tribology in industry

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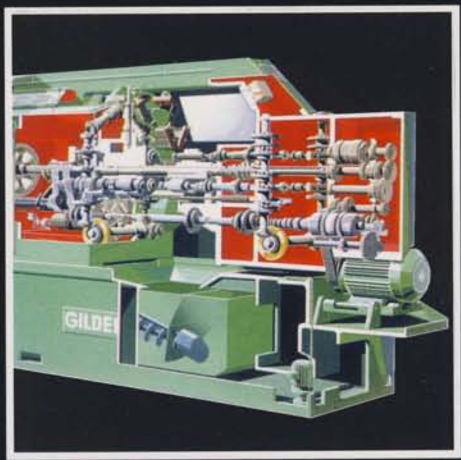
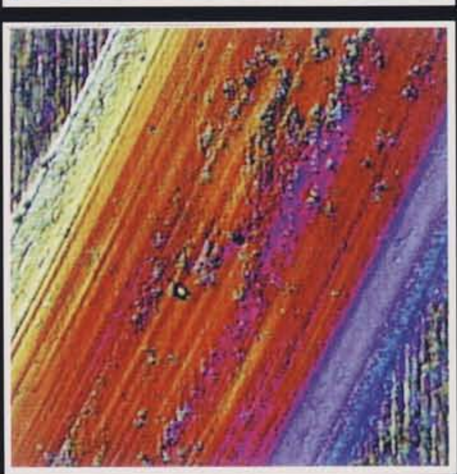


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contents

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Tribological Processes in The Cutting Zone

RESEARCH

The paper presents the contemporary views on tribological phenomena in the metal cutting processes. Besides that, the physical nature of the phenomena of some latest applications in production is pointed out.

Keywords: Tribology, cutting tool, cutting

1. GENERAL

Tribology has enormous importance in production processes, especially in metal machining. In this presentation we shall primarily deal with tribological processes that are accompanying metal cutting.

Tribological processes in cutting conditions are characterized by contact surfaces, stress and temperature field distributions, as well as fast appearance of new surfaces, what all makes these conditions specific.

In depth knowledge of tribological processes in general, and especially in the cutting process, enables achievement of optimum solutions both in technical end economical sense. Here is primarily referred to introduction of the new processes, but also the special materials, both for tools and machined pieces (e.g. hardly machined materials that are causing problems during their machining).

By analysis of machining costs for one operation U_0, we can state that they consist of labor costs R, costs related to tool amortization A and machine costs M, i.e.,

$$U_0 = R + A + M + SHP$$

where:

$$R = n \cdot k_1 \cdot t_k$$

$$M = \frac{C_M \cdot p}{F \cdot \eta \cdot 100 \cdot 60}$$

$$A = A_1 + A_2 + A_3$$

$$A_1 = n \cdot k_1 \cdot t_1 \cdot \frac{t_g}{T}$$

$$A_2 = k_2 \cdot t_2 \cdot \frac{t_g}{T}$$

$$A_3 = \frac{C_A}{i_0 + 1} \cdot \frac{t_g}{T}$$

$$SPH = \frac{Q_{SPH} \cdot C_{SPH} \cdot t_k}{60}$$

$$t_k = t_g + t_a + t_p + t_{pz} + t_i$$

$$t_g = i \frac{L}{s_n}; \quad t_a = t_z \frac{t_g}{T}; \quad B = t_p + t_m + t_{pz} + t_i = const.$$

$$U_0 = E \cdot B + t_g \cdot \left(1 + \frac{t_z \cdot \frac{G}{E}}{T} \right)$$

$$E = n \cdot k_1 \cdot \frac{C_M \cdot p}{F \cdot \eta \cdot 100 \cdot 60}$$

$$G = k_2 \cdot t_2 + \frac{C_A}{i_0 + 1}$$

$$n = 1 + \frac{k_3 \cdot N_1}{k_1 \cdot N_2}$$

where:

k_1; k_2; k_3 are the gross salaries of the productive worker; sharpener, expert worker (brigadier), respectively in din/min;

t_k - commanding time,

C_M - machine price;

p - amortization rate;

F - annual time fund;

η - efficiency ratio;

A_1; A_2; A_3 - costs of replacement, sharpening and amortization, respectively;

t_g - main machine time;

t_a - time for tool replacement per machined piece;

t_p - auxiliary time;

$t_{pz} = T_{pz}/z$ - preparation/finishing time per machined piece;

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i - number of passes;
i_0 - number of sharpenings;
n - number of revolutions (rpm);
C_A - machine price;
Q_{SPH} - quantity of cutting fluids in l/h;
C_{SPH} - price of 1 l of cutting fluids.

Thus, under certain conditions, machining costs depend on tool life. By influencing the tool life, i.e., by applying the tribological knowledge, we can significantly influence on costs. Tribological knowledge is also necessary for the sake of avoiding unnecessary costs in production, for instance big, expensive machined pieces, where the cut must not be interrupted during the pass (if it is interrupted the product is a waste, so it is necessary to ensure the sufficient tool reliability).

Global figures, that would point to possible influences of tribology in machining, are very hard to obtain, but certain analyses point to significant spending, e.g., energy, and to possible savings.

Research Committee of ASME (American Society of Mechanical Engineers) have published data which states that about *5.5%* of total energy in USA is consumed in primary metal machining and metal working industry, and that with better awareness of already known tribological knowledge savings of *1.5%* can be realized. With other possible savings this percentage of savings could be increased to 1.5%, what in 1980. was an amount of *21.5* billions of US$, i.e., *25%* of US budget deficit.

Important investigations, related to savings of energy through tribology, were conducted by DOE (Department of Energy) in USA. According to those investigations, energy losses due to friction in machine tools amount to $20 \cdot 10^{12}$ Btu per annum what is equal to $5 \cdot 10^{12}$ of Kcal per annum, or $21 \cdot 10^{15}$ J per annum. Out of that *9%* could be saved by application of the existing surface modificators. Another data is that total potential savings of energy through tribology in USA can reach 23% of total energy that is consumed for driving the machine tools, what amounts to *4.8* millions of barrels of oil annually, or *US$ 144* millions in 1980., or *US$ 85* millions annually, according to oil prices in 1989.

British industry consumes about *27%* of all national energy resources, while $45 \cdot 10^9$ *kWh* is the share of electrical power for machine tools drives. It is estimated that by application of known tribological knowledge savings of up to *25%* could be achieved.

2. TRIBOLOGICAL CONDITIONS IM METAL CUTTING

The cutting process is today considered as the tribomechanical system, that is characterized by input and output variables, where the input variables are: machined piece material, energy spent on the process, while the information are used for the process control. The first element of the tribomechanical system is the machined piece, the second - the cutting wedge, and the third - the cutting fluid - SPH (Figure 1).

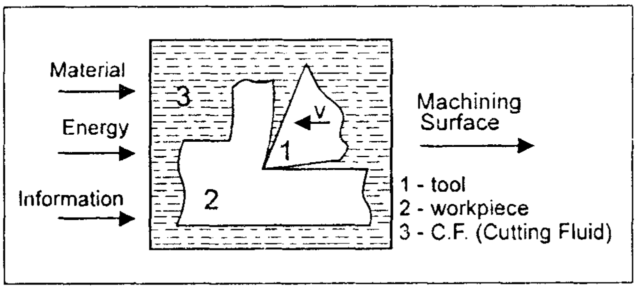

Figure 1. Tribomechanical system in metal cutting

The cutting process, or more accurately, the process of chip formation, is very complex. It is characterized by very difficult conditions - high pressures and variables temperatures in the cutting zone, that can reach very high values. Besides that, the whole transformation is performed in the very limited area (the cutting zone). From the aforementioned reasons, the cutting process modeling is very difficult and insufficiently precise, so it can be generally concluded that it is approximate. Thus one usually speaks about average values, e.g., average values of loads on the rake and clearing faces, average cutting temperatures, etc.

