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WEAR OF POLISHED STEEL SURFACES IN DRY FRICTION LINEAR CONTACT ON POLIMER COMPOSITES WITH GLASS FIBRES

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Abstract: *It is generally known that the friction and wear between polymers and polished steel surfaces has a special character, the behaviour to friction and wear of a certain polymer might not be valid for a different polymer, moreover in dry friction conditions. In this paper, we study the reaction to wear of certain polymers with short glass fibres on different steel surfaces, considering the linear friction contact, observing the friction influence over the metallic surfaces wear. The paper includes also its analysis over the steel's wear from different points of view: the reinforcement content influence and tribological parameters (load, contact pressure, sliding speed, contact temperature, etc.). Thus, we present our findings related to the fact that the abrasive component of the friction force is more significant than the adhesive component, which generally is specific to the polymers' friction. Our detections also state that, in the case of the polyamide with 30% glass fibres, the steel surface linear wear rate order are of* 10^{-4} *mm/h, respectively the order of volumetric wear rate is of* 10^{-6} cm^3 */h. The resulting volumetric wear coefficients are of the order (*10^{-11} *–* 10^{-12}*)* cm^3*/cm and respectively linear wear coefficients of* 10^{-9} *mm/cm.*

Keywords: *wear, composite thermoplastics, comparative wearing coefficient.*

1. INTRODUCTION

The tribological behaviour of polymers has distinctive characteristics, some of them being described by Bowden and Tabor [1]. The main concept related to the polymers' tribology is composed of three basic elements involved in friction: (i) junctions adhesion, their type and resistance; (ii) materials' shearing and fracture through friction during the contact; and (iii) the real contact area.

Friction's straining component results from the polymer's resistance to "ploughing" made by the asperities existing on the harder counter-face. The polymer's surface asperities bear elastic, plastic and viscous-elastic strains, according to the material's properties. Friction adhesion component comes out of the adhesion junctions formed on the real contact spots between the paired surfaces. Friction adhesion component in what the polymers are concerned is considered to be much greater than the straining component. Special attention should be granted to the transfer films, these transfer films being the key factors determining the tribological behaviour of polymers and polymeric composites. In what the glass fibers reinforced polymer is concerned, we also encounter a strong abrasive component [2].

Several models were developed to describe the contact adhesion. The Johnson-Kendall-Roberts (JKR) model, mentioned sometimes as the contact mechanics model [3-4] and the Derjaguin-Muller-Toporov (DMT) model [5] are the best known. The models' comparative analysis [6] shows that the JKR model is applied to bodies with micrometric dimensions and larger than that, with polymer properties, whilst the DMT model is valid for bodies with nanometer dimensions, with metal properties.

Several authors [7-17] studied the polymers' friction on hard surfaces. By using the method of contact's conformity [18] they obtain the hardness, the deformability value (index) (which describes the coarse surfaces' deformation properties), as well as the elasticity module for organic polymers polymethylmethacrylate – PMMA; polystyrene – PS; polycarbonate – PC, ultra high molecular weight polyethylene – UHMWPE. We also describe the dependence of the imposed penetration depth, the maximum load and the straining speed, the hardness and the elastic modulus [18-22]. The typical penetrating depths are included within the approximate 10 nm to 10 μm range, whilst the applied loads are smaller than 300 mN.

We can observe the fact that almost without exception, the ploughing is accompanied by adhesion and in certain conditions it may lead to micro-cutting, which represents a supplementary adding to increase the friction force.

There are other mechanisms to dissipate the energy while straining. For instance, whenever a polymer with viscous-elastic reaction slides on a hard surface, the energy dissipation is caused by the high losses through hysteresis. This straining component is known under the name of friction due to elastic hysteresis [1]. The energy can, as well, be transported further, for instance through elastic waves generated at the interface and coming out at infinit, as, a nucleation and micro-cracks development within the material, consequence [20].

