DEFORMATION INDUCED TRANSIENT AND STATIONARY CHANGES OF THE NEAR-SURFACE LAYER

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SUMMARY
The transformation of the near-surface layer of the friction surfaces, due to the friction load, has been a widely known phenomenon for a long time. This phenomenon can be demonstrated and recognized, even in case of extreme small specified normal load and already at the beginning of the displacement (of the friction), but it has not yet been clarified, in consequence of which and what kinds of transformation processes take place in the near-surface layer during the friction. Plastic deformation investigations and friction tests were performed in favour of clarifying of the mechanism of tribological transformation of surface (TTS). Based on the presented results as well as on the earlier published ones, we can propose an explanation for the formation of TTS which composes on the one hand of a conventional deformation process governed by the irreversible displacement of dislocations, but limited for a small layer of surface. On the other hand, TTS composes of a transition from micro- to nano-structure, which results in a significant change of the mechanical properties of near-surface layer.

Keywords: tribology, near-surface layer, nano-structure, TTS

1 INTRODUCTION
The transformation of the friction surfaces has been a widely known phenomenon for a long time. From 1921 until the 1980’s, the transformation subjected to large plastic strain of the surface was considered as an amorphisation of the near-surface layer [1]. This surface often is called the Beilby layer which for a long time was thought to be amorphous because its microstructure could not be resolved with the instruments commonly used at the time. Tribologists accepted the fact of the amorphisation with scepticism, but they could neither confirm nor confute it, rather they gave them a neutral expression: Tribological Transformation of Surface = TTS [2, 3, 4]. One of the first definitions of the TTS comes from Maurice Godet: “A good material sacrifices its surface to protect its volume” [5]. On the other hand, TTS is a collective term used by mechanical engineers for those processes, which occur in the near-surface layer (in the “skin” of the friction surface) during the friction and which change the essential properties (such as the structural-, physical-, chemical- and thermal-properties) of this layer, which thickness alters from some nanometres up to mm scale. Generally we can say that TTS is one of the responses of the surface to the friction load (the other one is cracking) [6]. TTS was identified first in the case of the examinations of oscillatory displacement as a system protective surface layer [2, 4], which developed under effect of oscillatory (repetitively) motion. Later it was possible to detect its formation even at the beginning of the continuously displacement [6]. In the mid-80’s, it was first possible to identify that the anomalous physical-mechanical properties of a wear track are a consequence of the structural transition of near-surface layer [7, 8, 9]. From this time on, the systematic research concerning to the TTS formation as well as its role during friction has been accelerated. This research integrates the parallel performances of the investigations of severe plastic deformation (SPD), friction tests and numerical simulations.

2 CHARACTERISATION OF THE FRICTION LOAD
The loading of the friction surface can be characterized generally by the common effect of the following components: surface pressure, velocity accommodation, heat, radiation, and magnetic space. Between the listed components, the present study does not mean with – the otherwise not negligible – effect of radiation and magnetic space.

2.1 Effect of the surface pressure
In favour of knowing of the phenomenon, which takes place in the near-surface layer, we have to distinguish between frictions of thick/thin film lubricated surfaces and dry friction.

The presence of a thick fluid lubricant (hydrodynamic and elasto-hydrodynamic lubrication) allows the distribution uniform of surface pressure and the exoneration of the surface from the direct load transmitting. In this case the local surface pressure is equal to the average one, which is equal to the hydrostatic pressure in the lubricant.

In the presence of a thin fluid lubricant, the distributing role of the fluid lubricant decreases, the surface pressure is taken up by the micro-hydrodynamic effect of the closed lubricant “pouches” and the roughness peaks which are in contact, commonly (mixed and boundary lubrication). The load transmitting between roughness peaks does not take place directly, but with interposal of some kind of sorption’s layer. The local
surface pressure is greater than the average one, but the average surface pressure is also greater than the hydrostatic pressure in the first case.

In the case of dry friction, the load transmitting takes place between the contact regions of surface directly. At these points/regions the local surface pressure is highly greater than the average value and it exceed largely that value what could be supported by the material without plastic deformation [10].

