This is an eprint of paper published by Elsevier in Tribology International (2015) kris@kubiak.co.uk
http://dx.doi.org/10.1016/j.triboint.2015.04.013

Roughness and wettability of surfaces in boundary lubricated scuffing wear

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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 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 analysed. 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.

Nomenclature:

α	Statistical significance
Θ_E	Equilibrium contact angle [°]
Θ_I	Initial contact angle [°]
Kr	Mean slope of roughness motifs
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]

Keywords: Scuffing; Wettability; Boundary lubrication; Surface roughness.

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 characterised 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 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 behaviour 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 play 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 $0° < \Theta < 90°$. Another attempt to describe heterogeneity of the surfaces was a theory

proposed by Cassie and Baxter (appropriate for the range of contact angles 90° < Θ < 180°) [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, aluminium 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 direct correlation between surface polarity and scuffing performance in the case of steel-cast iron friction pair lubricated by gear oil with surface-active sulphur additives. On the basis of the results and conclusions presented in [2] and [10], it may be assumed that properties of solid and liquid phase (especially surface and liquid tension, surface polarity and morphology) can influence surface wettability and contribute to its tribological behaviour. Particularly interesting, but the most complicated as well, is the role of wettability in the case of catastrophic wear. One of the most dangerous and less understood types of that sort of wear is scuffing. According to the ASTM G40 standard, scuffing can be defined as 'a form of wear occurring in inadequately-lubricated tribosystem that is characterized by macroscopically observable changes in texture with features related to the direction of relative sliding'. Several theories concerning scuffing activation [2] have been suggested in the literature but none of them unequivocally determine the process evolution. The most relevant of them connect the initiation of this process under boundary lubrication (BL) with a critical temperature [11], a debris generation size [12], a kinetic of their accumulation in interface [13], a plastic deformation of asperities [14], formation and destruction of protective oxide films [15], a surface polarity [2], an energetic activation of metallic surfaces [16] and an adiabatic shear instability [17]. Irrespective of above factors the boundary lubrication cannot provide a long-term protection against scuffing as can be schematically illustrated on (Fig. 1). That is one of the reasons why it is fundamental to recognize breaking point of the boundary mono-layer [18, 19] activating scuffing wear and the influence of surface morphology in relation to wettability.

3. The impact of morphological properties of manufactured surfaces of contacting bodies via 3D systematic before tribological experimental investigations has been treated in previous papers showing clearly the ways to identify invariant of scuffing process [3].

Authors present the topological approach to this problem where interaction between rheological, morphological and physicochemical properties of layers of contacting surfaces plays an essential role [2, 4, 18÷20]. Rigours experimental strategy were developed to prepare a set of the surfaces finished by burnishing process. Precisely controlled surface manufacturing conditions allowed us to investigate variety of tribological conditions reflecting the real scenario of boundary lubrication in contact between AISI 4130 and EN-GJN 300 cylinder/plane specimens. The mutual interactions between morphology parameters and wettability (dynamic contact angles) in the context of scuffing activation were investigated and elucidated.

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2. Methodology

The French Academy of Sciences in 1784 introduced the first so called ‘blind experiments’. More recently, this technique became more popular, however its application in tribology is still limited. Blind testing eliminates unintentional influence or any other bias of person performing experiments or analysis, as they are not aware of expected results. In presented here research a double blind experimental strategy was implemented. It consists of rigorous way of conducting experiments which eliminate subjective, unrecognized or unsuspected biases carried by scientist and/or technician. In the case of present study the research was carried out separately and then combined in three different locations France, United-Kingdom and Poland.

The presented study is also part of a large research process which flow chart is shown in Fig. 2. Specimens tested in the experiment were made of AISI 4130 steel in the shape of cylindrical "rings" of 45mm+/-10μm external diameter and of 12 mm width. Cylindrical surfaces of all specimens were subjected to grinding so that their surface roughness Ra was equal to approx. 0.5 μm. The specimens were then divided into six batches, all of which were subject to burnishing with sixth values of pressure in order to create different levels of energy introduced to the superficial layer. In order to control residual stresses the burnishing of cylinder was performed by two symmetrical spherical sector-shaped rolls of 50 mm diameter. Particular levels of burnishing pressures comply with the following pressures of burnishing tools on machining surfaces: 1st: 1,3 GPa, 2nd:1,64 GPa, 3rd: 1,87 GPa, 4th: 2,06 GPa, 5th: 2,22 GPa, 6th: 2,36 GPa. Kinematic conditions are: burnishing speed - 100 m/min, burnishing feed - 0.08 mm/rev., number of tool pass - 2, lubrication by a 1 to 1 mixture of mineral oil and kerosene.