The mechanical component consists in the resistance of the softer material to harder asperities' ploughing. The adhesion component comes of the adhesion links formed between the surfaces during the friction contact. We believe that for polymers the adhesion molecular component exceeds by far the mechanical one [20], and we can explain it through the generated films' transfer on the metal counter-face. The following factors considerably affect the friction force: the contact load, sliding speed and temperature. The effects are not independent. For instance, according to the contact load and contact speed, the temperature may considerably vary, changing the friction mode [21].

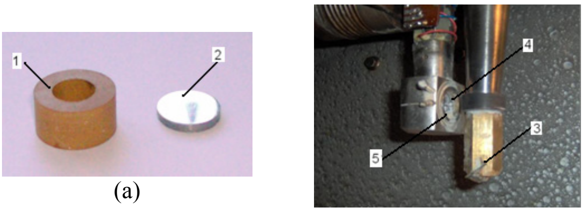
2. MATERIALS AND METHODS

In order to study the metallic counter-part's wear in dry contact with glass fibres reinforced plastic materials we use Timken type friction couples (with linear contact), cylinder on plan, which allows us to attain high contact pressures, hence high contact temperatures. In this manner we notice, whether and in which conditions the plastic material transfer on the metallic surface appears, as well as the influence of the glass fibres filling during this phenomenon, and its effect on the surface's wear. As we do not follow the polymer's wear, but only the polymer's friction influence, over the samples' metallic surfaces wear, we use the unidirectional sliding movement.

We perform the tests using experimental equipment containing a Timken type linear contact friction couple, continuously controlling the normal and friction loads, and contact temperature. The unidirectional movement and the linear contact allow us to attain very high contact pressures and temperatures. We build the friction couple out of a plastic cylinder Nylonplast AVE polyamide + 30% glass fibres, which rotates at different speeds against the polished surface of a steel plan disk. The cylinder has an outer diameter of 22.5 mm and 10 mm height.

We choose as sample steel disks with 18.2 mm diameter and 3 mm thickness. We polish the disks' surfaces successively using sandpaper of different granulations (200, 400, 600 and 800) and, finally, we polish them on the felt with diamond paste. We obtain mirror polished surfaces, with roughness R_a of 0.05 μm. This metal surface's quality allows us to eliminate the influence of the metallic surface's state on the friction coefficient's evolution and visualization, to make measurements using optical microscopy and to accurately record the wear traces appeared on the metallic surfaces.

Fig.1 shows the friction couple (a) and its installation within the experimental equipment (b).



(a) (b)

Figure 1. Friction couple (a) and its installation in the experimental equipment (b), where 1 - cylindrical liner; 2 – steel disk sample; 3 – nut; 4 – hole; 5 - knife-edge.

The friction couple is build out of a cylindrical liner (1) and a plane disk type sample (2). The liner is fixed with the help of a nut (3) on the driving shaft (4), and the disk sample is placed in a special hole made within the elastic blade (5). We build the sample disk base in such a manner so that the base allows the sample to make small rotations around the edge of a knife fixed in the sample's bezel, perpendicularly on the driving arbour. In this way we ensure a uniform repartition of the load on the entire linear contact between the liner and steel sample, even if there are small building or assembling imperfections. An electric engine puts the shaft into a rotation movement using trapezoidal transmission belts.

The experimental device allows us to simultaneously measure the normal and tangential (friction) efforts through resistive converter strain-gauges, assembled on the elastic blade (5). The use of a pair of converters strain-gauges connected within the circuits of two strain-gauges bridges, offers us the possibility to make simultaneous measurements, while separately, gives us the possibility to measure the normal and friction forces. We apply the normal load to the elastic blade, through a calibrated spring system. The installation allows us to register the friction force on an X-Y recorder. We control the tests' duration through an alarm clock and we measure the contact temperature with the help of a miniature thermocouple, connected to a millivoltmeter calibrated in ^{0}C.