2.2 Velocity accommodation

The knowledge of the velocity accommodation is basically important for understanding of the near-surface layer’s behaviour. The velocity accommodation signifies that phenomenon when the speed difference between the friction surfaces drops to zero on the given surface [11].

In the case of thick fluid lubricant, the velocity accommodation will be realized in the lubricant film, the surface will not be loaded by shear stress; therefore residual deformation does not set up in the near-surface layer (Fig. 1).

![Figure 1: Velocity accommodation in the adsorbed lubricant film.](image)

In the case of dry friction, the velocity accommodation can only occur partly inside of the third body situated between the friction surfaces, partly in a very thin layer of the surface (in the near-surface layer), building in an important shear stress (Fig. 2).

![Figure 2: Velocity accommodation in the near-surface layer during dry friction.](image)

The mechanical effect of the velocity accommodation in the case of dry friction can be characterized by a high level of the strain (\(\varepsilon\)), of the strain rate (\(\dot{\varepsilon} = d\varepsilon / dt\)), and strain gradient (\(\text{grad} \varepsilon = d\varepsilon / dz\)). Conforming to the experiences, the strain reaches a value of \(\varepsilon \geq 1\), the strain rate \(\dot{\varepsilon} = 10^3 - 10^4 \text{s}^{-1}\), and the strain gradient \(\text{grad} \varepsilon \geq 50 \text{mm}^{-1}\).

2.3 Effect of the temperature

Being thick lubricant film between the surfaces, the increase of temperature is a consequence of the internal friction of lubricant; it is negligible from point of view of the loading of friction surface.

If the surfaces are separated only by thin film of lubricant (mixed or boundary lubrication), the elastic collision of the roughness peaks produces heat flashes. These local heat flashes can activate only superficial physical-chemical reactions (adsorption/desorption) and are thus unable to cause a global heating of the surface, furthermore they can not produce significant atomic diffusion in the near-surface layer.

In the case of dry friction, through the velocity accommodation, basically plastic deformation produces. The role of the heat flashes due to the elastic collisions is negligible, while the work of the residual (plastic) deformation transforms entirely into heat, which means the global heat loading of the surface. The principal part of the produced heat will be conducted by the bulk material, so the global increase of temperature of the near-surface layer is not important. The effect of temperature will only be significant, if the Debye-temperature \(T_D\) of the given material is reached and if the heating time exceeds that necessary for a transition (e.g., the motion of the vacancies).

The high strain gradient of the near-surface layer, due to the velocity accommodation, results in an important translation between the atomic planes of the near-surface layer, which is accompanied by the deflection and reestablishment of the atomic bindings. The heat, which occurs during the split and re-establishing of the atomic binding, means an energy surplus for the near-surface layer, and can amplify the activation of the structural changing of the high strain loaded very thin layer. For transitions, which cause changes in the mechanical properties, even in a very small layer of the material, it is necessary that local heating reach the enthalpy difference between the two states.

2.4 The stress and strain state of the near-surface layer during dry friction

The development of a stress and strain state in the near-surface layer is the first or prompt response of the surface to the friction load. If this response will be a stress-like or a strain-like one, it depends on the actual dynamic stiffness condition of loaded surface region.

As expected in 2.1, among the load components, the surface pressure is preponderant. In the context of thermodynamics, “pressure” is taken to mean a uniform hydrostatic pressure in all directions. In mechanics, hydrostatic pressure is only one component of the three-dimensional stress state.

The stress tensor, which describes the stress state of a given point/region of the surface, can be decomposed into two components, a hydrostatic sphere tensor and the deviator-tensor, which describes the deviation from the hydrostatic sphere tensor.
The stress deviator, which expresses the difference from the hydrostatic stress state (see Equation 3), causes plastic deformation, while the sphere tensor causes only elastic deformation.

The intensity of the stresses can be characterized by the relation between the second invariant of the stress tensor and the shear yield stress \( k \) of the material:

\[
f = \frac{1}{2} s_{i,j} s_{i,j} - k^2
\]

As long as the value of the function \( f \) is negative, the material sustains only elastic deformation. If \( f = 0 \), plastic deformation begins. If \( f > 0 \), then the material will break, or, in the case of ductile material, below the critical strain to fracture, strain hardening will occur and the state of \( f = 0 \) sets in.

