

CONSIDERATIONS REGARDING THE DEFORMATION OF POLYMERIC MATERIALS IN SLIDING CONTACT WITH METALLIC MATERIALS

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Abstract: The effects of friction on polymeric materials are difficult to explain due to complex interactions, both at the microscopic and macroscopic levels, between the surfaces of the friction pair sliding over each other. The friction and wear behaviour of the surfaces in relative sliding motion can be deemed an essential criterion in the design process. The estimation and evaluation of the parameters specific to abrasive wear are of particular interest in order to optimize the design of sliding pairs. In order to establish the area of application of different material combinations, it is necessary to know their friction behaviour under experimental conditions as close as possible to those found in the industrial environment. The paper analyses several specific aspects that occur at the interface between a metallic material and a polymeric material under conditions of abrasive wear.

Keywords: wear, friction, strain, deformations, asperities

1. INTRODUCTION

The increasing complexity and degree of automation of specific technical systems in the machine building industry requires knowledge of the phenomena that occur at the interface of the sliding contact surfaces.

Thermoplastic polymeric materials are widely used in various industrial fields due to their ability to bear high mechanical and thermal stresses. In order to be integrated into tribological applications, they must have good abrasion resistance. Meeting this requirement is difficult, as their viscoelastic behaviour significantly complicates the tribological analysis [1–6].

Metallic-polymeric material pairs are frequently encountered in practice. Understanding the tribological behaviour of different polymer/metal combinations requires extensive experimental research before their implementation in industrial applications. An essential aspect is the analysis of the deformation mode of the polymeric material and the stress state induced during sliding contact with the roughness of the metallic surface. This step is the starting point for assessing the friction and wear conditions and determining the tribological performance of the selected material pair [7].

It is known that the asperities of the metallic surface cause, at least in the initial phase of sliding, abrasive wear on the polymeric material. In this paper, the

metallic asperities are modelled as cones with variable angles [8]. Based on Hencky's slip-line field theory and the friction and wear models established in the literature, this article aims to analyse the phenomena that occur at the metallic-polymeric interface in the case of abrasive wear.

2. ASPECTS REGARDING THE BEHAVIOR DURING SLIDING CONTACT BETWEEN A POLYMERIC AND A METALLIC MATERIAL

2.1. Theoretical aspects regarding the evolution of the sliding friction coefficient

The aspects regarding the reaction of polymeric materials to sliding in contact with conical or pyramidal bodies with a higher hardness than the tested polymer have been studied by numerous researchers; they concluded that the type of deformation can be elastic, smoothing, ductile grooving, ductile cutting and cracking, and brittle cutting.

For the quantitative analysis of the wear process, the case of plastic deformation with the detachment of the wear particles after a specific number of cycles (according to the Manson-Coffin low-cycle fatigue model) is taken into account when the approach angle is less than a critical value (α_{cr}) [9, 10].

When the approach angle is greater than a critical value (α_{cr}), the material's reaction is micro-cutting, and in this case, the plastically deformed volume is detached as a wear particle in a single cycle.

For the purpose of analyzing the frictional coefficient evaluation, a metallic asperity with an inclination angle α in contact with a polymeric material is considered. The asperity moves on the flat surface (of the polymeric material) at a speed v_a , as shown in Figure 1.

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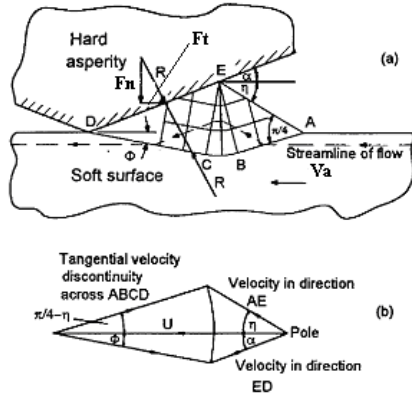


Figure 1. Flowchart of the wave-shaped deformation model a. slip line field b. hodograph

The classical definition of the friction coefficient is:

$$\mu = \frac{F_t}{F_n} \quad (1)$$

where: F_n - the normal force on the width unit ED;

F_t - the tangential force from the slip line Hencky theory.