I used the uni-directional testing because the purpose of investigations was the study of metallic surface wear. We perform the tests, based on Hooke's law, at normal loadings of 10; 20; 30; 40 and 50 N, loadings which are adequate to some contact pressures all calculated considering the elastic contact hypothesis, that is: 16.3; 23.5; 28.2; 32.6 and 36.4 MPa (for Nylonplast AVE polyamide with 30% glass fibres) respectively, we use sliding speeds, adequate to the diameter of the plastic composite sample, which are: 0.1856; 0.2785; 0.3713; 0.4641; 0.5570; 1.114 and 1.5357 m/s, and which resulted as a consequence of electric motor's speed and the belt pulleys' primitive diameters.

As we know [21], we may characterize a material's wearing coefficient (percentage) by wearing factor k. Archard's relation defines this factor:

$$V_u = kNvt \tag{1}$$

where: V_u – the wear's material volume; N - the test load; v - the sliding speed; t - the test period; k – volumetric wearing factor.

By dividing both of this relation's terms (4) by nominal contact area A, we obtain:

$$V_u / A = kNvt / A \tag{2}$$

Which means that:

$$h_u = k^* pvt \tag{3}$$

where: h_u - wear's material depth; p - the pressure on the nominal contact area and k^* is the linear wearing factor. Relation (6) expresses a general law of the wear as a function of the contact pressure p and the length of the wearing path, so that $L_f = vt$.

We could then write:

$$k = V_u / Nvt = V_u / NL_f \tag{4}$$

respectively:

$$k^* = h_u / pvt = h_u / pL_f \tag{5}$$

Considering the large area of the load (N) or pressure (p) and the relative speed values used during tests in order to evaluate the wearing reaction of the metallic counter-pieces amid the frictional couples, we use comparative wear coefficients K and K^*, defined by:

$$K = V_u / L_f = kN \ (\text{cm}^3 / \text{cm}) \tag{6}$$

and:

$$K^* = h_u / L_f = k^* p \ (\text{cm} / \text{cm}) \tag{7}$$

We consider these wearing coefficients with respect to the period in which the frictional couple functions at different sliding speeds, under certain loading conditions (contact pressure).

The main objectives of these tests are the determination of the volume of material removed by wearing, the mean depth of the wearied layers, the frictional factors and coefficients, for different loading conditions.

Coefficients k and k^* are coefficients of the wear process, while the comparative factors K and K^* are coefficients of this process's consequences, that is, the amount of resulted wear and reported to the length of the friction pathway. They can be qualitatively expressed in units of wear volume on a measure of the length of the friction pathway (cm^3 / cm), as wear's depth on a measure of the length of the friction pathway (cm / cm) or as wear's weight on a measure of the length of the sliding friction pathway (mg / cm). Coefficients K and K^* have no mathematical implication (can not simplify).

Using the procedure described in [22], at the end we obtain the mean depth (8) and the volume of worn metallic material (9):

$$h = \left(l^2 / 8r_1\right) - 0{,}527N\left(E_1 + E_2\right)LE_1E_2 \tag{8}$$

and:

$$V_u = \sum_{i=1}^{n}\left(S_i q_i\right) = 0.351\left(E_1 + E_2\right)Nl_m / E_1E_2 \tag{9}$$

where l_m is the mean width of the wear imprint.

Practically, we have to measure the width of wear imprints in three points established before, computing then the mean value of this width. With this value we can obtain the volume of worn metallic material V_u and the removed layer's mean depth h_{mu}.

We study the wearing of the friction couple's metallic component on linear contact Timken machinery, see Fig. 1. Almost all tests are made without lubricating the frictional surfaces, but there are also tests with micro-lubricating.