Tribological conditions in metal cutting are characterized by:

- Stress states in the deformation zones (Fig. 2 and 3)
- Area and condition of the contact surface on the rake face
- Chips sliding over the rake face
- Temperature fields of the cutting wedge, chips and cutting zone on the machined piece (Figure 4 a-c)
- Chemical influences between the tool and the machined piece, namely between the cutting fluid SPH and the machined piece.

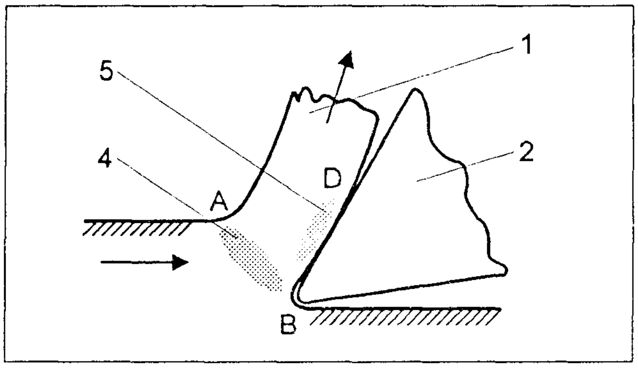

Figure 2. Contemporary model of the metal cutting process
1 - chip; 2 - tool; 3 - crack in front of the knife;
4 - primary deformation zone; 5 - secondary deformation zone.

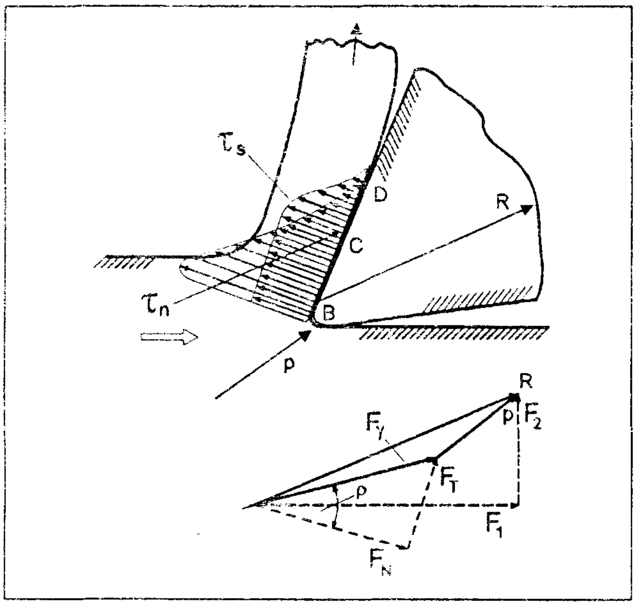

Figure 3. Contact surfaces between the chip and the tool σ_n *- normal stresses distribution;* τ_s *- shear stresses distribution;* $R = F_\gamma + F_\alpha$ *- resultant force acting on the tool (*F_γ *- force on rake face, and* F_α *- force on clearing face), and - tangential and normal forces on the rake face;* F_1 *- main resistance;* F_2 *- penetration resistance that acts on the tool;* ρ *- friction angle.*

The first notions about the chip formation mechanism assumed that the crack appears in front of the cutting wedge blade, and then the chip is started to separate from the machined piece (Figure 5). Contemporary theories have repudiated this statement, and now it is generally accepted that in the cutting process three zones can be observed (Figure 2).

Primary deformation zone 4 is in the chip root, where the continuous shearing process is unfolding. This zone can be considered as the zone of the maximum internal friction.

The secondary deformation zone 5, is the zone that is appearing between the tool rake face and the chip.

The tertiary zone appears between the tool clearing face and the machined piece.

As it was already mentioned earlier, in considering the phenomena during the metal cutting, one usually operates with average values. Thus, for instance, the average value of the friction coefficient μ is determined based on the Merchant's static model of the force diagram, during the orthogonal cutting (Figure 8).

$$\mu = tg\rho = \frac{F'_t}{F'_n}$$

where the appearance of friction on the clearing face is neglected.

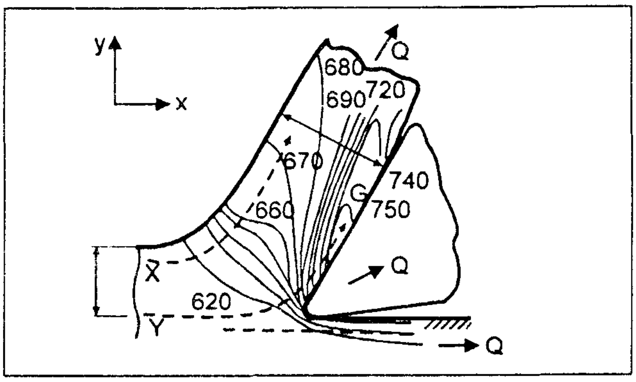

Figure 4-a. Temperature distribution in the cutting zone for orthogonal cutting

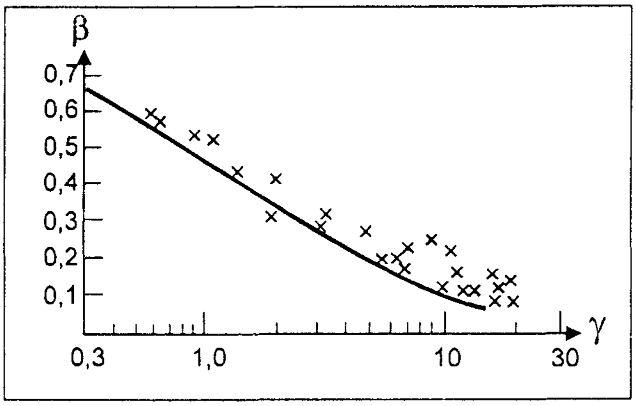

Figure 4-b. Heat distribution in the shearing zone between the chip and the machined piece

$\beta = \frac{Q_0}{Q'_t} = f(R_t)$; $R_t = \rho \cdot C_p \cdot V \cdot \frac{\delta}{k} Q'_t$ *- amount of heat that arises in the primary deformation zone;* Q_0 *- amount of heat that is transferred to the machined piece;* R_t *- the heat characteristics (*ρ *- specific mass,* C_p *- specific heat, v - feed rate, d - cutting dept, k - specific conductivity,* φ *- shearing angle)*

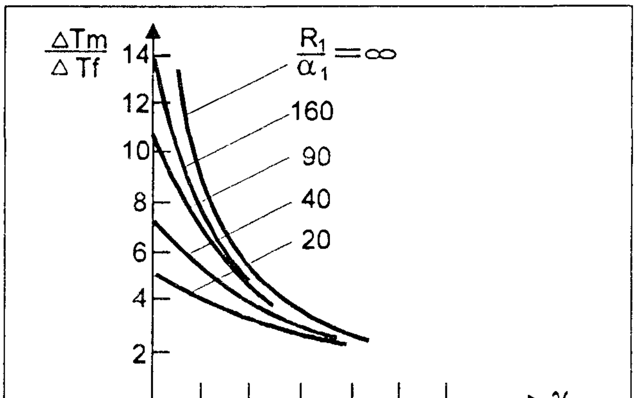

Figure 4. c) Influence of the secondary defomation zone width on the chip temperature $\frac{\Delta T_m}{\Delta T_f} = f(\gamma)$

ΔT_m *- corresponding temperature increase in the secondary defomation zone due to chip friction over the rake face;* ΔT_f *- average temperature increase in the chip;* γ *- ratio of the secondary deformation zone width to the chip thickness;* $\alpha 1$ *- coefficient that determines the width of contact between the tool and the chip*

