ORIGINAL PAPER

COMPARATIVE STUDY ON THE FRICTION CHARACTERISTICS OF TWO POLYMERIC MATERIALS SLIDING INTO ENVIRONMENTS DRIED OR LUBRICATED WITH OIL

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Abstract. *Thermoplastic polymeric materials used in the case of friction couplings with sliding movement such as guides, bearings, linear bearings, must have good tribological properties related to friction and wear. Indication of these characteristics is a convenient means for faster characterization of the tribological behavior of any pair of materials when operating conditions are changed.The paper presents a comparative study of the friction characteristics for two thermoplastic polymeric materials (Relamid B-10-FC and Turcit B Slydway) that slide on a metal surface in dry or oil-lubricated environments.The evolution of the coefficient of friction for a non-compliant and a conforming contact under different operating and lubrication conditions was analyzed. The experimental research was done on a stand of pin on disk tribological tests illustrating graphically the evolution of the coefficient of friction with the load, speed and time for different surface roughness. The values of the normal experimental forces used to act on the pin were:* $F_{n1} = 0.5N$, $F_{n2} = 1N$, $F_{n3} = 5N$, $F_{n4} = 10N$. *The rotational speed of the disc can be changed using a variable speed drive. Experimental sliding speeds were:* $v_1 = 0.02m/s, v_2 = 0.04m/s, v_3 = 0.06m/s$ *și* $v_4 = 0.08m/s$. *The temperature and humidity of the experimental conditions were as well 18°...22° and 60...70%. Each experiment was evaluated for a period of 30 min. The results of this research can be used to design high-performance mechanical systems to improve the various mechanical processes in which friction phenomena occur.*

Keywords: *coefficient de frecare; material polymeric; pin cilindric/conic; operating parameters.*

1. INTRODUCTION

In order to establish the field of use of the different material couplings, it is necessary to know the friction behavior under experimental conditions similar to those in the industrial environment. Sliding friction is a surface phenomenon that depends on the hardening properties of the material, the lubrication state, the processing mode estimated in terms of the size and shape of the roughness [1-4].

The tribological behavior of materials has been extensively studied over the years, due to its importance and multiple implications, not only in industry but also in medicine [5-7].

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Numerous researchers have designed and developed experimental stands and simulators for measuring friction in the material couplings of orthopedic prostheses, in order to improve quality of life [8, 9] and have developed constructive solutions to reduce friction, based on replacing sliding friction with rolling friction [10].

This study investigates the evolution of the coefficient of friction when two thermoplastic materials slip in contact with a metallic material. The evaluation of the friction coefficient is made on a tribological stand of pin on disc type, starting from the hypothesis according to which the friction does not depend on the size of the contact surface [1, 2] determining: A) the friction coefficient for the cylindrical pin / surface contact flat; B) coefficient of friction for conical pin / flat surface.

Asperities are those that take over the action of the normal pressing force at the sliding contact of two surfaces and deform (elastic, plastic, elastic-plastic) to reach equilibrium. In tribological terms the measured contact area is generally much larger than the true contact area.

2. MATERIALS AND METHODS

2.1. MATERIALS

The use of thermoplastic polymeric materials in various industrial fields is obvious due to their ability to withstand high mechanical and thermal stresses. To be suitable in tribological applications, thermoplastic polymeric materials must have good abrasion resistance. This is not easy to achieve because the viscoelastic properties of polymeric materials make the tribological analysis quite complicated [1,11-16]. Knowing the tribological behavior of different pairs of polymer / metal materials requires a lot of experimental research to introduce and use them in different industrial fields. One of the aspects of interest in this field is the evaluation of the size and evolution of the coefficient of friction with the working parameters.

The materials under analysis are Relamid B-10-FC and Turcit B Slydway in contact with an S235 steel metal material. Relamid B-10-FC is a polymer based on polyamide 6, thermostabilized and added with carbon fiber in a proportion of 10-30% and, the stabilization giving it the possibility of use for friction torques subjected to high thermal stresses.

Turcite B Slydway is a high-performance thermoplastic material based on PTFE, with bronze filling characterized by friction and reduced wear.

Physical-mechanical characteristics of these materials are presented in Table 1 [17, 18].

Table 1. Physical-mechanical characteristics of the analyzed materials

Mechanical properties		Relamid B-10-FC	Turcit B Slydway
Tensile strength	[MPa]	62	75
Hardness	[Shore D]	50-60	70-80
Thermal conductivity at 20^{o}C	[W/m K]	0.35	0.17
Modulus of elasticity at 20^{o}C	[N/mm^2]	2007	1000
Thermal expansion	[m/°C]	6.3 10^{-5}	6 10^{-5}
Density	[kg/m^3]	1350	1210
Max/Min working temperature	[°C]	-200 / +250	-170 / +200

The experimental part analyzes the sliding of the two materials on a universal S235JR steel, used for machine constructions, manufactured in accordance with the SR EN 10025/2-2004 standard with the Yield strength $\sigma_c = 235\ MPa$ and Tensile strength $\sigma_r = 360 - 510\ MPa$.