The friction coefficient, in the case of softer material deformation, is:

$$\mu = \frac{\beta \cdot \sin(\alpha) + \cos(2\varepsilon - \alpha)}{\beta \cdot \cos(\alpha) + \sin(2\varepsilon - \alpha)} \quad (2)$$

where:

$$\beta = 1 + \frac{\pi}{2} + 2\varepsilon - 2\alpha - 2 \arcsin\left(\frac{\sin \alpha}{\sqrt{1-f}}\right) \quad (3)$$

f - parameter that characterise the friction between the asperity and the deformed material ($f=1$ for perfect clean materials, without grease; $f=0$ for material with continuous lubricant film-named adhesion coefficient).

$$\varepsilon = \frac{1}{2} \arccos(f) \quad (4)$$

The theoretical evolution of the friction coefficient during wave-like deformation of the polymeric material depending on the inclination angle of the penetrator for

dry ($f=0$) and mixed ($f=0.2$; $f=0.3$; $f=0.6$) lubrication conditions is shown in Figure 2. It is considered that for friction coefficient values greater than 1, the deformed material moves wave-like, but detaches after a number of cycles, according to the Manson-Coffin model.

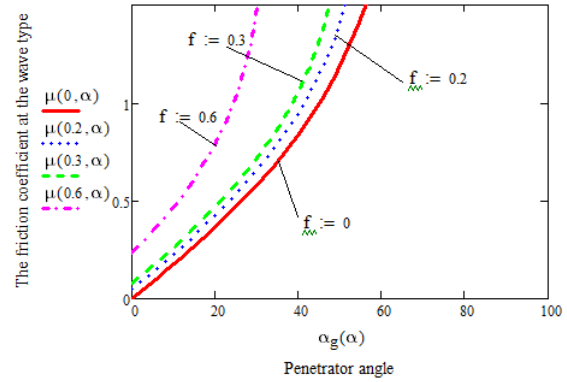


Figure 2. Theoretical evolution of the friction coefficient during wave-like deformation of the material, depending on the angle of the penetrator

It is noted that for the same inclination of the penetrator, the friction coefficient decreases as the amount of lubricant between the surfaces increases ($f \downarrow 0$).

Figure 3 shows the evolution of the friction coefficient during wave-like deformation depending on the lubrication state ($f=0, \dots, 0.6$) for the inclination angles of the penetrator of $\alpha=5^\circ, 10^\circ, 20^\circ, 30^\circ$.

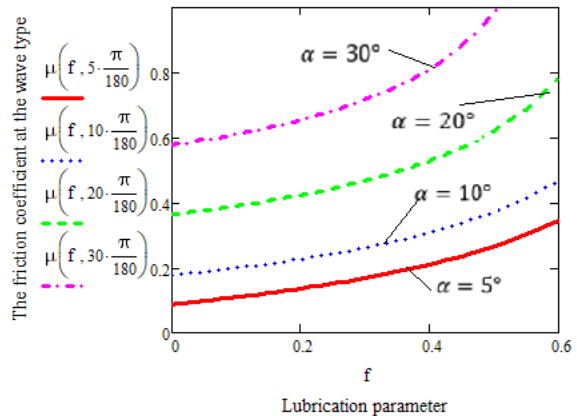


Figure 3. Variation of the friction coefficient depending on the coefficient of adhesion f

It is deemed that for the same lubrication conditions, the friction coefficient increases with the increase in the inclination angle of the penetrator.

The deformation that occurs with repeated passage of the conical roughness will eventually lead to wear. To explain the more severe forms of wear, Challen and Oxley [11, 12] introduced the wave removal and chip formation models shown in Figure 4 and Figure 5. The wave removal model applies when the wave is no longer pushed along the surface in front of the asperities but is torn off. Theoretically, this will happen when (referring

to Figure 1) the angle $\Phi \leq 0$, a condition that results from the increase in the inclination angle α or a weaker lubrication $f > 0$.

