A point of view about dry linear contact between glass fiber reinforced thermoplastic polymers materials on steel

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Abstract: In this paper we show, both analytically and graphically, the evolution fo wear occurring on the steel surface in contact with glass fiber-reinforced polymers. The evolution in time of this process depends on the evolution of the friction coefficient in the process of the dry linear contact between polymers and different types of steels. We have made a connection between the theoretical case and the experimental results. The experimental method used was the “wear imprint method” through which the wear depth and wear volume were determined. The wear process is complex and is accompanied by adhesion and corrosion phenomena. Any modification of the input parameters such as speed, temperature, load, quantity of glass fibers in the polymer lead to a change in the evolution of the wear behaviour of the composite material.

Keywords: Friction coefficient evolution, contact temperature, wear of the steel surface, influence of steel surface hardness.

1. INTRODUCTION

Thermoplastic materials with glass fibers structurally present a mechanical association of glass and polymer fibers. Basic polymer acts as a bridge between the reinforcement glass fibers. The role of the basic polymer is first of all mechanical and is to provide the bond with the reinforcement fibers. One of the most sophisticated tribosystems is the one between a polymer with short fibers (SGF) on steel, where the contact is dry. Thermoplastic composite materials with glass fiber are characterized by high plasticity under high pressure and temperature. It is necessary to ensure a minimum adhesion between these two phases. In specialist papers, values are given for the friction coefficient for different couples, plastic material/plastic material, plastic material/metal corroize. The basic polymer ensures the tightness against humidity, because most of the reinforcement fibers have a high affinity for water. In this case, the input parameters are permanently modified. Thermoplastic polymers does not allow a big deformation, limiting the significant deformation of the composite material. These thermoplastic materials are biphasic, consisting of a polymer mass and reinforcement materials such as glass fibers. The evolution of wear was highlighted depending on the duration, the load, contact pressure and sliding speed. It is good to use alkali-free glass fibers for a slow degradation in time and oxides can be added to maintain the high values of the elasticity module. Based on comprehensive experimental tests, a study for the evolution of wear for a certain duration, as well as for certain loads and contact temperatures. The values are given for couples with lubricant or with dry contact. The couples are formed from reinforced composite materials or composite materials without reinforcement. The materials used were composite thermoplastic materials reinforced with glass fiber. Thermoplastic materials can be machined so that they return to their initial shape after being cast, in order to obtain good mechanical characteristics as a result of the fact the stresses are transmitted through the glass fibers. Starting from an extended study, we have tried to come up with a graphical representation of the wear process for a dry contact between polymers reinforced with glass fibers and C120 steel, respectively Rp3 steel. For experimental tests, Archard’s relationship for adhesion wear was used and also a analytical method. In our paper we have studied on Timken type couples (with linear contact), in conditions of dry sliding friction. We have studied the influence of the percentage of glass fiber, as well as the influence of load and speed on the wear process. In specialist literature there is a heterogeneous approach, because different test installations, different experimental conditions and different materials are used.

Stachowiak, et all [1] have studied the abrasive effect for the three body abrasion of metal samples, the tests were carried out on two ball-on-flat installations and modified pin-on-disk tribometer. The ball-on-flat testes yielded the most significant results.

Dwyer-Joyce [2] has noticed that during contact the wear due to contamination with solid compounds of lubricants occurs, the phenomenon closely resembling the abrasion with three bodies.

Shen and Dumbleton [3] have studied comparatively the tribological behaviour of the polyoxymethylene and of the high density polyethylene (UHMWPE). They suggest a
relationship for the calculation of the wear as follows:

Where: \( h \) – linear wear; \( k \) - wear factor; \( p \) - nominal pressure; \( x \) - sliding distance.

Kukureka, et all [4] have studied the wear of PA66 in rolling-sliding contact. For the polymer they added glass, carbon or aramid, and both for the glass fibers and for the carbon fibers a drop in the friction coefficient was noticed.

Bartenev, Lavrentiev [5] establish that for the metal/plastic contact, the increase of the friction force is proportional to the sliding speed. This dependency is shown through the increase of the friction force together with the normal load. This was also demonstrated by Vinogradov.

Chang and Friedrich [6] have noticed that the particles, respectively the nanoparticles do not entirely contribute to the film transfer, thus reducing the adhesion and, as a consequence, also reducing the friction coefficient.

