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Impact of morphological furrows as lubricant reservoir on creation of oleophilic and oleophobic behaviour of metallic surfaces in scuffing

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Abstract

This paper analyses the key role of the surface morphology in the creation of oleophilic or oleophobic behaviour (via oil capacity) of metallic surfaces and its hypothetical influence on the initiation of the catastrophic mechanism of scuffing. Taking into consideration the fact that the commonly used roughness parameters do not correlate with the scuffing performance, the application of the morphological furrows to analysis of the susceptibility of metallic surfaces to this type of surface's failure was proposed and elucidated. Furrows' characteristic was based on the analysis of their three typical parameters (max. and mean depth and max. density in the initial and scuffed surface state) in the mechanical and physicochemical aspects of the surface and lubricant relationship. Improved strategy offering the discriminating methodology of scuffing transition was presented and discussed. Obtained results enabled the identification furrows' parameters predisposed to the scuffing prediction and therefore worthy to consideration for use in manufacturing of frictional operating metallic parts exposed to catastrophic failures.

Nomenclature:	
HD	Hydrodynamic lubrication
EHL	Elastohydrodynamic lubrication
MDF	Mean depth of furrows [µm]
Sa	Arithmetic mean height [µm]
Sz	Maximum roughness height [µm]
t_{SC}	Time to scuffing [s]
XDF	Maximum depth of furrows [µm]
XNF	Maximum density of furrows [cm/cm^2]

1. Introduction

The surfaces of all solids in nature have some texture. However, the textures can differ in properties, from the smoothest polished plate glass to the rough surface of mountain ranges as can be seen on aerial pictures. These specific, textural properties of a surface determine its interaction with the surrounding environment. In the technical sense, texture can be defined as irregularities (peaks and valleys) formed on the surface by the machining or treatment process. Generally, it is accepted that texture is composed of two elements: waviness (widely spaced unevenness generated by vibrations during a machining or treatment process) and roughness (smaller irregularities produced by the direction of the machining). Commonly, the terms "surface texture" and "surface roughness" are synonymous. This is due to the fact that roughness parameters are measured and analysed in engineering practice more often than waviness characteristics [1].
Superficial properties (including roughness and waviness) can be used to accurately analyse specific surfaces, which can make it possible for these surfaces to be consciously formed in a way that makes them suitable for their purpose. That is why surface texturing is gaining a more and more important role in modern science and engineering. Its application covers such completely different areas as classifying skin lesions [2], identifying wood surface defects [3], analysing the lunar surface [4], evaluating concrete features [5] and even industrial robots learning to distinguish between different materials based on their texture [6].
In tribology, surface texturing is mostly used to prepare surfaces for cooperation with lubricants and/or in order to reduce friction (very popular in a design and manufacturing of cylinder liners [7,8] or bearing components [9,10]). One way of doing this is by increasing the surface's oil capacity with the formation of some special "pockets" or "grooves" obtained by different treatment methods, e.g. by laser techniques [8,11], the combination of laser and heat treatment [12], milling [13], burnishing [14] or plateau honing [15]. The increased oil capacity ensures a better distribution of oil in the real contact zone and hence a faster and easier formation of the lubricant's film between rubbing surfaces. In addition, oil "pockets" can be used as a type of "wastebasket" for debris generated during friction. As long as the volume of the pockets ensures the storage or leading out of wear debris, the flow of oil in the contact zone remains unthreatened. However, if the volume of the pockets is not able to accommodate a larger quantity of debris, this debris will accumulate in the contact zone [16]. Consequently, the oil flow will be disturbed and the scuffing process will be activated. Additional attention also needs to be paid to the relationship between the oil capacity of the surface and the volume of oil distributed into the contact zone. It is theoretically possible that oil pockets with too much capacity can generate some problems with the maintenance of a specific volume of oil, indispensable for full film forming, due to the oil

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spreading down from asperities to pockets. That is why full control of creating the surface texture must be maintained, possibly by the identification and analysis of roughness parameters.

It is a widely-held opinion that a reduction in roughness height leads to increased wear resistance due to the growth of individual asperity areas, which causes a reduction in the pressure occurring in the contact zone. However, in the case of catastrophic forms of wear such as scuffing, the role of roughness is not so clear. For example, Qu et al. [17] stated that rougher surfaces allow thicker oil films to form, which help remove abrasive wear debris from the contact area and decrease the temperature of the heated-up asperity areas. Simultaneously, these researchers paid attention to the fact that when a surface is too rough, it also tends to generate high wear due to the high true contact stresses on the peaks of the asperities. These statements are confirmed by Wojciechowski et al. [18] and Kubiak et al. [19], who found that surfaces with a higher Kr parameter have better wettability properties in terms of oil spreading on such surfaces, and lower contact angles due to the spreading dynamics of the oil.

Kr determines the mean slope of roughness motifs, which according to the ISO 12085 standard can be determined as a portion of the primary profile between the highest points of two local peaks of the profile, which are not necessarily adjacent. A higher Kr creates grooves on the surface and facilitates the spreading of oil along those grooves, due to capillary action. Therefore, it can be concluded that not only the volume but also the shape of valleys can influence the lubricating behaviour of oil in the contact zone. This is all the more important because the shape of valleys can also be a factor that determines the direction of oil flow through the contact zone (regardless of the dispersive and polar interactions between lubricants and solid surfaces). That is why it seems that geometric control of the oil in the contact zone is possible and should involve finding an advantageous compromise between the volume and shape of the valleys of the surface. What is more, geometric control will make it possible to directly affect the mechanical component of the oleophilic and oleo-phobic surface response caused by its contact with oil.

