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Influence of roughness on contact interface in fretting under dry and boundary lubricated sliding regimes

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Abstract

This paper presents experimental results of wear process under dry and boundary lubricated metallic (AISI 1034/AISI 52100) contacting bodies with different surfaces morphologies subjected to a wide range of kinematic fretting conditions. Analysis of damage mode observed under such fretting conditions is elucidated in context of surfaces morphologies therefore associated with surface manufacturing processes. Various surface topographies due to specific machining processes (cutting and abrasive modes) have been investigated. Under boundary lubricated (ZDDTP zinc-dialkyl-dithiophosphate) fretting contact paradoxally has a high coefficient of friction at the transition between Partial and Full slip sliding regime. This paper attempts to bridge the gap between the damage mode, sliding conditions and surface roughness to provide an approach to evaluate the surface finishing as a factor in friction and wear damage processes.

Keywords: Surface morphology, Boundary lubrication, ZDDTP zinc-dialkyl-dithiophosphate, Fretting.

1. Introduction

Fretting is a small oscillatory movement in the contact between two surfaces subjected to vibrations or cyclic stresses. The relative displacement in the fretting might result in the damage of contacting surfaces such as cracking, wear, plastic deformation and oxidation.

Nomenclature

δ - displacement (μm),

δ^* - displacement amplitude (μm),

δ_t - sliding transition displacement amplitude (μm),

$\Delta\delta$ - incremental step of displacement amplitude (μm), P - normal force (N),

Q - tangential force (N),

Q* - tangential force amplitude (N),

p_o - maximum Hertzian's contact pressure (MPa),

a - Hertzian's contact half-length (µm),

N - number of cycles,

ΔN - number of cycles between the incremental steps of displacement,

S_q - 3D surface root mean square (RMS) roughness (µm),

S_a - 3D surface average roughness (µm),

S_z - 3D surface peak-to-valley average maximum height (µm),

µ - coefficient of friction where µ=Q*/P,

μ_t - coefficient of friction at the transition PS/FS,

μ_{stab} - stabilized coefficient of friction in FS,

v_{max} - maximal relative speed in the contact (m/s).

Depending on the relative displacement at the contact, different sliding regimes can be defined. Partial Slip (PS) sliding regime is associated with a small relative displacement and is characterized by a closed elliptical fretting loop (i.e. evolution of the tangential force (Q) versus the applied displacement (δ)). Fretting scar is characterized by the stick zone at the middle of the contact and sliding zone at the contact extremities. In the PS regime the main damage observed at the contact is the cracking phenomenon. For the larger relative displacement, full sliding of the contacting surfaces is observed and fretting loop is characterized by a quadrilateral dissipative shape. This Full Sliding (FS) regime is related to the wear of the contacting materials (Fig. 1).

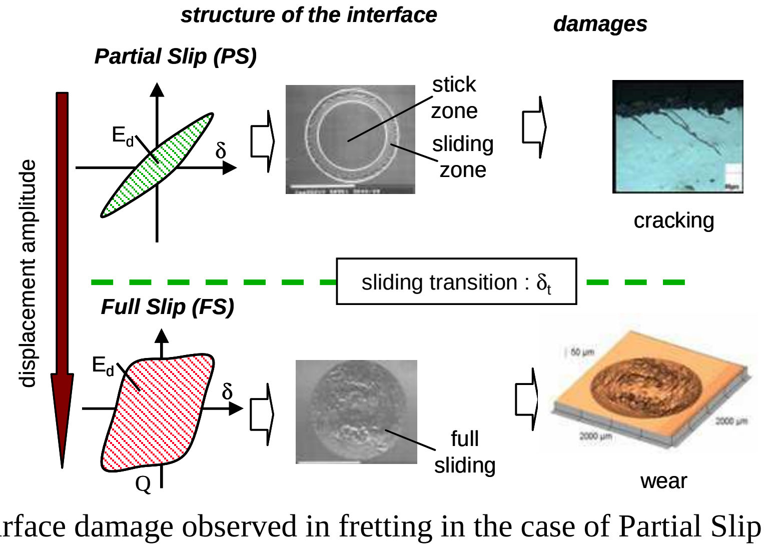

Fig. 1: Typical surface damage observed in fretting in the case of Partial Slip and Full Slip [1].

