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Surface morphology in engineering applications:Influence of roughness on sliding and wear in dry fretting

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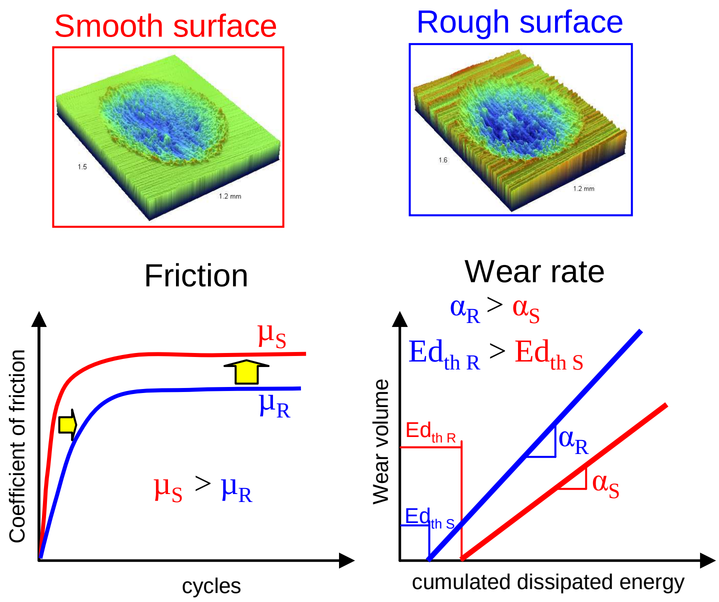
Abstract
Influence of initial surface roughness on friction and wear processes under fretting conditions was investigated experimentally. Rough surfaces (*Ra*=0.15-2.52 μm) were prepared on two materials: carbon alloy (AISI 1034) and titanium alloy (Ti-6Al-4V). Strong influence of initial surface roughness on friction and wear processes is reported for both tested materials. Lower coefficient of friction and increase in wear rate was observed for rough surfaces. Wear activation energy is increasing for smoother surfaces. Lower initial roughness of surface subjected to gross slip fretting can delay activation of wear process and reduce wear rate, however it can slightly increase the coefficient of friction.

Graphical Abstract



Research Highlights

- Initial surface roughness can influence friction and wear processes under fretting conditions,
- Rough surface reduce coefficient of friction and increase wear rate,
- Smooth surface increase coefficient of friction and delay activation of wear process,
- Lower initial roughness reduce wear rate.

***Keywords**: fretting wear, contact roughness, finishing process, surface morphology.*

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1 Introduction

It has been found that initial surface roughness has a significant influence on friction [1] and wear [2] processes in classical pin-on-disc wear tests. It has been also suggested that optimum surface roughness can be established for a certain tribo-couple resulting in a minimum wear [3] and, in general, higher initial roughness of contacting surfaces results in increase of wear rate [4]. In terms of friction behaviour, coefficient of friction is usually higher for smooth surfaces and decreases when the surface roughness increases [1]. Under fretting conditions, initial surface roughness can be a major factor in determining sliding conditions at the interface and the corresponding fretting damage mode, i.e. cracking in partial slip and wear in gross slip [5]. During wear process, degradation of the surface is modifying the initial geometrical state of the interface [6], which affects the sliding conditions and can lead to change in sliding regime from partial slip to gross slip [7]. For aluminium alloy under dry contact, Proudhon et al. [8] reported that the rough surface tends to decrease the tangential force needed for crack initiation but in experiments the authors did not notice roughness influence on the transition point between partial and gross slip regimes. Yuan et al. [6] observed evolution of surface roughness during ball-on-disc test under lubricated conditions and correlated systematic increase of the roughness with wear rate. Previous investigations [5, 9] of friction phenomenon under fretting conditions revealed strong influence of initial roughness of the interface. In this paper, apart from friction, also fretting wear rates are correlated with wide range of initial surface roughness parameters.