Another factor that affects the mutual interaction between the surface and the lubricant is connected with the physical chemistry of these two components, including issues such as a wettability, surface polarity, Lifsitz-van der Waals interactions, etc. There is a possibility to morphologically influence on oil behaviour in the contact zone. Making use of roughness height and the shape of the peaks and volume of valleys, one can have an impact on the value of the static and dynamic contact angles of liquids on the surface. Thus, at least partially, it is possible to control the level of the physicochemical lubricant-surface interactions. The classic 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 application is difficult and limited. Thus far, the basic principles of these theories have been applied primarily in the design of so-called self-cleaning materials [20,21] and superoleophobic surfaces [22]. Unfortunately, none of these applications considers the direct influence of the relationship between a surface roughness and a liquid behaviour on friction and wear.

Taking into account the tribological point of view (including the mechanical and physicochemical aspects of the relationship between the surface and the lubricant), the oleophilicity and oleophobicity of the surface have been proposed and defined as:

- Oleophilicity: the state or condition of being oleophilic; the ability of the surface to retain the oil in the contact area, whether achieved by morphological action, physical adsorption, chemisorption or chemical reaction;
- Oleophobicity (the antonym of oleophilicity): the state or condition of being oleophobic, the inability of the surface to retain an adequate volume of oil in the contact area.

A conscious creation of the shape and dimensions of the surface texture makes it possible to retain the desired amount of oil in the contact area and to force the direction of its flow. Taking into consideration the multithreading of this issue, authors have decided to apply a more global view to surface roughness based on morphological analysis of furrows. This specific analysis makes it possible to estimate the fluid retention capability of some surfaces thanks to the original technique of vectorising the micro-valley network formed on the surface. Although this technique is not widely used in surface engineering, more and more attempts are made to apply it to analysis of the technological effects on surfaces machined or treated by different methods (e.g. Refs. [23,24]).

An insufficient volume of oil in the contact zone generally leads to the initiation of catastrophic types of wear, which is why analysis of the impact of furrows on the oleophilic or oleophobic behaviour of metallic surfaces has been investigated in the context of their scuffing resistance. Therefore, for the purpose of this work, it was assumed that an increase in scuffing performance is equivalent to a growth in the surface's oleophilicity (and vice versa: a decrease in scuffing performance is equivalent to a decrease in the surface's oleophilicity).

2. Methodology

Specimens investigated in the experiment were made of AISI 4130 steel in the shape of cylinders with a 45 mm ± 10 µm external diameter and a 12 mm width. The cylindrical surfaces of all specimens were subjected to grinding so that their surface roughness (Sa) was equal to approx. 0.5 µm. Then, the specimens were divided into six groups, all of which were subjected to burnishing with six levels of pressure in order to create different types of superficial layer. In order to control residual stresses, the burnishing of cylinders was performed with two symmetrical spherical sector-shaped rolls that were 50 mm in diameter. The levels of burnishing pressures complied with the pressures of burnishing tools on the machining surfaces in the following way: 1st: 1.3 GPa, 2nd:1.64 GPa, 3rd: 1.87 GPa, 4th: 2.06 GPa, 5th: 2.22 GPa, 6th: 2.36 GPa. The kinematic conditions of burnishing were as follows: speed: 100 m/min, feed: 0.08 mm/rev., no. of tool pass: 2, lubricated by a 1 to 1 mixture of mineral oil and kerosene. The kerosene in this case played a double role as a solvent and as a lubricant miscible with mineral oil. Kerosene is composed of carbon chains that typically contain between 6 and 16 carbon atoms per molecule, providing a preventive boundary-lubricating layer during machining. As counter-specimens, cast iron (EN-GJL-300) ground (Sa = approx. 0.5 µm) planes were used.

Systematic areal morphological analyses were performed using an optical interferometer (Veeco Wyko NT1100) on the millimetric region relevant to the contact surface [25]. An area of 1.2 mm x 0.9 mm in five parts of the cylindrical surfaces every 72° was analysed. Morphological analyses were conducted very carefully, taking into consideration calibration as well as transfer function and the measurement limitations of the topometric device. The selected parameters of furrows (max. depth, mean depth and max. density) were measured and characterised for the purpose of this analysis.
Scuffing tests employed single drop lubrication using gear oil (Total Transmission Syn FE 75 W/90) with ca. 5% of the olefin sulphide as an Extreme Pressure additive. In order to examine the impact of the direction of oil supply to the contact area on a scuffing activation, the lubricant was applied using two methods:

- Fully lubricated (orthogonal test, Fig. 1a): the drop of oil was released vertically onto the cylindrical surface of the specimen, where it was free to spread. After that, the preloaded flat counter-specimen was applied to the cylinder and the test could begin (Fig. 2);
- Capillary lubricated (parallel test, Fig. 1b): the preloaded flat counter-specimen was first applied to the cylinder and then the drop of oil was forced between the parts of the friction pair. In this case, the oil on the contact zone was distributed by means of free spaces (the network of furrows) in the texture of the surfaces. After that, the test could begin.

