ORIGINAL PAPER

THEORETICAL AND EXPERIMENTAL STUDIES ON SLIDING AT LOW SPEEDS WITH INTERMITTENCIES

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Abstract. *The guides of the machine tools, brakes, clutches there is the possibility of the intermittent movement of stick-slip. This opens in the case of frictional couples with sliding motion, due to the low sliding speeds. Intermittent slip introduces vibrational phenomena and influences the uniformity of movement and the state of the surface of the couples due to their use. In this respect, the concerns related to the study of this phenomenon represent an interest in the machine building industry. The paper aims to achieve an original theoretical model for calculating the static and kinetic friction coefficients and its experimental verification on a stick-slip stand. The proposed theoretical model establishes the calculation relations of the static and kinetic friction coefficient and the connection between them taking into account the surface processing method. The originality of the approach is that the model is considered friction between the conical penetrator (steel material) and a polymer material. In the literature, the stick-slip phenomenon is approached only in terms of the analysis of flat surfaces. The torques of said materials is frequently used on the parts of sliding machines where this phenomenon is possible. The paper highlights the influence of exploitation factors (load, speed), the processing of surfaces, and the quality of the lubricating liquid on the stick-slip phenomenon, for a friction coupling of polymeric material / metallic material.*

Keywords: *sliding motion; static friction coefficient; kinetic friction coefficient; polymeric material; operating conditions.*

1. INTRODUCTION

The concepts and hypotheses set out over time, related to dry rubbing, began with Leonardo da Vinci (around 1500), taken over by Amonton (about 1699) and extended by Coulomb (during the year 1785), after which they were continued and developed by other researchers. Leonardo da Vinci was the one who emphasized that depending on the movement or rest of the bodies, the friction can be static or kinetic, and the coefficient of friction can be static or kinetic. The tribological explanation is that the asperities of the friction surfaces during the sliding period intersect until the driving force is high enough to slip over each other or to break them.

The intermittent movement is characteristic of rubbing type couplings: guides, brakes, clutches, etc. at which the sliding of the surfaces in contact is achieved at a reduced speed (0.1- 180 mm/min), considered the critical speed [1, 2].

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During the slip between the two surfaces of the coupling, there is a phenomenon of adhesion due to the formation of microjunctions at the level of the asperities in contact. Their breakdown is achieved after a very short period of time ($10^{-7} - 10^{-4} s$). On this line, stick-slip movement can be considered a static phenomenon. Welding and breaking of the microjunctions between the peaks of the asperities in contact constituting the two extremes of the dynamic balance [3, 4]. This explains the variation in the coefficient of friction over time and implicitly the friction force during the slip period [5]. The characteristic of the intermittent slip is shown in Fig. 1.

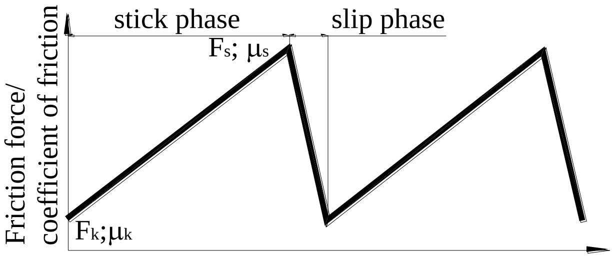

Figure 1. Motion diagram with flashing (Stick-slip classic) [1, 3].

From a phenomenological point of view it is considered that static friction exceeds kinetic friction. The explanation of this phenomenon is that for two surfaces in contact, the stick-slip type friction occurs when the difference between the kinetic and static friction coefficient produces a certain elasticity in the mechanical system. The movement of one surface on the other occurs with flashes and appears due to the variation of the sliding motive force.

The relative movement does not take place until a critical shear stress of the microjunctions formed between the peaks of the asperities in contact is reached. At that moment, the surfaces begin to slip again. The slip behavior is estimated to depend on the topography of the surface and on the elastic and plastic properties of the materials of the rubbing joint.

It has been found that although polymeric materials have lower rigidity and resilience than metallic materials, they are used (due to their ability to absorb vibrations) in industrial applications where the phenomenon of stick-slip is possible.

