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INTERDISCIPLINARY APROACH OF TRIBOLOGICAL TEST PROGRAM FOR POLYMERIC COMPOSITES

Lorena Deleanu[1], Sorin Ciortan[1], Laura Maftei[2], Alexandru Petrică[1], Cantaragiu Alina[1], Gianina Podaru[1]

[1]University Dunarea de Jos of Galati, Romania
[2]Collegium for Agriculture "Constantin Angelescu" Buzau, Romania
email lorena.deleanu@ugal.ro

ABSTRACT

Based of the team experience in tribology testing of materials, the authors present an interdisciplinary approach of investigating tribological behaviour of composites, results interpretations, non-destructive analysis methods in order to improve reliability of tribosystems using composites, and to link test results to design solutions.

KEYWORDS: tribology test program, interdisciplinary approach, cutting, modelling, research area etc.

1. POLYMERIC COMPOSITES IN TRIBOLOGICAL APPLICATIONS

The importance of interdisciplinary approach in tribological studies [1, 6, 29, 34] is underlined by Fig. 1, the tested composite or a family of composites, being a complex system and the specialists are not able to characterise as simply as other materials, needing different test scale and performant investigating equipment. New technologies and materials are developing and investigate for different fields of applications, requiring an evaluation of their properties in particular conditions [13]. Polymers with nano and micro particles or fibers are promising materials and they are expected to replace polymers and polymer blends. This trend [26, 29] is justified by improving functional properties without a sacrifice of manufacturing ones.

The tribology of polymers with macro and nano particles is an important and actual research subject due to these particles' capacity for modifying composites'properties, although they could be considered as small defects in the matrix. The major characteristic of the micro- and nano-polymeric composites is a relatively great contact area with the matrix leading to peculiar reticular structures [3, 22, 40].

Interdisciplinary research on tribological behaviour of polymer composites is necessary and of actual interest as it is done according to an adequate

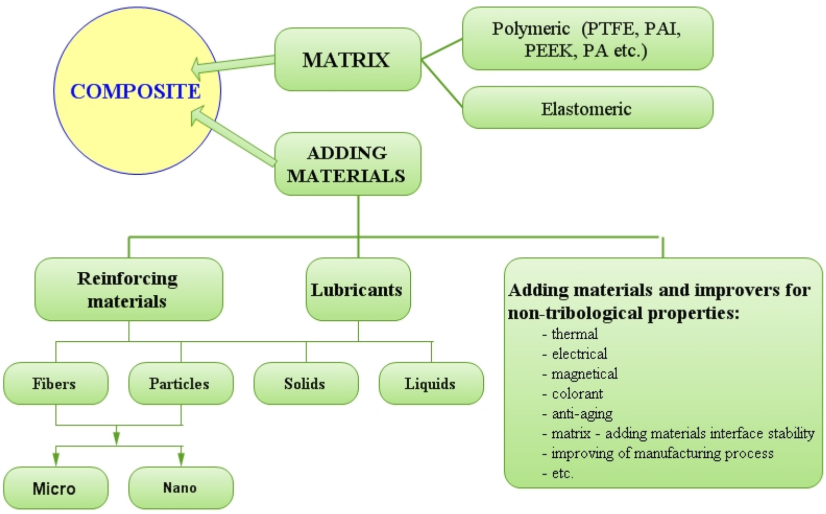


Fig.1. The complexity of a polymeric composite.

methodology using modern methods and equipment for testing and analysing, capable of pointing out the inter-dependences of influence factors, specific tribological processes within the superficial layers and possibilities of directioning the tribological behaviour as desired by researchers.

Studies on the influences of the nanoparticles in polymeric composites are still few and for narrow range of concentration and testing parameters (as for instance the sliding distance is taken from 150m to 40km, results being impossible to be compared in order to obtain information for actual systems).

Adding materials as fibers and powders substantially improve the mechanical and tribological properties [7, 8, 11, 23, 30, 41]. Bahadur reported that adding CuS, CuF_2, CaS, and CaO reduces wear of polyamide and polyetheretherketone [2], but others as CuAc and CaF_2 increase the wear rate. The irregular shape of the particles is accentuated if they have increasing dimensions; more irregular the shape of the particles, the possibility of an intense abrasion increases, decreasing wear resistance, thus the nanoparticles seems to make the composite to behave better. Furthermore, as the ratio area/volume is greater, this increases the possibility of improving the bond between particles and the matrix they are embedded into [20, 25, 31]. Incorporating inorganic nanoparticles and fibers generates a synergic respond, not entirely studied and explained, upon the wear resistance [8, 35, 37]. A synergic action was reported in the behaviour of composites with polyamide, carbon fibers and micropowder of MoS_2 [30]. Bhijmaraj [2] tested nanocomposites with PET matrix and noticed the particle dispersion was maintained till a massic concentration up to 10%.

The concept of improving tribological behaviour of polymeric composites [31] relies on reducing the material adhesion to the mating surface and increasing the hardness, stiffness and compression strength using fibers (aramide [16], glass [13, 23, 38 40, 42] and organic (PTFE) and inorganic powders (graphite, metallic oxides etc.) [2, 3, 35, 39]. Some researchers appreciate the continuous long fibers are more efficient as compared to the short ones, having a lower wear [38], but polymeric composites with short fibers are technologically cheaper and thus, easier to use and, on the other hand a long fiber net could dislocate more material when it is worn off. One of the mechanisms for reducing friction coefficient is the generation of a transfer film on the mating surface [1, 6, 16]. Sometimes it is more advantageous to have a more rigid polymer as matrix and fibers and PTFE in order to obtain optimal tribological conditions [19, 37]. Adding materials for increasing thermal conductivity of a composite (PTFE + bronze) [10, 21] are able to reduce the thermal regime. Not any adding material is benefic in improving the composite tribological behaviour. Wear resistance increases if the adding material reacts and generates products with stronger bonds between the transfer film and the mating surface [2, 6, 16], while others decrease the wear resistance by generating discontinuities and voids into the material. Thus, it is important to understand the initiation, the development and the degradation of the transfer films and their dynamics because these are involved in wear mechanisms. Chemical and mechanical interactions of the transfer films are complex, thus being justified the efforts for investigate them. The barrier between nano and micro analysis is hard to trace as the efficient manufacturing technologies for nanocomposites are still expensive at industrial scale [21] and many adding materials are commercially available in a range "small" micro and larger than nano (simply saying around several microns to several tens microns) [6, 13, 42].

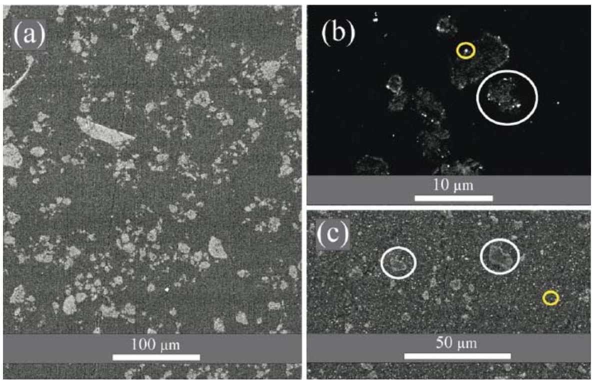


Fig.2 SEM images of three polymeric composites (a) EP/PTFE, (b) EP/PTFE/0.2, (c) EP/PTFE/3.0. Micro particles of PTFE (large circles) and two examples of nanoparticles (small circles) [21].