Wettability properties of the tested surfaces were analysed by dynamics contact angle measurements using PG3 goniometer from Fibro System AB. Small droplet of 2 μl of selected oil is deposited on a tested surface and dynamic contact angle is measured analysing camera images taken from side view during droplet deposition. Measurement are starting to be recorded when droplet first is touching the surface assuring good synchronisation between all recorded dynamic values of contact angle during oils spreading. All surfaces were cleaned with propanol and dried shortly before droplets deposition. Dynamic contact angle measurements were taken every 100 ms during first second from deposition to capture initial spreading dynamics and then every second between two and five seconds time.

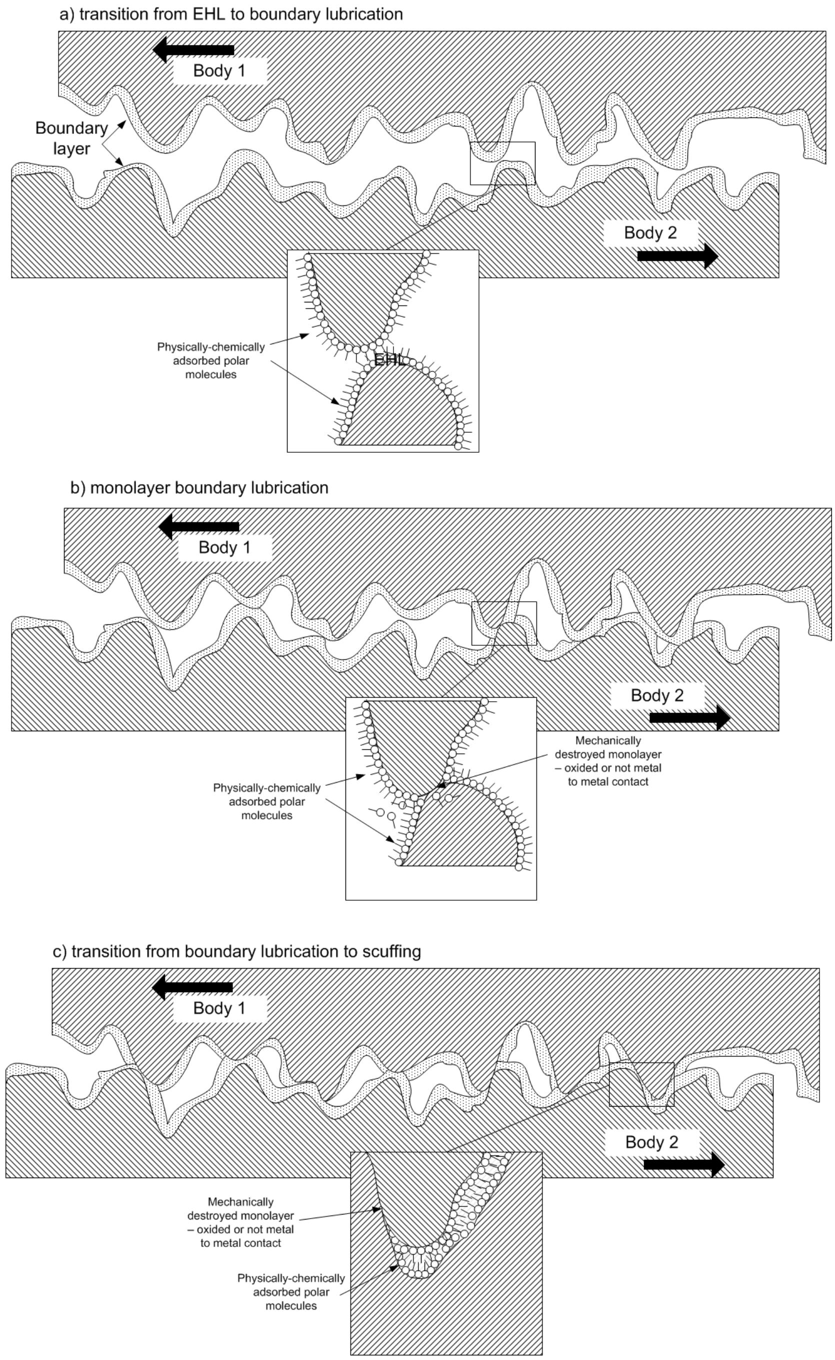

Fig. 1. Schematic view of transitions from the EHD regime through Boundary Lubrication to scuffing (for illustrative purpose only as vertical and horizontal scales may not be respected).