Jacobi [7] presents friction coefficient values between 0.04 and 0.5 for glass fiber reinforced polyamides.

Guo, et all [8] have used in their studies composites based on epoxy pitches filled with hybrid particles nano-SiO2 and short pitches based on carbon fiber. A reduction of the friction coefficient was noticed in the case of hybrid polymers as compared to polymers with added nano-SiO2 particles.

Barlow [9] shows that, for lubricated surfaces, an increase of the friction coefficient occurs with the increase of the relative sliding speed at the level of the friction surface.

Chang et all [10] studies the properties of composite materials, respectively the properties of polyetheretherketone (PEEK) and polyetherimide (PEI), reinforced with short carbon fibers (CSF). They have determined that by adding submicron particles (TiO2 and ZnS), for the high contact temperature of the pin-on-disk type tribometer, the wear rate has decreased.

L. Capitanu et all [11][12] have highlighted the behaviour of polyamide and polycarbonate reinforced with glass fibers (SGF) in friction on steel surfaces.

U.S. Tewari, J. Bijwe [13] have highlighted the low manufacturing costs achieved through a composite polymer injection. [14] L. Chang, Z. Zhang show that the injection machines suffer from considerable wear due to the glass fibers.

Lancaster and Evans [15] have studied the tribological behaviour of glass fiber reinforced composite polymers, hydro dynamically lubricated, and notice the decrease of vd3/N for beak type couplings.

Schwartz and Bahadur [16] have studied the transfer of the material film using infrared technology. They have observed the following phenomenon, an increase in the density of the polymer leads to an increase in the cohesion energy.

Clerico [17] has discovered that for the polyamide/metal couple the value of the friction coefficient is higher for short periods of operation than for longer periods of operation, due to the viscoelastic behaviour of the composite material.

Vos, et all [18][19] have studied polyetheretherketone composites reinforced with short glass fibers and carbon fibers and have shown that the wear rate is influenced by the morphological structure of the matrix of the composite polymer.

Lancaster [20] has studied different natural glass fiber reinforced polymers. He has shown that the friction coefficient decreases with the decrease in the ruggedness of the metal surface. Jost [21] shows that for polyamide/metal couples the most encountered type of wear is adhesion wear.

Derjaguin-Muller-Toporov [22] (DMT) model. This model is correct for nanometrically sized bodies, with steel characteristics. The main characteristic of short fiber reinforced polymers (SFRP) is their high level of resistance to rapid loads. This occurs at a relatively low price compared to other materials.

Watanabe et al [33] shows the influence of the friction coefficient depending on the temperature and the transfer of the plastic material unto steel.

Li, et all [34] have studied analytically and experimentally the epoxide nano-composites, reinforced with short carbon fibers (SCF), of the nano-TiO2 particles, of the powder of polytetrafluorethylene (PTFE) and graphite flakes, in order to understand the mechanism for adding filler to modify...
the wear parameters of the two epoxide nano-composites on metal counterpieces.

Myshkin [35] mentions that, at the surface of the composite material, the links are viscous-elastic and that the abrasive friction component is higher than the adhesive friction component.

Bilik [36] has shown that, for the couple polyamides/steel, the friction coefficient is not constant. The coefficient depends on several factors: temperature, the ruggedness of the surface, the sliding speed and the contact pressure.

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2. MATERIALS AND METHODS

Wear and friction are analysed from several points of view, such as speed relative to load and stress. The two samples are cylindrical liner and flat sample[37].

2.1 ANALYTICAL METHOD

The functioning under load of the Timken type friction couple (with linear contact) subjected to a load and in the presence of a relative sliding movement of the bushing made of glass fiber reinforced plastic on the surface of the steel sample highlights the occurrence of a wear imprint on the plane metal surface, the imprint being graphically represented in (Figure 1)

\[ F_f = a + bN^n \]  (3) \[ F_f = kN^n \]  (4)

Where \( n \) is sub unitary.

We express the friction coefficient for the plastic materials:

\[ \mu = \frac{\tau_f}{p_c} \]  (5)

Where \( \tau_f \) represents the shear strength of the softer material \( p_c \) represents the flow pressure of the same material.