2. SCALE TEST

For classifying testing methods specialists divide them into different categories, depending on the gradation of testing procedures corresponding to a step-by-step reduction and modification of the tribosystem. A classification with 6 categories is done according to DIN 50322 and Gold [17]:

• **service and field tests with actual subsystems or actual machines**:
I: service (field) tests,
II: tests on the rig with the total system,
III: rig tests with partial systems;
• **tests using models with simplified or with scaled-down sample:**
IV: tests on unchanged or scaled-down components,
V: tests with similar stresses on laboratory models,
VI: tests with simplified laboratory models.

The system structure remains unchanged up to category III, whereas the stress state is changed; furthermore there may be environmental influences that should not be neglected. The categories II and III present the advantage that the stress state is reproducible. From categories IV to VI the system structure changes dramatically because of using simplified laboratory models, according to similarity relations and scaled-down criteria.

Caused by the step-by-step reduction and modification of analysed actual system, the security of negotiability of results decreases, whereas on the other hand availability of measuring points and the strength of evidence increases. The time and cost expenses for wear tests decreases simultaneously. To guarantee the negotiability of results, it has to consider that similarity relations are fulfilled, i.e. certain system parameters of the actual system have to be kept for the laboratory test model [4, 15].

To compensate for some degree the setback of the diminishing correlation between test results and the behaviour of the actual tribosystem, the test chain must additionally include the below mentioned correlation tests:

• comparison of damage images or wear mechanisms,
• comparing temperature values, their time evolution,
• comparison of wear rates,
• comparison of design variants, materials, lubricants.

The test chain must be designed for all typical wear cases, as a rule, but it should be developed for each specific case, including the above mentioned correlation tests. A further problem of growing importance is that the costs for tests continue to augment.

3. TRIBOLOGICAL TEST PROGRAM AND METHODOLOGY

To analyse and optimise friction and wear processes of triboelements it is important to have measuring and testing techniques at hand that provide clear evidence. The tribological testing procedures may be classified in three sections [17]:

• testing methods, e.g. the type and kind of testing a tribosystem;
• testing systems, e.g. which measuring and testing devices are used;
• methods of analysis, including measuring and testing procedures used for examining the structure and stress analysis as well as for checking the wear appearance forms.

The tribological testing technology is characterised by a high standard of analysis methods. Nevertheless, there continues to be great insecurity towards transferring measuring results to other testing systems or to actual components and systems. Consequently, as a rule, the results of a wear test should be limited in their applicability to the individual wear case examined.

3.1. *Selecting a tribotester and a test program*

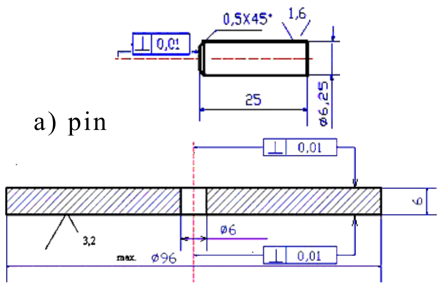
Tribotesters are very different and specialised depending on the aim of the testing program, but a common characteristic is the sophisticated and accurate monitoring system, especially for tribotesters dealing with simple shapes, as for instance pin-on-disc (Fig. 3), laboratory models [11-13, 36], but also 4 ball tester that is specialised and recommended for lubricant characterisation [28].

For each adding material concentration, lubricant, other conditions as working regime and environment that are kept constant, there could be selected a matrix, here-bellow of two variables: p (average pressure, MPa) and v (sliding speed, m/s) influencing wear (w_{ij}) or another output parameter of interest.

	v1	**v2**	**v3**	**…**
p1	w_{11}	w_{21}		
p2	w_{12}			
p3			w_{33}	**…**
…				**…**

This is similar to a 2D or 3D space, frequently named wear maps if wear is an output desired to be known. Of course the test program could introduce more variables, but investigating time and the necessary samples and equipment costs will increase and the combined (synergic) influence of more variables is difficult to express in relationships that could be "translated", with acceptable probability, towards the actual applications.

When discussing the test results it is very important to underline how the test output parameters are calculated or/and measured. For instance, in pin-on-disc testing the average pressure is a satisfactory parameter to use, due to the shape of the loaded contact aria between the pin and the disc. But for rolling contact, the average pressure could be a "false friend" in estimating how loaded is the contact as it could "screened" that Hertzian pressure is greater than the coupling materials allow [29, 34]. Thus, the parameters involved as variables could be calculated measured and verified with a high accuracy, in order to be introduces as input variable and to offer o solid and useful information for actual applications.

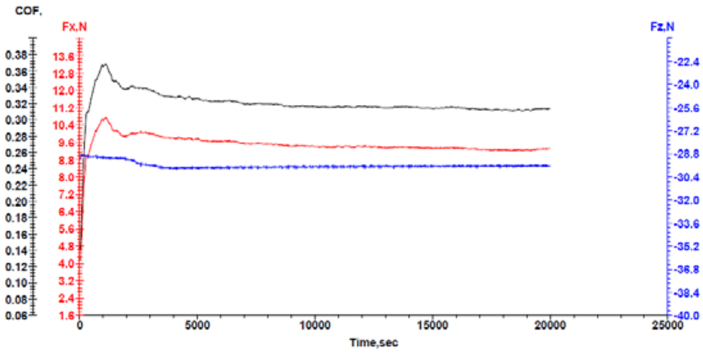


b) disc

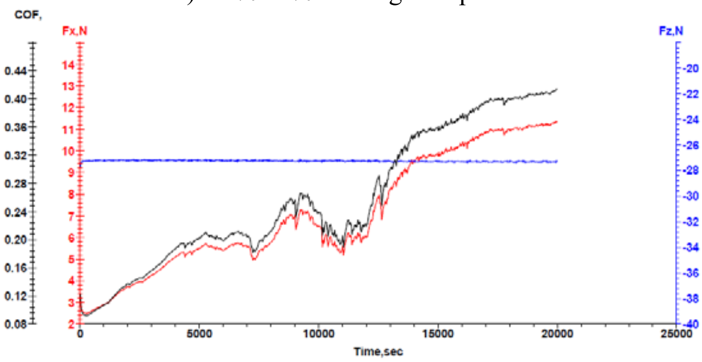
Fig. 3 Dimensions for triboelements used in pin-on-disc tests [for CETR®].

This paper intends to relate the methodology to sliding tribomodels, using polymeric composites, especially to pin-on-disc one, in order to offer a robust argumentation for complex investigations of superficial layers as basis for understanding tribological processes, supported by the authors' experience and results [11-13, 32, 33].

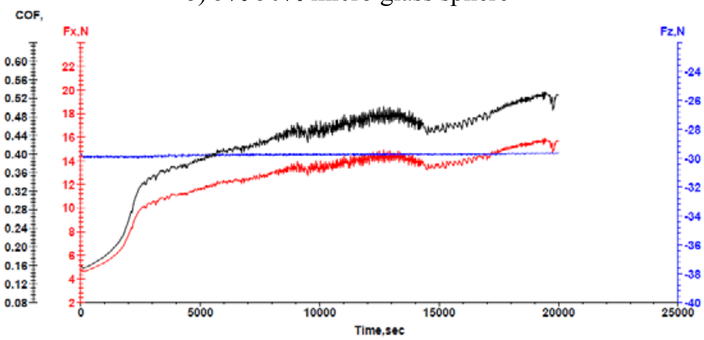
Specialised firms [43, 44] offer testing unit with different modules, users selecting the suitable one for the research they are interested in (pin-on-disc, ball-on-disc, ball-on one, two or three balls, pin-on-V-block, block-on-ring, disc-on-disc (flat-on-flat), screw-in-nut etc.) with or without controlled environment enclosure (for temperature, humidity, atmosphere composition etc.).