Fretting is a dynamic wear process therefore the initial surface roughness can be a major factor in determining the sliding conditions of the interface and the corresponding damage mode (i.e. cracking in PS and wear in FS). During wear process, the degradation of the surface changes the initial roughness of the interfaces. This will affect the sliding conditions and for instance lead to sliding regime changes from PS to FS (i.e. from cracking to wear damage mode). The important question is the influence of the machining process and surface topography on the sliding conditions under the fretting loadings. Surface roughness has been investigated for different materials, but rather under the full sliding condition than under Partial Slip fretting. Wong et all. [2] have reported the roughness influence on ceramics under mixed and hydrodynamic lubrication, a decreasing friction coefficient has been found for smoother surfaces. For aluminium alloy under dry contact Proudhon et all. [3] have noted an inverse influence of roughness where the rough surface tends to decrease the coefficient of friction and transition from PS to FS. Moreover, a rough surface can increase the cracking nucleation risk. Another issue is the influence of the contact lubrication on sliding regimes in rough contact conditions under fretting. Yuan et all. [4] reported the variation of the surface roughness during the ball-on-disc test under lubricated conditions, they noted the systematic increase of the roughness and wear rate. In many industrial applications like joints, clutchs etc. a high coefficient of friction is required, surface morphology in these components can be a major parameter to control the sliding conditions. This paper tends to highlight the experimental observations, and answer the pointed out questions: initial surface roughness influence on fretting sliding conditions under dry and lubricated fretting.

2. Experimental procedure

The experimental procedure is based on a selection of well known materials and machining processes following the application of strict tribological and metrological measurement procedures. The machining processes are well known and proven, surfaces morphology characterisations involve calibrated equipment, and collected data are analysed thanks to proven standardized software. Fretting metrological device is systematically calibrated and adapted to specific purpose of the study described in this paper. The Design of Experiment methodology has been uses in order to perform an optimized experimental investigation and analyze the roughness, the contact pressure and the lubrication influence on tribological response of tested materials. All experimental tests have been performed in the sphere/plane contact configuration.

2.1 Metallurgical and rheological characteristic of tested materials

The tested plane material was machined into a small rectangular prism (10x10x14mm). The material used for the plane specimens was low carbon alloy AISI 1034 which, after a specified heat treatment, provides the mechanical properties listed in Table 2. As a counterbody for tested material, a sphere of 50 mm radius was used. The sphere material was AISI 52100 ball bearing steel. The chemical compositions of tested materials are presented in Table 1.

Table 1: Chemical composition of tested materials.

Materials		C	Mn	Cr	Ni	Ti	Cu	Si	P	S	Mo	V
AISI 1034 (plane)	max (%)	0.38	1.2	0.3	0.3	-	0.3	0.5	0.02	0.02	0.08	0.06
AISI 52100 (sphere)	max (%)	1.0	0.3	1.5	0.4	1.0	1.0	0.2	0.02	0.02	0.1	0.3

Table 2: Mechanical properties of tested materials.

Materials	E (GPa)	Poisson ratio ν	$\sigma_{Y(0.2\%)}$ (MPa)	σ_{UTS} (MPa)
AISI 1034 (plane)	200	0.3	350	600
AISI 52100 (sphere)	210	0.3	1700	2000

2.2 Macro and micro geometrical configuration

From a macro geometrical point of view, the fretting experiments were performed in sphere/plane contact configuration, where the sphere radius was R=50 mm +/- 10µm. The plane surface was machined (cutting then milling or abrasive polishing) into a rectangular prism. The morphologies of contacting bodies determine micro-geometrical configurations. During this study unidirectional surface texturing has been used. The results of the experimental investigation are limited here to fretting tests orthogonally oriented to the main direction of anisotropy of surface's motifs.

2.3 Machining of plane samples

Two methods of machining process for plane specimens based on different processes: milling and polishing have been selected not only to cover a wide range of technologically applied process, but also to produce well finished (orthogonally oriented to sliding direction) morphologies. Any machining has two purposes: obtaining shape and functional surface topography. The first is easy to achieve, the second one has no simple rules relating the manufacturing process to surface morphology [5]. Effort into research of relationships between manufacturing process and 3D topography parameters has been recently observed [6, 7].

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For the rough plane surfaces, three types of milling process have been used. For the abrasive process, the planes where machined with sand papers (SiC) from 240 up to mirror-polished on 4000 grid paper. A wide range of surface roughness on plane samples from S_z=1.02 µm up to S_z=35.05 µm has been achieved. The initial surface roughness parameters: S_a - Arithmetic mean height, S_q - Root mean square height, S_z Maximum height, of the plane materials are listed in Table 3.

Table 3: Parameters of initial surface roughness (ISO 25178).