In order to calculate the metallic component's wear, we use the method described above. The equations (8) and (9) take into consideration, for the studied materials, particular forms obtained by introducing the interfering parameters numerical values, thus obtaining for a mean depth h_{mu} and a worn material volume V_u the following relations:

- Nylonplast AVE polyamide + 30% glass fibres / steel:

$$h_{mu} = l_m^2 8r_1 - 6.94 \cdot 10^{-5} N \text{ (mm)} \tag{10}$$

$$V_u = 4.55 \cdot 10^{-4} N l_m \text{(mm}^3\text{)} \tag{11}$$

The studies concerning the metallic semi-couple wear are generally based on the elastic contact hypothesis. For these plane half-couple the values for the equivalent elasticity module for Nylonplast AVE polyamide + 30% glass fibres, E = 20.25 MPa. Assuming that the plastic liner does not crush, we impose the condition p_{max} < □0.5H, where H stands for the Brinell hardness. The required condition allows us to establish the following values of the maximum loadings (contact pressure) of the couple:

p_1 = 16.3 MPa; p_2 = 23.5 MPa; p_3 = 28.2 MPa;
p_4 = 32.6 MPa; p_5 = 36.4 Mpa.

We perform the experimental tests considering broader domains to vary the relative speed and normal loadings, or contact pressures. We use couples with liner made from thermoplastic material with linear contact on a steel surface (C120, Rp3, a.s.o.).

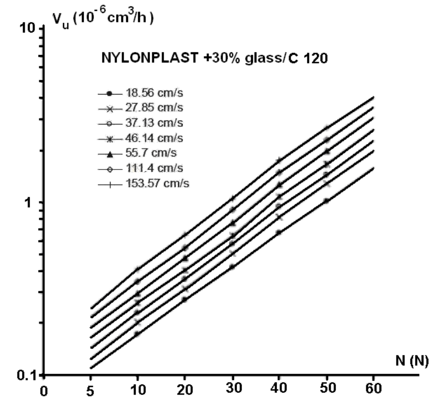
3. RESULTS

Table 1 is the representation of the experimental tests results, testing two friction couples, for one of the 8 different relative sliding speeds used. Table 1 represents the results of the tribological experimental tests, e.g. the mean values of the wear imprint depth h_u (10^{-4} mm), and the average values of the worn material volume V_u (10^{-6} cm^3). The average width l_m represents the arithmetical average calculated based upon 3 measured values of the wear trace's width. By dividing h_u and V_u to the duration of experimental test, we obtain the values of the wear rate in terms of depth h_{mu}(10^{-4} mm/h) and volume V_{mu}(10^{-6} cm^3/h).

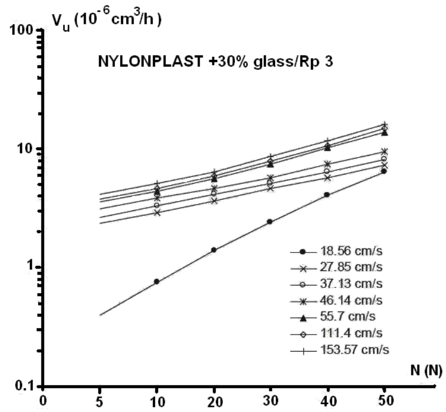
Based upon the methodology described above, we process the results obtaining the variation curves of the wear with normal loading and relative speed, presented in Fig. 2 (a) and (b), for two of the tested couples, Nyloplast AVE Polyamide + 30% glass fibres / C120 steel, and respectively Nyloplast AVE Polyamide + 30% glass fibres / Rp 3 steel.

Table 1. The results of the experimental tests performed in order to determine the wear rate of metallic component. Frictional couple: Polyamide Nylonplast AVE +30% glass fibres / C120; v = 18.56 cm/s.

N (N))	t (hour)	Average wear rate	
		h_{mu} (10^{-4} mm/h)	V_{mu} (10^{-6} cm^3 /h)
10	1		
10	1	0.9649	0.1387
20	1		
20	1	2.4798	0.4404
30	1		
30	1	4.0336	0.8381
40	1		
40	1	5.4874	1.3086
50	1		
50	1	7,1635	1.8667



(a)



(b)

Figure 2. The results of variation curves of the wear volume with normal loading and relative speed, for tested couples (a) Nyloplast AVE Polyamide + 30% glass fibres/ C120 steel and (b) Nyloplast AVE Polyamide + 30% glass fibres/ Rp 3 steel. Measurement errors were ±1.5 %.