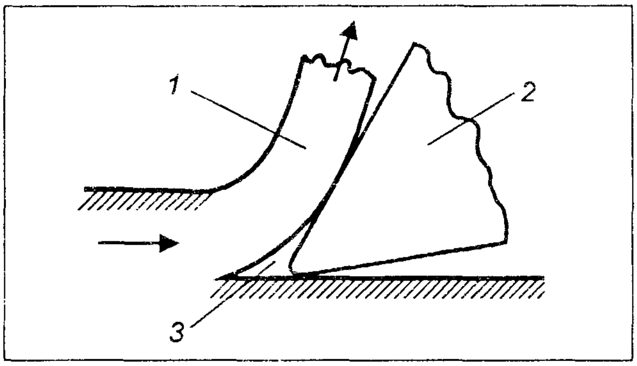

Figure 5. Ideal model of the cutting process

Since the cutting process is the typical dynamical process, Kronenberg had, applying the D'Alembert's principle, set the dynamic equilibrium conditions between the inertial force and the friction force on the rake face, and by solving the system of differential equations, he obtained the equation for determination the average value of the friction coefficient (Figure 6):

$$\mu = ln\lambda \cdot \left(\frac{\pi}{2} - \gamma\right)$$

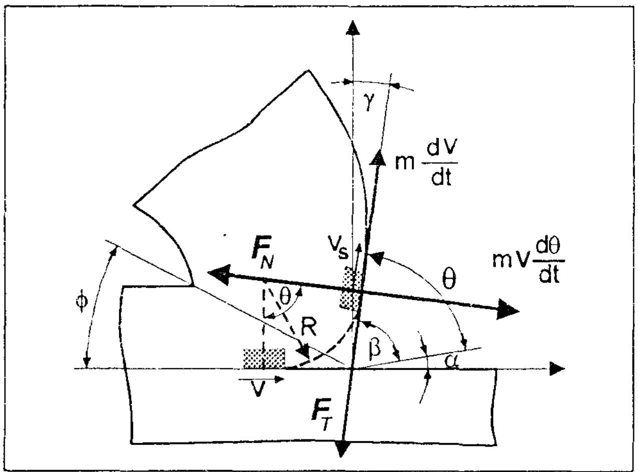

Figure 6. With the Kronenberg dynamical model

As the experimental investigation show, the average value of the friction coefficient μ is basically a function of the average normal pressure on the rake face. The average value of the friction coefficient is also affected by the cutting speed v and the rake angle γ (Figure 7).

In Merchant's model, and models similar to it, the phenomena occurring at the contact point between the clearing face and the machined surface are neglected. Zorev had introduced correction in calculations of the forces, i.e., cutting resistance, so he represented the individual components by the sum:

$$F_i = R_i + F'_i$$

where the additional parts took into account phenomena of wear on the clearing face. Thus, the correction for the main cutting force (cutting resistance) is:

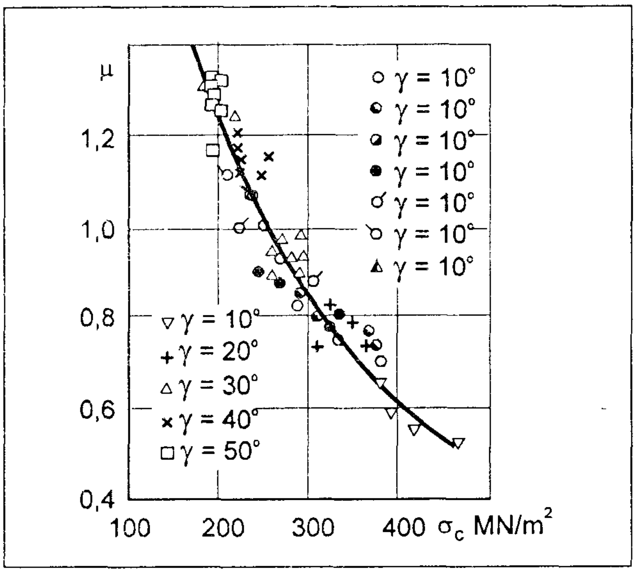

Figure 7. Influence of the normal pressure on the variation of the friction coefficient μ on the rake face

$$F'_1 = q'_n \cdot \mu' \cdot f'$$

where q'_n is the normal pressure, μ' is the friction coefficient and f' is the contact area between the clearing face and the machined surface. (In determination of F_2 and F_3 the corresponding projections of the contact area are taken into account).

The ratio of the friction energy between the rake face and the ship can be determined according to the energy necessary for chip formation (Figure 8) can be determined according to expression:

$$\frac{A'_t}{A'} = \frac{\mu}{\lambda} \cdot \frac{\cos\rho}{\cos(\rho - \gamma)} = f(\lambda, \gamma)$$

where, according to Kronenberg:

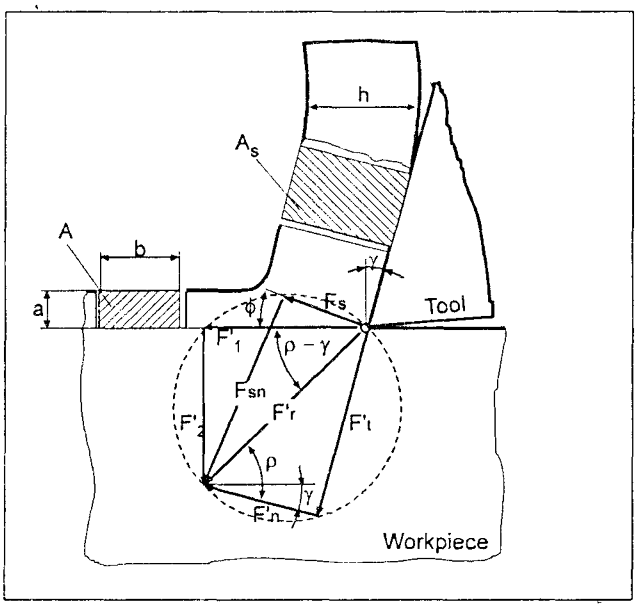

Figure 8. Merchant's force diagram in orthogonal cutting

$$tg\rho = \mu = \frac{\ln\lambda}{\frac{\pi}{2} - \gamma}$$

or values red off the diagrams in Figures 6 and 7.

The ratio of energies spent on friction between the clearing face and the machined piece, and the energy of friction between the rake face and the chip, can be determined according to expression (Figure 8):

$$\frac{A''_t}{A'} = \frac{\rho_1}{a} \cdot \frac{\sin\phi \cdot \cos(\phi+\rho-\gamma)\cdot\lambda}{\mu\cdot\cos\rho\sqrt{\cos\phi}} \cdot \frac{0.625\cdot\cos\gamma}{\sqrt{\sin\alpha}} = f(\gamma,\alpha,\rho_1,a,\lambda)$$

$$\frac{A''_t}{A'} = \frac{\rho_1}{a} \cdot \phi_1(\gamma,\lambda)\cdot\phi_2(\alpha)$$

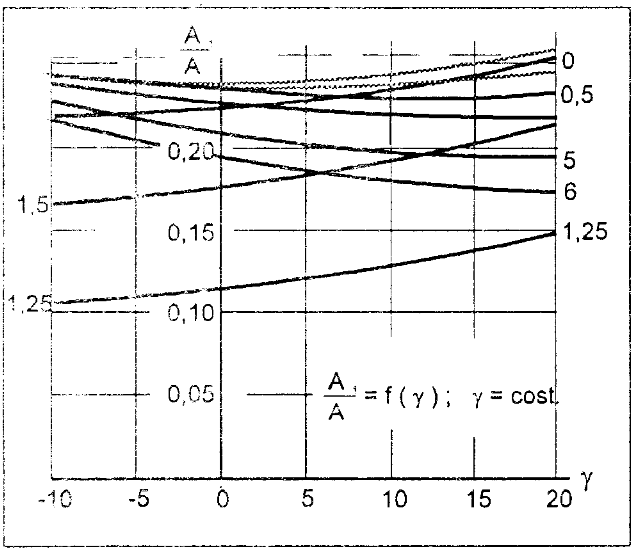

Figure 9. Diagram for determination of the ratio between the energy consumed on friction between the chip and the rake face and the total energy consumed in the cutting process

