Chapter

A New Concept of the Mechanism of Variation of Tribological Properties of the Machine Elements Interacting Surfaces

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Abstract

The methods of estimation and prediction of tribological properties of the contact zone of interacting elements of machines are characterized by the low informativeness and accuracy that complicates provision of the proper tribological properties and hinders reliable and effective operation of machines. For obtaining more wide information about factors influencing tribological properties of the interacting surfaces, the experimental researches on the high speed (up to 70-m/s) and serial twin-disk machines were carried out. Our researches have shown that with different properties and degrees of destruction of the third body, the coefficient of friction can change up to 10 times or more, the wear rate up to 10^2-10^4 times, etc. This was the basis for a new concept of the mechanism of variation of tribological properties of interacting surfaces. The researches have shown a dependence of tribological properties of the contact zone on the properties and destruction degree of the third body that was assumed as a basis of new concept of the mechanism of variation of tribological properties of these surfaces. The monitoring of the third body destruction onset and development was carried out in the laboratory conditions and a criterion of the third body destruction was developed. The reasons of the negative, neutral and positive friction and mild, severe and catastrophic wear are shown.

Keywords: interacting surfaces, tribological properties, third body, friction coefficient, wear

1. Introduction

Between the interacting surfaces can be continuous or discontinuous third body. Until 70s of the last century the oil layer of hydrodynamic generation existent in the contact zone, was considered as a parameter determining a working capacity of the heavy loaded frictional contact. Many experimental and theoretical works are devoted to study of thickness of this layer [1–5]. An approximate (digital) solution of the elasto-hydrodynamic problem considering thermal processes is given in the work [6], where the temperature, pressure and thickness of the oil layer between the cylinders interacting with the rolling-sliding friction, are determined. However, in spite of many attempts, ascertainment of the reliable relations between the thickness of the oil layer and tribological properties of the contact zone turned out to be problematic [7]. The supplements to the lubricants developed in succeeding years and technical means of study the processes proceeding in the contact zone have radically widened direction of the researches.

The fundamentals of materials science and contact mechanics are developed in works [8–10] and in recent years a new direction of tribology – nano-tribology appeared [11, 12]. New materials were created (graphene etc.) [13]. For tribological modeling are used the methods of mechanics and multiphysics [14–18], methods of finite and boundary elements [19–21], discrete dynamics of dispositions [22], and atomistic methods [23]. However, in spite of this, some engineer aspects of the problems of tribology are not yet properly studied and their solution needs additional researches.

At common operational conditions, various types of boundary films - products of interaction with the environment that prevent the direct contact of rubbing surfaces, cover these surfaces with thin layers. Depending on the friction conditions, properties of the surfaces and environment, these layers may have various tribological properties that will have the great influence on the boundary friction [24–26]. This is confirmed by the results of the experimental researches in the inert gas environment and vacuum, that excludes the possibility of oxidation during friction. Under such conditions, the seizure and intensive wear rate are observed. To prevent these undesirable phenomena, it is necessary to provide the presence of the third body in the contact zone with due properties, control of the friction factor and protection of the third body from destruction.

When the interacting surfaces are separated by the continuous third body, the friction forces mainly depend on the rheological properties of the third body [25, 26] or on the third body viscosity and area of the contact zone: $F = f(\eta, \frac{\Delta v}{\Delta x}, S)$, where S is area of the contact zone; η — viscosity; $\frac{\Delta v}{\Delta x}$- velocity gradient.

Usually, the surfaces are covered with various types of natural and artificial coatings, which represent the components of the third body in the contact zone of the interacting surfaces, are subjected to heavy power and thermal loads. This causes deformations of these coatings, their destruction, activation of the physical and chemical processes proceeding between them and the surfaces and generation of new coatings. Thus, during the interaction of surfaces, the processes of the third body destruction and restoration takes place in the contact zone continuously. When the intensity of destruction of the third body is greater than the intensity of its restoration, the amount of the micro-asperities coming into direct interaction leads to seizure and the wear rate increase because of various kinds of surface damage.

A part of micro-asperities of the heavy loaded interacting surfaces are in direct contact with each other causing their seizure and the remaining part interact with each other through the third body that is schematically shown in **Figure 1**.

For heavy loaded interacting surfaces is typical seizure. This can happen when continuity of the third body is disrupted in individual places; the parts of the direct contact are cleansed from various coatings and boundary layers and are approached to each other at the distance of several atom diameters. As molecular dynamics [27] and atom microscope [28] show, in such conditions they will attract each other generating electron-pair bindings.

Adhesive approach to the friction means invasion of micro-asperities into each other in the contact zone, their close contact without the third body and adhesive scuffing of micro-asperities. The thermal effects accompanying the process have direct influence on the deformation area and value, volume of the deformed

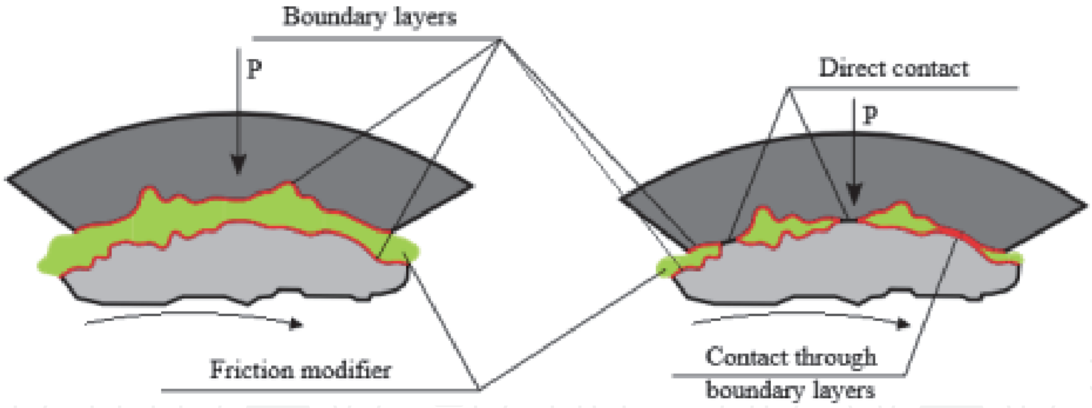


Figure 1.
Types of interaction of the surfaces.

material, variation of the surface structure and physical and mechanical characteristics and damage of various types proceeding simultaneously.