2. MATERIALS AND METHODS

2.1. MATERIALS

The behavior of materials in a mechanical system, under the action of work factors (load, speed, temperature, lubrication etc.) influences its proper functioning. Polymeric materials have an essential role in future technological development in all heavily industrialized countries. They successfully replace the metallic materials used to make sliding couplings. Progress in understanding the tribological behavior of polymeric materials requires multiple experimental research [6-13], to its introduction and use in the realization of various machine parts. In this paper it is proposed for analysis the polymeric material Turcite [14] in contact with a metallic material (carbon steel). The material coupling chosen for the study is frequently used on the sleigh-guide machine parts, where the occurrence of the stick-slip phenomenon is possible.

2.2. METHODS

The frictional behavior of the different machine organs can be analyzed using physical models which are then validated in the laboratory experimentally and compared with the operating conditions in production. Physical models are generally made based on the operating conditions of the coupling and take into account the shape and type of its movement, the type of contact between surfaces and the loading mode, to correspond as accurately as possible to the operating conditions.

The specialized literature presents studies on the stick-slip phenomenon [4, 15, 16]. The proposed theoretical model establishes the calculation relationships of the static and kinetic friction coefficient and the relation between them taking into account the surface processing mode. In the proposed theoretical model the friction between a conical (steel) penetrator and a polymeric material is considered. The conical-shaped penetrator is considered to be similar to the roughness of the surface of the harder material (steel) that can soften the softer material (polymeric).

The friction coefficient in the perpendicular direction to the normal load applied (F_n) is considered to be:

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

where: F_t is tangential force *[N]*.

It is considered that the friction coefficient is dependent on the processing of the surfaces and that the asperities of the harder conical material can furrow the softer material [15-17]. The proposed model considers the relationship necessary to establish the static coefficient of friction of the form:

$$\mu_s = \frac{2}{\pi} ctg\left(\alpha \frac{\pi}{180}\right) \tag{2}$$

where: α is the semi-angle of the rigid cone.

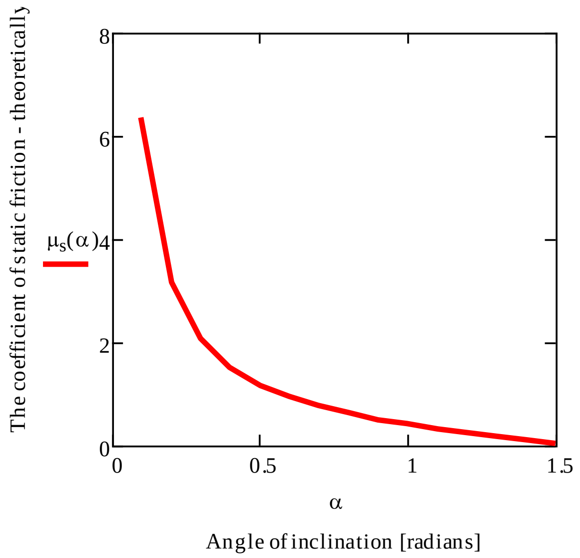

Figure 2. Theoretical evolution of the static friction coefficient depending on the angle of the conical penetrator.

Fig. 2 shows the theoretical evolution of the static friction coefficient depending on the angle of the conical penetrator. In order to determine the kinetic friction coefficient [17-19], its dependence on the sliding speed (*v*) and on the static friction coefficient, of the form:

$$\mu_k = \mu_s \cdot v^a \tag{3}$$

where *a* is a coefficient that depends on the pair of materials and is determined experimentally (for polymeric materials *a=0.1*). Fig. 3 shows the theoretical evolution of the kinetic friction coefficient for different values of the sliding speed.