These curves characterize only the tested frictional couples (one combination of materials). Furthermore, we can make the comparative evaluation of different couples only qualitatively.

Thus, using relations (8) and (9) we obtain the variation curves of the "comparative wear coefficients" (as volume and depth), K (cm^3 / cm) and K^* (mm / cm). These master-curves are plotted in Fig. 3 and Fig. 4 representing the two tested and taken into discussion couples, for different normal loading values.

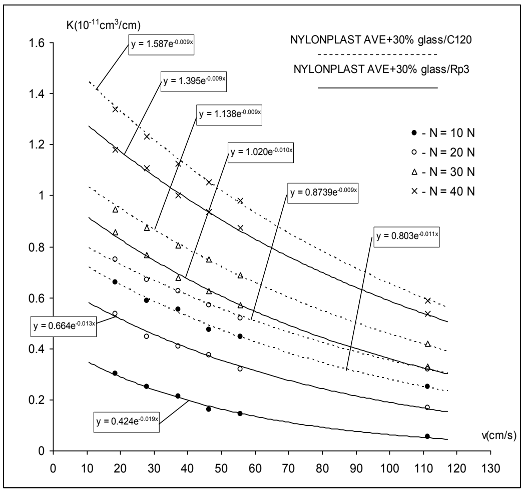


Figure 3. The variation curves of the volumetric comparative wear coefficients K (cm^3 / cm).

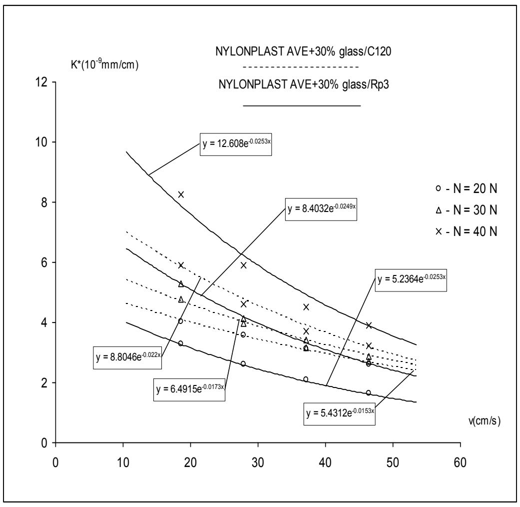


Figure 4 The variation curves of the linear comparative wear coefficients K^*(mm / cm).

In Table 2 are listed the equations for the comparative wear coefficients (the volumetric and the depth ones), for C120 and in Table 3. for Rp3 steel.

Table 2. The variation curve of compatative wear corfficient equations for Nylonplast AVE Polyamide + 30% glass fibres/C120

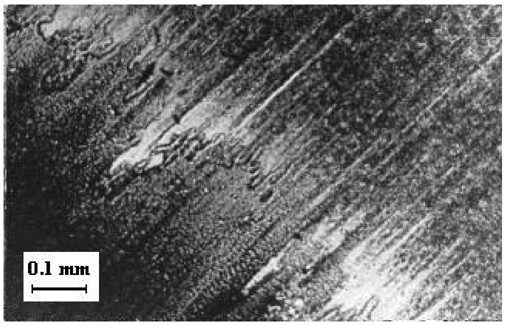
Load (N)	K	K^*
10	$K = 0.8030\ e^{-0,0110\ v}$	
20	$K = 0,8739\ e^{-0,0090\ v}$	$K^* = 5,4312\ e^{-0,0153\ v}$
30	$K = 1.1380\ e^{-0,0090\ v}$	$K^* = 6,4915\ e^{-0,0173\ v}$
40	$K = 1.5870\ e^{-0,0090\ v}$	$K^* = 8,8046\ e^{-0,0200\ v}$

Table 3. The variation curve of compatative wear corfficient equations for Nylonplast AVE Polyamide + 30% glass fibres / Rp3