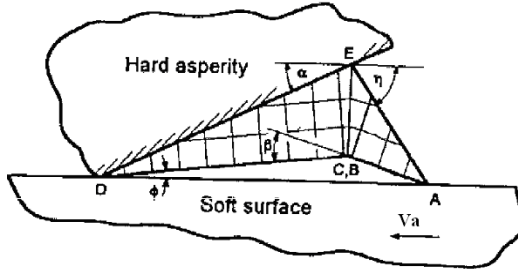


Figure 4. Schematic representation of the sliding model for wave removal

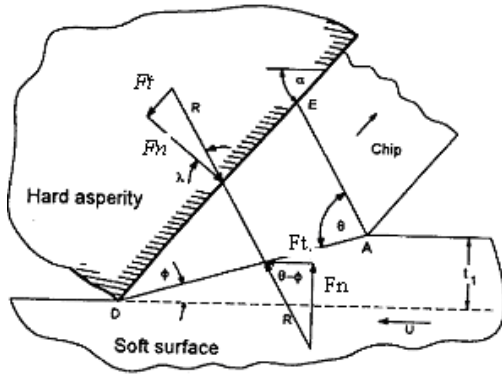


Figure 5. Schematic representation of the chip formation model

This form of wear can be compared to Archard's theory of adhesive wear, but there is an important difference in that the produced wear particle does not have to be welded onto the hard asperity. For rougher surfaces, the material will be removed by a chip formation process shown in Figure 4, similar to the case of abrasion [13, 14].

For the wave removal model (Figure 4), which applies when $\Phi \leq 0$, the expression for the friction coefficient μ is given by the relationship:

$$\mu_a = \frac{\left[1 - 2 \sin \beta + (1 - f^2)^{1/2}\right] \sin \alpha + f \cos \alpha}{\left[1 - 2 \sin \beta + (1 - f^2)^{1/2}\right] \cos \alpha - f \sin \alpha} \quad (5)$$

where:

$$\beta = \alpha - \frac{\pi}{4} - \frac{1}{2} \arccos(f) + \arcsin\left(\frac{\sin \alpha}{\sqrt{1-f}}\right) \quad (6)$$

Figure 6 shows the theoretical evolution of the friction coefficient in the case of the deformed wave displacement model.

When the inclination angle of the asperity exceeds a critical value, according to the micro-cutting model, the angle of the shear plane Φ and the chip angle θ are determined from the equations:

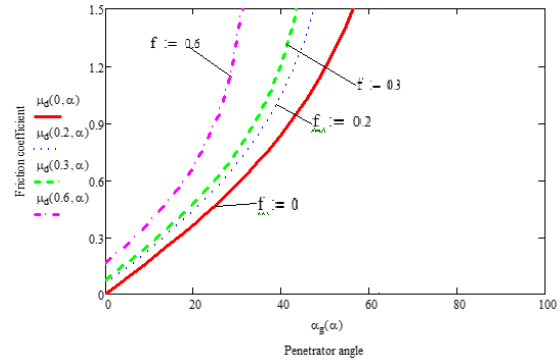


Figure 6. Theoretical evolution of the friction coefficient in the case of the deformed wave removal model

$$\operatorname{tg}(\theta) = 1 + 2 \left(\frac{\pi}{4} - \Phi \right) - C_n \quad (7)$$

$$\theta = \frac{\pi}{2} + \Phi + \frac{1}{2} \arcsin(f \cdot \sin(2\theta)) - \alpha$$

where C_n is a hardening parameter of the plastically deformed material, which can be determined experimentally ($C_n \approx 0.8, \dots, 1.2$).

Chip deformation occurs if the shear angle Φ is greater than zero, $\Phi > 0$, in which case micro-cutting wear occurs (only for $\alpha \geq \alpha_{cr}$).

For the micro-cutting wear model, the friction coefficient μ_a is determined based on the diagram in Figure 4 and the theory of plastic deformation.

$$\mu_a = \operatorname{ctg}(\theta - \Phi) \quad (8)$$

This expression is valid for angles of asperities greater than the critical value α_{cr} .