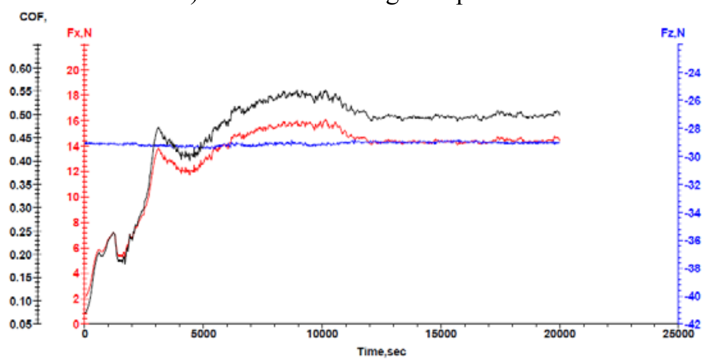
a) 2.5% 50% micro glass sphere



b) 5% 50% micro glass sphere



c) 10% 50% micro glass sphere



e) 50% micro glass sphere

Fig.4. Friction coefficient, normal load and friction force, as registered from UMT-2 soft for p=1MPa and v=0.5m/s, dry regime, pin made of steel, pin axle positioned at a radius of 40mm from the disc axle. (Results obtained on CETR® UMT-2 Multi-Specimen Test System, at Machine Design Department from University „Dunărea de Jos” of Galati.

Tests on pin-on-disc tribomodel are simpler and allow complex analysis of the superficial layers and evaluation of one of the most important tribological parameters: friction coefficient and wear. The results and an accurate interpretation lead to composite optimization or establishing a tribological hierarchy of the tested materials.

3.2. Tribological Parameters

Friction coefficient. Designers are interested in having tribosystem with low and stable friction coefficient in order to reduce energy consumption in exploi-tation. For some applications (frictional tribosys-tems as brakes), the value of this parameter is required to be higher but not unstable. Calculation of friction coefficient for a certain regime and tribomodel depends on monitoring and measuring facilities added to the laboratory model. For instance, UMT-2 register F_x (the friction force between pin and disc, its resulting direction being considered tangential to the radius at which the pin acts), and F_z being the normally applied load; a dedicated soft calculates the friction coefficient as

$$\mu(t) = \frac{F_x(t)}{F_z(t)}, \qquad (1)$$

for any moment *t* in the test time interval.

This monitoring of the friction coefficient could give valuable information about the processes developed during friction. For instance, a composite with a dynamic change in the reinforcing material concentration within the superficial layer will have a oscillating value of the friction coeffi-cient, higher value being a prove of reinforcing material agglomeration in within the superficial layer (see the middle zone of fig. 4b, the zone after 8km of sliding for composite PA + 10% micro glass sphere +1% black carbon, Fig. 4c).

The more stable value and the lowest was obtained for a concentration of 2.5% micro glass spheres, but selecting this mate-rial without information about wear parame-ters is hazardous. Thus, tribological parame-ters have not to be analysed separately.

Wear parameters may be analysed for understanding the tribological behaviour in time for the tested material. Δm_{total} and wear rate Δm_i could be calculated as:

$$\Delta m_{total} = m_o - m_{final} \qquad [g] \qquad (2)$$

$$\Delta m_i = m_i - m_{i-1} \quad [g] \qquad (3)$$

i takes values from *1* to *n* - number of time intervals during the test. Δm_i is mass loss for L_i sliding distance (here 1,500 m) during the *i*-th interval. m_o (*i=1*) is the initial mass of the sample (here a shoe of ϕ60x25 mm); m_{final} is mass loss after the total sliding distance established for the test (here 10,500 m). The conclusion one may get from Fig. 5 is that wear rate has a dynamic evolution, less uniform for polymer and composite with high concentration of fiber and with much more lower values for composites with 15% and 25% (wt) glass fiber concentration.

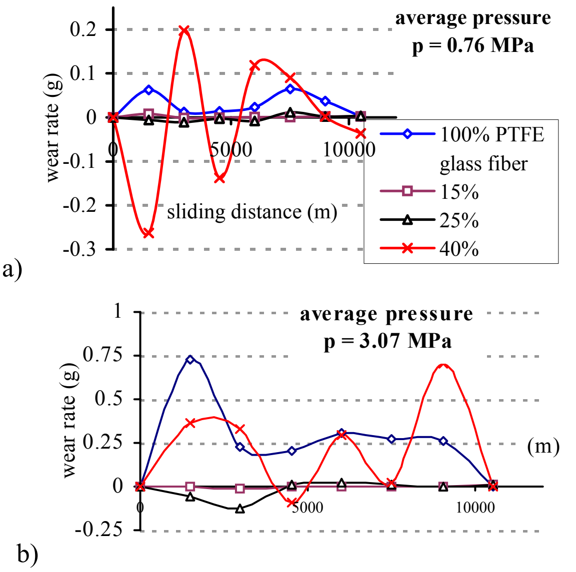


Fig.5 Wear rate measured for a roller/shoe tribotester (water lubrication, sliding speed v=2.5m/s) [11].

Wear intensity [4] or specific wear rate W_s could be calculated with the following relation:

$$W_s = \frac{\Delta V}{F_N \cdot L} \quad \left[mm^3 / (N \cdot m) \right] \tag{4a}$$

$$W_s = \frac{\Delta m}{F_N \cdot L} \quad \left[g / (N \cdot m) \right] \tag{4b}$$

ΔV being the volume loss, F_N – the normal load and L – the sliding distance. The relationship (4b) is a variant in which wear is expressed as mass loss Δm . This parameter is good to be evaluated when the researcher has to compare two or more materials tested under the same conditions, close to actual ones. After comparing the results he could recommend the material with the lowest wear intensity.

Wear rate could revealed that wear process are more intense at the beginning of sliding and than it is reduced but calculation of this parameters means to repeatedly stop the test, measure the mass loss of the triboelement and start the experiment. This repeated operation could alter the final results. For instance, these stops allow the polymer matrix cooling out and regaining the mechanical properties lost when the temperature is rising during the test. But the researcher has to select the value for the sliding distance L in order to obtained results that could be useful for practice. For instance, Fig. 6 shows how W_s is varying depending on the sliding distance taken into account. If for all tested materials [11, 32] the wear intensity became lower for the longest distance that could be interpretated as wear processes are more intense in the first 4…6km of running. The shape of lines could give the following information: PTFE has a better behaviour for p around 1.5 MPa, for higher average pressure, the composiute with 15% glass fibers two composite the wear intensity has a convergent trend for higher average pressure p=3MPa the polymer and the composite with 40% ranforsant revealed an increasing after this average pressure, thus the test resultsrecommend the composite with 15%.