Load (N)	K	K^*
10	$K = 0.4240\ e^{-0,0190v}$	
20	$K = 0,6640\ e^{-0,0130\ v}$	$K^* = 5,2346\ e^{-0,0253\ v}$
30	$K = 1.0200\ e^{-0,0100\ v}$	$K^* = 8,4032\ e^{-0,0249\ v}$
40	$K = 1.3950\ e^{-0,0090\ v}$	$K^* = 12,6080\ e^{-0,0253\ v}$

While measuring the wear traces widths with the help of optical microscopy, we also take microphotographs, in order to identify the plastic material's transfer and the metallic surfaces' wear mechanisms. These microphotographs prove that the wear mechanisms vary from one couple to another, due to surfaces' nature: metallic and composite plastic material, especially their hardness (59 HRC for C120 hardened steel and 62 HRC for Rp3 hardened steel), the glass fibres content, 30% and 20%, the composite plastic materials' elasto-plastic characteristics while in contact with metallic surfaces. he glass-fibres torn from the polymer matrix.

(a)

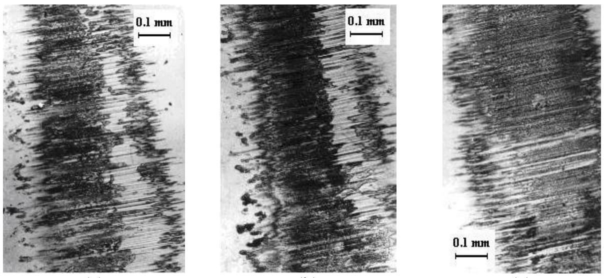


(b)

Figure 5. Wear and plastic material transfer on C120 steel surface, following the friction with Nylonplast AVE polyamide reinforced with 30% fine glass fibres (a), in experimental conditions: v = 27,85 cm/s; N =20 N; T = 150 ^{0}C; t = 60 min and (b) in experimental conditions v = 27,85 cm/s; N =30 N; T = 175 ^{0}C; t = 60 min.

Considering the same loading conditions, the two couples to which we make reference have a different behaviour. On C120 steel sample (Fig. 5), at a normal load of 20 N and a contact temperature of 150 ^{0}C, there are plastic material transfer bridges, broadways on the wear traces (Fig. 5a), as well as the glass-fibres torn from the polymer matrix. At 175 ^{0}C contact temperature, corresponding to a normal load of 30 N and a contact pressure of 2879.5 MPa, the plastic material transfer on the wear trace's edge is obvious (Fig. 5b), leaving the impression that the plastic matrix melts and drips off on the wear trace's exit edge.

Considering the same mechanical stress conditions (load and relative speed), the microscopic inspection of the Rp3 steel samples, while in friction contact, with the same composite plastic material, reveals a less pronounced plastic material transfer through adherence onto the metallic surface, visible on the left side in Figs 6 (a) and 6 (b), and if the test duration is double (120 min), practically there is no plastic material transfer as one can see in Fig 6 (c).



(a)	(b)	(c)
v= 27,85 cm/s; N = 40 N; t = 60 min; T=217 ^{0}C	v = 27,85 cm/s N = 30 N; t = 120 min; T= 175 ^{0}C	v = 27,85 cm/s; N = 40 N; t = 120 min; T =237 ^{0}C

Figure 6. Wear and plastic material transfer on Rp3 steel surface, following the friction with Nylonplast AVE polyamide reinforced with 30% short glass fibres.

We consider that due to high registered contact temperature (237 ^{0}C) the transfer takes place for sure, but the transferred material is subsequently removed through friction from the contact area, under the form of wear particles following the glass fibres abrasive action. After this stage, the abrasive wear due to glass fibres becomes predominant.

It is possible that the less pronounced plastic material transfer emphasized on the Rp3 steel surfaces to be due to this steel's chemical composition and structure.

We detect the same findings in the case of Noryl polyamide +20% glass fibres in friction on the same steels, but to a lesser scale. In the case of Lexan 3412 polycarbonate reinforced with 20% glass fibres friction onto the same metallic surfaces and considering the same stress conditions, generally speaking there is no plastic material transfer. The transfer appears only if the load reaches 40 N, which corresponds to a contact pressure of 3449.7 MPa, and when the contact temperature reaches 251 ^{0}C. We do consider that probably the polycarbonate has a lesser transfer capacity than the polyamide.

