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THE QUANTITATIVE – QUALITATIVE CORRELATION OF FRICTION AND WEAR IN LINEAR DRY CONTACT BETWEEN STEEL SURFACES AND SHORT GLASS FIBER REINFORCED POLYMERS

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ABSTRACT

The aim was to highlight the evolution of the wear process depending on the evolution of the friction coefficient and the dependency between wear and load, coupled with the sliding speed. As a result, it was possible to graphically illustrate the evolution of the friction coefficient and the resulting change in the wear process, emphasizing the abrasive, adhesive and corrosive wear. The evolution of the plastic material transfer as a function of the contact temperature, namely of the power lost by friction (product between the contact pressure and sliding speed, p·v*) was aimed at and it was, thus, highlighted. It has been demonstrated that in the case of a 30% shor glass fibers (SGF) content the contact temperatures can reach and even exceed the yield limit of the plastic material. We illustrated the evolution of the steel surface wear and the contact temperature as a function of the friction coefficient. A detailed evaluation of the influence of the normal load and the sliding speed (and, also, of the metallic surface roughness) on the friction coefficient was conducted.*

Keywords: PTFE + glass fiber composites, water lubrication, wear

Composite thermoplastic materials are biphasic materials consisting of a mass of polymer and the reinforcement embedded in it. The polymer provides the material with compressive strength while the reinforcement improves the tensile strength. The homogeneity of the material and its cohesion play an important part in obtaining good mechanical characteristics. The disposition of the reinforcement considerably influences the tensile strength. Conversely, the elasticity of the polymer can also improve the compression or bending resistance of the reinforcement. The role of the basic polymer is first of all mechanical, that is, to provide the bond with the reinforcement fibers. The polymer delivers the stresses between the reinforcement fibers. It is therefore necessary to ensure the proper minimum adhesion between these two substances.

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As the adhesion cannot be achieved by mechanical means, it is necessary to create a chemical bond for the polymer coating with the basic polymer. Treatments applied in this sense are specific to each thermoplastic material.

The basic polymer acts as a bridge between the reinforcement glass fibers. If the binder is slightly deformable, the fibers cannot move, so only a small number of them will support the loads. The polymer must allow a balanced distribution of load stresses between the reinforcement fibers, but at the same time must limit their movement to prevent excessive deformation. The basic polymer also provides waterproofing, as most reinforcement fibers have a high affinity for water which can result in the loss of some of their properties. The nature of the short glass fibers is quite important in respect to the preservation of the mechanical, electrical and chemical properties of the reinforced thermoplastic material. Alkali-free glass is used in order to obtain stable products, as fibers with a high Na or K content have characteristics that rapidly deteriorate as a result of superficial hydrolysis in the presence of humidity. Glass containing metal oxides is used in certain proportions in order to improve some mechanical properties, the elastic modulus, in particular.

The glass fibers used to reinforce the thermoplastic materials have a minimum tensile strength of 25 MPa, when they are defect free; however, taking into account usual surface defects, they achieve a maximum tensile strength of 15 MPa, although the glass itself only has a resistance of 0.5 – 0.6 MPa. The achieved elastic modulus ranges from 750 – 790 MPa. The fiber elongation is about 2 – 3 %, completely elastic. No permanent deformations occur before breaking and there is no hysteresis at normal temperatures.

Also, the presence of glass fibers leads to the reduction of the factor time in the sliding process. Dimensional changes due to water absorption remain a polymer inherent, hygroscopical problem. By incorporating glass fibers in the thermoplastic materials, their mechanical properties are preserved even under the influence of a wide temperature range.

Thermoplastic materials with glass fibers feature a structural mechanical association between the glass fibers and the polymer. The thermoplastic compounds are characterized by high plasticity under certain temperature conditions and by their returning to the initial stage, when cooling. In the plastic stage, they can be processed into finished products.

In 1964, Bowdon and Tabor [1] experimentally found that the values of the friction coefficient of the "clean" metal on plastic couples in the presence of some moderate loads are similar to those of the plastic on plastic friction couples. They concluded that the shear force is due to friction of the micro-junctions, formed on the contact surface of the two samples.

Several studies provide values for the friction coefficient of plastic on metal and plastic on plastic couples, either reinforced or unreinforced, operating both under dry friction and in the presence of lubricants. Jacobi [2] finds friction coefficient values ranging between 0.04 and 0.5 for polyamide reinforced with glass fibers. Bilik [3] determins values of up to 2.0 for the friction coefficient of polyamides on steel. These studies emphasize the fact that the value of the friction coefficient is not constant, but dependent on relative sliding speed, contact pressure, surface roughness, temperature, etc.

Clerico [4], studying the friction behavior of polyamide on metal couple, found that the friction coefficient values are higher for short periods of operation than those obtained for the long term operation of the couple. He indicates friction coefficient values ranging between 0.1 and 0.65, for the first three hours of the couple operation, values that decrease to 0.42 in the next 67 operation hours. He explains this through the viscoelastic properties of the polymer.

Hrusciov and Babicev [5, 6] show the growth of the microcutting component of the friction force for plastic material reinforced with glass fibers acting on steel, when increasing the polymer content.

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Bely [7], Bartenev and Laventiev [8] studied the influence on the friction coefficient of the polymer nature and of the glass fibers orientation in its mass and found that the friction coefficient values increase when glass fibers do not have the same orientation as part of the basic polymer.

Watanabe et al. [9] show the increase of the friction coefficient as a consequence of an increase in the normal load. They explain the influence of temperature on the decrease of the friction coefficient value through the obviously intensified transfer of plastic material to the steel, at high temperatures.

Lancaster [10], while studying the friction behavior of the polymers reinforced with different fibers, established the dependence of the friction coefficient of the ratio $\eta{\cdot}v{\cdot}d^3/N$ for lubricated couplings beak (of diameter d) to the disc type. He found the decrease of the friction coefficient with the reduction of the metallic surface roughness and with the increase of the value of the mentioned ratio. The friction coefficient decreases from 0.19 to 0.04, when the ratio $\eta{\cdot}v{\cdot}d^3/N$ increases from 10^{-14} to 10^{-11}, for a roughness of 0.15 μm of the steel surface. For roughness values of 0.46 μm, the friction coefficient is constant when the mentioned ratio increases from 10^{-14} to 10^{-11}. Studying the friction behavior of the thermoplastic materials, Barlow [11] provides values of 0.1 ÷ 0.28, for the friction coefficient, applicable to these surfaces on lubricated steel. He notes the increase in the value of the friction coefficient with the increase of the relative sliding speed and the friction torque between the surfaces.

West [12], while examining the friction behavior of the polyethylene/steel couple, shows the reduction of the friction coefficient from 1.24 to 0.78 when the normal load increases from 10 N to 5000 N. He demonstrates that for normal loads of 250 N to 1500 N, the friction force is proportional to the factor ($N^{0.88}$) and the friction coefficient is proportional to ($N^{0.22}$).

Bartenev, Lavrentiev et al. [13] establish that, in the case of friction bweeen plastic materials and metallic surfaces, the friction force increases at the same time as the logarithmic increase in the sliding speed. This dependence is also expressed by Vinogradov for the friction of crystalline polymers on metals. Where adhesion processes are overwhelming, he also found an increase in the friction force, dependent on the normal load.

All of the above works lead to conclude that the friction process in thermoplastic materials is extremely complex, with a variety of parameters influencing both the value of the force and of the friction coefficient.

Although research and published works are quite numerous on the theme of the friction behavior of couples thermoplastic materials on metal, not the same can be said about those published in the wear domain. The data presented in the specialty literature concerning the wear of this couple are specific to certain limited domains of use for reinforced thermoplastic materials. Most papers treat qualitative aspects of the wear phenomenon and only a few have touched on its qualitative side. Thus, Bowden and Tabor [14] have highlighted the importance of the distribution of stresses on the contact surface, showing that, for a Hertzian contact with elliptically distributed pressure, the central area of the contact surface will be more seriously damaged than the marginal areas due to higher values of surface tensile stresses ($\mu{\cdot}p$) that tend to exceed a certain critical value $(\mu{\cdot}p)_c$.

Jost [15] points out that adhesion wear is predominant for polyamide/metal couples, both in dry friction conditions and in the presence of a lubricant.

Lancaster and Evans [16], studying the wear behavior of reinforced polymers under hydrodynamic lubrication, observed a decrease in the wear rate when increasing the value of the factor $\eta{\cdot}v{\cdot}d^3/N$ for beak type couples with diameter (d), made of plastic material,

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undergoing friction on metal discs. The decrease is more pronounced as the roughness of the metallic surface is reduced.

In a comparative study of the wear behavior of high density injection processed polyethylene and polyoxymethylene (of Delrin 150 commercial type), Shen and Dumbleton [17] discover wear coefficient values of 7.8×10^{-10} to 28.6×10^{-10}. Their proposal for a calculation of the linear wear of high density polyethylene (UHMWPE) is a relation of the type:

$$h = k \cdot p \cdot x \tag{1}$$

where *h* – linear wear; *k* - wear factor; *p* - nominal pressure; *x* - sliding distance. Based on the above relation they have documented values ranging from 1.33×10^{-11} to 3×10^{-11} cm^2/N, for the wear factor of high-density polyethylene.

Myshkin [18] studied the deformation component in the friction process as a result of the polymer resistance to the “ploughing” effect caused by the asperities of the rougher counterpart. The asperities of the polymer surface bear elastic, plastic and viscous-elastic deformations, according to material characteristics. The adhesion component of friction accrues from the adhesion junctions formed as “stains” on the real contact area, which appear between twined surfaces. For polymer composites, the abrasive component of the friction force is more significant than the adhesive component.

Special care must be taken in the case of transfer films as they are the key factor that determines the tribological behavior of polymers and polymer composites. A strong abrasion component appears in the case of polymers reinforced with glass fibers [19]. Several models were developed to describe the contact adhesion. The Johnson-Kendall-Roberts (JKR) model (sometimes mentioned as a model of contact mechanics) [20-21] and the Derjaguin-Muller-Toporov (DMT) model [22] are the best known. A model comparative analysis [23] indicates that the JKR model applies to bodies of micrometric sizes or larger, while the DMT model is valid for bodies of nanometric sizes, with metal characteristics.

Short fibers reinforced polymers (SFRP) form an important class of tribo-materials, beginning with their high specific wear resistance, good and fast loading capacity and low cost processing. Nevertheless, their evolution is still in development, their properties need to adapt to more extreme loading conditions and there is a niche to expand the application fields for these materials. Recently, nano sizes started to be taken into consideration in regards to organic particles. It was determined that, by adding a small percentage of rigid nanoparticles in SFRP, their resistance to wear improves significantly, especially in high $p{\cdot}v$ conditions. However, the detailed mechanisms of such improvements were not fully understood yet.

To deeply understand the role of nanoparticles in the modification of the SFRP materials behavior to sliding wear, Chang and Friedrich [24] investigated the effects that nanoparticles have on contact mechanics and on the wear behavior of the film transfer. It was determined that supplementary nanoparticles do not directly contribute to the high performance of film transfer. Nevertheless, the presence of such nanoparticles within the contact area may efficiently reduce the adhesion between the transfer film and the polymeric sample, thus obtaining a smaller value for the friction coefficient. The rolling behavior of nanoparticles in particular may significantly improve the tribological performance of SFRP materials, when it comes to extreme sliding conditions.