Figure 7 shows the variation of the friction coefficient during micro-cutting of the polymeric material, depending on the inclination angle of the penetrator α and the coefficient of adhesion f ($f=0$; $f=0.2$; $f=0.3$; $f=0.6$).

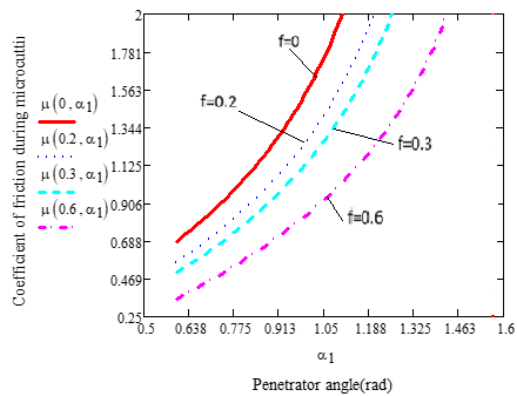


Figure 7. Theoretical evolution of the friction coefficient during micro-cutting

It has been found that in the case of micro-cutting, consistent lubrication worsens the surface damage process, causing the friction coefficient to increase significantly.

2.2. Theoretical aspects regarding the deformation strain of the material

In order to understand the formation of wear particles, it is necessary to define the deformation state for the material layer in contact with the asperity.

The Young-Torrance model [10] is accepted, so that the material crossing the distance AD (Figure 1) will undergo three shear deformations, in axial (x) and tangential (y) directions.

$$\begin{aligned} & \text{on AB direction:} \\ & \varepsilon_{xxA} = \sqrt{2} \sin \theta \cos \eta - 1 \\ & \varepsilon_{yyA} = \sqrt{2} \sin \eta \cos \theta \\ & \varepsilon_{yxA} = -\sqrt{2} \sin \theta \sin \eta \end{aligned} \quad (9)$$

$$\begin{aligned} & \text{on CD direction:} \\ & \varepsilon_{xxC} = 1 - \frac{\cos \alpha \sin \Phi}{\sin \varepsilon} \\ & \varepsilon_{yyC} = -\frac{\sin \alpha \cos \Phi}{\sin \varepsilon} \\ & \varepsilon_{yxC} = -\frac{\sin \alpha \sin \Phi}{\sin \varepsilon} \end{aligned} \quad (10)$$

$$\begin{aligned} & \varepsilon_{xyC} = \operatorname{ctg} \Phi - \frac{\cos \alpha \cos \Phi}{\sin \varepsilon} \\ & \text{on BC direction: (rel 11)} \\ & \varepsilon_{xxB} = R \left\{ \cos \Phi - R + R \ln(\cos \Phi - R) - \sin \left(\frac{\pi}{4} - \eta \right) - R \ln \left[\sin \left(\frac{\pi}{4} - \eta \right) \right] \right\} \end{aligned}$$

$$\varepsilon_{xyB} = - \left\{ 2R \left[\sin \Phi - \sin \left(\frac{\pi}{4} - \eta \right) \right] + 2R^2 \left(\theta - \frac{\pi}{4} - \eta \right) + R \frac{2R^2 - 1}{\sqrt{1 - R^2}} A \right\}$$

where: $R = \sqrt{2} \sin \eta$

$$A = \ln \left| \frac{(1+R) \tan \frac{\Phi}{2} + \sqrt{1-R^2}}{(1+R) \tan \frac{\Phi}{2} - \sqrt{1-R^2}} \right| - \ln \frac{(1+R) \tan \left(\frac{\pi}{8} - \frac{\eta}{2} \right) + \sqrt{1-R^2}}{(1+R) \tan \left(\frac{\pi}{8} - \frac{\eta}{2} \right) - \sqrt{1-R^2}}$$

Thus, Yang and Torrance experimentally found that the specific characteristic deformation (C) depends on the following:

$$C = \exp(a \cdot \varepsilon_f + b) \quad (12)$$

where: a, b- constants (a=1.62, b=2.15)

ε_f – the deformation produced at the section reduction (RA) of the bar, during the traction fracture test.

$$\varepsilon_f = -\ln \left(\frac{100 - RA}{100} \right) \quad (13)$$

Knowing the reduction of the RA section (%) at breakage under uniaxial tensile load allows the definition of the specific deformation (C) (relation 9).