2 Experimental procedure

Experimental programme presented in this paper consists of: (i) rough surfaces processing, (ii) topography measurements, (iii) fretting wear tests using sphere/plane configuration (Fig. 1), (iv) fretting scar measurements and (v) wear volume calculations.

2.1 Tested materials

Two commonly used engineering materials were selected in this study in order to evaluate the influence of basic material properties: low carbon alloy (AISI 1034) and titanium alloy (Ti-6Al-4V). In order to avoid the high degradation rates in the contact and reduce material transfer and plastic deformation, AISI 52100 ball bearing steel has been selected as the counter-body (Ø 25.4 mm). Mechanical properties of tested materials are presented in Table 1.
The experimental specimens were machined into small rectangular blocks and the abrasive polishing process was applied on one of the surfaces in order to obtain wide range of roughness values: *Ra*=0.15 - 2.52 µm.

Table 1: Mechanical properties and chemical composition of tested materials.

	AISI 1034	Ti-6Al-4V	AISI 52100
Elastic modulus, E (GPa)	200	119	210
Poisson ratio, ν	0.3	0.29	0.29
Yield stress, σ_{Y02} (MPa)	350	970	1700
Maximum stress, σ_R (MPa)	600	1030	2000
Chemical composition (weight %)	C 0.34 % Fe 98.9 % Mn 0.65 % P <= 0.04 % S <= 0.05 %	Ti 89.5 % Al 6.1 % V 4.0 % C <= 0.08 % H <= 0.015 % N <= 0.03 % O <= 0.2 %	Fe 96.9 % Cr 1.5 % C 1.0 % Mn 0.35 % Si 0.22 % P <= 0.025 % S <= 0.025 %

2.2 Fretting wear device and test conditions

Fretting tests were carried out using fretting device with electrodynamic shaker under 15 Hz sinusoidal displacements. Fig. 1 shows schematic diagram of fretting device and contact configuration.

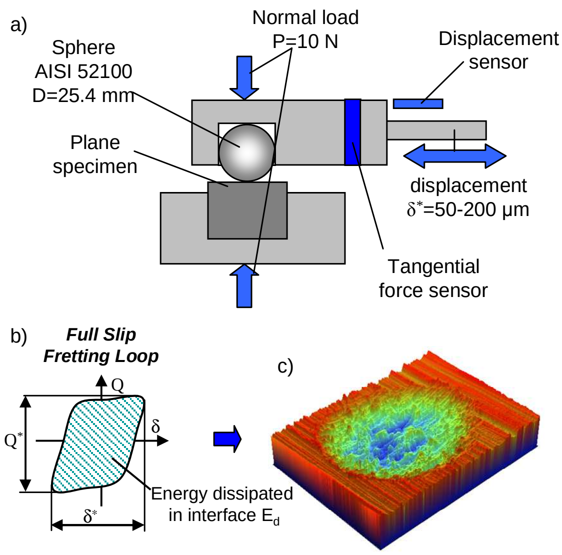

Fig. 1: Fretting test a) - contact configuration, b) - fretting loop, c) - fretting wear scar (Ti-6Al-4V).

During tests, normal load was kept constant at P=10 N within the contact by applying dead weight. Tangential force (Q) and relative displacement (δ) were recorded continuously, which allowed to characterise every fretting cycle with a characteristic fretting loop (Fig. 1b) [10]. Tests were performed at 23°C in laboratory ambient conditions at 40-45% relative humidity. All specimens were cleaned in acetone and ethanol before tests.

For both materials three different surface morphologies were prepared. On each surface four tests were carried out with the following displacement amplitudes: δ^*= 50, 100, 150 and 200 µm. Due to extensive and time-consuming experimental procedure only tests, which did not follow the wear kinetics graphs (Fig. 8) were repeated. If four tests with different parameters gave a good linear trend, it was assumed that the results are statistically valid and correct.

In this study, only initial surface roughness of plane specimens was changed and therefore wear analysis does not include counter-body ball.

