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RESEARCH

Nature of the Tribology - Maintenance Relation

The structure of the various technical systems is composed of multitude of tribomechanical systems, whose function is caused b relative motion of elements in contact. The processes of tribological nature in the contact zones, by which the transfer of high specific energy is realized (high pressures, relative motion speeds, contact temperatures, chemical activity, etc.), as well as fundamental dissipative processes, require corresponding actions pf maintenance, which would decrease, prevent and eliminate negative consequences of friction and wear.

The nature of these relations and their practical effects are the subject of analysis in the material presented in this paper. Based on it, the basic conclusion comes up, by which the tribology is frequently the main cause and simultaneously the solution of the maintenance problem. On the other hand, maintenance is a chance for achieving the greatest savings through tribology.

Keywords: *tribology, maintenance*

1. INTRODUCTION

Basic tribological processes of friction, wear and lubrication are present in the human life since the beginning of the human race. Namely, friction, as the inevitable and omnipresent resistance to all types of contact relative motion, is a part of his everyday experience. There, this experience reflects essentially important contradiction, which is immanent to phenomenon of friction. The friction is simultaneously both the condition for and restriction on real life. It is the condition for human motion on the ground, regardless of whether he is using his feet or the car tires. By using friction, the prehistoric man in Paleolithic period lit the first fire. Without friction the processes of transfer the mechanical loads between the contact surfaces, would be impossible, and they are the bases for functioning the whole spectrum of technical systems in everyday service of man's needs. In some of them, like the brakes and clutches, the increased friction is desirable. However, friction and accompanying phenomenon of wear, as the fundamental processes of energy and material dissipation, are causes of the whole series of direct and indirect losses, significant even at the global levels of national economies, of preservation of the nonrenewable energetic and material resources and ecological protection of the planet.

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Confronted with friction as a cause of resistance to relative motion, even without clear notion about nature and global consequences of friction, the struggle for its reduction is present since the man's first attempts to use the principles of friction for transport of high loads on primitive sleigh. The main weapon in this struggle was always lubricant. Proofs of application of lubrication by greases are present in archaeological excavations in ancient Egypt. The oldest drawing that shows the application of grease for lowering friction in transporting a heavy statue dates from 2400 years BC.

Every newly manufactured technical system is inevitably, during the exploitation process, subjected to undesired changes physical and chemical changes of materials of elements in its structure, which represent the irreversible process of degradation. Those changes are manifested through worsening of the system's function and can lead to failure. Regarding the fact that the structure of various technical systems is composed from multitude of tribomechanical systems, whose functions are caused by relative motion of elements in contact, dissipative tribological processes frequently represent the dominant reason of degradation.

The delicate role of preserving the systems' function above the previously set level during the whole working life belongs to the function of maintenance. It embraces different activities like monitoring of the changes in components and system state, diagnostics of their function, as well as definition and undertaking the concrete actions of cleaning, lubrication, regeneration, repair, elements substitution, etc.

The nature of the tribology/maintenance relation, and their practical (primarily economic) effects, are the subjects of analysis in material presented in this paper. Based on this analysis, the main conclusion appears to be the fact that at one side, tribology is frequently the basic cause and simultaneously the solution of the maintenance problem and at the other side maintenance offers possibility of largest savings through tribology.

2. MICRO LEVEL OF TRIBOLOGICAL PROCESSES UNFOLDING

Friction and wear represent the fundamental processes during the relative motion of solid objects, liquids and gases, which are of the stochastic nature and they manifest themselves as dissipative, nonlinear, dynamic effects in the contact zone. They are consequences of physical-chemical interactions on real contact surfaces of elements in relative motion. Namely, discrete contacts over the tips of micro roughness form the real contact surface (approximately 1/10000 of the nominal one), which causes the appearance of very high specific mechanical and heat loads during which the tribological physical-chemical processes occur.