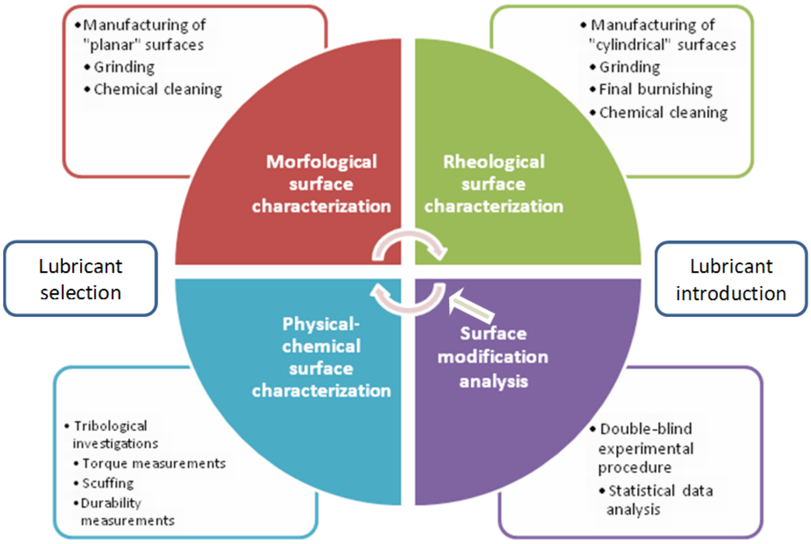

Fig.2. Flow chart of experimental research strategy.

Systematic areal morphological analyses were performed thanks to optical interferometer on milimetric region relevant to contact surface during experimental tribological investigations. The area of 1,2 mm x 0,9 mm in five parts of cylindrical surfaces every 72º were performed. Metrological analyses have been done very carefully and consciously taking into consideration calibration as well as transfer function and measurement limitations of selected topometric device. Cylindrical grinding offers anisotropic morphologies, therefore single profile analysis would be sufficient to characterise tested surfaces. Measurements and full topographical analysis were focused on the parameters proposed by Kubiak et al. [4, 7] as the relevant to surface morphology in the wettability. These parameters are Kr - mean slope of roughness motifs and Rmr - material ratio of roughness profile. Additionally, it was proposed to take into consideration the Rdc parameter (profile section high difference) in order to exclude the highest peaks that will be worn out and the deepest valleys that will be filled in. Basic height morphology parameters (ISO 25178) were also measured to fully investigate tribological system.

The criterion for scuffing determination is determined by increase of friction coefficient under constant load (Fig. 3).

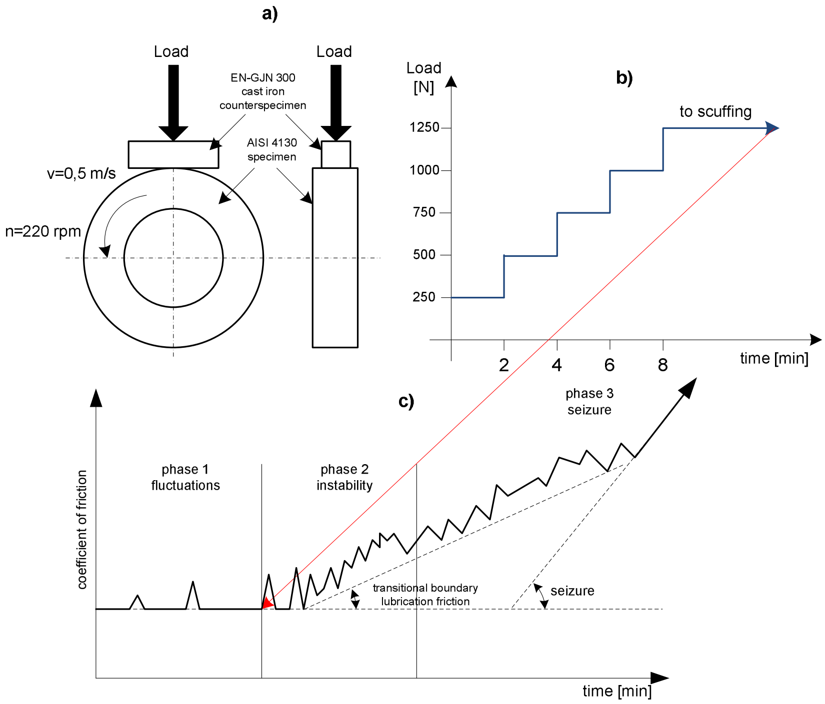

Fig.3. Kinematics and geometry of scuffing experiments (a), procedure of load application (b) and coefficient of friction versus time (c).

Cylinder/Plane contact in tribological tests were used (Fig. 3a). The load was applied incrementally to the friction pair (Fig. 3b). The scuffing kinetics at sliding speed between rotating cylinder (AISI 4130) and the stationary block (EN-GJL-300 cast iron with flake graphite) was determined at 0.5 m/s. The experiment featured single drop lubrication using gear oil with ca. 5% olefin sulphide as an extreme pressure additive. Therefore, scuffing activation period was measured by the time it took for scuffing to occur which is equivalent to the situation of lubricant starvation at the tribological interface.