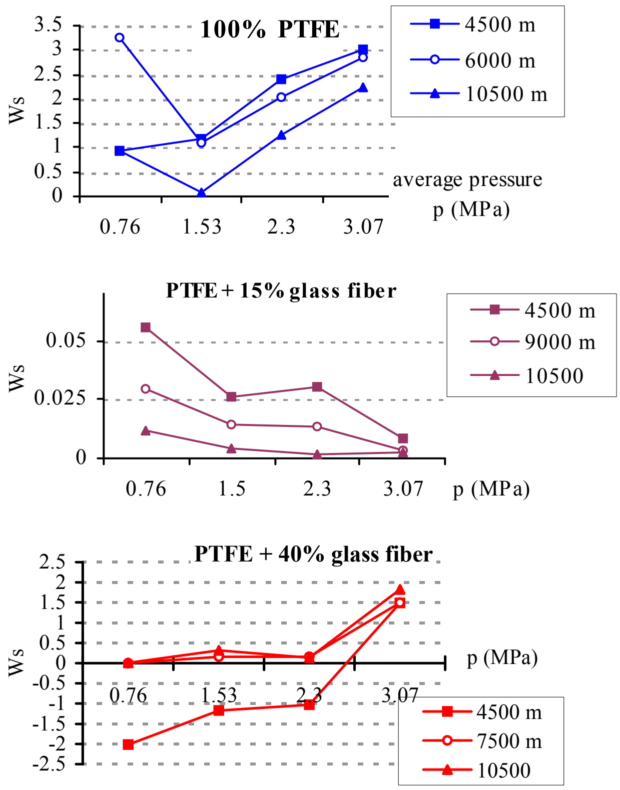


Fig. 6 Wear intensity (*Ws*) expressed in 10^{-8}mm^3/(N·m) for v=2.5 m/s; water lubrication, roller/shoe tribotester [11].

3.3. Non-destructive analysis of tribolayers

The dificculty of non-distructive investigation of polzmeric composites relies on the fact that the tribolayer has not to be altered by the investigation method and the analysis has to be done close enough to the moment of test end not to include processes influenced by this pause-time.

There are only few methods of actual-time investigation of the tribolayer, because any measuring of observing device, as small as nowadazs technology offers, will alter the contact behaviour. For instance, the film thickness for rolling contacts has been evidenced by optical microscopy, used steel ball and special transparent materials for a plate discs [29]. The results were important in the tribology history but it is obvious that the tested contact is not closer to the actual one in the rolling bearing even with same dimension and geometry.

The conclusion is that the tribologist is udes to do analysis by comparing the parameters’modification before and after testing the laboratory model, trying to explain by non-distructive analysis what it is happening during the experiment. For instance, during pin-on-disc tests involving composites, the polymeric matrix could melt or only softening in the superficial layer, due to friction and generatering an enough high temterature that the polymer acts like a very viscous "grease" that are not evacuated from the contact due to the ranforsant net. A test surveyance with a thermographic camera will offer maximum temperature on the outside contour of the contact, and used an appropriate FEM model the specialists could obtained a maximum temperature in contact that sustained or not its theory.

Processes within the superficial layers of a polymeric composites involves
- processes related to the polymeric matrix (deforming, cracking, melting, flowing, orientation, thermal or/and oxidative degradation, transfer),
- processes related to adding material (fragmentation, cracking,
- chemical and physical processes with the mating surface or characterising the interface matrix-adding material.

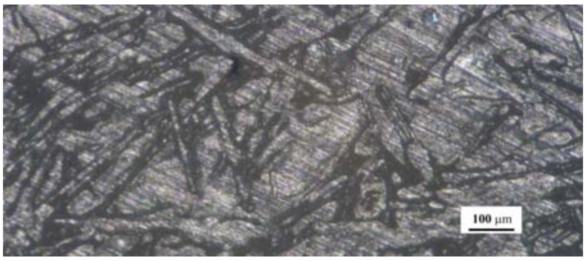
All these processes modify the mechanical, physical and tribological behaviour of the polymeric composite in a manner hardly to predict without testing and complex investigations, especially of non-destructive nature.

Optical microscopy helps to determine these concentrations especially for imiscible constituents [1, 10] but it can not point out mechanisms of fiber degradation and matrix changes near the fibers or particles.

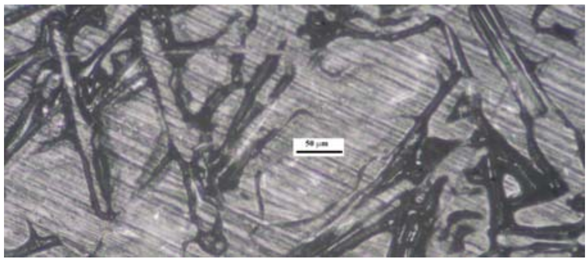
Fig. 7 is an example of optical investigation used for improving the technology of a polymeric composite, the images being taken on the finished moulded disc made of PA + glass fibers + black carbon: a) a smaller scale offers the opportonity for studying the ranforsant and black carbon dispersions and one may notice the disc surface has no uniform dispersion for both components; b) a larger scale reveals how the matrix material flows along the mould and how the black carbon agglomerates or remains around glass fibbers; c) the image at the largest scale reveals that interface between glass fibber and polymeric matrix is discontinuous and contains impurities. After transmitting these optical investigation and conclusions to the composite producer (ICEFS Savinesti), their specialists could have improved the technology for manufacturing the discs, including ranforsant prepartion, technology parameters (temperature, mixing time, moulding technology etc.).

As compared to metallic samples, composite samples and especially the worn ones require better skills, more experience and knowledge when using optical microscope [6].

A comparison of images obtained by optical microscopy between polymer and composite, tested under same conditions (test parameters having narrow, acceptable variations, for instance ±5% for the normal load etc.) could reveal different processes that could be directioned for increasing the durability of actual tribosystems.



a)



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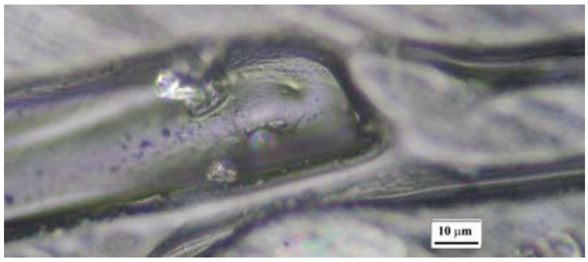
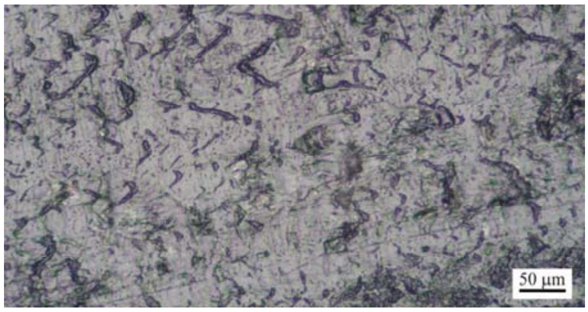
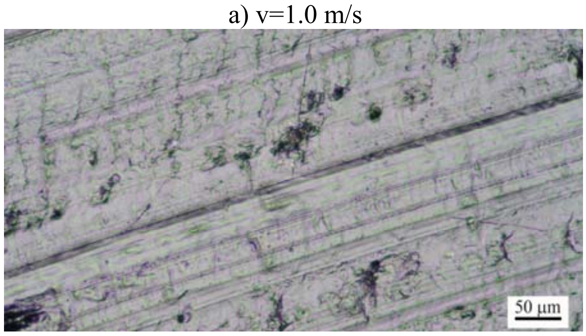


c)

Fig.7 Optical images at different scales for a non-worn discs made of composite with PA matrix and glas fibers.

