Tribology International ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Roughness and wettability of surfaces in boundary lubricated scuffing wear

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ARTICLE INFO

Article history:
Received 7 October 2014
Received in revised form
4 April 2015
Accepted 10 April 2015

Keywords:
Scuffing
Wettability
Boundary lubrication
Surface roughness

ABSTRACT

The diversity of multidisciplinary approaches suggests that fundamentals of scuffing require systemic, complex multi-scale and multi-physics analysis of an irreversible process as it is postulated in present study. That is probably one of the reasons of lack of an unequivocal model of this irreversible transitional process from stable more or less lubricated wear to scuffing described only by one or few authors in equation(s) form. Therefore, it is useful to characterize the tribological surface properties in frame of systemic approach looking simultaneously for the optimal compromise between rheological, morphological and physicochemical features of contacting surface's layer. Hypothetical role connected to any group of features in the topological approach is elucidated and experimentally confirmed via the wettability, strongly combined with surface roughness and surface free energy. Due to the fact that the free energy is directly related to the surface wettability it can as well affect the scuffing activation process. For scientific and rhetoric reasons some selected results of limited boundary lubrication investigations under double blind trial conditions in case of gear oil with anti-wear (AW) and extreme pressure (EP) additives are elucidated here. The results issued from scuffing tests on AISI 4140 ground steel burnished under different forces in order to generate different surface roughness, residual stresses and surface energy are analyzed. It was stated and numerically correlated that the wettability by lubricating medium influences the scuffing resistance. Additionally, the dependence of wettability on selected parameters of roughness and a time to scuffing activation have been stated. On that basis, it is proposed to reinforce concept of "oleophilic" and "oleophobic" properties of metallic surfaces as autonomous invariants determining the activation of catastrophic wear process under boundary lubricated conditions.

1. Introduction

The scuffing process is generally considered as the failure of sliding bodies. The practical problem motivating the study of scuffing is the unexpected and catastrophic failure of a few among many otherwise highly successful lubricated sliding components. Such process may occur in a great number of interfaces as: gear teeth, piston ring – cylinder, cams and followers, splines and sleeve bearings. There is still a little agreement of Tribologists on what scuffing is or what its emergence, manifestation and appearance is.

As started Ludema in his historical review of scuffing "The slow progress in the understanding of scuffing (scoring) and running-in of most lubricated surfaces is probably due to an inadequate understanding of the details of asperity deformation and oxide formation" [1].

Therefore it is obvious that the title of present paper "Roughness and wettability of surfaces in boundary lubricated scuffing wear" has to be correctly interpreted in its semantics context and not as any ambition pretention to explain totally complex tribological process only via few relationships between experimentally characterized properties of surfaces.

However, it is very useful to characterize the tribological surface properties in frame of systemic approach looking simultaneously for the optimal compromise between rheological, morphological and physicochemical features of contacting surface's layer. This days the diversity of multidisciplinary approaches suggests that fundamentals

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http://dx.doi.org/10.1016/j.triboint.2015.04.013
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Nomenclature

α	Statistical significance
Θ_E	Equilibrium contact angle [°]
Θ_I	Initial contact angle [°]
Kr	Mean slope of roughness motifs
r	Pearson correlation coefficient
r_{CR}	Critical value for Pearson correlation
Rdc	Profile section high difference [μm]
Rmr(c)	Material ratio of the profile [%]
Sa	Arithmetic mean height, mean surface roughness [μm]
Sku	Kurtosis of the surface height distribution
Sp	Maximum peak height, height between the highest peak and mean line [μm]
Sq	Root mean square height, standard deviation of height distribution of surface roughness [μm]
Ssk	Skewness of the surface height distribution
Sv	Maximum pit height, depth between mean line and the deepest valley [μm]
Sz	Maximum height between the highest peak and the deepest valley [μm]
t_{SC}	Time to scuffing [s]

of scuffing require systemic, complex multi-scale and multi-physics analysis of an irreversible process as it is postulated in present study. That is probably also one of the reasons of lack of unequivocal model of this: i) muti-physics, ii) complex irreversible, iii) mutli-scale, iv) transitional wear process from stable more or less lubricated pairs to scuffing described only by one or few simple equation(s).

