WEAR MODEL OF FLAT SLIDING SURFACES USED IN THE MACHINE-TOOLS INDUSTRY

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Abstract. *Wear is defined as the process of destruction of the superficial layer of a sliding coupling in a small volume of material, that leads to the occurence of wear particle. The mechanism of wear particle formation depends to a great extent on the deformation state in the contact area (elastic, plastic, elasto-plastic), on the nature of the material (breaking tenssion, flowing tenssion etc) and on the working conditions (pressure, velocity, temperature etc). The harder material, may be elastically or plastically distorted, thus changing the state of the conjugate surface, function on the maximum deformation on the friction surface, on the angle and the geometry of asperity (or abrasive particles). The paper proposes both an analysis of the way the materials behave under the action of a sliding coupling, for materials with different hardnesses and the drawing up of some maps in order to establish the frictional and wear behaviour of a sliding coupling function on the above-mentioned parameters, thus, the processing, loading and lubrication conditions that might influence the good working of the sliding coupling may be avoided.*

Keywords: *deformation, asperity, wear particle, wear intensity, fatigue, superficial friction layer*

1. INTRODUCTION

Wear, defined as a process that destroy the superficial layer of a body when in contact with another body (solid) is a permanent phenomenon that occur in the working of a coupling. It may be presented in different ways - adhesion, abrasion, oxidation etc, but no matter the predominance of any of these is, the effect on the coupling remains the same – the destruction of the superficial layer in the friction area and often the destruction of the material volume of the coupling.

The destruction that occurs at the level of the superficial layer of the material takes place in a small volume, resulting in the wear particle forming. The variety of models and constructive forms of cinematic couplings, the variety of the materials used as well as the mainntenance and operating conditions have led to a great diversity of responses regarding the reaction of couplings to friction and wear [2,7].

The mechanism of wear particle forming involves an analysis of the material (elasticity, plasticity, viscosity) and working (pressure, velocity, temperature) factors specific to each kind of coupling. The flat friction couplings of sliding-guide type, with sliding motion, are part of those couplings where the motion cyclicity leads to the fatigue of the friction superficial layer of the material of the coupling.

The different hardness of the materials of slide and guide (HB guide>HB slide) is a factor that leads to local plastic deformations of the friction surface.The presence of wear particles, as a result of the plastic deformations that occur in the friction surface or, the accidental penetration of some particles from the outside (by means of coolant fluid or driven by the lubricant), leads to impairments of the friction surface.The shape and dimensions of the asperities or of the abrasive particles, the deformation state in the contact area and the material nature contribute to the surfaces wear [4].

The present paper proposes the analysis of the way the material of the slide behaves (smaller hardness) when a harder surface slides across it (bed guide).

2. WEAR MODEL

During the sliding process of a coupling, the adhesion and abrasive wear are prevailing. The adhesion wear is a permanent phenomenon, at least from the perspective of the material transfer from a side of the coupling to another, and abrasion is also present, part of the factors that influences it are above-mentioned.

The scientific literature reveals the fact that the friction force is due to the interaction of the asperities of the materials in contact, each of these interactions makes a contribution to the friction force increase. The transmission of the friction forces involves transformings of the coupling material both in superficial layer and in the volume. In this respect, the way of response of the material of the coupling may be elastic, elastoplastic or plastic. The behavior of a rigid asperity (the harder material) in contact with a perfectly flat surface (the less hard material) is analyzed, the case of more asperities depending to a great extent on the number of asperities that are in contact.

2.1. Adhesion – a measure of the relative displacement of the sliding couple

The adhesion wear (a permanent phenomenon that occurs in the working of a coupling) is characterized by relatively increased wear velocity and instability of the friction coefficients that occur during the working of a coupling.

In order to analyse the adhesion wear of a sliding coupling, the case of a rigid asperity with a triangular prism shape in contact with a elastic deformable flat surface is considered (fig.1). The asperity is characterized when in contact with the flat surface by the angle α and the contact lenght $L = ED$; the flat surface is characterized by the shear resistance $\tau_c = k$.

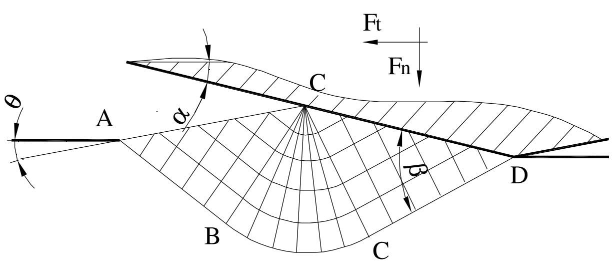

Figure 1. Model of deformation lines to asses adhesion

The displacement force needed depends on the nature of adhesion on the contact surface ED between the materials of coupling. If there is no adhesion, the friction force is null, and when the adhesion gets its maximum, the friction force gets its maximum, too. The solution of this problem is got by using the Hencky sliding-line theory [5, 6].