The benefic tribological effects, observed in the behavior of composite polymers with short fibers, was attributed to a low ploughing and tearing capacity and to other non-adhesive wear components [25].

Vos et al. [26] examined the wear behavior of polyetheretherketone composites reinforced with short glass fibers and carbon fibers, in extremely different loading conditions. Sliding wear tests were carried out on plan steel surfaces, revealing that, by adding short fibers, the wear rate decreases for certain sliding speed and contact pressure conditions, mostly when it involves carbon fiber reinforcement. The wear rate is also influenced by a change in the polymeric matrix morphology due to thermal treatment. However, no improvements of the wear resistance on abrasive paper could be obtained by reinforcements containing short fibers.

In comparison to polymers reinforced with continuous fibers, SFRP have the advantages of faster processing and lower costs through injection and jet molding [27]. However, due to fibers fracture and thermal failure of the polymeric matrix, machine components made of SFRP risk suffering severe wear and sometimes abrupt obstruction, mostly in the case of large loads. This risk is naturally related to increases in friction as well as contact temperature [28]. Current tendencies in SFRP development are to adapt their characteristics (properties) to more extreme loading conditions and environments and to explore new application fields for these materials.

Chang et al. [29] investigated the tribological properties of two types of composites made of thermoplastic material resistant to high temperature, polyetheretherketone (PEEK) and polyetherimide (PEI), reinforced with short carbon fibers (SCF), graphite flakes and submicron particles of TiO_2 and ZnS, in dry sliding conditions. They carried out the experiments of friction and wear in a device of pin-on-disk type, using composite pins on polished steel counter-pieces. Tests were carried out in a moderate $p{\cdot}v$ range, at room temperature, as well as at high temperatures of up to 150 °C. It was determined that conventional fillers, such as SCF or graphite flakes may efficiently improve the wear resistance as well as the stress capacity of the polymeric matrix. By adding submicron particles, both the friction coefficient and the wear rate of the composites were reduced, mostly in the case of high temperatures. Authors discussed the dominant wear mechanisms, based upon the microscopic analysis of worn surfaces.

Kukureka et al. [30] studied the effect of fiber reinforcement on the friction and wear of PA66 in rolling-sliding contact. They examined three types of composites with short fibers: aramid, carbon and glass, rolling on identical materials, in a testing machine with twin discs. It was determined that the aramid fibers reinforcement significantly modifies the friction of the matrix material. However, both carbon fiber and glass fiber reinforcements substantially reduce the friction coefficient. The wear of composites with aramid and carbon fibers was, essentially, linear in time, and in general, approximately 10 times higher than that of the non-reinforced material. The wear of glass fiber composite was complex, with an initial period where the wear rate was similar with the one of the non-reinforced material. After a significant wear depth was produced, the wear rate changed to a similar value, but slightly higher than that of other reinforced materials. It seems that one of the main benefits of the introduction of fiber reinforcement, mostly of the one containing glass, is that it reduces friction coefficient and, consequently, it allows the material to be used at higher stresses, without surpassing the matrix softening point. However, the increase of stress is in the detriment of component life expectancy, which is shorter, due to an increased wear rate.

Wang et al. [31] studied samples of Nylon 1010 composite with MoS_2 filler and short carbon fibers as reinforcement. The friction and wear behavior of composite materials were investigated on a block-on-ring wear tester, where the sliding takes place in conditions of dry friction, at a speed of 0.42 ms^{-1}, under different loadings. The results indicated that the addition of carbon fibers was efficient in reducing friction and wear of pure nylon, but MoS_2 filler increased its wear. The reduction of wear and friction was more significant when carbon fibers were used as reinforcement together with MoS_2 filler. Tribochemical studies through XPS indicated that particles of MoS_2 decomposed and, while sliding,

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MoO_3, FeS, $FeSO_4$ and $Fe_2(SO_4)_3$ were produced. They concluded that FeS, $FeSO_4$ and $Fe_2(SO_4)_3$ compounds might increase the adherence between the transfer film and the counter surface. The filler synergic capacity to form a fine, uniform and continuous transfer film may contribute to the increase in wear resistance of nylon composites.

Cho and Bahadur [32] studied compression formed samples of polyphenylene filled with nanosize CuO and polyphenylene sulfide composites (PPS) reinforced with fibers. The tribological behavior of these materials, as well as the synergism due to the incorporation of nanoparticles and fibers, were also investigated. The employed reinforcement materials were short carbon fibers (CF) and aramid fibers (Kevlar grade). The proportions of the filling material varied from 1% to 4% vol. and that of the reinforcing material from 5% to 15% vol. In order to measure the wear volume and friction coefficient, a pin-on-disk sliding configuration was employed. The counterface was made of tool steel, hardened at 55-60 HRC and finished at an average roughness R_a=0.09-0.11 µm. The wear tests were carried out at a sliding speed of 1 m/s and for more than 6 hours, tests which provided wear data for steady state sliding. For filler only, the lowest steady state was registered for the composite with PPS 2% CuO and in the case of fiber reinforcement for the composite PPS 10% Kevlar.

Guo et al. [33] prepared composites based on epoxy pitch filled with hybrid nano-SiO_2 particles and carbon fibers. Styrene copolymer and maleic anhydride were spliced on ("blended into") nanoparticles beforehand, so that they would be covalently connected to the composite matrix. The reaction, however, only appeared between the anhydride and epoxide groups during maturation. Consequently, the nano-SiO_2/matrix interface interaction was increased. By assessing the sliding wear characteristics of composites according to compounds' concentrations, a positive synergetic effect was found. The wear rate as well as the friction coefficient of hybrid composites were significantly smaller than those of composites containing nano-SiO_2 particles or short individual carbon fibers. The composite with 4 wt.% nano-SiO_2 and 6 wt.% carbon fibers indicated the best tribological performance.

When polymers slide on metal surfaces, transfer films are formed. The same phenomenon occurs when sliding takes place between two polymers. In the case of polymer/polymer sliding, the material transfer was documented by Schwartz and Bahadur [34] through infrared studies that have shown that the polymer having a low density cohesion energy transfers its material to the one that has a higher density cohesion energy. The transfer film formed on a non-polymeric counterface is regulated by the counterface roughness and the material that it is made of and, of course, by the sliding conditions. Another documented fact was that the transfer film increases with the number of iterations. The effect of counterface roughness on the process is also examined. The wear mechanism is discussed in correlation with the transfer film. This discussion leads to the conclusion that when polymers are modified, such as by adding fillers, the transfer film affects the tribological behavior. Some fillers affect the transfer film development and the improvement in its adhesion to the counterface. These filling materials often drastically reduce the wear rate of the polymer. On the other side, there are many types of fillers that do not have this effect on the transfer film and wear is increased in these particular cases.

Li et al. [35] published a study aimed at the experimental and analytical determination of the tribological properties of the epoxide nano-composites reinforced with short carbon fibers (SCF), containing nano-TiO_2 particles, polytetrafluorethylene (PTFE) powder and graphite flakes, in order to understand the role the filler plays in modifying the wear behavior of materials. The influence of two solid lubricants, PTFE and graphite, was studied and compared. The transfer films established in the presence of these two lubricants in the sliding wear process of two epoxide nano-composites on metal counterpieces were

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characterized for different sliding conditions. The transfer film morphology was examined using electronic scanning microscopy (SEM), while the mechanic properties of the film were investigated through micro-hardness tests. A method based on micro-indentation was proposed for determining the thickness of the transferred films. The role of the transfer film in heat dissipation due to friction was also studied.

Components frequently fail during contact due to abrasion caused by solid contaminants contained in the lubricant. This process is classified by Dwyer-Joyce [36] as very close to the abrasion involving three bodies. The mechanisms through which embedded particles induce material removal are not fully understood. The study describes tests using the elasto-hydro-dynamic contacts model to study these mechanisms. An optic assembly of elastic-hydro-dynamic lubrication was employed to study the deformation as well as the ductile and friable fractures produced by the particles borne by the lubricator. A ball-on-disk machine was employed to study the behavior of particles in partial sliding contact. Small diamond particles were employed as abrasive materials as they do not decompose in contact. In such case, wear could be directly related to a known dimension of the particles. Particles were found to be embedded on the softer surface, grating the harder surface.

Stachowiak et al. [37] studied the effects of certain features of abrasive particles, mainly their shape and hardness, in the process of three body abrasion in metal samples. Experimental tests were carried out on a modified pin-on-disk tribometer with dry abrasive particles and on a ball-on-flat model employing suspension. The best correlation between wear rates and particle angularity was observed during the tests on the ball-on-flat model. Quartz particles were the exception, as they generated less wear than expected during all tests. Additional characteristics, such as the particle tenacity, its orientation during contact and the embedment in worn surfaces, further affected the wear results.

Capitanu et al. [38, 39] reported on the behavior of polyamide and polycarbonate reinforced with glass fibers in friction on steel surfaces. Capitanu and Florescu [19] presented some tribological aspects of steel surfaces wear with polymer composites reinforced with glass fibers, during dry friction.

As it may be observed, studies published in specialized literature focused mostly on polymer wear and not on steel counterpiece wear.

Generally, the results presented in this review of the specialty literature are in accordance with the results of our researches. But no published study has yet presented a correlation between friction and wear. The authors believe their paper will provide the reader with an overview of the complex process of friction - wear.

The authors studied the friction and wear of steel surfaces on Timken type couples (with linear contact), in dry sliding friction conditions, for contacts with polyamide reinforced with 20 - 30% glass fibers and polycarbonate reinforced with 20% glass fibers. Their focus was to establish the influence of the glass fiber content, the normal load (and, implicitly, the contact pressure), the relative sliding speed and the contact temperature on the friction and wear mechanisms of steel surfaces.

2. MATERIALS AND METHODS

The friction and wear processes were analyzed for a relatively wide range of tribological parameter values that affect them (load, relative speed, contact temperature). The range of values used for the afore mentioned parameters includes both values commonly encountered in industrial applications and some extreme, less common values that are nonetheless interesting from the point of view of studying the friction and wear

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mechanisms. Although the values of the stresses and the speeds, some parts made of thermoplastic materials usually work in the range between 0.2 MPa – 1 MPa, respectively 1.0 cm/s – 500 cm/s, attempts were made at speeds well outside these ranges.

The two elements of friction couples, the cylindrical liner and the flat sample, were made of plastic and, respectively, metal. The metallic elements of the examined couples were made of steels of different qualities, exhibiting different surface states. Out of the tested steels, only few quality ones, widely used in industrial practice, have been selected for presentation.

For friction and wear tests, polyamides and polycarbonates were selected from the wide range of thermoplastic materials processed in industry on account of their increased reinforcing possibilities when using glass fibers and high density polyethylene because of its use as a replacement of metals in some practical applications. Experimental tests have been conducted using polyamides and polycarbonates reinforced with 20% and 30% glass fibers. Experimental tests have used the thermoplastic materials whose characteristics are presented in [39]. A certain variation of such characteristics according to the various commercial types is observed, variation which occurs in rather limited ranges.

