

Static friction coefficient of some plastics against steel and aluminum under different contact conditions

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Abstract

The static friction behavior was investigated in the case of POM-based polymers containing additives, designated DE20076, DE100KM and DE12017 as well as Nylon-66 designated ZY103HSL, when in contact with AISI 1045 steel and 6061 aluminum alloy. A designed apparatus that detects the exact moment corresponding to the transition from rest to slip was used to measure the coefficient of static friction. The impact of normal load, dwell time before slip, apparent area of contact and lubrication by water and paraffin oil on the static friction characteristics was studied. A decrease of the static coefficient of friction with low normal load followed by a levelling off governed by its effect on the real area of contact and stiffness of the counterface was observed. This also yielded a linear decrease of slip acceleration as well as stick time. A polynomial equation, which increases monotonically, was found to express well the effect of stick time on static friction, independently of the materials in contact. Adhesive effects were generated by the presence of both lubricants with the result of increase of the static coefficient of friction.

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1. Introduction

In the phase of static friction or pre-sliding, the shear stress applied to two contacting surfaces in order to cause relative sliding is not high enough to break the interface linkages. It has been revealed that the behavior during stiction phase, which would induce difficulties in the case of high-precision positioning, is the result of non-linear behavior in dynamic systems [1]. Moreover, a condition known as stick–slip generated in some occasions at low speed and producing brief interruptions of motion can limit the accuracy and resolution of friction drive systems. Many studies on the variation of the dynamic friction force with relative slip velocity during sliding motion have been reported in the literature. But limited research works on surface friction have focused on near-zero sliding velocity. A number of theories based on different hypothesis and observations resulting from experimental data have been proposed to explain the variations of the friction force

under different conditions of the interface. The main conclusions of these studies applicable to the stage of incipient sliding are as follows:

- (a) The static coefficient of friction is governed by the load that is related to the real area of contact, the adhesion force a consequence of the bonds formed at the intimate contact regions and the force needed to shear them, hence the friction force. This concept was expressed mathematically by the following [2]:

$$\mu_s = \frac{F_t}{F_N - F_a}, \quad (1)$$

where F_t is the lateral force needed to shear the junctions subjected to an adhesive force F_a and a normal load F_N .

- (b) As a deviation from Amontons–Coulomb Law, a new concept of the static friction suggests that micro-displacements occur, generated by the strain at which the junctions are subjected during the static phase [3,4].
- (c) The micro-displacements during the static phase are non-linear functions of the tangential force [5].

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- (d) Dependence between the coefficient of friction and the time of steady contact was observed.

Understanding of static friction phenomena is also crucial for optimizing the design of many important mechanical systems, in particular head/disk interface for computers and micro-machines containing micro-electro-mechanical systems known as MEMS. Additionally, many parts intended to be ultimately in static contact with adjacent components experience in reality minute interfacial sliding. These micro-motions due mainly to vibrations and deformations inherent to the system containing them could generate stick–slip responses. The phenomenon of static friction is also present in the case of mechanisms subjected to reciprocating movement, which imply transition state at zero velocity.

Studies conducted in this field have indicated that the static friction coefficient is related to many factors including materials properties, topography, applied load and environmental conditions such as temperature, humidity and lubrication. As well, the literature review has revealed the importance of the effect of dwell time on static friction. Some studies have indicated that the coefficient of static friction tends to increase with the dwell time. Specifically, Ferrero and Barrau [5] have found that, during quasi-static states of the interface, the friction coefficient increases according to the stationary contact time. Theoretical and experimental analysis demonstrated that the stiction friction grows with the dwell time of the slider on the hard disk [6]. In addition, some studies pointed out that the static friction decreases with the load and surface roughness. A study of the static and quasi-dynamic friction coefficient of three thermoplastics (UHMWPE, PA 66 and POM), revealed that static friction coefficient decreases when normal load or roughness increase [7]. Paslay and Plunkett [8] have also studied the effect of load as well as surface roughness on the static friction of steel and reached the same conclusions of decrease with the increase of contact pressure for a given surface roughness, and increased roughness. Concerning the surface roughness, Bhushnan et al. [9] have found that it was the kurtosis, one of the parameters that define it, that influences the most stiction in the case of magnetic tapes. Zhao and Talke [10] investigated the effect of humidity and temperature on the stiction behavior of hard disk media. Their results showed that the coefficient of stiction for mechanically textured media increases with humidity but remains nearly unchanged for laser-textured media. On the other hand, the increase of temperature was found to cause reduction of stiction for mechanically textured media due to the change of lubricant properties. The effect of relative humidity on stiction is mainly explained by the mechanism of formation of menisci at the contact region between asperities and near-contact areas. Persson et al. [11] used molecular dynamics simulations to analyze the nature of the static friction, kinetic friction and creep. They suggested that the static friction coefficient is generally

higher than the kinetic friction coefficient because of various thermally activated relaxation processes, but there is no single value of the static friction coefficient, since it depends on the initial dwell time and on the rate of starting. Similar suggestions, that static friction is time and position varying, and that it is difficult to get consistent results for different contact systems have been proposed by Hsieh and Pan [1].