3 Results and discussion

Influence of initial roughness of contacting bodies under fretting loading condition is often neglected in research field and in practical applications. Available literature on roughness in fretting is also very limited. Previous investigations carried out by authors [9] revealed the influence of initial roughness on friction and sliding conditions. Increase in coefficient of friction at the transition between partial and gross slip has been reported for smoother surfaces. Evolution of coefficient of friction in early stage of friction in full sliding obtained in this study, is in good agreement with previous results from partial slip regime [9]. This paper is an extension of previous analysis and presents the initial surface roughness influence in gross slip regime where the entire contact area is in full sliding condition and main damage mode observed in this regime is wear of material.

3.1 Surface Roughness measurements

Surfaces prepared by abrasive polishing have been measured by optical interferometric profiler (Veeco). All the surface were anisotropic and sphere/plane sliding direction was perpendicular to the surface texture. Examples of measured 3D topologies on Ti-6Al-4V material are presented in Fig. 2.

Recorded surface roughness was slightly different for two tested materials due to different material microstructure, e.g. *Ra*=0.34 µm and *Ra*=0.45 µm for process 2 for low carbon steel and titanium alloy respectively. Low carbon alloy was easy to polish hence the lowest value of roughness *Ra*=0.15 µm was recorded for Process 3 in case of that material. Roughness parameters *Ra*, calculated for all tested surfaces are summarized in Table 2.

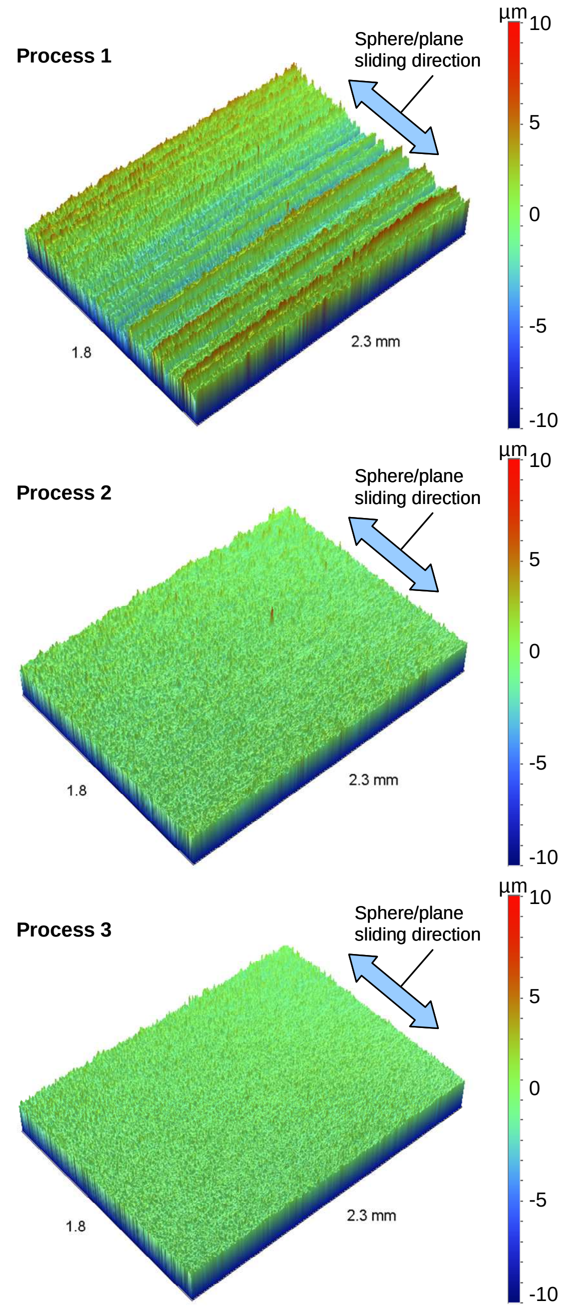

Fig. 2: Example of measured 3D morphologies of tested surfaces prepared by abrasive polishing (material titanium alloy Ti-6Al-4V).