Because \( p_c = \frac{HB}{3} \), we have:

\[ \mu = 3\frac{\tau_f}{HB} \]  (6)

The bush is rigid and accounting for the generally low non-uniformity of the imprint, considered as being formed by a series of cylindrical sectors having the length \( q \). The area of the lateral surface of the cylindrical sector is a circle segment:

\[ S_i = 0.5r^2\left(\pi\varphi_i^0/180^\circ - \sin \varphi_i\right) \]  (8)

Where \( S_i \) – lateral surface of the crystal sector;

\( \varphi_i \) - the angle;

\( r \) - the circle radius.

The radius \( r \) could not be identified with the cylindrical bush radius for the plastic / metal couples.

It is possible due to the elastic deformation of the bush under loading conditions and we illustrated this by the sketch in (Figure 2)

\[ S_i = 0.5r^2\left(\pi\varphi_i^0/180^\circ - \sin \varphi_i\right) \]  (8)

Figure 1 The imprint scheme for Timken friction couples

Knowing Coulomb’s law that the friction force \( F_f \) is direct proportional to the normal force \( N \):

\[ F_f = a + bN \]  (2)

More studies have shown that \( \mu \), the friction coefficient is not only dependent on the normal load applied. Relations for variations of the friction force, depending on the load applied:

\[ F_f = a + bN^n \]  (1)

Using \( r_1 \) for the non-deformable liner radius and \( r_2 \) for the radius – in the contact area – of the deformed liner, we see in (Figure 2b):

\[ r_2 > r_1 \]  (9)

Increasing the bush radius in the contact area leads to the decrease of the depth of the wear imprint from \( h_1 \) -
which would appear if the elastic deformation of the bush would be neglected, to the value \( h \) with the quantity \( h_2 \):

\[
h_2 = h_1 - h
\]

(10)

Using \( l \) for the width of the wear imprint, from \( \Delta ABC \) it is:

\[
(2r_1 - h_1)h_1 = l^2 / 4
\]

(11)

Because the value of the depth \( h_1 \) is very small, the term is negligible, we write:

\[
h_1 = l^2 / 8r_1
\]

(12)

Similarly, in \( \Delta FGH \), we have:

\[
(2r_2 - h_2)h_2 = l^2 / 4
\]

(13)

Using the same assumption, for the term \( h_2 \), we obtain:

\[
h_2 = l^2 / 8r_2
\]

(14)

Considering the frictional couple is loaded in the elastic domain with an elliptic distribution of stresses, the Hertz formula is:

\[
l^2 / 4 = 8N r (1 - v^2) / \pi EL
\]

(15)

Where:

- \( v \) - Poisson ratio
- \( l \) - the length of the wear imprint
- \( E \) - equivalent Young modulus

Using index 1 for quantities related to the cylindrical bush, and index 2 for those related to plane half-couple, the equivalent elasticity modulus is:

\[
1/E = 0.5 \left[ (1 - v_1^2) / E_1 + (1 - v_2^2) / E_2 \right]
\]

(16)

\[
E = 2E_1E_2 / 0.91(E_1 + E_2)
\]

(17)

From (17) we can express the width of the wear imprint:

\[
l = 4 \left[ 2Nr(1 - v^2) / \pi EL \right]^{1/2}
\]

(18)

Introducing in (18) the equivalent elasticity modulus and the equivalent radius expressions, the numerical value of Poisson ratio is:

\[
h = 0.527N(E_1 + E_2) / LE_1E_2
\]

(19)

Considering (12) and (11), we have for the depth of the wear imprint:

\[
h = (l^2 / 8r_1) - 0.527N(E_1 + E_2) / LE_1E_2
\]

(20)

The wear imprint is the sum of cylindrical sectors, expanding in series the relation (21), neglecting the high-order terms and reducing the similar terms, the area of the lateral surface of a sector is:

\[
S_i = r^2 \phi^3 / 12
\]

(21)

Replacing in the relation above the angle \( \phi \) with the ratio \( b / r \) and accounting for (15) and (16):

\[
S_i = l^3(r_2 - r_1) / 12r_1r_2 = 2lh_2 / 3
\]

(22)

Replacing the value of \( h_2 \) obtained (22) in (24), we obtain the expression for the area of lateral transversal surface of a cylindrical sector:

\[
S_i = 0.35l(E_1 + E_2)N_l / E_1E_2
\]

(23)

The volume of worn metal material will be:

\[
V_a = \sum_{i=1}^{n}(S_i q_i) = 0.351(E_1 + E_2)N m / E_1E_2
\]

Where \( m \) is the mean width of the wear imprint.