Characterizing the stress state by principal stresses, Equation (1) can be developed:

\[
\sigma_{i,j} = s_{i,j} + \sigma_m \cdot \delta_{i,j}
\]

where: \( s_{i,j} \) is the stress deviator, \( \sigma_m \) is the hydrostatic sphere tensor, which can be expressed as one third of the first scalar invariant of the stress tensor, \( \delta_{i,j} \) is the Kronecker symbol, \( \delta_{i,j} = 1 \) if \( i = j \) and \( \delta_{i,j} = 0 \) if \( i \neq j \)

In Equation (3) \( \sigma_m \) is the hydrostatic component of the stress state, which is equal to the average of the principal stress components:

\[
\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}
\]

The hydrostatic component of the stress state - with opposite sign - is equal to the intrinsic hydrostatic pressure:

\[
p_h = -\sigma_m
\]

It will be argued that this hydrostatic pressure \( p_h \) component produces conditions thermodynamically favourable to transient and non-transient (stationary) changes induced by deformation.

The character of the deformation of near-surface layer is determined by the actual mechanical properties of the given material; while the occurrence of the limit states (elastic-plastic transition, brittle-ductile fracture, fatigue) depends on the thermodynamic state factors, such as hydrostatic pressure, temperature and the strain rate.

The elastic deformation means a change in binding length for material with ionic and metallic bindings; while for the material with covalent binding, it means only a change in binding angle. During plastic deformation, the atomic binding will be broken and new bindings will be re-established. The mechanism of plastic deformation is – as long as the structure of the material does not change – a shifting between atomic planes and the twinning, which are related to the irreversible motion of dislocation. During plastic deformation accompanied by a structural change (by grain refining after a dynamic recrystallisation), the mechanism of deformation changes too; rather than slipping and twinning, a grain boundary displacement occurs.

As follows, the possible transients and stationary changes of the near-surface layer will be analyzed, which may have an important influence on the responses of the surface to the friction load.

3 CHANGES OF THE PHYSICAL-MECHANICAL PROPERTIES OF THE NEAR-SURFACE LAYER

Structural change and changes in physical-mechanical properties of the near-surface layer can be induced by stress, strain and magnetic field, as well as radiation. Between them the effect of the temperature, stress and strain state can not be separated completely because this role is similar in the thermodynamically activated processes. However, we will see that from point of view of the changes, which modify the responses of the near-surface layer, the deformation plays a preponderant role, the heat and the actual stress state catalyze (accelerate) the changes induced by the deformation.

Changes in the mechanical properties of the near-surface layer determine the behaviour of this layer during friction, e.g. the accommodation of the friction surface to the friction load. All local, temporary changes of the physical-mechanical properties of the near-surface layer under friction are here termed transient changes. These are dependent on the elastic deformation of the crystal lattice and are reversed with the removal of the load. Non-transient (stationary) changes here refer to transitions induced by plastic deformation of the near-surface layer (e.g. tribologically transformed structure, grain refining, mechanical alloying, non-equilibrium phase formation). These determine the mechanical properties of the layer after friction.
The potential changes of the near-surface layer will be investigated by two different ways. On the one hand we try to synthesize the possible mechanisms using procedures of severe plastic deformation; on the other hand, on the wear track produced by wear test, we try to identify the transformation mechanisms well known.

### 3.1 Transient changes of mechanical properties

Transient changes of the mechanical properties are strongly associated with elastic deformation of the near-surface layer. Pure hydrostatic pressure produces only elastic deformation. All mechanical properties change temporarily with elastic deformation of the near-surface layer and depend on the compressibility, $\chi$, of the lattice:

$$\Delta V = \frac{V_0}{3(1-2\nu)}$$

$$E = \frac{1 + \nu}{2G}$$

In Equation (6) and (7) $\Delta V$ is the change of volume, $V_0$ the volume in equilibrium, $E$ Young’s modulus, $G$ the shear modulus, $\nu$ Poisson’s ratio and $p_h$ the hydrostatic pressure.