In this study, the static friction will be assessed using an experimental setup whose design is based on the principle of slip generated by centrifugal force applied to a sample resting on a spinning platform representing the counterface. Four engineering thermoplastics namely Delrin-based DE20076, DE100KM and DE12017 as well as Nylon-66 designated ZY103HSL will be investigated when in contact either steel or aluminum alloy surfaces. The impact of important parameters such as normal load, dwell time before slip, apparent area of contact and lubrication of the interface on the static friction characteristics will be presented.

2. Experimental conditions

2.1. Experimental setup

The design of the experimental apparatus is based on the generation of an incremented centrifugal force that would progressively overcome the friction force between two bodies in static contact and loaded by a normal force. This principle was initially put forward and used by Dunkin and Kim [12]. According to Fig. 1, each experiment consisted of placing the sample to be tested on a platform acting as counterface of the tribo-system. The system is then subjected to spinning thus generating increasing centrifugal force acting on the sample that would cause slippage. The detection of the critical moment at which initial relative motion takes place is of prime interest in this case because of its important impact on the accuracy of the measurement of the static coefficient of friction. The initial distance between the center of gravity of the sample and the center of rotation of the platform is also critical therefore an edge was machined on the platform, against which the sample was initially positioned, thus guarantying an accuracy of at least ± 0.1 mm on the reference distance of 91.75 mm. A 1 kW brush-less motor equipped with a servo amplifier and precisely controlled by a computer generated the spinning of the platform. Rotating speeds with and accuracy equivalent to ± 0.08 rpm were developed.

Although the general configuration of the present setup is original, the mode of detection of the initial motion of the sample, using an infrared proximity sensor (IPS), differs from the one used by Dunkin and Kim [12] who recorded the event on videotape. The rotating speed that corresponds to the detected critical time was then determined. In its basic form this sensor was composed of two components: the receiver array and transceiver unit as shown in Fig. 1. The transceiver consisted of an infrared

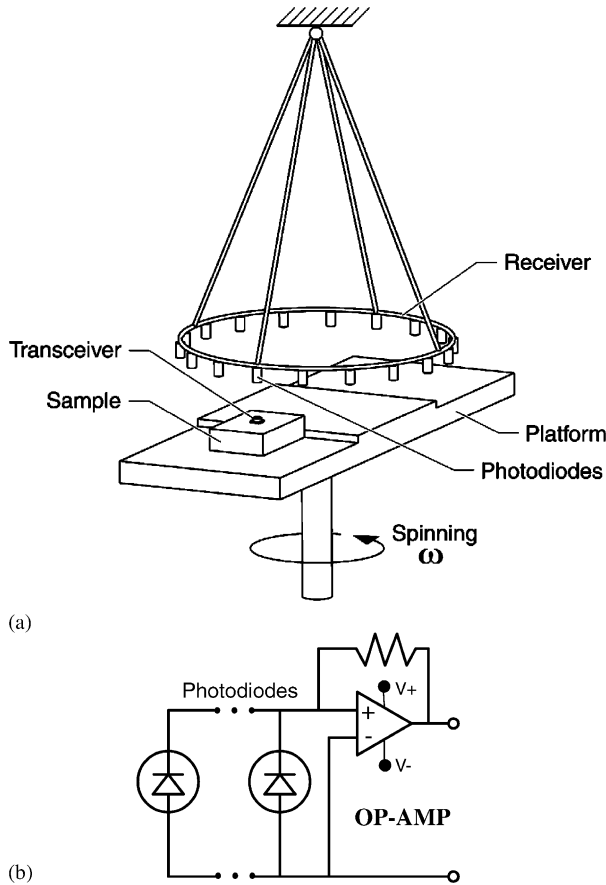


Fig. 1. (a) Schematic diagram of the testing apparatus and (b) photodiodes and Op-Amp circuit.

light-emitting diode (LED) unit powered by a miniature battery and a switch. It was attached to the sample by an adhesive. The emitted light is received by fixed photodiodes positioned in the space along a circular trajectory at regular angular intervals of 20° . All were connected in parallel to an operational amplifier (Op-Amp), as shown in Fig. 1b). As the platform spins, the sample passes underneath the stationary photodiodes, which are triggered by the LED. The output signal of the Op-Amp was recorded at high frequency and any sudden drop in voltage was associated with a slip of the tested sample.

To vary the normal load, dead weights were secured on the top of the samples.

2.1.1. Friction model

The analysis of friction in this study is based on the free body diagram shown in Fig. 2. Three forces are involved: the gravity (normal load) F_n , the static friction force F_f and centrifugal force (inertia) F_c . F_f is represented by a spring of a certain stiffness for clarity only. At the onset of sliding, corresponding to the precise moment of transition from rest to motion, the condition of equilibrium is represented by

$$F_c = F_f. \quad (2)$$

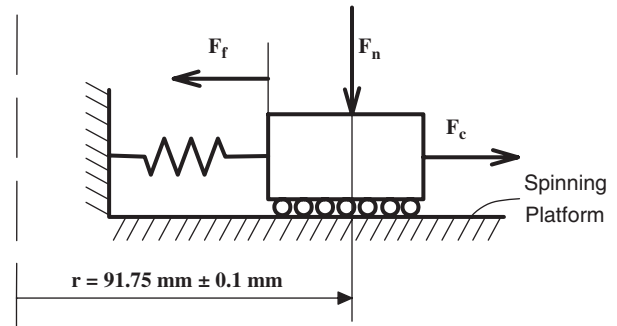


Fig. 2. Free body diagram for the analysis of friction.