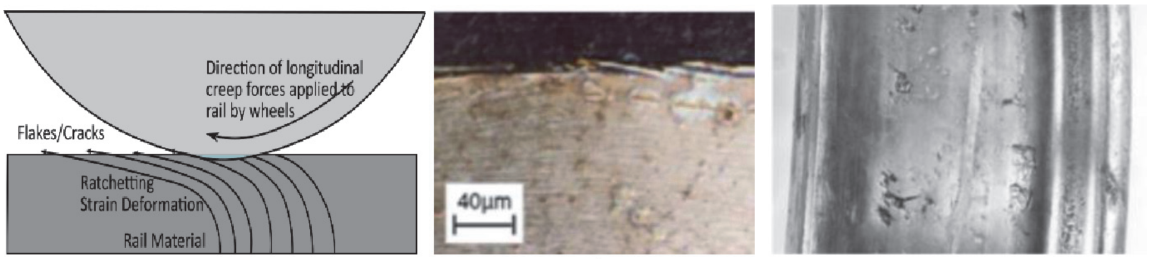
The friction forces between interacting surfaces (at lack of the third body in the places of actual contact) depend on the total area of the actual contacts $Ff = \psi$ $(\sum \tau Aasp)$ [24], where τ is effective strength on shear of the actual contact area of interacting surfaces; Aasp – seizure area of the actual contact that depends on the thermal load of the contact zone, thickness of the heated up layer, properties of the surfaces and environment of individual micro-asperities etc.

Hence, the friction forces depend on the contact area in both cases, when the surfaces are separated from each other by the third body fully or partially.

The surfaces are the weakest places of the rigid body from which their destruction begins [29]. Displacement of the coupled places of surfaces relative to each other causes sharp increase of the shear stresses and corresponding deformations, value and instability of the friction forces and rupture of the coupled places. It is possible in this case transfer of the pulled out material from on surface on the other, sharp change of roughness of these surfaces and development of the process of catastrophic wear – scuffing. The shear deformation generated on the surface sharply decreases towards the depth and multiple repetition of such processes results in superficial plastic deformations, lamination and fatigue damage (**Figure 2**) [30, 31].

The damage scales and dominant types in such cases depend on the working conditions. Thus, for providing the interacting surfaces with due tribological properties, their separation from each other by the continuous third body with corresponding properties is necessary.

It should be noted that various types of surface take place simultaneously and proceed with various intensity and a dominant type of damage ascertained visually. The experimental researches have shown that damage intensity and type, of



a b c

Figure 2.
The scheme of the surface plastic deformation (a); appearance of cracks and lamination (b); appearance of fatigue pits (c).

interacting surfaces are especially sensitive to the relative sliding velocity and shear stresses. Thereat, at low total and relative sliding velocities of the surfaces, when power of the thermal action, velocity and resistance of the shear deformation in the contact zone are comparatively small, stability of the third body and its resistance to scuffing are high and a main type of damage is fatigue wear [4]. With increase of the total and relative sliding velocities of surfaces, thermal load of the actual contact zone and destruction intensity of the third body increases. However, time of action of this load, thickness of the heated up layer and sizes of micro-asperities generated because of the scuffing and subsequent rupture of the seized places, decrease. Such phenomena take place on tread surfaces of the train wheel, near the pitch point of the gear drives, in the rolling bearings etc. (**Figure 3**). At increase of the relative sliding velocity, share of the adhesive wear and scuffing increases and it often becomes a dominant type of damage. For example, a steering surface of the train wheel, places of tooth profile of the gear drive distant from the pitch point, cam mechanisms etc.

For avoiding the above-mentioned non-desirable phenomena, providing the contact zone with the third body having due properties, its protection against destruction and control of the friction coefficient are necessary. However, despite the great number of scientific works this direction could not attract due attention of the scientists until today.

Variation of tribological properties of the surfaces is a result of various mechanical, physical and chemical processes proceeding simultaneously in the contact zone whose essence and mechanism of action are not properly studied [20–22]. This complicates control of the mentioned processes that needs consideration of many factors acting simultaneously. Such factors are:

- Initial tribological properties of the third body and surfaces; influence of interaction of the friction modifier and other materials existent in the contact zone and the surfaces on the properties and stability of the third body and surfaces.

- Structural, physical and mechanical peculiarities and tendency to scuffing of the clean (juvenile) surfaces in the places of the third body destruction; destruction peculiarities of the seized places;

- Influence of the contact zone working conditions on the wear type and rate, variation of the micro- and macro-geometry etc.

a b c

Figure 3.
The damage types: (a) train wheel with fatigue damage of the tread surface and adhesive wear (scuffing) of the flange; (b) gear wheel with the traces of scuffing on the tooth face; (c) inner ring of the rolling bearing with the traces of fatigue damage.

Various interacting surfaces of machines should have different tribological properties: tooth gear drives, cam mechanisms, guides of various types etc., should have stable and as small as possible friction coefficient (≤ 0.1) and friction clutch and brakes – comparatively high and stable friction coefficient (0.25-0.4).

Especially should be noted operational peculiarities of the wheel and rail interacting surfaces. The existent profiles of wheels and rails can be divided into the tread surfaces (which take part in the “free” rolling, traction and braking) and steering surfaces (the wheel flange and rail gauge, which take part in the steering mainly in curves and prevent the wheel-set from derailment). The flange root can roll on the rail corner, and it can take part in traction, braking and steering (**Figure 4**).

But traction (braking) and steering require mutually excluding properties and the “ideal” value of the friction coefficient ($\mu < 0{,}1$) in the contact zone of the flange root and the rail corner is not acceptable for both cases.

As it is seen from **Figure 5**, the power and thermal loads of tread surfaces are relatively low. At working of wheels in the modes of traction and braking, the lateral displacement, rotation about vertical axis and skidding, sliding velocity and distance increase. The flange root and rail corner in the contact zone are characterized by the increased creeping, that at destruction of the third body results in the increased shearing stresses and temperatures.

For interacting surfaces of some mechanisms, such as tooth gear drives, cam mechanisms, wheel and rail etc., the main types of wear are adhesive wear (and its heavy form – scuffing, whose nature is not studied sufficiently and under heavy working conditions it is followed by sharp increase of the friction coefficient instability and wear rate or catastrophic wear) and fatigue wear, that proceed simultaneously and are quite different processes.

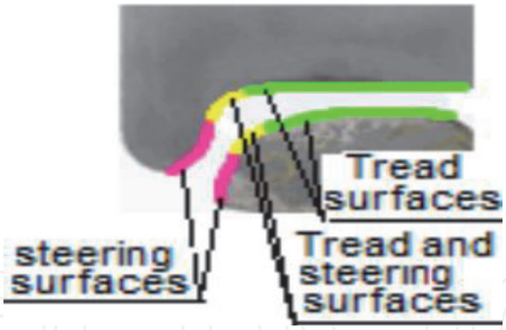


Figure 4.
Components of the wheel and rail interacting surfaces.