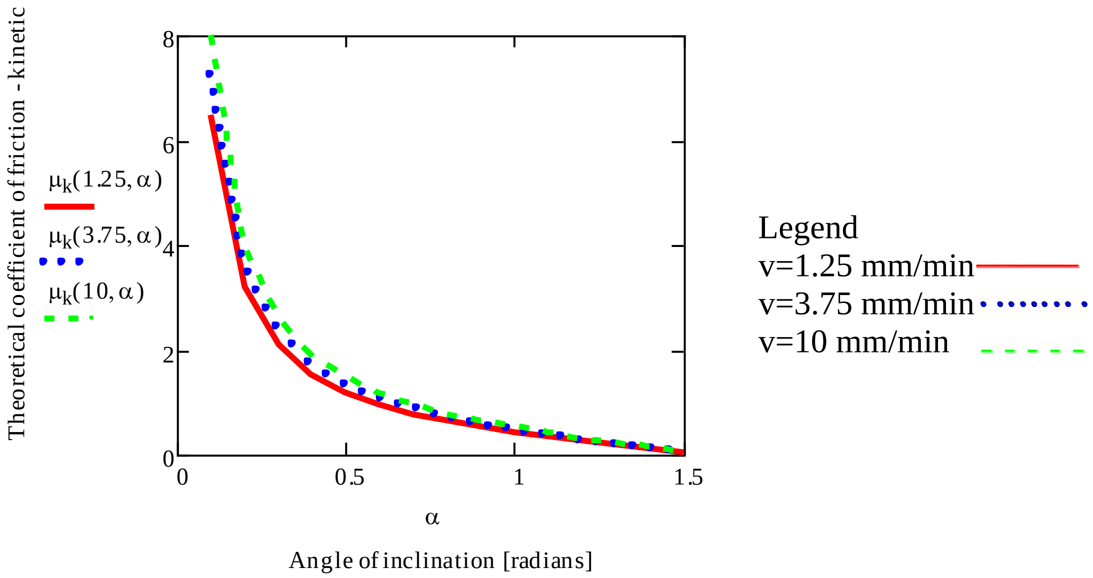

Figure 3. Theoretical evolution of the kinetic friction coefficient depending on the angle of the conical penetrator.

2.3. THE EXPERIMENTAL PART

To verify the theoretical model, experiments were performed on a stick-slip friction stand. On this stand you can measure the friction properties of some material couplings at low sliding speeds for which some changes have been made regarding the shape of the pin. Thus the cylindrical pin was replaced with a conical-shaped penetrator with angles $\alpha = 5°\text{-}80°$. The samples were made by turning, from non-alloy construction steel SR-EN 10025, and the angle accuracy was ±0.5°.

The samples were loaded with normal forces $F_n=0.1N$ and $F_n=5N$ the sliding speed was also varied at the values: *v=1.25 mm/min* and *v=3.25 mm/min*. The samples were degreased to highlight the tribological behavior under conditions of dry friction between the penetrator and the polymer surface. Because the size of the coefficient of friction is generally influenced by the amount and viscosity of the lubricant, the experimental part also proposes a study on the influence of lubrication on the size of the coefficient of friction.

Two types of additive oils TIN 25 EP (with v_{50}*=21-26 cst* kinematic viscosity) and TIN 125 EP (with v_{50}*=125-140 cst* viscosity), purchased commercially, were analyzed. The experimental conditions were also the sliding speed. The samples were "greased" with the mentioned lubricants so that the lubrication regime was mixed-limit. The values in the graph represent the average of five identical attempts. The statistical variation of the experimental results is assessed by the coefficient of variation $c_v=0.12$ (the ratio between the mean square deviation and the arithmetic mean).

3. RESULTS AND DISCUSSION

3.1. RESULTS

The experimental research has validated most of the theoretical model. The evolution of the static coefficient of friction with the load shows a significant increase of the coefficient of friction for values of the conical coulter element of $\alpha = 7°\text{-}12°$ and a decrease with the normal load for angles $\alpha = 15°\text{-}80°$. Fig. 4 shows the evolution of the static coefficient of friction for a load of the conical penetrator with a normal pressing force $F_n=0.1N$, respectively $F_n=5N$, at a sliding speed of $v=3.25$ *mm/min*.