At the micro level, thus, the friction of sliding occurs through interaction of micro-roughnesses of the real rough surfaces. The nature of this process can be analyzed on the simplified model of interactions in the elementary contact of two micro-roughnesses of materials of different hardnesses (Figure 1). There, conditionally can be noticed three phases of their relative motion, which are necessary for understanding of all the mechanisms of appearance of the friction force at the level of micro-contacts: a) phase of establishing the micro contact and elastic-plastic deformation, b) phase of adhesive bonding, i.e., of the micro welded joint, and c) phase of breaking the bond. Thus, simplified analyzed contact phenomena explain the nature of the friction process. Namely, to overcome the material resistances: to deformation process, breaking the adhesive joints and scratching of the softer material by micro-roughnesses of the harder material, it is necessary to spend certain mechanical energy, i.e., to overcome the phenomenon of the resistance to relative motion, namely the phenomenon of friction.

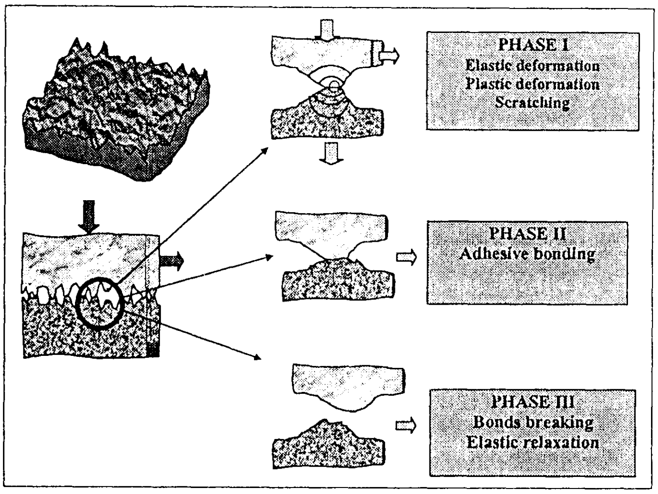

Figure 1. Interaction of micro-roughnesses in three phases of contact

Thus, at the micro level, the sliding friction occurs through interaction of micro-roughnesses, i.e., through the dissipative process of forming and breaking the micro-contacts. The total resistance to relative motion, i.e., the friction force F_T, represents the sum of micro components of F_T and all the three mechanisms of friction (resistance to elastic and plastic deformation, resistance to jamming of micro-roughnesses and resistance to adhesive bonds) on the total real surface, and dissipation of energy is represented as the sum of elementary dissipation processes.

$$F_T = \Sigma F_{Ti}$$

$$F_T = \Sigma F_1 + \Sigma F_2 + \Sigma F_3 + \Sigma F_4$$

F_1 - resistance caused by elastic deformations of material

F_2 - resistance caused by plastic deformations of material

F_3 - resistance caused by jamming of micro-roughnesses, and

F_4 - resistance caused by breaking of adhesive bonds.

Contrary to this model of contact of the two micro roughnesses, in real conditions of contact surfaces in mechanism of their scratching, especially important role is played by hard inclusions and wear products.

The sliding friction of material is accompanied by the inevitable complex wear process, which results in progressive losses of the surface layers material of the contact elements in the structure of the tribomechanical system. The nature of wear process, regardless of the type and form of wear, is determined by the fundamental mechanisms which are based on the phenomena of adhesion, fatigue, abrasion and tribo-chemistry, which are schematically illustrated in Figure 2.