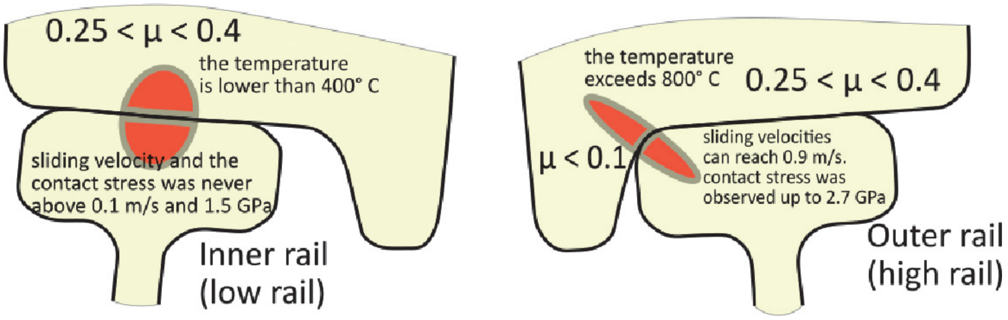


Figure 5.
The ideal values of the friction coefficients and stress distribution in the contact zone of the wheel and rail according to [32] and the thermal loads.

For revealing the factors influencing tribological properties of the interacting surfaces, the experimental researches were carried out on the high-speed and serial twin-disk machines.

2. The experimental researches into variation of tribological properties of the interacting surfaces

2.1 Research into tribological properties on the high-speed twin disk machine

A great number of scientific works are devoted to ascertainment of laws of variation of tribological properties of the interacting surfaces and with perfection of machines, actuality of such works increases. Despite the considerable quantity of works in this direction, the expected results are not obtained yet. The unexpected and catastrophic failure, unlike fatigue, corrosion and other slowly progressing wear types, are subjected some heavy loaded interacting surfaces of gear teeth, cams and followers, sleeve bearings etc. The wheel and rail contact zone is characterized by heavy operational conditions [33] (direct impact of the environmental conditions, high relative sliding and contact stresses) that enhances adhesive and fatigue processes. The wheel and rail contact zone is characterized by the heavy operational conditions (direct impact of the environmental conditions, high relative sliding and contact stresses) that enhances adhesive and fatigue processes raise the problems to be solved for many-sided study of these processes.

For some heavy loaded interacting surfaces of machines are typical unpredictable change of tribological properties and sharp increase of the friction coefficient and wear intensity, so called catastrophic wear. As main cause of the latter is considered the heaviest form of the adhesive wear – scuffing [4] that is not properly studied yet [34] and whose signs are appearance of pits and scratches on the surfaces and transfer of the material from one surface on the other. The various aspects of the complex physical, tribo-chemical and mechanical processes proceeding in the contact zone are not properly studied yet that is accordingly reflected on the operation quality and resource. As an example can be cited interaction of the wheel and rail that occurs on: the tread surfaces during rolling, traction and braking; steering surfaces mainly in curves; flange root and rail corner at rolling, traction, braking and steering. The friction coefficient for wheel-rail interaction can vary in the range 0.05 - 0.8. The values of the friction coefficient for the tread and steering surfaces must be correspondingly in the ranges of 0.25-0.4 and <0.1 [32]. The optimal value of the friction factor for tread surfaces is 0.35 [32] and for steering surfaces - as low as possible. The scuffing on the wheel and rail steering surfaces causes rise of the friction coefficient, energy consumed on rolling, vibrations, nose, wear intensity and probability of derailment.

For more detailed study of the properties and state of the third body in the contact zone we performed the experimental researches on the twin disk machine MT – 1 (**Figure 6**) with the use of existing lubricants and ecologically friendly friction modifiers, developed by us.

The tests were performed at single application of the friction modifier on the rolling surface of the roller. After certain number of revolutions, a thin layer of the friction modifier was destroyed that was revealed by sharp increase of the friction moment and initial signs of scuffing on the surfaces. Without repeated feeding the friction modifier, the damage process was progressed. The rollers with various degree of damage are shown in **Figure 7**: (a) with initial signs of damage; (b) damage in the form of a narrow strip; (c) damage on the whole contacting area.

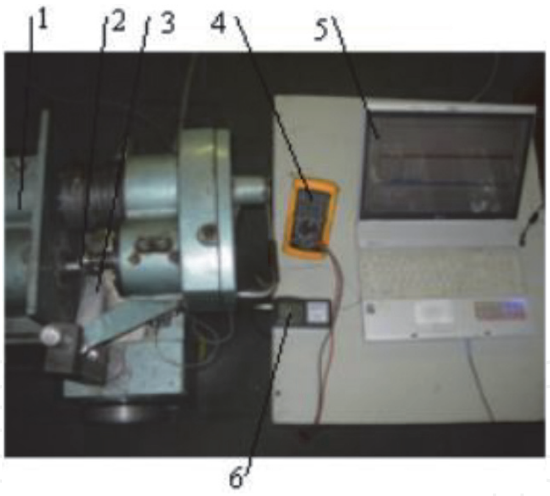


Figure 6.
The twin disk machine model MT1 and measuring means: 1 - twin disk machine, 2 - tribo-elements, 3 - the wear products, 4 - tester, 5 - personal computer, 6 – vibrometer.

Experimental research was performed at rolling of discs with up to 20% of sliding. The rollers had diameters of 40 mm and widths of 10 and 12 mm. The tests were performed at single application of the friction modifier on the interacting surface of the rollers. After certain number of revolutions, a thin layer of the friction modifier (FM) was destroyed that was revealed by sharp increase of the friction moment and initial signs of scuffing on the surfaces. Without repeated feeding of the friction modifier the damage process were progressed. The rollers with various degrees of damage are shown in **Figure 7**: (a) with initial signs of damage; (b) damage in the form of a narrow strip; (c) damage of the whole contacting area.

The graphs of dependences of the friction coefficient and number of revolutions of rollers until appearance of the first signs of scuffing on the contact stress for initial linear contact of disks are shown in **Figure 8**. It is seen from these graphs that for the initial linear contact, when the contact stress is in the range of 0.65-0.77 GPa increase of the contact stress leads to decrease of the friction coefficient. It can also be seen that increase of the contact stress leads to decrease of number of revolutions until the destruction of the third body and onset of scuffing.

The graphs of dependences of the friction coefficient and number of revolutions of rollers until appearance of the first signs of scuffing on the contact stress for initial point contact of disks and anti-frictional friction modifiers are shown in **Figure 9**.