Nylonplast AVE Polyamide [40] has incorporated 30% glass fibers of a 12 μm diameter, resulting in an accentuated decrease in product deformation. At 50 ^{0}C and a compression of 140 daN/cm^2, the deformation decreases from 1.4% in the case of unreinforced polyamide, to 0.2% for the reinforced one. Noryl Polyamide [41] reinforced with 20% glass fibers is characterized by very low water absorption and high values for the elastic modulus. Lexan Polycarbonate [42] reinforced with 20% glass fibers has a high mechanical strength, a very good dimensional stability and a high resistance to shock.

The friction and wear behavior of the above materials, a significant factor in the tribological behaviour of the polyamides and polycarbonates, has been studied and will be presented in detail in this paper.

The metallic samples of the tribologically tested couples were made of the following steel grades: C 120 steel grade hardened to 59 HRC and Rp3 steel grade, hardened to 62 HRC. Their mechanical characteristics, chemical compositions and some microstructure considerations are provided in [39].

The surfaces of metal samples were processed by grinding, wet polishing with aluminium oxide and then polishing with a diamond paste, for different grain sizes. This technology has allowed to obtain surfaces with R_a=0.025 μm, R_a=0.045 μm, R_a=0.075 μm and R_a=0.125 μm. However, the authors have experimented with samples exhibiting roughness values higher or lower than the ones just mentioned, in order to obtain a more complete characterization of the friction and wear process.

An experimental installation with a Timken type friction couple (with linear contact) was used due to the wide range of loads and speeds that could be considered and the need to achieve the greatest possible variety of working conditions (contact pressures, sliding speeds and temperatures) for a more complete characterization of the tribological behavior of composite material / steel couple. This can achieve very high contact pressures (between 16 MPa and 36 MPa). The testing rig is presented in detail elsewhere [39].

The tests were carried out in order to determine the influence of the main factors affecting friction of thermoplastic material reinforced with glass fibers on metal couples. The well known Coulomb law (1780) establishes that the friction force F_f is directly proportional to the normal force applied N:

$$F_f = \mu N \tag{1}$$

Later studies have shown that μ, the friction coefficient, is dependent on more than the normal force.

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Relations for variations of the friction force, varying with the applied load can be considered in the form of:

$$F_f = aN + bN^n \tag{2}$$

or more simply:

$$F_f = a + bN \tag{3}$$

or:

$$F_f = a + bN^n \tag{4}$$

Last relationship leads to the conclusion that when the normal force is equal to 0, the friction force has other values than 0 ($F_f = a$). This could be explained by the presence of a remanent force of adhesion between the two surfaces, even after the removal of the normal load. However, The authors propose a more accurate use of a relationship of the form:

$$F_f = kN^n \tag{5}$$

where *n* is sub-unitary.

The friction coefficient, according to Coulomb's Law, is expressed as $\mu = F_f / N$. The friction coefficient for plastic materials can also be expressed as:

$$\mu = \tau_f / p_c \tag{6}$$

where τ_f represents the shear strength of the softer material, and p_c represents the flow pressure of the same material.

Because $p_c = HB/3$, it results:

$$\mu = 3\tau_f / HB \tag{7}$$

The authors found that equation (7) is in agreement with preliminary experimental results.

As it is shown in [28], the characterization of the wear rate of a material may be done with the help of a wear factor *k*, defined by the relation:

$$V_u = k \cdot N \cdot v \cdot t \tag{8}$$

where V_u is the volume of material removed through wear; N is the normal load; v is the relative sliding speed; t is the functioning time; k is the wear factor.

Dividing both relation terms (1) by the contact nominal area A, we obtain the relation:

$$V_u / A = k \cdot v \cdot t \cdot N / A \tag{9}$$

that is:

$$h_u = k \cdot p \cdot v \cdot t \tag{10}$$

where h_u is the depth of the layer of worn material; p is the pressure over the contact nominal surface.

Eq. (10) expresses a general law of wear dependency, according to the pressure between the bodies in contact (p), and the distance run through friction, meaning $L_f = vt$.

Hence, we can write:

$$k = h_u / pvt = h_u / pL_f \tag{11}$$

respectively:

$$k = V_u / Nvt = V_u / NL_f \tag{12}$$

The wear tests were aimed at determining the volumes of material removed through wear, the average depths of worn layers and, also, the volumetric and linear wear rates.

Tests were carried out at six different speeds: 18.56 cm/s, 27.85 cm/s, 37.13 cm/s, 46.41 cm/s, 55.70 cm/s and 111.4 cm/s.

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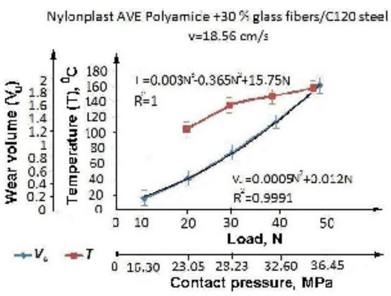
3. EXPERIMENTAL RESULTS AND DISCUSSION

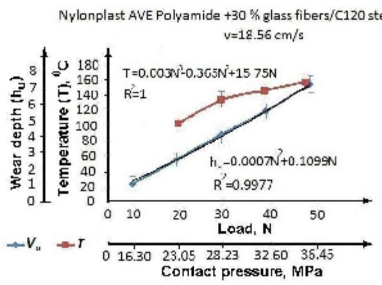
Increasing the friction coefficient increases the wear rate, but so far there is no mathematical relation between the two parameters, although one is widely accepted. In the following, The authors will give some suggestive graphical representations that make a qualitative correlation between these two, tying them to the contact temperature. All tests have lasted 1 hour and, as such, wear rates are expressed in either cm^3/h or mm/h. Quantitative data concerning wear rates have been detailed elsewhere [39].

This paper presents the variation gradient in wear rates (as worn volume and depth) while also measuring the contact temperature during tests. Diagrams (a) and (b), on top of main figures, represent the variation in the normal load and the contact pressure. For a more complete view of the wear process, the authors have included, at the bottom of main figures, variation curves in the contact temperature and the friction coefficient with the normal load. The authors also show, through optical microphotography images, representative for the wear scars. The authors believe this quantitative-qualitative approach can be used to better highlight the complexity of the friction – wear process and its evolution in time.

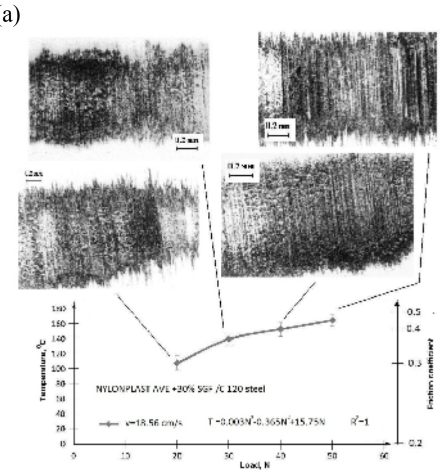
The influence of the load on the friction coefficient of the Nylonplast AVE PA + 30% glass fibers/ C120 steel couple is shown in Figures 1 and 2, for Timken type couple with linear contact, at the sliding speed of 18.56 cm/s.



(a)



(b)



(c)

Fig. 1. Wear evolution as a scar wear volume (a) and depth (b) function of the normal load and the contact temperature and the variation of the contact temperature (c) as a function of the normal load and friction coefficient at the sliding speed of 18.56 cm/s, for Nylonplast AVE Polyamide + 30% SGF / C120 steel

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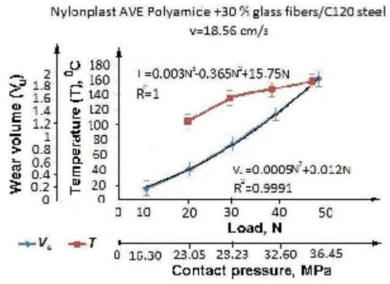
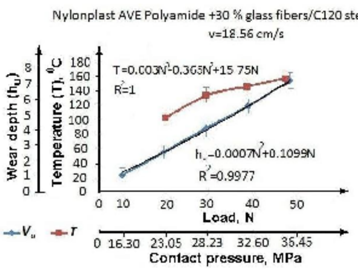
The authors have used two different figures in order to properly illustrate the qualitative analysis of the process of loss in fiber glass reinforcement from the plastic material matrix, as well as the beginning of the transfer of plastic material, initially observed on the edge of the wear scar and, subsequently, inside it, too. The curves in (a) and (b) show, as expected, the increase in wear rate in both volume and depth when the normal load (and the contact pressure) are increased, resulting in an increase in the contact temperature as a consequence of the increase in the friction coefficient.



(a)



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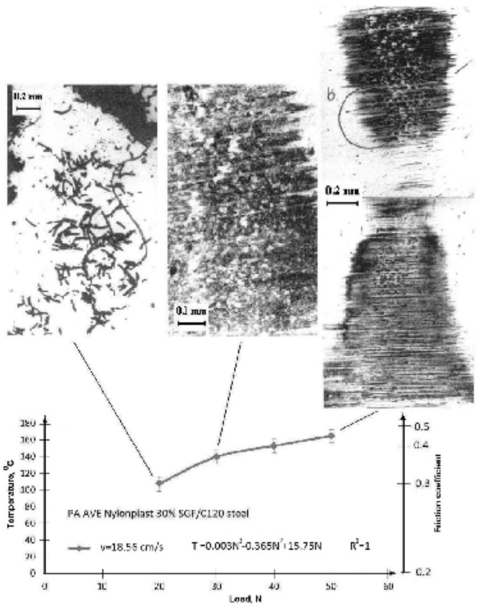


(c)

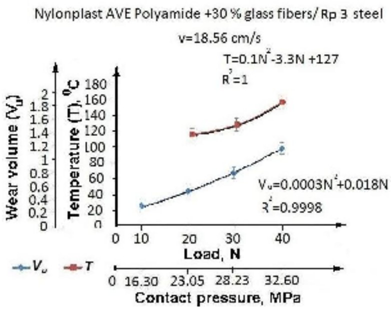
Fig. 2. Another aspects of wear evolution as scar wear volume (a) and depth (b) function of the normal load and the contact temperature and variation of wear mode (c) depending of the contact temperature and the normal load, at speed sliding of 18.56 cm/s, for Nylonplast AVE Polyamide + 30% SGF / C120 steel

An increase of the friction coefficient with the increase of the normal load applied to the couple can be observed. The variation of friction coefficient is nonlinear, in accordance with equation (5). The wear rate also increases, from $0.1387 \cdot 10^{-6}$ cm^3/h to $1.8667 \cdot 10^{-6}$ cm^3/h, when the normal load increases from 10 N to 50 N.