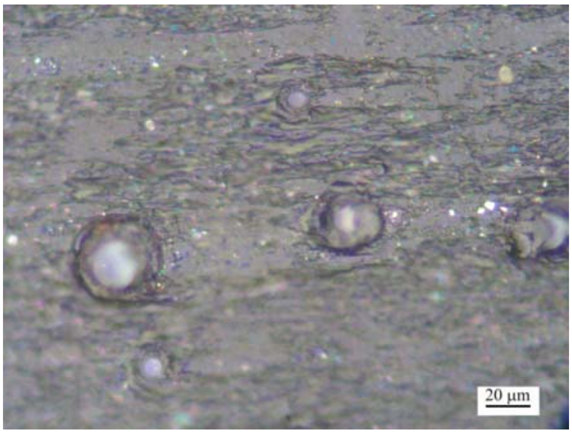


a) v=1.0 m/s

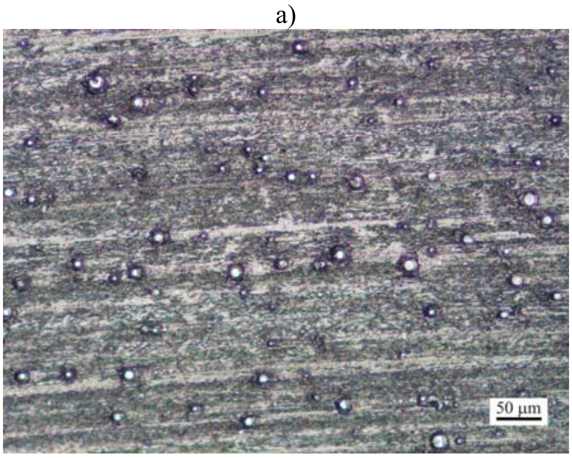


b) v=1.5 m/s

Fig.8. Aspects of wear tracks on polyamide (PA) used as matrix in the composite presented in the Fig. 9.



a)



b)

Fig.9 Optical views of worn surface for the composite PA + 1% black carbon + 20% (wt) microglass spheres (v=1.5 m/s and p=1MPa).

One may notice the very different aspect of the tested surface for the polymer (Fig. 8) with local displacements, flows and local melting of the polymer as compared to the composite having the same polymer as matrix and 20% (wt) micro glass spheres as adding material (Fig. 9).

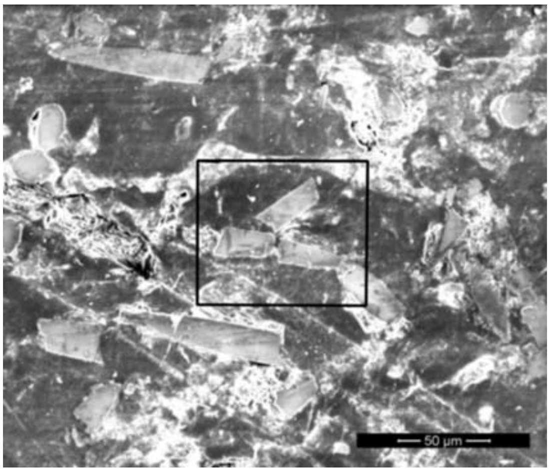
SEM images revealing possibilities of identifying processes within superficial layers of polymers and polymeric composites at a much smaller scale than optical microscopy with a good clarity.

SEM images evidence the particle dispersion in the polymeric matrix (see Fig. 11). For the composite PTFE and glass fibers, both friction coefficient and wear increased due to fibers’ accumulation, especially for concentrations greater than 20…25% (wt), as one may notice when comparing Fig. 10a to Fig. 11d.

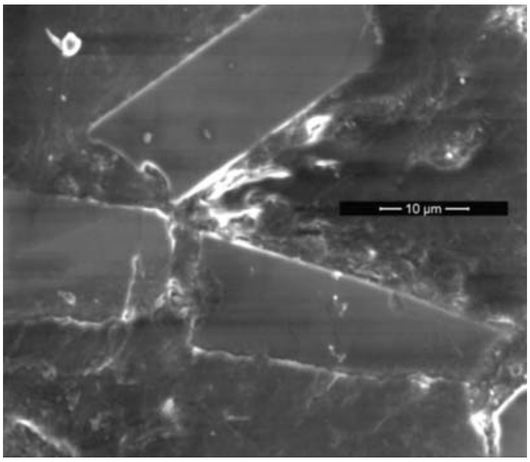
The difficulty is that analysis is time consuming and the method for enlarging the investigation scale is quite expensive and could alter the surface resulted after testing. As for instance, by the help of SEM equipment from Physics Department of University “Dunarea de Jos” there were obtained images of the superficial layers of PTFE and PTFE + glass fibers composites till a magnification of 3000:1…4000:1 without any surface preparation for PTFE composites (Figs. 10 and 11) but for composites PA + micro glass spheres + 1% black barbon the images had low quality and the team will try to find a method of preparing sample surface in order to get a better view.

The SEM images obtained from PTFE composites sliding in water at 2.5m/s and an average pressure p=2.02 MPa reveals a dramatically changes of processes within the superficial layers, as comparing the polymer with one of its composites (here, one with 15% glass fibers.

One may notice for the polymer tribolayer that at low scale it is possible to point out small and large wear particles of polymer, bonded or embedded in the superficial layer, abrasive traces and local plastic deformation of former wear traces (Fig. 11a). A closer look (4000:1, 5000:1, Figs. 11b and c) reveals intense deformation, overlapping of torn and rolled micro-volumes of polymer, bonding of large wear particles already detached (Fig. 11b).

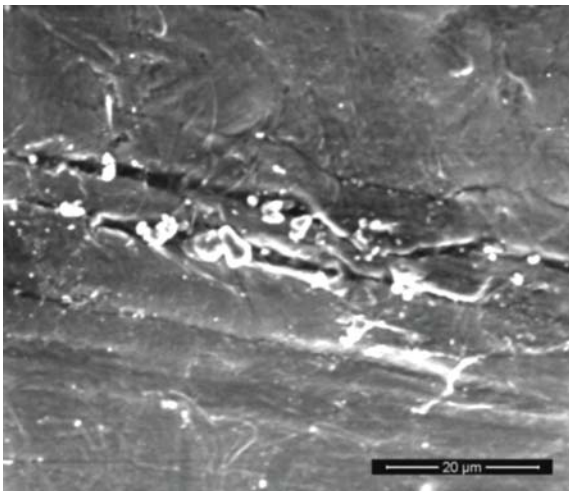


a)

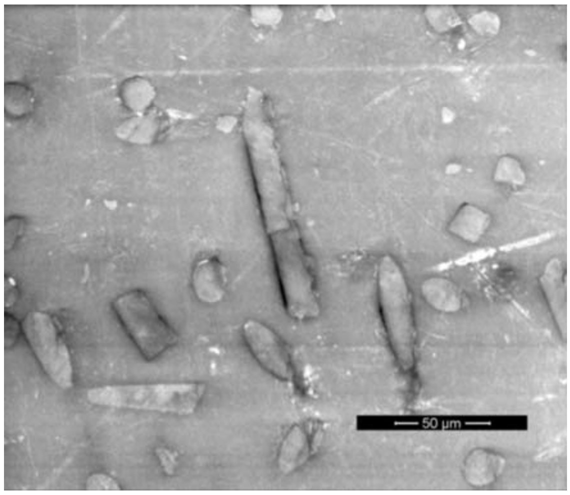


b)