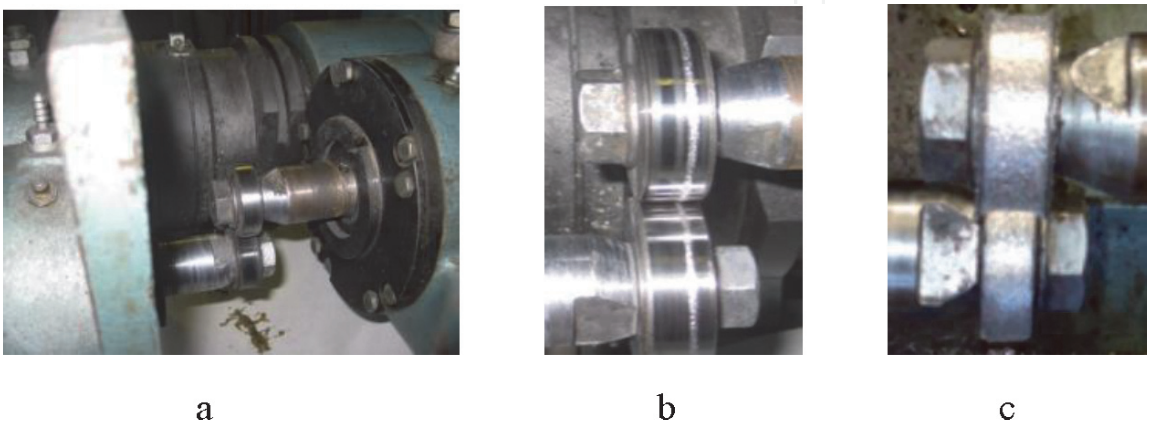


Figure 7.
The stages of damage of the interacting surfaces: (a) damage in the separate points; (b) damage in the form of the narrow strip; (c) damage on the whole area of the contacting surfaces.

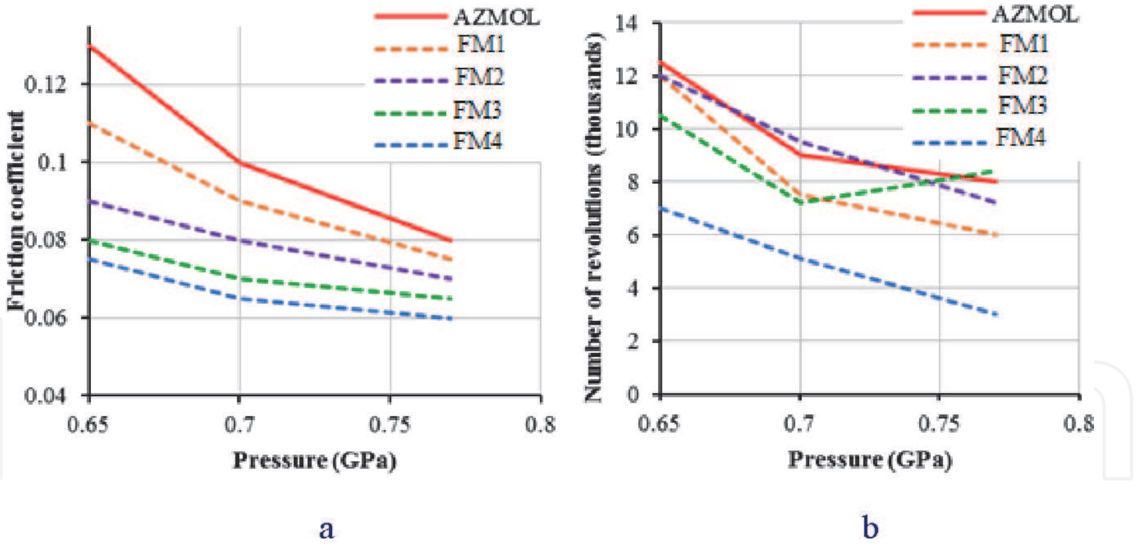


Figure 8.
Dependences of friction coefficients (a) and numbers of revolutions (b) until appearance of the first signs of scuffing on the contact stress for initial linear contact of disks and different anti-frictional friction modifiers.

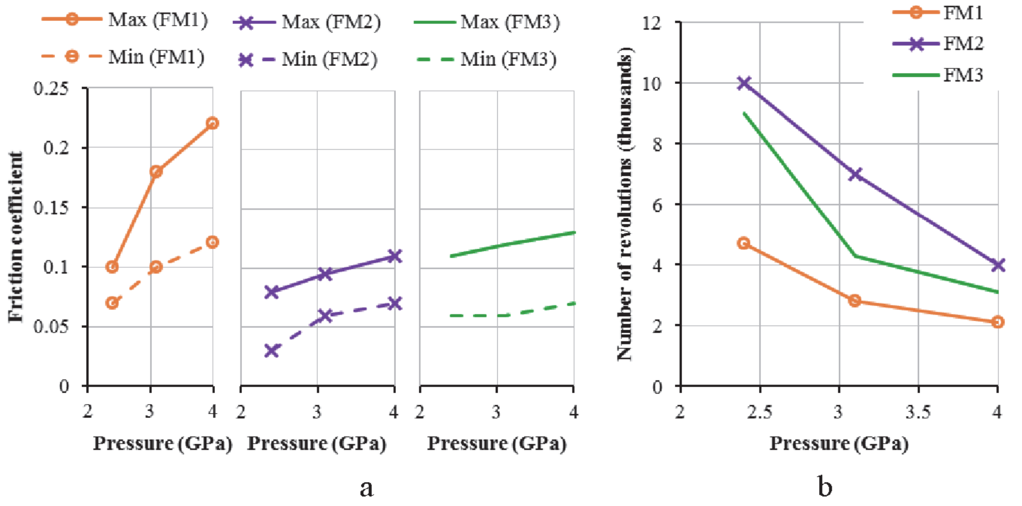


Figure 9.
Dependences of friction coefficients (a) and numbers of revolutions (b) until appearance of the first signs of destruction of the third body (first signs of scuffing) on the contact stress for initial point contact of disks and three different frictional FM-s.

When the contact stress is in the range of 2.42-3.96 GPa the friction coefficient increases with increase of the contact stress. It can also be seen that increase of the contact stress leads to decrease of the number of revolutions until the destruction of the third body and onset of scuffing more intensive than in the previous case.

2.2 Research into tribological properties on the high-speed twin disk machine

At high working velocities, the maximal power and thermal stresses approach to the surfaces and intensity of the third body destruction/restoration and sensitivity of the contact zone tribological properties to working conditions, increase. To promote the mentioned problem, the experimental researches were carried out on the high-speed twin disk machine with independent drive of rollers (**Figure 10**).