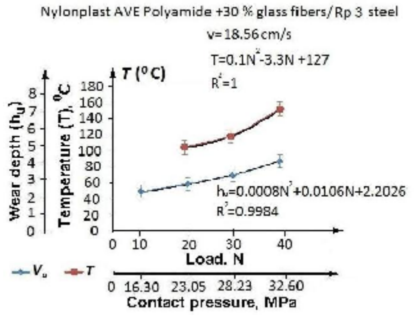
At this sliding speed, the dry friction coefficient on C120 steel grade has values ranging from 0.27 to 0.37, for a contact temperature between 108 ^{0}C and 165 ^{0}C. In the case of friction on C120 steel grade, dry friction coefficient values (Fig. 2) are between 0.25 and 0.38, the contact temperature ranging between 78 ^{0}C and 155 ^{0}C. The polynomial variation of the friction coefficient is remarkable, as is the wear rate (both in volume and in depth) as a function of the load (contact pressure). An increase of the friction coefficient with the increase of the normal load applied to the couple can be observed. The variation of friction coefficient is nonlinear, in accordance with equation (5). The wear rate also increases from $0.1387 \cdot 10^{-6}$ cm^3/h to $1.8667 \cdot 10^{-6}$ cm^3/h, when the normal load increases from 10 N to 50 N.

For the same sliding speed and for friction on Rp3 steel grade, dry friction coefficient values (Fig. 3) were found to be between 0.25 and 0.38 while the contact temperatures range between 81 ^{0}C and 155 ^{0}C. Here, the authors can observe the same polynomial growth in the friction coefficient, the wear speed and the contact temperature as a function of the normal load. However, the wear rate increases from $0.2136 \cdot 10^{-6}$ cm^3/h to $1.1247 \cdot 10^{-6}$ cm^3/h and from $2.3815 \cdot 10^{-4}$ mm/h to $3.9708 \cdot 10^{-4}$ mm/h, respectively, for increases in the normal load from 10 N to 40 N. The increase in the wear rate is not as pronounced as for C120 steel grade, probably owing to greater hardness of Rp3 steel grade.

It can also be seen the corrosion wear (upper left), the plastic material transfer containing glass fibers removed from the matrix (upper centre) and the adhesion marks on the wear scar (upper right), in Fig. 3c.



(a)



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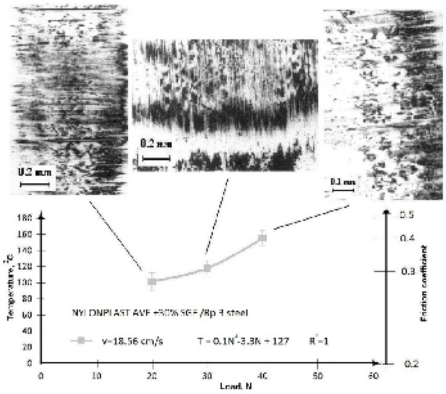

(c)

Fig. 3. Wear evolution in scar wear volume (a) and depth (b) as a function of the normal load and the contact temperature with a variation of the contact temperature (c) as a function of the normal load and the friction coefficient at the sliding speed of 18.56 cm/s, for Nylonplast AVE Polyamide + 30% SGF / Rp3 steel grade

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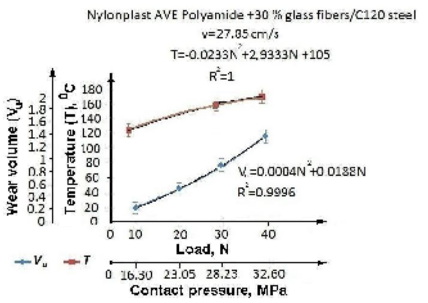

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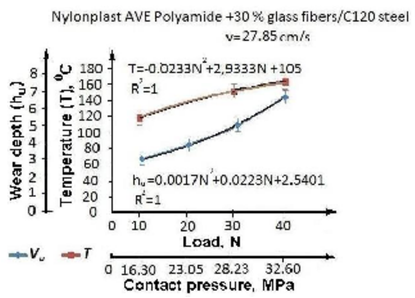

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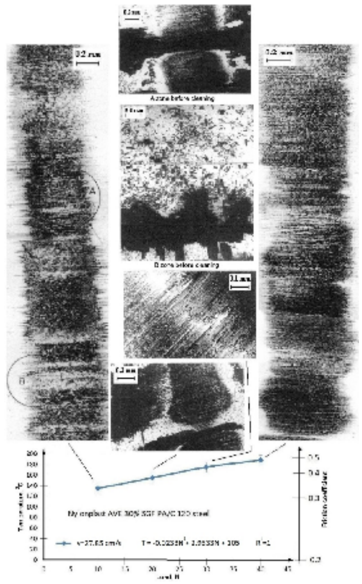

(c)

Fig. 4. Wear evolution of the scar wear volume (a) and depth (b) as a function of the normal load and the contact temperature and the variation in contact temperature (c) as a function of the normal load and the friction coefficient atthe sliding speed of 27.85 cm/s, for Nylonplast AVE Polyamide + 30% SGF / C120 steel grade

Figure 4 shows the variation of wear, friction coefficient and contact temperature as a function of the normal load, for Nylonplast AVE + 30% glass fibers / C120 steel couple, at a sliding speed of 27.85 cm/s.

Comparing the images in Figs 2, 3 and 4, they show different facets for the adhesive and abrasive wear of metallic surfaces, at small loads (20 N), followed by a powerful plastic transfer at 30 N - 40 N loads, with the formation of bridges at 30 N and even plastic flow at 40 N, in which case the metal surface temperature reaches 190 ^{0}C (Fig. 4). At the beginning of the wear process, glass fibers are ripped from the polymer matrix, broken and expelled on the output of the wear scar. At a sliding speed of 27.85 cm/s, the wear rate ranges between $0.2352 \cdot 10^{-6}$ cm^3/h to $1.3796 \cdot 10^{-6}$ cm^3/h and $2.9149 \cdot 10^{-6}$ mm/h to $6.1374 \cdot 10^{-6}$ mm/h, at loads between 10 N and 40 N.

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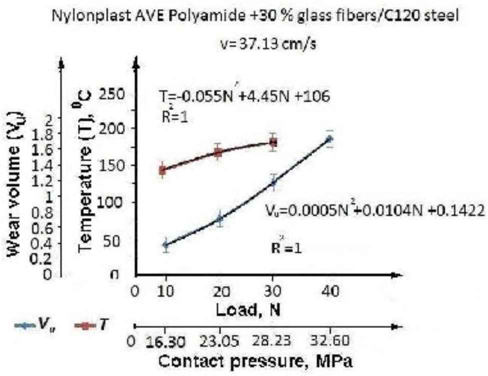
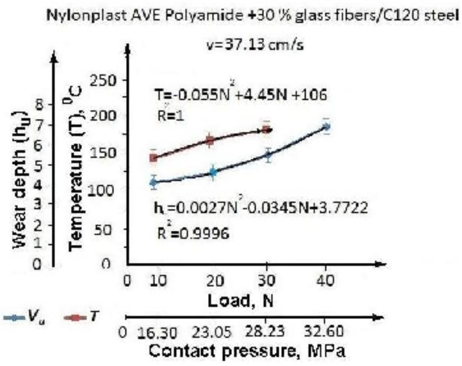
Figure 5 shows the variation of the friction coefficient and the contact temperature as a function of the normal load, for Nylonplast AVE + 30% glass fibers / C120 steel couple, at a sliding speed of 37.13 cm/s.



(a)



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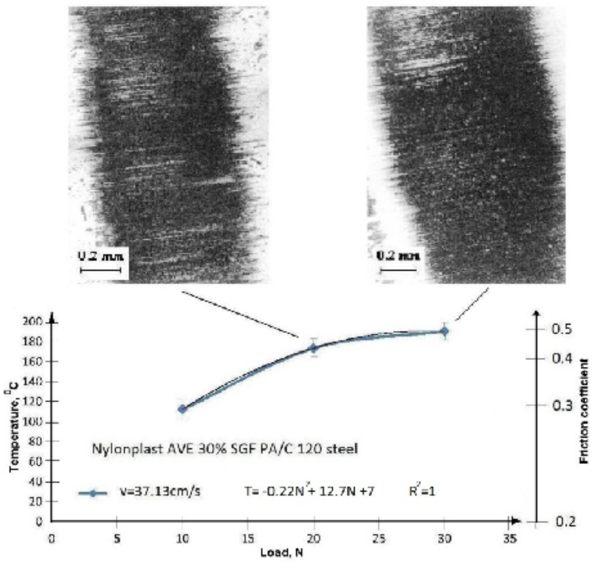

(c)

Fig. 5. Wear evolution of the scar wear volume (a) and depth (b) as a function of the normal load and the contact temperature and the variation in contact temperature (c) as a function of the normal load and the friction coefficient at the sliding speed of 37.13 cm/s, for Nylonplast AVE Polyamide + 30% SGF / C120 steel grade

At this sliding speed, the dry friction coefficient has values between 0.32 and 0.35, the contact temperature ranging between 108 ^{0}C and 165 ^{0}C. In the case of friction on C120 steel grade, dry friction coefficient values are between 0.27 and 0.38, the contact temperature ranging between 135^{0}C and 188 ^{0}C, as a function of the applied normal load.

The wear of the metallic surface changes visibly, becoming mostly abrasive, with adhered material being removed and deposited on the resulting wear scars (Fig. 5).

Corrosion wear begins to appear, manifested through pits in the centre of wear scars. At this sliding speed, the wear rate was between 0.2999·10^{-6} cm^3/h and 0.7767·10^{-6} cm^3/h and

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$3.6871 \cdot 10^{-4}$ mm/h and $3.9104 \cdot 10^{-4}$ mm/h, at loads of 10 N – 40 N. The evolution of contact temperatures and friction coefficients for C120 steel surfaces and the appearance of wear at the sliding speed of 55.70 cm/s is shown in Fig. 6, with the friction coefficient varying between 0.37 and 0.40, for contact temperatures ranging from 150 ^{0}C to 267 ^{0}C.

