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The Effect of the Slippage Degree at Rolling with Slipping on the Wear Resistance of Contact Surfaces

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Abstract

The regularities of the wear of the steel 1045 during cutting off the feed of a lubricant under the non–stationary friction conditions were established. The influence of the properties of the secondary structures, formed on the contact surfaces under conditions of rolling with a different degree of slippage, on the wear of advancing and lagging surfaces was determined. The influence of specific friction work, the degree of hardening – weakening of surface layers of metal and the intensity of saturation by active elements of near–surface layers of metal on the wear resistance of friction pairs is examined. The change is established in localization of the depth of spreading the stressed and deformed state of material of the contact surfaces with an increase in the slip rate from 0.315 m/s to 1.14 m/s at rolling with the slippage.

Keywords: secondary structures, specific friction work, wear, micro hardness, shearing stresses.

1. Introduction

The problem of increase in reliability of tooth gears is multifunctional. It can be solved in different ways. Firstly, due to selection and creation of more wear–resistant antifriction materials for the assigned modes of loading and the operating conditions of tooth gears. Secondly, it can be solved through application of the more effective lubricants with poly-functional additives. Thirdly, by optimization of the friction parameters and the operating modes of tooth gears with subsequent development of regulated technological conditions. In this case, it is necessary to take into consideration that the wear resistance of metal is determined not only by the structure of metal in the initial state, but also by the structure, which is formed as a result of mechanic and chemical processes, occurring in the course of friction. The establishment of interrelation between the processes of energy storage in the secondary structures and the wear is an important structure and energy characteristic, which determines durability of the contact surfaces in many respects. This, in turn, will make it possible to solve the problems associated with forecasting the working resources of the friction pairs with a local form of contact.

1.1 The Influence of Lubricant on the Wear Resistance of Tooth Gears

The reason for the uneven wear of involute tooth gears is the inconstancy of friction conditions for all points of contact surfaces along the involute profile. The surface layers in the process of operation of the tooth gears are destroyed as a result of cyclic action of bending stresses and wearing from the slippage of contact surfaces along the meshing line to the apex (root) of a tooth. The wear of the polar and the circumpolar zones depending on the material hardness, contact loads and rates is examined in paper (Ognjanovic, 2004), the ductile deformations in the indicated zones as a result of the distortion of involute profile with the wear are possible to reveal by the high degree of wear hardening of the material (Burdukov et al., 2010).

When using transmission oils with the active constituents of anti–wear and anti–fretting additives as a lubricant for middle– and highly loaded stressed tooth gears, mechanic and chemical properties of the tribocontact change substantially. The adsorbed film changes the surface energy of the main material. The linear correlation between the wear and the dissipated energy is established in articles (Jahangiri, 2014; Colaco et al., 2007; Nurnberg et al., 2008). Furthermore, the quantity indicator of the energy dissipation can be considered as an index of changes in the mechanical and structural properties of contacting bodies. The energy of activation of chemical interaction of medium with material of the surface layer, according to the results of paper (Quinn, 1998), has the order of magnitude of 10 –

10^3 kJ/mol, which characterizes high rate of formation of oxidizing films. The dependence of the wear resistance of materials on the hardness of the hardened layer during the self–organization of dissipative structures is given in article (Ibatullin, 2006). An increase in resistance to fatigue with an increase in the degree of work hardening during the deformation by friction is established in paper (Ibatullin, 2006). For the 40X steel, depending on the degree of work hardening, the values of activation energy can change in the range of 42 – 100 kJ/mol; for the ShKh–15 steel, this parameter is located in the range of 73 – 195 kJ/mol.

The initial process of plasticizing the material with adsorption of surfactants finishes with the stage of significant hardening of the surface layer of metal (Dmitrichenko et al., 2009).

The hardening of the surface layer in active lubricating medium renders screening effect for spreading plastic deformation into the depth of metal (Shchukin et al., 2000). In article (Kovalsky et al., 2014), the interrelation between the passage of the plastic deformation, which causes the wear intensification, to the elastic deformation, which is characterized by minimum wear, and the stages of forming the shielding durable boundary lubricant films, was established. The experience of operating tooth gears shows that the contact endurance of teeth surfaces depends on the thickness of lubricant films, which, in turn, influence the frictional forces and the stressed state in contact (Hutchings, 1992). In paper (Magalhaes et al., 2007), direct correlation between development of the fatigue failures (pitting and splitting) of the surface layers of the metal of tooth gears with the parameters of the lubricating action and the roughness of contact surfaces was established. In the case of poor lubricating, shearing stresses are localized at a certain depth, which leads to crack initiation under the surface layer of metal (Ognjanovic, 2004). However, sufficient amount of a lubricant creates prerequisites for shearing stresses coming out to the surface, in this case, the cracks initiation occurs in the cavities of rough surfaces. The gears with shaving showed better wear resistance than milling ones, since they delay the initiation of sub–surface cracks (Muraro et al., 2012). The wear mechanisms and the damage morphology, identified by microscopic observation of the tooth surface, show the importance of surface finish, the level of contact stresses and the lubricant film thickness to wear on gear teeth. Nevertheless, the given articles do not cite the criteria for evaluation of localization of shearing stresses vector during the transition of a tribosystem from hydrodynamic condition to the boundary mode of the lubricating action.

1.2 Factors that Influence Fatigue Resistance in a Local Contact

Shearing stresses, which act in the zone of contact of active surfaces of teeth, should be considered responsible for the initiation and development of damages. With the removal of the contact zone from the pitch point of a tooth, the tensions τ_{max} increase in value and approach the surface layers, intensifying destructive processes in them (Vorobyov & Kovergin, 2004). The contact conditions predetermine the initiation of cracks on the surface or in the sub–surface layers of the lateral edges of teeth. The spread of cracks can lead to failure as a result of pitting, exfoliation or the fracture of a tooth edge (Cheng, 1983). Accordingly (Zafosnik et al., 2007), for the conditions of rolling and rolling with the slip, fatigue resistance depends on different factors, such as elastic–plastic deformation, properties of the material of contact surfaces, physical and chemical properties of a lubricant, roughness of surface, residual stresses and the load and rate parameters of the contact. In this case, the initiation of cracks can be manifested near the surface of the deformed zone or in the area of maximum cyclic shear stress. In paper (Sadeghi et al., 1988), a mathematical model of determining the maximum shearing stresses in the elasto–hydrodynamic contact is presented. According to the represented results, during simple rolling, the localization of maximum shearing stresses is at the depth of 0,78*b* below the surface. The slip, load and rate have an essential effect both on the depth of the bedding of shearing stresses and on the localization of the point of stress concentration from the center to the zone of coming out in the EDG–contact. The dependence of the gradient of spreading shearing stresses along the depth on geometric parameters of tooth gears and load is examined in article (Tobie et al., 2002).