Plane Reference	Surface Preparation	S_a (µm)	S_q (µm)	S_z (µm)
Surf. 1	milling-cutting	4.15	5.11	35.05
Surf. 2	milling-cutting	4.15	5.10	30.76
Surf. 3	milling-cutting	3.66	4.31	27.56
Surf. 4	polishing-abrasion (240)	1.52	2.00	27.00
Surf. 5	polishing-abrasion (800)	0.32	0.45	6.41
Surf. 6	polishing-abrasion (1200)	0.28	0.40	5.78
Surf. 7	polishing-abrasion (4000)	0.09	0.11	1.02

2.4 Surface morphologies

To evaluate the influence of surface roughness, seven different surfaces have been prepared on plane specimens. The surfaces numbered 1, 2 and 3 were prepared by milling process where material has been removed by cutting. The 3D isometric topographies of initial surface roughness are presented in Fig. 2

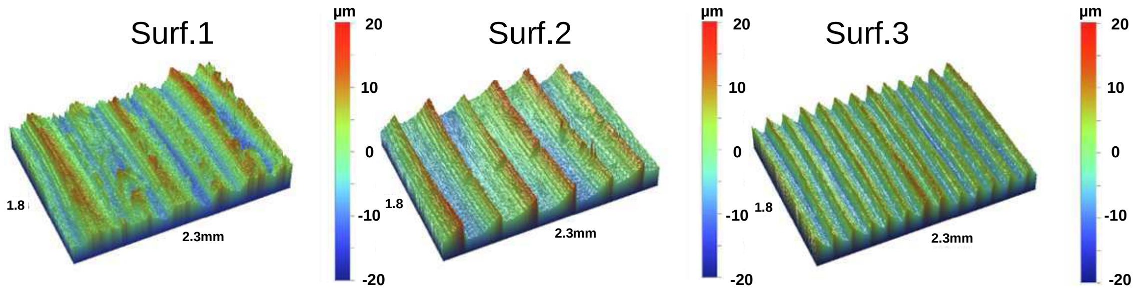

Fig. 2: 3D morphology images of initial surface roughness on plane specimens, prepared by milling process [8].

The polishing by abrasive process has been performed at the metallographic polishing machine with the 240, 800, 1200, 4000 grid papers, obtained surfaces are numbered 4, 5, 6 and 7 respectively. The 3D topographies of initial surfaces roughness are presented in Fig. 3.

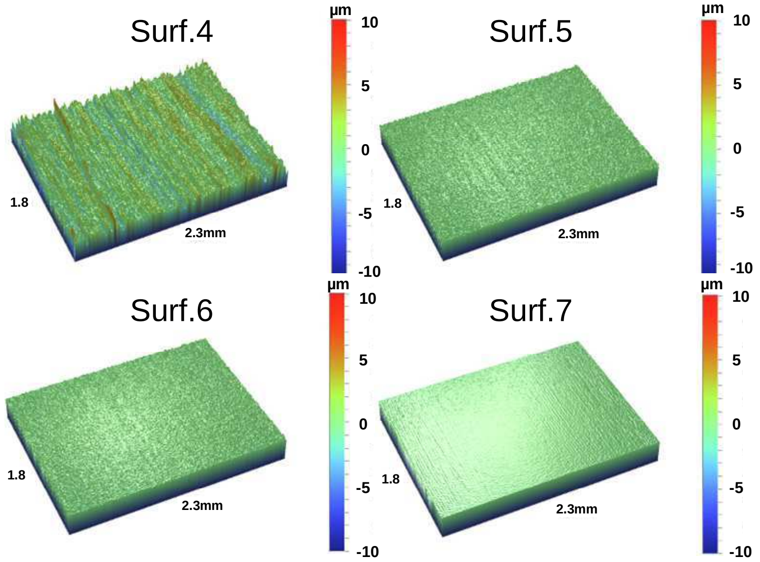

Fig. 3: 3D morphology images of initial surface roughness on plane specimens, prepared by abrasive polishing [8].

In the case of studied surfaces the degree of isotropy, periodicity, fundamental period size and the principal direction have been systematically calculated. The tested surfaces are strongly anisotropic (isotropy less than 5%) with very high periodicity of motives (over 70%). More detail on the surface morphology of the tested materials can be found in the previous study on similar morphologies [8].