Table 2: Average value of roughness parameter *Ra* calculated along the direction of sliding (perpendicular to surface texture).

Materials	Topographical characteristic of tested surfaces *Ra*, µm		
Process	Process 1	Process 2	Process 3
Sand paper grid	80	600	2500
Low carbon alloy (AISI 1034)	1.52	0.34	0.15
Titanium alloy (Ti-6Al-4V)	1.51	0.45	0.23

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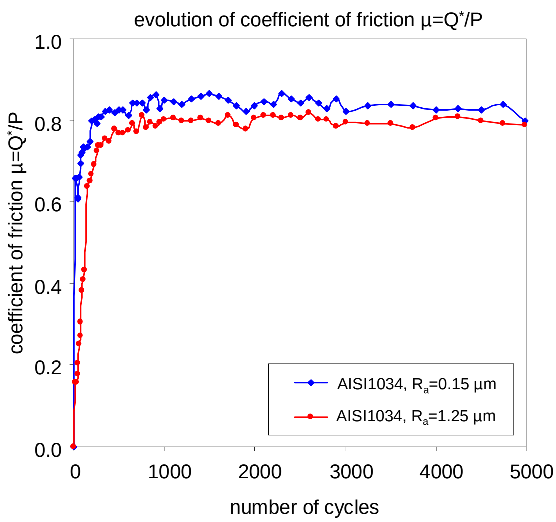
3.2 *Friction analysis*

All tests have been carried out in gross slip conditions, therefore ratio of tangential force amplitude Q^* and applied constant normal force P can be considered to represent coefficient of friction $\mu=Q^*/P$. Evolution of coefficient of friction and initial roughness influence are presented in Fig. 3.

a)



b)

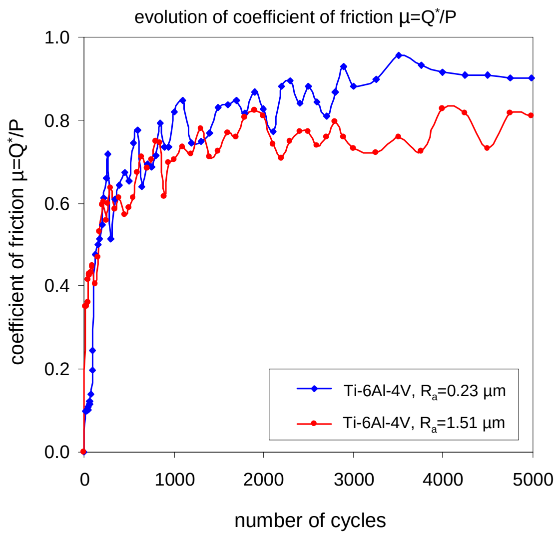


Fig. 3: Influence of initial roughness on friction behaviour and evolution of coefficient of friction during the fretting test for a) - low carbon alloy and b) - Titanium alloy (displacement amplitude δ*=150 µm, configuration sphere/plane, normal force P=10 N, frequency f=15Hz).

For smooth surfaces coefficient of friction evolves more quickly to its stable value and remains at that level during the test. Hence, for rough surfaces, lower coefficient of friction was observed. In theory, this can help to control the transition between partial and gross slip sliding and therefore can lead to faster degradation of the interface. Higher oscillation of coefficient of friction can be observed on titanium alloy.

Influence of initial roughness on coefficient of friction is compared for individual tests performed under 150 µm displacement amplitude (Fig. 4). Slightly increasing tendency is observed for smoother surfaces for both materials. Higher value of coefficient of friction for smoother surfaces can be beneficial in order to prevent transition and wear damage mode in industrial components like dovetail, notch, screw joints etc.

