In case of the layered polymer composites with a fiber content of 60%, E and e values rise. Also, (IS)N is greater than (IS)P, because the carbon fiber obtained from PAN precursor has a structure with layers of graphite circumferentially oriented. Due to the fact that the connection between the two layers is poor, the inter-laminar shear strength tends to be small in the direction of the fiber axis, while the shear strength normal to the axis of the fiber tends to be greater, due to a stronger strength of the covalent bond of the carbon atoms are along the carbon chain, i.e. (IS)N > (IS)P.

The net effect of these factors (E, µ and IS) makes (WS)N to be less than (WS)P. The wear rate difference between the samples P and AP types comes from the difference between the IS factors, given that there is no difference for E and µ between P and AP types. Such a difference in IS seems to be generated by the fiber morphology specific for the PAN layer and the morphology of the cylindrical envelope of the lamellar plates by semi-crystalline polymer matrix. The orientation of the plates is parallel to the sliding direction across the sample P, while the lamellar morphology of the AP specimen can be parallel or perpendicular to the sliding direction, as is shown in figure 7.

Briefly, (IS) AP > (IS) OP due to the morphology of the lamellar layer of the graphite sheet and, in addition, the crystalline lamellar plates which surrounds, like a cylinder, a fiber from to a polymer matrix. In addition, if the case of N-type specimens (IS) AP < (IS) N (WS) N < (WS) AP < (WS) P. Another possible source of low wear rate of the N type is the ease with which can be breaked and removed from the wear surface the fibers from the higher parts.
The difference between the friction coefficients in N and AP direction decreases with the load, is substantially constant, as seen in Figures 3 and 4. Mechanical component of the friction force may explain the large difference between the coefficients of the abrasive wear or the adhesive wear, i.e: $\mu_{ab} > \mu_{ad}$. In case of the adhesive wear rate, the temperature rise in the contact area and is forming a third layer between the two components of friction tend to reduce the gap between the different fiber orientations. All these factors seem to contribute to the impossibility to establish a clear relationship between the tribological parameters in case of polymer composites reinforced with the carbon fiber.

For the friction coefficient of the adhesive wear may involve a similar reasoning to that in case of the abrasive wear, to conclude that $\mu_N > \mu_P > \mu_{AP}$.

The specific PAN carbon fiber morphology ("leaf onion" type) was correlated with the friction wear behavior to explain the difference between the specimens' P and AP type. The wear adhesive rates for different orientations of the fibers are still very difficult to correlate with the properties of the mechanical strength or with the microstructure, only that the effect of fiber orientation is relatively weak and almost nonexistent, which is probably due to a third layer newly formed as a lubricant between the two surfaces which is sliding one another (sample plate of stainless steel).

5. Conclusions

Unidirectional reinforces carbon fiber materials are more effective if refer to specific properties per unit volume compared to conventional isotropic materials. Some benefits of carbon fibers composite materials are: low density and high resistance to wear; low or high friction coefficient; resistance to high temperatures; high resistance to breakage and high value ratios strength/density.

As can be seen from the analysis conducted in this paper, due to morphology of the laminated plates of the graphite plates layer and the crystalline lamellar which surrounding a fiber from a polymer matrix and through a low wear rate N type is eased the way which can be broken and removed from the wear surface, fibers from the larger pieces.

In this paper was analyzed the formulations used in the production of the composite materials with short carbon fibers and the polymer matrix, the characteristics of polymer composite materials made with short carbon fiber polymer in the solid state and the tribological characteristics for polymeric composite materials reinforced with short carbon fibers for a better understanding of the phenomena.

The experiments were conducted on the composite material reinforced with short carbon fibers, with polymers in the solid state, and by means of microscopic investigation on the samples subject to wear can be detected some differences in the wear mechanism, related to the behavior of matrix fibers.

The presence of fibers tends to inhibit the formation of the large chips of the matrix material, by accumulating of the polymer layers from sheared material generally being present in these fibers oriented. Electron microscopy investigations have revealed, in this case, a particular behavior of the friction tests, generated by the presence of short fibers, but also because the areas with polymerized epoxy resin.
References
[1] P. C. Verma and others, 2016 Wear, Volumes 346–347, pp. 56-65.
[2] R. M. German, 2004 Powder Metallurgy, no 8.
[3] J. P. Davim and R. Cardoso, 2009 Wear, Vol. 266, Issues 7–8 pp. 795-799.
[4] K.K. Chawla, 2005 Journal of Minerals, Metals & Materials, pp. 47.
[5] A. Molazemhosseini, H. Tourani, A. Khavandi, and Y. B. Eftekhari, 2013 Wear, Vol. 303, Issues 1–2, pp. 397-404.
[6] J. P. Davim, N. Marques and A. M. Baptista, 2001 Wear, Elsevier Sc., 251, pp. 1100-1104.
[7] Z-Z. Zhang, H-J. Song, X-H. Men and Z-Z. Luo, 2008 Wear, Vol. 264, Issues 7–8, pp. 599-605.
[8] M. Minus and S. Kumar, 2005 Journal of Minerals, Metals & Materials, pp. 52-58.
[9] N. Chand and M. K. Sharma, 2008 Wear, Vol. 264, Issues 1–2, pp. 69-74.
[10] K-J. Lee, H-Z. Cheng and J-S. Chen, 2006 Wear, Vol. 260, Issues 1–2, pp. 99-108.
[11] S. Rawal, 2001 Journal of Minerals, Metals & Materials, pp. 14-17.
[12] J. M. Kunze and C. C. Bampton 2001 Journal of Minerals, Metals & Materials, pp. 22-25.
[13] J. P. Davim 2000 Comparative study of metal matrix composites machinability with diamond cutting tools, Diamond 2000-11th European Conference, Elsevier Sc, Porto, Portugal 15.7.19.
[14] T. Policandriotes and P. Filip, 2011 Wear, Vol. 271, Issues 9–10, pp. 2280-2289.
[15] B. S. S. Kishore, S. Seetharamu and P. S. Kumaran, 2009 Wear, Vol. 267, Issues 9–10, pp. 1405-1414.
[16] I. Dutta, K. A. Peterson and C. Park, 2003 , Journal of Minerals, Metals & Materials, pp. 38-43.
[17] J. Grácio, J. P. Davim, F. Q. Hua and N. Ali, 2002 New Developments on Tribology: Theoretical Analysis and Application to Industrial Process, Proceedings 8th Portuguese Conference of Tribology, University of Aveiro.
[18] S. S. Kim, M. W. Shin and H. Jang, 2012 Wear, Vol. 274–275, pp. 34-42.