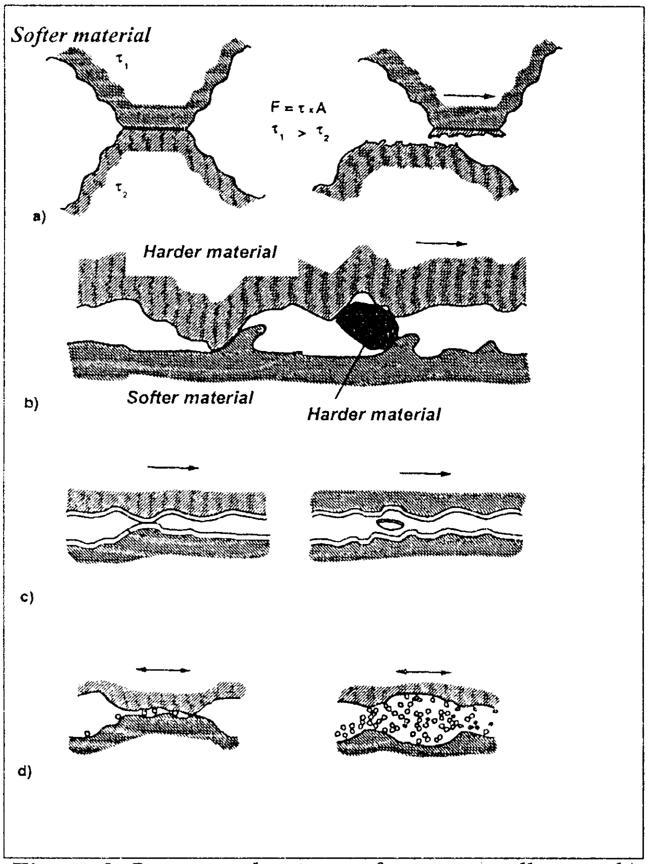

Figure 2. Basic mechanisms of wear: a) adhesive, b) abrasive, c) fatigue, d) tribo-chemical

Bearing in mind all the wear mechanisms, the complex process of wear can be described in the simplified form, by, conditionally separated, following phenomena (Figure 3):

- Forming of surface layers of the contact elements (1) and (2) in the adsorption process, or the tribo-chemical reactions of contact surfaces with environment (3);
- Adhesive transfer between the contact elements of the base material and the surface layers materials, obtained by adsorption and tribo-chemically;
- Generating of the wear products of the base material, reaction products and the transferred material, which occurs through effects of the surface fatigue and abrasion.

The total wear of the real contact pairs represents the consequence of simultaneous occurring of all these wear mechanisms: adhesive, abrasive, fatigue and tribo-chemical. The degree of presence and dominance of individual ones in the real systems are determined in conditions of contact realization.

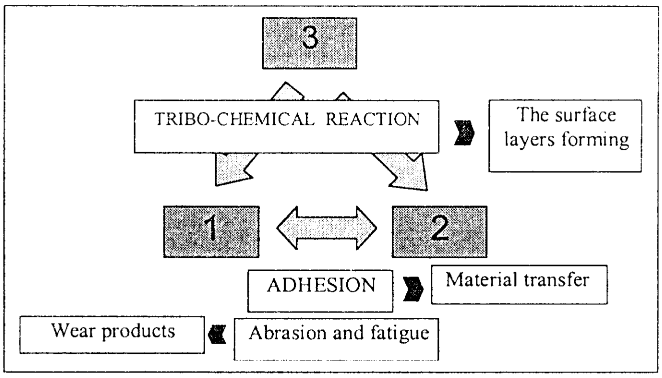

Figure 3. Schematics of the complex realization of the wear process

3. MACRO LEVEL OF THE TRIBOLOGICAL PROCESSES MANIFESTATION - THE NECESSITY OF MAINTENANCE

These physical-chemical dissipative processes at the micro contact level, though frequently neglected at the academic level, due to complexity of the problem, have the inevitable technological consequences and they are manifested at the macro level in all the variety of systems, which perform technically useful functions (generating, guiding, transmission, and limiting of motion, transmission of forces over the contact surfaces, transmission or transformation of mechanical energy, transport of solid bodies, fluids and mixtures, processing and shaping and reproduction of signals, etc.) due to relative motion of functional surfaces in contact.

All these systems represent the so-called tribo-mechanical systems, of more or less complex structures, with the input and output variables. There, as the input variables, usually appear motion + work and + material, and as the output variables appear motion, work, information and material, depending on the primary function which the system performs.