Thus, we carried out a brief analysis of scientific studies, connected with establishment of regularities between a change in the energy characteristics of a contact, the mode of lubricating action, the localization of maximum shearing stresses and the wear resistance of friction pairs. This analysis showed that there is no unanimous opinion on the influence of the mentioned parameters on the wear of non–conformal friction units. In connection with this, there is a need for developing comprehensive procedures of tribological tests, which would consider the variety of the effects of interaction of the components of lubricants with the activated metal surface. In particular, the study of the friction pairs of rolling and, especially, rolling with variable slippage, comprising a considerable part of friction units of machines and mechanisms (antifriction bearings, tooth drives), are not numerous and need further deep analysis.

1.3 The Aim of the Study

The aim of the work was studying the influence of a different degree of slippage of contact surfaces on the kinetics of the change in specific friction work, the strength properties of the surface layers of metal and the wear resistance of contact surfaces under conditions of terminating the feeding of lubricant to the contact zone.

2. Installation and Methods for Determining Lubricating, Anti-Friction, Anti-Wear and Rheological Properties of Lubricants

2.1 Device for Studying Parameters of Friction in a Local Contact

The research of tribological parameters of friction pair was conducted with the device for evaluating the tribological characteristics of tribocoupling elements (Mikosyanchik, 2013). As it is shown in Figure 1, the device for evaluation the tribological characteristics of tribocoupling elements contains two drives 5, 6, at the outlet shafts of which the studied rollers are mounted 7, 8. Control of frequency of the drives rotation is performed by programming the unit of control 2 of the electric pitch motors 3, 4, which are connected to the power source 1. The electric pitch motor 3 is fixed on the motor–scales, to which the strain gauge of the friction moment is attached 9. The lower tested sample 7 is submerged in the lubricant 10, which is located in the tank 11. Two heating elements 12 are attached to the lower housing of the given tank, the thermocouple 13 is attached to the rod 14. The load mechanism consists of the system of levers with the loading device 15 and the counterweight 16.

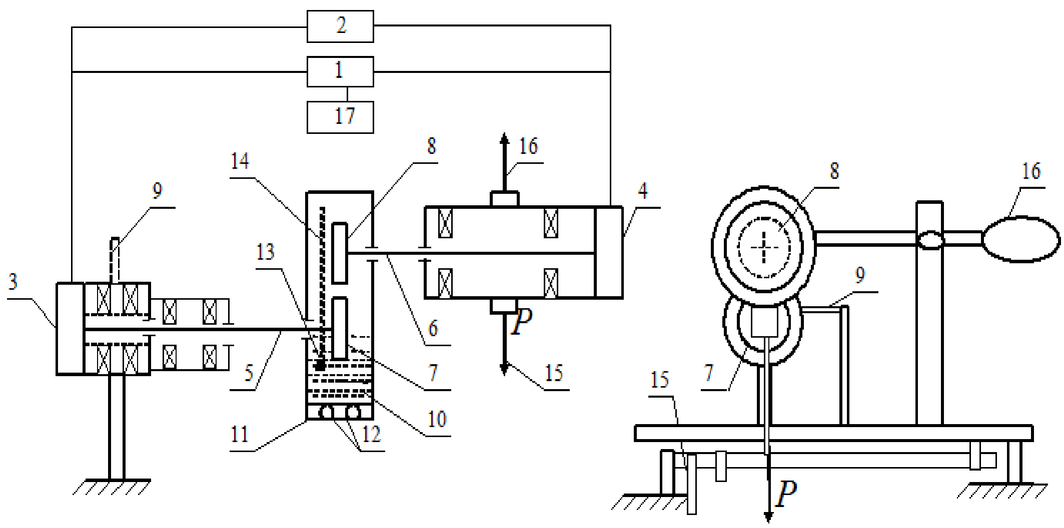


Figure 1. Schematic of tribological complex for evaluation of lubricating, antifriction and rheological characteristics of lubricants

The device works according to the following scheme. The tribosystem, which consists of two movable rollers contacting in the process of friction 7, 8 and a lubricant 10, is located in the tank 11. The tribosystem with the aid of the loading device 15 is loaded by the assigned effort P and the rollers are set in motion by the revolving drives 5, 6. The frictional torque, rotation speed of the rollers, temperature of the lubricant, and thickness of lubricant layer are measured by the method of voltage drop during normal glow discharge which is recorded and processed on a computer in real–time with graphical representation of changes at each cycle.

The studied non–stationary friction conditions implied the cyclic recurrence of conducting the experiments in the mode: start – stationary work – braking – stop (Figure 2).

Section I corresponds to the initial operating cycle of friction pairs and is characterized by a gradual increase in the rolling speed of rollers, in this case V_{sl}=0. The assigned maximum slippage of rollers is reached in section II, the rolling speed of friction pairs in this operating cycle is constant. Section III corresponds to braking, which consists of two periods: an initial decrease in rolling speed of rollers with retention of the assigned slippage at point A and a gradual decrease to zero in the slippage degree at point B (IIIa). Further braking occurs under conditions of simultaneous decrease in the rolling speed of both rollers with maintaining the condition V_{sl}=0 (IIIb). Section IV corresponds to a stop. If we project the selected cycle to involute gearing, the polar zone of gearing corresponds to sections I and IIIb, circumpolar zone corresponds to section IIIa and extreme points of gearing with the maximum slippage corresponds to section II.