4. DISCUSSION

The wear's rate values, considering the used experimental conditions, cover a large range. For greater clarity, they are presented in Table 4.

Comparing the metallic element's wear rates values at v = 46.41 cm/s and N = 40 N, it results that the polyamide reinforced with 30% glass fibres induces to the C120 steel a wear of approximately 1.110 times more higher than to the Rp3 steel. We do estimate that this phenomenon is due to Rp3 samples' higher hardness (62 HRC), in comparison to those from C120 (59 HRC).

Table 4. The variation curve of compatative wear corfficient equations for Nylonplast AVE Polyamide + 30% glass fibres/Rp3

Friction couple	Volumetric wear rate (10^{-6} cm^3/h)	Linear wear rate (10^{-4} mm/h)
v = (18.56 - 46.41) cm/s; N = 10 – 50 N		
Polyamide + 30% glass fibres/ C120	0.139 – 1.621	0.965 – 8.549
Polyamide + 30% glass fibres / Rp 3	0.214 – 1.369	2.382 – 6.004
Polycarbonate + 20% glass fibres / C120	0.244 – 1.309	3.592 – 6.366
v = (46.41 - 111.4) cm/s		
Polyamide + 20% glass fibres / C120	0.440 – 2.578	3,269 – 6,794
Polyamide + 20% glass fibres / Rp 3	0,473 – 2,549	3.792 – 6.627

Normal loads and corresponding contact pressures for the linear friction contact used during this research, lead to very high contact temperatures (180-240 ^{0}C) according to the applied normal load and relative sliding speed (see also Fig. 6a).

In several cases they exceed the polymer's melting temperature, thus being transferred on the metallic surface together with glass fibres fragments. Part of the glass fibres is smashed and still produced a predominant abrasive wear of the metallic sample's contact area, while another part is pushed out on the contact's exit edge, together with a multitude of ejected glass fibres.

We notice that only in the case of the friction couple Nyloplast AVE Polyamide + 30% glass fibres / C120 steel, there is a large plastic material transfer onto the metallic surface, which justifies the assertion that the transfer through adhesion depends on the nature and characteristics of the contact materials. From a qualitative point of view, obviously there is the fact that initially the wear process manifests itself as a wear through adherence and polymer transfer onto the metallic surface, which subsequently transforms itself into a process of abrasive wear, which leads to the plastic material removal clung onto the contact area. In what the friction couples are concerned – also see Fig. 6a.

The process' intensity depends on the fibres' content. The larger it is, the higher the intensity is. Metallic surface mechanical properties (especially the hardness), has a distinct influence over the plastic material transfer and metallic surface wear.

5. CONCLUSION

The diagrams' analysis plotted in Figs. 3 and 4 allows us to establish the variation equations for the comparative volumetric wear coefficient K and for the comparative depth wear coefficient K^*, for steel in linear contact, while in friction with glass reinforced thermoplastics.

The equations listed in Table 2 and 3, for the comparative wear coefficients (the volumetric and the depth ones), show that the variation is not a linear one, these coefficients evolving exponentially. We also notice that the decrease of the K^* coefficient with the increase of relative speed is faster than the decrease of the K coefficient.

We consider that this effect is due to the fact that the thermoplastic material deforms under load which means that for Timken type couples the increase of the wear imprint width is more effective than that of the depth of the wear imprint. From the diagrams plotted here, one can notice that the values of wear coefficients for the metallic component of the couple glass reinforced thermoplastic/steel are in the domain $(10^{-11} \div 10^{-12})$ cm^3/cm and respectively 10^{-9} mm/cm. The comparative wearing coefficients and their master-curves vs. relative speed have a special importance from the practical point of view. Based on these findings we can establish an optimal couple of materials from the design phase.

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