The shear stress that acts on the contact surface ED has an opposite direction to the dispacement (DE direction), and on the surface AE there is no tension, thus , the sliding-lines have an inclination angle of 45^o to AE. Then:

$$AE \sin\theta = ED \sin\alpha \quad (1)$$

$$AE \sin(\pi/4) = ED \sin\beta \quad (2)$$

The shear stress to DE is:

$$\tau_{DE} = fk = k \cos\beta \quad (3)$$

Where: f adhesion coefficient;

k material shear resistance

The adhesion coefficient is a measure of the lubricating condition between the surfaces in contact, so, for unlubricated materials $f = 1$ and for lubricated materials $f \cong 0$. The behaviour of a material when an asperity passes over depends on the adhesion coefficient f and on the asperity inclination angle:

$$f = \cos 2\beta \quad (4)$$

Thus, the size of asperity inclination angle to which the deformations may be elastic (Fig.2) can be determined. It is noted that the asperity inclination has a maximum of 16 corresponding to an adhesion coefficient of $f = 0{,}5$.

From the given relations one may determine the shear angle θ (fig.3) function on the adhesion coefficient f and the asperity angle α :

$$\theta = \arcsin\frac{\sin\alpha}{\sqrt{1-f}} \quad (5)$$

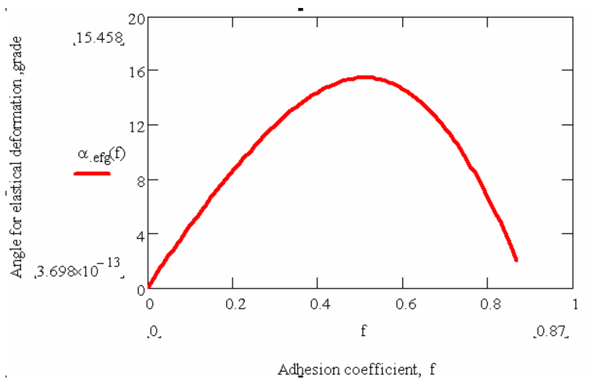

Figure 2. Variation of the asperity angle α with the adhesión coefficeint that causes elastic deformations

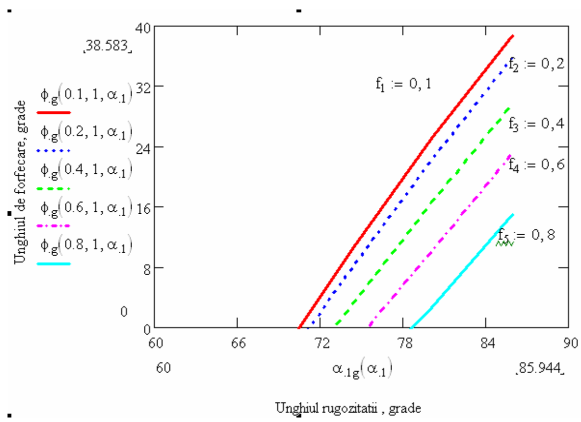

Figure 3. Variation of shear angle θ function on the asperity angle α

The resulting forces on the direction of dispalcement F_t and the normal to surface F_n are:

$$F_t = A \sin\alpha + \cos(\arccos f - \alpha) \quad (6)$$

$$F_n = A \cos\alpha + \sin(\arccos f - \alpha) \quad (7)$$

where: $A = 1 + \frac{\pi}{2} + \arccos f - 2\alpha - 2\arcsin\left(\frac{\sin\alpha}{\sqrt{1-f}}\right)$

According to the Amontons-Coulomb friction theory, the friction coefficient between two surfaces is:

$$\mu_a = \frac{F_t}{F_n} \quad (8)$$

and because the forces are defined by the adhesion coefficient f , then the above-mentioned relation may be defined as an adhesion component of the friction coefficient [5, 6].

If no asperities, the surfaces will be perfectly flat and the angle $\alpha \to 0$. The adhesion component of the friction coefficient in case of a flat surface will be:

$$\mu_{a0} = \frac{f}{1 + \frac{\pi}{2} + \arccos f + \sin(\arccos f)} \qquad (9)$$

The variation of adhesion friction coefficient with the inclination angle and the adhesion parameter f is given in fig.4.