The wear scar volume and the wear scar depth are according to the normal load \( N \) in polynomial forms:

\[
\mu = A \ln N + B
\]

(24)

Where \( A, B \) are determined from regression functions.

From relations (13) obtain

Also, contact temperature as a function of \( \mu \) such:

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

(25)

\[
V_a = b_2 T + \left( b_1 - \frac{b_2}{a_2} a_1 \right) N + c_0 - \frac{b_2}{a_2} a_0
\]

(26)

Or after substitution of \( N \) its replacement we will have:

\[
V_a = b_2 T + \left( b_1 - \frac{b_2}{a_2} a_1 \right) e^{(B - A_t) / a_2} - \frac{b_2}{a_2} a_0
\]

(27)

In a similar fashion, the depth of the wear mark is (31)


\[ h_u = \frac{c_1}{a_2} T + \left( c_1 - \frac{c_2}{a_2} a_0 \right) N + c_0 - \frac{c_2}{a_2} a_0, \]

Or

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

(32)

Also, we can express the contact temperature as a function of \( \mu \) as follows:

\[ T = \sum_{i=0}^{2} a_i \exp \left[ \frac{\mu - B/\mu}{A} \right]. \]

(33)

\[ V_u = k N v + b_2 T + \left( b_1 - \frac{b_2}{a_2} a_0 \right) N + c_0 - \frac{b_2}{a_2} a_0. \]

(34)

Writing Archard’s relationship for the worn depth of the metal material, from relationships (31) and (32) we obtain that:

\[ h_u = k' p v + \frac{c_1}{a_2} T + \left( c_1 - \frac{c_2}{a_2} a_0 \right) N + c_0 - \frac{c_2}{a_2} a_0. \]

(35)

The relationships (33), (34), (35) show the connection between the output parameters \( V_u \), \( T \), \( \mu \) and input parameters \( N \), \( v \), \( t \) of the wear process respectively between \( h_u \), \( T \), \( \mu \) and \( p \), \( v \), \( t \). These relationships show the complexity of the wear process for metal surfaces in the case of the dry friction linear contact with the glass fibers reinforced polymers.

2.2 EXPERIMENTAL METHOD

A Timken type couple with linear friction contact was used as experimental equipment. Thus the normal load and the contact temperature can be controlled. The friction couple is built out of a plastic cylinder which revolves at different speeds. The friction couple is built out of a cylindrical liner (1) and a flat disk (2). The liner is fixed by means of a nut (3) on the driving shaft (4). The disk sample is placed in a hole made in the elastic blade (5) (Figure 3). The plastic piece rests on the polished surface of a steel plan disk. The cylinder has a diameter of 22.5 mm and a thickness of 10 mm.

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

![Figure 3](image-url)

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

3. RESULTS AND DISCUSSION

All the tests were limited to an hour. The regression functions and the regression factor were calculated for each couple. Tests were made at six sliding speeds, 18.56, 27.85, 37.13, 46.41, 55.70 and 111.4 cm/s.

Tables 1, summarize the correlation functions between the contact temperature \( T \) of the wear and normal load \( N \). It is noted, the polynomial variation of all these quantities functions of normal load.

Friction and wear processes were analyzed for a relatively wide range of tribological parameter values that affect it (load, relative speed, contact temperature). Increasing the friction coefficient increases the wear rate, but no one establish a mathematical relation between the two quantities. All presented tests lasted 1 hour, so all wear data represent the wear rate, expressed in cm³/h and mm/h. For a complete image of the wear process, on the bottom of the figures, are different curves of contact temperature and friction coefficient function on normal load.