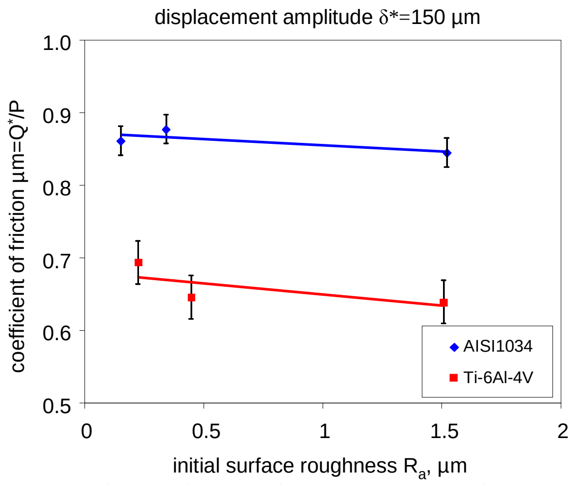


Fig. 4: Influence of initial surface roughness (*Ra*) on friction coefficient (µ=Q*/P) under fretting displacement (δ*=150 µm).

3.3 *Wear analysis*

In fretting test, energy dissipated at the interface is represented by an area of friction loop (i.e. plot of tangential force Q versus displacement δ). By integrating surface of this loop one can calculate energy dissipated (E_d) for every individual cycle and by adding energy dissipated in all cycles, Cumulated Dissipated Energy ΣE_d can be estimated. This energy approach has several advantages over classical Archard theory and is more accurate in case of variable loading conditions and material configurations [10].

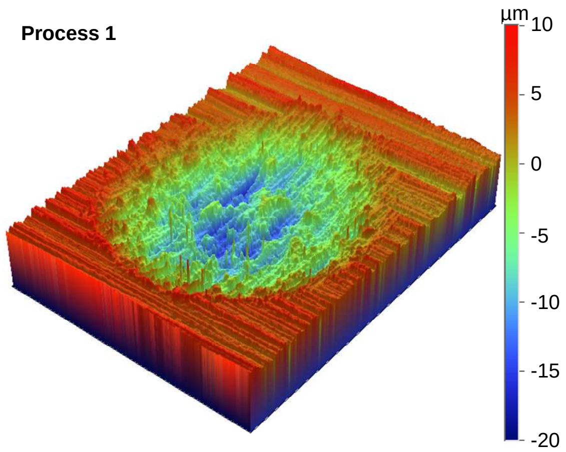


Fig. 5: 3D morphology of fretting scar (material titanium alloy Ti-6Al-4V, Process 1, δ^*=200 µm).

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Wear volume has been calculated from 3D morphologies measured on plan specimens (Fig. 5). Similar depth of wear for all values of initial roughness can be observed on 2D profiles in mid-plane cross section (Fig. 6). For rough surface, it is important to define procedure for wear volume estimation as the energy dissipated at the interface corresponds to volume of material removed during sliding. At the beginning of test, only asperities are in contact and material is relatively easy removed.

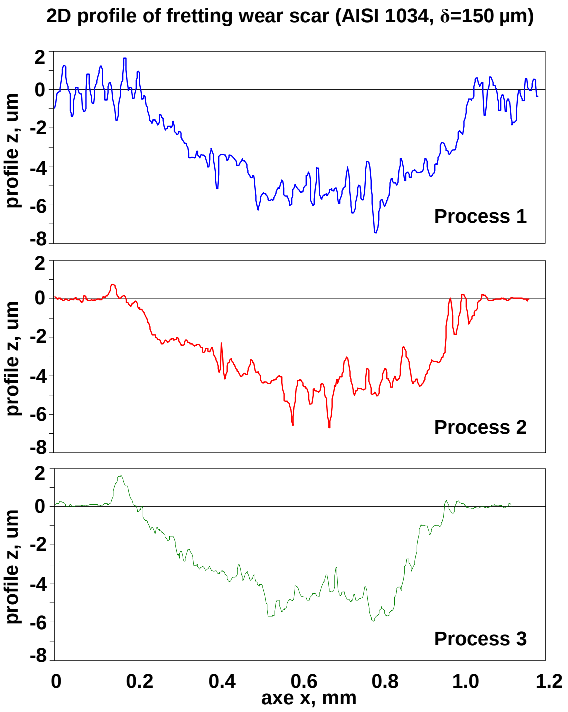

Fig. 6: 2D profile of fretting wear scar, AISI 1034, δ^{*}=150 μm.