The procedure applied here to identify scuffing activation process, differs from commonly used approach. Typical scuffing test consists of gradually increasing load as long as it will be sufficient to break the EHL or boundary layer. Of course, this type of methodology is appropriate, however it is characterized by some limitation associated with the dynamics of scuffing process. The continuous increase of load leads to breakdown of the oil film but the transition from the boundary lubrication conditions to scuffing is really violent. That is why authors decided to propose a new method in which the final load is constant (Fig.3b) and available volume of lubricant is limited. Due to such experimental approach, the transition from the fully lubricated friction to boundary lubrication is achieved as a function of initially increasing load and later on transition from boundary lubricated contact to scuffing is a function of time (Fig.3c). Consequently it is possible to discriminate the time to activate scuffing phenomenon and therefore respective mechanical conditions. It allows the observation of different material nuances and lubricants in relation to the scuffing activation process and subsequently "tribological resistance of boundary lubricated friction pairs".

In order to satisfy the statistical requirements, the scuffing investigations were performed four times for each assembly lubricant and the pair of cylinders and blocks.

3. Results and discussion

3.1Morphological analysis

3D morphological views of surfaces as illustrated on Fig. 4 shows visible topographical changes for different levels of burnishing conditions. Values of characteristic parameters of surface plastic deformation (Sa, Sq, Sp, Sv, Sz) is significantly changing as a function of burnishing pressure.

Decrease of the values of all this parameters for the first four levels of burnishing pressures can be observed (e.g. average value of Sq is reduced from 0,45 ± 0,03 µm to 0,38 ± 0,03 µm). Further increase in pressure is probably caused the beginning of surface destruction process and notable growth of these parameters (e.g. Sq=0,49 ± 0,03 µm for the pressure of 2,22 GPa and Sq=0,54 ± 0,05 µm for the pressure of 2,64 GPa). The plausible reason is beginning of the surface destruction process caused by achieving the critical cold work. Additionally, values of skewness Ssk are negative which is characteristic for grinding process, moreover it indicates that majority of the material is localized nearby the peaks of surface due to increasing plastic deformation of asperity's summits due to burnishing process. That hypothesis finds its confirmation in changes of Kurtosis Sku, indicating flattening peaks of the surface and increasing bearing area contact, due to plastic deformation. Two lowest average values of this parameter were achieved for the highest, fourth (Sku=7,45 ± 1,17) and fifth (Sku=5,23 ± 0,83) levels of burnishing pressures.

3.2Wettability analysis

Contact angle measurements on all tested surfaces were systematically carried out. On Fig. 5 is shown a representative example of the dynamic contact angle of 2µl drops of oil measured for each type of burnished cylinders. Easy noticeable are two characteristic points during spreading of oil onto analyzed surfaces. The first is related to the instantaneous value of the contact angle after deposition of oil drop on the cylinder surface and that is why it is defined as "initial" contact angle” (Θ_I). The second is associated with stable spreading condition and equilibrium contact angle which for all types of cylindrical surfaces occurred after about 1s. Therefore, the contact angle at this point is determined to be a quasi-static "equilibrium" contact angle (Θ_E). Values of both characteristic contact angles Θ_I and Θ_E depends on the degree of cold work of plastically deformed material. Subsequent analysis of this relationship was performed on the basis of the roughness parameters strongly influencing the surface wettability: mean slope of the roughness motifs Kr (Fig. 6a Θ_I=f{Kr} and Fig. 6b Θ_E=f{Kr}), material ratio of roughness profile Rmr (Fig. 7a Θ_I=f{Rmr} and Fig. 7b Θ_E=f{Rmr}) and profile section high difference Rdc (Fig. 8a Θ_I=f{Rdc}) and Fig. 8b Θ_E=f{Rdc}).
In order to eliminate the impact of individual extreme peaks of profile on wettability, the Rmr value was determined at the level of c=1 µm. It means that the material ratio of roughness profile was determined at the distance of 1 µm from the highest peak. A similar approach was applied for the Rdc parameter which value was measured for the range of 20÷80 % of material ratio. It makes it possible to eliminate not only the influence of extreme peaks but also influence of extreme individual valleys on the surface wettability. For those reasons, total dynamic wettability analysis of oil in terms of contact angles versus time on surfaces for different burnishing pressures and therefore diversely plastically deformed asperities is not discussed in this paper in details.

It can be observed in Fig. 6 that the surfaces with higher Kr parameter have better wettability properties in term of oil spreading on such surface, lower initial contact angle Fig. 6a) and lower equilibrium value Fig. 6b) corresponding to spreading dynamics. Those results are coherent with previous authors’ research presented in [4]. Higher Kr creates grooves on the surface and due to the capillary action facilitates spreading of the lubricating fluid along those grooves. Kr determines mean slope of the roughness motifs, which according to ISO 12085 standards can be defined as a portion of the primary profile between the highest points of two local peaks of the profile, which are not necessarily adjacent.