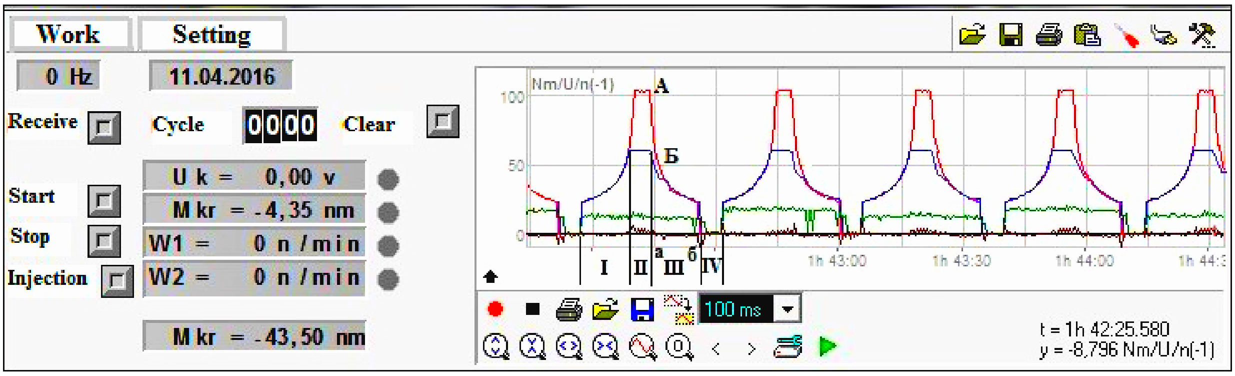


Figure 2. Scheme of work of tribosystem under non–stationary conditions of friction: section I – start; section II – stationary work; section III – braking; section IV – stop

2.2 The Algorithm of Determining Tribotechnical Characteristics of Friction Unit Under Conditions of Rolling

For obtaining the reliable results of studies of the elements of tribocoupling, the reproduction and convergence of results with the repeated experiments, the clear structure of the procedure of tribological studies is necessary (Figure 3). It must include: experimental means for conducting experiments (the scheme and the setup of the device), the objects of the study (materials, construction, manufacturing precision), and conditions of conducting the experiment (load, kinematic and temperature factors), monitoring and measuring means and the methods of processing the results of experimental study.

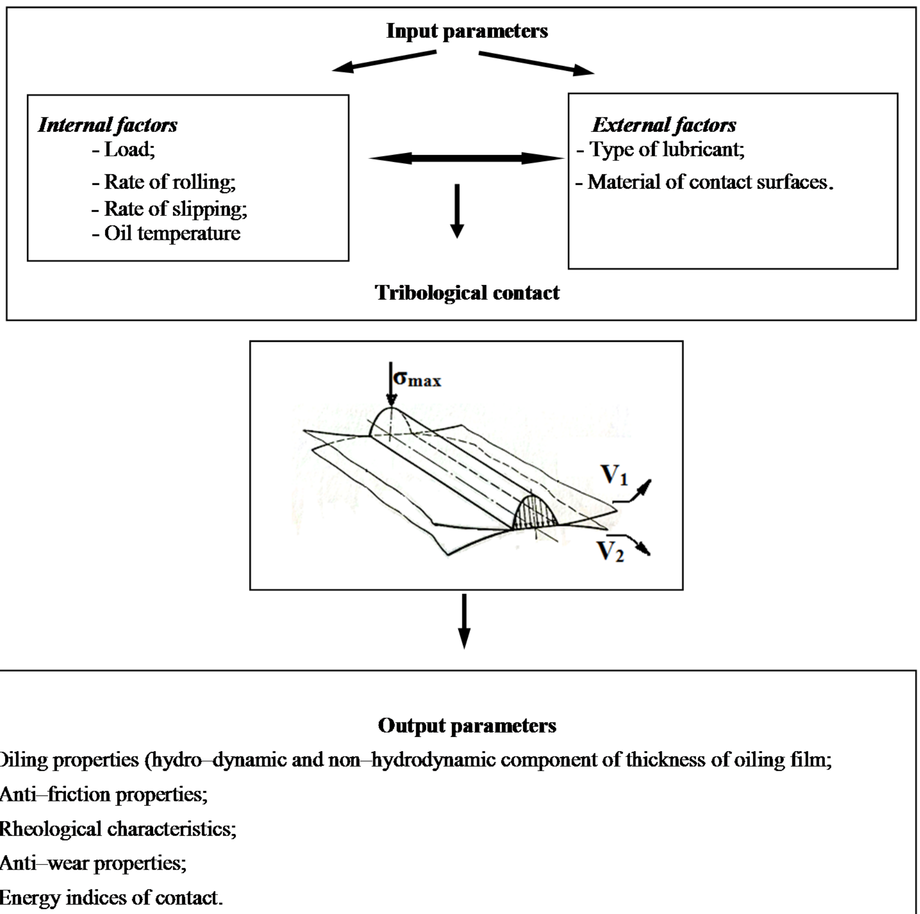


Figure 3. Estimation Scheme of tribological parameters in a linear contact.

The lubricating qualities (hydrodynamic and non–hydrodynamic component of the thickness of lubricant film) are determined by the method of a voltage drop in the mode of normal glowing discharge (Raiko, 1974). According to this procedure, a voltage drop in the lubricant film at current strength of 2 and 4 A (amperes) is measured, and then according to calibration tables, the thickness of the lubricant film is determined:

$$h = \frac{2U_{2A} - U_{4A}}{k} , \quad (1)$$

where U_{2A} and U_{4A} are the voltage drop in the lubricant film at current strength of 2 and 4 A; k is the coefficient, depending on the type of lubricant.

The calculation of the friction coefficient is performed by the following formula:

$$f = \frac{2M}{dN}, \quad (2)$$

where M is the torque moment , d is the diameter of the sample, N is the load.

Determining the rheological characteristics of a lubricant includes calculation of gradient of the shearing rate (γ) and shear stresses (τ) of lubricant films, effective viscosity in the contact (η_{ef}) by the following dependences:

$$\gamma = \frac{V_{sl}}{h}, \quad (3)$$

$$\tau = \frac{f \cdot N}{S}, \quad (4)$$

$$\eta_{ef} = \frac{\tau}{\gamma}, \quad (5)$$

where V_{sl} is the slip rate, S is the contact area.

The calculation of specific friction work (W_{fr}) is performed by integrating the area, enclosed by the curve of a change in the friction moment. The selection of the range of integration for the X–axis (the coordinate of time of working of friction pairs in a cycle) is performed with the maximum friction moment. Specific friction work is determined by the formula:

$$W_{fr} = [\left|\int_0^{t_i} M_i\,(t) \cdot 2\pi n_i(t)d(t) - \frac{1}{2}\sum_0^{i=n_{ti}} J\pi_i \cdot \omega_i^2\right|]/\,S, \quad (6)$$

where n, ω are the rotation frequency and the angular rotation rate; t is the time of the cycle duration; $J\pi$ is the polar moment of inertia of rotating components of the tribotechnical device.

2.3 Materials and Method Of Studying the Tribotechnical Characteristics of Contact Under Conditions of Cutting Off the Lubricant Feed to the Friction Zone

The rollers made of steel 1045 according to ASTM (*HRC* 38, *Ra* 0.57 microns) were used as the samples. The lubrication of contact surfaces was achieved by dipping the lower roller into a tray with oil. Mineral transmission oil for mechanical gearboxes and main drives of passenger cars and trucks Okko GL–4 80w/90 was used as the lubricant. The volumetric temperature of oil was 20^o C.