2.2. THE EXPERIMENTAL PART

The friction processes were analyzed over a relatively wide range of values of tribological parameters (load, relative speed, time). The range of values used for the mentioned parameters were chosen in accordance with the values frequently encountered in industrial applications. The researches were made on a tribological stand of pin on disc type friction, for the evaluation of the friction coefficient (the principle scheme is presented in Fig. 1) [19].

The tribological stand was adapted for use in two work variants for conducting experimental research:

A) the steel plate is placed on the surface of the disc, and the pin has a cylindrical shape with a diameter of 10 mm and is made of thermoplastic polymeric material (Fig. 1a);

B) plate made of thermoplastic polymeric material 3 mm thick has the shape of a disc and is placed on the flat surface of the device and the pin (steel) has a conical shape with semi-angles at the top $\alpha_1 = 10°, \alpha_2 = 20°, \alpha_3 = 30°, \alpha_4 = 45°, \alpha_5 = 60°$ (Fig. 1b).

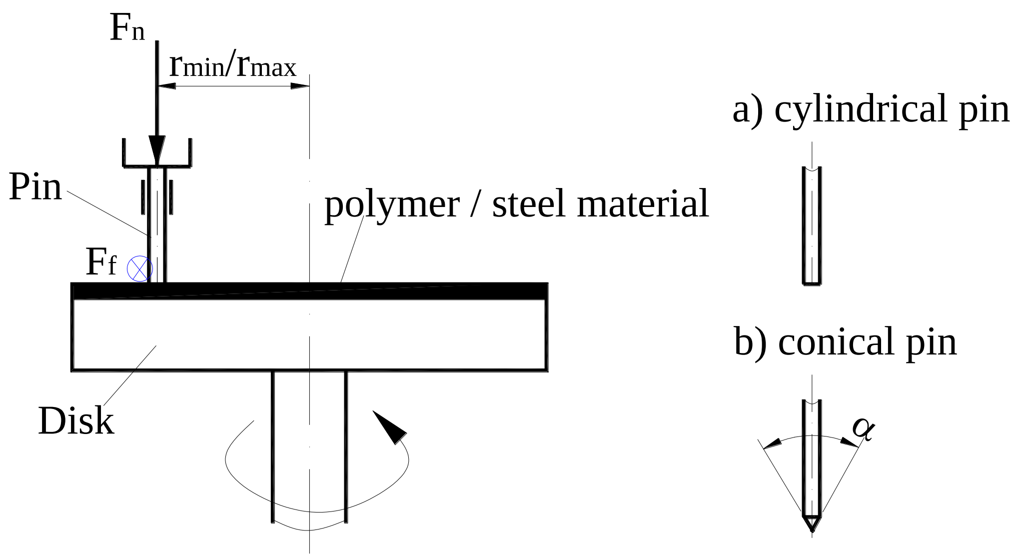


Figure 1. Schematic diagram of the pin / disc tribological stand.

For both working variants the pin is loaded with certain weights. The values of the normal experimental forces used to act on the pin were $F_{n1} = 0.5\ N$, $F_{n2} = 1\ N$, $F_{n3} = 5\ N$, $F_{n4} = 10\ N$. The rotational speed of the disc can be changed using a variable speed drive. Experimental sliding speeds were $v_1 = 0.02\ m/s, v_2 = 0.04\ m/s, v_3 = 0.06\ m/s$ și $v_4 = 0.08\ m/s$. The temperature and humidity of the experimental conditions were *18°...22°* and *60...70%*. Each experiment was evaluated for a *30 min* period.

In order to analyze how the evolution of the surface processing mode can influence the evolution of the friction coefficient, the steel plate for the variant A is processed by two technological cutting processes: turning at which the measured roughness was $R_a = 3.2\ \mu m$ and grinding at which the measured roughness was $R_a = 0.8\ \mu m$.

In order to see the influence of surface lubrication on the evolution of the coefficient of friction, three lubrication situations with an industrial transmission oil are proposed:

- good (fluid) lubrication, with sufficient lubricant between the surfaces so as to create " micro oil wedges", possibly bearing,
- border lubrication, with a few drops of oil spread with a spatula;
- without lubrication, the specimens are initially cleaned and degreased with alcohol.

The experimental evaluation of the coefficient of friction is estimated by measuring the tangential frictional force and the normal pressing force. This was done on average of 3 measurements per duration of each test. The statistical variation of the experimental results is assessed by the coefficient of variation $c_v = 0.11$ (the ratio between the mean square deviation and the arithmetic mean).