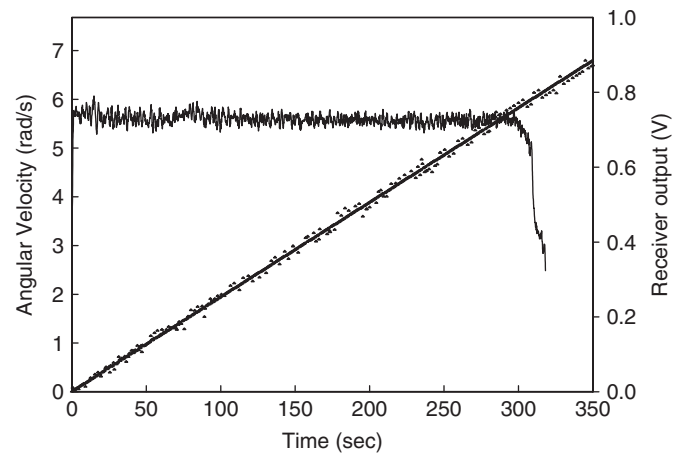


Fig. 3. Time dependence of spinning platform angular velocity and receiver output voltage.

Using the definition of each term of Eq. (2) and taking F_n into account one can write

$$F_f = \mu_s F_n = \mu_s mg \quad (3)$$

in which the product mg represent the normal load; and

$$F_c = mr \left(\frac{d\omega}{dt} + \omega^2 \right), \quad (4)$$

ω being the angular velocity at which initial slip occurs and $d\omega/dt$ the acceleration rate of the spinning platform called $\dot{\omega}$.

The static coefficient of friction is then determined as follows:

$$\mu_s = \frac{r}{g} (\dot{\omega} + \omega^2). \quad (5)$$

An example of the signals necessary for the determination of μ_s is shown in Fig. 3. The angular velocity measured by an optical encoder is represented by the symbols that were best fitted by linear relationship whose slope is reported on the figure. As indicated earlier, the receiver output voltage is used to determine the angular velocity at which slip occurs that in turn triggers a sharp decrease of the signal visible on the same figure.

Table 1
Characteristics of plastics used in the study

Designation	Product characteristics	Tensile strength (MPa)	Modulus of elasticity (GPa)	Vickers hardness micro-indentation (MPa)
DE20076	Acetal containing 2% silicone oil	67	2.8	125
DE100KM	Acetal containing Kevlar aramid resin	65	2.9	147
DE12017	Medium viscosity acetal	60	2.6	130
ZY103HSL	Heat stabilized PA-66 resin	83	2.83	205

2.2. Materials and testing conditions

Four plastics were investigated in this study among them three POM-based polymers, three containing additives, designated DE20076, DE100KM and DE12017 as well as Nylon-66 designated ZY103HSL. Some of their important physical characteristics and mechanical properties are listed in Table 1. Samples of these materials were in the form of small plates, cut from injection molded dog-bone-shaped specimens prepared according to ISO 3167 standard. Four sets of dimensions were considered for the study of the effect of apparent area of contact: 47.5 mm × 6 mm; 95 mm × 6 mm; 95 mm × 12 mm and 95 mm × 24 mm all having a thickness of 3 mm. All other experiments were performed using samples with the dimensions 95 mm × 12 mm × 3 mm thus having an apparent area of contact of 1140 mm². The contacting surface was carefully polished to obtain a uniform surface roughness R_a of 0.3 μm. After-worth, it was cleaned using compressed air and a soft brush then the samples were conditioned in an environmental chamber set at 23 °C and 50% RH.

AISI 1045 steel and 6061-aluminum alloy with surface roughness R_a of 1.74 and 1.68 μm, respectively were selected as matting materials (platform). Before each test, the platforms were thoroughly cleaned with acetone then dried.

For tests under lubricated conditions, thin film of de-ionized water or paraffin oil was deposited on each of the two contacting surfaces ensuring 100% coverage. The chosen paraffin oil had a density at 20 °C varying between 0.83 and 0.86 g/ml, and kinematic viscosity at 37.8 °C of 30 cSt.

3. Results and discussion

3.1. Effect of normal load

The frictional force arises from the shear of adhesive junctions taking place at the real area of contact, principle expressed by the following:

$$F_f = \tau A_r \quad (6)$$

in which A_r is the real area of contact.

The literature reveals that A_r is conditioned by the surface topography considered in most analysis as covered

with asperities each characterized by a tip radius and height obeying a certain distribution. Tabor [13] has reported about the relationship between this parameter and the load F_n in the following observations:

- If the number of asperities remains constant when the load is increased then a power law represents the relationship between A_r and F_n when the asperities deform elastically.
- If the number of asperities making contact increases then A_r is proportional to F_n .
- In the case of plastic deformations, as predicted by Greenwood–Williamson criterion, then the law of proportionality applies also.