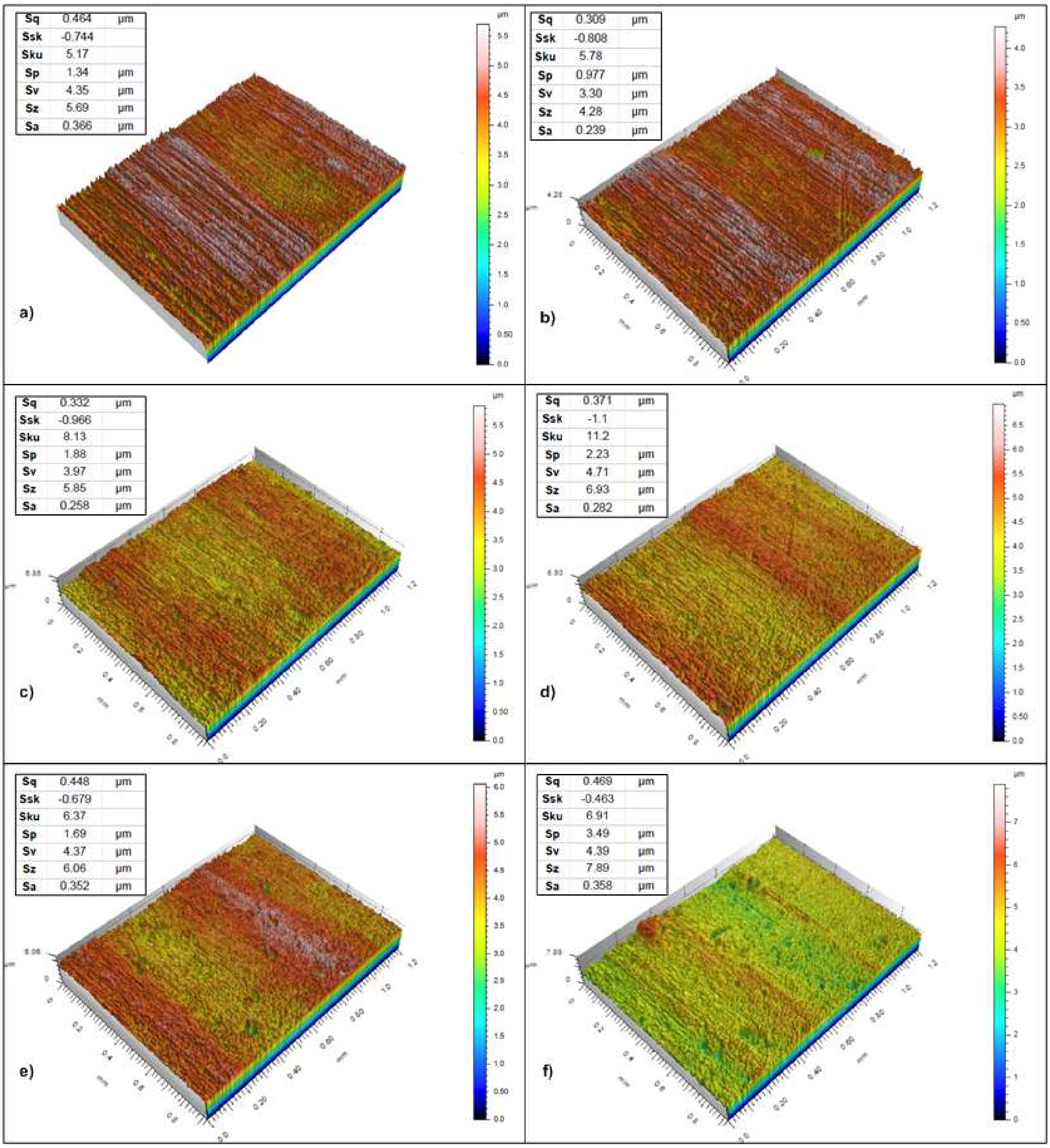

Fig. 4. 3D isometric views and statistic characteristics (ISO 25178) of AISI4130 cylinders surfaces for different 1st (a), 2nd (b), 3rd (c), 4th (d), 5th (e) and 6th (f) level of burnishing conditions.

