

SURFACE LAYER'S TRANSITIONAL AND PERMANENT CHANGES IN CASE OF LUBRICATED AND DRY FRICTION

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Abstract: *It's a well known fact for a long time that rubbing machine parts' surface suffers important structural changes. The parts' surface layer supports plastic deformation due to the surface load until a border state. During this plastic deformation, the surface layer's grain size decreases significantly and the layer transforms in a micro grain structure, also called Tribologically Transformed Surface. This surface, due to the continuous load, tears and breaks. A portion of the broken parts leaves the rubbing surface's contact layer; another portion sticks up to the rubbing parts or forms third bodies. The phenomenon restarts cyclically in the lower, capable-to-transform surface layers. The transformation of the surface layer is in close relation with the deformability of metals. We can describe the surface layer's deformation with the pure metal specimens' response on different effects which dominate the fretting phenomena. That's why we proceeded deformability experiments and studied the presence of the transformed surface in laboratory and real circumstances.*

Keywords: *tribology, friction, TTS, hexagonal metals*

1. INTRODUCTION

The constitution of metallic surfaces differs from the internal, homogenous structure of metallic parts. The surface homogeneity and the grain size change due to the manufacturing. Different environmental effects influence also the constitution of the surface layer. The surface contains a gas adsorbed coating (1), an oxide coating (2), a highly deformed layer due to the manufacturing (3), and the bulk metallic layer (4) (Fig. 1.a).

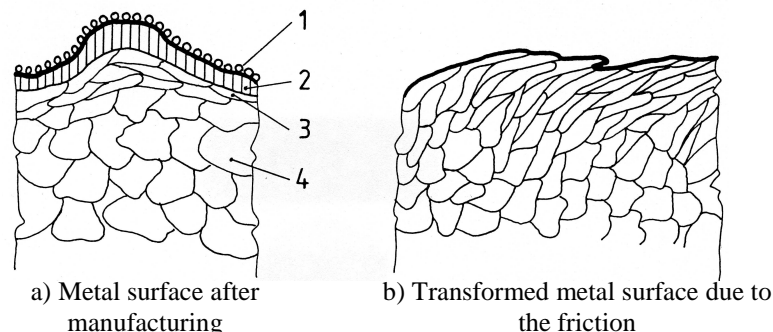


Fig.1. Constitution of the surface layer

During friction, the grain structure changes continuously (Fig. 1.b). It becomes thin and the grains smaller, induced by the mechanical and thermodynamical loads. It finishes with a modified, nanostructural grain layer containing 20-200 nm sized grains. This layer's

characteristic hardness differs from the homogenous, bulk material; its hardness is four or six times higher than the hardness of bulk material.

The shear stress, induced by the friction, forces the surface and the near surface layers into a plastic deformation and as a result, the grain structure changes. This modified grain sized layer is called Tribologically Transformed Surface. The plastic deformation of metallic surfaces is inhibited by a limit deformability, beyond this limit deformability the surface layer tears and breaks. A portion of the broken parts leaves the rubbing surface's contact layer, another portion sticks up to the rubbing parts or forms third parts. The phenomenon restarts cyclically in the lower, capable-to-transform surface layers. The presence of different oxides and impurities on the contact surfaces can give us some idea in relation with the mechanical alloying, as a result, the surface's mechanical characteristics change and it becomes more and more difficult to describe the exact mechanism of friction in real circumstances and on used machine parts.

The surface's tribological transformation is a well known phenomenon nowadays, its reproduction in laboratory is possible but the development mechanisms of this surface layer, its role in the fatigue and in the use is still discussed. The research becomes more difficult because of the short lifetime of the TTS layer. It breaks and renews continuously [5]. It means that the hardening, the breaking and the detaching phenomenon of deformed parts happens at the same time in different points of the surface so the detection of a well deformed surface layer is difficult.

2. MECHANISMS OF PLASTIC DEFORMATION

The dislocation's movement explains the plastic deformation of metallic surfaces. In extreme circumstances, such as high speed deformation, other mode of plastic deformation can also appear like twinning and adiabatic localized deformation, induced by the local softening due to the heat shock.

The plastic deformation explained with the dislocation's movement happens along the slip plan. A slip plan and a correspondent slip direction are called a slip system. The chosen hexagonal metals have three different slip systems: basal, prismatic and pyramidal (first and second rank). The activity of a slip system depends on the crystalline parameters. Its rapports, the axial ratio determine the activation of a slip system, beyond the temperature and the deformation speed that's why it's important to know the crystalline parameters of the choosed

hexagonal metals [3]. If the axial ratio $\frac{c}{a} > \sqrt{\frac{8}{3}}$ (where c and a are lattice parameters) then the

basal slip system is active. If $\frac{c}{a} < \sqrt{\frac{8}{3}}$ then the prismatic and the pyramidal slip systems are

active. This is the case of the titanium. If $\frac{c}{a} \approx \sqrt{\frac{8}{3}}$ then the basal slip system is partially replaced by the prismatic and the pyramidal systems. This case concerns the magnesium. The characteristic lattice parameters can be seen on the Tab.1.