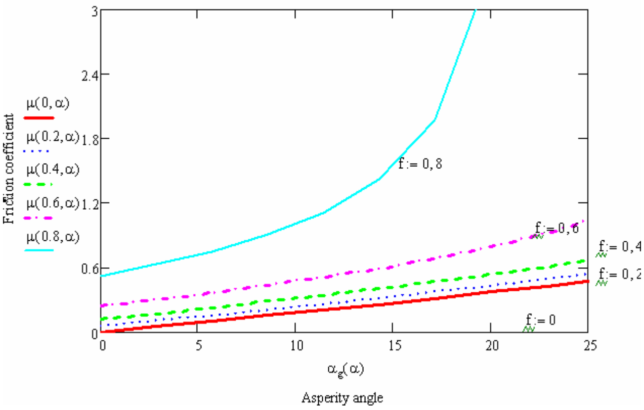

Figure 4. Variation of adhesion friction coefficient with inclination angle and adhesion parameter f

It is noted that for unlubricated materials ($f \rightarrow 0$) and small angles, the adhesion friction coefficient has small values and, in case of increased angles and lubricated surfaces the adhesion friction coefficient increases as well.

2.2. Abrasion –a modality to wear the friction surface

Abrasive wear – as widely known – is a mechanical process that means erosion of softer materials when asperities get into the coupling surfaces.

The behaviour of the abrasive wear depends on the roughness of the friction coupling surfaces and the real contact pressure between surfaces. For the process analysis, it is considered that the friction force and implicitly tensile stresses on the contact surfaces (σ) occur. An asperity may be cyclicly-stressed, without breaking, for a value of the equivalent contact stress which does not exceed the limit of elasticity of the material.

It is considered that the detachment of a wear particle takes place only after a number of stress cycles and it is based on fatigue. This phenomenon is determined by the tangent friction stress τ_f (Wöhler-type stress curve).

Within the volume of deformed material one considers that besides friction stresses, normal stresses also occur real contact stresses p_r), which generates the idea that the number of stress cycles is:

$$N = \left(\frac{\sigma}{k\tau_{ef}}\right)^t = \left(\frac{\sigma}{k\mu p_r}\right)^t \qquad (10)$$

where:

μ molecular component of the friction coefficient;

k depends on the theory of resistance (breaking hypothesis of the máximum normal stresses or of the maximum tangential ones $k = 3$);

t characteristic coefficient of each material (for steel $t = 7{,}90$, for cast iron $t = 4{,}15$);

σ_o material tensile breaking stress (for steel $\sigma_o = 700 MPa$, for cast iron $\sigma_o = 647 MPa$);

If the asperity is considered cone-shaped (where the radius r , the elastic modulus E , Poisson coefficient υ , and the tensile stress are known) when in contact with a rigid plane, in the presence of friction, the number of crossing cycles the asperity needs to impair the elastic layer with a width δ is:

$$N = \left(\frac{\pi}{2k\mu}\frac{\sigma_r}{E^*}\sqrt{\frac{r}{\delta}}\right)^t \qquad (11)$$

where: δ is thickness of the destorted layer $\delta = \frac{a^2}{r}$;

a - contact halfwidth $a = \left(\frac{3p_r}{4E^*}\right)^{1/3}$;

E^* - elastic modulus reduced $E^* = \frac{E}{1-\upsilon^2}$

p_r - real pressure $p_r = \frac{2}{\pi}E^*\sqrt{\frac{\delta}{r}}$.

For such a sliding coupling where the loading F is known, the variation in the number of the asperity stresses to which the fatigue deterioration of the superficial layer (for elastic deformations) occurs, is shown in figure 5.

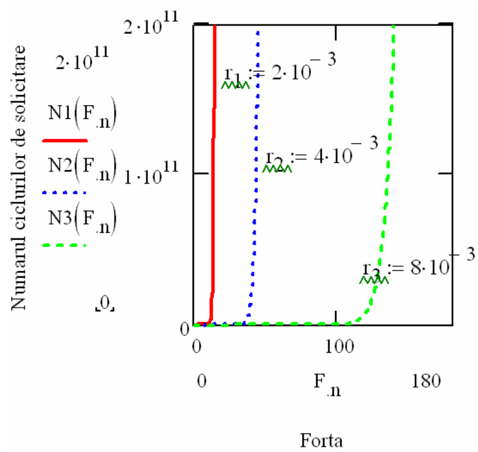

Figure 5. Variation of stress cycles number function on loading

2.3. The case of plastic deformation with a single asperity

The aspects regarding the behavior of materials with different asperities in the field of plastic deformations have been studied by many researchers. It has been ascertained that depending on the geometry of the harder surface, on its processing mode, more ways of manifestation may occur: crossing, splintering, cracking etc.