2.5 Tribological conditions of fretting test

The experimental fretting tests were performed on a fretting setup device rigidly mounted on a servo hydraulic test machine. During the test, normal force was kept constant and a sinusoidal displacement with frequency of 20Hz was applied. Relative displacement δ(t), normal force P and tangential force Q(t) were acquired and recorded as a function of time (t). All tests were carried out in ambient laboratory conditions, at room temperature ~23ºC and with a relative humidity between 40 and 45%. A detailed description of the fretting setup used in this study can be found in [8]. In order to evaluate the contact pressure influence on frictional behaviour several additional test were run for p_o=500, 700, 900 and 1000 MPa. Fretting tests were performed under incremental displacement amplitude method.

2.7 Incremental displacement method

To identify the displacement amplitude of the transition from PS to FS conditions, an incremental displacement methodology has been applied [9]. At the beginning of the test a very small displacement amplitude was imposed (δ*=1 μm) and increased by regular steps at regular intervals. Hence, through a single fretting test, a complete overview of the sliding response can be provided. Previous investigation [10] have shown that a perfect coherence with classical constant sliding test conditions is achieved if the incremental step of the sliding amplitude remains smaller than Δδ=0.2 μm, and the interval between displacement amplitude increment above ΔN=1000 cycles (Fig. 4). The total number of cycles for each test was 200 000. The quantitative variables (p_o, μ_t) defining the tribological behaviour of the studied tribosystems are listed in Table 5.

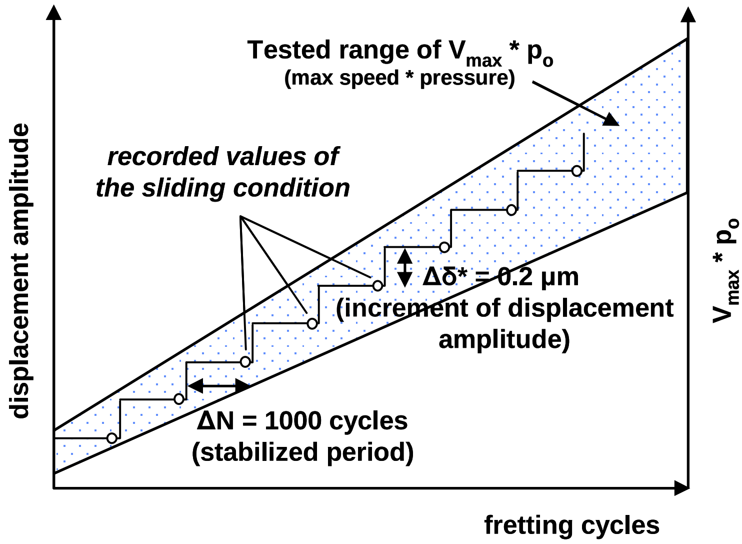

Fig. 4: Illustration of incremental displacement test method.

3. Results and discussion

3.1 Friction

The experimental study presented in this paper is a continuation of previous investigations [8] carried out in dry contact conditions on similar specimen morphologies. In the present paper the phenomenon of the boundary lubrication in sliding contact conditions has been evaluated. Tested material is AISI 1034 low carbon alloy on which the selected surface finishing processes (milling cutting and abrasive polishing) have been applied. Cutting process by plane milling on specimens Surf. 1-3 and abrasive sand paper polishing on specimens Surf. 4-7. Topographical parameters of the initial state of prepared surfaces are summarized in Table 3.
From the obtained experimental results, the influence of the initial roughness and the Hertzian pressure in the contact, under boundary lubrication conditions, has been elucidated.