1) The impact of rheological properties in terms of elasto-plastic behavior of contacting bodies via residual stresses has been treated in previous papers showing clearly that the increase of the compressive residual stresses causes the increase of the scuffing performance [2,3]. The present paper is focused on morphological and physicochemical features of contacting surface's layer.
2) The physicochemical aspect in scuffing is presented here via wettability of rubbing surfaces. Wetting and spreading phenomena plays a huge role in many branches of live and modern industry, determining the ability of solids to interact with liquids. Naturally, wettability involves in our mind water and hydrophobicity or hydrophilicity of surfaces. Talking about wettability and lubrication spontaneously is associated with living organs containing majority of water, therefore involving biotribology. In case of metallic surfaces lubricated with the oil the concept of "oleophilic" and "oleophobic" properties of metallic surfaces comes into sight immediately. The understanding of wettability property is very important not only for typically technical applications (oil reservoir management, lubrication, coatings, painting, soldering, jet-printing, spraying etc.) but also for these related to human existence (detergents, cosmetics, windscreens and wipers, wetting of eyes, watering planar, etc.). In terms of tribology, wettability is primarily associated with application of liquid lubricants and their spreading on rubbing surfaces. The liquid deposited on the solid surface, under gravity has tendency to spread until the cohesion (internal) forces of the liquid, the gravity forces and the capillary (surface tension) forces are in balance and some equilibrium state is reached [4]. This state may have a significant meaning in the case of lubrication by chemically inactive liquid lubricants. If the liquid does not form the boundary layer due to the reaction with metallic surfaces, the way in which it covers these surfaces may decide about the efficiency of lubrication. It is well known that contact angles depend on the configuration of the wetted surface roughness. According to Wenzel theory [5], a rough surface extends the solid–liquid interface area in comparison to the projected smooth surface and that is why the apparent contact angle is proportional to the ratio of the real rough surface area and the projected perfectly smooth surface. In practice, this theory is used only for the contact angles in range of $0^\circ < \Theta < 90^\circ$. Another attempt to describe heterogeneity of the surfaces was a theory proposed by Cassie and Baxter (appropriate for the range of contact angles $90^\circ < \Theta < 180^\circ$) [6]. Assuming the special case, where liquids on the heterogeneous rough solid surface leave the gas pockets, an apparent contact angle is dependent on the fraction of the liquid–solid interface. The Wenzel's and Cassie-Baxter's theories confirm the relationship between the wettability of surface and its roughness, however due to the use of individual and specific quantities their engineering use is difficult. Therefore, Kubiak et al. [4,7] suggested the approach based on the replacement of these quantities by standard geometry profile parameters, which can be measured with commercial apparatus. This research evidenced the importance of topographical parameters in both 2D and 3D morphology analysis. Authors using covariance analysis related various material ratio parameters to wettability and spreading dynamics. The most important parameters found were: Rmr – material ratio of the roughness profile, Trc – microgeometric material ratio, and Pmr – relative material ratio of the raw profile. Another important parameter is $Kr = AR/2R$ (mean slope of the roughness motifs). It is defined as a ratio between mean spacing of the roughness motifs (AR) and the mean depth of the roughness motifs ($2R$). The Kr parameter was recognized by authors [7] as a key parameter which correlates strongly with an increased droplet spreading effect for different tested materials (steel, aluminum alloy, titanium alloy, ceramic, PMMA). Based on this analysis it can be presumed that by controlling wettability with appropriate roughness parameters it is possible to influence lubrication and to improve the conditions of friction. This hypothesis applies only to friction pairs lubricated by liquids without surface-active additives and can be supported by following literature review. In the case of water lubrication, Borruto et al. [8] found that in order to have a reduction of the friction and wear it is necessary to make the friction pair of materials which have very different wettability and also one of them should have the hydrophilic characteristic. Observed beneficial tribological effect, authors explained by hydrostatic lifting due to the different adhesion of the molecules of water to the two different types of surfaces (hydrophobic and hydrophilic). The fundamental question arises about the possibility of the similar situation obtained for lubrication by oils and particularly in transition from Elasto-Hydro-Dynamic Lubrication (EHD) to Boundary Lubrication (BL). Then local breakdown of protective last mono-layer can initiate the wear as it has been experimentally observed, described and theoretically solved by Mathia [9]. Even if Podgornik et al. [10] stated that there is not direct correlation between wettability and tribological performance of lubricated surfaces, the modifications in surface morphology undoubtedly leads to changes in surface free energy (especially in its polar share), which in combination with the appropriate lubricant can improve solid surface wettability and wear resistance. This conclusion was partially confirmed recently by Wojciechowski and Mathia [2]. They found

Please cite this article as: Wojciechowski L, et al. Roughness and wettability of surfaces in boundary lubricated scuffing wear. Tribology International (2015), http://dx.doi.org/10.1016/j.triboint.2015.04.013