Scuffing test kinetics were performed at a sliding speed between the rotating cylinders (AISI 4130 steel) and stationary planes (EN-GJL-300 cast iron) at 0.5 m/s. The criterion for determining the beginning of scuffing was an abrupt and fluctuating increase in the value of the coefficient of friction under constant load. (The procedure for load application is presented in Fig. 2). The scuffing activation period was measured by the time (including initial 8 min of the load implementation) it took for scuffing to occur (t_{SC}), which is equivalent to a case of poor lubrication of the friction pair. In order to satisfy the statistical requirements, the scuffing test was performed four times for each pair of steel cylinders and cast iron flat planes. Fig. 2 shows the details of the geometry and kinetics of the scuffing tests.

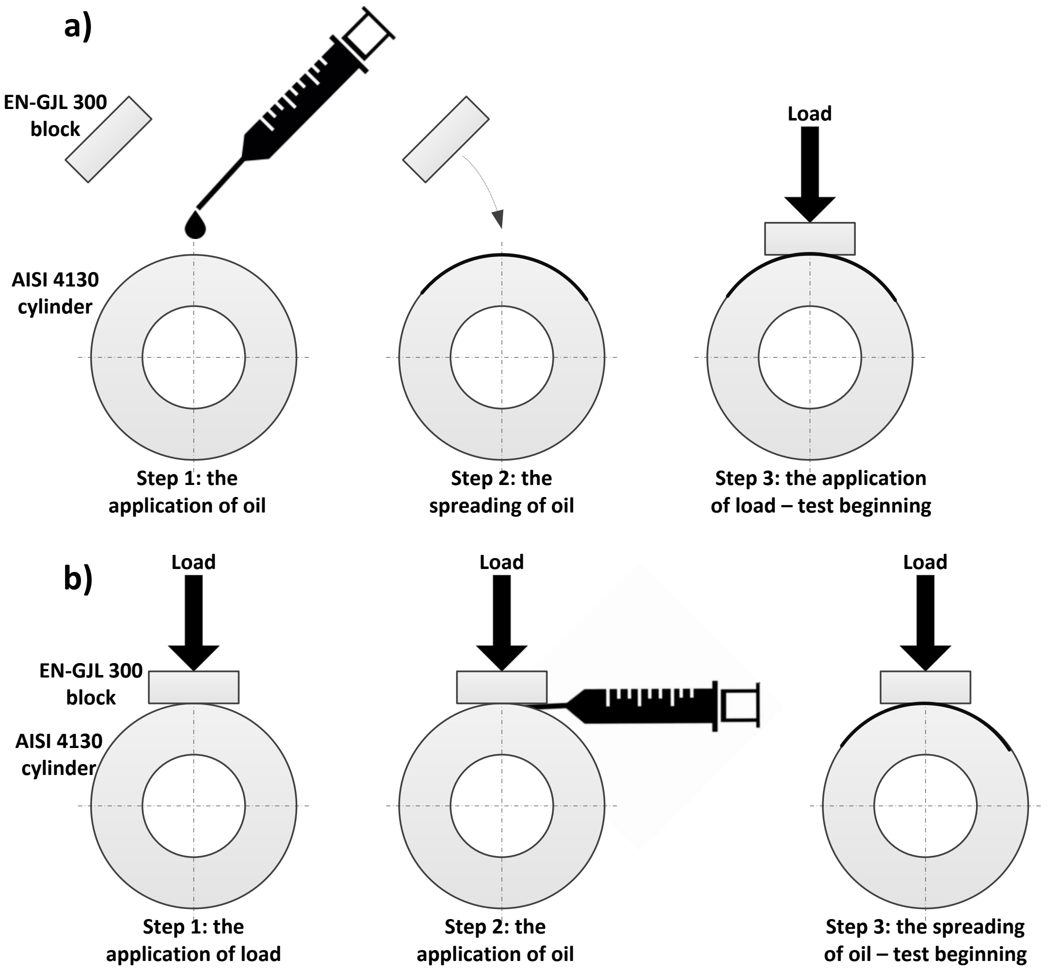


Fig.1. Two methods of the oil application in the scuffing test: fully lubricated (a), capillary lubricated (b).