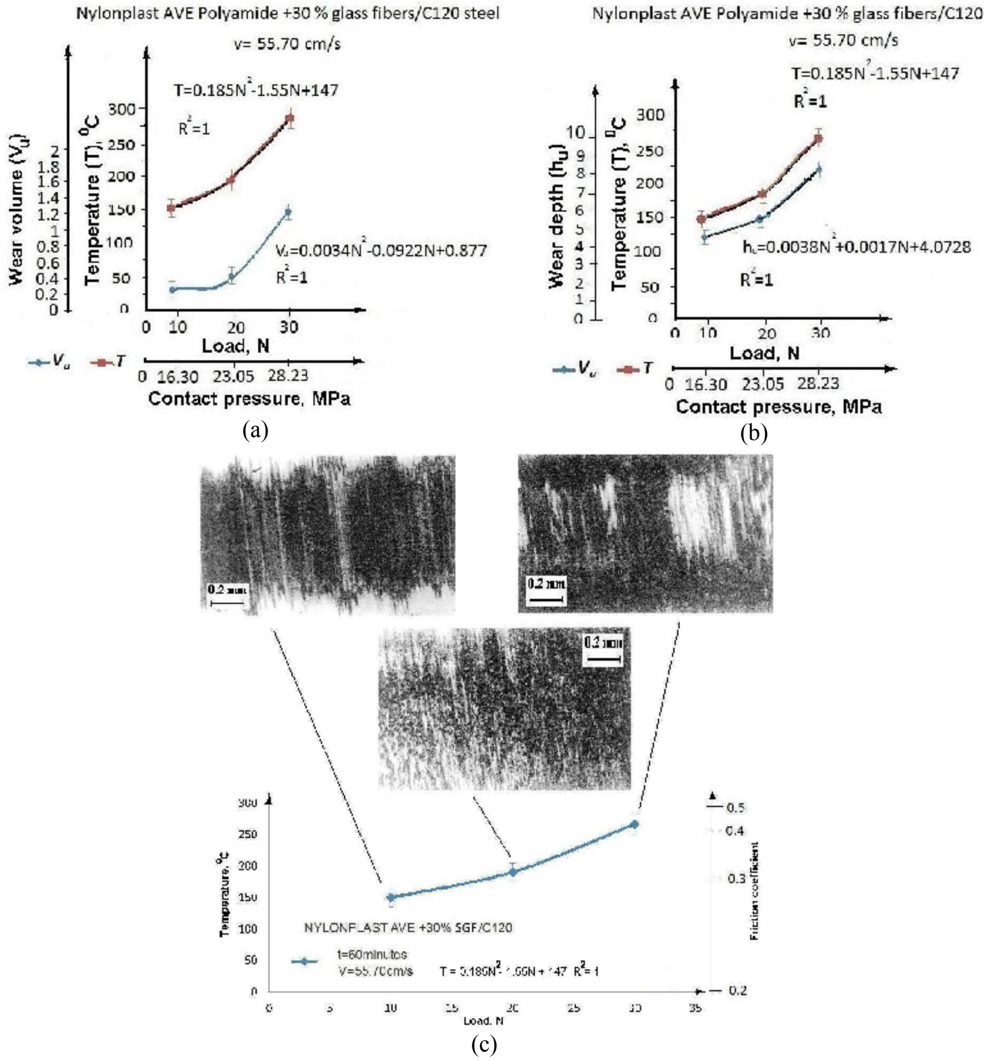

Fig. 6. Wear evolution of the scar wear volume (a) and depth (b) as a function of the normal load and the contact temperature and the variation in contact temperatures (c) as a function of the normal load and friction coefficient at the sliding speed of 55.70 cm/s, for Nylonplast AVE Polyamide + 30% SGF / C120 steel grade

At this sliding speed, the wear rate was between $0.2914 \cdot 10^{-6}$ cm^3/h and $1.1404 \cdot 10^{-6}$ cm^3/h and $4.4704 \cdot 10^{-4}$ mm/h and $7.5505 \cdot 10^{-4}$ mm/h, at loads of 10 N – 30 N. The wear character becomes visibly adhesive when the applied load increases to the value of 30 N (for a contact temperature of 238 ^{0}C). At the highest sliding speeds used for testing, 111.4 and 153.57 cm/s, the C120 steel reaches friction coefficients of 0.37 and 0.48,

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respectively, the measured contact temperatures ranging between 279 ^{0}C and 295 ^{0}C. This translates in the wear manifesting itself mainly by adhesion and corrosion (Figs 7 and 8).

The wear character becomes visibly adhesive when the applied load increases to the value of 20 N (contact temperature 238 ^{0}C, at 111.4 cm/s). At this sliding speed the wear rate ranged between $4.9482 \cdot 10^{-4}$ mm/h and $8.0003 \cdot 10^{-4}$ mm/h, or 0.2830 and 1.1732 cm^3/h, respectively, for loads of 10 N -30 N.

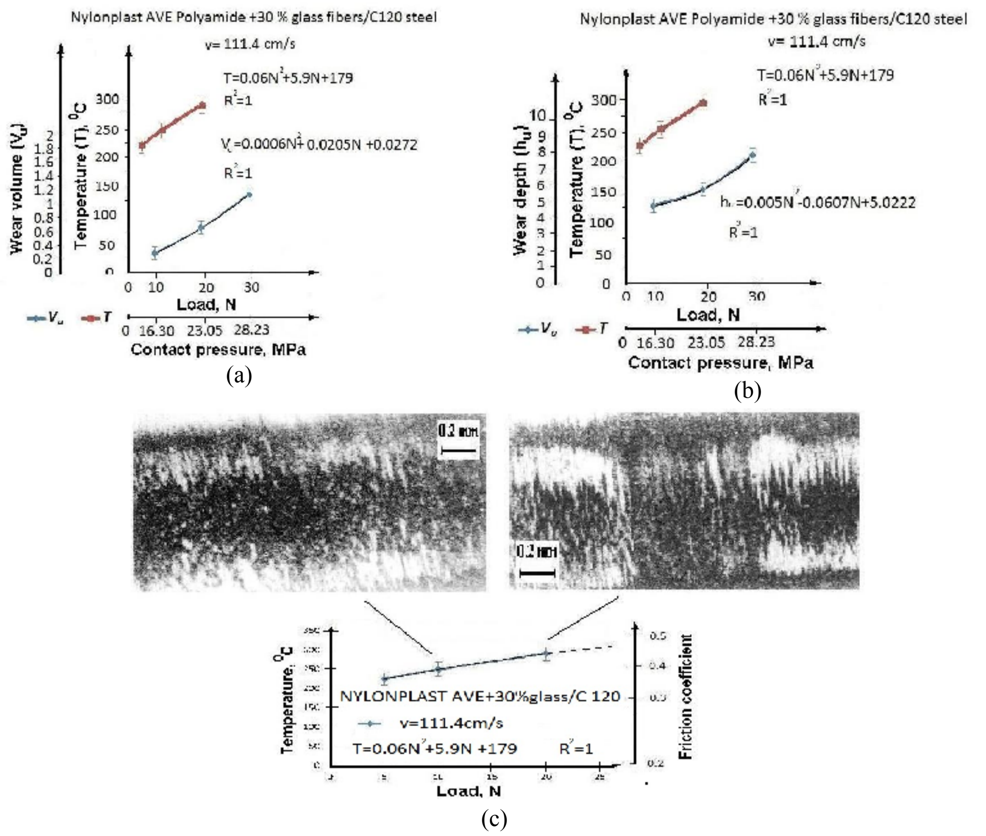

Fig. 7. Wear evolution of the scar wear volume (a) and depth (b) as a function of the normal load and contact temperature and the variation in contact temperature (c) as a function of the normal load and friction coefficient at the sliding speed of 111.4 cm/s, for Nylonplast AVE Polyamide + 30% SGF / C120 steel

At the highest sliding speed used for testing, 153.57 cm/s, C120 steel friction coefficient values between 0.37 and 0.48 are reached, with the measured contact temperatures ranging between 279 ^{0}C and 295 ^{0}C. Again, the wear is characterised mainly by adhesion and corrosion (Fig. 8).

At loads of 40 N, the tests are inconclusive because the surface of polymeric sample moves into a vitrification (glassy) state due to very high temperatures, covering the metal with a glassy layer. At this sliding speed, the wear rate decreased to values between $5.1760 \cdot 10^{-6}$ cm^3/h to $9.0170 \cdot 10^{-6}$ cm^3/h, and between $0.3101 \cdot 10^{-4}$ mm/h and $1.2435 \cdot 10^{-4}$ mm/h, at loads of 10 – 30 N.

For the friction of polymers reinforced with 30% glass fibers on Rp3 steel surfaces (that are harder than C120 steel surfaces, having – 62 HRC), the authors obtained the same

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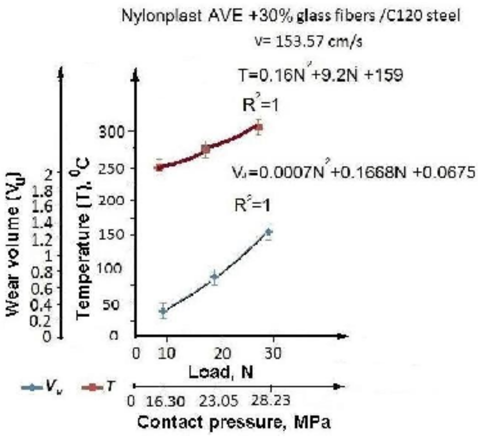
results on the wear evolution as a function of the normal load and the sliding speed as in the case of C120 steel grade.

Thus, under the same test conditions, the wear increases with the increase in the normal load and the sliding speed, while the values of friction coefficient are somewhat lower, ranging in 0.27 - 0.42 domain, but the recorded contact temperatures are between 164 ^{0}C and 249 ^{0}C. For example, Figures 9 and 10 show the wear rate, contact temperature and friction coefficient variation as a function of the normal load, at speeds between 37.13 cm/s and 46.41 cm/s, for friction between polyamide Nylonplast AVE + 30% SGF and Rp3 steel surfaces.



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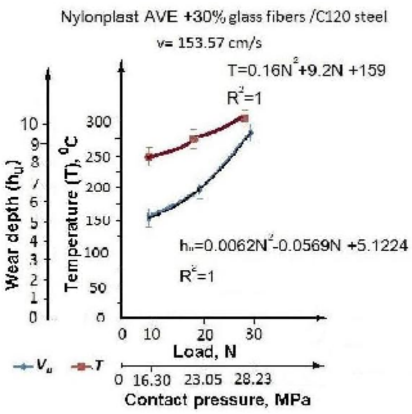

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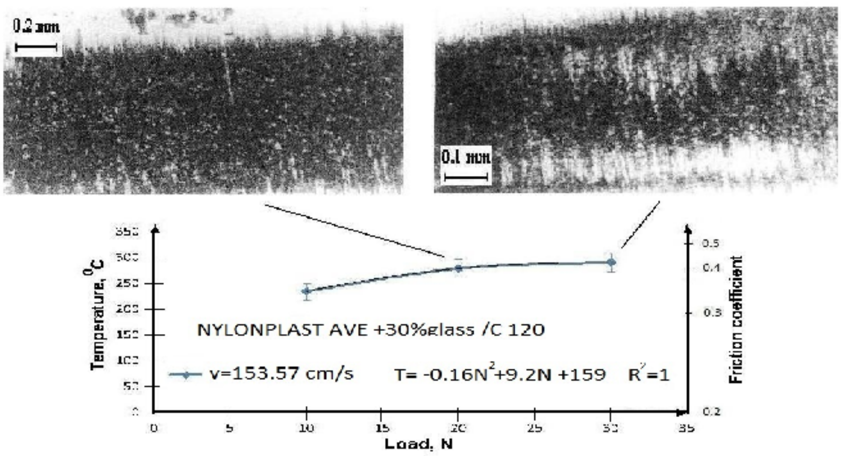
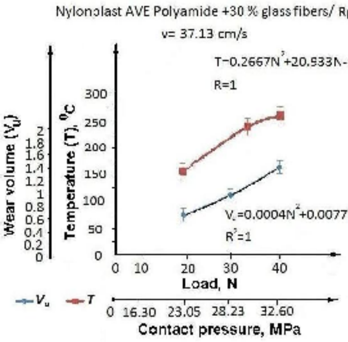


(c)

Fig. 8. Wear evolution of the scar wear volume (a) and depth (b) as a function of the normal load and contact temperature and the variation in contact temperature (c) as a function of the normal load and friction coefficient at the sliding speed of 153.57 cm/s, for Nylonplast AVE Polyamide + 30% SGF / C120 steel grade

For speeds of 37.13 cm/s, the wear rate values ranged from $0.5619 \cdot 10^{-6}$ cm^3/h to $1.2531 \cdot 10^{-6}$ cm^3/h and $4.1076 \cdot 10^{-4}$ mm/h to $5.0041 \cdot 10^{-4}$ mm/h, respectively, for loads of 20 – 40 N. For speeds of 46.41 cm/s, the wear rate values ranged from $0.5833 \cdot 10^{-6}$ cm^3/h to

$1.3686 \cdot 10^{-6}$ cm^3/h and from $4.5242 \cdot 10^{-4}$ mm/h to $6.0041 \cdot 10^{-4}$ mm/h, respectively, for loads between 20 N and 40 N.