2.3. THEORETICAL EVALUATION OF THE FRICTION COEFFICIENT

The tribological behavior of the friction torques is analyzed based on theoretical models which are then compared with the results obtained in laboratory conditions or with those of operation of the torque in operation. For the plane contact between the surfaces (cylindrical pin / disc) - variant *A*, the coefficient of friction is according to Amonton-Coulomb's law given by the ratio between the frictional force (F_f) and the normal pressing force (F_n) [2, 20, 21].

For the conical pin / disc contact (variant *B*), the proposed theoretical model considers the case of a rigid conical penetrator that slides on a deformable flat surface. For this type of contact it was found that the thermoplastic material can deform elastically in the form of a wave or plastic by micro-cutting. These modes of deformation are dependent on the size of the penetrator angle and the hardening characteristics of the material [1,3,22-28].

The contact diagram for the case of material deformation is shown in Fig. 2a and for the contact at micro-cutting is shown in Fig. 2b.

The force required to move the rigid penetrator on the flat surface depends on the adhesion of the cone on the contact surface. The friction force is zero when there is no adhesion and is maximum when the adhesion is maximum. The solution to this problem is obtained using Hencky's sliding line theory [22-26]. According to the laws of friction, starting from the classical definition, the coefficient of friction is:

$$\mu = \frac{F_t}{F_n} \tag{1}$$

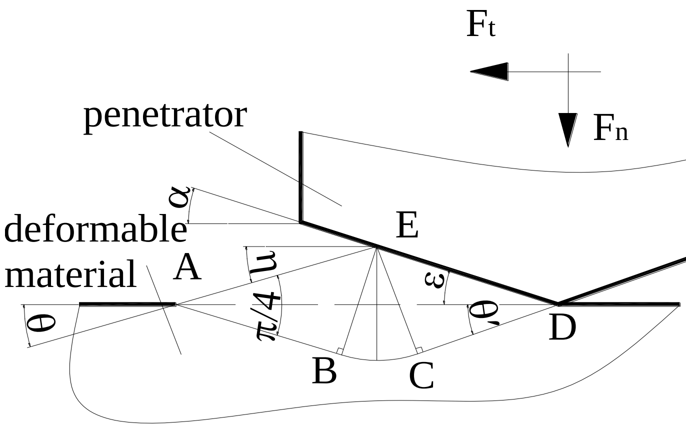
The expressions of the coefficient of friction for the two response modes of the polymeric material when a conical penetrator slides on its surface are of the form:
- in the form of a waveform:

$$\mu = \frac{F_t}{F_n} = \frac{\beta \sin\alpha + \cos(2\varepsilon - \alpha)}{\beta \cos\alpha + \sin(2\varepsilon - \alpha)} \tag{2}$$

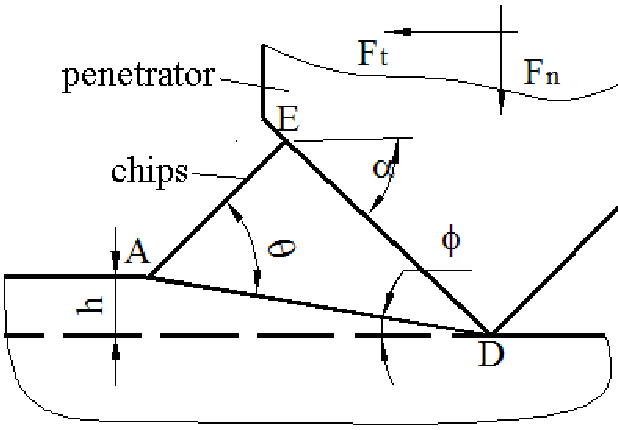
where: $\beta = 1 + \pi/2 + 2\varepsilon - 2\alpha - 2\arcsin(\sin\alpha / \sqrt{1-f})$

$\varepsilon = 0{,}5\arccos(f)$

f is an adhesion parameter.



a



b

Figure 2. Contact diagram in the case of the conical penetrator.

- for micro-cutting:

$$\mu = \frac{F_t}{F_n} = ctg(\theta - \phi) \tag{3}$$

where:

$$\theta = \phi + \frac{\pi}{2} + 0{,}5\, arcsin(f \cdot sin 2\phi) - \alpha$$

$$\phi = \theta - \frac{\pi}{2} - 0{,}5\, arcsin(f \cdot sin 2\theta) + \alpha$$

The adhesion parameter introduced in the expression of the coefficient of friction indicates the influence of the lubrication on the friction of the material couple. It can be considered a measure of the lubrication state (f = 1 non-lubricated materials, $f = 0$ lubricated materials). The chip angle (θ) depends on the hardening characteristics of the materials ($C_n = 0{,}8 \ldots 1{,}2$ experimentally determinable values) [24-26, 29, 30].