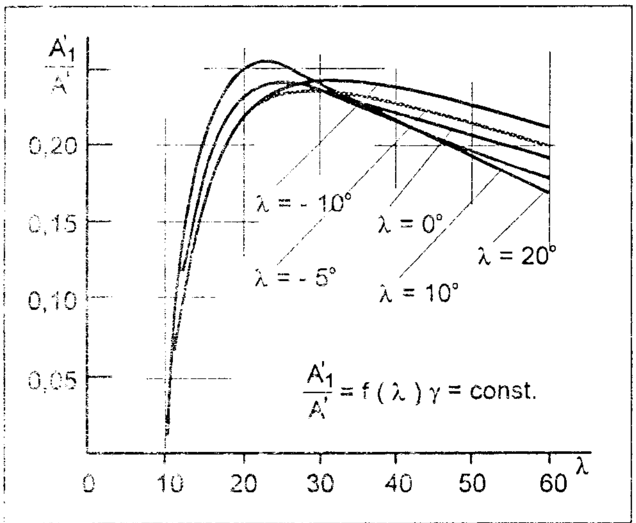

Figure 10. Diagram for determination of the ratio between the energy consumed on friction between the chip and the rake face and the total energy consumed in the cutting process

where:

$$\phi = arc\ cot\ \frac{\lambda - \sin\gamma}{\cos\gamma}$$

or by using diagrams in Figures 12 to 15.

As the total energy A can be represented approximately as the sum of energies of the internal and external frictions:

$$A \approx A_{ut} + A_{st}$$

where:

$$A_{st} = A'_t + A''_t$$

thus the ratio is:

$$\frac{A_{st}}{A'} = \frac{A'_t}{A'} \cdot \left(1 + \frac{A''_t}{A'_t}\right)$$

EXAMPLE: For the cutting depth of $a=0.5\ mm$ and the tool with the rake angle $\gamma=5^o$, the clearing angle $\alpha=6^o$, and the rounding radius of the blade $\rho_1=0.020\ mm$, and for the chip slenderness ratio $\lambda=2.5$, we have:

$$\frac{A_1}{A'} = 0.23529$$

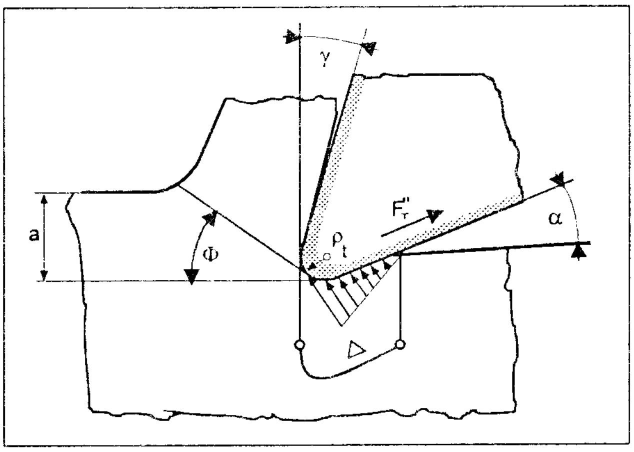

Figure 11. Contact of the blade and the active part of the tool clearing face

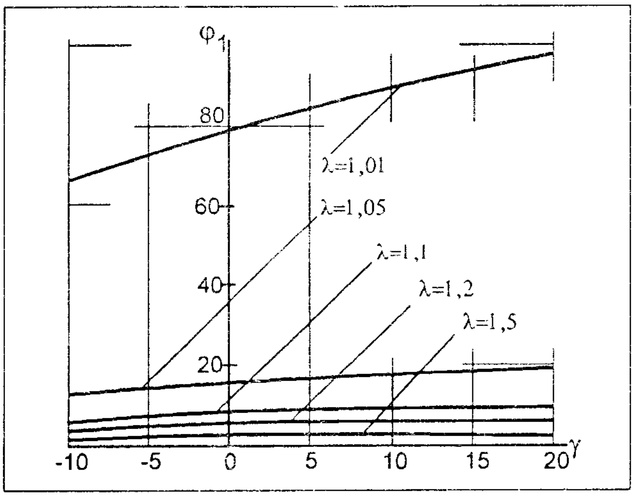

Figure 12. Auxiliary function φ_1 for determination of the ratio between energies consumed on friction between the clearing face and the machined piece, and between the chip and the rake face

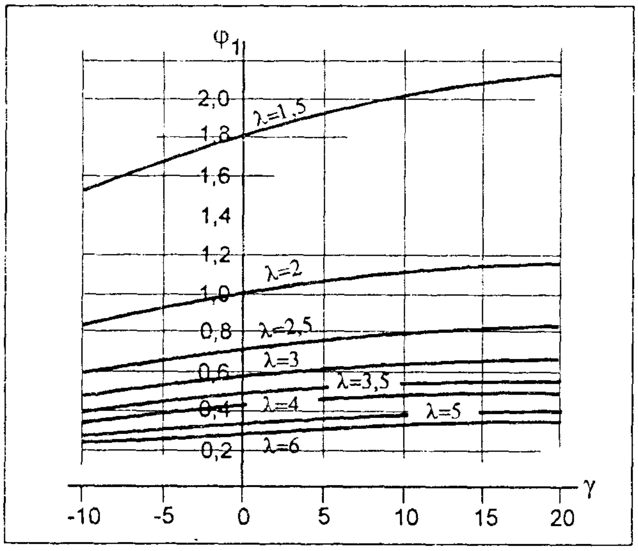

Figure 13. Auxiliary function φ_1 for determination of the ratio between energies consumed on friction between the clearing face and the machined piece, and between the chip and the rake face

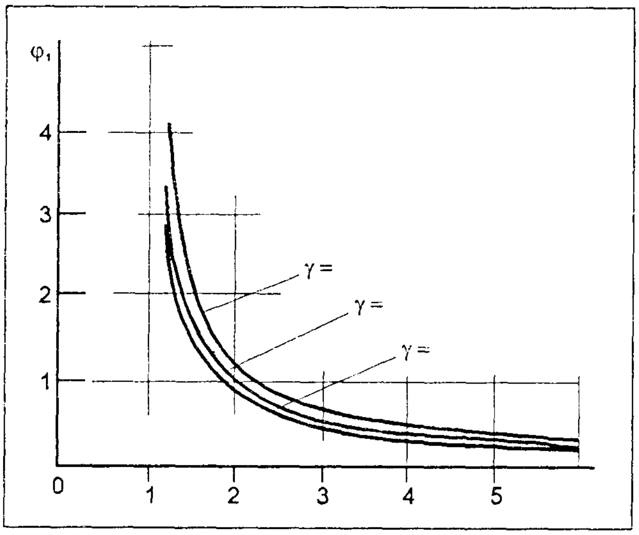

Figure 14. Auxiliary function φ_1 for determination of the ratio between energies consumed on friction between the clearing face and the machined piece, and between the chip and the rake face

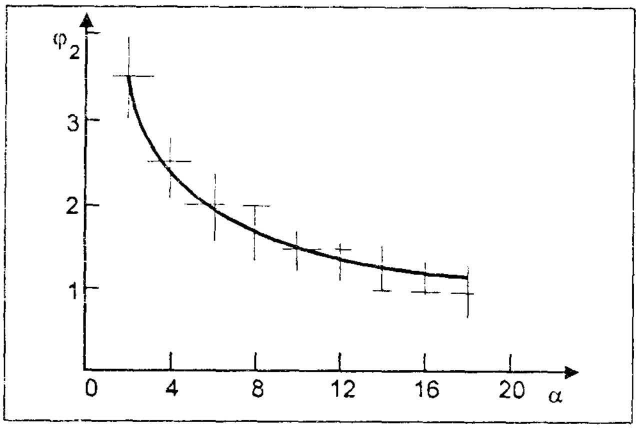

Figure 15. Auxiliary function φ_1 for determination of the ratio between energies consumed on friction between the clearing face and the machined piece, and between the chip and the rake face

$$\varphi_1(\gamma,\lambda) = 0.76327$$

$$\varphi_2(\alpha) = 1.933.$$

By substituting the above numerical values into the equation, we obtain:

$$\frac{A''_t}{A'_t} = \frac{0.020}{0.5} \cdot 0.76327 \cdot 1.933 = 0.059016$$

and the expression further gives:

$$\frac{A'_t}{A'} = 0.23529 \cdot (1 + 0.059016) = 0.249176$$

so we conclude that in the above example the energy of friction over the clearing face is *5.9%* of the energy of friction over the rake face, and that the energy of friction on the contact surfaces on the rake and the clearing faces is *24.9%*, and the energy for overcoming the internal friction is *75.1%* of the energy needed for chip formation.