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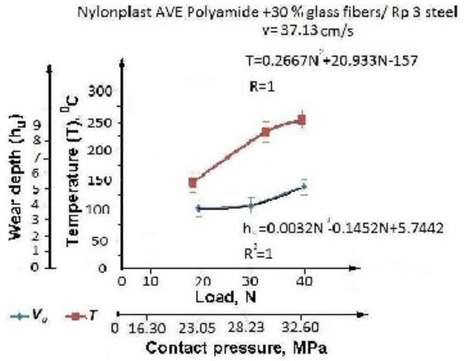

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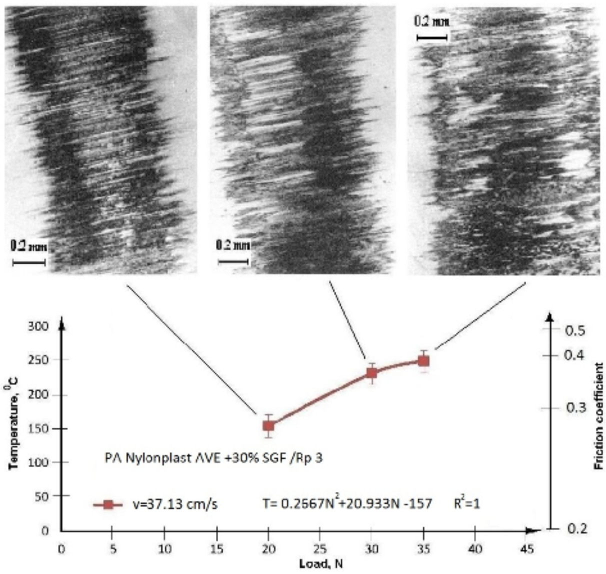

(c)

Fig. 9. Wear evolution of the scar wear volume (a) and depth (b) as a function of the normal load and contact temperature and the variation in contact temperature (c) as a function of the normal load and friction coefficient at the sliding speed of 37.13 cm/s, for Nylonplast AVE Polyamide + 30% SGF / Rp3 steel grade

For the friction of Lexan 5412 + 20% SGF polycarbonate, at sliding speeds of 27.85 cm/s, the friction coefficient value varies between 0.35 and 0.50 and the contact temperatures vary between 220 ^{0}C and 251 ^{0}C, depending on the test conditions. A massive polymer and removed glass fibers transfer occurs due to abrasion, on the inside of the wear scar, while a massive transfer of melted polymer from the composite material matrix occurs on the outside of the wear scar. For example, Figure 11 shows the diagram of contact temperature variation and images of the phenomena described above.

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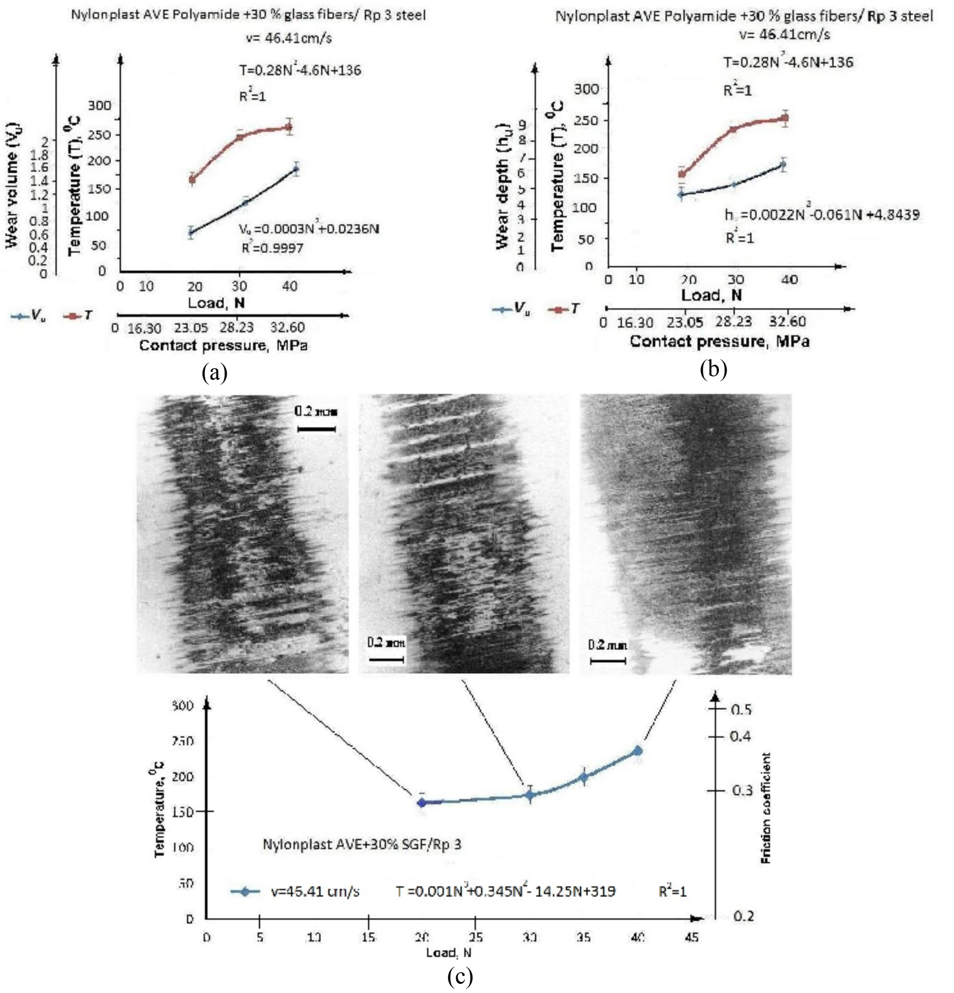

Fig. 10. Wear evolution of the scar wear volume (a) and depth (b), as a function of the normal load and contact temperature and the variation in contact temperature (c) as a function of the normal load and friction coefficient at the sliding speed of 46.41 cm/s, for Nylonplast AVE Polyamide + 30% SGF / Rp3 steel grade

At this sliding speed, the wear rate ranges between $0.2440{\cdot}10^{-6}$ cm^3/h and $1.1594{\cdot}10^{-6}$ cm^3/h, or $3.5917{\cdot}10^{-4}$ mm/h to $4.9169{\cdot}10^{-4}$ mm/h, respectively, for loads between 10 N to 40 N. Tables 1, 2, 3 and 4 synthesize the correlation between volume (V_u) and depth (h_u) of the wear scar, functions between the contact temperature (T), the friction coefficient (μ) and the normal load (N). There is a notable polynomial variation of these parameters as a function of the normal load.

The complexity of the processes of friction and wear in the case of dry friction contact plastics with SGF on steel surfaces, which the authors tried to present in quantitative and qualitative terms, as well as clear as possible, can be synthesized through a suggestive schematic representation of the process, with input, output factors (consequences) and their influence on the evolution of the entire tribological process (Fig. 12).

The authors give some correlation functions between wear scar volume (V_u) or wear scar depth (h_u) and the normal load (N), friction coefficient (μ), contact temperature (T).

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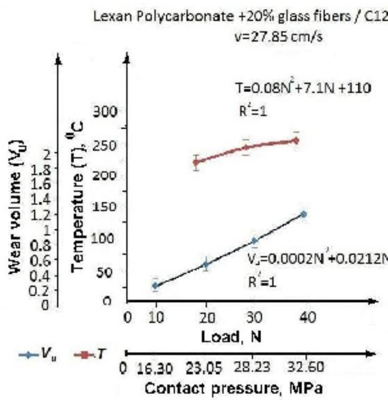
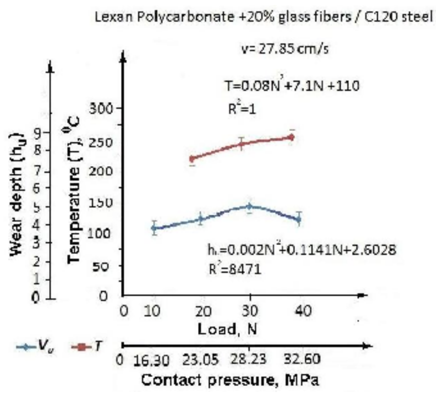
Table 1. Regression function between contact temperature (T) and normal load (N)

Friction couple	v (cm/s)	Regression function	Correlation factor
Polyamide + 30% SGF/C120 steel	18.56	$T=0.003\ N^3-0.365N^2+15.75N$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	27.85	$T=0.0233\ N^2+2.9333\ N+105$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	37.13	$T = 0.055\ N^2 + 4.45\ N + 106$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	55.70	$T = 0.185\ N^2 – 1.55\ N + 147$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	111.4	$T = 0.06\ N^2 + 5.9\ N + 179$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	153.57	$T = 0.16\ N^2 + 9{,}2\ N +159$	$R^2 = 1$
Polyamide + 30% SGF/ Rp3 steel	18.56	$T = 0.1\ N^2 – 3.3\ N + 127$	$R^2 = 1$
Polyamide + 30% SGF/Rp3 steel	37.13	$T= 0.2667\ N^2 +20.933\ N-157$	$R^2 = 1$
Polyamide + 30% SGF/Rp3 steel	46.41	$T = 0.28\ N^2 – 4.6\ N + 136$	$R^2 = 1$
Polycarbonate + 20% SGF/C120 steel	27.85	$T = 0.08\ N^2 +7.1\ N + 100$	$R^2 = 1$



(a)