During experiments were studied the character of the wear process of working surfaces, influence of various parameters on the lubricant film thickness and friction coefficient at the use of popular mineral lubricants. The researches were

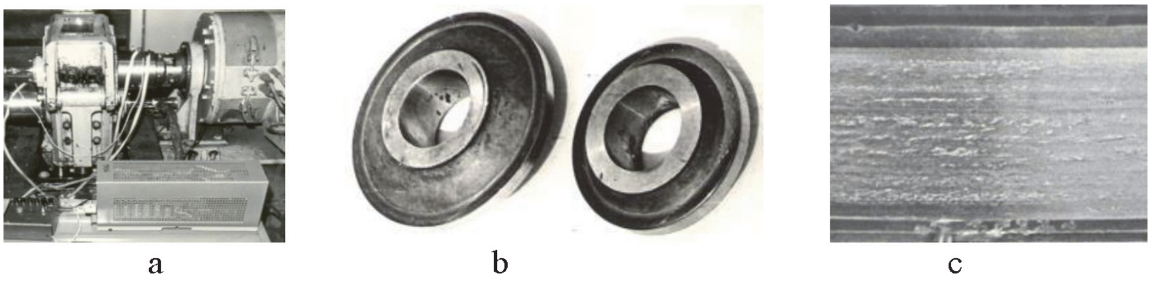


Figure 10.
High speed twin disk machine (a), experimental pieces (b) and a working surface of the roller with traces of scuffing (c) at total speed of rolling 7 m/s, sliding speeds of 3 m/s, linear load 100 N/m.

executed with the use of the high-speed roller machine with independent drive of rollers. Conditions of the experiments and measured sizes were:

- Rolling speed – up to 70 m/s;
- Diameters of rollers 183 mm and 143,3 mm; width of rollers 12 mm and 17 mm;
- Sliding velocity- up to 35 m/s;
- Contact pressure – 5 × 105 – 2 × 106 N/м;
- Dynamic viscosity 49-140 mNs/m^2;

During experiments at the given loading and rolling velocity, the friction torque, sliding velocity and lubricant film thickness were measured. For measurement of speeds of rotation was utilized magnetic pickups, for measurement of the friction torque was utilized the strain gage transducer and contactless skate. The lubricant film thickness was measured by capacitance method [35]. The beginning of scuffing was revealed by the surges of the friction moment. Development of the friction process was accompanied by sharp rise of temperature and characteristic noise. Results of experimental research are shown in **Figure 11**.

The studies have shown that with increase of the rolling speed, the thickness of the lubricating film initially increases (in our case up to 14 m/s) and then decreases slightly.

With increase of the sliding velocity, sharp decrease of the lubricated film thickness is observed. Though measurement of the particularly thin film (boundary

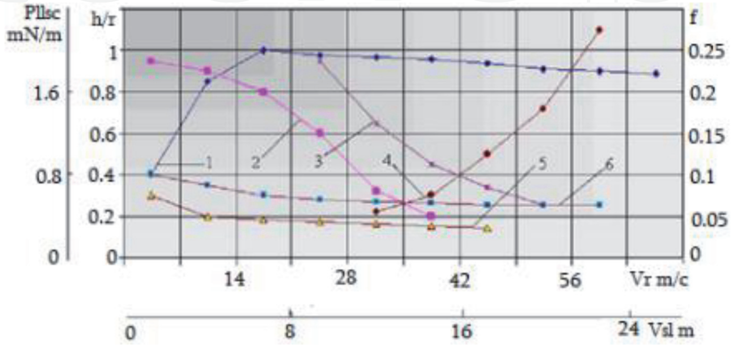


Figure 11.
Dependence of relative lubricant film thickness (h/R), linear scuffing load (P_{llsc}) and coefficient of friction (f) until the appearance of the first signs of scuffing from rolling speed (V_r) and sliding velocity (V_s) at various viscosities (ν) of lubricants: (1) $h/R = \varphi(V_r)$, $P_{ll} = 10^6$ H/m; $\nu = 157$ cSt, (2) $h/R = \varphi(V_{sl})$, $P_{ll} = 2 \times 10^6$ H/m, $\nu = 157$ cSt, $V_r = 50$ m/s, (3) $P_{llsc} = \varphi(V_{sl})$, $\nu = 49$ cSt, $V_r = 50$ m/s, (4) $P_{llsc} = \varphi(V_r)$, $\nu = 157$ cSt, $V_{sl} = 22$ m/s, (5) $f = \varphi(V_{sl})$, $P_{ll} = 1.5 \times 10^6$ H/m, $\nu = 49$ cSt; $V_r = 50$ m/s, (6) $f = \varphi(V_r)$, $P_{ll} = 10^6$ H/m, $\nu = 157$ cSt.

film) is technically difficult, its presence in the contact zone is indicated by the magnitude and stability of the friction coefficient. Further worsening of the working conditions leads to destruction of the third body in individual places of interacting surfaces.

A particular instability of the friction coefficient was observed at low velocities and high loads: intensive impulses of low frequency were marked and the scuffing marks of significant sizes – scratches and pits were noticed on the rollers surfaces. With increase of the velocity, the time of dwelling of the surfaces in the real contact zone and duration of the thermal impact, values of the amplitude of the friction force variable component decrease; the frequency increases and the individual impulses turn into noise. With further increase of the velocity the friction process is progressed, the temperature on the actual contact area of the interacting surfaces reaches the metal melting point, tonality of the noise rises and turns into whistle and when the frequency exceeds 20 KHz it becomes imperceptible for man.

3. Analysis of results of the experimental researches

The complex physical, mechanical and tribo-chemical processes proceeding in the contact zone of interacting surfaces at direct impact of the environmental conditions raise the problems whose solution demands many-sided approach to these processes. There are many works devoted to these problems [36–38] but they are not solved properly yet. Namely, prediction of the friction coefficient in the contact zone, its control and character of influence of many parameters on its variation are still problematic.

At heavy working conditions, when destruction of the third body is irreversible and scuffing is spread over the factual contact area of the whole surface relative displacement of the surfaces causes sharp increase of the shear stresses, corresponding deformations, values and instability of the friction forces and rupture of the seized places. Strength of the seized places may exceed the strength of the interacting bodies because of which the material pulled out from one surface can form a wear product or can be transferred on the other surface and attached to it that is followed by development of the scuffing process.

Multiple repetition of the shear deformation generated on the surfaces (that sharply decreases towards the depth) causes appearance of cracks on the surfaces, their development and fatigue damage, superficial plastic deformations and lamination. The area of each seized place in the contact zone depends on its power and thermal load; initial micro-geometry of the surfaces; value, velocity and resistance of the deformation etc. Therefore, various working conditions are characterized by corresponding variation of the tribological parameters, namely friction forces, amplitude and frequency of their variable component, wear intensity and roughness of the surfaces. Development of these processes leads to the catastrophic wear due to scuffing.

At low velocities of interacting surfaces, the thermal load of the factual contact zone, velocity of the surface and environment tribo-chemical reaction and resistance of deformation decrease and time of the thermal action and thickness of the superficial heated up layer increase. In such conditions, at destruction of the third body, due to rupture of the seized places, the jerks of low frequency and high amplitudes and sharp instability of the friction coefficient take place and relatively large-size asperities (pits, scratches, asperities, cracks and layers) appear on the surfaces. This is correspondingly reflected on the damage type and roughness of the surfaces.

At high velocities of interacting surfaces, despite several works in this area [39–43], some problems have not yet been resolved. The thermal load of the factual contact zone, velocity of the surface, tribo-chemical reaction of the environment and resistance of deformation increase, whereas time of the thermal action and thickness of the superficial heated up layer decrease. In such conditions, at destruction of the third body, due to rupture of the seized places, the jerks of high frequency and comparatively low amplitudes and instability of the friction coefficient take place and relatively small-size asperities (pits, scratches, asperities, cracks and layers) appear on the surfaces. This is correspondingly reflected on the damage type and roughness of the surfaces. Under the conditions of our experiments at a high rolling speed (more than 40 m/s), traces of fatigue damage and scuffing are not visually observed, however, a high wear rate remains.