Pascoe and Tabor [14] have suggested that the above principles apply as first approximation to polymers with multi-asperity contacts, for which the time-dependant behavior may induce different relationships.

τ in Eq. (6) is the shear strength of the bonds formed at the interface, for the weaker material. The approximation of equating the interfacial shear strength with the bulk shear strength was found to be reasonable for polymers. Many authors have reported the relationship between this parameter and the contacting pressure for the case of thin film of materials as follows:

$$\tau = \tau_0 + \alpha P \quad (7)$$

in which τ_0 and α are constants depending mainly to the material.

Combining Eqs. (6) and (7) would give

$$F_f = (\tau_0 + \alpha P) A_r. \quad (8)$$

The static coefficient of friction is then expressed by the following equation:

$$\mu_s = \frac{\tau_0}{F_n} A_r + \alpha. \quad (9)$$

Eq. (9) indicates that μ_s is dependant on A_r and F_n . This simple model that takes the effect of pre-stressing due to contact load into account neglects the effects of temperature, rate of increase of the shear load and contact time.

Figs. 4 and 5 present the results of the effect of moderate normal load on the static friction coefficient for the studied plastics in contact with steel and aluminum considering a low acceleration rate $\dot{\omega} = 1.78 \text{ mm/s}^2$. Overall the data are

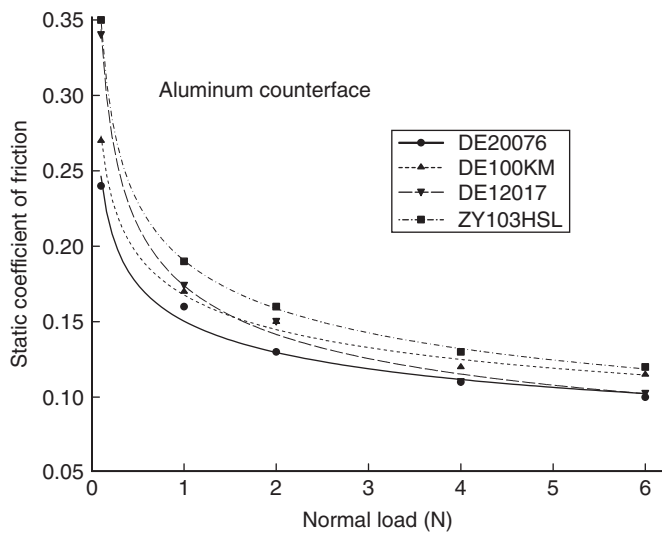


Fig. 4. Effect of normal load on the static friction coefficient case of aluminum counterface.

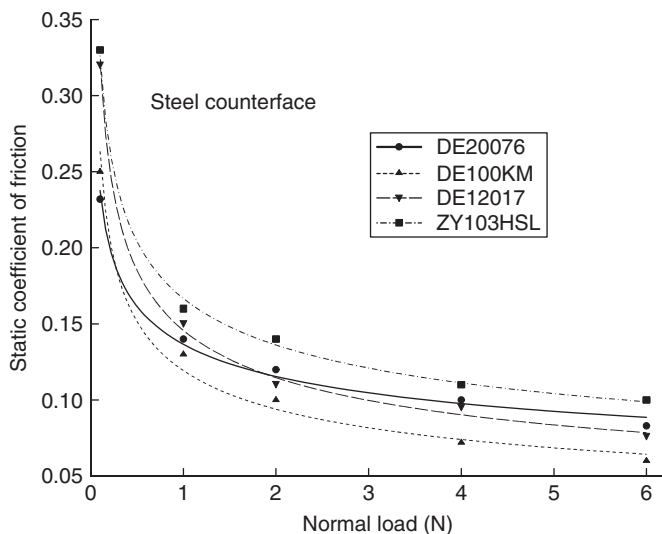


Fig. 5. Effect of normal load on the static friction coefficient: case of steel counterface.

comparable to those obtained for related plastics using different experimental setup in a previous study [7]. Evident decrease is apparent for increasing loads to about 4 N followed by a leveling off, especially in case of aluminum counterface.

The present results suggest that assuming the low range increase in normal load does not affect the number of asperities initially in contact, which in turn imply a power law relationship between A_r and F_n , the decrease of μ_s with F_n is justified by Eq. (9). On the contrary, at relatively higher loads μ_s approaches a constant value due to the linear relationship of A_r with F_n that prevails in this condition. This also implies that at this stage, the

interfacial shear strength of the micro-junctions becomes independent of the normal load. Additionally, due to the nature of these experiments conducted almost instantaneously after the application of the normal load and at a high rate of increase of the tangential loading, the effect of asperity creep is proven to be minimal knowing that it would have induced an increase of μ_s [15]. Although the same trend applies to both contacting surfaces the matting material markedly influences the results. Lower static friction is generated in the case of steel contacting steady surface compared to aluminum. Additionally, higher static coefficient of friction was found for Nylon-66. Furthermore, the effect of the filler in the case of POM is linked with the type of counterface. DE100KM produces lowest static friction when in contact with steel; on the other hand it is the case of DE20076 with aluminum interface.