When the initial roughness (Fig. 7a) is removed, wear process should continue at constant rate. Therefore, it is important to define the reference plane in roughness section to calculate wear volume below this plane. Setting-up this plane in the middle of roughness profile is eliminating top section of roughness asperities to be treated as wear volume, however lower part of roughness asperities still contains empty spaces (blue area on Fig. 7b) which are considered as wear volume. Therefore, those empty spaces in lower part are partially compensated by material removed from top part of roughness asperities (red area on Fig. 7b) which has been removed from material but was not considered as a wear volume. This procedure leads to lower error in wear volume estimation on rough surfaces, and when red and blue surface areas on Fig. 7b are equal, estimation error should reach minimum value.

Relation between wear volume (V) and cumulated dissipated energy (ΣE_d) is presented in Fig. 8. A linear relationship ($V = \alpha \cdot \Sigma E_d + \beta$) can be observed. Nevertheless, the extrapolation of this tendency does not cross the origin of the graph as it could be expected. This results from the fact that during the first phase of test certain amount of the energy is dissipated in order to activate Tribologically Transformed Structure (TTS) and create wear debris [11]. Threshold of this activation energy E_{d_th} can be estimated from wear volume (V) - cumulated dissipated energy (ΣE_d) relation (Fig. 8). From this graph, also energetic wear coefficient can be calculated: $\alpha = \Delta V / \Delta \Sigma E_d$.

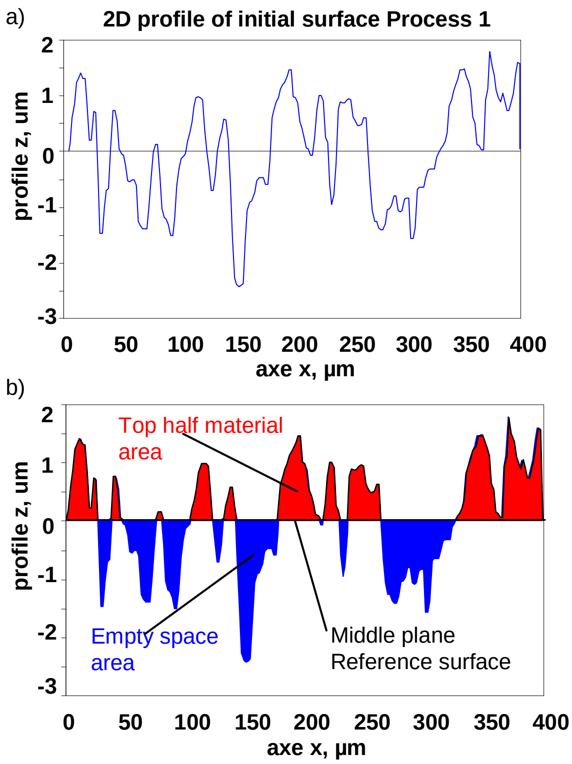

Fig. 7: Wear volume of rough surface, a) - profile of initial surface, b) - reference surface plane for wear volume estimation on rough surface.

Influence of initial surface roughness in terms of different slope (energy wear coefficient α) and wear activation energy threshold (E_{d_th}) for both tested materials can be observed in Fig. 8. To better illustrate this influence wear rate coefficient α and wear activation energy E_{d_th} can be plotted as a function of initial surface roughness *Ra* (Fig. 9 and Fig. 11).