For the plastic deformation of polycrystalline metals, five independent slip systems are necessary.

Tab.1. Lattice parameters of titanium and magnesium

Metals	Structure	a [nm]	c [nm]	c/a
magnesium	Compact Hexagonal	0,321	0,521	1,6231
titanium- α	Compact Hexagonal	0,295	0,468	1,5864

3. DIFFERENCES BETWEEN TITANIUM AND MAGNESIUM IN PLASTIC DEFORMATION

It can be seen on the Tab.1. that the most important difference between the titanium and the magnesium is the number of slip systems activated at the same time. Under the same conditions, in case of the magnesium four systems, for the titanium six slip systems are active. So the significant deformability differences between the two metals, the rigidity of magnesium and the deformability of titanium can be explained purely with the crystalline structure.

4. INFLUENCES OF THE THERMODYNAMICAL STATE FACTORS ON THE DEFORMABILITY

The one order of magnitude difference between the nominal and the real contact surfaces results an extremely high Hertzian stress on the surface (1..10 GPa).

This high stress exceeds the tensile stress of most metals. Nevertheless we can see that in friction contacts, despite of this high contact pressure, the surface supports plastic deformation. The limit deformability of the material may change under effect of friction load.

The flow curve gives information about the plastic-elastic deformability of structural materials. This plastic-elastic deformability is influenced by the thermodynamical state factors. In our experiments we had the theoretically well known fact that the increase of the deformation speed increases the resistance to the deformation. The influence of the temperature is contrary: the resistance of deformability decreases. The third state factor, the additional hydrostatic pressure component increases the plasticity of the chosen material, offering the possibility in some cases, the extreme deformations and the plastic shaping of rigid materials at room temperature. The influence of the thermodynamical state factors on the deformability is summarized on the following graph Fig.2.

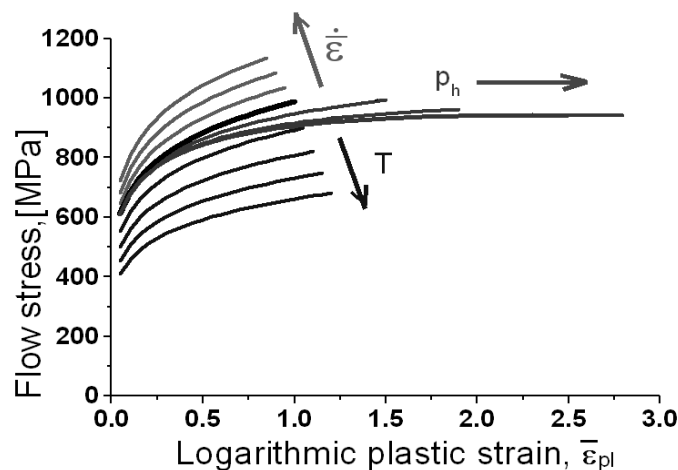


Fig.2. Effects of the thermodynamical state factors on the deformability

5. CHARACTERISTICS OF SPECIMENS AND EXPERIMENTS ON THE DEFORMABILITY

High purity magnesium, titanium and microstructural titanium specimens were used for the examinations. They were turned from 25-50 mm diameter extruded bars. For the high speed deformability tests, I used cylindrical, 6x6 mm specimens.

First, the effect of deformability speed on the resistance of deformation was studied. These examinations were done with Hopkinson's Bars, at room temperature and pressure. The average speed of deformation was between $2000-2500 \text{ s}^{-1}$. The *ISL French-German Military Research Institute* offered the possibility of these examinations in its material laboratory.

The effect of the additional hydrostatic pressure component was studied with four types of specimens: cylindrical, cylindrical notched, plate notched and shear specimens [4]. High viscosity HYDROKOMOL U-32 type oil agent was used to establish the uniform additional hydrostatic pressure between 0 MPa and 800 MPa at room temperature. The results were presented on Bogatov's surfaces representing the limit of deformability.

The third thermodynamic state factor was considered from literature [2]. The results are summarized on the following diagram Fig.3.a) and b).

