

Numerical considerations regarding the occurrence of plastic shearing with implications in scuffing

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Abstract. Scuffing occurrence is also correlate with rheological behaviour of the lubricant. Using a viscous-plastic rheological lubricant model and an idealized roughness, as a symmetrical planar pad, a theoretical model of the pad-plane contact behaviour was developed. Based on this theoretical lubricating model, a numerical study was conducted in order to reveal the possibility of plastic shearing occurrence, in a pair formed by a symmetric pad, with dimensions comparable to the real roughness of the specimens previously used in previous experiments and a plane for values of operating parameters comparable to the real ones. The effect of the relative speed in contact, the effect of the minimum film thickness and the effect of the tilt angle of the idealized asperities flanks was analyzed. The numerical results, obtained based on the analytical model developed, correspond as order of magnitude and tendency of the parameters influence with the experimental scuffing results obtained by the authors and those presented in the literature and highlight the possibility of the occurrence of plastic shearing in the vicinity of the peak of the asperity and therefore the possibility of initiating the scuffing phenomena into contact.

1. Introduction

Mechanical equipment operates on the basis of a transfer of energy from the leading elements to the controlled elements. This transfer involves the presence of controlled moving parts, subjected to links in the mechanical couplings pairs that support them, and the relative movement of the couplings is accompanied by the natural phenomena of friction and wear.

Over time, researchers have been constantly concerned with the reduction of these effects, which lead to a decrease in the efficiency of the machines but also to their breakdown.

Between the types of the damages that occur in mechanical pairs, the catastrophic damage is the most dangerous, because it leads to unexpected stop working of the machinery, with serious consequences on economic implications. The catastrophic failure occurs suddenly and the recovery is impossible.

Of the catastrophic damage, which can suddenly stop working the mechanical pairs, the most dangerous is the tribological damage known as scuffing, characterized by the avalanche of adhesion between the micro asperities of the surfaces. Main subject of research many of authors, as: Block, [1], Ludema, [2], Jacobson, [3], Castro, [4], Dyson, [5], Bujoreanu, [6], Diaconescu, [7,8,9] Balan, [10], Fomin, [11] and others, scuffing remains a catastrophic deterioration whose causes are not fully elucidated and understood.



Of the parameters accepted as having a decisive influence on the occurrence of scuffing, the sliding velocity into the contact, the load and the size of the surface roughness are distinguished. Less studied from the point of initiation of the phenomenon of scuffing (but having a particular phenomenological significance) is the rheological manifestation of the lubricant, to which authors such as Diaconescu, Huang and Wen, [12], Balan, [10], Nelias, [13], Fomin, [11], pay a special attention, showing that the lubricant transition from viscous to plastic behavior, there are effects that may favor the occurrence of scuffing, which is especially noted to reduce the lift effect of the lubricant film.

The present paper proposes, in this context, to carry out a numerical two dimensional simulation of the lubricant behavior in a micro-contact, formed between a micro-asperity and a plane, in view of reaching the plastic shear stress and thus eventual occurrence of the plastic behavior.

2. Mathematical and geometrical model

To study the viscous plastic behavior of the lubricant in a micro-contact, we consider the geometric model formed by an idealized asperity, in the form of double symmetrical pads, as used by Fomin, [11], figure 1, and the analytical model of equations:

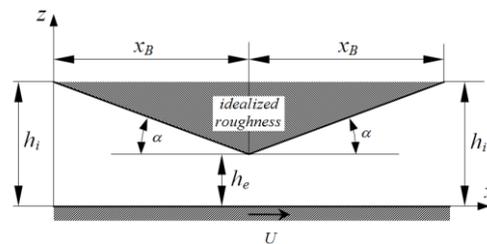


Figure 1. Geometrical model of the idealized roughness.

-The film's thickness equation

$$h(x) = \begin{cases} h_i + k_1 x & x \in [0, x_B] \\ h_e - k_2 x_B + k_2 x & x \in [x_B, 2x_B] \end{cases} \quad (1)$$

where $k_1 = -k_2$ are the pads tilts (symmetrical pads).