Chang et al. [2] conducted a theoretical analysis of static friction coefficient for metallic rough surfaces and concluded that the static friction coefficient decreases with the load for a given surface roughness. The present results support the theory presented by Malzbender and de With [16], applicable to the case of surface scratching by a spherical indenter. The combination of the area of contact as predicted by Hertz's equation and the shear stress at the deformed surface of the body, predicted by Hamilton permitted these authors to develop a solution that expresses the friction coefficient as function of the normal load, equivalent modulus, shear stress and work of adhesion. According to this solution, they concluded that the friction coefficient should decrease as function of the normal load. Assuming that in the present study, each asperity of the metallic counterface behaves in a similar manner, one can conclude that the effect of the load on the static coefficient of friction is predominant in comparison with the induced variation of the shear stress. This implies that the decrease of the static coefficient of friction, at pressures below yield level of asperities and negligible creep, is governed by the effect of the normal load on the real area of contact. Coming back to the same derived solution, it also predicts an increase of the static coefficient of friction with the decrease of the stiffness (modulus of elasticity) of the counterface material; aluminum in the present case.

Finally, although small differences were noted in reported average value of the static coefficient of friction when considering each Delrin, there is no strong observation that could be made on the effect of the filler. However, a substantial reduction of the static friction coefficient was observed for the non-virgin Delrin at lighter normal load. It is not clear whether this is associated with the effect of the filler or that some other phenomena related to environmental conditions including interface chemistry (oxides) become more prevalent at this condition. It has been reported that the adhesion ability of a contact is function of the interfacial surface free energy.

3.2. Effects of acceleration rate of spinning platform and stick time

Eq. (4) reported earlier indicates that the static coefficient of friction determined as described would depend on the acceleration rate of spinning as well as the angular velocity at the instant when the transition from rest to motion of the sample takes place. Experiments were therefore conducted in order to assess the importance of the first parameter using three levels: $\dot{\omega} = 1.78, 3.21$ and 4.52 mm/s^2 . These results are plotted in Figs. 6 and 7 for the case of steel counterface and loads of 0.10 N (lowest) as well as 6 N (highest). As expected, it is shown that at low load, there is a decrease of the static friction with $\dot{\omega}$ for all tested materials. Coming back to Eq. (4), this finding indicates that by increasing $\dot{\omega}$, the contribution of the second term (ω^2) becomes less important which means that the preliminary displacement occurs faster thus affecting the dwell time. However, at higher load, as depicted by Fig. 7, the effect of $\dot{\omega}$ is less pronounced and could be neglected. At this condition of low friction, the normal load effect on the interface junctions is predominant. It was noted that the transition marked by a change in behavior takes place at about 2 N of load. Similar observations apply in the case of contact involving aluminum counterface. It is worth mentioning that there is a direct relationship between the starting rate of slip (acceleration) of the sample and $\dot{\omega}$ expressed by Eq. (3) although it was not measured nor controlled experimentally. The acceleration of the slip is in the present case equivalent to $r(\dot{\omega} + \omega^2)$. However, the stick time, defined by the time required for the sample to begin slipping during the spinning process was determined experimentally (see Fig. 3). These two important parameters were plotted against the load for a spinning acceleration $\dot{\omega} = 1.78 \text{ mm/s}^2$ in Fig. 8, not considering the lower load of 0.1 N. The obtained results together with those gathered at higher $\dot{\omega}$ have shown a linear decrease of slip acceleration as well as stick time with the increase of

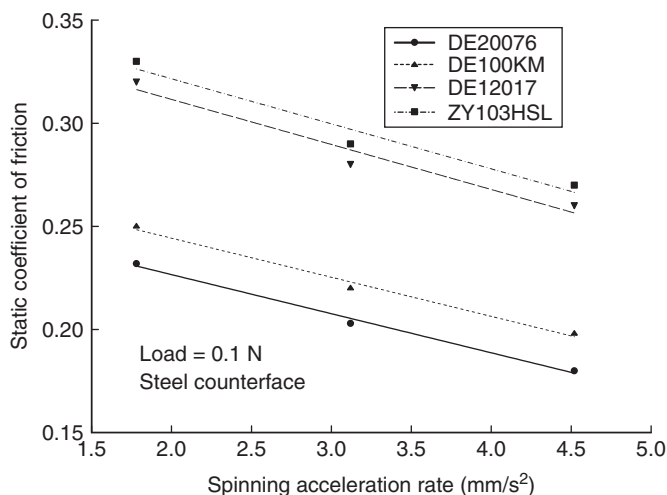


Fig. 6. Effect of spinning acceleration rate on the static friction coefficient: case of steel counterface and 0.1 N load.

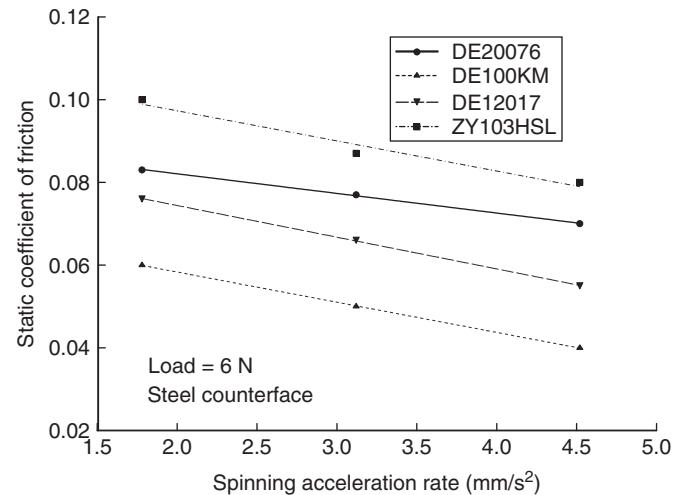


Fig. 7. Effect of spinning acceleration rate on the static friction coefficient: case of steel counterface and 6 N load.