Relatively high normal stress on the contact surface between the chip and the rake face, has as a consequence lowering of the friction coefficient, and thus the real contact surface is increased, over which the micro welding will occur between the asperities on the chip surface that is sliding over the tool rake face.

The friction conditions on the rake face, as it is shown, are complicated due to appearance of friction on the clearing face. Earlier, simplified force schematics, enables determination of the average value of the friction coefficient on the rake face. It is based on the assumption about equality and collinearity of the resultant force and forces in the shearing plane and the rake face (Figure 16). The friction coefficient determined in this way has not many common points with real condition. The more realistic scheme is that presented in Figure 3.

Considering the complexity of the tribological conditions in metal cutting, today are applied, for the purpose of identification of the real conditions, transparent tools made of sapphire, that enable photoelastic studies of the boundary conditions, and the stress distribution over the tool, between the tool faces and the chip and the machined piece, in real conditions.

When we speak about the wear mechanism, the whole series of possible types of wear is suggested, like:

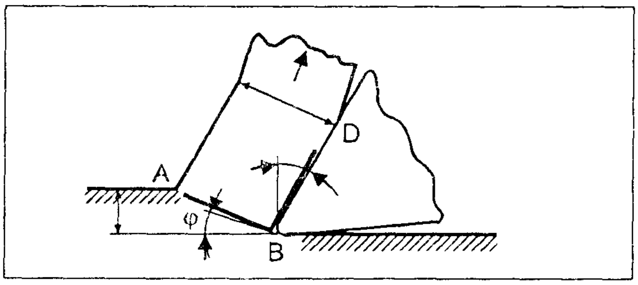

Figure 16. The first model of the metal cutting process

- abrasion
- adhesion
- diffusion
- dissolution
- dislocation of hard particles
- dissociation
- thermal and mechanical fatigue
- phase/structural transformations
- micro-chipping
- fractures
- erosion of the emulator
- chemical effects.

However there are remarks about applicability of some of these mechanisms, since they do not belong into the domain of real cutting regimes.

The well known is the model of the diffusive wear, that is explaining the appearance of the tool wear. However, some researchers point out that there are physical foundations for adhesive and diffusive wear. As a result of abrasion during the machining with hard metal tools, the wear in form of craters and races appear (Figure 17).

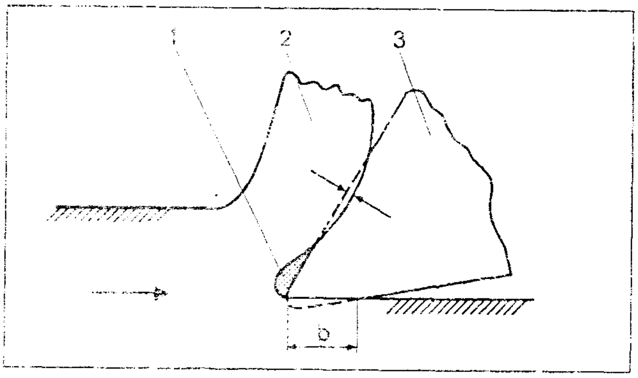

Figure17. Areas of progressive tool wear. b - wear race; 1 - deposit; 2 - chip; 3 - tool

At high feed rates, during the development of the wear process, some tool material components are transferred into the material of the machined piece, what points to the necessity of achieving certain conditions for unfolding of these processes. However, it is also pointed out to dissociation of some tool material components, e.g., carbon in hard metals. This is why the high temperature stability of hard parts in the tool, with respect to solubility in the machined piece, is of the primary importance.

In literature are also emphasized other anomalies, that can occur in machining of titanium alloys with polycrystalline diamond tool. Titanium form the chip, in the adhesion process, moves to the tool, and in reacting it forms titanium carbide TiC. This disables new contacts between the chip and the rake surface, and thus limits the tool wear, by presence of the diffusive barrier. However, as it is known, titanium carbide TiC, is used as a coating on the hard metal, nut this coating has no importance in machining the titanium alloys, with respect to hard metal without coating.

In other studies is concluded that at certain machining regime, the dominant influence has at least one of the wear mechanisms. By changing the regime, the dominant influence of wear is also changed, Figure 18.

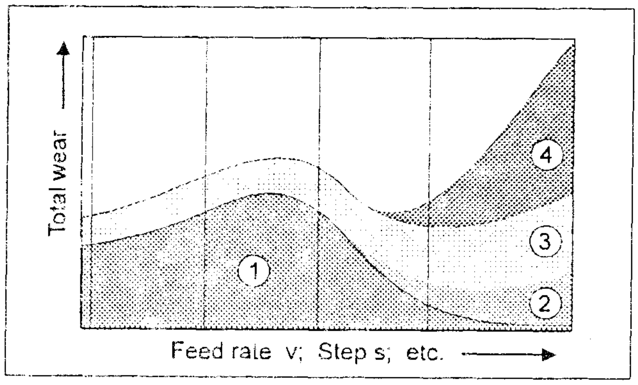

Figure 18. Total magnitude of wear as a function of temperature (feed rate, step, ...). 1 - adhesive wear; 2 - oxidative wear; 3 - abrasive wear; 4 - diffusive wear

Previously presented considerations were not able to describe the complete model of the wear mechanism, but they enabled establishing of relative relations between individual influential parameters. The more complete, physically founded model, will be reached in the future, based on long term complicated and expensive experimental investigations.

3. TOOL COATINGS

Hard coatings made of aluminum oxide Al2O3, titanium carbide TiC, and titanium nitride TiN, or their combinations, on tools made of hard metals (tungsten carbide WC) were developed in the sixties. They are deposited by chemical procedure (CVD - chemical vapor deposition) and they caused the increase of productivity through increased tool life, i.e., the feed rate and chip cross section. Coatings usually have multiple functions, to reduce diffusion, to realize chemical and heat barrier, to increase abrasive resistance, to create barrier to phase boundaries in order to prevent erosion of hard metal, or barrier to adhesion between the tool material and machined piece material.

For the purpose of increasing the productivity in machining with tools made of high speed cutting steels, in the seventies were developed the thin coatings made of titanium nitride TiN, that are reducing the depositions on these tools. Considering that the CVD procedure requires heating of the substrate to a temperature over *1000°C*, what surpasses the transformation temperature of this tool material, here is applied the PVD (Physical

Vapor Deposition) procedure, that requires significantly lower temperature of the substrate (*400°C*).

From the above mentioned , it follows that if we want to use all the potentials, that are offered by coatings, it is necessary to, through further investigations, better study tribological characteristics of coatings, and adhesion between the coating and the substrate.

Several studies point to the different mechanisms through which an explanation is given how the wear is slowed down by presence of coatings. However, until today the model is not yet developed, that would, in satisfactory way, show what type of coating should be applied for certain type of material, or for the particular type of machining regime.

4. TOUGH CUTTING CERAMICS

Knowing the characteristics of the elements of the tribomechanical system in the cutting process is of the primary importance. For the rough machining of super-alloys based on nickel-iron (Ni-Fe) the composite material was developed that consists of aluminum oxide reinforced by silicon-carbide. During the machining of steel the chemical interaction occurs between silicon carbide and iron. In that case it is easy to replace SiC with some other filler, like TiC. That is very well illustrated by the example of choosing the quality of ceramic platelet in final machining of quenched steel. As it ca be seen from Figure 19, for instance for criterion of life on the clearing surface of *VB=0.25 mm*, by proper application of the mixed ceramics, with respect to the oxide one, the increase of life is obtained of 2.86 times. This deserves the special comment about the importance of necessity to know the tribological characteristics of the tribomechanical systems elements in the cutting processes.