The elastic moduli of metal crystals are vector values and vary with crystallographic direction. Thus the elastic deformation of a surface layer composed of crystals with random orientation is not homogenous. Consequently, the grains of polycrystalline metals, under mechanical load below the elastic limit, interfere with the deformation of each other, so that, apart from the stress due to the external load, local internal pressures appear also. The additional internal pressure between two crystals can be calculated by Eq. (6):

$$p_i = \chi \frac{E}{3(1-2\nu)} \frac{\Delta V}{V_0} = \frac{E}{3(1-2\nu)} p_h$$

Assuming spherical grain and sphere cup like deformation, the additional internal stress is inversely proportional to the grain diameter:

$$p_i = K \cdot \left( \frac{1}{R} \right)$$

As noted, increasing hydrostatic pressure increases the lattice energy, increasing also the evaporation energy of the metal. Young’s modulus, melting temperature and thermal expansion coefficient are similarly influenced. The greater the evaporation energy, the greater the melting point, the elastic moduli and the smaller the thermal expansion coefficient and compressibility [12].

From the point of view of the near-surface layer, these local and transient changes due to the elastic deformation resulting from compression are not negligible, because they may determine the response of the friction surface to the friction load, tending to influence the physical-mechanical properties of the near-surface layer in a favourable direction.

The foregoing applies only to the case, when deformation due to the three-axial stress state remains elastic, i.e. when $f<0$, Eq. (2).

The transient effect of the hydrostatic sphere tensor of the stress state appears when the near-surface layer is deformed plastically. Johnson [13] first called attention to the role of the hydrostatic pressure component in increasing the deformability of the near surface layer. This has been supported by subsequent work [14], [15], [16]. By way of example, the boundary surfaces of deformability of 99.9% magnesium, is shown in Fig. 3. The points of the boundary surfaces of deformability were determined by upsetting test experimentally (test methods and experiments are described in [16]).

![Figure 3: Boundary surface of deformability of polycrystalline magnesium 99.97.](image)

The equivalent deformation to fracture ($\varepsilon_f$) is drawn as the vertical axis and the two factors characterizing the actual stress state are shown on the horizontal axes. The stress state dependent variables are:

- the Mayer’s stress state index:
  $$k_f = \frac{\sigma_{max}}{3k_f}$$

where: $k_f$ is the actual yield stress, which is equal to the comparative stress at the moment of the plastic flow:

$$k_f = \sqrt{\frac{1}{2} \left( \frac{\sigma_1 - \sigma_2}{2} + \frac{\sigma_2 - \sigma_3}{2} + \frac{\sigma_3 - \sigma_1}{2} \right)^2}$$

- and the Lode-parameter:

$$|\mu_i| = \frac{2e_{i_2} - e_{i_3}}{e_{i_1} - e_{i_3}}$$

where: $e_{i_1}, e_{i_2}, e_{i_3}$ are the principal strain components from the real history of deformation.

It can be seen that the deformability increases with increasing values of the pressure component of the stress state. However, the highest deformability was
found not always to correspond with the greatest hydrostatic pressure. The hydrostatic component of the stress state has a double effect from point of view of the increase of deformability; on the one part it closes the intro- and inter-crystalline fissures, on the other, it activates new slip systems (see details in chapter 4).

3.2 Non-transient (stationary) changes of mechanical properties

All processes which are accompanied by the rearrangement of atoms or quantitative or qualitative changes to the phases in the materials result in non-transient changes of the mechanical properties of the near-surface layer. The attribute “stationary” refers to the fact that, in conformance with thermodynamic laws, these changes can only be reversed by processes which involve a decrease of enthalpy.

Deformation below the temperature of recrystallisation can generate the dissolution or transformation of the instable phases. This phenomenon is well known for the austenitic steels; under effect of the cold deformation, the γ-phase transforms partially in α-phase, i.e. in martensite (auto-sharp effect of the shears, knives, medical instruments). From tribological point of view this phenomenon is not always advantageous, because with the presence of α-phase the austenitic steel becomes magnetizable and corrodbile locally. We confirmed experimentally [16] that the presence of imposed hydrostatic pressure results in a decrease of the transformed phase quantity (Figs. 4-5).