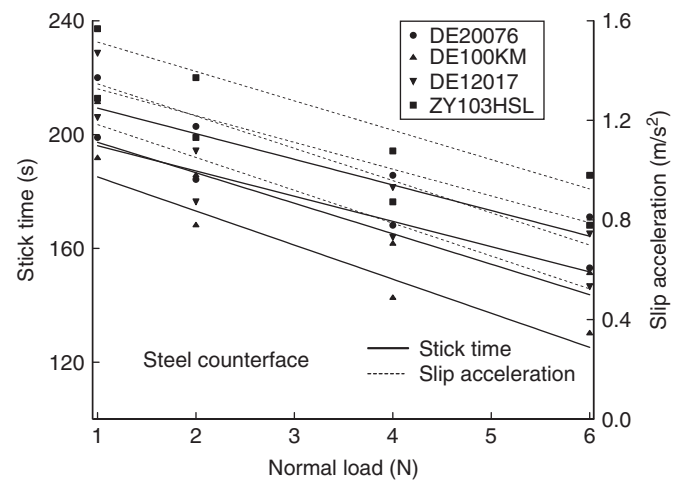


Fig. 8. Stick time and Slip acceleration as function of load.

normal load. This is consistent with the observed friction reduction with the load. Further investigation of the importance of $\dot{\omega}$ has determined that its effect on the slip acceleration vanishes at loads higher than 4 N.

Previous studies have reported a dependence of the static friction on the contact time between two surfaces when at rest. This was explained by a strengthening phenomenon of the interface junctions with the stationary time. In this research we have instead focussed on the stick time that was varied for a certain load using different spinning rates. It is to note that the so called stick time is short contact time that may take place in stick–slip conditions and that the stationary contact time refers to long-term contact between sliding parts when at rest. An example of the resulting trend of static coefficient of friction when the stick time is varied is shown in Fig. 9. It is seen that a polynomial equation, which increases monotonically, fits reasonably well all data for each load independently of the materials in contact. This observation may indicate that the initial friction force depends only on the stick time. Several

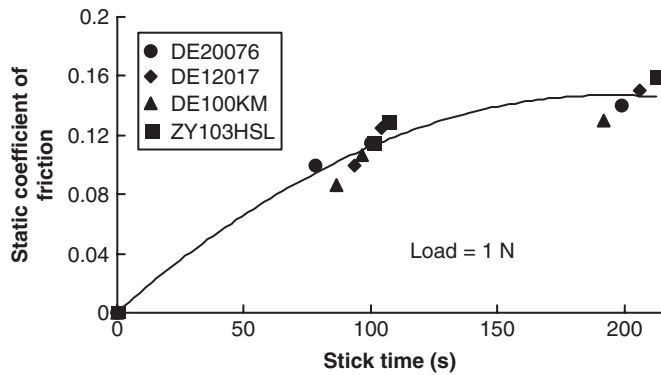


Fig. 9. Static coefficient of friction as function of stick time at 1 N load for steel counterface.

mechanisms have been described [11] to illustrate the influence of time of stationary contact on static friction. According to these authors the increase of static friction in these conditions can be explained by

1. The formation of capillary bridges produced by condensation of humidity (from the atmosphere) at the regions of contact between surfaces.
2. Increase in the contact area with time.
3. Shear stress relaxation at the interface that occurs generally during a stop time after sliding process.

A study of static friction behavior in polymer–polymer micro-bearings [17] has also revealed an increase of friction coefficient with the time of stationary contact.

In the present case, it is rather the increase of contact area that would explain the observed behavior. Early research have shown that the decrease of friction with the normal load (see Figs. 4 and 5) is indicative of the importance of the adhesion component defined as the product of the shear strength at the interface, that could be assumed constant during the very slow process of transition from rest to early stages of relative motion, and the real area of contact. Therefore, any increase of the latter would trigger an increase in friction. It is interesting to mention that Rymuza et al. [17] did not notice any significant increase of the real area of contact during the development of the shear force that tends to create relative displacement contrary to earlier belief. On the other hand, their results corroborate with the present findings in the manner that the increase of friction occurs during the first instants of static contact reaching a maximum value after about 200 s independently of the normal load. This pronounced effect is a strong indication that the static friction increase is not only governed by the time-dependent increase of the real area of contact but also the phenomenon of decrease of the elastic modulus of micro-contacts due to their rheological deformation. Both processes are in fact the result of contact creep [15]. As supporting argument, Eiss and Hanchi [18] have observed a decrease in static coefficient of friction when glass fibers

were added to polymers and concluded that it was due to the reduction in contact area resulting from improved stiffness. Our results have also showed higher static friction for DE12017 compared to DE100KM a stiffer Delrin containing Kevlar. On the other hand, the silicon oil contained in DE20076 did not improve the static friction. Explanations about this behavior will be provided hereafter. Finally, our experiments showed that ZY103HSL consistently experiences the longest stick time independently of load and slip acceleration compared to the other plastics. One can speculate that this type of contact involving highly hydrophilic surface, in contrast with the counterface, is certainly affected by the environment humidity that would promote capillary adhesion. It is to note that many reports have indicated that Zytel is the most prominent plastic material to generate squeaking during sliding friction. There is certainly a contribution of the capillary force to this behavior.