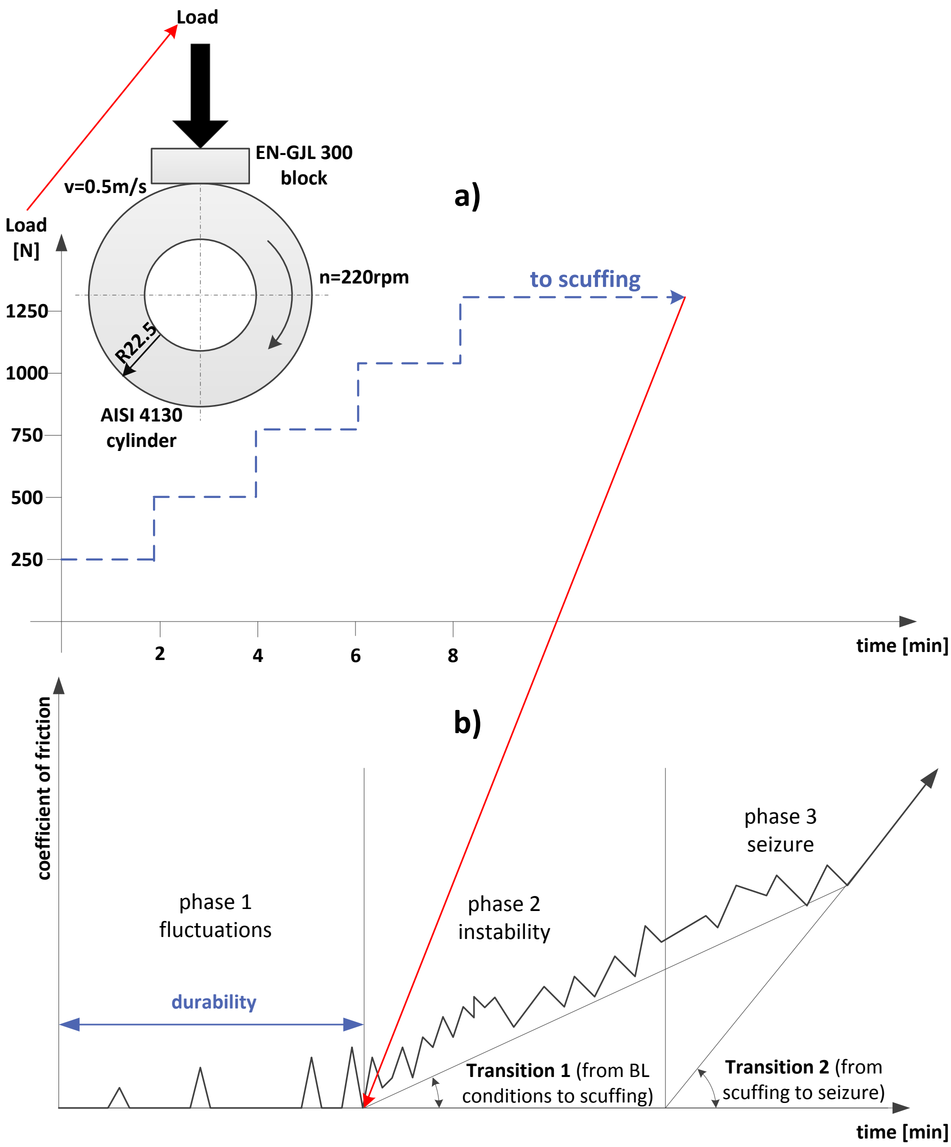


Fig.2. Tribological kinematics and geometry of contacting bodies revealing the transition from boundary lubricated to scuffing and procedure of the load application (a), coefficient of friction versus time of friction (b).

3. Results and discussion

Fig. 3 presents selected 3D isometric views, images of furrows, and mean values of furrow parameters (max. depth, mean depth and max. density) for each configuration of the friction pair.
Analysis of the presented data points to a significant decrease in the value of the mean depth of furrows (MDF) as a function of the increasing contact pressure of the burnishing tools on the machining elements. This decrease was at a level of 0.161 μm (from 0.573 μm at a pressure of 1.3 GPa to 0.412 μm at a pressure of 2.06 GPa). It is worth noting that the lowest value of MDF was observed at pressure slightly lower than the maximum level and equal to 2.22 GPa. At maximum burnishing pressure (2.36 GPa), a district increase (0.258 μm) in the value of MDF was found. This is probably caused by what is known as critical cold work – when the level of crystallites packing the material is so high that further plastic deformation causes no further strengthening of the surface layer, and its destruction begins. For this reason, cylinders burnished with the maximum burnishing pressure were considered as damaged and were not taken into account in further analysis.