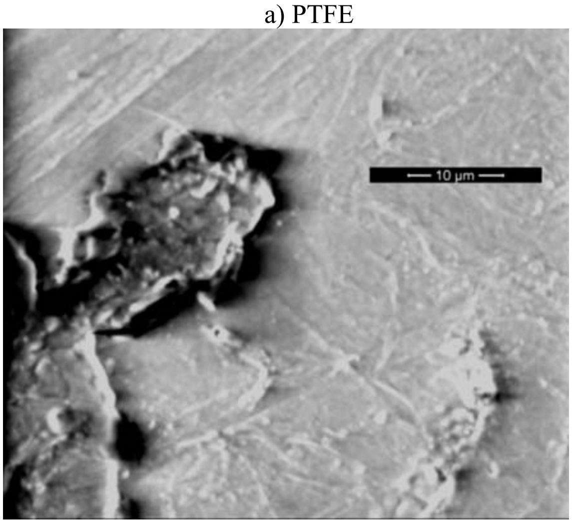
Fig.10 SEM images suggesting that the concentration of ranforsants is too high and under load the fibers could damage one each other, the fiber in the upper part of image b) acting like a lever that brokes easily like a rigid beam (plate (40 x 60 x 6 mm) on steel disc, water lubrication, sliding speed of the plate centre v=2.5m/s, calculated average pressure on each plate p=2.02 MPa).



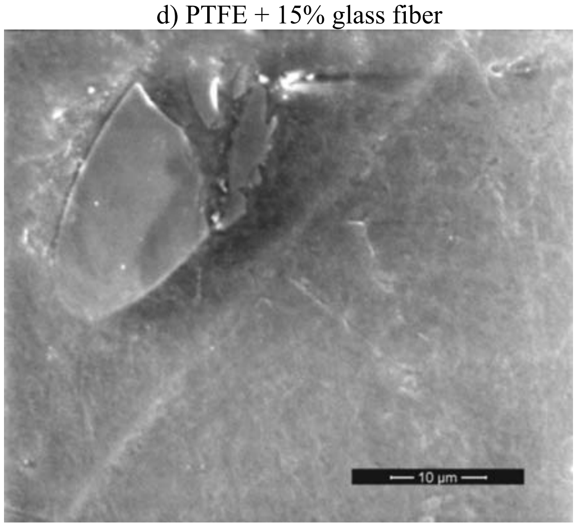
a) PTFE



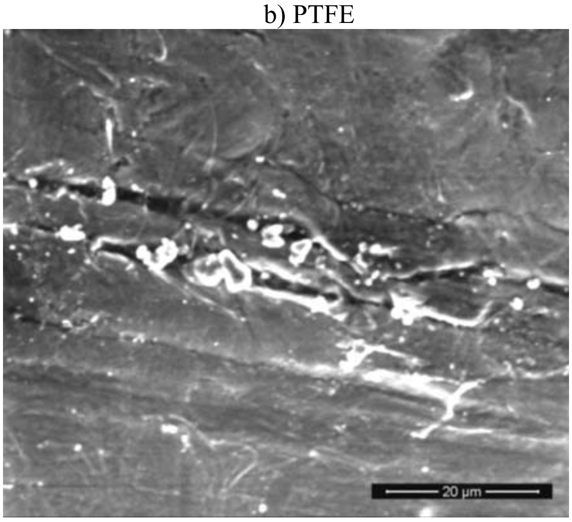
d) PTFE + 15% glass fiber



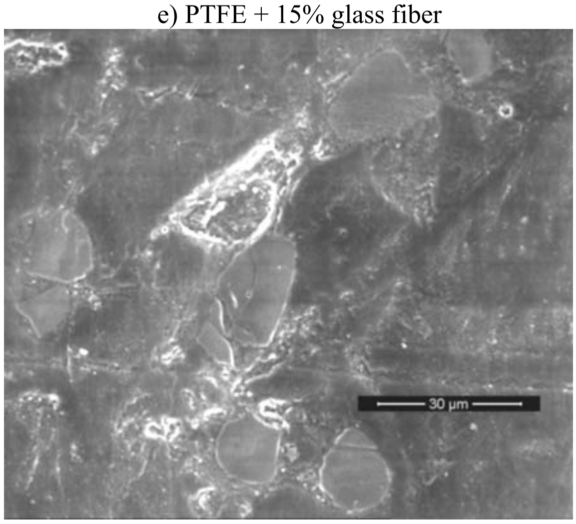
b) PTFE



e) PTFE + 15% glass fiber



c) PTFE



f) PTFE + 25% glass fiber

Fig.11 Comparing SEM images underlining the different damaging process of the polymer and of the composite.

One may notice the very different aspect of the tested surface for the polymer (Fig. 11a, b and c) with local displacements, flows and local melting of the polymer as compared to the composite having the same polymer as matrix and 20% (wt) micro glass spheres as adding material (Fig. 11c, d and e).

The randomly orientated fibers within the superficial layer of the composite do not allow the matrix to flow, to roll, all the processes seen on the pure polymer being less ntense and of smaller dimensions. But pressure generated in the partial or total water film is high enough to brake/fragmentate the fibers'zones under load.

A fingerprint of a material, obtained **by X-ray diffractometry** gives information on three parameters: position of diffraction maxima, their intensity and the intensity distribution as a function of Bragg diffraction angle. Information is used for identifying and quantification of constituents, crystallinity degree evaluation and stress and stain state. [18, 16]. Although in principle this fingerprint is unique for a material, in practice there are enough similarities to create confusion, especially for multiphasic materials. Physicists estimate there are more than 2 millions of possible fingerprints but only 120,000 are given in catalogues. The constituent identification after testing explains for instance the chemical inertia of PTFE by the presence of C-F, C-CF, CF_2 and CF_3 bonds [18].

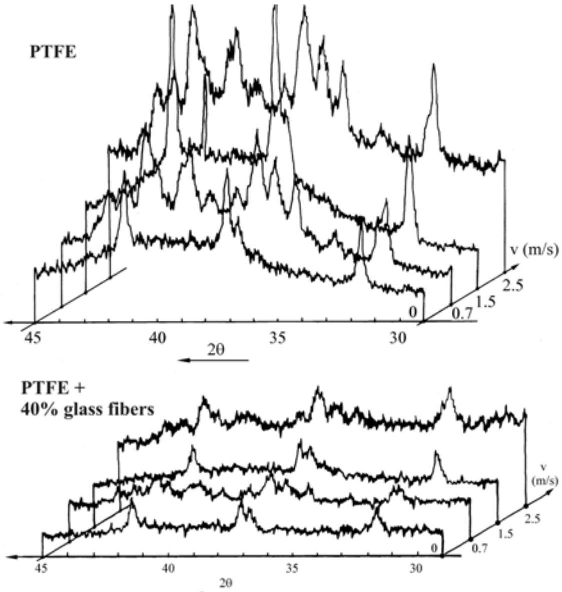


Fig.12 Diffractograms, same load (water lubrication, plates (polymer or composite)-disc (steel) [12]

Qualitative changes were pointed out (reorientations and fragmentations) within the superficial layers of composites with PTFE matrix (fig. 10) [14], influenced by glass fiber concentration and sliding speed; it would be necessary quantitative evaluations, possible now due to the dedicated soft added to the existing X-ray diffractometer at our university.