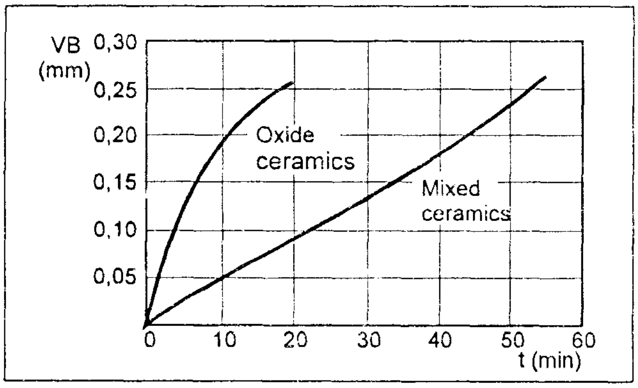

Figure 19. Example of oxide and mixed ceramics wear in fine turning of the quenched steel

These substitutions can be useful in interrupting cutting. Generally speaking, these substitutions will play an important role in application of ceramics in the future.

5. ULTRAPRECISE MACHINING AND FINISHING

The concept of surface, based on discontinuity between the two continua with two-dimensional demarcation between the regions, is no longer considered as adequate. The surface is today considered as the three-dimensional region, as a function of size, expressed by atoms, molecules and micro-structural components. In order to obtain ultra-smooth surfaces, their reliable production is necessary and measurement of their roughness. Preparation of these surfaces for finishing (lapping) with abrasives, and in machining with the single-crystalline diamond tools, required significant application of tribological knowledge. The new processes like the EEM (Elastic Emission Machining), and the new measuring technique, like the atom and electron microscope, enable creation and measuring of these surfaces.

6. CUTTING FLUIDS

For improvement of dry friction conditions, into the cutting zone is brought either liquid or gaseous agents that provide for lubrication or cooling, or both of these functions. In order to increase the cooling effect, water is added to mineral oils, so the emulsions are created. When the lubricating function is more important, then oils are applied.

By cooling the increase of working life is achieved, due to lower temperature, easier handling of the machined pieces, reducing o the thermal strains, that arise during the machining process. The last two factors primarily influence the grinding process.

Knowing the third tribological characteristics, coolants and lubricants (cutting fluids - SPH) is also of a great importance. This is well illustrated by the diagram of Figure 20, that is related to two cutting fluids A and B. Thus for the life criterion *VB=0.33 mm*, ratio of SPH A to SPH B is *1.77*, and for *VB=0.6 mm* it is *1.69*, what proves that SPH B has better tribological characteristics.

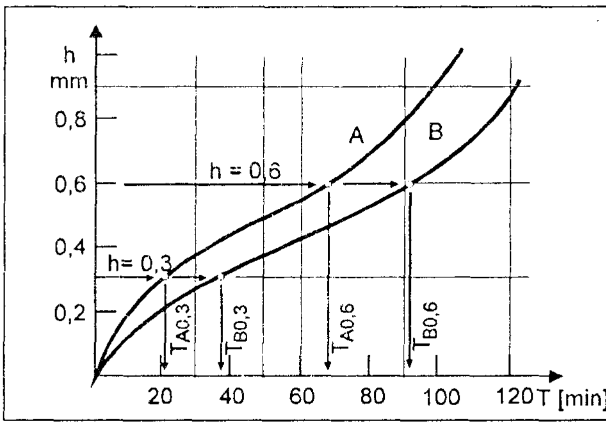

Figure 20. Experimental wear curves obtained for cutting fluids A and B

Action of cutting fluids in metal cutting unfolds in conditions of limited lubrication, due to very high pressures on the contact surfaces, so the hydrodynamic lubrication is not complete, that would provide for the film of CF between the contact surfaces. The lubricant, in fact has primarily the chemical, and not the physical nature. Thus, for instance, carbon tetra chloride CCl_4 that is not applied in practice, can positively affect the cutting processes by reducing the consumed specific power up to 60%.

In order to provide for efficient lubrication pure chemical substances should have:

- small molecule size, for easier unfolding of diffusion and bringing to the contact surfaces
- corresponding chemically active adhesive force that enables the boundary lubrication regime
- capability of dissolution at temperatures and pressures on contact surfaces.

All characteristics mentioned above possesses carbon tetra chloride, Figure 21.

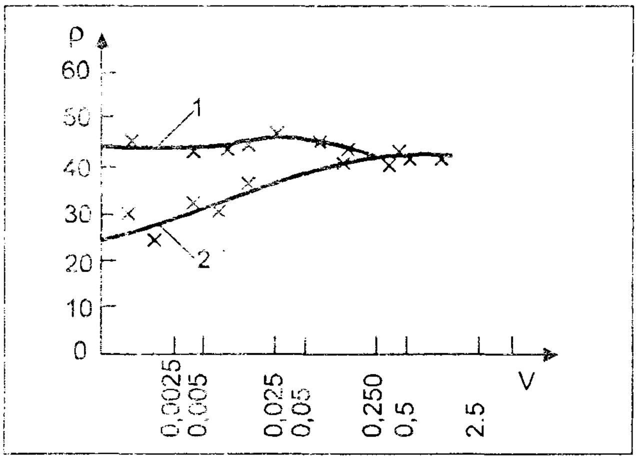

Figure 21. Influence of feed rate on lubricating action of the CCl_4 (carbon tetra chloride); $\rho = f(v)$, ρ - the friction angle; 1 - without CCl_4, 2 - with CCl_4

As it can be seen from Figure 21 the influence of lubrication is smaller at higher feed rates, what is true for all CFs. These effects are explained by partial loss of fluid's ability to reach the contact point, and partially by simultaneous increase of temperature, that causes reducing of the effects of the firm boundary lubrication. The important factor is, of course, the surface roughness, that does not influence only the CF action.

Deposit that is periodically separated is transferred to chip and the machined surface, what has multiple consequences (vibrations, uneven - jerky tool motion, etc.).

7. CONCLUSION

All presented above, point to the importance of tribology in machining, and to its application on real, existing and future, new, processes. The new technical materials point to the necessity of better recognizing the basic tribological knowledge, and their application in concrete operations. Thus, one day we shall be able to design technically perfect tool material for every specific type of machining.

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RESEARCH

A. RAC

Contemporary Lubricants: Role and Reqiurements

Solving of tribological problems in moving parts of machines and devices inevitably includes the application of the appropriate types of lubricants. Their characteristics are determined by equipment manufacturers and environmental protection legislation.. The object of this paper is to analyse the state and tendencies of the modern lubricants development in the light of the requirements mentioned.

Key words: *Lubricants, Basic properties, Requirements*

1. INTRODUCTION

Lubricants are vital components in transportation, as well as with most of industrial equipment. A proper selection of the lubricant and lubricating methods increase the lifetime of machinery and decrease operation and maintenance costs. These effects manifest themselves in a decrease of energy consumption, lower working temperatures and shorter down times.

Historically, the first application of lubricants coincides with the beginnings of civilization, while the first research was carried out during the industrial revolution. From that time till today, lubricants have played an important role in the development of industrial society [1].

The general technical progress, requirements for high conformity of all parameters of machine operations and ever stricter regulations over environmental protection have in the last several years resulted in a series of solutions that should ensure highly productive and also environmentally friendly lubricants.

Thousands of products nowadays cover all the aspects of lubrication technology. This will undoubtedly remain so in the future. A large number of different types of lubricants and products has been brought about by tasks that lubricants have to perform in different constructions, and under different working and environmental conditions.

2. ROLE OF LUBRICANTS IN TRIBOMECHANICAL SYSTEMS

Application of lubricants is inevitable in solving tribological problems in the majority of basic machine elements (gears, sliding and rolling bearings, joints, ropes, chains, etc.), as well as in different machines (IC engines, pumps, turbines, compressors, etc.), and technological processes of metal machining.