It is estimated that for a value of the subunit friction coefficient $\mu > 1$, the material is deformed in the form of a wave and for super unit values $\mu > 1$ the plastic deformation of the material with abrasive particle detachment and micro-cutting of the material takes place.

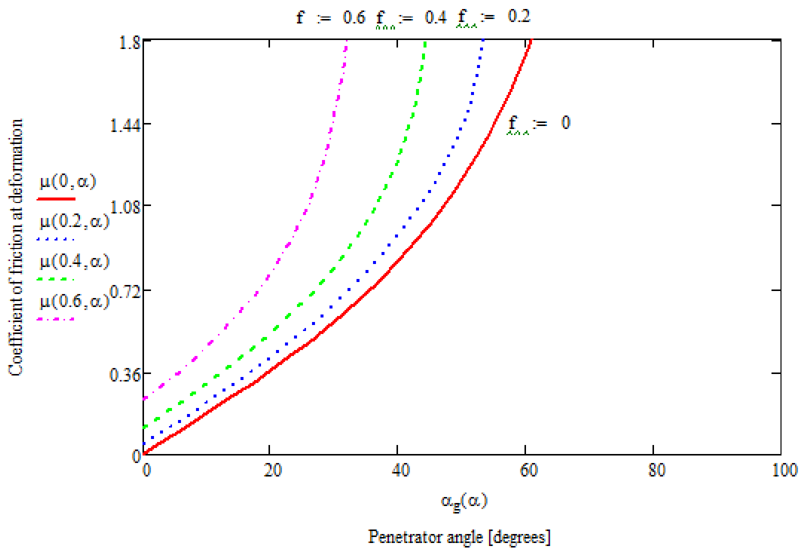


Figure 3. Evolution of the coefficient of friction at deformation, depending on the angle of attack of the penetrator with the lubrication state.

Fig. 3 shows the evolution of the coefficient of friction to deformation depending on the angle of attack of the penetrator and the lubrication state. The coefficient of friction under lubrication conditions increases more than in the case of dry friction.

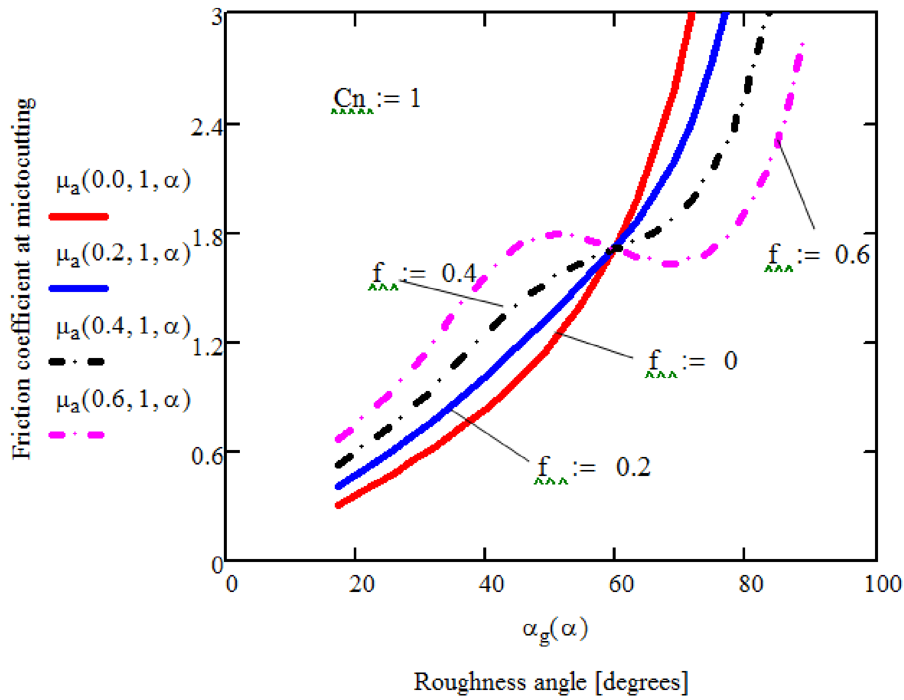


Figure 4. Evolution of the coefficient of friction at micro-cutting, depending on the angle of attack of the penetrator, the lubrication state and the hardening properties

Fig. 4 shows the evolution of the coefficient of friction at micro-cutting depending on the angle of attack of the penetrator with the state of lubrication and hardening properties of materials, there is a rapid increase in the coefficient of friction with the angle of the penetrator. Lubrication is a way to reduce friction. In the case of micro-cutting, lubrication reduces friction. There is a value of the penetration angle at which both elastic and plastic deformation of the material takes place. Above this value the polymeric material is micro-chipped.