In the process of functioning of the tribo-mechanical systems, the most directly and the most obviously is manifested the friction, causing the direct energy losses, what also influences the input/output relation and the decrease of the degree of the system energetic efficiency.

Wear is the irreversible process, time wise, which has the clear and characteristic dependence on time, known as the wear curve. To this curve corresponds worsening of various aspects of technically useful output. Namely, wear primarily causes change of the system structure (state of the contact surfaces and layers, shapes, clearances), what negatively reflects upon various aspects of functioning and leads to failure. For friction there is no such a clear dependence, though one can speak about existence of correlation between increase of wear and increase of the losses due to friction.

These tribological consequences, at the level of tribomechanical systems appear and superimpose to each other in technical systems of higher order (like the manufacturing equipment and the transportation means), which represent more or less complex structures of the series of elementary tribomechanical systems. There, failure of the critical element of the tribomechanical system has as a consequence the interruption of the function of a system as a whole.

Direct macro consequences of tribological processes in the tribomechanical systems, contained in various technical systems, can, thus, be identified as: direct loss of energy due to friction (decreased degree of energetic efficiency) and irreversible degradation of system with time due to wear which leads to failure.

Real technical systems are characterized by efficiency ratio (ratio of technically used and totally brought energy) that is smaller, and frequently significantly smaller than 100 %. There, in structure of totally lost energy, based on different causes, a significant share belongs to energy spent for overcoming the external and internal friction.

Contemporary level of science and technology, with corresponding results in areas of construction materials, advanced measuring technologies, modeling and engineering computations, caused that today, as the most frequent reason of failures in mechanical systems, does not appear fracture of critical elements, but impermissible development of the wear process, namely tribological degradation of contact surfaces in tribological critical tribomechanical systems.

Direct consequences of friction and wear, with accompanying indirect consequences (primarily of economical character), related to failures and capital investments (investments that are consequences of tribological shortened working life of equipment, as well as needs for increasing efficiency) have strategic character and represent one of the primary motives for maintenance activities. These activities are principally performed in order to:

- Decrease intensity of tribological phenomena of friction and wear (lubrication),
- Preventing the tribologically caused failures (tribomonitoring and tribo diagnostics) and
- Elimination of tribologically caused failures (reparation replacements, regeneration, etc.).

In this way, maintenance, as a set of activities with primary task to respond to consequences of tribological processes, can be counted also as one of direct tribological consequences, as shown in Figure 4.

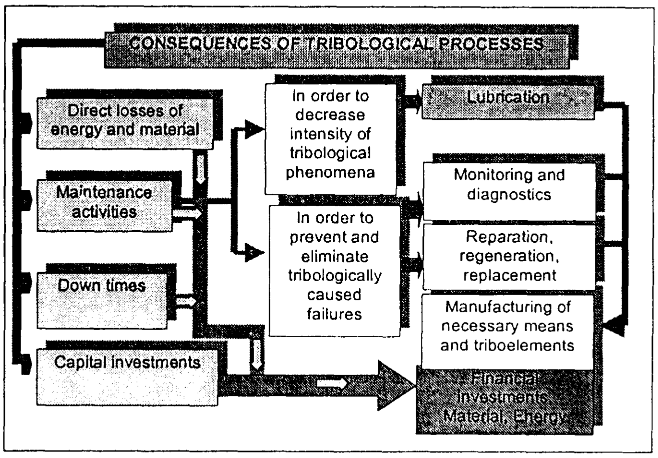

Figure 4. Consequences of tribological processes

4. TRIBOLOGY AND MAINTENANCE - ECONOMICAL IMPORTANCE

Having in mind all the enumerated and superficially analyzed macro consequences of occurring of tribological processes on contact surfaces of elements in relative motion, generally can be defined the tribological losses of a direct and indirect character.