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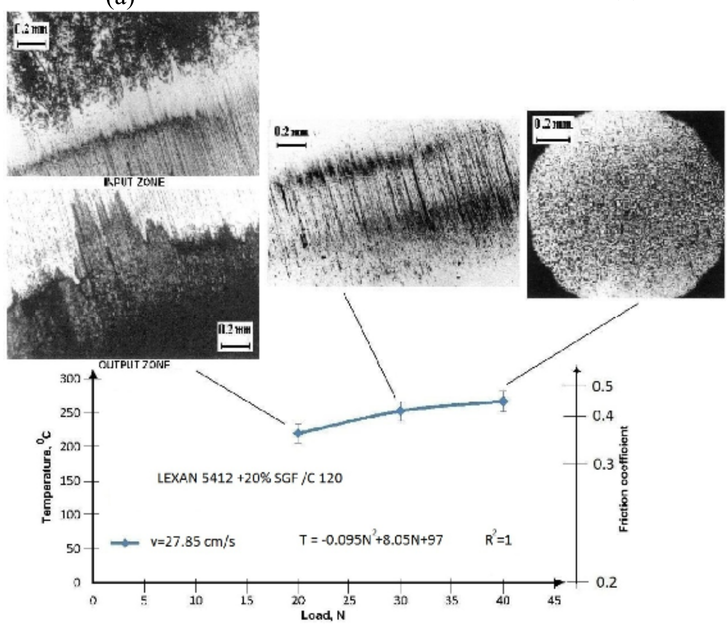

(c)

Fig. 11. The evolution in contact temperatures and wear appearance at speeds of 27.85 cm/s, for PC Lexan 3412 + 20% SGF / C120

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Table 2. Regression functions between wear scar volume (V_u) and normal load (N)

Friction couple	v (cm/s)	Regression function	Correlation factor
Polyamide + 30% SGF/C120 steel	18.56	$V_u = 0.0005\ N^2 + 0.012\ N$	$R^2 = 0.9991$
Polyamide + 30% SGF/C120 steel	27.85	$V_u = 0.0004\ N^2 + 0.0188\ N$	$R^2 = 0.9996$
Polyamide + 30% SGF/C120 steel	37.13	$V_u = 0.0005\ N^2 + 0.0104\ N + 0.1423$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	55.70	$V_u = 0.0034\ N^2 - 0.0922\ N + 0.877$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	111.4	$V_u = 0.0006\ N^2 - 0.0205\ N + 0.272$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	153.57	$V_u = 0.0007\ N^2 + 0.1668\ N + 0.0675$	$R^2 = 1$
Polyamide + 30% SGF/ Rp3 steel	18.56	$V_u = 0.0003\ N^2 + 0.018\ N$	$R^2 = 0.9998$
Polyamide + 30% SGF/Rp3 steel	37.13	$V_u = 0.0004\ N^2 + 0.0077\ N + 0.2291$	$R^2 = 1$
Polyamide + 30% SGF/Rp3 steel	46.41	$V_u = 0.0003\ N^2 + 0.0236\ N$	$R^2 = 0.9997$
Polycarbonate+20% SGF/C120steel	27.85	$V_u = 0.0002\ N^2 + 0.0212\ N + 0.0138$	$R^2 = 1$

Table 3. Regression functions between wear scar depth (h_u) and normal load (N)

Friction couple	v (cm/s)	Regression function depth	Correlation factor
Polyamide + 30% SGF/C120 steel	18.56	$h_u = 0.0007\ N^2 + 0.1099\ N$	$R^2 = 0.9977$
Polyamide + 30% SGF/C120 steel	27.85	$h_u = 0.0017\ N^2 + 0.0223\ N + 2.5401$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	37.13	$h_u = 0.0027\ N^2 - 0.0345\ N + 3.7722$	$R^2 = 0.9996$
Polyamide + 30% SGF/C120 steel	55.70	$h_u = 0.0038\ N^2 + 0.0017\ N + 4.0728$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	111.4	$h_u = 0.0005\ N^2 - 0.0607\ N + 5.0222$	$R^2 = 1$
Polyamide + 30% SGF/C120 steel	153.57	$h_u = 0.0062\ N^2 - 0.0569\ N + 5.1224$	$R^2 = 1$
Polyamide + 30% SGF/ Rp3 steel	18.56	$h_u = 0.0008\ N^2 + 0.0106\ N + 2.2026$	$R^2 = 0.9984$
Polyamide + 30% SGF/Rp3 steel	37.13	$h_u = 0.0032\ N^2 - 0.1452\ N + 5.7442$	$R^2 = 1$
Polyamide + 30% SGF/Rp3 steel	46.41	$h_u = 0.0022\ N^2 - 0.061\ N + 4.8439$	$R^2 = 1$
Polycarbonate +20% SGF/C120 steel	27.85	$h_u = 0.002\ N^2 + 0.1141\ N + 2.6028$	$R^2 = 0.9400$

Table 4. Regression functions between friction coefficient (μ) and normal load (N)

Friction couple	v (cm/s)	Regression function	Correlation factor
Polyamide + 30% SGF/C120 steel	18.56	$\mu = 61.548 \ln(N) - 73.884$	$R^2 = 0.9831$
Polyamide + 30% SGF/C120 steel	27.85	$\mu = 38.278 \ln(N) + 44.7$	$R^2 = 0.9826$
Polyamide + 30% SGF/C120 steel	37.13	$\mu = 72.83 \ln(N) - 52.862$	$R^2 = 0.9731$
Polyamide + 30% SGF/C120 steel	55.70	$\mu = 101.4 \ln(N) - 91.376$	$R^2 = 0.9004$
Polyamide + 30% SGF/C120 steel	111.4	$\mu = 47.609 \ln(N) + 145.71$	$R^2 = 0.9808$
Polyamide + 30% SGF/C120 steel	153.57	$\mu = 53.32 \ln(N) + 116.61$	$R^2 = 0.9718$
Polyamide + 30% SGF/ Rp3 steel	18.56	$\mu = 75.554 \ln(N) - 129.31$	$R^2 = 0.9078$
Polyamide + 30% SGF/Rp3 steel	37.13	$\mu = 171.93 \ln(N) - 358.7$	$R^2 = 0.9922$
Polyamide + 30% SGF/Rp3 steel	46.41	$\mu = 94.086 \ln(N) - 126.86$	$R^2 = 0.9922$
Polycarbonate + 20% SGF/C120 steel	27.85	$\mu = 68.698 \ln(N) + 15.708$	$R^2 = 0.9828$

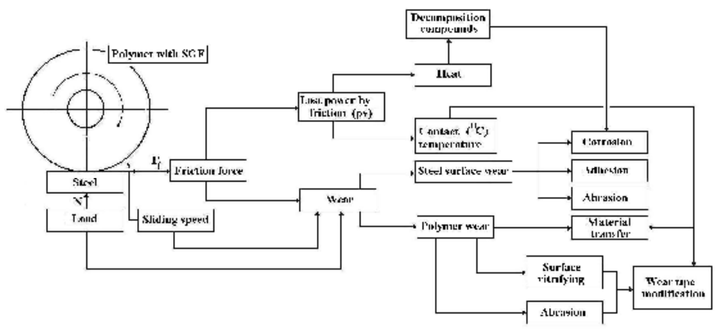

Fig. 12. The complexity of the evolution for the process of friction-wear at a linear contact polymer with SGF/ steel

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So, the contact temperature, the wear scar volume and the wear scar depth are written according to the normal load (*N*) in polynomial forms, as:

$$T = \sum_{i=0}^{2} a_i N^i;$$

$$V_u = \sum_{i=0}^{2} b_i N^i; \tag{13}$$

$$h_u = \sum_{i=0}^{2} c_i N^i,$$

and functions between friction coefficient μ and normal load N are

$$\mu = A \cdot \ln N + B \tag{14}$$

where a_i, b_i, c_i and A, B are determined from regression functions.

From relations (13) we obtain

$$V_u = \frac{b_2}{a_2}T + \left(b_1 - \frac{b_2}{a_2}a_1\right)N + c_0 - \frac{b_2}{a_2}a_0, \tag{15}$$

or, after substituting N from (14) and replacing in (15), we have

$$V_u = \frac{b_2}{a_2}T + \left(b_1 - \frac{b_2}{a_2}a_1\right)\exp[(\mu - B)/A] + c_0 - \frac{b_2}{a_2}a_0. \tag{16}$$

Similarly, the wear scar depth is

$$h_u = \frac{c_2}{a_2}T + \left(c_1 - \frac{c_2}{a_2}a_1\right)N + c_0 - \frac{c_2}{a_2}a_0, \tag{17}$$

$$h_u = \frac{c_2}{a_2}T + \left(c_1 - \frac{c_2}{a_2}a_1\right)\exp[(\mu - B)/A] + c_0 - \frac{b_2}{a_2}a_0. \tag{18}$$

Also, we can express the contact temperature as a function of μ such:

$$T = \sum_{i=0}^{2} a_i \exp[(\mu - B)i / A]. \tag{19}$$

Considering that wear is generally adhesive, in the case of linear polymer/steel contact, it could be taken into consideration the volume of wear material relationship of Archard (8) [35]. In this case, taking into account the relationships (8) and (9), it can be written:

$$V_u = kNvt = \frac{b_2}{a_2}T + \left(b_1 - \frac{b_2}{a_2}a_1\right)N + c_0 - \frac{b_2}{a_2}a_0 \tag{20}$$

and from relationships (8) and (16), we obtain:

$$V_u = kNvt = \frac{b_2}{a_2}T + \left(b_1 - \frac{b_2}{a_2}a_1\right)\exp[(\mu - B)/A] + c_0 - \frac{b_2}{a_2}a_0. \tag{21}$$

Writing the Archard relationship for the wear depth (10), from relationships (15) and (17), it is obtained:

$$h_u = k^* pvt = \frac{c_2}{a_2}T + \left(c_1 - \frac{c_2}{a_2}a_1\right)N + c_0 - \frac{c_2}{a_2}a_0 \tag{22}$$

Also, from the relationships (10) and (11) we can write:

$$h_u = k^* pvt = \frac{c_2}{a_2}T + \left(c_1 - \frac{c_2}{a_2}a_1\right)\exp[(\mu - B)/A] + c_0 - \frac{b_2}{a_2}a_0 \tag{23}$$

4. CONCLUSIONS

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From all of the above, the authors can draw several conclusions:

- the wear process of metallic surfaces in dry friction contact against plastic materials reinforced with short glass fibers evolves over time and depends on the load, moving from the initial abrasive wear, caused by glass fibers, to adhesion wear characterized especially by the transfer of plastic material on the metallic surface, but also by corrosion;
- the friction coefficient has values in a wide range, comprised between 0.2 and 0.5;
- the contact temperatures increase as a function of the applied load and the sliding speed, reaching values of 295 ^{0}C, resulting in the flow of plastic material, exceeding the transition temperature to the glassy state and even reaching the flow state of the latter;
- the values of friction coefficient for the reinforced plastic materials on the surfaces of the C120 steel samples are higher than those obtained on the surfaces of Rp3 steel samples. The explanation for this phenomenon lies in the difference in hardness of the two steel sample surfaces. This behavior confirms equations (6) and (7). Equation (7) is consistent with the results shown in Figures 4, 10 and 11;
- the values of friction coefficient for thermoplastic materials reinforced with glass fibers on the C120 steel pass through a minimum located in the normal loads domain of 20 N - 30 N. In the case of the same materials friction on the Rp3 steel surfaces, the increase of the friction coefficient with the normal load is quasi-linear. The explanation for this phenomenon is that, under the action of the stress states, the C120 steel grade undergoes superficial cold hardening, manifested by an increase in its hardness in the friction area. Hardening occurs at contact pressures between 1.75 MPa and 2.0 MPa, corresponding for the linear contact couples used for a load of 20 N. At higher loads and respective greater efforts, the hardened layer is destroyed and, in turn, it entails an increase of the friction coefficient as a function of the decreasing in hardness;
- although any mathematical relation cannot be established among the friction coefficient, the contact temperatures and the metallic surface wear, the authors believe that the manner in which they graphically presented the wear state of the metallic surface as a function of the contact temperature (friction coefficient) allows for significant conclusions to be drawn in the plastic material on studied steel contacts.