Micro hardness of the surface layers of metal was measured at the instrument PMT–3. Measurement of the mass fraction of elements was carried out by the method of X–ray microanalysis in the mode of high vacuum on the raster electronic microscope REM–106I.

The maximum rotation frequency for the advancing surface amounted to 1000 r/min. The slippage 3 %, 10 %, 20 %, 30 % and 40 % was imitated in the work. The maximum contact stress according to Hertz was 250 MPa.

The alignment of contact surfaces, including 100 cycles and subsequent operation of friction pairs during 400 cycles, was achieved under conditions of rich oiling, after which the feed of lubricant was cut off. The total number of cycles in each experiment comprised: 500 (rich oiling by dipping the lower roller into the tray with oil), 400 (imitation of the mode of oil deficiency due to the cut off regular feed of the lubricant from the tray to the contact zone), 100 (forced removal of the lubricant from the contact surfaces by wiping rollers with cleaning cloth).

3. Results of Experimental Studies and Their Discussion

The study of the processes of the mutual influence of external and internal factors in the process of self–organization of the tribosystem at friction will make it possible to determine the kinetics of a change in the tribotechnical properties of contact and to reveal the main mechanisms, which determine the wear resistance of contact surfaces. An important stage in this direction is studying the processes in the thin surface layers of metal. Specifically, the surface layers of metal make up a complex unbalanced system, which is characterized by nonlinear processes.

3.1 The Influence Evaluation of Secondary Structures Properties on the Wear of the Tribocoupling Elements

The total linear wear of advancing and lagging surfaces during the work of friction pairs under conditions of rich oiling, limited oiling and the forced removal of a lubricant is represented in Figure 4.

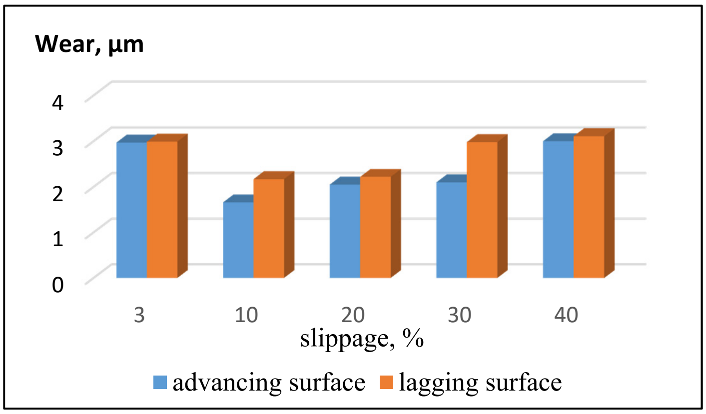
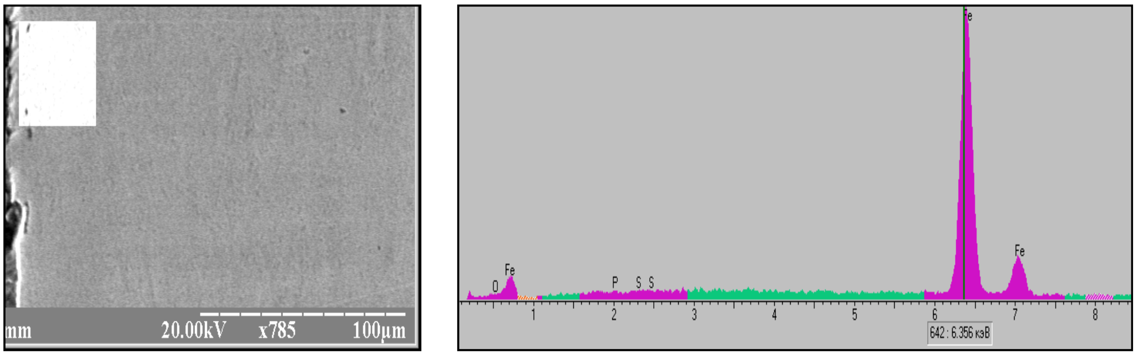


Figure 4. Linear wear of contact surfaces under conditions of rolling with slippage

While with an increase in the slippage from 10 to 40% there is a clear tendency toward a decrease in the wear resistance of contact surfaces, for the minimum slippage, a rather high wear is established. The explanation of the obtained results, in our opinion, lies in the plane of identification of the types of secondary structures, which are formed on the contact surfaces as a result of structural adaptability in the course of friction. We assume that the secondary structures of type I are formed on the friction surfaces with the slippage of 3%, which, according to B.I. Kostetskyi (Kostetsky et al., 1976), possess the superplasticity properties, are poorly saturated with active elements and are characterized by the low indices of specific friction work during formation.

The following established regularities serve as a proof of our assumptions. Firstly, the obtained results of determining the mass fraction of elements by the method of *X*–ray microanalysis at the depth of 20 – 50 µm under the friction surface attest to the fact that the element composition of near–surface layers at friction is identical to the original material, which characterizes it's low activation ability as a result of mechanical and chemical processes (Figure 5, Table 1).



a) b)

Figure 5. Determining the mass fraction area of elements in metal (a) Intensity of characteristic spectra of analyzed elements (b)

Table 1. Concentration of mass fraction of the analyzed elements (C, %) in near–surface layers of metal

Element	Original metal	Lagging surface with slippage, %		
		3	20	40
O	0.65	0.58	0.75	1.02
P	0.03	0.03	0.05	0.03
S	0.05	0.05	0.12	0.15
Fe	99.27	99.34	99.08	98.8

Secondly, the indices of specific friction work for these surfaces are characterized by the lowest values, in comparison with 10 – 40% slippage, which indicates insignificant energy capacity of the contact both because of the dominance of the speeds of rolling and due to implementation of the predominantly hydrodynamic mode of the lubricating action (Figure 6). While during the start–up phase under conditions of simple rolling (section I) specific friction work amounted to 2 – 5 J/mm^2, then in the period of slippage (section II), this parameter increases by 2 times.