3.3. Effect of apparent area of contact

An example of the effect of the apparent area of contact on the static friction is shown in Fig. 9, which depicts the case of $\dot{\omega} = 1.78 \text{ mm/s}^2$, high load of 6 N and steel counterface. The range of apparent areas investigated in this study was from 285 to 2280 mm^2 . It is now recognized that the real area of contact is an important tribological parameter that defines the behavior of surfaces in contact. As an example; the product of the shear strength at the interface and the real area of contact describes the adhesion component of friction, which would be close to the static friction force in the present case of relatively smooth surfaces in contact. Because of the difference in hardness (metal against plastic) an indentation process by the asperities of the hardest material takes place. In such case the real area is defined by the ratio of the applied load (normal load) and the hardness of the softest material. The apparent area of contact is related to the load through the contact pressure, which permits to derive the general equation that expresses the relationship between the two areas:

$$A_r = A_a \frac{P}{H} \quad (10)$$

knowing that A_r and A_a are the real and apparent areas of contact, P the contact pressure and H the hardness. A rapid evaluation of A_r for the case of highest experimented contact pressure considering the plastic having the lowest hardness (see Table 1) gives 0.048 mm^2 , which means that it is considerably smaller than A_a as predicted by the theory despite the high smoothness. Therefore, as indicated by the results shown in Fig. 9 the static coefficient of friction was found to be relatively independent from the apparent area of contact. This could also be interpreted by considering Greenwood and Williamson theory stating that the real area of contact is independent on the apparent contact area. (Fig. 10)

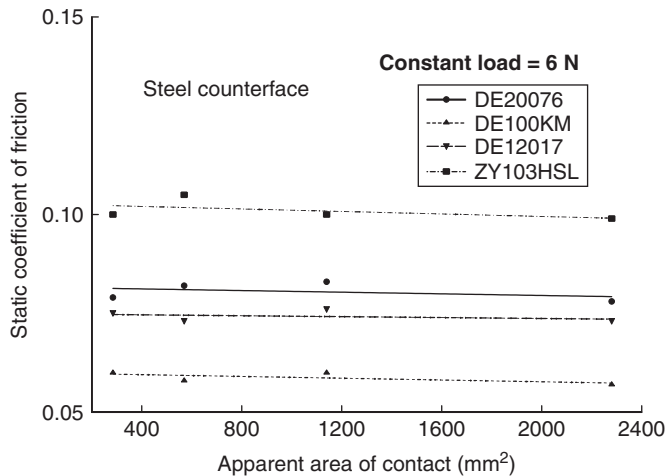


Fig. 10. Effect of the apparent area of contact on the coefficient of static friction.

3.4. Effect of lubrication

Lubrication using water was investigated as a way to simulate the behavior of contacting surfaces in static contact under conditions of humid environment with the potential of formation of water film at the interface due to condensation. Oil, on the other hand is generally used to improve dynamic friction and reduce wear. Although, it is believed that stick-slip motion encountered in machine parts and induced during accelerating and decelerating stages of friction may be overcome by lubrication.

It has been reported that high humidity causes high stiction for mechanically textured surfaces. When the contact region is completely submerged with liquid (lubricant), the capillarity force is proportional to the product of surface tension and the combination of contact angles the liquid makes with each of the two involved bodies [19]. Li et al. [20] have found a dramatic increase of the stiction when the relative humidity exceeded 85%. Sundararajan and Bhushan [21] have suggested that lubrication of MEMS by mobile lubricants produces adverse effects of increasing static friction force.

Figs. 11 and 12 present the effect of water and paraffin oil on the static friction coefficient of the investigated plastics on steel and aluminum alloy surfaces at a load of 2 N taken as example. All results, not necessarily included here, showed a clear increase of the static friction under lubrication in comparison with the dry case. More precisely, in presence of paraffin oil a more substantial rise takes place. Recent research has now established that the presence of lubricant or adsorbed water films increases the adhesion force between contacting surfaces due to the formation of meniscus forces. Thus, the present results are in agreement with this finding. It is to note that extra precaution was taken in order to ensure that the same quantity of lubricant was used, thus guarantying that the film thickness remained constant when repeating the

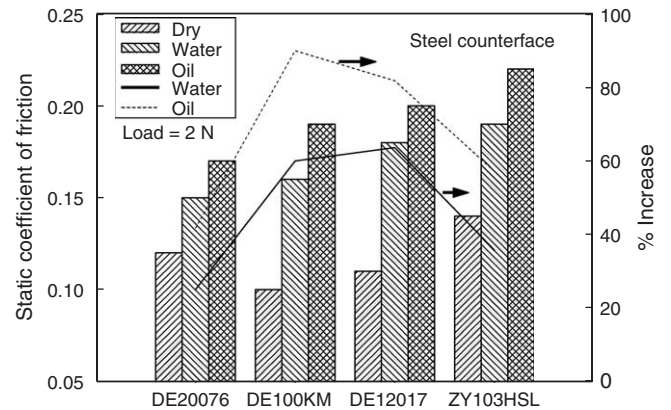


Fig. 11. Effect of lubrication on the coefficient of static friction: case of steel counterface.