3.4. 3D profilometry of worn surfaces

Recent studies of topography for polymeric composites revealed the strong influence of the harder material surface topography (usually metallic) [5] but topographies of the transfer films and a 3D characterisation of the surface are few [5, 13]. Generally, metallic surfaces involved in tribological tests are obtained by fine polishing, expensive for large scale applications.

The authors started a complex analysis of the surface topography of the tested composites’surfaces in order to notice and argue the correlation among some of the 3D and tribological parameters as wear and friction coefficient and results will be the subject of future papers. The figure 13 is given only for exemplifying the influence of sliding speed on the surface quality, for a composite PA + 20% micro glass sphere + 1% black carbon, tested under an average pressure p=1MPa.

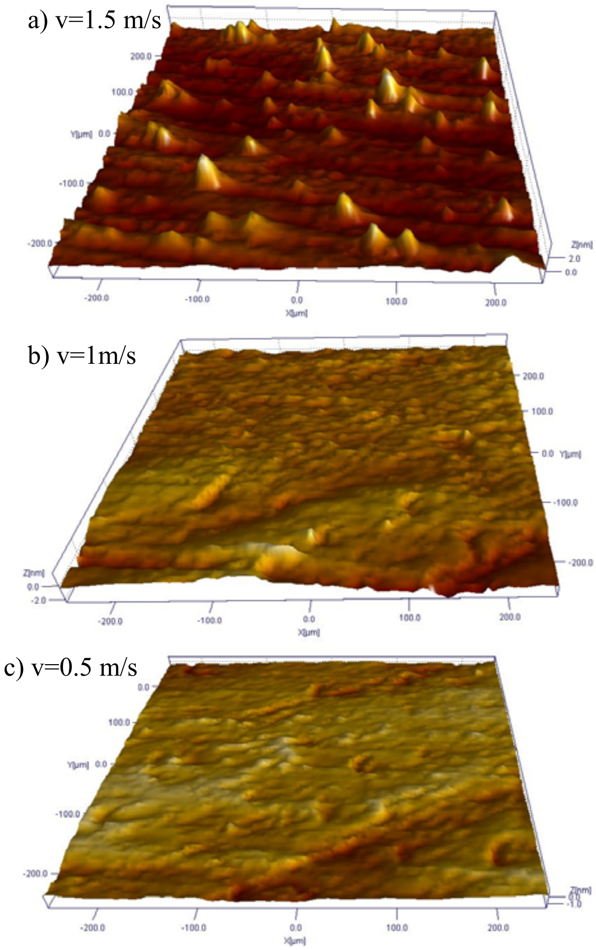


Fig. 13 Surface aspects of the composite disc after testing (same scale for Z in μm, 10:1).

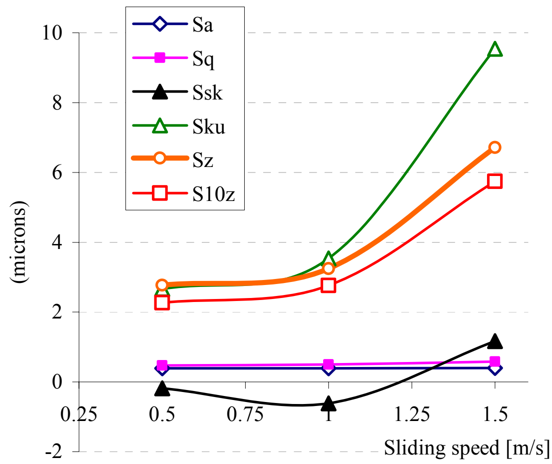


Fig. 14. Influence of sliding speed in dry regime on 3D amplitude parameters for a disc made of composite (PA + 20% microglass sphere + 1% black carbon), with steel pin, average pressure p=1 MPa.

This is a qualitative evaluation of sliding speed influence. Values of some 3D parameters could give quantitative information on surface aspects, but it had to be taken care that these values are the results os a statistical evaluation, here the average of monitoring 3 paches of 500 μm x 500 μm, situated equiangular on the wear trace in its middle. The number of the evaluated surface topography samples depends on materials, on the desired accuracy and of the time available to do the investigation.

From Fig. 14 one may notice that Sku is the amplitude parameter that is the most influenced by the sliding speed (average pressure p=1 MPa), Sa and Sq has a very slow increase with the same parameter. The conclusion is that for tribological study of the quality of tested surface these two parameters are not so relevant as compared to Sku and St or Sz and Ssk had to be analysed together with Sku in order to recommend one of the three sliding speeds if the user is interested in maintaining the surface quality after sliding.

4. USING THE RESULTS

This chapter gives some examples of using the test results.

a) working regime (best set of speed-load-lubricant for increasing durability) and data for design solution or establishing the influence of a parameter involved in modifying the tribological behaviour (an example is given in Fig. 15).

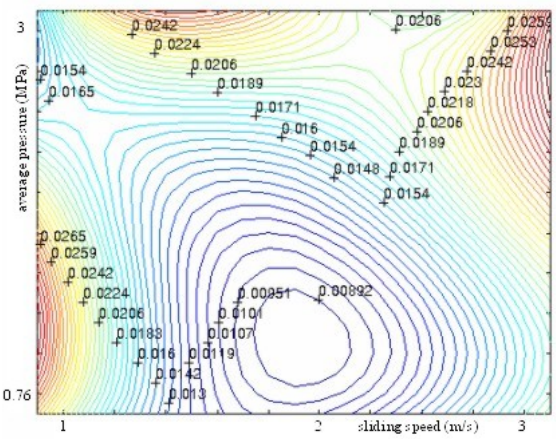


Fig. 15 mathematical modelling with spline curves in order to emphasis the parameters set that "give" the lowest friction coefficients for water lubrication (shoe/roller) for PTFE [10]

In [21, 41] different behaviours were revealed for regime low pressure – high sliding speed and regime high pressure – low speed, but without a clear delimitation for other types of materials but the tested ones: for regime low pressure – high speed the wear rates increased for the composites nano-CuO+ epoxy matrix without PTFE, on the worn surfaces being noticed big cracks; the conclusion would be that nanoparticles diminished the fracture resistance of the matrix. Adding PTFE in the same composite slightly decreased the friction coefficient and wear, with a minimum value for 0.4 vol.% CuO, after that both parameters increased, this evolution being the attributed to nano particle agglomeration within the superficial layers during friction. Larsen [20] also studied physical and mechanical properties of some composites proving the influence of PTFE on the glass transition temperature and on hardness but the addition of nano particles in epoxy matrix increased the wear rate for all the tested composites. For regime high pressure – low speed the composites without PTFE had wear rates much greater and oscillating.