As expected in the previous chapter, the friction load induces an important deformation in the near-surface layer under conditions of a high hydrostatic pressure component of the stress state. In the case of materials having more than 5 slip systems (f.c.c., b.c.c. structures), this deformation is characterized by a deformation mechanisms based on the motion of the dislocations until the exhausting of the deformability [17]. With increase of the dislocation density, the dislocations after their irreversible motion densify at the grain boundaries, furthermore they will be arranged in walls (dynamic restoration). If this process will not be accompanied by heat ingestion, i.e. the energetically conditions of recrystallisation will not be satisfied, the dislocation concentrated along the grain boundaries will result in formation of sub- and intercrystalline fissures, which – taking into consideration, that the stress required to the fissure propagation is inversely proportional to the fissure length – leads to cracking.

We established experimentally that the hydrostatic pressure component of the stress state retards the increase in dislocation density; it closes the fissures in initial state, and increases hereby the deformability [14]. As en example, Fig. 6 shows the flow curves of carbon steel and a RS/PM AlMgSi alloy.

![Figure 4: Specimen upset without imposed hydrostatic pressure (a); with imposed hydrostatic pressure (b); images from identical location on specimen.](image)

![Figure 5: Flow curves (upper) and X-ray spectra of the investigated austenitic steel (lower). a) base material; b) specimen upset with superimposed hydrostatic pressure; c) specimen upset without hydrostatic pressure (Cu Kα radiation, 43 kV, 30 mA, graphite monochromator, proportional counter).](image)
Materials do not have enough active slip systems to set up the slipping (e.g. magnesium and titan crystallized in close-packed-hexagonal system), the deformation occurs thus far by twinning, whereas under effect of some external or internal energy surplus (heat or pressure) further slip systems will not be active. This energy necessary to the activation of slip systems is proportional with the square length of Burgers-vector defined at the plane of the slipping.

The presence of the hydrostatic pressure component causes an important increase in deformability for these materials (Fig. 7) [18], which means that the needed energy was covered by the hydrostatic pressure and the high strain. However, it was observed that the deformation concentrated to the so-called slip bands, along of which the deformation needed smaller energy than the deformation of the bulk material (Fig. 7).

The strain softening which can be observed on the flow curve is a consequence of the dynamic recrystallisation (Fig. 8), which is accompanied by grain refining, and decrease of dislocation density due to the common effect of the intensive deformation of the slip bands as well as the hydrostatic pressure component of the stress state (Fig. 9). In the slip bands the dislocation density has been decreased to 1/10 comparing to the initial state.

The recrystallized structure is nanometric, because the grain diameter is <1 µm. The physical-mechanical properties of this nanostructure differ significantly from the properties of the bulk material. We can observe an important increase in mechanical resistance (UTS, YS) and in micro (nano)-hardness, however, the further deformability of the nano-structure significantly decreases, but in certain case can increase [19, 20]; while paradox-like the thermostability of the refined structure remains very stable [21].
Figure 9: Changes in the combination and the density of dislocations after upsetting of polycrystalline magnesium 99.97 under imposed hydrostatic pressure.

The results obtained by SPD investigations were compared by results of the wear tests. In an effort to reproduce the mechanical grain refinement in the near-surface layer during friction, reciprocating wear tests were performed on flat magnesium specimens using a hemispheric steel counterface, a Hertzian pressure of 200 MPa and an amplitude of 5 mm. In the transverse section of the wear track the grain boundaries do not run out to the surface (Fig. 10).

Figure 10: Longitudinal section of the wear track of magnesium specimen.

The transformation of the near surface layer from micro to nano-structure was confirmed by x-ray diffraction and nano-hardness measurements. From x-ray spectra we observed that the orientation of the grains in the wear track was changed to a more random arrangement, furthermore the numerical analysis of line-broadening and equivalent grain diameter (xSize) indicated an increased level of lattice disorder compared with the original structure (Table 1).