Effectiveness of lubricants depends on numerous interrelated factors that are determining the influence of a lubricant on friction and wear of the vital machine parts and equipment. They include the properties of lubricants and changes that occur in the properties during exploitation, characteristics of frictional surfaces, character of interactions of the lubricant components and surface material, speed, load, temperature, and other parameters of the working regime [2].

This points to the mutual dependence of the development of machnes, their components and lubricants, which is one of the characteristic features of modern mechanical systems. Thus, for instance, the solutions realized in the area of lubrication theory and lubricant production technology enabled the designing of hydrodynamic sliding bearings of high reliability and efficiency [3], they helped to achieve high performances and long life of rolling bearings and gears [4], they contributed to the decreasing of fuel consumption and improvement of the IC engines performances [5], etc.

As far as their history is concerned, lubricants were the subject of intense development during the fifties and the sixties of this century. The multigrade oils were introduced, as well as highly refined mineral base oils, new additives, synthetic lubricants, etc.

In the mid-seventies, which were witness to crude oil crises, the trend shifted towards the saving of energy and other resources, and to the solving of accumulated problems related to environmental protection. During that period economic aspects of lubricants application, especially their influence on energy saving in machinery, became more prominent.

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The end of this century, i.e., the nineties, is the period of globalization in all the aspects of lubrication technology (technology of lubricants manufacturing, testing, standardization, application, ecology), through the activities of many international organizations founded in Europe, America and Asia. These activities are primarily aimed at:

- lowering the system costs and
- environmental protection.

Lower costs in systems where lubricants are applied can be achieved by:

- extending the interval of lubrication application
- lower maintenance costs during the whole machine lifetime, and
- application of for-life lubricants.

The use of ecologically acceptable lubricants, the so-called "green" lubricants, is also an imperative. Ecological problems can be solved by:

- improving the applied lubricants efficiency
- decreasing and/or elimination of emission, and
- application of rapidly biodegradable lubricants.

It follows that the basis for characterization of future lubricants is going to be a combination of economic and ecological factors.

3. LUBRICANTS FOR TRANSPORTATION MEANS AND MECHANIZATION

Basic types of lubricants that are applied in transportation and mechanization are engine oils, gear oils and lubricating greases. Out of the lubricants mentioned here the dominant ones according to application are engine oils with about *85%*, while the consumption of gear oils amounts to cca *13%*, and lubricating greases *2* to *3%*. It should be kept in mind that transportation consumes over *50%* of the total quantity of lubricants [6, 7]. These data explain why engine oils and gear oils are in the focus of interest of both lubricants manufacturers and consumers.

3.1.Engine oils

Development of new engines requires new high quality lubricants of precisely defined properties. Also, consumers today damand higher performances from lubricants, since they are striving for lower system costs and higher efficiency of the equipment. Manufacturing of such lubricants makes necessary the improvement of the characteristics of both base oils and additives.

The future belongs to the family of base oils that includes: hydrocracked oils (HC), polyalphaolefins (PAO) and rapidly biodegradable esters.

Hydrocracked oils, whose production was realized a few years back, exhibit certain advantages with respect to parrafinic solvent raffinants (Tab 1).

Table 1. Properties of hydro-cracked base oils

HC-I	HC-II	HC-III
Viscosity index 100	Viscosity index 130	Viscosity index 145
Chemically clean	Chemically clean	Chemically clean
Without sulfur	Without sulfur	Without sulfur
Increased thermal stability	Increased thermal stability	Increased thermal stability
Volatility (Noack) similar to SN	Volatility (Noack) decreased	Volatility (Noack) decreased
Manufacturing costs similar to SN	Manufacturing costs significantly lower than for PAO	Manufacturing costs lower than for PAO

New technology offers base oils of such quality that can satisfy present-day specifications. In their properties hydrocracked oils surpass typical solvent raffinants, especially in applications where thermal and oxidation stability is important. In literature, these base oils are frequently called pure base oils (PBO) or unconventional hydrocarbon base oils (UHBO).

Generally, base oils used for manufacturing modern engine oils, ought to provide for [8]:

- fuel efficiency (lubricants rheology)
- low emission (low volatility at low viscosity)
- extended oil drain intervals (chemical purity).

Decrease of fuel consumption in engines (better fuel efficiency) can be achieved by lowering friction, which in the case of engine oils means applying low viscosity base oils. Due to this, the use of monograde oils in Diesel engines is becoming ever smaller, while in multigrade oils there is a tendency to change from grade 15w-x to 10w-x. As regards petrol engines, oils with grade 5w-x are already to be found on the market.

Low volatility of the base oil results in lower oil consumption and in lower emission, which is significant in Diesel

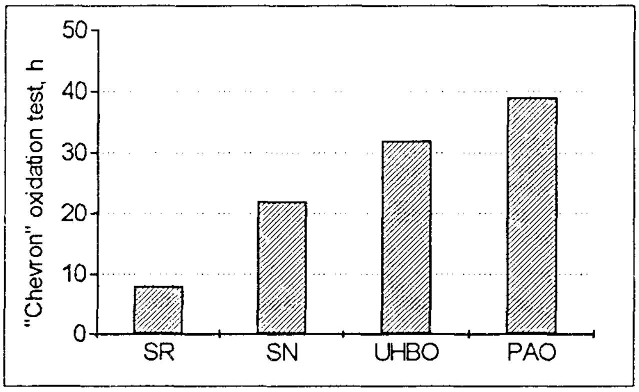

Figure 1. Differences in evaporation behavior of base oils (Noack test)

engines, where there are restrictions on particulate emission. Investigations show that in total particulate emission in Diesel engines, the engine oil's contribution is about 35%. Volatility of certain base oils is presented in Figure 1.

High purity of base oils provides for excellent oxidation stability, which is a means of preventing oil degradation (Fig 2). In that way longer drain interval is achieved.

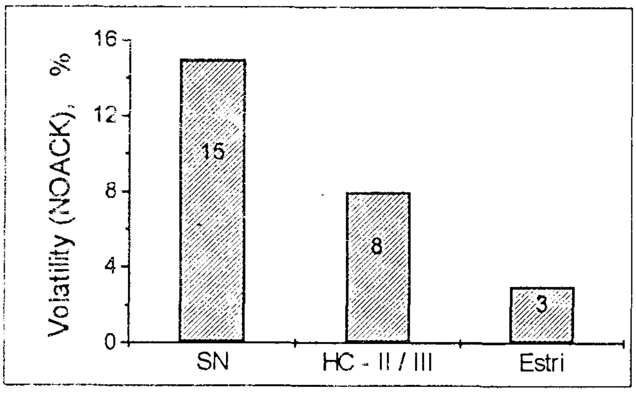

Figure 2. Oxidation stability of different base oils

3.2. Gear oils

There are numerous factors that influence the development of lubricating oils for gears. Growing specific loads of gear elements have as a consequence high thermal and mechanical straining of oils. Reducing mechanical losses in gears is also an important task of their lubricating oils. European manufacturers strive to extend the drain intervals of oils or to eliminate oil replacement, i.e. their choice is for permanent lubrication. Automatic transmission is becoming more common with European car manufacturers too.

The facts cited above determine the necessary properties of future gear oils, and these are: high oxidation stability, convenient frictional characteristics, good low temperature behavior, low volatility, high natural viscosity index, good carrying capacity and wear resistance. The hydrocracked base oils (HC II/III) and PAO satisfy the majority of the requirements mentioned. They are especially convenient for the production of high quality ATF oils.

4. INDUSTRIAL LUBRICANTS

Principal factors that will determine formulations, manufacturing and the market of industrial lubricants in the future, are the needs of equipment manufacturers and of final consumers. Energy saving and the need for environmental protection favor "green", less ecotoxic, rapidly biodegradable products [9,10]. In order to comply with these requirements, the development of new manufacturing technologies of the basic components of industrial lubricants becomes an imperative.