Direct losses are the immediate energy losses due to friction and losses due to wear of the contact elements material, as well as losses related to maintenance. Direct losses of energy due to friction are marked as the primary direct losses. These losses are the most easily noticeable, and in superficial approach to this problem, they are usually mistaken for the total losses of tribological nature. The truth is that in the totally lost energy in functioning of technical systems, the major part belongs to losses due to friction. Thus, for instance, very low efficiency coefficients of machines in the textile industry are mainly caused by losses due to friction. According to objective estimates, based on investigations in this industrial branch, energy spent on friction represents about 80 % of totally consumed energy. As illustration of the energy, consumption on overcoming the resistance to friction can also serve some examples in the area of the largest energy consumers. Thus in the case of energetic, which, in the general sense, enhances obtaining of the energy carriers (coal mines, oil exploitation, etc.), and their processing, the energy losses due to friction amount to 8 to 10 %, what in FR Germany in 1982. was equivalent to amount of 1.1 to 1.6 billion DEM [5]. In industry, losses due to friction in the part of driving energy, vary, depending on the manufacturing processes technology and applied equipment, from 8 to 15 % in mining to 5 to 8 % in food manufacturing industry. In the area of transportation, the largest portion of energy is consumed in road transport. There over 80 % are the tribological losses.

In the Jost's report [9] from 1966 it is stated that out of total energy consumption in the amount of 40000 million kWh one third is being wasted in the friction processes. In addition, in USA annual direct energy losses due to friction for 1978 were estimated to 4.22 $\times$ 10^6 TJ, what is an equivalent of 20 billion US dollars [6].

The secondary direct losses are mainly related to necessity of producing the new and substituting the worn critical elements of tribomechanical systems and to lubrication in order to decrease the intensity of friction and wear. There should be kept in mind that there are not always present requirements for simultaneous decrease of both friction and wear, what is compatible. Sometimes are simultaneously presents requirements for increase of friction and decrease of wear (wheel/rails, car tires/ road, brakes, frictional transmitters, belts, etc.). The tertiary direct losses mainly refer to material for producing the worn elements.

Same as primary losses, both secondary and tertiary direct losses have dimension of energy. Namely, the metal machining procedures, as well as material for manufacturing the triboelements itself, have their own energy equivalent [9].

The current maintenance and repair, by their costs surpass the original price costs of technical systems, several times. Thus, for instance, that ratio for an automobile is 6, for an airplane 5 and for machine tools 8 [7]. Calculations show that about 2.6 % of the energy consumed in USA is related to maintenance, repair and manufacturing of the spare parts of automobiles. As an example of the great "tribological sink" can serve metallurgy, where the tribological losses, caused by wear, share in maintenance costs is 40 to 50 %. Losses caused by tribological reasons, mainly wear, are especially series in the so-called heavy sector of this industry branch, i.e., in the ore preparation, manufacturing the wrought iron and coke, casting and primary rolling.

Voluminous investigations of economical importance of maintenance in Japan, conducted in the eighties, have shown that the total costs of mechanical systems maintenance in 1979. were 8.3 $\times$ 10^{12} Yen, what represents 3.73 % of the gross national product [10] . There, the mechanical systems were defined as equipment and machines in mining, manufacturing, transport, communication, energetic and civil engineering. Percentage ratio is different for different branches of industry, and it amounts to, for instance 5 % for the textile industry, metallurgy and paper industry, and 2 % for food manufacturing industry. The share of annual costs of maintenance in the procurement price, according to investigations in Germany, amounts to 1.5 to 15 %, and most frequently it is about 6 % - same as in the area of industry [5].

The totally spent means in the maintenance process, only partially refer to tribologically caused maintenance. However, data from practice testify that in the total number of failures, share of tribologically caused ones is very high. Thus, for instance, out of total maintenance costs in 1982. for Germany, i.e., the amount of 46.93 billion DEM, share of 68.9 % (amount of 32.24 billon DEM) refers to maintenance activities, which eliminate consequences of wear.