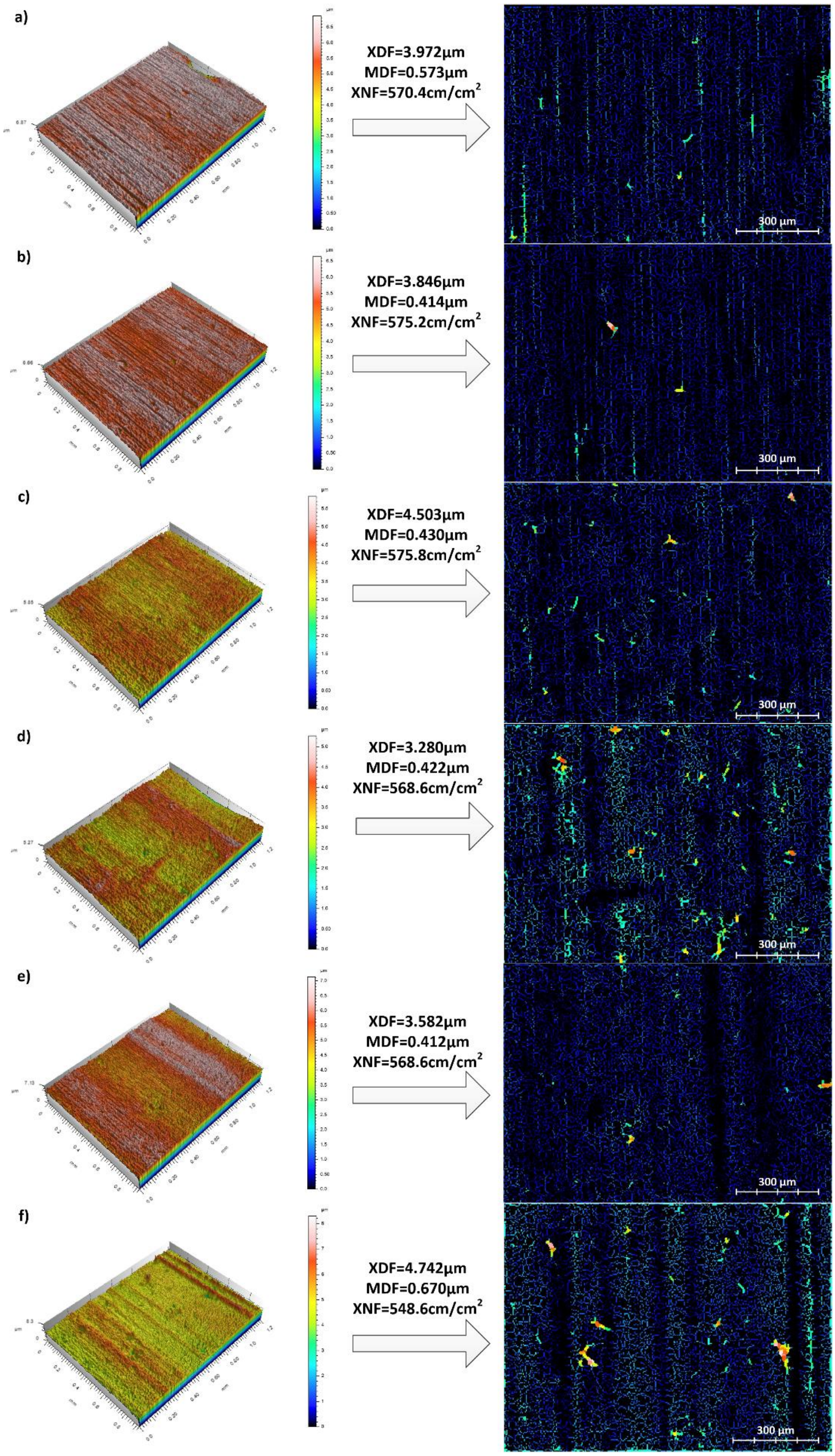


Fig.3. Initial (before scuffing tests) surface morphology: 3D isometric views, morphological furrows depictions and their characteristics for AISI4130 cylinders initial surfaces for different levels of burnishing pressures: 1.3 GPa (a), 1.64 GPa (b), 1.87 GPa (c), 2.06 GPa (d), 2.22 GPa (e), 2.36 GPa (f); (furrows morphological parameters cf. Nomenclature).

A less clear trend can be observed for the maximum depth of furrows (XDF), whose value decreased from 3.972 µm at a pressure of 1.3 GPa–3.280 µm at a pressure of 2.06 GPa. However, it should be noted that at an intermediate pressure of 1.87 GPa, the value of XDF "jumped" to 4.503 µm. This parameter can achieve some unusual extreme values on the analysed surface due to its single discontinuity or damage (similarly to changes in max. roughness height [Sz], a popular parameter in roughness investigations). Irrespective of that, the changes of both depth parameters (MDF and XDF) indicate a flattening of the surface and an increasing contact area due to plastic deformation. Simultaneously, a small decrease in the value (from approx. 575 cm/cm^2 to approx. 548 cm/cm^2) of the maximum density of furrows (XNF) can be observed. This is due to burnishing. Therefore, it seems that XNF slightly depends on the conditions of this method of treatment. Fig. 4 presents the relationship between XDF and scuffing performance (t_{SC}) of the analysed friction pair in the orthogonal and parallel test.

Based on Fig. 4a, it can be stated that there is a statistically-confirmed dependency between t_{SC} and XDF in the orthogonal test. The trend of this relationship is a little surprising (the best t_{SC} was achieved for the lowest values of XDF), and is most likely connected to the favourable shape and volume of the furrows in terms of oil retainment and distribution in the contact zone. Therefore, this conclusion should not be generalized, and requires further confirmation in other scuffing investigations. Simultaneously, there is no statistically-confirmed dependency between t_{SC} and XDF in the parallel test. However, the trend of t_{SC} changes the function of XDF is very similar in both tests (Fig. 4a and b). What is interesting is that there is also no confirmed correlation between t_{SC} and MDF (Fig. 5). This fact may be caused by the "hiding" of any extreme values of furrow depth in MDF. In fact, these deepest furrows may be responsible for the supply of an adequate volume of oil, and thanks to that, safe lubrication in the contact zone. Hence, there is a statistically-confirmed dependence between t_{SC} and XDF (in contrast to the relationship between t_{SC} and MDF). On the other hand, the best t_{SC} was achieved for the minimum values of XDF (3.280 µm) in this investigation. This means that this value of XDF is the optimum compromise between the volume of oil (and eventual direction of distribution) in the contact zone and critical pressures at asperities. However, one must be aware that a further reduction in XDF will lead to the achievement of some limit state in which the quantity of oil in the contact area will be insufficient to maintain the HD/EHL film or boundary layer, and t_{SC} may fall dramatically.