- Lubricant behaviour,

$$\begin{cases} \tau = \eta \left| \frac{\partial u}{\partial z} \right| & \left| \frac{\partial u}{\partial z} \right| < \left| \frac{\partial u}{\partial z} \right|_{cr} \\ \tau = \tau_l & \left| \frac{\partial u}{\partial z} \right| \geq \left| \frac{\partial u}{\partial z} \right|_{cr} \end{cases} \quad (2)$$

where τ_l is the plastic limit shear stress and the critical shear $\left| \frac{\partial u}{\partial z} \right|_{cr}$ are an intrinsic characteristic of

the lubricant

-Flow speed equations, in Newtonian flow:

$$u(x, z) = \begin{cases} \frac{1}{2\eta} \frac{dp_1}{dx} (z^2 - zh_1) + U \left(1 - \frac{z}{h_1} \right) & 0 \leq x \leq x_B \\ \frac{1}{2\eta} \frac{dp_2}{dx} (z^2 - zh_2) + U \left(1 - \frac{z}{h_2} \right) & x_B \leq x \leq 2x_B \end{cases} \quad (3)$$

where η is the lubricant viscosity, p pressure and U relative speed.

By introducing the velocities into the continuity equation, the expressions of pressure along of the contact can be computed,

$$p(x) = \begin{cases} \frac{6\eta U}{k_1} \left(-\frac{1}{h_1(x)} + \frac{h_{m1}}{2h_1^2(x)} \right) + C_1 & 0 \leq x \leq x_B \\ \frac{6\eta U}{k_2} \left(-\frac{1}{h_2(x)} + \frac{h_{m2}}{2h_2^2(x)} \right) + C_2 & x_B \leq x \leq 2x_B \end{cases} \quad (4)$$

where: $C_1 = \frac{6\eta U}{k_1} \left(\frac{1}{h_i} - \frac{h_{m1}}{2h_i^2} \right)$, $C_2 = \frac{6\eta U}{k_2} \left(\frac{1}{h_i} - \frac{h_{m2}}{2h_i^2} \right)$ and $h_m = \frac{2h_i h_e}{h_i + h_e}$.

-Tangential stresses distribution,

$$\tau(x, z) = \begin{cases} \frac{dp_1}{dx} \left(z - \frac{h_1}{2} \right) - \frac{\eta U}{h_1} & 0 \leq x \leq x_B \\ \frac{dp_2}{dx} \left(z - \frac{h_2}{2} \right) - \frac{\eta U}{h_2} & x_B \leq x \leq 2x_B \end{cases} \quad (5)$$

-The limit shear stress,

$$\tau_{lim} = \begin{cases} \tau_{i0} + \beta p & 0 \leq x \leq x_B \\ \tau_{i0} + \beta p & x_B \leq x \leq 2x_B \end{cases} \quad (6)$$

where the pressure is taken according to the geometric position and β is a coefficient.

The transition from the Newtonian to the plastic regime is highlighted by the graphical comparison of the calculated viscous shear stresses with the plastic shear stresses, in agreement with Balan, [10], and Fomin, [11]. If somewhere, along the pads, the computed numerically viscous shear stress exceeds the calculated plastic shear stress value, which is physically unfeasible, it is considered that along these domains of the model the lubricant has a plastic behavior.

3. Numerical results

The presented analytical model was implemented in a numerical computation software. The numerical values of the dimensions of the asperity were adopted based on the evaluation of the specimen micro-topography of the experiments presented by Fomin, [11].

Table 1. The numerical values of the dimensions of the idealized asperity.

Specimen	1	2
Finished	$x_B = 2.5 \cdot 10^{-5}$ (m), $h_{rug} = 1,89 \cdot 10^{-6}$ (m)	$x_B = 6.8 \cdot 10^{-5}$ (m), $h_{rug} = 1,54 \cdot 10^{-6}$ (m)
Superfinished	$x_B = 3.8 \cdot 10^{-5}$ (m), $h_{rug} = 1,77 \cdot 10^{-6}$ (m)	$x_B = 3.5 \cdot 10^{-5}$ (m), $h_{rug} = 1,37 \cdot 10^{-6}$ (m)

For these values the calculated values of the tilt parameter are in the range from 0.02 to 0.07.

The considered values of the kinematic, load and lubricant parameters are similar with the values used in experiment, [15], corresponding to the scuffing occurrence: viscosity, $\eta = 0.3$ (Pas), plastic limit shear stress, $\tau_i = 0.5 \cdot 10^6$ (Pa), $\beta = 0.15$, normal load 100 (N) and 18 (ms^{-1}) relative speed. Minimum film thickness, h_{min} , calculated using Hamrock&Dowson formulas, [14], was evaluated as

$$h_{\min} = 7 - 8 \cdot 10^{-7} \text{ (m)}.$$

Three categories of influences were analyzed respectively: sliding effect, film thickness effect and pad tilt effect.