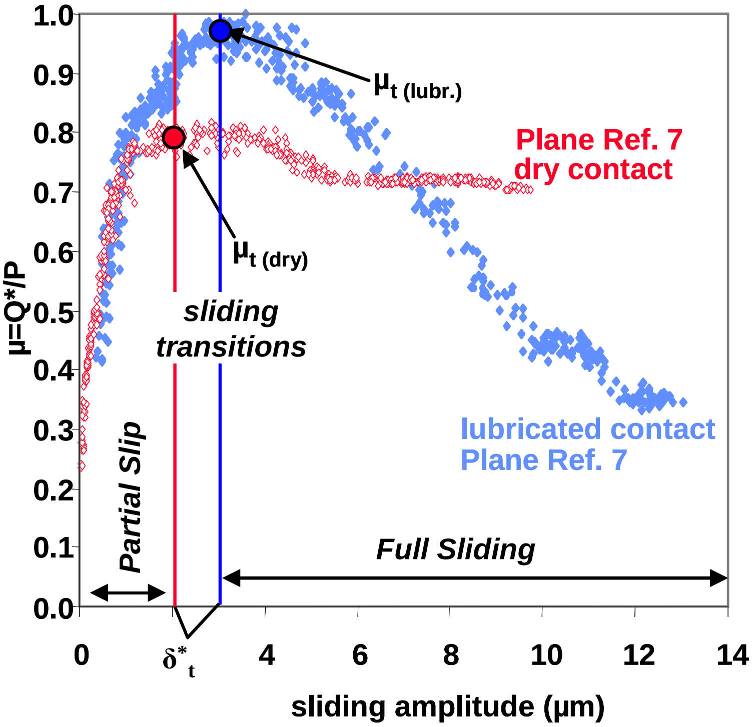

Fig. 5: Fretting sliding response under dry and lubricated contact, identification of sliding transition parameters depending on surface roughness (plane specimen - Surf. 7) from incremental test (normal force P=1000N).

In the Fig. 5 example results of the variable displacement test are presented and evolution of the forces ratio Q*/P have been plotted. It can be noted that in the first stage of the test in Partial Slip conditions the evolution is very similar for dry and lubricated contacts. However, for the lubricated contact the coefficient of friction at the transition μ_t between Partial and Full Sliding is significantly higher than for dry contact. In addition, the relative sliding amplitude at the transition PS/FS is slightly higher (δ^*_t), however the impact of the initial surface roughness and lubrication conditions on transition sliding amplitude is very limited. The relative sliding amplitudes observed at the transition for all of the experimental conditions remains between 2 and 4 μm. This phenomenon can be explained by the chemical reactions between the zinc-dialkyl-dithiophosphate (ZDDTP) lubricant or 2-pentanol solvent and the metallic contacting surfaces. The above-mentioned interactions could also be supported by the work of Kajdas and Obadi [11]. They supposed that alcohols did react with the steel surface under boundary lubrication and that metal alkoxide might be generated, which differs from what has been widely accepted; that alcohols do not react with metallic surfaces. In this respect, further work is needed to reveal the tribochemical mechanism concerned. Under high contact pressure, a tribofilm (ZDDTP) of zinc-dialkyl-dithiophosphate can be created. The presence of a tribofilm in fretting contact subjected to partial slip sliding leads to an increase in the coefficient of friction at the transition (μ_t) [12]. Scientists from LTDS reported [13] results which demonstrate that to activate the anti-wear protection of ZDDTP tribofilm the specific relative speed sliding is necessary. In the Full Sliding regime where all area of surface contact is

subjected to relative sliding, the coefficient of friction significantly decreases (Fig. 5) [14], while the coefficient of friction in dry contact remains stable at the level of $\mu=0.7$.
In order to evaluate the synergetic influence of the initial surface roughness, Hertzian's pressure in the contact and boundary lubrication (ZDDTP) effect on the tribological properties of AISI 1034/AISI 52100 tribo-couple, the statistical approach of Design Of Experiments (DOE) methodology has been used. The method permits us to optimize and significantly reduce the number of experimental tests by using statistical methods to analyse the influence of test parameters like roughness, pressure, lubrication (variable factors) on the tribological behaviour, in this study coefficient of friction μ_t (response factor). For this kind of experiment, a very useful statistical method is the so-called "Surface Response". First, we need to specify the three experimental factors and one response variable. In the next step the range of tested parameters have to be defined. Therefore, the designed experiment will be the 3 factorial "Box-Behnken" method. Often some preliminary tests are required to experimentally validate the range of the tested conditions. In this study the pre-screening test in a large range of pressures has been performed in order to obtain the "dome shape" response surface. Once the range of tested parameters has been found, we can calculate and perform several experimental tests. To analyse the obtained results the analysis of Variance (ANOVA) can be use. Calculated parameters for ANOVA analysis are summarized in Table 4.

Table 4: Analysis of Variance for coefficient of friction at the transition PS/FS(μ_t).