Indirect losses appear because of the direct ones of any type. Losses due to downtimes (primary indirect losses) are economically very significant, but they do not have the dimension of energy. Secondary indirect savings of the tribological nature reflects on the level of the capital investments, and not only through the money, but through energy and material. Here we speak about investments, which are consequences of tribologically shortened working life of equipment, as well as needs for increasing efficiency.

Enormous tribological losses, expressed through economic indicators (1976/77 in USA 100 billion dollars, 1981/82 in FR Germany 32 to 40 billion DEM) represent the serious motive for undertaking the possible measures for savings through tribology.

5. TRIBOLOGY AND MAINTENANCE - "PARTNERS OUT OF NECESSITY"

For a long time, in engineering the main attention was directed towards manufacturing processes of technical systems of different purpose and degrees of complexity, namely towards the phases of definition the attributes of the system for the required functions - through activities of design and giving to material the defined attributes - through processing technology. There, tribology, as a powerful ally in all the phases, from design (tribodesign), through processing (technological inheritance), to exploitation (tribologically oriented maintenance), was neglected. However, today is increasingly present the awareness of importance of tribology and maintenance. This is the consequence of ultimative requirements for providing the availability and reliability of the system in various areas of manufacturing, transport, communications, conditions, etc., because of:

- Economic pressure,
- Increasing complexity of the system, namely the possibility that a small failure of a simple component can cause breakdown in functioning of the whole system, and even catastrophes of different nature,
- Problems of limited resources, namely requirements for the full use of the available technical resources.

A contribution to answering these questions can be achieved through tribology, as well as through maintenance, which is based on tribology. There, due to a natural unity of these two aspects of engineering, progress in one field inevitably affects the other, and vice versa, according to the coupled containers principle. Namely, the tribomechanical systems are placed in the center of the synergic efforts through tribology and maintenance. The aim is, at one side their tribological improvement, through decrease of inevitable effects of friction and wear, and at the other side, fight against their tribological degradation during exploitation. Since the degradation processes of the tribological nature are immanent to real systems, tribology, in the sense of tribological principles, which are fundamental for tribologically advanced constructions, and maintenance, as a defense against tribological degradation, also based on the same tribological principles, represent the "partners out of necessity".

Thus, the tribological improvements of tribomechanical, and through that also the technical systems as a whole, in the given maintenance conditions, can results, primarily through:

- Decrease of energy spent on friction,
- Decrease of maintenance costs through maintaining the functionality and increasing the working life,
- Decrease of lubrication costs through better lubrication process and increased working life of lubricant,
- Decrease of costs through shortening the downtimes,
- Decrease of investments through longer working life of the tribomechanical systems.

It can be seen that the greatest part of effects of tribological improvements (over 90 % [2]) directly or indirectly appear through costs of the corresponding maintenance. The fundamental potential in that view, at this moment, is attributed to tribodesign (design with implementation of the existing tribological knowledge), of the critical tribomechanical systems and improvement of lubricants' characteristics.

On the other hand, the tribological response and tribological degradation of the tribomechanical system of the given level of tribological properties are in exploitation determined, largely, by the strategy and activities of maintenance. Even the tribomechanical systems of high tribological quality can be annulled by inadequate maintenance. As an illustrative example can serve data related to exploitation of rolling bearings (which represent a highly advanced system for guiding the rotation). For them, lubrication and contamination (consequences of poor maintenance) represent the main cause of failures (Figure 5).

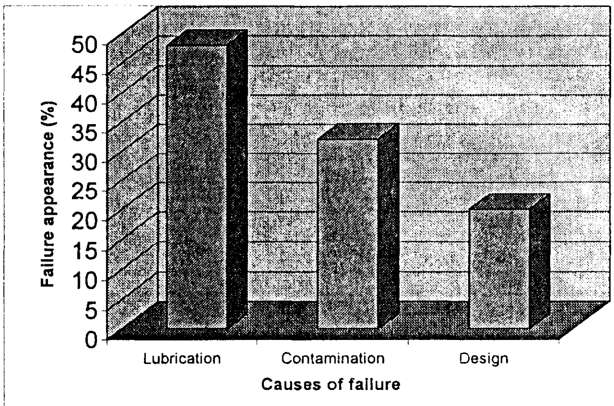

***Figure 5.** Fundamental causes of failures of rolling bearings [8].*

The special case in the concept of maintenance according to state of system belongs to state monitoring technologies and diagnostics of deviation from the required functional level.