**Table 1.**

<table>
<thead>
<tr>
<th>Friction couple</th>
<th>( v ) (cm/s)</th>
<th>Regression function</th>
<th>Correlation factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyamide and 30% glass fiber on C120 steel</td>
<td>18.56</td>
<td>( T = 0.003 N^{0.26} + 0.365 N^{2} + 15.75 N )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on C120 steel</td>
<td>27.85</td>
<td>( T = 0.0233 N^{2} + 2.9333 N + 105 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on C120 steel</td>
<td>37.13</td>
<td>( T = 0.055 N^{2} + 4.45 N + 106 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on C120 steel</td>
<td>55.70</td>
<td>( T = 0.185 N^{2} - 1.55 N + 147 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on C120 steel</td>
<td>111.4</td>
<td>( T = 0.06 N^{2} + 5.9 N + 179 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on C120 steel</td>
<td>153.57</td>
<td>( T = 0.16 N^{2} + 9.2 N + 159 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on Rp3 steel</td>
<td>18.56</td>
<td>( T = 0.1 N^{2} - 3.3 N + 127 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on Rp3 steel</td>
<td>37.13</td>
<td>( T = 0.2667 N^{2} + 20.933 N - 157 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>Polyamide and 30% glass fiber on Rp3 steel</td>
<td>46.41</td>
<td>( T = 0.28 N^{2} - 4.6 N + 136 )</td>
<td>( R^2 = 1 )</td>
</tr>
<tr>
<td>steel</td>
<td>27.8</td>
<td>T = 0.08 N(^{-2}) +7.1 N + 100</td>
<td>(R^2 = 1)</td>
</tr>
<tr>
<td>-----------------------</td>
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<td>----------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Polycarbonate and 20% glass fiber on C120 steel</td>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure.4** Wear evolution variation of contact temperature function of the normal load and friction coefficient at the sliding speed of 18.56 cm/s for Nylonplast AVE Polyamide and 30% glass fiber on C120 steel

**Figure.5** Wear evolution as variation of contact temperature function of the normal load at the sliding speed of 18.56 cm/s for Nylonplast AVE Polyamide and 30% glass fiber on Rp3 steel

**Figure.6** Wear evolution as variation of contact temperature function of the normal load at the sliding speed of 27.85 cm/s for Nylonplast AVE Polyamide and 30% glass fiber on C120 steel

**Figure.7** Wear evolution as variation of contact temperature function of the normal load at the sliding speed of 55.70 cm/s for Nylonplast AVE Polyamide and 30% glass fiber on C120 steel

**Figure.8** Wear evolution as variation of contact temperature function of the normal load at the sliding speed of 111.4 cm/s for Nylonplast AVE Polyamide and 30% glass fibers on C120 steel

**Figure.9** Wear evolution as variation of contact temperature function of the normal load at the sliding speed of 153.57 cm/s for Nylonplast AVE Polyamide and 30% glass fiber on C120 steel
Figure 10 Wear evolution as variation of contact temperature function of the normal at the sliding speed of 37.13 cm/s for Nylonplast AVE Polyamide and 30% glass fiber on Rp3 steel

Figure 11 Wear evolution as variation of contact temperature function of the normal load at the sliding speed of 46.41 cm/s for Nylonplast AVE Polyamide and 30% glass fiber on Rp3 steel

Figure 12 Wear evolution as variation of contact temperature function of the normal load at the sliding speed of 27.85 cm/s, for PC Lexan 3412 and 20% glass fiber on C120 steel

4. CONCLUSION

The complexity of processes of friction and wear in the case of dry friction contact thermoplastic polymers with SGF on steel surfaces. We 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. 13).

Fig. 13 The complexity of the evolution process of friction–wear at a linear contact polymer with glass fiber on steel

The friction and wear of metal surfaces in friction couples, in linear contact with short glass fiber reinforced thermoplastic material / steel, were influenced by the input parameters of the tribosystem (normal load, contact pressure, relative sliding speed).

From the information presented above we can draw some conclusions:

It is difficult to establish a mathematical relationship between the input and output parameters. The linear dry contact between the composite material and steel is highly complex. By changing a single input parameter, all output parameters of the systems will change.

The wear process of metal surfaces in dry friction contact against plastic materials reinforced with short glass fibers evolves over time.

The friction coefficient for the composite material and for the C 120 steel samples is higher than the one obtained at the surface of the steel samples. This is due to the differences in hardness between the two types of steel.

This phenomenon is very complex that evolves from abrasion to adhesion wear and to corrosion, simultaneously with the transfer of thermoplastic material unto the metal surface.

Presenting the evolution of the tribosystem with dry linear contact, SGF-reinforced polymer / steel is very useful for tribological research.

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