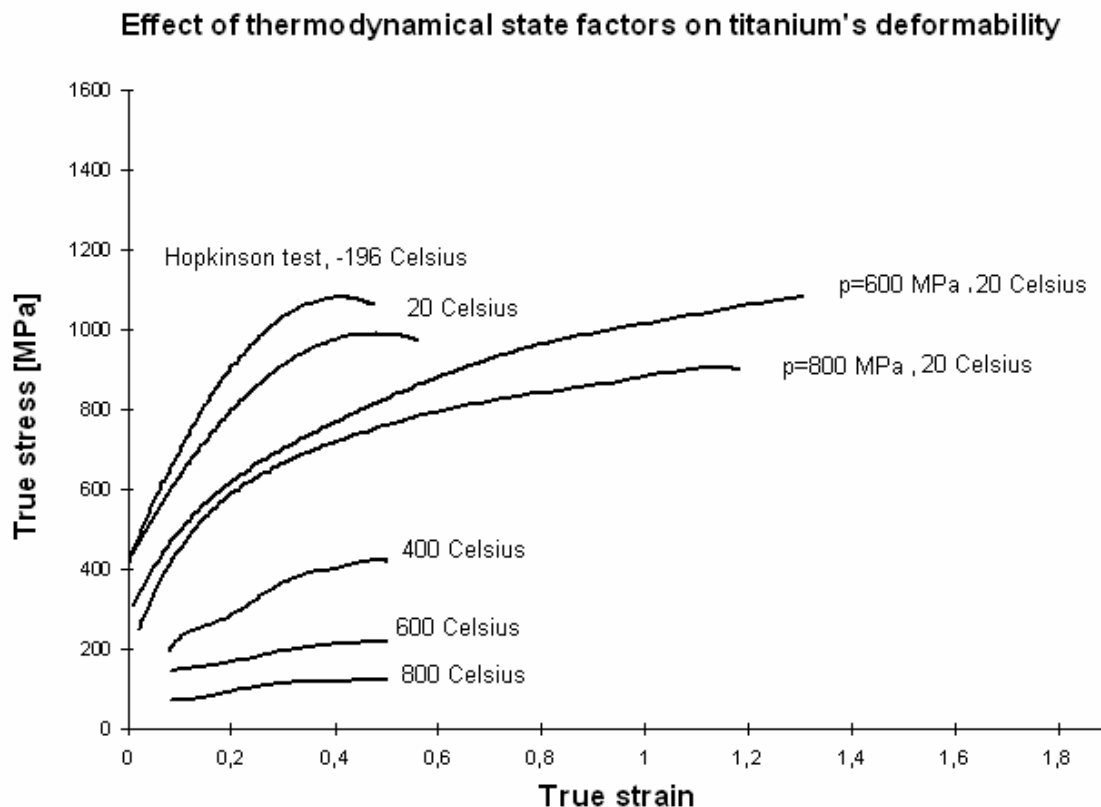


Fig.3. a) Effect of thermodynamical state factors on titanium's deformability

The results show us clearly the differences between the different thermodynamical factors' effects. The high speed deformation increases the resistance, the temperature decreases it, the hydrostatic pressure stretches the interval of deformability so the plasticity could be increased.