Source	Sum of Squares	Mean Square	F-Ratio	P-Value
A: Roughness S_z	0.1702	0.1702	13.25	0.0054
B: Hertzian Pressure	0.0371	0.0371	2.89	0.1234
C: Lubrication	0.1378	0.1378	10.72	0.0096
A^2	0.0471	0.0471	3.67	0.0878
B^2	0.0348	0.0348	2.71	0.1343
Total error	0.1156	0.0128		

From this analysis it can be noted that 2 parameters have the significant influence on the coefficient of friction at the transition PS/FS(μ_t), parameter A which is roughness S_z and C lubrication. For these parameters the P-values are less than 0.05 (see vertical blue line at Fig. 6), this indicates that they are significantly different from zero at the 95.0% confidence level and can be considered as the major factors influencing the μ_t. The R-Squared statistic indicates that the model as fitted explains 77% of the variability in μ_t.
Results of the influence, of variation in test condition parameters (factors), on the coefficient of friction at the transition (μ_t) are presented graphically in the Pareto chart, where the bars represent the linear (A, B, C) and parabolic (A^2, B^2) effect of each test parameter (Fig. 6). As mentioned above there are two factors A: Roughness (S_z), C: Lubrication, which are statistically important. The B: Hertzian Pressure (p_o) in the studied range (500-1000 MPa) has less influence on coefficient of friction at the transition (μ_t) and statistically does not have significant effect.

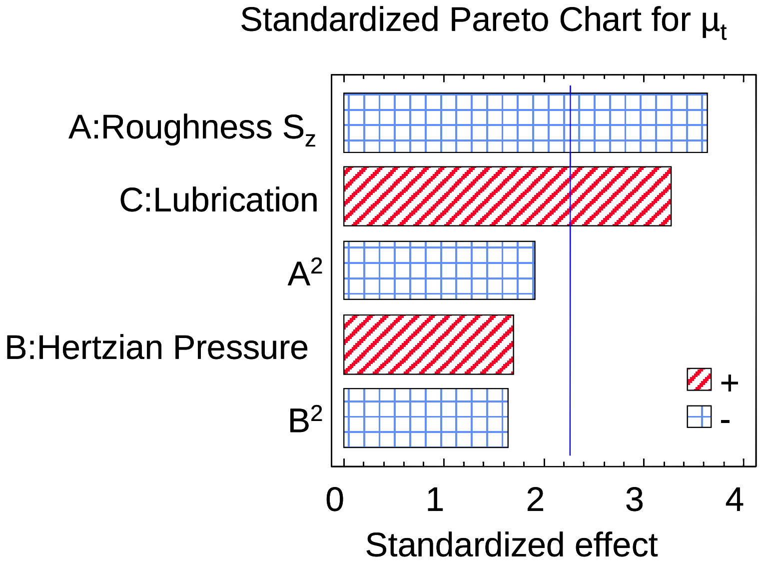

Fig. 6: Pareto chart of the standardized effect of A: Roughness (S_z), B: Hertzian Pressure (p_o), C: Lubrication, at the α=5% significance level.

Results of surface response analysis are presented in Fig. 7 and Fig. 8, this demonstrates the influence of the roughness (S_z), Hertzian pressure (p_o), and boundary lubrication (ZDDTP) [15] on the coefficient of friction at the transition PS/FS μ_t. As previously mentioned the range of tested parameters have been selected from the pre-screening tests to obtain the "dome shape" surface response. Plotted surfaces present the maximum value in the tested range of evaluated tribological factors. The initial surface morphology and the finishing process have a strong effect on μ_t value. The second parameter is the lubrication effect where the boundary lubrication kinematic contact conditions are present under fretting sliding. A less significant effect on μ_t can be observed for Hertzian's contact pressure.

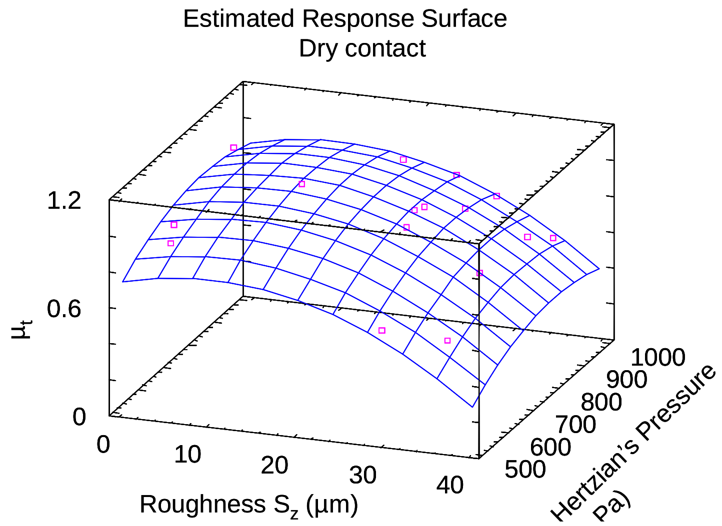

Fig. 7: Estimated surface response of COF at transition PS/FS - μ_t in dry contact under fretting conditions loading.