It was esperimentally proven that for a hard asperity (cone-shaped) in contact with a softer surface, the surface deterioration may result in:

- the flow of the material in front of the asperity in the form of a wave, the separation from the material taking place after more strain cycles – it is the case of asperities with a large peak angle, rounded or "blunted";

- detachment of the material in the form of wear particle (from the first cycle) because of the material flow - it is the case of asperities with small angle, sharp asperities [8], [9];

- asperities that can produce or not splints, depending on the strain in the contact area and on the size of the attack angle.

If the cone-shaped asperity and the contact with the flat plastic-type surface (Fig.6) are accepted, the Hencky sliding-line theory may be applied [2, 6, 7].

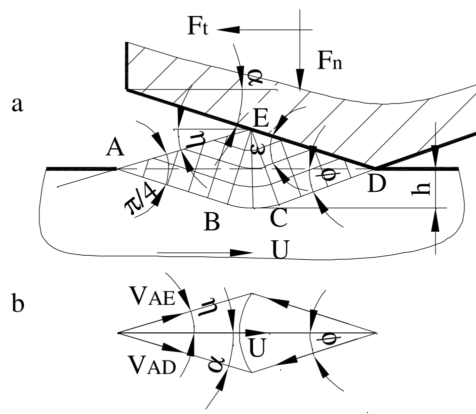

Figure 6. Distribution model of the sliding tracks field

Two cases are considered significant to explain the phenomenon:

- small asperity angles ($\alpha \le \varepsilon$);

- large asperity angles ($\alpha > \varepsilon$).

$$\varepsilon = 0{,}5\arccos(f) \qquad (12)$$

where: α - asperity inclination angle;

ε adhesion angle;

f adhesion coefficient which is independent on pressure and velocity.

If the asperity moves along a distance d, the tangential force (F_t) on the width unit of the asperity will distort the thickness layer h. The total energy developed by this force must overcome the energy needed to distort the layer as well as the friction energy on the surface ED.

In this case, the equation of energetic equillibrium is:

$$F_t \cdot d = h \cdot L \cdot d \cdot \gamma \cdot \tau_c + f \cdot L \cdot d \frac{V_{ED}}{U} \tau_c \qquad (13)$$

where: γ average deformation along the displacement direction;

τ_c shear resistance of the less hard material;

$L = ED$ contact lenght between asperity and the softer material;

U relative displacement velocity;

V_{ED} velocity component on the contact surface.

From the deformation hodograph (fig.6.b):

$$\frac{V_{ED}}{U} = \frac{\sin\phi}{\sin\varepsilon} \qquad (14)$$

where $\phi = \alpha - \varepsilon$

where: $\beta = 1 + 0{,}5\pi + 2\varepsilon - 2\alpha - 2\eta$

$$\eta = \arcsin\left(\frac{\sin\alpha}{\sqrt{1-f}}\right)$$

$$f = \cos 2\varepsilon$$

From these relations one may deduce (by replacements in the energetic equillibrium equation) the average deformation:

$$\gamma = \frac{LfV_{ED}}{hU} \qquad (15)$$

If on the softer surface a number n of asperities are in contact, then the nominal pressure p_n put on the surfaces in contact may be correlated with the normal force on the unit of lenght of asperities F_n:

$$p_n = nF_n = n[\beta\cos\alpha + \sin(2\varepsilon - \alpha)]L \cdot \tau_f \qquad (16)$$

From the right-angled triangles ΔDCE and ΔEMD one may deduce the thickness of the deformed layer when an asperity passes over:

$$\frac{h}{L} = \sin\varepsilon - \sin\alpha \qquad (17)$$

$$h = L(\sin\varepsilon - \sin\alpha) \quad (18)$$

The volume of the deformed material located in front of the asperity ΔAED, may be assumed to break down thus, turning into wear particle [5, 6] after a number of cycles N_c, and it will be:

$$V_n = 0{,}5nL^2(\sin\alpha\cdot\cos\alpha + \sin^2\alpha\cdot\cos\eta) \quad (19)$$

where n is the number of asperities

and the total volume:

$$V = V_n + h \quad (20)$$

Starting from the relation of the wear liniar intensity, one may deduce:

$$I_h = \frac{V}{L_f} = \frac{V\cdot n}{N_c} \quad (21)$$

where: L_f is the friction lenght till the occurence of the wear particle; N_c the number of cycles determinable based on Coffin-Manson relations [5, 6, 7].

Figure 7 presents the evolution of the wear intensity in plastic deformation for small asperity angles and for different loads.