3. RESULTS AND DISCUSSIONS

3.1. EXPERIMENTAL RESULTS

Experimental research has shown that the coefficient of friction depends on the load (normal pressing force), sliding speed, surface processing and lubrication.

Fig. 5 shows the evolution of the coefficient of friction with the sliding time for the two processing conditions of the disc surface (R_a = *3.2 µm*, R_a = *0.8 µm*) for the case of the cylindrical pin (made of thermoplastic) / disc (steel) contact. The analysis of the two materials was done for the conditions of: dry friction at a force of F_{n1} = *0.5 N* and a sliding speed of the pin on the disk of v_1 = *0.02 m/s*. It is noted that initially they have a slight increase in the coefficient of friction after which its value stabilizes. It should be noted that the value of the coefficient of friction is lower in the case of less rough surfaces (R_a = *0.8 µm*).

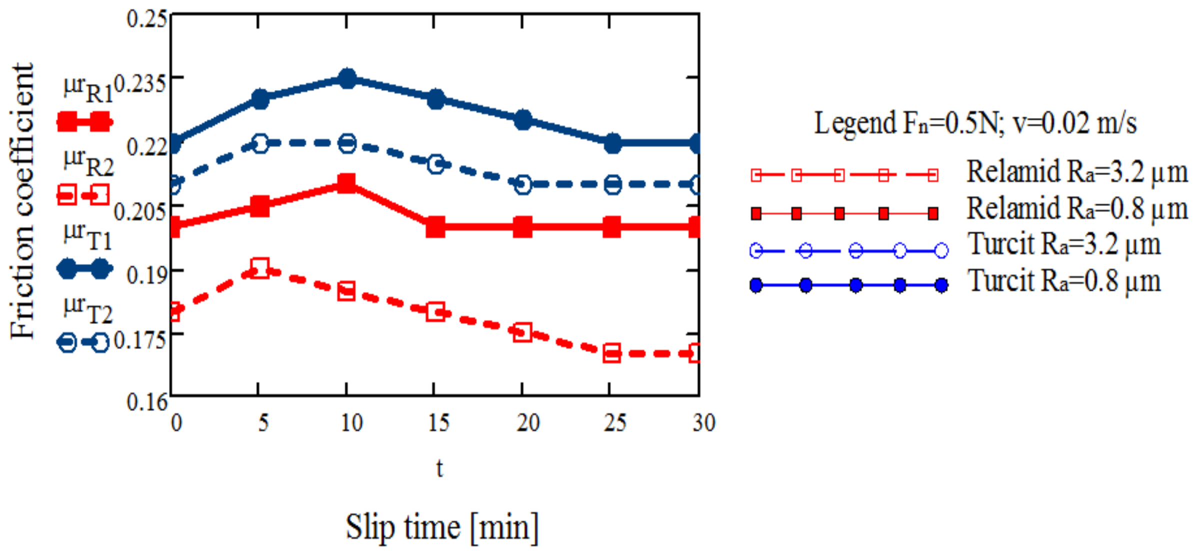


Figure 5. Evolution of the experimental friction coefficient with the sliding time for two values of the surface roughness of the steel disc.

Fig. 6 shows the evolution of the coefficient of friction with the sliding time for different surface lubrication conditions. The experimental conditions were: sliding time t = *30 min*, normal pressing force on the pin F_{n3} = *5 N*, the sliding speed of the pin on the disc v_2 = *0.04 m/s*, the surface roughness of the steel disc R_a = *3.2 µm*. There is a slight increase in the coefficient of friction after which its value stabilizes but also a decrease with the increase of lubrication.