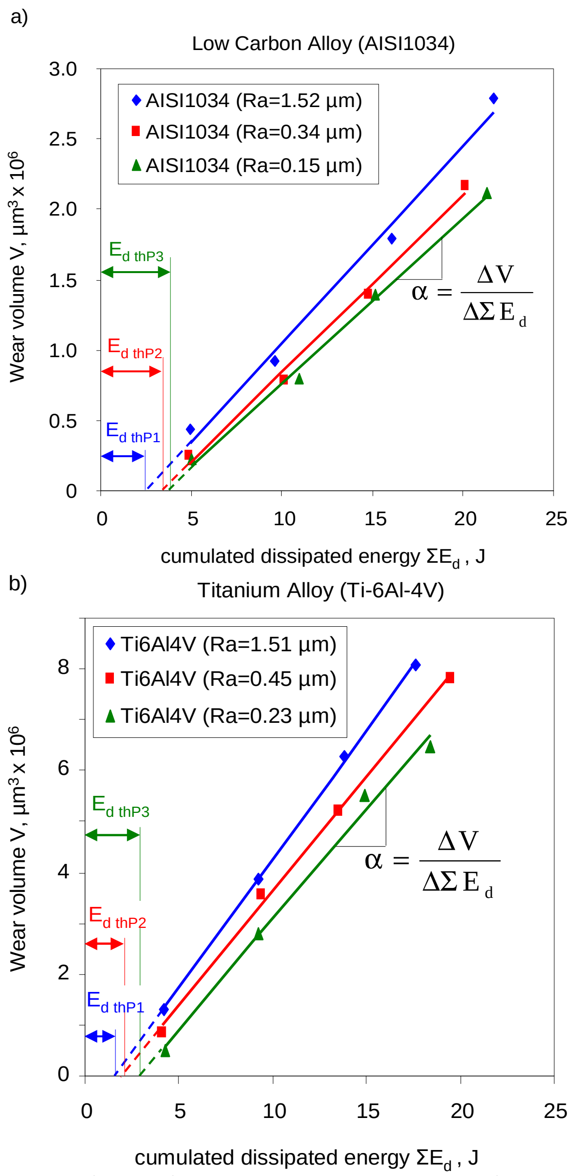

Fig. 8: Influence of initial roughness on wear rate under fretting condition for a) low carbon alloy and b) titanium alloy.

In Fig. 9 influence of initial surface roughness *Ra* on wear activation energy E_{d_th} is presented. It can be observed that lower activation energy is needed for rough surfaces. When two surfaces are mated, contact is established only at the surface asperities causing higher local contact pressure than in case of smooth surface. As a result higher contact pressure can lead to faster TTS layer formation and wear debris generation. This can decrease amount of energy needed to activate wear process. It can be noted that increase of activation energy is about ΔE_{d_th}=1 J and it corresponds to additional 800 to 1300 cycles before the first wear occurred for δ^{*}=200 and 50 µm respectively (Fig. 10).

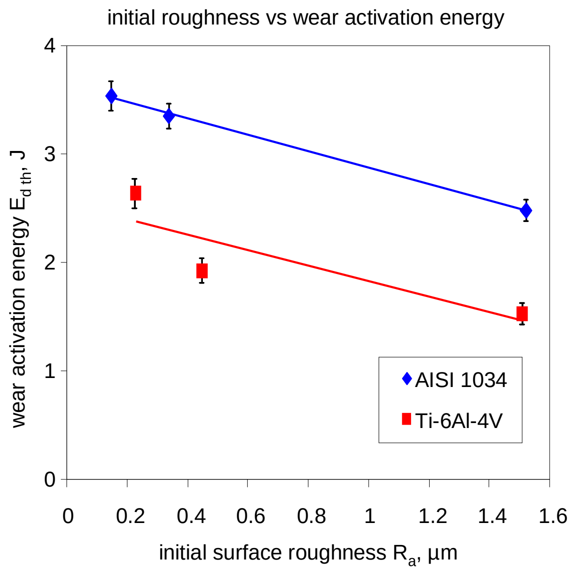

Fig. 9: Influence of initial roughness on wear activation energy under fretting condition.