3.1. The effect of the relative sliding speed into the contact

By maintaining the considered geometry and the mentioned parameters unchanged, the developed software was run for a minimum film thickness of 0.5 (μm) and a relative contact velocity $U = 10-190$ (ms⁻¹), with $-k_1 = k_2 = 0.04$ and $x_B = 0.025$ (mm).

From the obtained results, presented in figure 2, 3 and 4 it can be concluded that by increasing the relative speed, the viscous shearing stress increases progressively and the shear limit stresses decreases with speed. At the beginning of the diverging zone of the pad, from a certain value of the relative speed, there is a domain where the computed viscous stress value near the pad surface exceeds the limit of the plastic shear stress, so there occur a plastic shear zone into the contact, figure 2. At higher speed values, as it can be seen in figure 3, also the computed viscous stress value near the plane surface exceeds the limit shear stress. An intuitive evolution of the plastic limit shear stress and the viscous stress value near the pad are presented in figure 4, that confirm the previous conclusions.

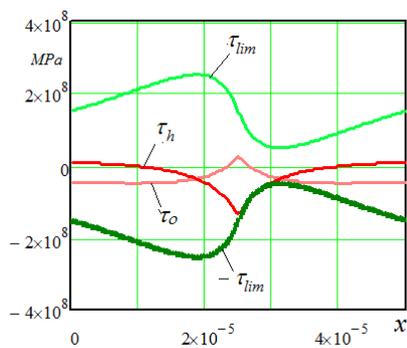


Figure 2. Speed effect at $U=90$ (ms⁻¹)

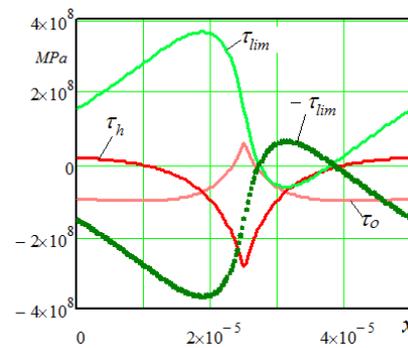


Figure 3. Speed effect at $U=190$ (ms⁻¹)

3.2. Effect of the minimum film thickness

By maintaining the geometry mentioned above considered as undeformable and the characteristics of the lubricant and the speed $U = 12$ (ms⁻¹) unchanged, the software was run to study the effect of the variation of the minimum film thickness of the lubricant for film thicknesses $h_{\min} = 0.1$ (μm) and $h_{\min} = 0.2$ (μm).

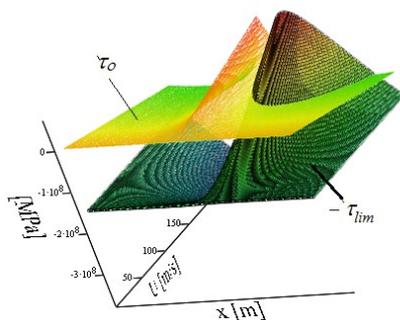


Figure 4. Speed effect - 3D View.

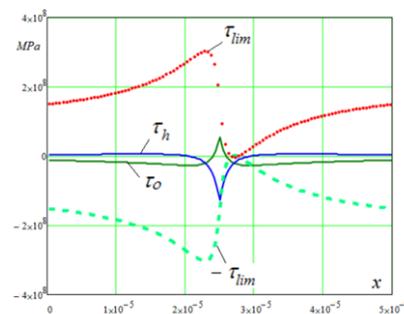


Figure 5. Effect of the minimum film thickness for $U=12$ (ms⁻¹) and $h_{\min}=0.1$ (μm).

The graphical representation of the viscous and plastic shear stresses shows that the diminishing of the minimum thickness of the film causes the increase of the limit shear stress gradient, but also the increase in the values of this stress, which increase on the first pad but decrease on the second one, thus the possibility of plastic shearing occurring in the first part of the diverging pad, when the thickness of film is decreased. At lower values of minimum film thickness the plastic shearing condition can occur.

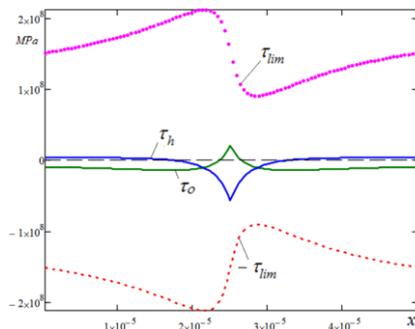


Figure 6. Effect of the minimum film thickness for $U=12$ (ms^{-1}) and $h_{\min}=0.2$ (μm).