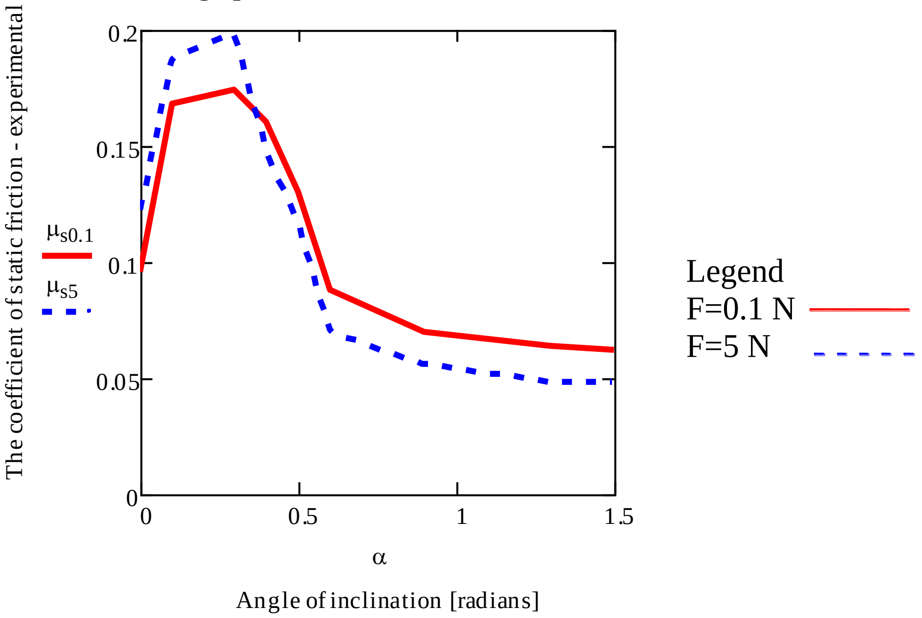

Figure 4. Evolution of the static coefficient of friction obtained experimentally.

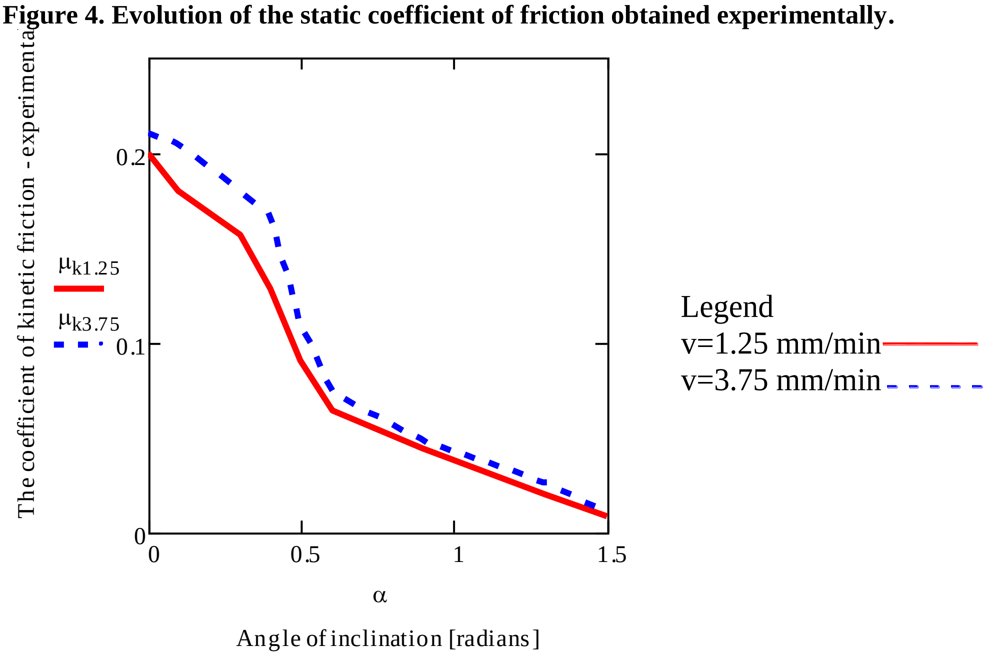

Figure 5. Experimental evolution of the kinetic friction coefficient for different speeds.

Fig. 5 shows the evolution of the kinetic friction coefficient obtained experimentally for different values of the sliding speed (*v=1.25 mm/min; v=3.25 mm/min*) at a load of the penetrator of $F_n=5N$. It should be noted that for polymeric materials the kinetic coefficient of friction increases with increasing sliding speed and decreases with increasing coulter's angle.