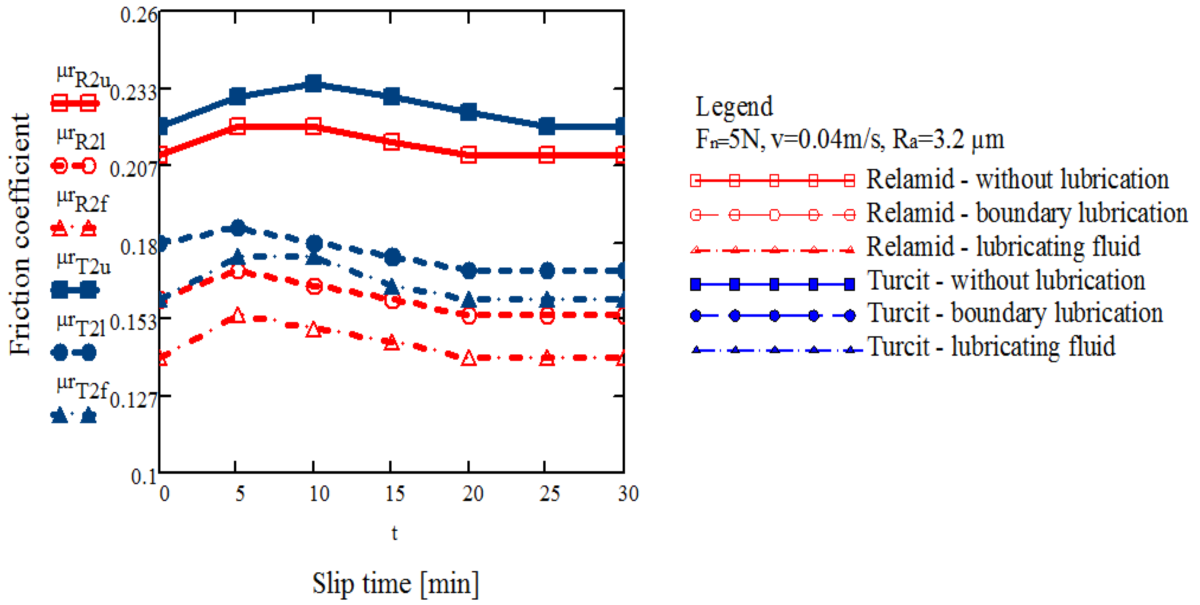


Figure 6. Evolution of the experimental friction coefficient with the slip time for the three lubrication conditions.

Fig. 7 shows the evolution of the coefficient of friction for three loads of the pin (*F_{n1} = 0.5 N*, *F_{n2} = 1.0 N*, *F_{n4} = 10.0 N*) with the sliding speed, observing an increase of the coefficient of friction with the normal pressing force on the pin.

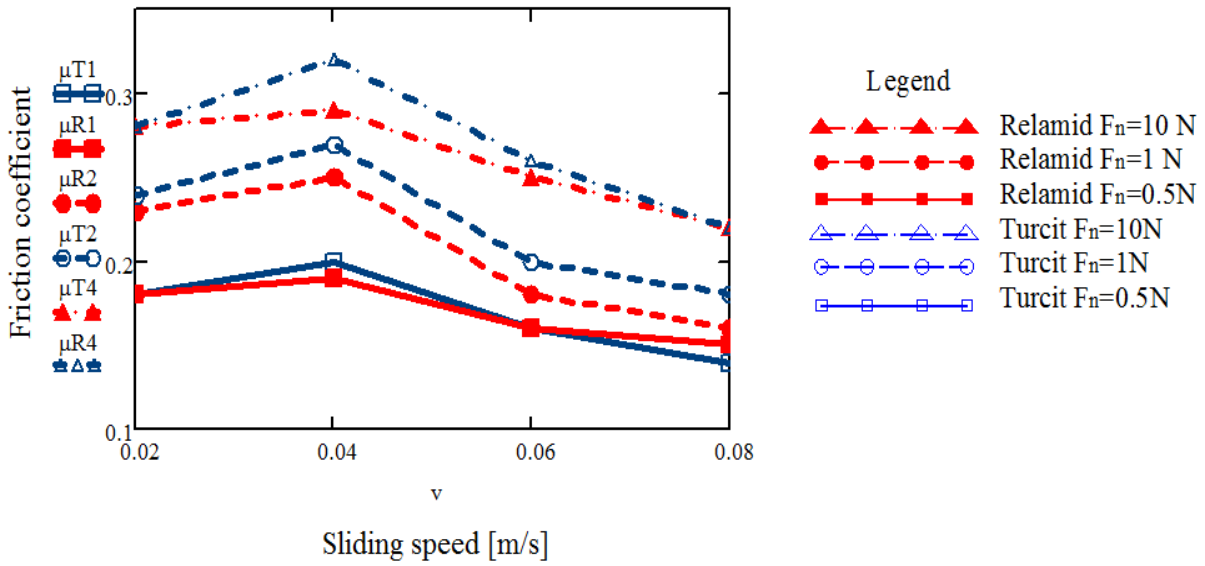


Figura 7. Evolution of the experimental friction coefficient for 3 loads of the pin with the sliding speed

The evolution of the coefficient of friction with the loads of the pin (according to Fig. 8) for different sliding speeds *v_2 = 0.04 m/s*, *v_3 = 0.06 m/s*, shows a slight increase of the coefficient of friction with the load of the pine after which its stabilization follows.