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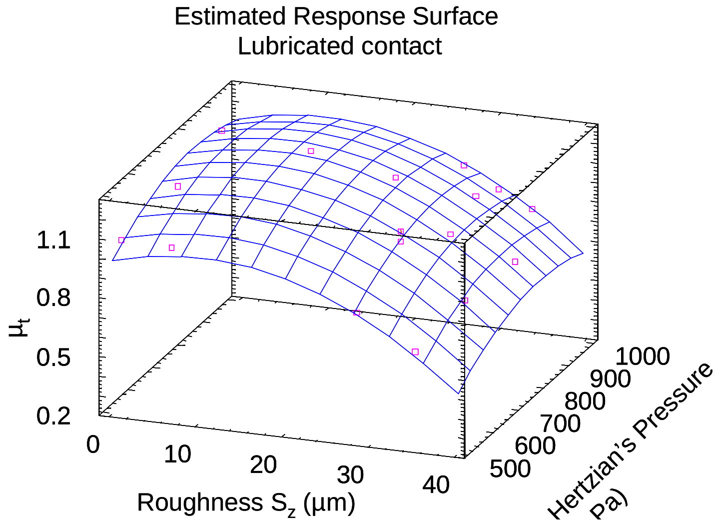

Fig. 8: Estimated surface response of COF at transition PS/FS - μ_t in boundary lubricated contact (ZDDTP) under fretting conditions loading.

3.2 Wear

This paradoxical effect when the coefficient of friction is higher under lubricated conditions can be used in many engineering applications where high forces have to be transmitted through the contact. However, for higher sliding amplitudes in the Full Sliding regime a high value of coefficient of friction can lead to a drastic increase of wear rate, for tested fretting conditions (variable displacement test methodology) the observed wear (Fig. 9) depending on the partial sliding friction history. Therefore, the number of cycles in Full Sliding and observed wear volume is different for the tested surfaces and conditions loading and cannot be compared directly. The further investigation carried out using a fixed number of cycles in full sliding regime is needed to evaluate the roughness influence on wear of materials under fretting.

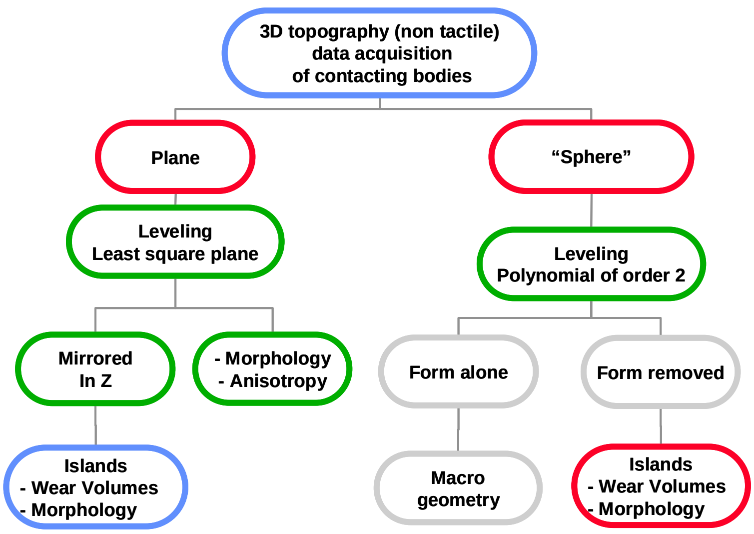

Fig. 9: 3D Topographical Wear Analysis Workflow of contacting bodies plane/sphere.

Material that is deformed, removed or transferred to the counter body can be calculated and related to tribological conditions and surface finishing process [16]. As illustrated in Fig. 10 external plastic deformation and transferred matter to the sphere counter body can be observed. In this case, the removed material is 1.17 mm^3 in comparison to transferred part representing 0.199 mm^3. In this paper, we are focusing mainly on the friction behaviour and therefore the wear analysis is restricted.