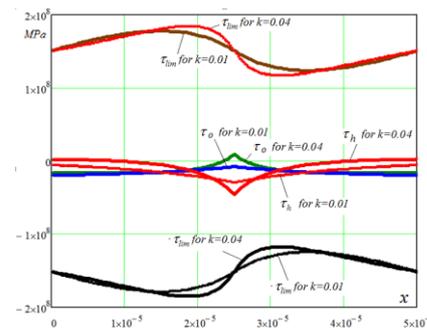


Figure 7. The effect of the pads tilt.

3.3. The effect of the pads tilt

Under the same conditions of constant preservation of the other parameters, only the angle of inclination of the pads from 0.01 to 0.04, for $U = 30$ (ms^{-1}), $h_{\min} = 0.5$ (μm) and $x_B = 0.025$ (mm) was varied. The results show that the variation in the angle of inclination of the lateral slopes of the micro-asperity has a much lower effect compared to the variation of the minimum film thickness and the relative sliding velocity. Changing the angle of inclination of micro-asperity flanks in the range of analyzes could not significantly alter the rheological behavior of the lubricant and thus could not favor the initiation of scuffing.

4. Validation and conclusions

The numerical results were obtained for values of the parameters comparable to the values at which experimental initiation of scuffing was revealed, [15], the results being consistent with other results from the literature mentioned by Nelias and Bujoreanu.

It has been found that the numerical results agree as order of magnitude with the experimental results. However, appreciating the degree of simplification adopted, namely, to consider the roughness as having the simple shape of symmetrical pads with plane flanks and infinitely long to deal with the two-dimensional problem, and also the neglect of the presence of a rounding region at the tip of the asperity, the authors appreciate the numerical results obtained as satisfactory.

Another aspect, in support of the validation of this model, is that of matching the phenomenological trends encountered in the experiments, of scuffing initiating faster to larger roughnesses (i.e., to smaller film thickness) at higher speeds (hence higher shear speed) are also found in the numerical study performed.

5. References

- [1] Block H 1937 Theoretical Study of Temperature Rise at Surfaces of Actual Contact Under Oiliness Lubricating Conditions *Proc. ImechE, Gen. Disc. Lubr.* **2** 222-35
- [2] Ludema and Kenneth C 1984 A Review of Scuffing and Running-in of Lubricated Surfaces, With Asperities and Oxides in Perspective *Wear* **100.1** 315-31

- [3] Jacobson B O and Vinet P 1986 A Model for the Influence of Pressure on The Bulk Modulus and the Influence of Temperature on the Solidification Pressure for Liquid Lubricants *J. Tribol.* **109** 709-1
- [4] Castro J and Seabra J 2008 Global and Local Analysis of Gear Scuffing Tests Using a Mixed Film Lubrication Model *Tribol. Int.* **41** 244–55
- [5] Dyson A 1975 Scuffing-A Review Part I, II *Tribol. Int.* 77-87, 117-22
- [6] Bujoreanu C 2002 Studies and Researches on Scuffing in Rolling Contact Applied on Ball Bearings (in Romanian) *Ph. D. Thesis* (Iasy) 235
- [7] Diaconescu E 1996 Lubricant Plastic Shearing in Plane Pad – Part I (in Romanian) *VAREHD 8* (Suceava) 70-8
- [8] Diaconescu E 1996 Lubricant Plastic Shearing in Plane Pad – Part II *VAREHD 8* (Suceava) 80-6
- [9] Diaconescu E 1996 About Isothermal Shearing Region in Hydrodynamic Plane Pad (in Romanian) *VAREHD 8* (Suceava) 78-80
- [10] Balan M 2003 Limit Shear Stress Effect in Lubrication (in Romanian) *Ph. D. Thesis* (Suceava) 155
- [11] Fomin M 2014 Speed Distribution Analysis in a Lubricating Fluid Near an Ideal Roughness *TEHNOMUS Journ.* **1** 44-9
- [12] Huang P and Wen S Z 1994 A New Model of Visco-Plastic Fluid Lubrication for Sliding Problems *Acta Tribol.* **2** 23-30
- [13] Nelias D 1997 Étude expérimentale et théorique du microgrippage dans le contacts élastohydrodynamiques *ELSEVIER Rev. Gén. de Therm.* **36** 26-39
- [14] Hamrock B J and Dowson D 1977 Isothermal Elastohydrodynamic Lubrication of Point Contacts: Part III—Fully Flooded Results *J. Tribol.* **99.2** 264-75
- [15] Fomin M 2014 Lubricant plastic shearing effect implications in scuffing occurrence (in Romanian) *Ph. D. Thesis* (Suceava) 185