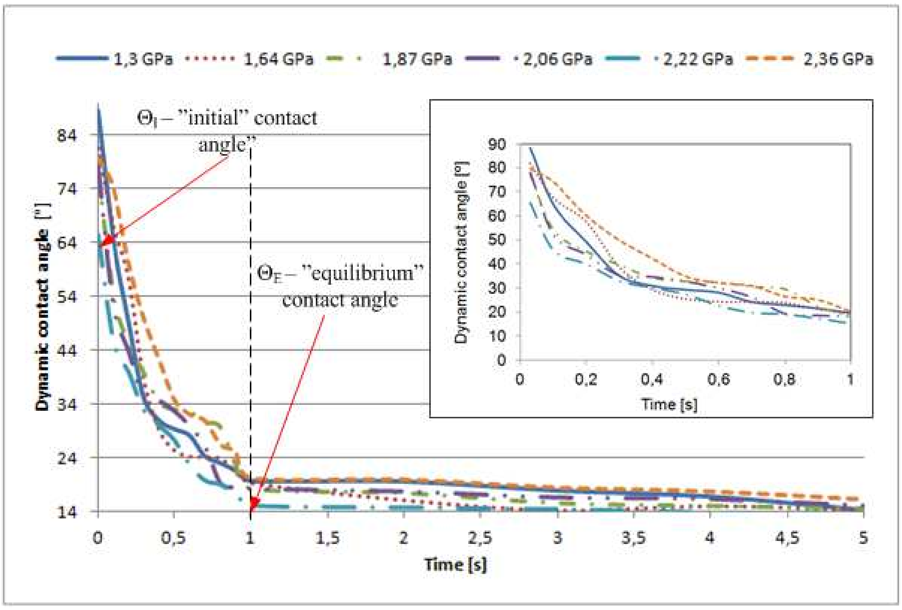

Fig. 5. Dynamic wettability of oil in terms of contact angles versus time on cylindrical surfaces for different burnishing pressures.

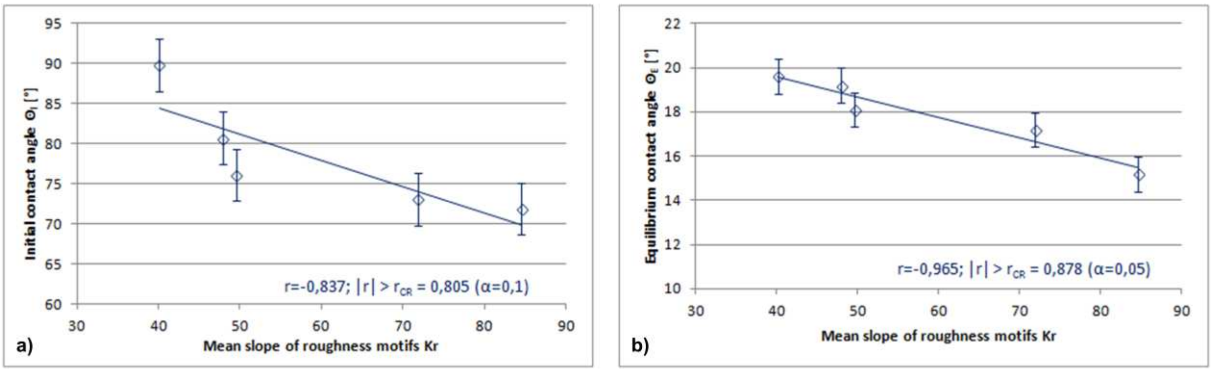

Fig. 6. Initial contact angles ΘI and "balance" contact angles ΘE versus mean slope of roughness motifs Kr (r-Pearson correlation coefficient, r_{CR}- critical value for Pearson correlation, α-statistical significance).

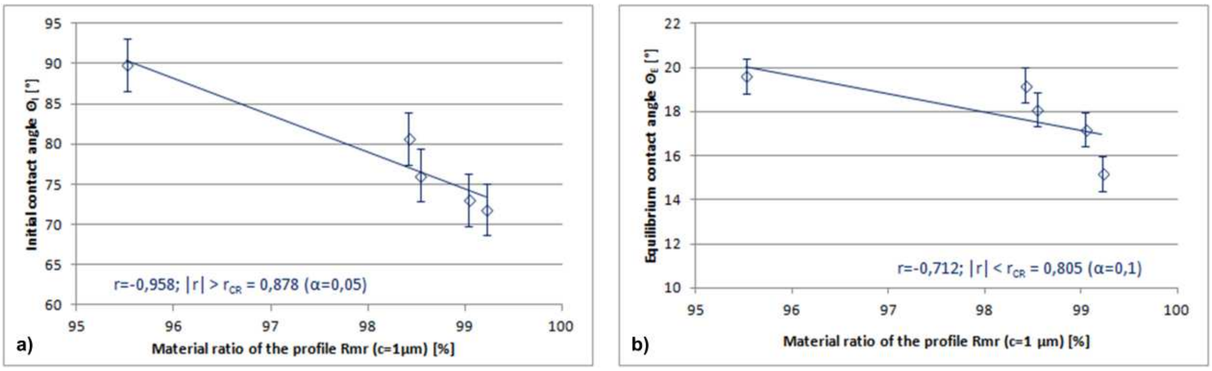

Fig. 7. Initial contact angle ΘI and equilibrium contact angle ΘE versus material ratio of the profile Rmr (c=1 μm).