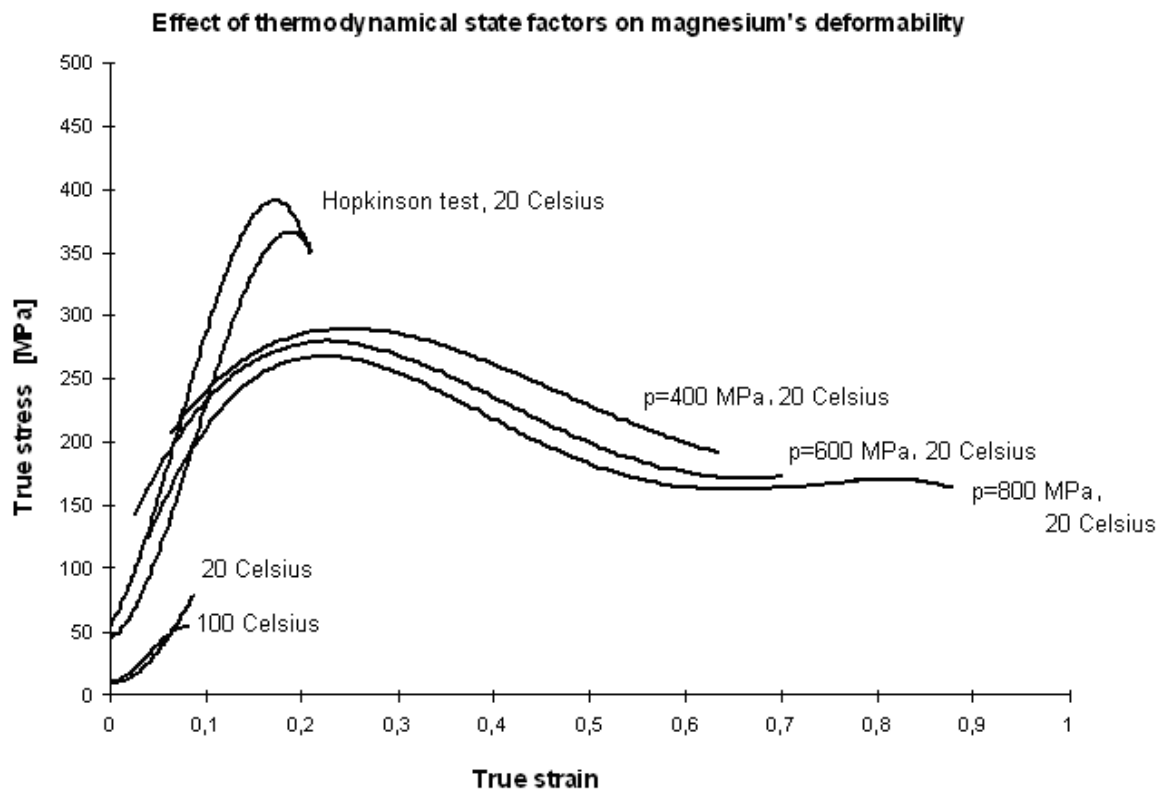


Fig.3. b) Effect of thermodynamical state factors on magnesium's deformability

In the additional hydrostatic pressure tests, the two metals show important differences. The titanium is quasi indifferent from the pressure component in opposition with the magnesium, which becomes more and more plastically deformable as the pressure increases.

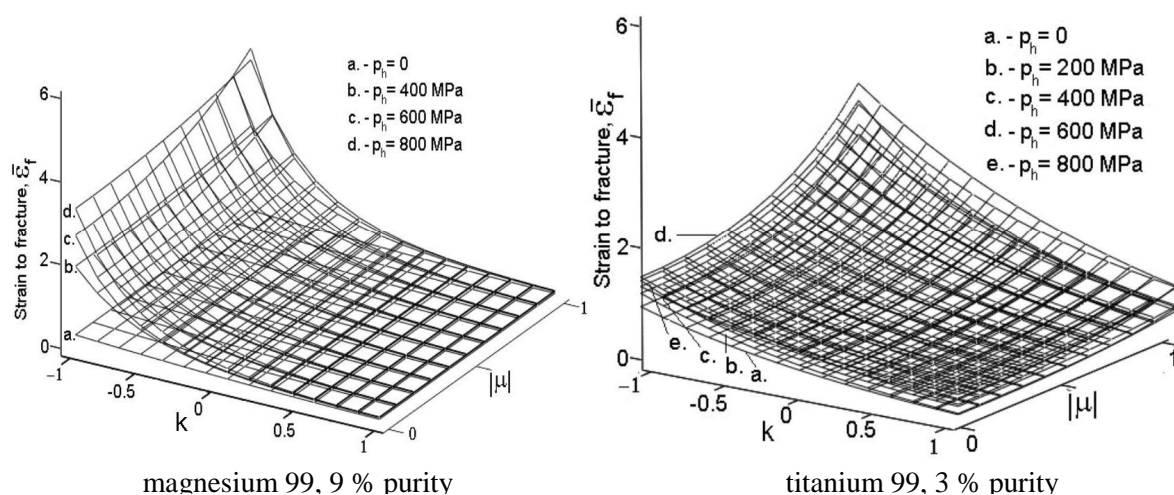


Fig.4. Results of the additional hydrostatic pressure deformability tests (k and μ are stress state parameters [4])

6. DRY FRICTION TESTS

Friction tests were realized with a high precision, pin-on-plate type (with sphere and plan contact geometry) device in the laboratory of *INSA de Lyon*. The precedent experiments complete this one, in the study of the TTS layer.

During these tests, magnesium and titanium plate lower specimens, steel (100Cr6) and sapphire, spherical upper specimens were used. The amplitude of movement of the lower plate specimen was 12 mm with a characteristic frequency of 0,1 Hz. After a few cycles (4-6) we could see highly deformed, tired and broken surface. The aims of these tests were the preparation of TTS layer in laboratory, and the study of the particle detachment. The normal force, the resistant force were measured to calculate their rate which is the friction coefficient for positive values. This coefficient gives us important information about tribological phenomenon on the contact surface.

On the rubbing surface's topography, viewed with SEM, the difference of deformability could be seen. The magnesium's topography is wide and broken, with many small detached particles. The titanium's topography doesn't contain as many detached particles, the material is much more plastic. The surfaces deformed during these tests are presented on Fig.5. and Fig.6.

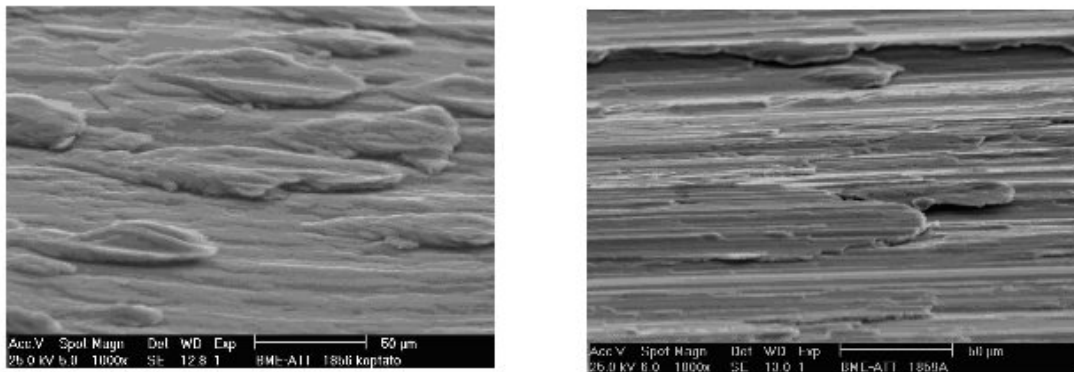


Fig.5. SEM pictures of the wear tracks, on the left magnesium and on the right titanium