Stuart [30] did a study on the hardness of polymeric blends and composites, pointing out an increase for the hardness of composites, meaning that the coating becomes softer towards the interface with the support material.

b) **new recepes for composites: in** [13] there was studied the influence of glass microsphere with large interval dispersion (several microns to 20…30μm);

c) **concentration optimization of one or more components of the composite** (fig. 16);

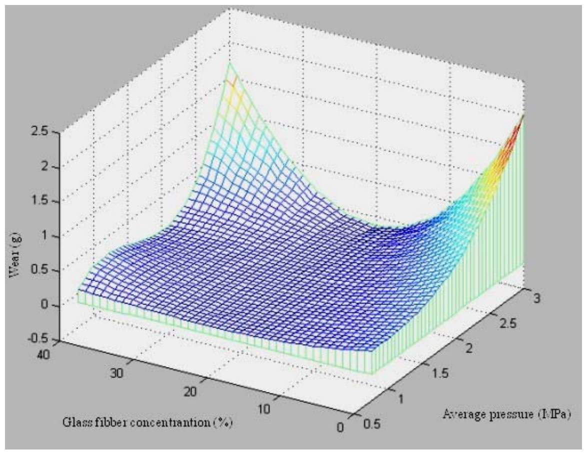


Fig. 16. Influence of the fibber concentration and of the average pressure on the wear of the shoe, for v=2.5m/s, after 10500m of sliding in water [11].

d) **qualitative non-destructive investigation** for modelling and better understanding the material behaviour and the processes within the superficial layers;

e) **modelling tribological behaviour**; the specialists had to choose very careful the mathematical model because even o very close relationship obtained with high confidence has to be corelated to actual test conditions. For instance using mathematical model for estimating the wear behaviour of the disc made of composite PA + 1% black carbon + x_2% micro glass sphere there was obtained a relation as

$$w = f(x_1, x_2) \qquad (5)$$

where x_1 is the sliding speed and x_2 is the microglass sphere concentration, but the 3D representation reveals a "negative" of the mathematical model that is not possible in dry regime when testing pin (steel)-on-disc (polymer composite).

Table 1. Wear of discs tested under F1=28.27 N (p=1 MPa), value obtained as average of results from two tests).

v (m/s)	Micro glass sphere concentration (%wt)						
	0	2.5	5	10	20	30	50
1.5	0.2101	0.0019	0.0306	0.0281	0.0246	0.0014	0.0026
1	0.0024	0.0009	0.0132	0.0104	0.0112	0.016	0.0072
0.5	0.0068	0.0134	0.0004	0.018	0.0048	0.0108	0.0145

Table 2. values of coefficients in relationships (5…7)

95% Confidence Intervals		
Variable	**Value**	**95% (+/-)**
(6)		
a	0.1921251462	0.2183133417
b	-0.2325571429	0.3746934973
c	0.07787142857	0.1359309044
d	-0.00662829656	0.01157631723
e	0.0002894662945	0.0006207495558
f	-3.474701352E-006	8.280820613E-006
(7)		
a	0.05820271231	0.06089158467
b	0.05274343293	0.06908622678
c	0.07829299344	0.1571803746
d	-0.03321580023	0.04104797574
e	0.005528258037	0.008476511565
f	-0.0003519713015	0.0006120312459
g	9.237764898E-006	1.739337522E-005
h	-8.307632549E-008	1.645804672E-007
(8)		
a	0.03677414028	0.07235754749
b	0.03320000025	0.04964552302
c	-0.03321580003	0.04040476801
d	0.005528258004	0.008343687532
e	-0.0003519712995	0.0006024409259
f	9.237764844E-006	1.712082699E-005
g	-8.30763250E-008	1.620015477E-007

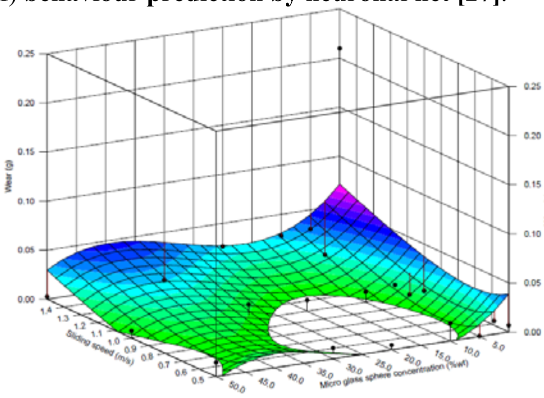
Of course, specialised soft offer many other mathematical models for the obtained results but they have to be evaluated in agreement to physical and tribological "logics", thus many of them could fail and not be used for an actual design.

For instance, for the data in table 1, using DataFit regression models there were obtained the mathematical models in Fig. 17. All three have similar qualitative conclusions:

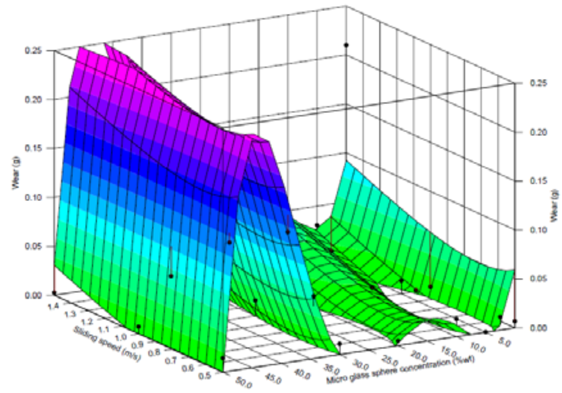
- wear is higher for the polymer and the composites with a microglass sphere concentration greater than ~20%,
- this tendency is more evident at greater sliding speeds,
- concentration seems to have a heavier influence on wear as compared to tested sliding speed range.

But physically it is impossible to accept negative wear (meaning transfer on the disc from the pin made of a much more harder material). Thus, mathematical models is not completely sustained by test results. Increasing the number of tests done under the same conditions will "tune" the mathematical models and the specialist could recommend one of it, underlining the possible deviations. Taking into account the authors'experience, models 2 and 3 seem to offer better mathematical models of the tribotester behaviour, but only for the tested parameter ranges, extrapolation being hazardous. Taguchi's method could give a good interpretation of the results [1, 6, 9]

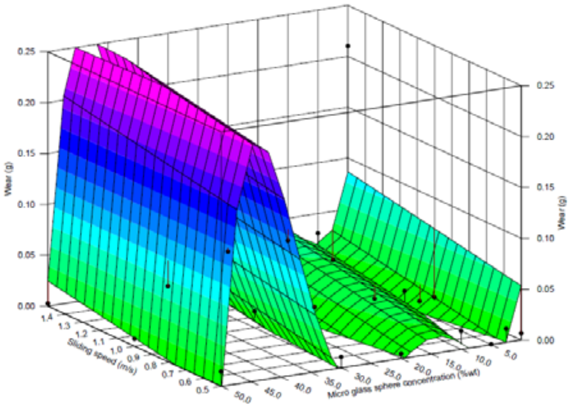
f) **behaviour prediction by neuronal net [27]**.



$$w = a + \frac{b}{x_1} + \frac{c}{x_1^2} + d \cdot x_2 + e \cdot x_2^2 + f \cdot x_2^3 \qquad (6)$$



$$w = a + b \cdot x_1 + c \cdot x_1^2 + d \cdot x_2 + e \cdot x_2^2 + f \cdot x_2^3 + g \cdot x_2^4 + h \cdot x_2^5 \qquad (7)$$



$$w = a + b \cdot x_1 + c \cdot x_2 + d \cdot x_2^2 + e \cdot x_2^3 + f \cdot x_2^4 + g \cdot x_2^5 \qquad (8)$$

Fig.17 Mathematical models for a wear map for laboratory model pin-on-disc for p=1 MPa.

Conclusions

This paper underlines:

- Increase in necessity and importance of knowledge, understanding and directioning of the tribological behaviour for the polymeric composites,
- both experience, skills and results of the experienced researchers give the opportunity for enlarging the application of composites, especially for tribological applications and for those requiring a set of properties including tribological, electrical, thernal ones,
- the necessity of having access to performant equipments (tribometer, non-contact 3D profilometer, microscope SEM, X-ray difractometer etc.),
- a closer interdependence with manufacturers and users in order to know what to (re)search.

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