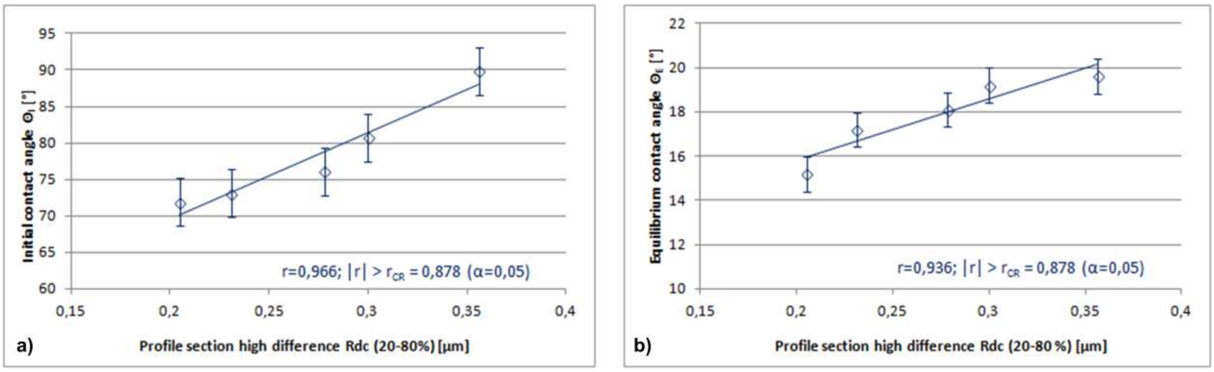

Fig. 8. Initial contact angle Θ_I and equilibrium contact angle Θ_E versus profile section high difference Rdc (20-80 %).

Changes of Rmr and Rdc parameters confirm previous observations that the flattening of the surface is useful for improving its wettability. The increase of the bearing surface (Rmr – Fig. 7) and the flattening of asperities (Rdc – Fig. 8) caused the decrease of contact angles what means better spreading of oil on more flat surface. In this case, capillary action along the grooves is rather limited, but oil can spread due to high surface flatness. It can be noted that proposed previously parameters Kr and Rmr [4, 7] and analysed in present paper Rdc parameter display relatively good coefficients of correlation (r) in term of wettability of tested surfaces. This confirms importance of those parameters in manufacturing process in order to control surface wettability. The exception to this rule is the relationship between ΘE and Rmr (Fig. 7b) for which the correlation cannot be statistical confirmed in the test of significance (nevertheless, it can be pointed some graphical trend compatible with a general conclusion).

From Fig. 9 and 10 it can be concluded that influence of morphology (Rdc, Rmr, Kr) and therefore wettability, correlates relatively well with the time required to activate catastrophic scuffing wear. It can be observed that the decrease of the Rdc (20-80 %) and the increase of Kr (Fig. 10a) contributed to improvement in scuffing resistance. A similar relationship exists between the time to scuffing and the Rmr parameter (Fig. 9a) but this correlation was not confirmed in the test of significance ($r<r_{CR}$). Summarizing, it may be stated that the improved wettability translates into better scuffing performance of metallic surface.

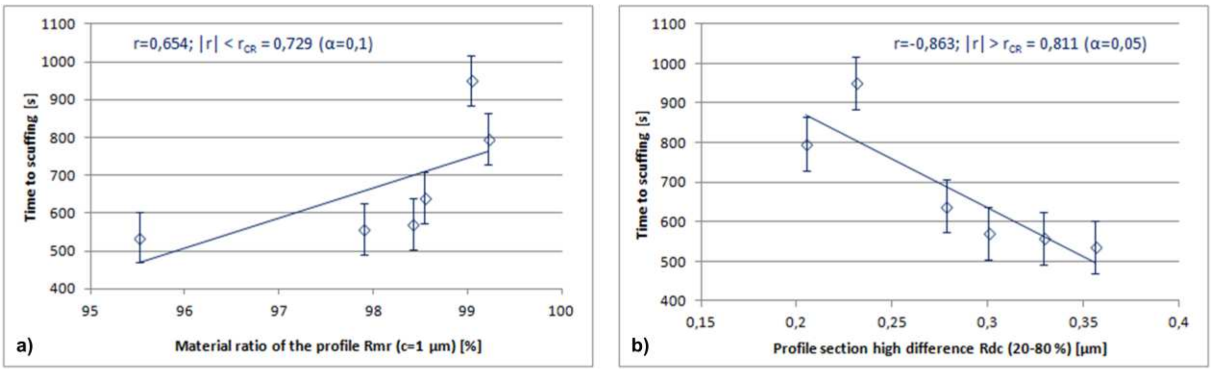

Fig.9. Time to scuffing tSC versus material ratio of the profile a) Rmr (c=1μm) and profile section high difference, b) Rdc (20-80 %).