When the specific deformation (C) is greater than a critical value (C_{cr}) defined by Yang-Torrance, wear causes wave deformation (ratchet):

$$C_r = \frac{(2\varepsilon_{xxt})^2}{|\varepsilon_{xyt}|} \quad (14)$$

where: ε_{xxt} – the relative axial total deformation;
 ε_{xyt} – the tangential relative deformation.

When $C < C_{cr}$, wear by deformation is uniform. Figure 8 shows the Yang-Torrance specific dependence of critical deformation, the formation of the "shear" angle for different values of the adhesion coefficient f and the material's hardening coefficient C_n .

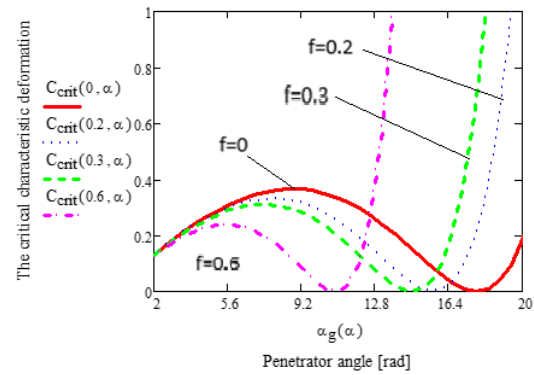


Figure 8. The specific critical deformation Yang-Torrance

2. MATERIALS AND METHODS

2.1. Analysed materials

The experimental part of this paper analyzes a thermoplastic polymeric material called Turcite-B Slydway in contact with S235JR universal steel, used for machine construction, manufactured in accordance with standard SR EN 10025/2-2004 [15].

The physical and mechanical characteristics of the polymeric material are presented in Table 1 [16], and S235JR steel has yield strength $\sigma_c = 235 \text{ MPa}$ and tensile strength $\sigma_r = 360 - 510 \text{ MPa}$.

Table 1. Physical-mechanical characteristics of the analysed materials

Mechanical properties	Turcite-B Slydway
Tensile strength [MPa]	75
Hardness [Shore D]	70-80
Thermal conductivity at 20°C [W/m K]	0.17
Modulus of elasticity at 20°C [N/mm ²]	1000
Thermal expansion [m/°C]	6 10 ⁻⁵
Density [Kg/m ³]	1210
Max/Min working temperature [°C]	-170 ⁰ ...200 ⁰

2.2. Experimental part

Experimental research to evaluate the friction coefficient was carried out on a pin-on-disc tribological friction test rig, whose schematic drawing is shown in Figure 8) [17].

The inner body (flat surface) is a plate made of the Turcite polymer material under analysis, and the upper body/pin, which simulates the asperity, is a conical pin with different approach angles ($\alpha = 3^\circ, 5^\circ, 12^\circ, 20^\circ, 30^\circ, 40^\circ, 60^\circ, 85^\circ$).

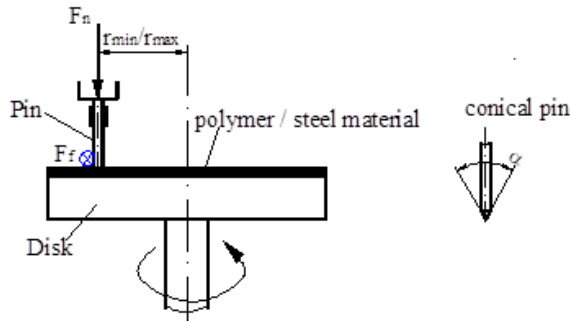


Figure 8. Schematic diagram of the pin/disc tribological rig

3. THE EXPERIMENTAL RESULTS

The experimental results regarding the determination of the friction coefficient were obtained by taking into account three distinct lubrication regimes: good lubrication (f), characterized by the presence of a significant amount of lubricant near the contact area, borderline lubrication (l), a situation in which the surfaces are lubricated exclusively in the initial phase of testing, and dry friction (u), defined by the intentional absence of the lubricant, the contact being made under conditions of ambient humidity at standard temperature.