Thus, destruction of the third body causes sharp worsening of tribological properties of the interacting surfaces and necessary condition of its avoidance is separation of these surfaces from each other by continuous third body with due properties.

It was ascertained by the experimental researches that destruction of the third body begins in individual points of the factual contact zone that is revealed by appearance of signs of the scuffing in these points. Restoration of the individual damaged points was often observed at unchanged operational conditions but at worsening, the operational conditions the superficial damage quantity increased and multiple damages appeared. At further worsening the operational conditions, a narrow strip of damage is generated spreading afterwards over the whole surface that causes worsening of the tribological parameters and catastrophic wear. The above-mentioned damage stages of the third body are shown in **Figure 12**.

Usually the friction process proceeds at presence of the continuous or discontinuous (restorable or progressively destructible) third body stipulating the character of variation of the friction coefficient. Experimentally it was revealed that to negative friction corresponds the continuous or discontinuous but restorable third body; to neutral friction – multiple seizures of the interacting surfaces and to positive friction – increasing scuffing process that is spread on the whole surface. In **Figure 13** is shown variation of the tractive (friction) force with creep [37].

As it were shown by our experimental researches, at presence of the continuous third body increase of the relative sliding velocity leads to increase of the friction power and contact temperature; decrease of the lubricant viscosity, film thickness and friction force (**Figure 13**, "negative friction"), stable (or smoothly variable) friction torque and low destruction rate of the surfaces. Worsening of the working conditions caused by the partial, non-progressive damage of the third body in the separate unit places corresponds to the separate small impulses of the friction moment. Destruction of the third body in the multiple places leads to the multiple damage of the third body, multiple adhesive junctions of micro-asperities, disruption of these junctions, and a bit little increased impulses of the friction torque and to "neutral friction."

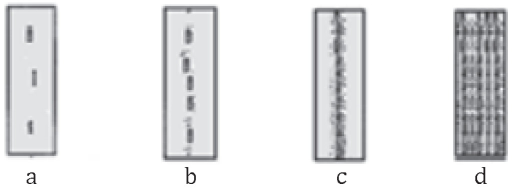


Figure 12.
The damage stages of the interacting surfaces. (a) Unit seizures; (b) multiple seizures; (c) seizures on the narrow strip; (d) seizures on the whole area.

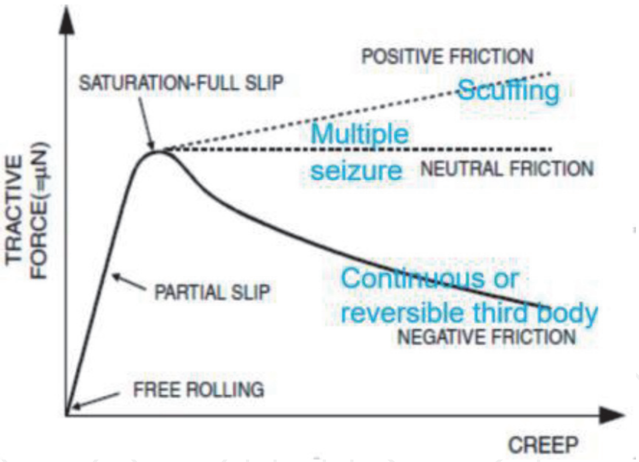


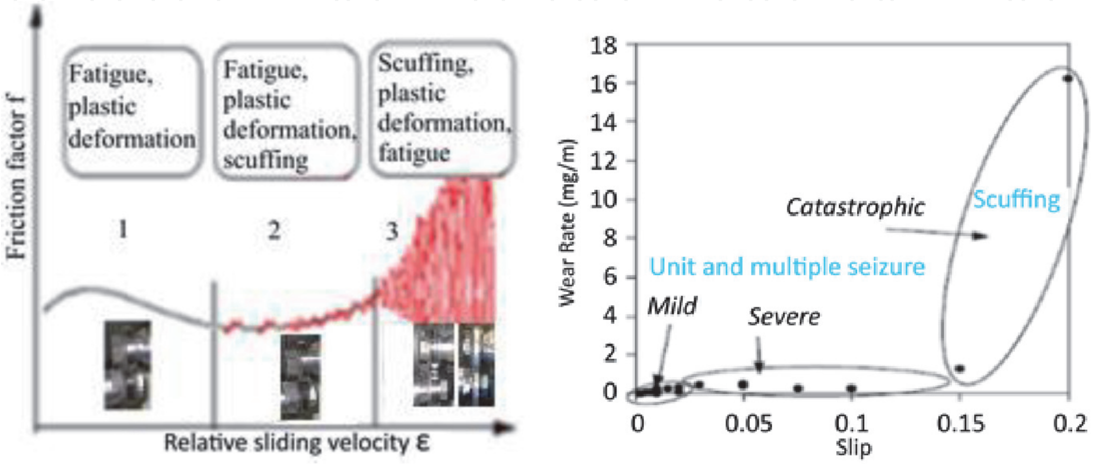
Figure 13.
Friction/creep relationship.

At progressive damage of the third body, the friction torque increases and corresponds to positive friction. Our experimental researches have shown that in other equal conditions the variation of the friction coefficient mainly depends on degree of destruction of the third body. Therefore, preservation of the third body between interacting surfaces and avoidance the scuffing, has a crucial importance for decrease of the friction coefficient, wear rate, etc. This issue became burning especially for wheels and rails in the last 50 years and many works appeared that are devoted to enhancing stability of the wheel flanges against the operational impacts.

In **Figure 14** are shown dependences of the friction factor and various damage types on relative sliding velocity (a) and of the wear rate (types) on slip (b) [32].

Three zones can be distinguished in **Figure 14a**. The low relative sliding velocity, full separation of the interacting surfaces and continuous third body provide high wear resistance of the interacting surfaces and relatively stable friction coefficient (zone 1, **Figure 14a**) that corresponds to “mild” [32] wear rate (**Figure 14b**). In such conditions, the main damage types are the fatigue and plastic deformations.

Small increase of the sliding velocity leads to appearance of small damage sources in multiple places and emergence of small surges of the friction torque (zone 2, **Figure 14a**). The rise of the third body destruction, as well as the magnitude of the friction coefficient and its instability, are clearly reflected in the



a b

Figure 14.
Dependences of the friction factor and various damage types on relative sliding velocity (a) and of the wear rate (types) on slip (b).

oscillogram of the friction torque and may be predicted on the base of results of the experimental researches. The typical damage types of this zone are fatigue, plastic deformation, adhesive wear and limited rate of scuffing and correspond to “severe” wear rate (**Figure 14b**).