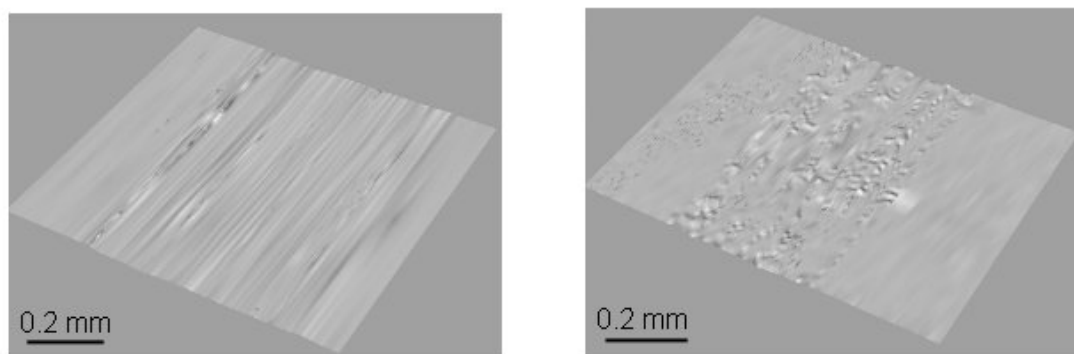


Fig.6. 3D profilometry of wear tracks; on the left magnesium and on the right titanium

7. ULTRA-MICRO- AND NANO-INDENTATION OF THE SURFACES

Before and after the friction tests, ultra-micro- and nano-indentation of the surfaces was performed. First the ultra-micro-hardness was measured in one point successively by Vickers indentation, increasing the load until the limits (for magnesium 0-50 mN, for titanium 0-200 mN). Further, a 4 x 4 grid using an increasing load from 1 mN to 10 mN was set out and then loading of a single location using the same load range. These results are shown in Fig.7. and 8.

Both the ultra-micro- and the nano-indentations show, that only the near-surface layer of the magnesium has been hardened. This suggests that the strain hardened layer has already been detached from the surface. For the titanium, the difference in hardness developed in a deeper layer. The measured nano-hardness values show a significant scatter near to the surface. The average values are constant and show no hardening tendency, so the near-surface layer has been recrystallised differently.

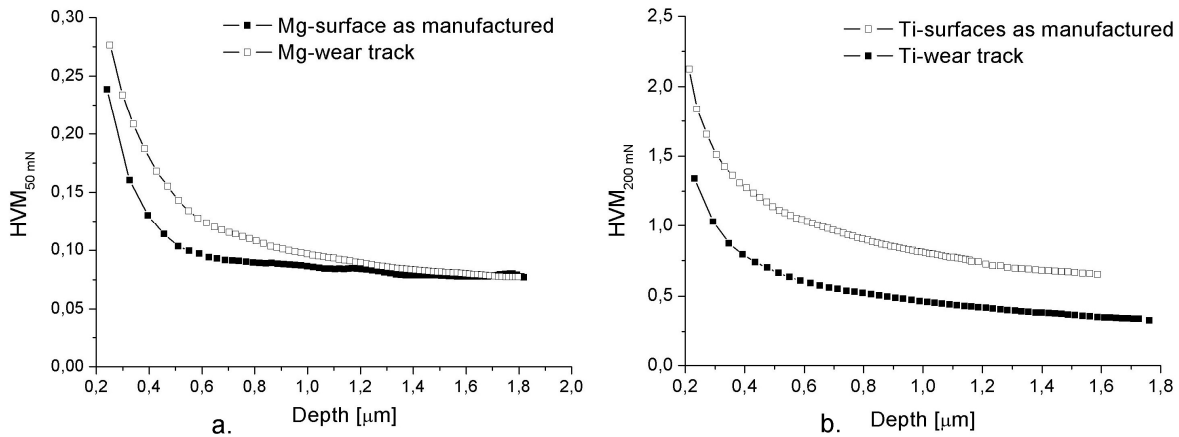


Fig.7. Ultra-micro-hardness of the near-surface layer before and after the friction test *a)* magnesium; *b)* titanium