Experimental research has shown that intermittent sliding motion can be influenced by lubrication of surfaces. The effect of lubrication on the intermittent phenomenon is all the more visible as the lubrication material has a higher viscosity.

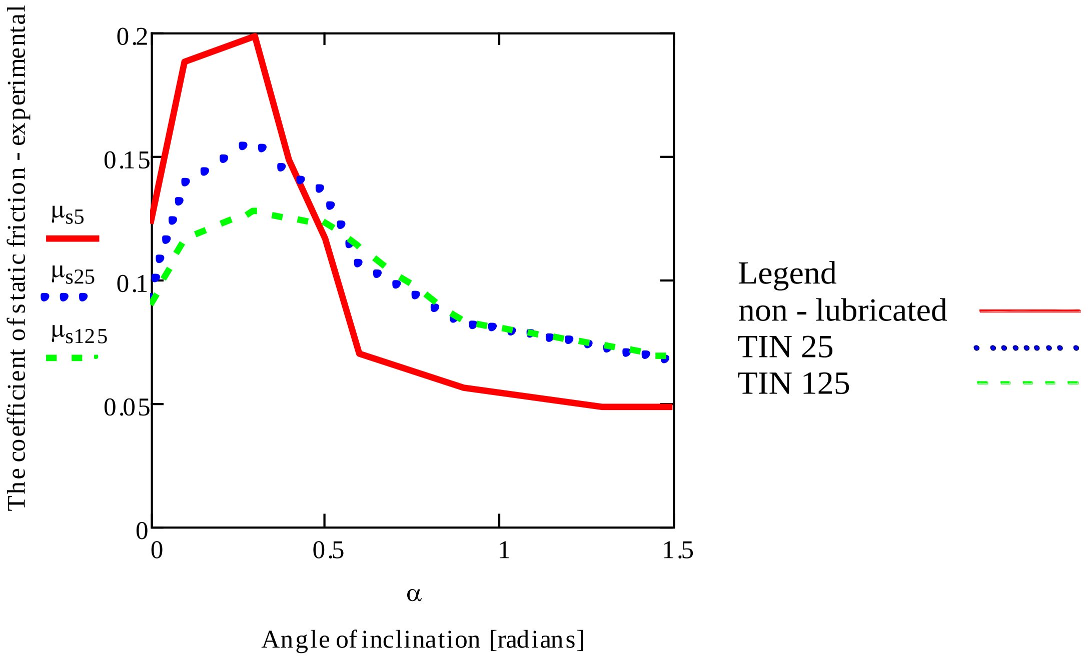

Figure 6. Variation of the static friction coefficient depending on the lubrication state.