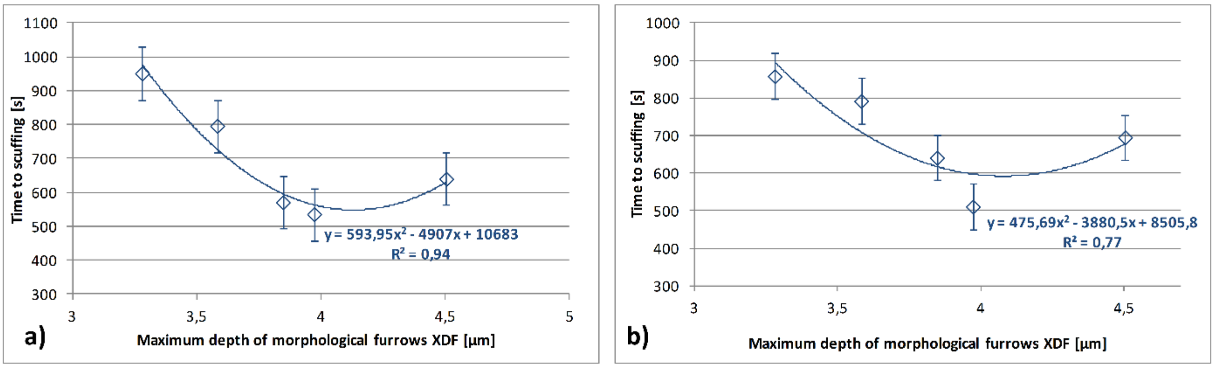


Fig.4. Time to scuffing versus maximum depth of furrows XDF in: an orthogonal (a) and a parallel (b) test.

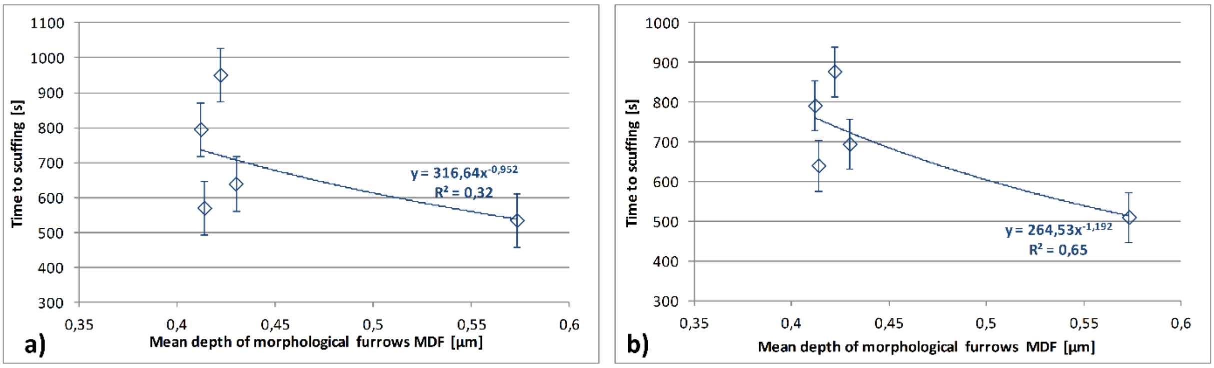


Fig.5. Time to scuffing versus mean depth of furrows MDF in: an orthogonal (a) and a parallel (b) test.

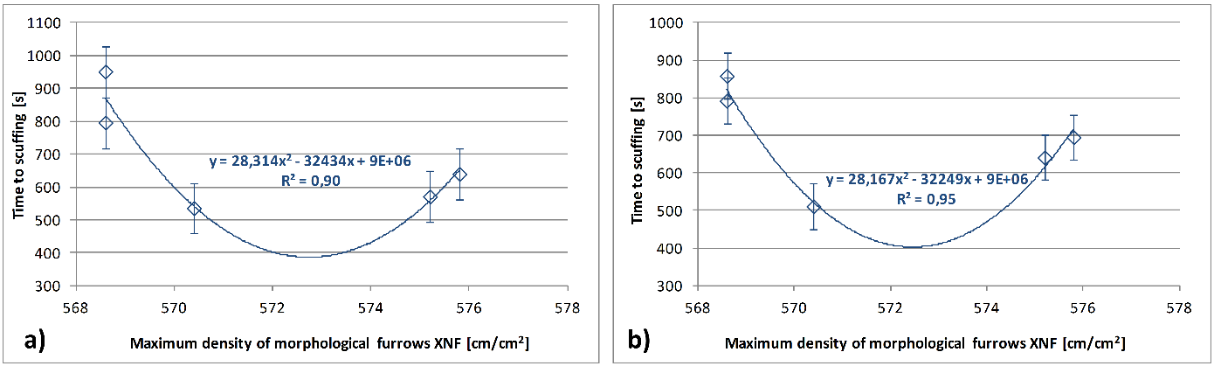


Fig.6. Time to scuffing versus maximum density of furrows XNF in: an orthogonal (a) and a parallel (b) test.

Certainly, special attention should be paid to the influence of the oil application method on t_{SC}. A reduction of the t_{SC} value by approx. 12% can be seen in the parallel test compared to the orthogonal test. This is probably caused by the slightly worse lubrication conditions on the surfaces of asperities at the beginning of the test. Consequently, peaks are subjected to the higher plastic deformations or/and abrasion wear and