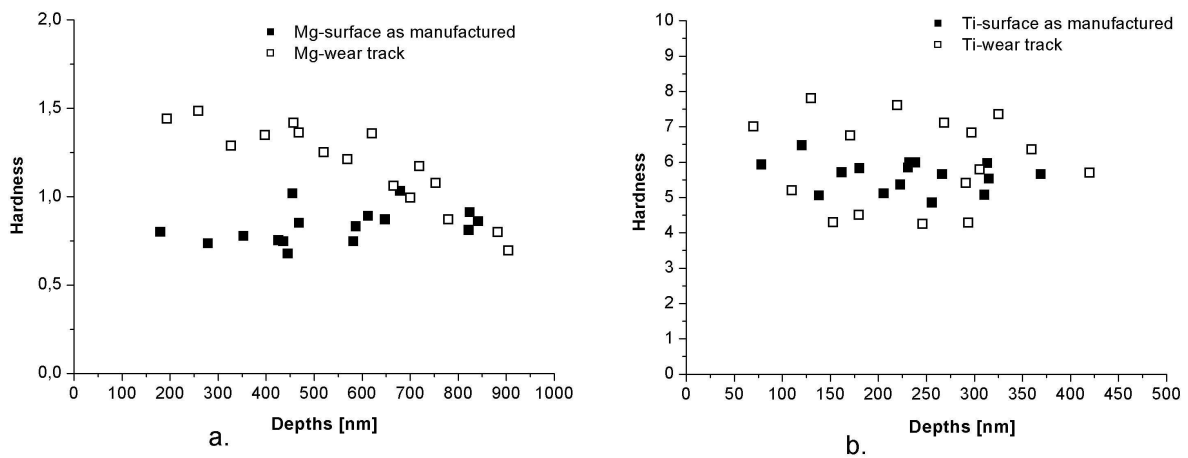


Fig.8. Nano-hardness of the near-surface layer before and after the friction test; *a)* magnesium; *b)* titanium

The nanoindentation measurements were completed by atomic force microscopy. AFM pictures of initial and worn surfaces are shown in Fig.9.

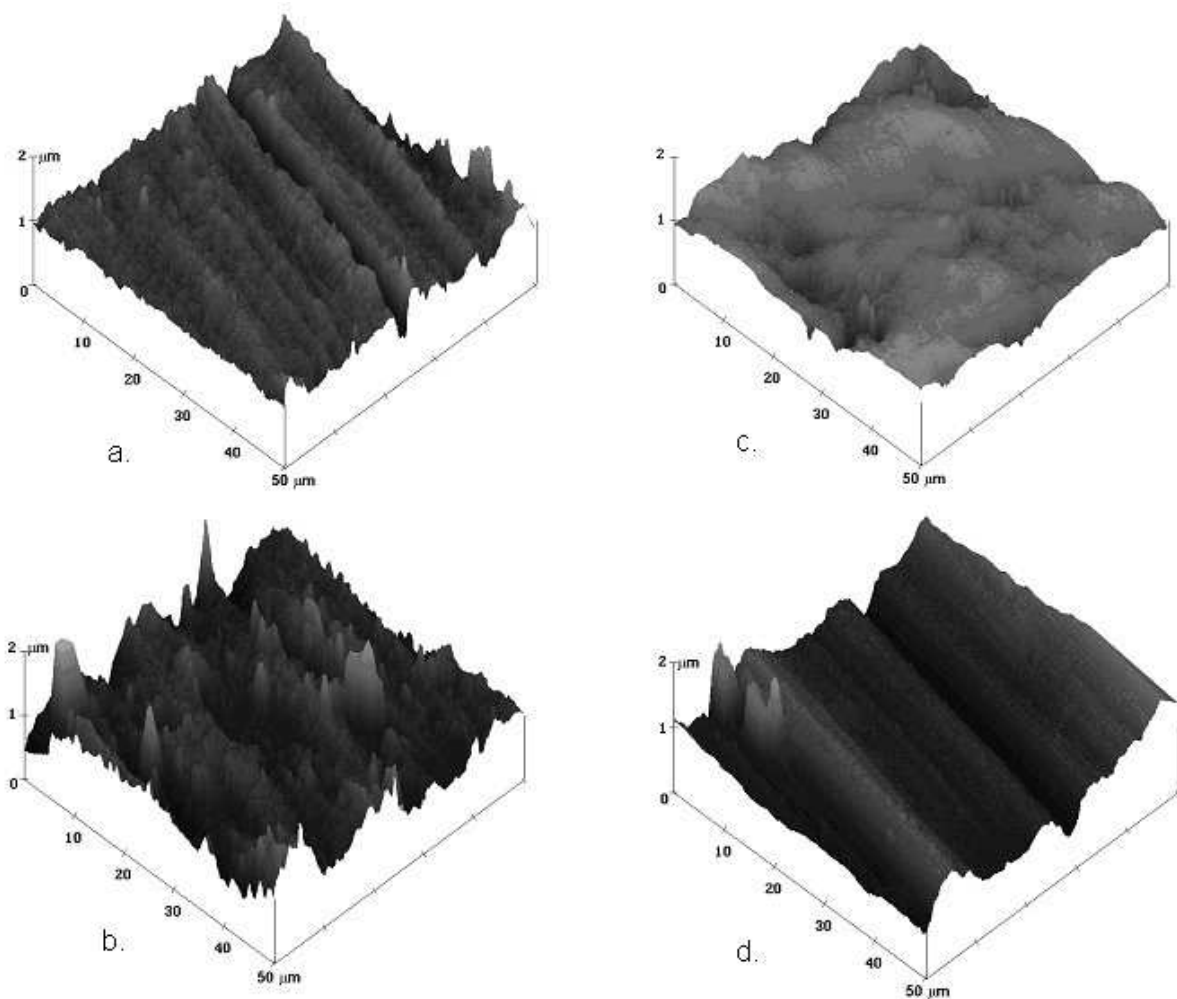


Fig.9. AFM images of the friction surface, left column magnesium, right column, titanium; a) and c) initial surface of specimens; b) and d) worn surface after friction test.