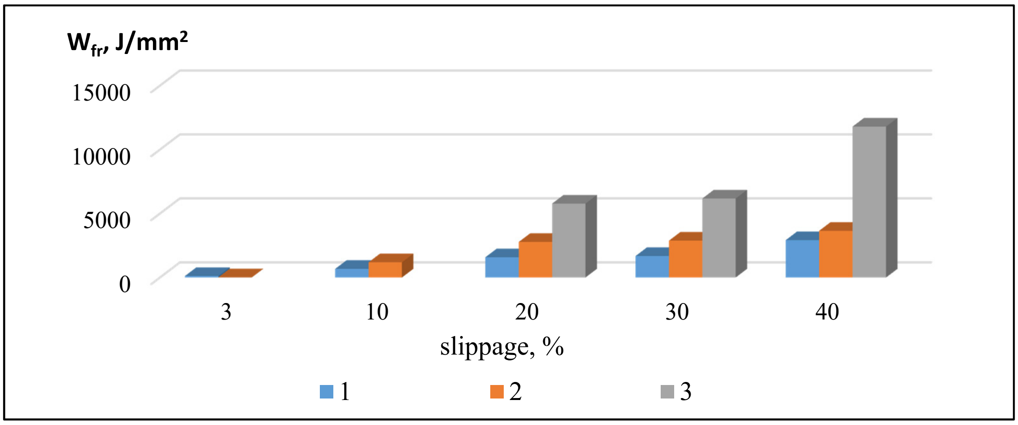


Figure 6. Influence of slippage degree on the kinetics of change in specific friction work (W_{fr}) in contact: 1 – Mode of rolling with slippage, rich oiling; 2 – Mode of rolling with slippage, limited oiling; 3 – Moment of setting in the mode of rolling with slippage

Thirdly, the superplasticity of the formed secondary structures is proved by the high degree of softening of the surface layers (microhardness of the advancing and lagging surfaces decreases by 990 and 940 MPa, respectively) and the amorphization of the near–surface layers of metal on the depth of 40– 50 μm (Figure. 7).

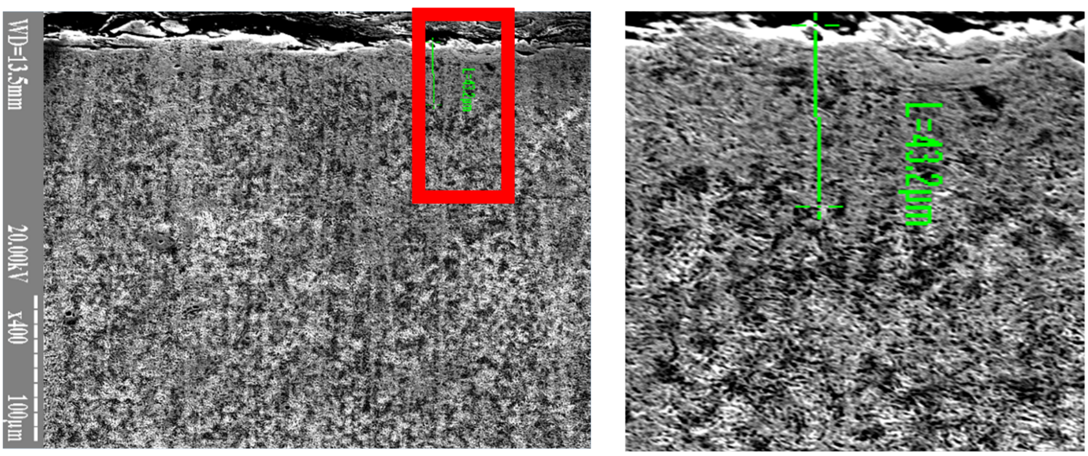


Figure 7. Microstructure of near–surface layers of lagging surface of steel 1045 with friction with slippage of 3% (×400)

The nature of change in the microhardness of near–surface layers testifies to the presence of positive gradient of their mechanical properties in the depth. However, the amorphized layer is characterized by a high degree of weakening of the order of 1100 – 1400 MPa, in comparison with the initial surface, which is caused by manifestation of the plasticizing effect of active components of a lubricant.

In the range of slippage of 10 – 40%, other mechanisms of the wear of the elements of tribocoupling elements are revealed. The growth of specific friction work in the slippage section as a result of increase in the slip rate causes mechanic and thermal activation of contact surfaces (Fig. 6). Specific friction work without a regular lubricant feed into the contact zone both under conditions of simple rolling at start (section I) and under conditions of rolling with the slippage (section II) increases, on average, by 1,75 times, in comparison with rich oiling (Figure 6). This creates prerequisites of the more steadfast boundary layers of lubricant on the friction surfaces – chemisorption films, and the surface layers of metal form secondary structures of type II (Kostetsky et al., 1976).We will present the actual results, which prove the formation of these structures. Firstly, the near–surface layers of metal at the depth of up to 50 m are saturated with active elements – the mass fraction of oxygen and sulfur increases (Table 1). Secondly, the surface layers of metal are characterized by an increase in the strength properties, which is manifested by the increase in their microhardness during operating time (Figure 8).