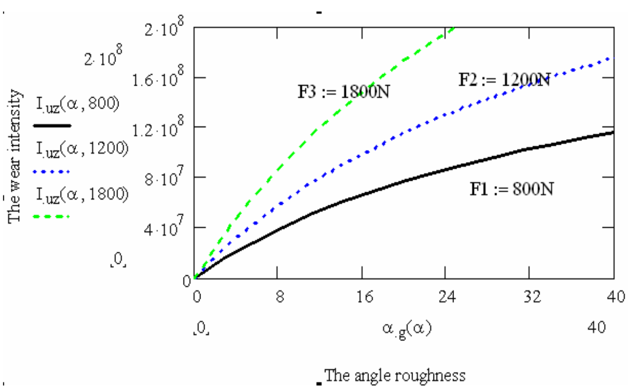

Figure 7. Evolution of wear intensity for plastic deformation when asperity angles are small

If the asperity angles are large, the distribution of the sliding tracks field in case of plastic deformation (Fig.8) is assumed to be in accordance with Challen and Oxley models [1, 2].

Following the same reasoning as in case of small angles, the volume of deformed materials in front of the asperity can be calculated from the equillibrium of the tangential and normal forces:

$$F_t = [1 - 2\sin\beta + (1-f^2)^{1/2}\sin\alpha + f\cos\alpha]L\cdot\tau_c \quad (22)$$

$$F_n = [1 - 2\sin\beta + (1-f^2)^{1/2}\sin\alpha - f\cos\alpha]L\cdot\tau_c \quad (23)$$

where: $\beta = \alpha - \frac{\pi}{4} - \varepsilon + \eta$

The distorted wave volume:

$$V_n = 0{,}5nL^2(0{,}5\sin 2\alpha + \sin^2\alpha) \quad (24)$$

$$L = ED = \frac{p_n}{\tau_c[1 - 2\sin\beta + (1-f^2)^{1/2}\sin\alpha - f\cos\alpha]} \quad (25)$$

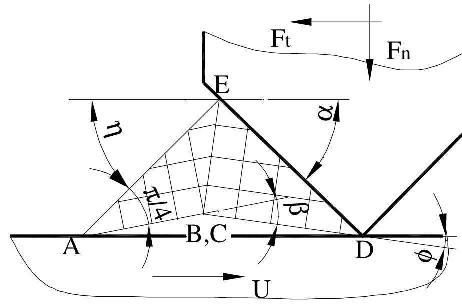

Figure 8. Distribution model of the sliding tracks field – large angles

The wear intensity for larger asperity angle is similar to the previous one, with the respective replacements:

$$I_h = \frac{V}{L_f} = \frac{V\cdot n}{N_c} \quad (26)$$

and the variation of the wear intensity function on the inclination asperity angle for different loads is presented in Figure 9.

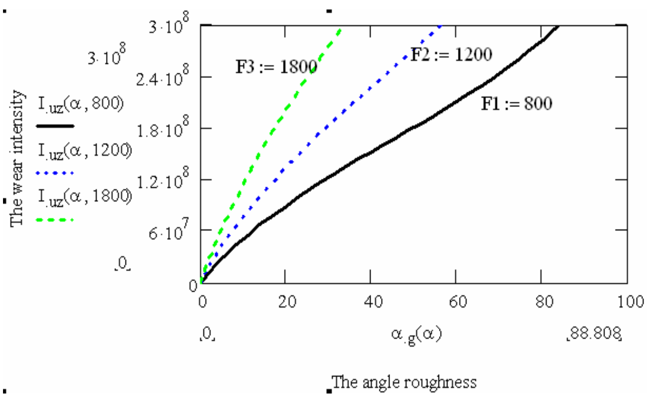

Figure 9. Evolution of wear intensity for plastic deformation when asperity angles are large

3. CONCLUSIONS

From the geometrical analysis of the presented models, based on the Hencky sliding theories, it is noted that in order to get to know the behavior of the material of a coupling in case of sliding and wear, the parameters of the microgeometry (radius, tilt angle of asperity) and the shear resistance of the deformable material must be known.

We note that when the tilt angle of asperity increases, the intensity of wear also increases for the same loads of the normal force. For measured values of the tangent and normal forces, appliable to the asperity, the contact lenght of the area deformed by asperity can be determined.

Preparation of such graphs is needed to establish the behavior of a sliding coupling to friction. Function on the previously-mentioned parameters, the processing, loading and lubrication conditions that might influence the good working of the sliding coupling may be avoided.

With the help of these graphs, the interconditioning way of the working parameters can be presented (sliding velocity, contact pressure, lubricant, temperature, etc) for an imposed durability or a given working accuracy or rigidity etc.

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