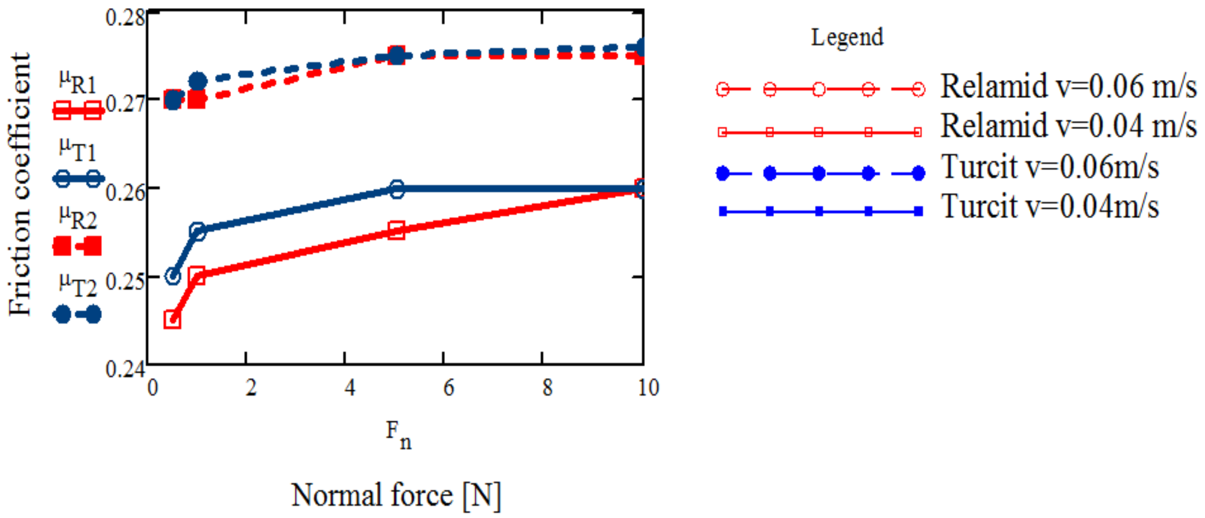


Figure 8. Evolution of the experimental friction coefficient with the pin loads for different sliding speeds

In Figs. 9- 10, for the case of the conical pin contact made of steel / disc thermoplastic polymeric material, the evolution of the coefficient of friction with the penetrator angle is presented according to the lubrication conditions (dry, limit and fluid). The evaluation of the coefficient of friction was made for the normal loading force of the pin $F_{n4} = 10\ N$ and its sliding speed on the disk $v_1 = 0.02\ m/s$, noting an increase in the coefficient of friction with the angle of attack of the penetrator.

Fig. 9 shows the evolution of the coefficient of friction for the three lubrication conditions in the case of Relamid B-10-FC material and in Fig. 10 for Turcit B Slydway material.

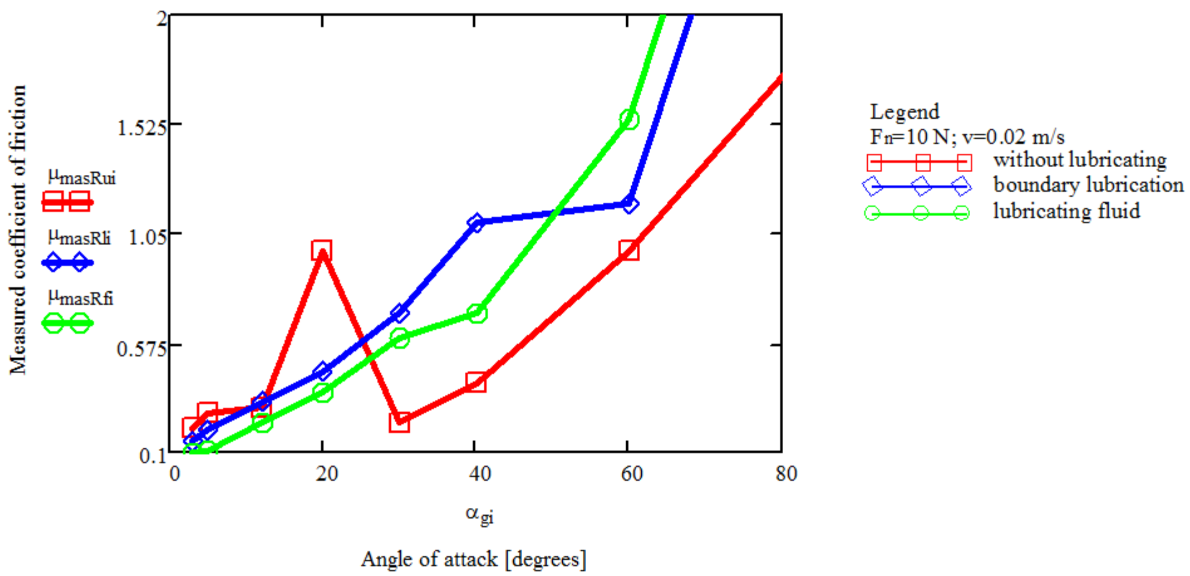


Figure 9. Evolution of the experimental coefficient of friction with the angle of attack for the analyzed materials under dry friction conditions