As may be seen on the AFM images, after testing the magnesium showed a more "crumpled" surface, while the titanium showed a surface deformed by plastic deformation.

8. X-RAY DIFFRACTION ANALYSIS OF THE WEAR TRACKS

The parameters of the classical power X-ray diffraction analysis were: $\text{CuK}\alpha$ radiation, Generator Voltage 45 kV, Tube Current 30 mA, graphite monokromator, proportional counter, Scan Step Size (2θ) 0.008, Data Angle Range 30° - 130° , instrumental FWHM 0.11.

For the evaluation of the measured results, first the FWHM values of the first 10 characteristic peaks were plotted against the familiar spherical reciprocal-space variable, $K=2(\sin \alpha)/\lambda$ (Williamson-Hall diagram).

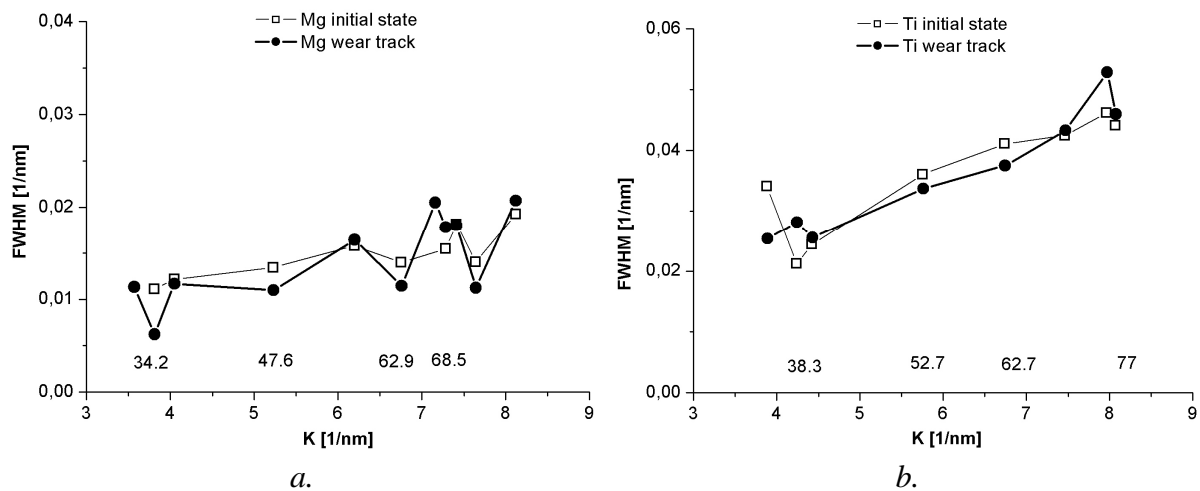


Fig.10. Williamson-Hall diagrams of the tested materials, before and after friction (a.- magnesium, b.- titanium)

The W-H diagrams show, at which peaks occurred a difference between reflections of base material and wear track, these peaks have been analysed separately too.

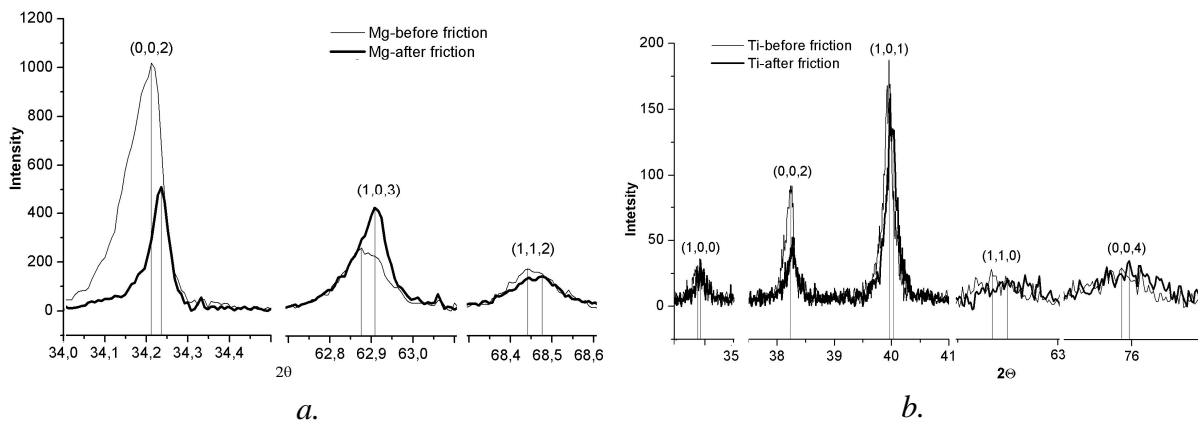


Fig.11. Characteristic peaks of the X-ray spectra of specimen surface and of wear tracks (a.- magnesium, b.- titanium)