Effects of savings through tribology (namely coupled through tribology and maintenance) can be estimated both in individual areas and on the global level. Thus, for instance, only in electric power industry in USA annually possible energy savings were estimated for 1981. at 2.8 % of the total consumed amount, what makes 4.4 billion US $ [6]. Also, out of 98 billion US $ (10^7 TJ of energy) that are spent annually in that country for drive in the area of traffic, possible savings, due to introducing the tribological improvements in the area of road vehicles, were estimated at 14.3 billion US $ (18.6 % of energy consumed by these vehicles). In FR Germany, annually (1981./1982.) potential savings through tribological measures were estimated at 6.4 billion DEM (0.239 billion in the sector of energy production, 0.298 billion in industry and 2.395 billion in traffic).

Thus, by decreasing friction and wear by various types of tribological improvements of tribomechanical systems, i.e., savings through tribology, decrease of all levels of direct and indirect losses is possible. Energetically expressed savings, according to data from 1980./1981. in USA are estimated to 11 % in the group of major consumers (traffic, industry and electric power production), what is equivalent to savings of 16.2 billion US $, per annum. Total savings, expressed economically, or energetically, are definitively results, primarily of savings in these areas of largest tribological sinks. However, it is necessary to keep in mind that tribology is of a generic nature and that a sum of small effects at numerous places, represent a significant result. Thus, for instance, though the agriculture and within it farming, at the global level, has a place at the bottom of the energy consumers' scale, data from a report *A Strategy for Tribology in Canada* point to possibility of annual savings in Canada in this area at the level of 337 million dollars.

Considering the world experiences of almost thirty years in this area, it can be expected that paying the adequate attention to tribology, especially in the area of education, research and application, can result in savings of up to 20 % of the gross national product. Up to 20 % of these effects are reached without significant investments. The largest part of such savings originates in decrease of maintenance costs of technical systems, replacement of the worn elements and downtimes due to tribological consequences.

6. CONCLUSION

Though the localized to micro, and even at submicro contact levels, the inevitable undesirable microdissipative technological consequences at levels of various tribomechanical systems, contained in different technical systems. To decrease those consequences, prevent and eliminate negative consequences of friction and wear, different activities maintenance are undertaken. On the other hand, tribologically decreased working life of technical systems, contained in various equipment, manufacturing means, transportation means, etc., and has as a consequences new investments. The most globally considered, negative consequences of tribological processes can be of direct and indirect consequences, with respect to tribological processes. Direct losses are immediate loss of energy due to friction and material of contact elements due to wear as well as losses related to maintenance. Indirect losses occur as consequences of direct losses of any kind. Tribologically caused costs (losses), and especially maintenance costs, are relevant at level of national economies.

The significance of tribology and maintenance, except due to economic requirement, stems also from other ones, like increasing complexity of systems, namely danger that a simple failure of a small component can cause breakdown in functioning of a system as a whole, even catastrophes of different natures, and the problem of limited resources, namely requirements for use of available technical systems.

The great importance of tribology and maintenance demands the necessity for their improvement. There, these two areas of engineering are characterized by mutual causal-consequential relation. Both areas have the role of causes and consequences of each other, and effects of improvements of each of them, have positive effects on the other one, or directly speaking, to total effects. Thus, tribological improvements of tribomechanical systems directly contribute to decrease of maintenance costs. Simultaneously, savings through tribology to the largest extent (over 90 %) manifest as savings through maintenance.

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