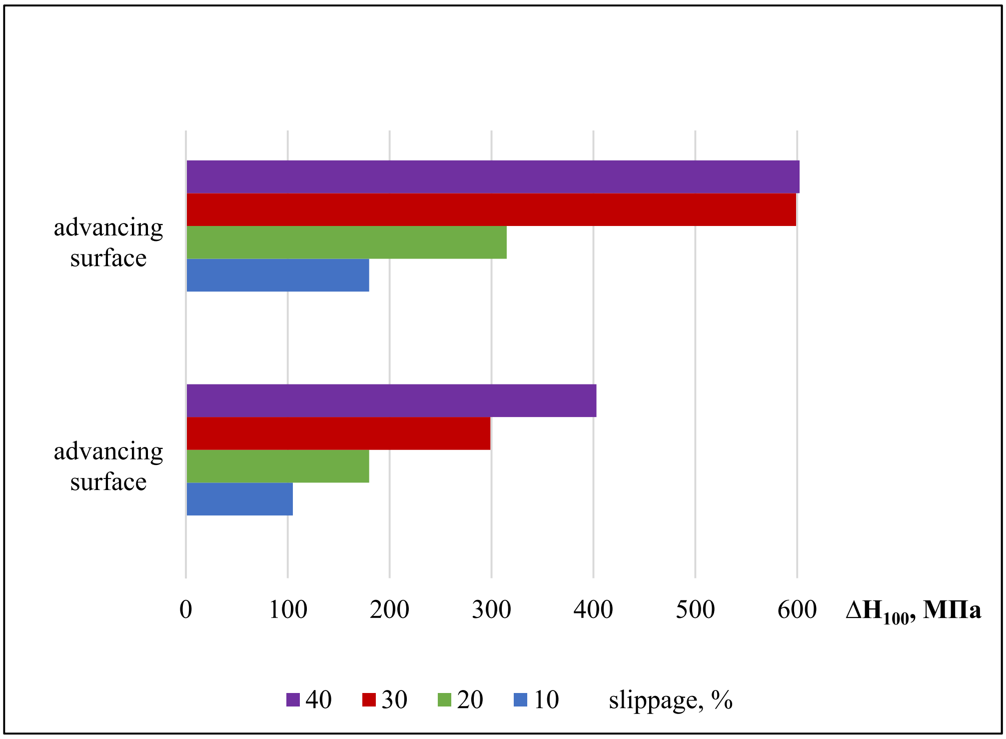
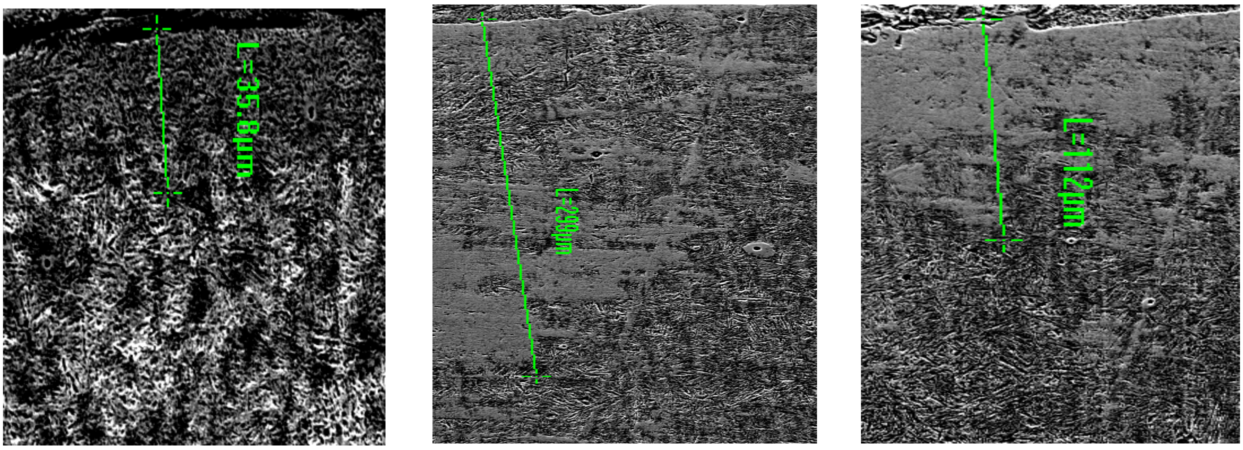


Figure 8. Degree of hardening of surface layers of steel 1045 at work under conditions of rolling with slippage

A distinct dependence of the degree of hardening of advancing and lagging surfaces on the slippage is traced: with an increase in the slippage, the hardening of contact surfaces increases, which is a result of the increase in the deformation component of the friction coefficient with the increase in the slip rate from 0.315 m/s to 1.14 m/s at 10% and 40% slippage, respectively. The complex stressed state of the near–surface layers of metal with an increase in mechanical and thermal effect under conditions of simultaneous influence of normal and shearing stresses leads to their intensive deformation and an increase in specific friction work in the contact. The depth of spreading the stressed and deformed state of friction pairs depends directly on the degree of slippage of contact surfaces. For example, the depth of the amorphizated deformed layer of metal after etching (by the 4% alcohol solution of nitric acid) of the microsections of the lagging surface with the slippage 20% covers 30 – 37 μm, and with the slippage 40% – 100 – 300 μm (Figure 9).



a) b) c)

Figure 9. Microstructure of near–surface layers of lagging surface of steel 1045 (×400):
a) – Slippage 20%; b, c) – Slippage 40%

In this case, the deformed volume of metal with the lower slippage is characterized by the homogeneous, strongly changed finely dispersed structure of martensite, and at the maximum slippage, we can trace the unbalanced structural phase state of the deformed layer with the poorly etchable centers. In paper (Bishutin, 2010), a change in the physical and mechanical properties of the deformed contact surfaces of medium–carbon steel was found, with an increase in temperature at friction due to formation of secondary structures, oxide and higher oxide films.

3.2 The Influence of Slip Rate on the Nature of Distribution of Micro-Hardness of the Surface Layers of Metal by Depth

Under friction conditions, the surface layers of metal are located within the influence of the complex stressed state, which is created by simultaneous action of normal and shearing stresses. In this case, the deformation of surface layers proceeds predominantly in the direction of action of shearing forces, which leads to texturing of surface layers, their hardening and work hardening. The hardening of the surface layer in active lubricating medium renders a screening effect for spreading the plasticity deformation into the depths of the metal (Shchukin et al., 2000). The formation of the hardened surface layer prevents formation of particles of the wear and, therefore, decreases wear intensity.

According to (Ognjanovic, 2004; Sadeghi et al., 1988), with availability of the sufficient lubricant in contact, the maximum shearing stresses, lying at the depth $h = 0.786 \cdot b$, where b is the half–width of contact, come out to the surface. However, in our opinion, this is true for the stationary friction conditions, where the elasto–hydrodynamic or hydrodynamic mode of lubricating action is implemented, which ensures effective separation of friction pairs. Under the experimental conditions created by us (mode – start – stop), the non–stationary processes dominate in contact, which causes a constant change of modes of lubricating action. Under conditions of limited oiling, for example, a whole spectrum of the modes of lubricating action is observed: from the medium dry to the hydrodynamic, independent of the degree of slippage in the contact. Specifically, in the periods of disruption of the lubricant film continuity, the vector of the action of maximum shearing stresses descends at a certain depth and is localized in the near–surface layers of metal. This leads to intensive ductile deformation of the upper volumes of metal, the action of mechanisms of internal friction and domination of deformation component of the friction coefficient, which, in the totality, increases the wear of contact surfaces. In the article (Wang et al., 2012), it was experimentally established that 85% of the total wear of friction pairs happens at the stage of domination of ductile deformation during disruption of the continuity of a lubricant film. The results of the maximum wear of contact surfaces with the slippage 40 %, obtained by us, prove significant influence of a lubricant on the wear resistance of friction pairs. The highest degree of destruction of boundary lubricant films was revealed, which under conditions of limited oiling makes up 30% of the entire operating cycle (Figure 10).