Based on the line profile analysis, we can conclude that in the wear track on magnesium, an important decrease in FWHM and in intensity occurred at (0,0,2) peak, while this difference more less is at the peaks characterising the inclined plans. We can conclude from this that the orientation of the domain structure of near-surface layer decreased, the structure has been cut up or recrystallised. The domain size in the wear track is 10 times smaller than the domain size of the original structure (~1000 nm). The line profile of the wear track of magnesium has been shifted with a value of $\Delta 2\theta = 0.02^\circ$ to the direction of the smaller distance between atomic planes, which indicates the presence of the residual stresses.

The spectra of titanium are noisier than the magnesium's, because the mass absorption coefficient of titanium is six times higher than the magnesium's. The changes in FWHM are negligible. Concerning the intensities, we can observe rather a reorientation and homogenisation of the structure. The shifting of the peaks occurred also in the direction of decreasing of atomic planes distance, but their values are different, even in the mean slip planes the differences are negligible. The characteristic domain size has not been changed

compared to the initial value (~50 nm). All results show that the friction did not cause any modification of the near-surface layer of titanium, or the whole structure has been dynamically recovered during the friction.

9. ANALYSIS OF USED MACHINE PARTS

All viewed tests were realized in laboratories, without considering the real circumstances of operating machine parts. The effects discovered on the tested materials appeared during dry friction. The major percent of machine parts works with lubrication. We suppose that these structural transformations can be discovered under lubricated conditions too. That's why we proceeded SEM analysis on used ball bearings' broken inner and outer rings. Two types, a 6305 and a 6205 ball bearings were used. Until this time, the ball track's SEM analysis doesn't prove unambiguously the presence of the TTS layer on Fig.12.

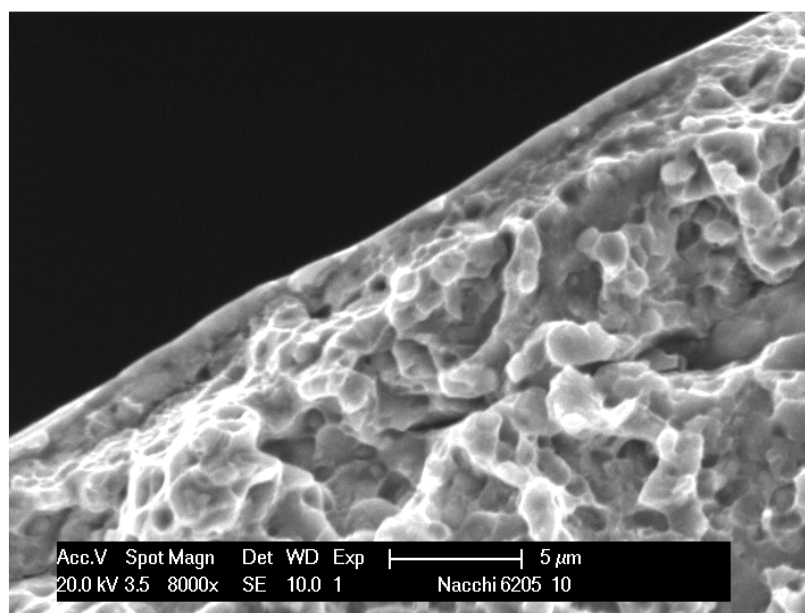


Fig.12. SEM photography of the broken surface of a 6205 single row ball bearing

CONCLUSION

High purity titanium and magnesium specimens' deformability were studied concerning the effect of deformability speed and the effect of additional hydrostatic pressure component. It can be concluded that the increase of deformability speed increases the resistance of deformability. The additional hydrostatic pressure stretches the interval of deformability, so it increases the plasticity.

Concerning dry friction tests, in the case of magnesium the high thermal conductivity quickly conducts away heat generated in the friction process. However, we propose that the hydrostatic component of the stress state plays a more important role in the plastic deformation of magnesium than in titanium. The thermal conductivity of titanium is considerably smaller than that of magnesium so that thermal activation energy can be conducive to recovery and recrystallization of the whole deformed volume.

Concerning lubricated rolling friction, we suppose that the grain structure transformation is inhibited by the friction's speed accommodation which takes place now mainly in the lubricant and not in the surface layer. To continue our work, the objective now is to polish some specimens for further SEM analysis and study the speed accommodation in the lubricant during friction.

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