At further increase of the relative sliding velocity, destruction of the third body becomes irreversible and extending and multiple seizures becomes uninterrupted (causing scuffing) and they propagate on the whole width of the interacting surfaces. The typical damage types of this zone are scuffing, plastic deformation and fatigue (zone 3, **Figure 14a**, and “catastrophic” wear rate **Figure 14b**). In this case, the scuffing can be avalanche in nature that quickly disables the machine.

Destruction of the third body makes especially heavy the working conditions of the interacting surfaces and is characterized by increased instability, high wear rate (‘catastrophic wear”), vibrations and noise, change of structure and micro-geometry of the surfaces at operation etc.

At low velocities, time of dwelling of individual places of the surfaces in the contact zone and power and thermal actions, variable components of the friction torque and scales of the superficial damage increase and inversely, decrease with increasing speed, although the high wear rate is maintained.

For each operational mode and frictional pairs, this stipulates corresponding micro-geometry and tribological properties.

The methods of calculation of the contact zone power and thermal loads, friction coefficient, wear rate etc., are characterized by low informativeness and precision. This complicates prediction and realization of proper tribological properties of surfaces at various working conditions that prevents machines from reliable and effective operation.

For heavy loaded interacting surfaces are typical destruction of the third body, direct contact of the surfaces and cohesion. The shearing forces, rate of the adhesive and fatigue wear rise sharply in the contact zone at such conditions and friction forces become instable causing the vibrations and noise.

The mentioned types of wear in the contact zone are the results of quite different processes proceeding simultaneously. Besides, identification of the wear type according to the wear signs is often ambiguous that hinders selection of methods for its decrease.

Dependence of tribological properties of the interacting surfaces on the properties of the third body and degree of its destruction were ascertained on the base of results of the experimental researches.

At existence of a continuous third body between interacting surfaces, tribological properties of the contact zone are stipulated by the properties of the third body and at existence of a discontinuous third body, tribological properties of the contact zone are mainly stipulated by the properties of the third body and degree of its destruction.

The signs of onset and development of the third body destruction and a criterion of its destruction are given there. The reasons of the negative, neutral and positive friction, mild, severe and catastrophic wear and types of surface damage at various relative sliding velocities are revealed.

4. Estimation of stability of the third body on the base of EHD theory of lubrication

The most complete mathematical model of lubrication is the elastohydrodynamic (EHD) theory of lubrication [44]. The effectiveness of the EHD theory of lubrication is described by ratio λ or film parameter [45], which is the ratio of film minimum thickness at the Hertzian contact zone to the r.m.s. of the rolling element surface finish:

$$\lambda = \frac{h_{min}}{\sqrt{R_{a_1}^2 + R_{a_2}^2}} \tag{1}$$

where Ra_1 and Ra_2 are the mean roughnesses of the surfaces.

Below are given the integro-differential equations of EHD theory of lubrication with the consideration of the thermal processes that take place in the lubricant film and on the boundaries of surfaces, and the corresponding boundary conditions:

$$\begin{gathered}
\frac{dp}{dx} = 6\mu(V_1 + V_2)\frac{h - h_0}{h^3}, \text{when } x = -\infty, p = 0 \text{ and } x = x_0, p = \frac{dp}{dx} = 0;\\
h = h_0 + \frac{x^2 - x_0^2}{2R} + \frac{2}{\pi}\left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}\right)\int\limits_{-\infty}^{x_0} p(\xi)\ln\left|\frac{\xi - x}{\xi - x_0}\right| d\xi;\\
\rho \mathrm{cV}\frac{\partial t}{\partial x} = \zeta\frac{\partial^2 t}{\partial y^2} + \mu\left(\frac{\partial V}{\partial y}\right)^2, \text{when } x = -\infty, t = t_0; \qquad (2)\\
t(x,0) = \left(\frac{1}{\pi\rho_1 c_1 \lambda_1 V_1}\right)^{0,5}\int_{-\infty}^{x} \zeta\frac{\partial t}{\partial y}\bigg|_{y=0}\frac{\partial\varepsilon}{(x - \varepsilon)^{0,5}} + t_0;\\
t(x,h) = \left(\frac{1}{\pi\rho_2 c_2 \lambda_2 V_2}\right)^{0,5}\int_{-\infty}^{x} -\zeta\frac{\partial t}{\partial y}\bigg|_{y=h}\frac{\partial\varepsilon}{(x - \varepsilon)^{0,5}} + t_0;\\
\mu = \mu_0 \exp\left(\beta p - \alpha\Delta t\right).
\end{gathered}$$

where p is pressure; V_1 and V_2 – peripheral speeds; μ – dynamic viscosity of lubricant oil in normal conditions; h – clearance; h_0 – minimum clearance; R – radius of curvature; E_1 and E_2 – modulus of elasticity; ν – Poisson's ratio of body materials; t – temperature; ρ, c, ζ, ρ_1, c_1, ζ_1, ρ_2, c_2, ζ_2 – correspondingly density, specific heat capacity and thermal conductivity of lubricant and interacting surfaces; μ_0 – dynamic viscosity of the lubricant; β – piezo coefficient of lubricant viscosity; ζ – lubricant thermal conductivity; α – thermal coefficient of lubricant viscosity; ξ, ε – complementary variables; x_0 – abscissa in the place of lubricant outlet from the gap.

Calculation of the oil film thickness, which separates the bodies, is the main problem of the EHD lubrication theory and there are numerous literature sources about it (Dowson, 1995; Ham rock and Dowson, 1981, etc.). There are various formulas for isothermal and anisothermal solutions for EHD problems describing the behavior of oil film thickness with various accuracies.

The modern friction modifiers contain tribochemically active products that have great influence on their operational properties. The various aspects of properties of these components are not sufficiently studied and they cannot be expressed mathematically. EHD theory of lubrication only considers the mechanical phenomena proceeding in the lubricant film of the contact zone, ignoring other layers.

The thickness of the rough surface boundary layers cannot be measured with the use of the modern methods of measurement of the oil layer thickness. Information about destruction of the boundary layers (and about onset of scuffing as well) can be obtained by sharp increase of the friction torque on the oscillogram. Therefore, onset of the friction torque sharp increase is considered as beginning of the third body destruction.

On the base of system of equations of EHD, theory of lubrication and results of experimental researches considering formula (1), criterion of the third body destruction was developed that has a form:

$$C = K\left(\frac{R}{\sqrt{{R_{a_1}}^2 + {R_{a_2}}^2}}\right) \cdot \left(\frac{\mu V_{\Xi K}}{P_n}\right)^{0,7} \cdot \left(\frac{P_n \beta}{R}\right)^{0,6} \cdot \left(\frac{\zeta}{\alpha \mu {V_{CK}}^2 {P_{e1,2}}^2}\right)^{e} \leq 1 \qquad (3)$$

As it follows from the formula (2), a criterion of the third body destruction depends on the mechanical and thermo-physical characteristics of interacting surfaces, geometric and kinematic parameters, thermo-physical and tribological parameters of the third body. The properties and stability of the boundary layers are revealed in values of coefficient K and exponent e. The researches have also shown special sensitivity of the third body stability to thermal loads and relative sliding velocities, which must be taken into account to improve working conditions.