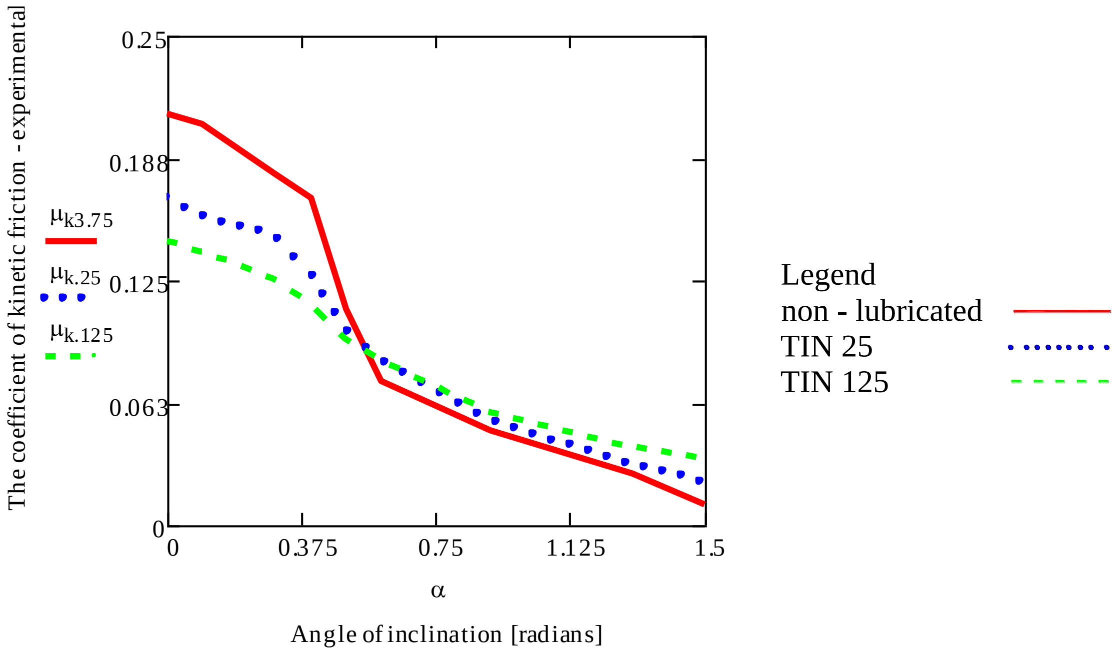

Figure 7. Variation of the kinetic friction coefficient depending on the lubrication state.

Figs. 6 and 7 show the evolution of the static or kinetic friction coefficient for a load of the conical penetrator with a normal pressing force of $F_n=5N$ and sliding speed *v=1.25* *mm/min* in the conditions of dry friction and friction in limit-mixed regime. It is observed that the lubricant used influences the evolution of the coefficient of friction.

3.2. DISCUSSION

In the case of the stick-slip phenomenon, the effects of gluing and dislodging with the possible breakages of the micro-junctions that appear between the peaks of the asperities in contact lead generally to an adhesive type wear. In addition, abrasive wear phenomena can be added. Abrasive wear can occur under roughness or tougher wear particles [20-23].

From the theoretical and experimental analysis the following can be seen:

- both in the theoretical model and the experimental part highlight the decrease of the coefficient of friction with the angle of inclination of the penetrator;
- the theoretical model is experimentally confirmed for α = 15°-80° penetrator angles;
- for α = 7°-12° penetrator angles, there is an increase in the experimental value of the static friction coefficient followed by a decrease in it. This is due to the phenomenon of penetration of the polymeric material by the penetrator. However, the increase may be due to its adhesion to the penetrator material.
- stick-slip phenomenon appears both in dry friction conditions and in mixed-boundary lubrication conditions;
- the amplitude of the phenomenon depends on the loading, the speed of sliding, the quality of the lubricant and the way of processing the surfaces;
- as the inclination angle of the asperities (the penetrator) increases, the amplitude of the phenomenon increases;
- the kinetic friction coefficient increases with increasing slip speed and decreases with increasing coulter angle;
- motion with stick-slip can be reduced by using suitable additive lubricants;
- the direct contact of the asperities and their plastic deformation is the consequence of the destruction of the lubricant film;
- the micro-joints between the contact asperities are, cold welds, and their rupture is performed at relatively high shear stresses.

4. CONCLUSIONS

The widespread use of polymer/metal friction torques in the machine building industry has shown considerable interest in knowing the behavior at low sliding speeds, which can lead to a much easier selection in industrial applications. The originality of the study consists in the fact that in the literature the stick-slip phenomenon is approached only from the perspective of the analysis of flat surfaces (cylindrical pin on the flat surface). Starting from a theoretical model for calculating the static and kinetic friction coefficients, the study highlights the factors that can influence the stick-slip phenomenon (in terms of surface processing and the nature of lubricant) without highlighting the self-vibrating phenomenon that arises during this period.

In this context, it is considered that the evolution of the stick-slip phenomenon is influenced by the following factors: loading, sliding speed, lubricant viscosity and surface processing mode; the friction coefficient has a maximum for an angle of the coulter member α = 7°-12° and a decrease with the normal load for angles between α = 15°-80°; the more viscous the lubricant, the more the stick-slip phenomenon is damped. From the researches carried out on this topic it can be stated that when using the friction coupling polymeric/metallic material in addition to the exploitation factors, the surface processing and the quality of the lubricant have a special importance.

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