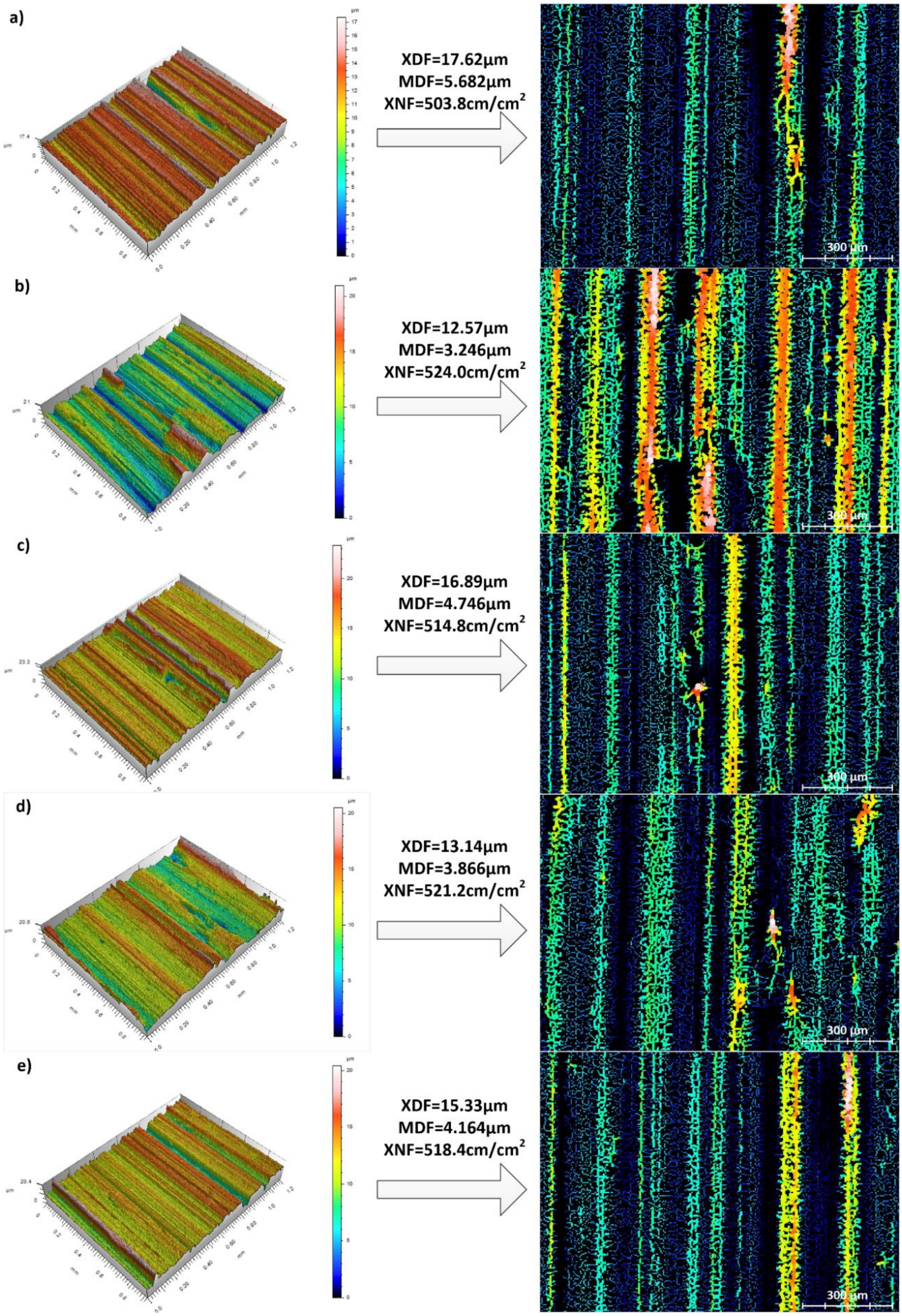
their newly formed surfaces are richer in structural failures. These points may be active sites that facilitate a dynamic formation of adhesive tacking and scuffing activation.

It can also be observed that there is a statistically-confirmed influence (in both tests) of XNF on tSC (Fig. 6). Scuffing performance increases with a decrease of XNF, but the difference is so small (only 7.2 cm/cm^2) that it is not possible to unequivocally state that the density of furrows determines scuffing resistance. This statement has to be confirmed or refuted with other configurations of tribosystems.

Assuming that the oleophilic behaviour of the surface advantageously affects its scuffing resistance, it can be expected that maximum depth (XDF) and maximum density (XNF) should have significant influence of the surface scuffing resistance. Presented results confirms that hypothesis and therefore one can expect the surface scuffing resistance improvement due to its better oleophilicity characteristic (determined by the XDF and XNF) and created in this case by the treatment process (grinding and burnishing). Therefore, it can be stated that it is possible to consciously create a network of furrows of a suitable depth and density conducive to improving scuffing performance.

Additionally, the characteristics of the furrows of analysed surfaces after scuffing tests were investigated. The results are presented in Fig. 7. There were no recognised correlations between t_{SC} and the furrows' characteristics (XDF, MDF and XNF). Instead, only the spectacular consequences of the scuffing process and the level of surface destruction caused by it could be observed.

In order to clarify whether the initial morphological state of a surface has some influence on the size of adhesive wear products, the evolution of furrows' characteristics generated by scuffing was examined (Fig. 8). Interestingly, a statistically-satisfying (R^2 = 0.82) dependency was recognised only between MDFs in the initial and scuffed state. According to this data (Fig. 8c), lower values of MDF in the initial state correspond to smaller sizes of scuffing failures. Additionally, it can be noticed that this situation explains the relationship between XDF and t_{SC} (the best scuffing performance was achieved for the lowest values of XDF). However, as analysis of this issue is based on only one tribosystem configuration and quite a low value of the R^2 coefficient, the statement concerning the influence of MDF on the final size of scuffing wear products should be treated as conjecture.



.Fig. 7. Surface morphology after scuffing tests corresponding to the initial state (Fig. 3): 3D isometric views, morphological furrows depictions and their characteristics of AISI4130 cylinders' surfaces for different levels of burnishing pressures: 1.3 GPa (a), 1.64 GPa (b), 1.87 GPa (c), 2.06 GPa (d), 2.22 GPa (e); (furrows morphological parameters cf. Nomenclature).