Figure 9 shows the evolution of the friction coefficient (μ) for Turcite-B Slydway material depending on the inclination angle of the penetrator for the three lubrication states. It can be seen that it is not desirable to lubricate the surfaces of the polymeric material during sliding.

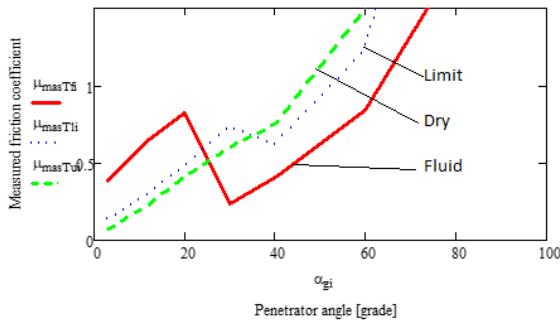


Figure 9. Evolution of the friction coefficient for Turcite-B Slydway material

The curves shown represent the average values resulting from five experimental measurements performed under identical conditions. The reproducibility of the results was evaluated using the coefficient of variation, defined as the ratio between the standard deviation and the arithmetic mean of the measured values, obtaining a value of $C_v = 0.13$, which indicates a moderate dispersion of the experimental data.

The analysis of the wear process by deterioration, associated with oligocyclic deformation mechanisms, requires a detailed characterization of the geometry of the deformed material layer under controlled experimental conditions. For this purpose, the geometry of the wear track was determined by measuring, with the help of a micrometer mounted on the test bench, the cross-sectional groove obtained by cutting the material being tested [1,2,15].

The wear track measurements were performed after 40, 80, and 160 sliding cycles.

Figure 10 shows the geometry of the wear track (h) depending on the tangible length of the worn area (x).

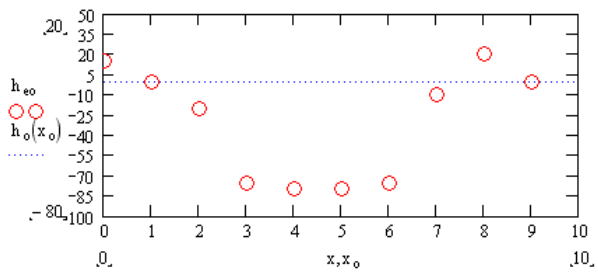


Figure 10. The wear track geometry

5. CONCLUSIONS

The proposed friction and wear model provides a conceptual framework to explain the tribological behavior of the polymeric materials in contact with metallic surfaces. The deformation state of the polymeric material is characterized by the critical inclination angle of the asperity, designated as α_{cr} , which delimits the distinct degradation regimes.

For values of the inclination angle smaller than α_{cr} , estimated to be around $20^\circ \dots 30^\circ$, the wear process is mainly associated with the deterioration of the plastically deformed surface layer. On the other hand, for values of the angle greater than α_{cr} , the prevailing degradation mechanism is micro-cutting, determined by the ability of the asperities to perform cutting actions on the polymeric material.

The experimental validation of the theoretical model highlighted the following aspects:

- The friction coefficient increases as the inclination angle of the asperity increases and decreases as the coefficient of adhesion increases, in the case of asperities with cutting potential;

- The shape of the plastic deformation wave depends on both the toughness of the material and the components of axial and tangential deformation;
- The lubrication regime significantly influences the deformation behavior of the material and the evolution of the friction coefficient;
- The coefficient of adhesion (f), deemed a defining parameter of the lubrication state, is not influenced by the inclination angle of the asperity, but depends on the properties of the material prone to plastic deformation;
- Geometric analysis of the wear track highlights the existence of two marginal areas of material accumulation, symmetrically arranged on either side of the groove, thus confirming the two distinct wear mechanisms, depending on the inclination angle of the asperity used for testing.

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