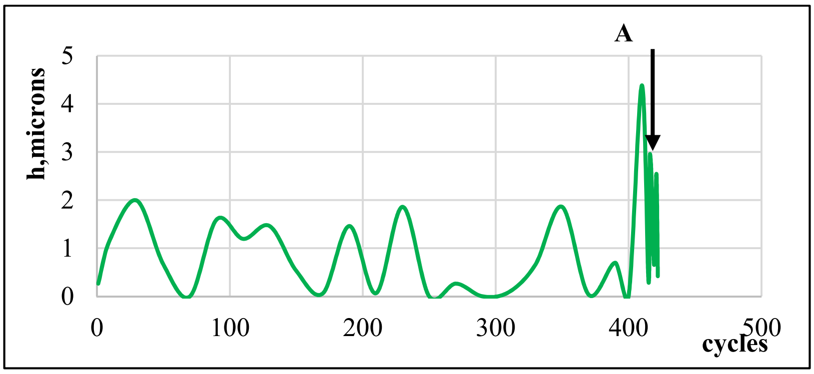


Figure 10. Kinetics of change in the thickness of lubricant film in the mode "start – stop" at rolling with slippage 40 %. At point A – forced removal of lubricant

In paper (Pravednikov, 2005), in the process of studying mechanisms of internal friction based on the results of measuring the microhardness of the surface layers of metal along the depth, the transition to the epures of shearing stresses took place. In this case, high correlation of the degree of ductile deformation of the volumes of a deformed body with an increase in microhardness and maximum shearing stresses was established.

The analysis of the change in the microhardness (H_{20}) of the near–surface layers of metal, which we carried out, revealed the non–homogeneity of the strength properties of the textured deformed volume. The initial surface of steel 1045 after hardening, high–temperature tempering and grinding is characterized by the positive gradient of mechanical properties with the maximum zone of the hardened layer at the depth of 75 – 95 μm, where H_{20} amounts to 5290 MPa (Figure 11a).

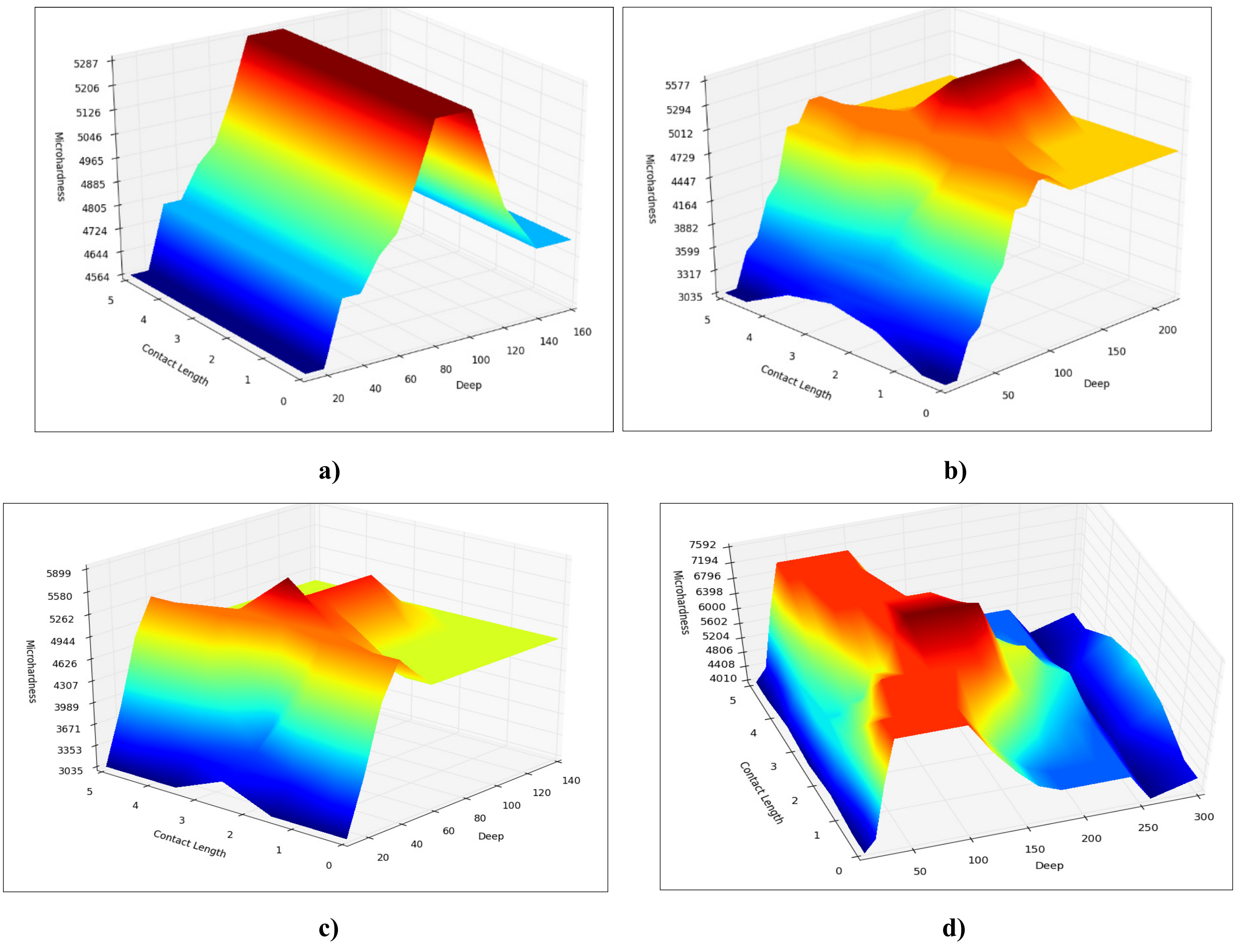
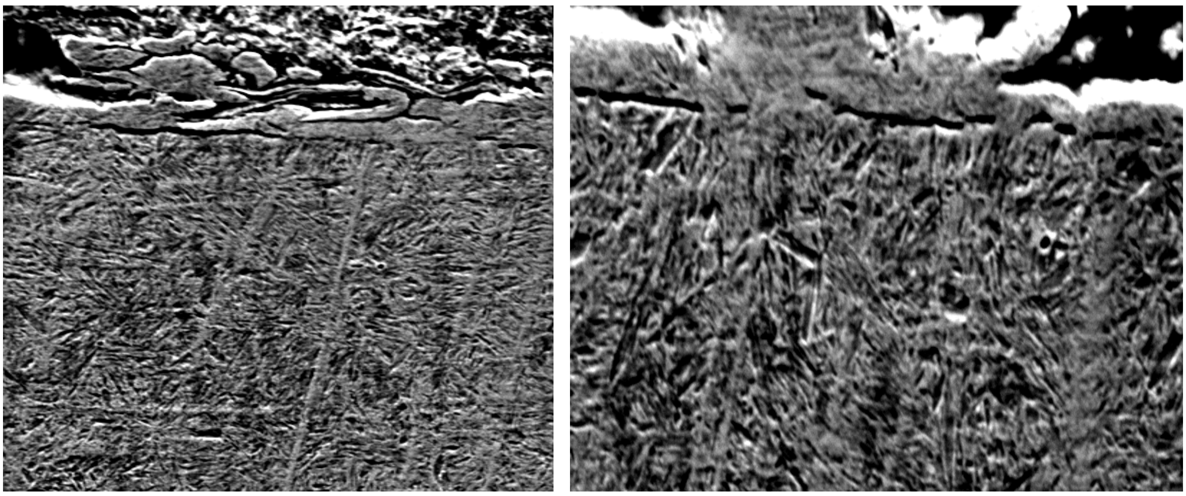