<table>
<thead>
<tr>
<th>Location</th>
<th>FWHM</th>
<th>xSize</th>
</tr>
</thead>
<tbody>
<tr>
<td>original surface</td>
<td>0.12</td>
<td>987 nm</td>
</tr>
<tr>
<td>wear track</td>
<td>0.26</td>
<td>235 nm</td>
</tr>
</tbody>
</table>

Table 1: X-ray diffraction results of the magnesium specimen.

Figure 11: X-ray diffraction spectra of the wear track on magnesium specimen; a) from the surface, b) from the wear track. (Cu radiation, 40 kV, 30 mA, graphite monochromator, proportional counter).

The character of TTS which is attached to the structure change of the near-surface layer can be observed even in the case of non crystalline material. Structure changes could be observed at amorphous diamond-like carbon (DLC) coating [22]. The amorphous coating at the wear track gave a more ordered “answer” during X-ray diffraction than the as formed coating; furthermore an increase in micro-hardness was also measured.

4 EFFECT OF TEMPERATURE AND HYDROSTATIC PRESSURE IN FORMATION OF TTS

Crystal boundaries possess higher enthalpy than the grain interiors. The smaller the grains, the greater the importance of grain boundaries in a given structure. Grain refinement is accompanied by an increase of enthalpy, the necessary energy for which is derived from intensive plastic deformation. It has been already mentioned in section 3.1 that the additional internal stress due to the deformation of neighbouring grains is inversely proportional to the grain diameter (Eq. 9). The smaller the grain size, the higher the additional internal hydrostatic pressure.

Hydrostatic pressure and temperature are equivalent thermodynamic state factors. However, their effect on a crystalline structure is quite different (Fig. 12).

Increasing temperature increases the amplitude and the frequency of the oscillatory motion of the atoms resulting in an increase of lattice parameter.

Increasing pressure produces a decrease of the lattice parameter. Both temperature and pressure increase result in a decrease of the potential energy compared to the equilibrium state, but with opposite sign of the lattice forces.
For transitions, which cause changes in the mechanical properties, it is necessary that local heating reach the enthalpy difference between the two states. During the recrystallisation the necessary heat depends on the one hand on the recrystallized volume, on the other hand the temperature and time of heating. The volume of the near-surface layer is negligible compared to the volume of the bulk material; the local temperature, which occurs during the slipping of the atomic planes, exceeds largely the recrystallisation temperature of the bulk material ($\approx T_{\text{melt}}/2$). Conforming to this, the time needed for the recrystallisation of the near-surface layer is in order of 0.01 s (the calculation was performed using the recrystallisation curves of copper).

5 CONCLUSIONS AND DISCUSSION

Investigations using processes of severe plastic deformation as well as friction tests, were performed in favour of clarifying of the mechanism of tribological transformation of surface (TTS). Based on the presented results as well as on the earlier published ones, the mechanism of structural changes of the near surface layer due to the friction load can be explained as follows:

1) The plastic deformation of the near-surface layer begins with a slipping based on the irreversible motion and multiplying of dislocations, and/or with twinning. Under effect of this conventional mechanism of plastic deformation, the near surface layer becomes hardened and its dislocation density increases.

2) After the work hardening there is not fissure formation, because under effect of the hydrostatic pressure component of the stress state, the deformability and the plasticity of the near-surface layer increases. The severe plastic deformation (typical strain rate $\dot{\varepsilon}=10^8 - 10^9 \text{s}^{-1}$, strain gradient $\text{grad } \varepsilon \geq 50 \text{ mm}^{-1}$) concentrates in a very small layer of the surface.

3) In the near-surface layer, under effect of the dynamic recrystallization, a grain refinement sets on. The decrease of the potential difference is a consequence of the hydrostatic pressure, the necessary energy to offset the enthalpy difference is ensured by the local heat which occurs between atomic planes due to the broken atomic bindings. The dislocation density of the new nano-structure does not reach the value of the initial state.

4) There is not more work hardening, because the deformation mechanism based on the motion of dislocations is blocked by the grain size; the deformation is only possible with grain boundary slipping, which is quite limited. The mechanical properties of the near-surface layer depend on the grain boundaries or the grain size ($\text{MH} \approx d^{-1/2}$).

5) Apparition of embitterment and micro-cracks at the near-surface layer, which means the internal source of debris.

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7 REFERENCES