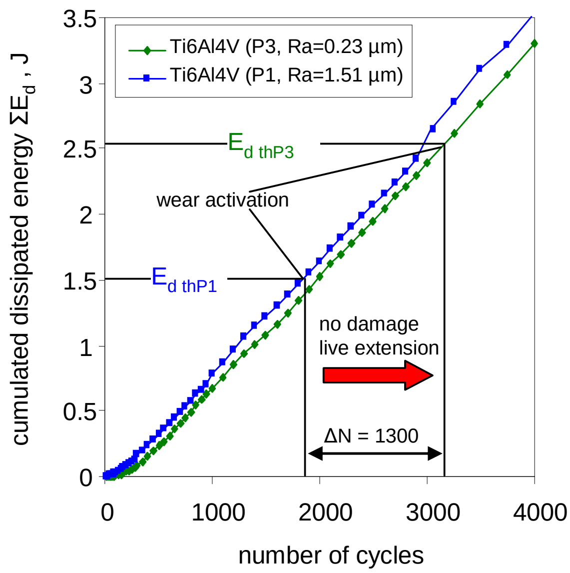

Fig. 10: Increase of number of cycles to activate wear due to initial roughness modification (Process 1 and Process 3 for δ^{*}=50 µm).

Initial surface roughness modification can be used to extend life and protect components exposed to fretting where damage of contacting surfaces is not allowed. In Fig. 11 an increasing tendency of wear rate can be observed for more rough surfaces. To explain this behaviour the wear process needs to be analysed carefully. Wear is a dynamic process of formation and ejection of debris. Again, in wear analysis we have to consider local contact at roughness asperities. Higher normal pressure at these points will lead to higher local wear rate, which will increase roughness and this process will continue at newly created roughness asperities. Depending on surface microstructure contact size and wear debris size, roughness of worn surface will reach a specific value. This theory can be supported by worn surface morphology observations (Fig. 6): initial surface roughness (perpendicular to sliding direction) has been removed and new rough surface has been generated within the contact area. However, it is interesting to note that effect of initial surface roughness was still sustained at the interface as shown by lower coefficient of friction for rough surface in Fig. 3. It can be also noted that initial surface roughness modify the wear dynamic and different wear rates can be observed for all tested initial surface morphologies (Fig. 8 and Fig. 11). This confirms that evolution of interface roughness in tested fretting contact conditions, depend not only on initial roughness, but also on history of this dynamic process.

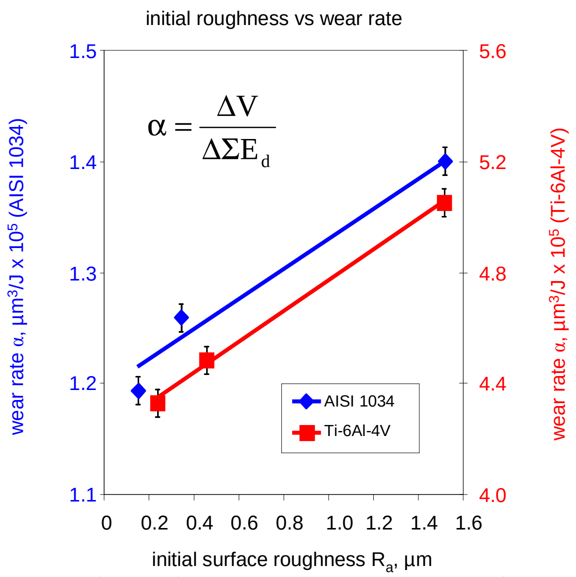

Fig. 11: Influence of initial roughness on wear rate under fretting condition.

4 Conclusions

From the experimental programme and analysis of initial roughness influence on wear in fretting contact, following conclusions can be obtained:

- initial surface roughness have an significant influence on friction, wear process and wear activation energy,
- lower coefficient of friction is observed for rough surfaces,
- wear rate increase when initial surface roughness is increasing,
- higher wear activation energy is needed for smoother surfaces.

General conclusion can be formulated as follows: lower initial roughness of surface subjected to gross slip fretting loading condition can delay activation of wear process and reduce wear rate, however it can slightly increase the coefficient of friction.

5 Acknowledgements

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