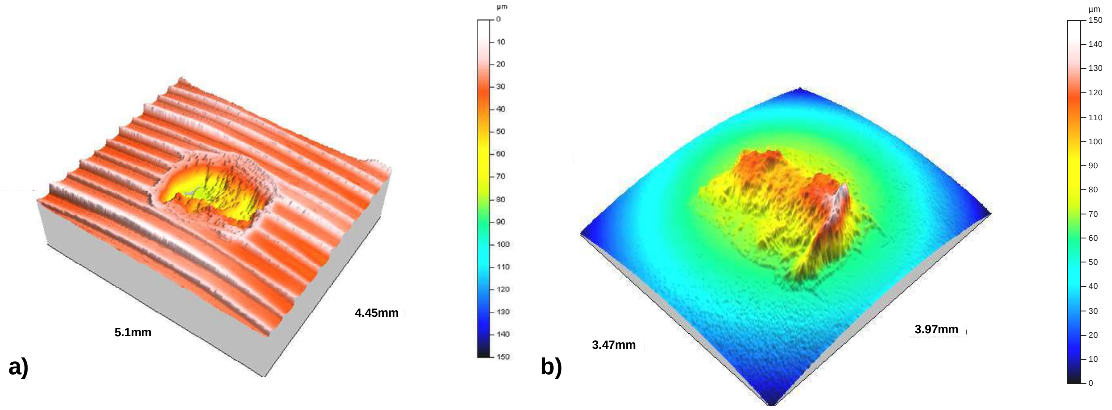

Fig. 10: 3D morphological view of fretting traces (Surf. 2) under lubricated contact conditions a) AISI 1034 plane, b) AISI 52100 sphere with radius R=50 mm.

Table 5: Sliding parameters obtained by incremental displacement method.

Specimen Reference	Roughness S_z (µm)	Hertzian's pressure (MPa)	μ_t	Contact conditions
Surf. 4	27.6	500	0.57	Dry
Surf. 4	27.6	900	0.80	Dry
Surf. 1	35.1	700	0.73	Dry
Surf. 7	1.0	700	0.82	Dry
Surf. 4	27.6	700	0.99	Lubricated (ZDDTP)
Surf. 1	35.1	500	0.59	Lubricated (ZDDTP)
Surf. 1	35.1	900	0.70	Lubricated (ZDDTP)
Surf. 7	1.0	500	1.09	Lubricated (ZDDTP)
Surf. 7	1.0	900	1.10	Lubricated (ZDDTP)
Surf. 4	27.6	700	1.04	Lubricated (ZDDTP)
Surf. 4	27.6	700	1.05	Lubricated (ZDDTP)
Surf. 1	35.1	1000	0.93	Lubricated (ZDDTP)
Surf. 2	30.8	1000	0.97	Lubricated (ZDDTP)
Surf. 3	27.6	1000	0.88	Lubricated (ZDDTP)
Surf. 4	27.0	1000	1.10	Lubricated (ZDDTP)
Surf. 5	6.4	1000	1.06	Lubricated (ZDDTP)
Surf. 6	5.8	1000	1.10	Lubricated (ZDDTP)
Surf. 7	1.0	1000	1.00	Lubricated (ZDDTP)

3.3 Lubrication regimes

Two types of interfaces: dry and lubricated with ZDDTP solution have been tested under fretting loading. In the case of dry contact, due to the wear process the formation of debris in

the form of fine powder can be observed. This phenomenon can progressively change the contact sliding condition into so-called “particulate lubrication regime” generally known as third body agglomeration [15-17]. Interfacial shear stress can be slightly reduced in Full Sliding (FS) regime as pointed out in Fig. 5. In the lubricated contact (ZDDTP solution) the debris formation has not been observed under the partial slip regime and therefore, the apparent friction coefficient μ_t at the transition is higher than in dry contact.
In Full Sliding the formation of debris occurs and with lubricant, they start to create the paste (grease) which leads to reduction of coefficient of friction (Fig. 5). This sliding lubrication regime is known as "colloidal lubrication regime" [18].
Presented in this paper, experimental results show that the surface roughness has strong effect on the friction behaviour under dry and boundary lubricated fretting conditions. Therefore, the surface roughness and selection of manufacturing process is essential for final application of assembled joins subjected to the fretting loading conditions.

4. Conclusions

The following purely tribological conclusions could be drawn from the presented study:

- The initial surface roughness (machining process) has a strong influence on coefficient of friction at the transition (μ_t), between Partial Slip (PS) and Full Sliding (FS), for instance surface roughness (Surf.1) where S_z=35.1 μm, decrease the μ_t by 36% to 0.7 in comparison to mirror polished surface (Surf.7) S_z=1 μm where μ_t is 1.1.
- Boundary lubricated (ZDDTP) fretting contact presents a 27% higher coefficient of friction (μ_t) at the transition (PS/FS) μ_t~1.1, than dry contact μ_t~0.8.
- The two zones of different surface degradation mode can be distinguished within contact area: central zone of wear damage and transfer of matter, and external zone of the friction and plastic deformation,
- Initially imposed pressure of contact does not present strong influence on sliding behaviour.

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