However, this research has some limitations. At high contact temperatures it is likely that the elastic contact assumption, under which the modelling was made, is invalid. Also, the contact temperatures were measured at 1 mm below the metallic contact surface, so, obviously, the real temperature was even higher. The evaluation of the friction coefficient was done over time as an average of the friction coefficient during the test and not as the friction coefficient value at a fixed point in time.

The wear rate of the steel sample increases with an increase in the normal load and, respectively, with an increase in the contact pressure. The increase is not linear, each of the studied couples exhibiting particular behaviors. The only common change was an increase in the wear rate of the metal element with the increase in the sliding speed.

Comparing the values of the wear rates of the metal element at the sliding speeds of 46.41 cm/s and normal loads of 40 N allowed to conclude that, in the case of the polyamide reinforced with 30% glass, the C120 steel grade wears off approximately 1,110 times more than the Rp3 steel grade. The authors believe that this phenomenon is due to the higher hardness of samples made of Rp3 (62 HRC), in comparison to those made of C120 steel grade (59 HRC). The fact that the polycarbonate reinforced with 20% glass wears off the C120 steel grade 1.48 times less than the polyamide with 30% glass, demonstrates that not only the reinforcement content, but also the physical-mechanical characteristics of the basic polymer influence the wear rate of the metal element of the friction couple.

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In the case of plastic material couples + 20% glass/steel, tests indicated that the wear of the material gennerally manifests an abrasive character. This stage is of short duration, after which, due to the increase of temperature in the contact area, the wear acquires a pronounced adhesive character, characterized through the transfer of plastic material onto the metal surface. The higher the load and the speed, the more intense is the transfer. The plastic material transferred onto the metal surface reduces the influence of abrasive wear, due to the obstruction in the direct contact of the glass fibers with the metal, the former not being able to completely remove the bridges created though transfer. The observations mentioned above are confirmed by the microphotography of the wear imprints obtained during the experimental tests presented in this study.

In the case of plastic materials with a higher content of glass fibers (30%), the abrasive effect due to the reinforcement increases, leading to the removal of transferred material and an accentuated increase in the wear rate of the metal, as compared to the one compliant with the quantitative law of adhesive wear.

The increase of the duration of tests also indicated an increase in wear. However, this increase is not proportional to the test duration. Experiments lasting 120 minutes indicated that the wear of the metal element during the first 60 minutes is higher than the wear produced during the rest of the test. The authors estimate that this phenomenon may be explained through the existence of a stage in the initial period of the friction couple functioning, when a geometric conformation takes place for the surfaces of the two elements that are in contact.

All of the above mentioned observations are confirmed by the microphotography of the wear imprints obtained during the experimental tests presented in this study.

REFERENCES

1. **Bowden, F., P., Tabor, D.,** 1967, Friction and Lubrication, Metheuen & Co. Ltd. London.
2. **Jacobi, H., R.**, 1957, Neue Erkenntnisse über Gleitenschaften von Polyamiden, *K*unststoffe, 47 (5): 234-239.
3. **Bilik, M.,** 1965, Parî trenia metal-plastmassa v maşinah i mechanizma*h*, Izd. Maşinostroienie, Moskva.
4. **Clerico, M.,** 1969, A Study of the Friction Wear of Nylon against Metal, *Wear, 13(3),* pp. 183-197.
5. **Hrusciov, M., M.,** 1957, Resistance of Metals to Wear by Abrasion, as related to Hardness, *Proc. Conference on Lubrication and Wear, Inst. Mech. Eng.*, London, pp. 979-986.
6. **Hrusciov, M., M., Babicev, M., A.**, 1982, Resistance to Abrasive Wear of structurally Inhomogeneous Materials, Friction and Wear in Machinery, part 2, *ASME, New York, 1958*, pp. 5-23.
7. **Bely, V.A., Sviridenok, A., I. et al.**, 1982, *Friction and Wear in Polymer based Materials*, Pergamon Press.
8. **Bartenev, G., M., Lavrentiev, V., V.**, 1972, *Trenie i iznos polimerov*", Izd. Himia, Leningrad.
9. **Watanabe, M., Korusawa, M., Marsubara, K.,** 1968, The Frictional Properties of Nylon, *Wear 32 (3)*. pp 185-191.
10. **Lancaster J.K.**, 1972, Lubrication of Carbon Fibre reinforced Polymers, *Wear 28(3)*. pp. 315-352.
11. **Barlow D.A**., 1972, Some Observations of the Friction Properties of Vinyl, *Wear 20(2)*, pp.151-157.
12. **West G.H., Senior J.M.**, 1973, Frictional Properties of Polyethylene", *Wear 19(1)*: pp. 37-52.
13. **Bartenev, G., M., Lavrentiev, V., V., Konstantinova, N., A.,** 1971, The actual Area and friction Properties of Elastomers under Frictional Contact with Solid Surfaces, *Wear 18(6)*: pp. 439-448.
14. **Bowden, F., P., Tabor, D.,** 1964, The Friction and Lubrication of Solids, part I-II, Clarendon Press, Oxford.
15. **Jost, H.,** 1970, Zum Verschleissverhalten von Polyamid, *Plaste und Kautschuk 17(4),* pp. 266-270.
16. **Lancaster, J., K., Evans, D., C.,** 1979, Wear of Polymers in *Treatise on Mat. Sci. And Technology*". Academic Press, pp. 13-86.

Mechanical Testing and Diagnosis, ISSN 2247 – 9635, 2013 (III), Volume 3, 15-39

17. **Shen, C., Dumbleton, J., H.**, 1978, The Friction and Wear Behavior of Polyoximethylene in Convection with Joint Replacement, *Wear 38(2)*, pp. 291-303.
18. **Myshkin, N., K., Petrokovets, M., I., Kovale, A., V.**, 2005, Tribology of polymers: Adhesion, friction, wear, and mass-transfer", *Tribology International 38,* pp. 910-921.
19. **Briscoe, B., J.**, 1986, Friction and Wear of Polymer Composites, Elsevier, Amsterdam, p. 25.
20. **Johnson, K., L., Kendall, K., Roberts, A.,D.**, 1971, Surface energy and the contact of elastic solids, *Proc. Roy. Soc.* A 324, p. 301.
21. **Johnson, K., L.**, 1987, Contacts Mechanics", Cambridge Uni versity Press, Cambridge, p. 468.
22. **Deryagin, B., V., Muller, V., M., Toporov, Yu., P.,** 1975, Adhesive contact deformation of a single microelastic sphere, *J. Colloid Interface Sci. 53*, pp. 314.
23. **Jonson, K., L., Greenwood, J., A.,** 1997, An adhesion map for the contact of elastic spheres, *J. Colloid Interf. Sci. 192*, p. 326.
24. **Chang, L., Friedrich K.,** 2010, Enhancement effect of nanoparticles on the sliding wear of the sliding wear of short fiber-reinforced polymer composites: A critical discussion of wear mechanisms, *Tribology International* **43**, pp. 2355-2364.
[25] **Hager, A., M., Davies, M.,** 1993, Advances in Composites Tribology: Short-fiber reinforced, high-temperatur eresistant polymers for a wide field of tribological applicants, Elsevier Science Publishers, BV, pp. 104-157.
[26] **Voss, H., Friedrich, K.,** 1987, On the wear behavior ofshort-fiber-reinforced PEEK composites, *Wear* **116**, pp. 1-18.
[27] **Tewari, U., S., Bijwe, J.,** 1993, Advances in Composites Tribology, Recent development in tribology of fiber reinforced composites with thermoplastic and thermosetting matrices, Elsevier Science Publishers, BV, pp. 159-207.
[28] **Chang, L., Zhang, Z.,** 2006, Tribological properties of epoxy-nanocomposites: 2. A combinative effect of short car -bon fiber and nano-TiO_2, *Wear* **206**, pp. 869-878.
[29] **Chang, L., Zhang, Z., Zhang, H. Schlarb, A., K.,** 2006, On the Sliding wear of nanoparticles filled polyamide 66, *Composites Science and Technology* **66**, pp. 3188-3198.
[30] **Kukureka, S., N., Hooke, C., J., Rao, M., Liao, P., Chen, Y., K.,** 1999, The effect of fibre reinforcement on the friction and wear of polyamide 66 under dry rolling-sliding contact. *Tribology International* **32**, pp. 107-116.
[31] **Wang, J., Bai, Songhao, M., G., Shirong, G.,** 2003, Investigation of the influence of MoS_2 filler on the tribological properties of carbon fiber reinforced nylon 1010 composites. *Wear* **255**, pp. 774-779.
[32] **Bahadur, S.,** The development of transfer layers and their role in polymer tribology. *Wear* **245** (2000) 92-99.
[33] **Guo, Q., B., Rong, M., Z., Jia, G., L., Lau, K., T., Zang, M., Q.,** 2009, Sliding wear performance of nano SiO_2 / short carbon fibre / epoxy hybrid composites. *Wear,* 266, pp. 658-665.
[34] **Schwartz, C., J., Bahadur, S.,** 2003, The role of deformability, filler-polymer bonding and counterface material on the tribological behaviour of polyphenyl sulfide (PPS). *Wear,* **251**, pp. 1532-1540.
[35] **Zhong, C. Li, Z., Lin, Y., Frederich K.,** 2007, Tribological properties of epoxy nanocomposites: III. Characteristics of transfer films, *Wear* **262,** pp. 799-706.
[36] **Davyer-Joice, R., S., Ioannides Sayles E.,** 1994, An investigation into the mechanisms of closed three-body abrasive wear. *Wear* **175,** pp. 133-142.
[37] **Stachowiak, G., B., Stachowiak G.,W.,** 2001, The effects of particle characteristics on three-body abrasive wear, *Wear* **249,** pp. 201-207.
[38] **Capitanu, L., Iarovici, A., Onisoru, J.,** 2003, On polyamide and polycarbonate materials behaviour under dry friction, *The Annals of University "Dunarea de Jos" Galati*, fascicle VIII, Tribology.
[39] **Capitanu, L., Florescu, V.,** 2013, Tribological aspects of wear of polished steel surfaces in dry friction contact on polymer composites with glass fibres, *American Jounal of Materials Science* 3(1), pp. 8-18. DOI 10.5923/j.materials.20130301.02.
[40] **Viers, D., Brendt,** 1999, *Polymer Data Handbook*. Oxford University Press, Inc. p. 189. ISBN 978-0195107890
[41] *** Material Selection Guide, 1.888.CURBELL, www.curbellplastics.com
[42] *** Lexan, Polycarbonate Resin, General Electric Data Sheet, www.vistatek.com