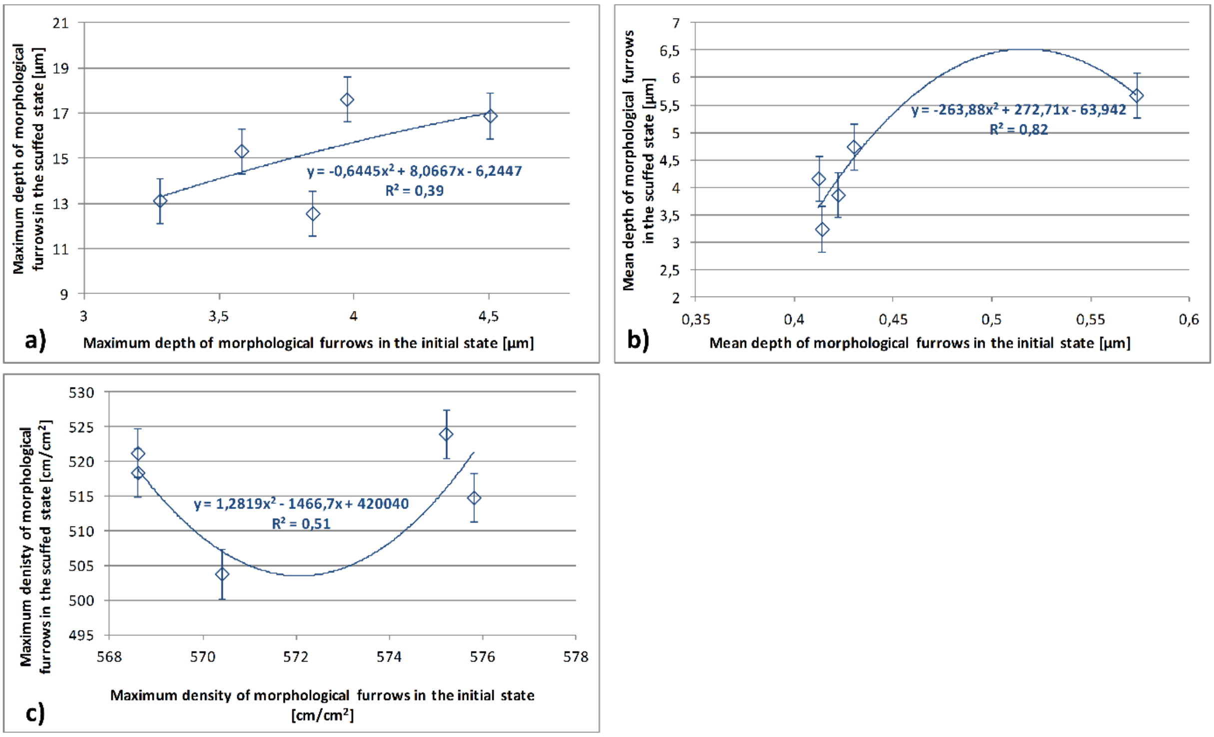


Fig. 8. The comparison of the morphological furrows' characteristics in the initial and scuffed state: maximum depth of furrows XDF (a), mean depth of furrows MDF (b) and maximum density of furrows XNF (c).

3. Concluding remarks

Experimental investigation of surface morphology (i.e. furrows) influence on catastrophic wear (i.e. scuffing) was carried out. Several surfaces with different initial morphology were prepared by grinding and burnishing processes. Scuffing tests were carried out with two different methods of lubricating oil application: fully (orthogonally) and capillary (parallel) based lubrication were employed. Both initial morphology and lubrication method have significant influence on resistance to scuffing. Surface performance can be related to texture, direction and inter-connectivity of micro-channels responsible for creating and maintaining continuous lubricating film between the contacting surfaces in very severe contact conditions. Also spreading of the lubricating oil can be associated with capillary action and surface oleophilicity. On the basis of the experimental observations presented in this investigation, the following conclusions can be formulated:

- There is statistically-confirmed dependency between the scuffing performance (t_{SC}) and the maximum depth of furrows XDF in the orthogonal test (in the parallel test this relationship was not statistically confirmed, however the trend is the same).
- There is a direct, statistically-confirmed dependency between t_{SC} and the maximum density of morphological furrows XNF in the orthogonal and parallel test. However, the changes are so small (7.2 cm/cm^2) that one should be wary of making an unequivocal statement that XNF determines scuffing resistance.
- The method of oil application influences scuffing performance. The parallel method of oil application resulted in a decrease of approx. 12% of t_{SC} in comparison to the orthogonal test. This is connected to the worse lubrication of the peaks of asperities at the beginning of the test, and their bigger plastic deformations at this time.
- Taking into consideration all formulated conclusions, it can be stated that selected parameters of furrows (XDF and XNF) can be considered as morphological factors creating the oleophobic or oleophilic behaviour (especially its mechanical part) of metallic surfaces exposed to scuffing.

4. Perspectives and future works

Further investigations regarding the problem of morphological impact on the oleophility and oleophobicity should include the following areas:

- The verification of the influence of selected furrows' characteristics (XDF & XNF) on scuffing resistance for other configurations of tribosystems (materials, lubricants, operational parameters etc.).
- The analysis of the surface morphology in terms of the synergism and antagonism of its characteristics and its influence on the scuffing process activation.

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