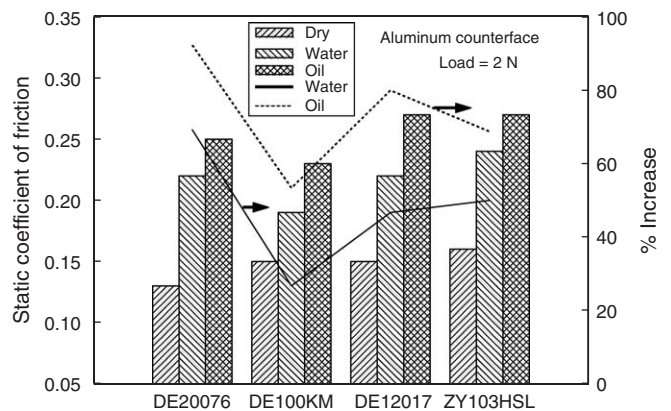


Fig. 12. Effect of lubrication on the coefficient of static friction: case of aluminum counterface.

experiments at the same condition for each plastic material. Tian and Bhushan [22] have presented a discussion on the relationship between liquid film thickness and meniscus formation at the contact interface of rough surfaces. They have shown that the meniscus force is a function of meniscus volume. It is clear that the meniscus volume is not only function of the film thickness but also the surface roughness and properties of the materials involved in the contact. It is to note that the smoothness of the contacting surfaces in the case of the present study has the effect of promoting the adhesive effects of lubricating films.

The lines of Figs. 11 and 12 depict the difference in behavior of the studied plastics, expressed in percentage of increase of the static coefficient of friction. DE100KM and DE12017 experienced the highest comparable increase of about 60% with water lubrication and about 85% in the presence of paraffin oil when in contact with steel. Conversely, comparable increase level was found for DE20076 against aluminum counterface. It is demonstrated that the surface chemistry has an important impact on the amount of increase of static friction due to lubrication. Assuming that the film thickness did not vary

substantially from one experiment to the other, the amount of increase is therefore mainly related to the type of material and lubricant. The thicker adsorbed layer in the case of paraffin oil, which promotes the formation of new bridges, explains the higher adhesion compared to water lubrication in addition to the rise in viscous friction. Additionally, the phenomenon water plasticization especially accentuated in the case of ZY103HSL would have an impact on the mechanical properties of the polymers. This would translate in an evident increase of the real area of contact, which affects the static coefficient of friction. It is at this stage difficult to disassociate the two simultaneous effects that take place. Further work is needed to clarify this observation.

4. Conclusions

In this study, the static friction behavior of four engineering thermoplastics namely Delrin-based DE-20076, DE100KM and DE12017 as well as Nylon-66 designated ZY103HSL was examined when in contact with steel and aluminum alloy. The influence of normal load, stick time, apparent area of contact and lubrication of the interface using water as well as paraffin oil was assessed.

Based on the obtained experimental results, the following conclusions can be drawn:

1. The static friction varies with the type of plastic, and decreases sharply with increasing low load then remain almost constant. Although the same trend applies to both contacting surfaces the matting material markedly influences the results. It was shown that an increase of the static coefficient of friction takes place with the stiffness decrease of the counterface material. The influence of the filler depends on the contacting surface.
2. A linear decrease of slip acceleration as well as stick time takes place with the increase of normal load.
3. The influence of stick time on static friction is marked by a monotonic increase independently of the materials in contact. It is therefore suggested that the initial friction force depends only on the stick time. This effect is a strong indication that the static friction increase is not only governed by the time dependant increase of the real area of contact but also the phenomenon of decrease of the elastic modulus of micro-contacts due to their rheological deformation. DE12017 showed higher static friction compared to DE100KM which is a stiffer Delrin containing Kevlar. Silicon oil contained in DE20076 did not improve the static friction. ZY103HSL consistently experiences the longest stick time independently of load and slip acceleration. This behavior is related to the capillary adhesion promoted by its highly hydrophilic nature.
4. The static coefficient of friction is relatively independent from the apparent area of contact.
5. There is an increase of static friction under lubrication in comparison with dry condition due to the formation of

meniscus forces. The thicker adsorbed layer in the case of paraffin oil, which promotes the formation of new bridges, explains the higher adhesion. DE100KM and DE12017 experience the highest comparable increase of about 60% with water lubrication and about 85% in the presence of paraffin oil when in contact with steel. Comparable increase level was found for DE20076 against aluminum counterface. This indicates that the surface chemistry has an important impact on the amount of increase of static friction due to lubrication.

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