The criterion of the third body destruction that is developed on the base of EHD theory of lubrication and results of experimental researches considering stability of the boundary layers has the form:

$$C = K \bullet {V_{\Sigma k}}^{a} \bullet {V_{sl}}^{b} \bullet {P_{ll}}^{c} \bullet {\mu_0}^{d} \bullet R^{l} \bullet \left(\sqrt{R_{a1}^2 + R_{a2}^2}\right)^{f} \bullet \beta^{g} \bullet \zeta^{h} \bullet \alpha^{i} \bullet a^{j} \bullet E^{n} \leq 1 \qquad (4)$$

where $V_{\Sigma k}$ is a total rolling velocity; V_{sl} – sliding velocity; P_{ll} – linear load; μ - dynamic viscosity of the lubricant; R – reduced radius of curvature of the surfaces; Ra1 and Ra2- average standard deviation of the interacting surfaces; β – piezo coefficient of the lubricant viscosity; ζ– the lubricant thermal conductivity; α – thermal coefficient of the lubricant viscosity; a – thermal diffusivity; The exponents a, b, c, … , n and coefficient K are specified on the base of the experimental data obtained by T.I. Fowle, Y.N. Drozdov, Vellawer, G. Niemann, A.I. Petrusevich, I.I. Sokolov, K. Shawerhammer, G. Tumanishvili and are given in the **Table 1**.

As it is seen from the **Table 1**, destruction of the third body is especially sensitive to the degree b of sliding velocity. It follows from formulae (2) and (3) that with increase of the rolling velocity, radius of curvature, piezo-coefficient of viscosity, heat conductivity factor, thermal diffusivity and coefficient of elasticity, the stability of the third body increases and with increase of the sliding velocity, linear loading, roughness of surfaces and thermal coefficient of viscosity it decreases.

As it was already mentioned, one of the indicators of the third body destruction (scuffing) is appearance of signs of scuffing on the surfaces. According to criteria of destruction of the third body, its destruction is supposed when values of the corresponding criteria are less than 1. K. Schauerhammer experimentally ascertains the conditions of the third body destruction (scuffing) for the gear drive on the gear drive test bench TUME 11 [46]. To predict the destruction of the third body

a	b	c	d	l	f	g	h	i	j	n
0.37 to 0.7	(−0.36) to (−1.32)	(−0.15) to (−0.265)	0.04 to 0.52	0.25 to 0.36	−1	0.6	0.18 to 0.66	(−0.18) to (−0.66)	0.09 to 0.33	0.045 to 0.165

Table 1.
The exponents of formula (3).

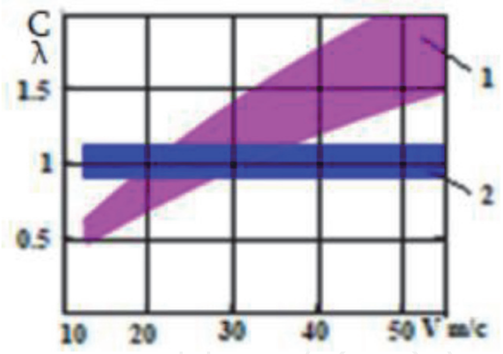


Figure 15.
Dependences of the fields of deviations of the values of λ parameter (1) and criterion C of destruction of the third body (2) developed by us, on the gear wheels circular velocity.

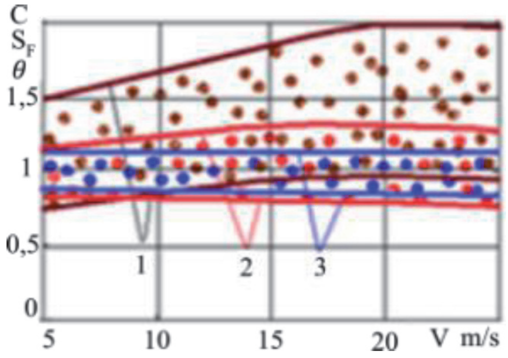


Figure 16.
Dependences of the fields of deviations of the temperature criterion (θ, 1) of H. block, criterion (SF, 2) of G. Niman and Saitzinger and offered criterion (C, 3) of destruction of the third body, on the gear wheels circular velocity.

(scuffing), we used the well-known Dowson and Higginson formulas to determine the lubricating layer parameter (λ) [44, 45] and the criterion C developed by us at the values of the coefficient K = 2.7 and the exponent e = 0.336 in formula (3). Dependences of the fields of deviations of the values of these criteria on the gear wheels circular velocity are shown in **Figure 15**.

As it is seen from the graphs, deviations of the criterion C of destruction of the third body developed by us, are small and constant, while deviations of the parameter λ and its values increase with increase of the gear wheels velocity.

Figure 16 shows the results of similar calculations using the C criterion with the values of the coefficient K = 1.55 and the exponent e = 0.29 in formula (3) and the formulas of H. Block [47] and Niemann G. and Saitzinger K. [48]. The studies were carried out on gear drive test bench FZG for transmissions A, L, N 141, 142, 143, 201, 202, and 203 with lubricant k1.

It is seen from the graphs that deviations of the offered criterion C of destruction of the third body little differ from the unit in the whole range of variation of the circular velocity, while deviations of other criteria significantly differ from the unit and they increase with increase of the circular velocity.

5. Conclusions

- Tribological properties of the interacting surfaces mainly depend on tribological properties of the third body, degree of its destruction, disposition of the surfaces to seizure etc. The researches have shown that the continuous or discontinuous but restorable third body at the initial stage of destruction and progressively destructing third body have quite different properties. In the first case the said properties are stable and depend on the properties of the third body and in the second case, these properties are instable and worsened that are characterized by increasing friction coefficient, catastrophic wear and typical noise.

- Prediction of destruction of the third body is possible in the laboratory conditions by estimation of the friction torque variation and with the use of the criterion of destruction of the third body, with ascertained beforehand values of the experimental coefficients;

- The friction coefficient (negative, neutral and positive), wear rate of the interacting surfaces (mild, severe and catastrophic), damage types (scuffing, fatigue, plastic deformation, adhesive wear) and vibrations and noise generated in the contact zone depend on tribological properties of the third body, its degree of destruction and area of the factual contact zone seized places;

- For the improvement of tribological properties of the interacting surfaces, it is necessary to provide the contact zone with continuous or restorable third body having due tribological properties at the initial stage of destruction.

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Conflict of interest

The authors declare no conflict of interest.

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