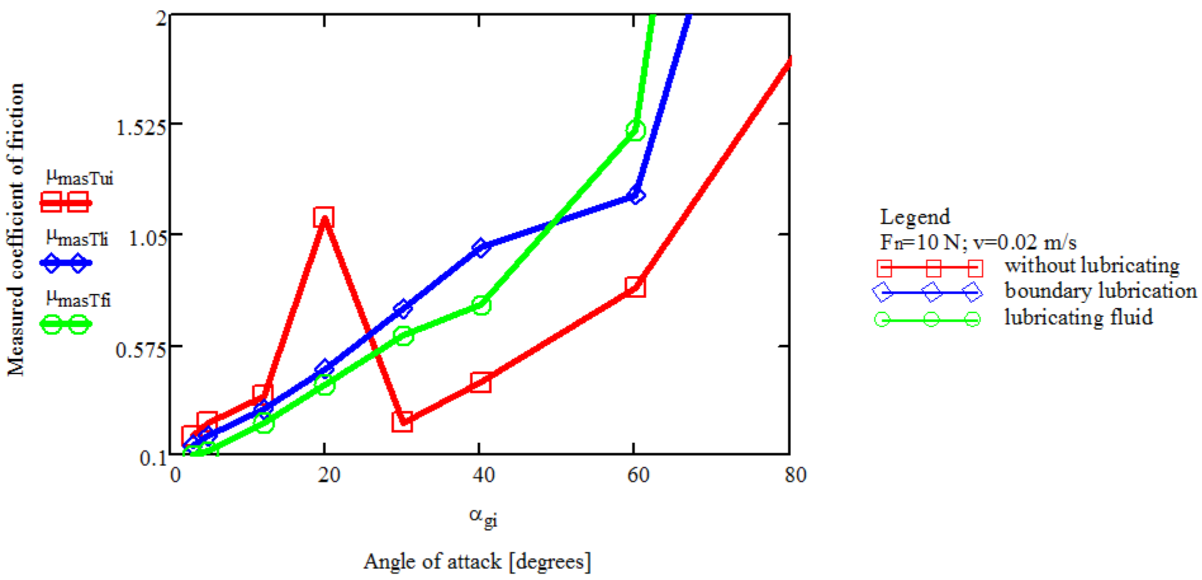


Figure 10. Evolution of the experimental coefficient of friction with the angle of attack for the analyzed materials under the conditions of limit friction

For each of the two materials, there are angles of attack at which the values of the coefficient of friction undergo essential changes. This confirms the theoretical model regarding the existence of the three modes of deformation of the thermoplastic material (elastic waveform, elastic-plastic, micro-chipped).

3.2. DISCUSSIONS

For the sliding speed range and the applied load values of the two thermoplastic materials subjected to this research, it was observed that the change in the coefficient of friction of all materials during the sliding process on steel follows the same evolution.

In the case of friction of the flat surface’s cylindrical pin / disc, a slight increase of the coefficient of friction was found during the sliding in the first part of the contact after which its value stabilizes. This is due to the adhesion of the surface of the polymeric material on the surface of the disc [1, 3, 19, 26-29, 31, 32].

The size of the coefficient of friction depends on the operating parameters (loading, sliding speed, lubrication state), the hardening characteristics of the material, etc. This leads to the fact that the coefficient of friction varies more with the sliding speed than with the load.

Theoretical models regarding the evolution of the coefficient of friction in the penetrator / flat surface contact, highlighted the fact that there is an angle of the penetrator for which the material can deform elastically in the form of a wave. Above the value of this angle, the polymeric material can deform elastic-plastic (deformation with detachment of wear particles) or plastic (micro-cutting) [30].

The evolution of the coefficient of friction for each response mode of the material depends on the hardening characteristics and the lubrication state, these things are in accordance with the experimental data from the literature [1, 3, 20, 30].

Experimental research in the case of micro-cutting has confirmed the theoretical model of the influence of lubrication on the coefficient of friction - namely that lubrication of surfaces with lubricant is preferable to dry friction conditions.

4. CONCLUSIONS

Under similar test conditions, a comparative study of the evolution of the coefficient of friction with the working parameters for the two materials in contact with a metallic material was performed.

The research was performed on a tribological stand of pin / disc type. It was sought that the experimental conditions be as close as possible to the industrial exploitation conditions so that there is a more real picture of the tribological behavior of these materials.

It was found that the tribological behavior of the pairs of analyzed materials depends on the mode of elastic-plastic deformation of the softer material, which contributes to a wider range of values of the coefficient of friction.

The results of this research can be used to design high-performance mechanical systems to improve the various mechanical processes in which friction phenomena occur.

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