The fact that the coefficient of correlation (r) between tSC and Rmr (Fig. 9a) relatively low (0,654 for α=0,1) may indicate that the wettability was not the only factor that determined the initiation of scuffing process in this case. In the analyzed studies, such an assumption may be particularly important, because as lubricant, a gear oil with surface-active sulphur additive was used. Previous author's investigations [2] suggest that the activation of the scuffing process in the presence of that kind of oil is directly dependent on the surface polarity (understanding as a quotient of the polar component of surface free energy and its total value). The analysis of this data allows for a certain trend to be observed in the value of time to catastrophic wear as a function of the surface polarity. The highest scuffing resistance was observed for cylinders with surface polarity equal to 0.33 for which the first scuffing symptoms appeared after 950s. It is worth to notice that there was a significant increase in time in comparison to the specimens exhibiting surface polarity of 0.17, the time here being approximately 571s as summarized on Fig. 10b.

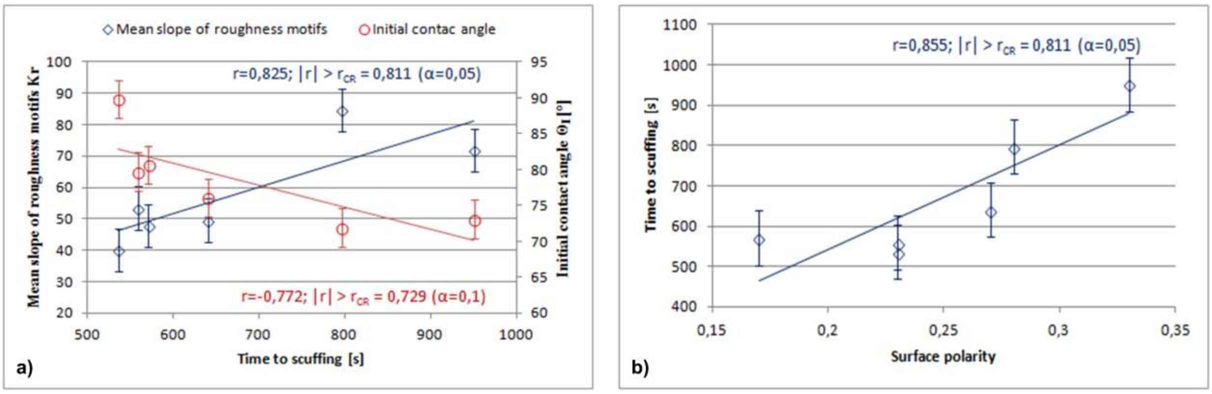

Fig.10. Time to scuffing tSC versus mean slope of roughness motifs Kr (a) and surface polarity [2] (b).

Additionally, it has been observed that the time to scuffing dependence of the Kr (Fig. 10a) and Rmr (Fig. 9a) parameters and the surface polarity (Fig. 10b) is very similar in nature. It seems that the results of these investigations may form building blocks of fundamental understanding to recognise that scuffing activation depends on wettability in case of surface-active oils in boundary lubricated contact. In case of water lubricated systems higher differences in wettability of surfaces in contact can enhance lubrication performance (Borreto et al. [8]). In case of oil lubrication the surfaces of metallic elements should have a good wettability to ensure better lubricant penetration and to allow the formation of homogeneous boundary layers even in hard to reach places. It is important to understand that in case of direct metal to metal contact wettability properties of the surface will decide how fast lubricating film will be restored. If boundary lubrication will be restored thanks to good wettability properties, before the catastrophic chain of cascade events will lead to scuffing, such contact will be able to recover and to avoid seizure.
Presented here results are limited to metal/metal contact and as a future direction this hypothesis of wettability influence should be verified for other similar and mixed pairs of material.

4. Concluding remarks and perspectives

Based on presented experimental results of surface wettability influence on boundary lubricated systems and its resistance to scuffing and catastrophic wear, following conclusion can be formulate:

- There is a direct relationship between the roughness of surface, wettability and resistance to scuffing,
- The following parameters have strong influence on fluid spreading on rough surface: Kr (mean slope of roughness motifs), Rmr (material ratio of the profile) and Rdc (profile section high difference). The increase of Kr and Rmr and decrease of Rdc cause the improvement of the surface wettability,
- Wettability can be controlled by surface morphology and choice of adequate manufacturing method,
- Better wettability of metallic surfaces by oil, improves resistance to scuffing,

5. Perspectives and future work

Further investigations on this issue should include the following elements:

- Verification of the beneficial influence of increased wettability on scuffing resistance for lubrication by surface-inactive oils and dissimilar configuration of friction pair's materials,

- Topological analysis of the surface in terms of synergism and antagonism of their properties and their influence on scuffing process activation.

Acknowledgments:
Authors would like to thank R. Majchrowski & M. Wieczorowski (Poznan University of Technology) for topography measurements and F. Blateyron (Digital Surf) for guidance and facilitating use of the Mountains Map® Software.

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