Figure 11. Distribution of micro-hardness of surface layers of metal by depth along the line of contact of friction pairs

For the contact surfaces with the minimum slippage of 3%, the loss of strength of near–surface layers of the metal within 1700 – 1000 MPa up to the depth of 50 μm was established, and in the central section, lengthwise of the contact of the corresponding contact line of the tested samples, the increase in the volume of the reinforced metal up to the depth of 200 mn is observed (Fig. 11b). The given contact surfaces are characterized by the lowest energy content, the formation of labile superplastic secondary structures, plasticizing of the surface layers of the metal, which is manifested by a significant loss of strength of near–surface layers and a decrease in the wear resistance of metal.

With an increase in slippage up to 20%, the zone of loss of strength includes the near–surface layers up to 20 –25 μm, the hardening of near–surface layers begins at the depth of 40 μm (Fig. 11c). The analogous epure of micro-hardness distribution along the line of the contact of friction pairs was established – the zone of maximum hardening spreads up to depth of up to 120 μm and corresponds to H_{20}=5500 MPa. For the given contact surfaces, an increase in the wear resistance is accomplished due to formation of the stable boundary chemisorption films of a lubricant, steadfast high–strength secondary structures, which prevent spreading the ductile deformation deep into metal.

For the contact surfaces with the slippage 40%, the minimum volume of the softened layer was established – the micro-hardness of near–surface layers decreases by 400 – 500 MPa up to 10 μm in the depth (Fig. 11d). The layers lying below are characterized by the gradual strong reinforcement up to 7600 MPa at the depth of up to 160 μm. The reinforcement of near–surface layers also occurs by the epure with the maximum, which corresponds to the central zone of the load line. The achievement of the largest surface strength of these layers due to the maximum energy content of the contact at high slip rates, which causes the frequent destruction of the boundary chemisorption films and the spread of deformation into the depth of the metal, leads to the decrease in their plasticity. The high micro-hardness of near–surface layers forms the stress concentrator (Bishutin, 2010), which decreases the wear resistance of contact surfaces due to scaling of brittle secondary structures (Figure 12).



a) **b)**

Figure 12. Scaling of near–surface layers of steel 1045 at friction: a) – ×400; b) – ×800

Since the metal deformation with the joint action of normal and shearing stresses leads to texturing and hardening of the near–surface layers predominantly in the direction of the influence of tangential forces (Menezes et al., 2006; Bernd, 1983), the epures of distribution of shearing stresses in the metal and micro-hardness's in the depth must correlate. However, from the results, obtained by us, the agreement of the calculated (h =41 μm) and the experimental indices of the depth of the bedding of maximum shearing stresses is obtained only for the contact surfaces with the slippage 20%: the epure of the change in the micro-hardness of near–surface layers characterizes the maximum of their reinforcement at the depth of 40 – 50 μm. For the rest of the tested contact surfaces, the calculated and the experimental values have a divergence of up to 50%. First of all, it is connected with the fact that theoretical dependences (Sadeghi et al., 1988) do not consider the presence and the nature of a lubricant, the slip rate and the temperature factor. Specifically, the kinetics of the change in the slip rate, the increase of which leads to an increase in the shearing rate and shearing stresses in the lubricant film, the growth of the specific friction work, the temperature increment in the contact, has the largest effect on the intensity of deformation changes in the metal.

The above given analysis of the epures of distribution of micro-hardness of the surface layers of metal along the line of the load application revealed a general regularity: the maximum zone of hardening corresponds to the central area of the contact, the degree of hardening decreases to the periphery of the contact line, on average, by 500 – 700 MPa and the volume of the deformed metal decreases.

In article (Gurskii & Chichinadze, 2007), the symptoms of zones of the maximum local wear along the meshing line of tooth gears, or of “the weakest” zones, depending on the temperature in the contact, were established: pitting is manifested in the zones of predominant influence of the rolling rates above the slip rates, and jamming – in the zones of the maximum slip rates.

The results of our studies under non–stationary friction conditions make it possible to supplement the ideas of the structural and energy state of zones of maximum local wear. With the minimum slippage (up to 3%), which is analogous to the circumpolar meshing zone of tooth gears, the processes dominate of the fatigue failure of the ductile secondary structures, which are characterized by the low indices of the specific friction work, the minimum increment in the temperature and by resistance to setting under the conditions of the insufficient feed of a lubricant into the contact zone. With an increase in the slippage up to 20 – 40 %, which corresponds to the off–polar zones of the tooth gears meshing, the processes of destruction of durable secondary structures are characterized by high indices of specific friction work, by an increase in the temperature in the contact, by hardening of the surface and near–surface layers of metal and by tendency of setting under conditions of limited oiling.

4. Conclusions

1) The decrease in the wear resistance of contact surfaces with the 3% slippage was established, which occurs as a result of their low activation and formation of the boundary adsorptive layers of physical nature, as a result of which the secondary structures of type I are formed and strong plasticizing of the surface and near–surface layers of metal is manifested.

2) An increase in the slippage up to 10 – 40% intensifies the processes, which characterize ormation of the amorphized deformed layer of metal by depth, an increase in the micro-hardness of secondary structures of type II, the saturation of the surface layers of metal with active elements and an increase in the energy capacity of metal at friction.

3) With an increase in the slip rate from 0.315 m/s to 1.14 m/s at rolling with slippage, there was established an increase in the depth of spreading of the strained deformed state of contact surfaces as a result of the tribosystem transition to the boundary mode of lubricating action, which decreases the wear resistance of friction pairs.

4) The formation of the epure of the micro-hardness distribution for the secondary structures of type II along the line of the load application was established, which is characterized by the maximum zone of hardening in the center of contact and a gradual decrease in the degree of hardening to the periphery of the contact line. In this case, the correlation between the degree of hardening of the surface layers of metal and the volume of the deformed metal along the depth was established.

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