However, in comparison to automotive lubricants, in industrial lubricants the activities aimed at defining the standard performances are limited. This is due to a great variety of equipment, industries, field of lubricant application and working conditions to which these lubricants are exposed. This leads to an extremely large number of products of various characteristics.

Working conditions of industrial machines and equipment are getting more difficult all the time. Universal trend is towards the growing loads and speeds to which lubricants are exposed, and longer drain intervals. In many cases for-life lubrication is required. These are the reasons for the increase in the application of synthetic lubricants, primarily polyalphaolefine (PAO), as a basic component of numerous synthetic lubricants. High disposal costs of used lubricants also contribute to the application of synthetic lubricants, so that the expected trend of increase in their consumption is at the rate of about 10% per year.

Nevertheless, mineral oils obtained from crude oil still have the largest application in industry. Improvements in the manufacturing technology, together with the already mentioned hydroprocesses, give high quality base oils.

Generally, the selection of the base oil has the primary influence on the following characteristics of industrial lubricants: viscosity stability, volatility, low temperatures fluidity, solubility of additives and contaminants, deemulsibility, air release and foaming, oxidation and thermal stability.

Typical industrial oils cover viscosity grades from ISO 32 to ISO 460.

In contrast to conventionally refined oils, base oils obtained by hydroprocesses usually belong to lower viscosity grades (Tab. 2).

Table 2. Viscosity range of base oil as a function of the production procedure

Base oil type	ISO viscosity group
Conventionally refined	10 - 460
Hydrofinished	10 - 460
Hydrotreated	22 - 100
Hydrocracked	22 - 46

By comparing them with viscosity grades most frequently applied in industrial oils (Tab. 3), it can be seen that base oils obtained by hydroprocesses can be used only for lower viscosity grades. In this respect special restrictions exist for those base oils that are produced by hydrocraking [11].

Table 3. Typical ISO viscosity groups for industrial lubricants

Hydraulic fluids	15 - 150
Turbine oils	32 - 100
Circulating oils	150 - 460
Industrial gear oils	68 - 680
Air compressor oils	32 - 150
Greases	15 - 460

Other factors that have to be considered when applying hydroprocessed base oils are solubility and dispersivity. Most industrial oils with a greater content of additives - hydraulic oils, gear oils, and others - require good solubility or dispersivity of additives and contaminants, in order to control sludge or deposit formation, and thus to extend the drain intervals and oil filter life.

A proper selection of the base oil, together with a balanced system of additives, is the fundamental approach in the manufacturing of highly productive industrial lubricants. The possibility of a wider application of base oils obtained by hydroprocesses will require new technologies that will produce wider ranges of base oils viscosity.

Basic types of lubricants, most frequently applied in industrial practice, are hydraulic fluids, gear oils, metalworking fluids and total loss lubricants.

4.1. Hydraulic fluids

Hydraulic fluids, whose consumption ranges from *15* to *20%* of the total lubricant consumption, represent an important group of lubricants. Their application is wide and it includes mobile machines and stationary equipment, machine tools, plants and equipment in food and beverage industry, etc.

Possible trends in hydraulic fluids development are illustrated in Table 4 by the example of Germany.

Table 4. Future development of hydraulic fluids in Germany

	1995	2005
	%	
Rapidly biodegradable lubricants	4	50
Incombustible fluids	7	10
Mineral oils based fluids	87	35
Others (PAO, HC)	2	5

It is obvious that a significant increase is expected in the application of biodegradable products, based both on vegetable oils and synthesized esters.

The future hydraulic fluids will have to satisfy a series of technical criteria - low temperature characteristics, resistance to aging, compatibility with sealing materials, hydrolytic stability, as well as to fulfill certain ecological requirements - not to contain hazardous materials, to be biodegradable, nontoxic, and not to pollute waters above the legally permissible values.

4.2. Metal working fluids

Metalworking fluids also constitute a large and for manufacturers very attractive group of lubricants. The largest estimated consumers of these fluids are USA with *36%*, followed by Asian countries with *30%*, Europe with *28%* and the rest of the world with *6%* [12].

According to their application metalworking fluids are divided into four groups: removal fluids or cutting fluids, forming fluids, protecting fluids and treating fluids. Cutting fluids are the largest group with the share of *54%* of the total consumption of metalworking fluids. The second largest group includes forming fluids (*28%*). These are followed by protecting fluids (*11%*), while the treating fluids' share is *7%*.

There are two categories of products in the cutting fluids group: straight oils and water-miscible products. Their ratio of consumption in three largest industrial regions in the world is shown in Figure 3.

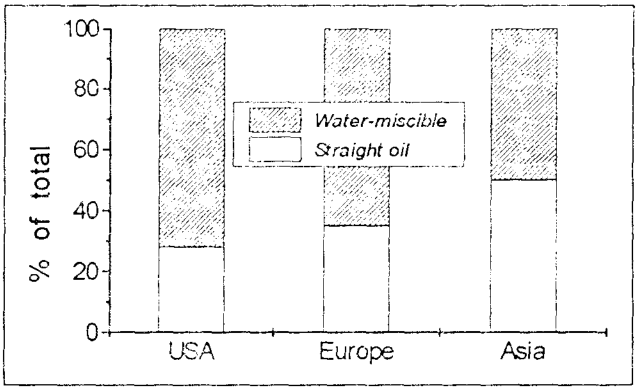

Figure 3. Estimate of the consumption ratio of straight oils and water-miscible products for three industrial regions

In Europe there is a tendency to apply hydrocracked oils, as they produce smaller oil mist, they evaporate less and are less cancerogenic. Restrictions are imposed on the application of certain additives (e.g., chlorine), primarily for the reasons of environmental protection.

It is obvious that for cutting fluids, like for all other lubricants, there exists a requirement for protection and safety, and that in product evaluation the possibility of waste disposal and the price are also taken into account.

However, where the application of cutting fluids is concerned, problems appear in flexible machine systems, as modern manufacturing systems. These systems are expected to machine the working piece as fast as possible and with least operator interventions and least setup time. In order to achieve this, sophisticated mechanical and electronic systems are needed, with high hydraulic pressures. Through the application of such systems higher productivity is achieved.

Fundamental problems appearing in their operation are related to process fluids (lubricants, hydraulic oils, cutting fluids). Their interactions can often result in destabilizing both the cutting fluids and lubricants, regardless of the fact that individually they were properly selected. Because of this, Mercedes for instance, is considering to eliminate water-miscible fluids in its production plants, and to use only straight machining oils, which are totally soluble with lubricants, and compatible with all materials that are used in machine tools manufacturing.

4.3. Total Loss Lubricants

Total Loss Lubricants (TLL) constitute about *7%* of all applied lubricants. According to their characteristics they are very different, but they have one common property and that is that they are, due to the way of their application, significant pollutants of waters and soil. This is the reason why in the future the application of biodegradable lubricants is expected, whether of vegetable or synthetic origin. Basic areas of the application of these lubricants are given in Table 5.

Table 5. Future Total Loss Lubricants

Grease applications	Rapidly biodegradable lubricants (esters)
Chain oils	Rapidly biodegradable lubricants (esters)
Mould release oils	Rapidly biodegradable lubricants (esters)
2 Stroke oils	Rapidly biodegradable lubricants (esters) Smoke-free combustion in motor bicycles (polyolefines)
Other applications of TLL	Rapidly biodegradable lubricants (esters)

5. CONCLUSION

Permanent technical progress, ecological aspects and economic factors (TEE) dictate the new qualities of lubricants. Of all base oils, that constitute *90%* of total quantity of produced lubricants, the ones that will be most applied in the future are hydrocracked oils, polyalphaolefines and biodegradable products obtained form natural raw materials. These base oils, together with the new types of additives give lubricants with optimal performances, which satisfy the TEE requirements.

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RESEARCH

S. TANASIJEVIĆ

Characteristics of Existence and Development of Macine Elements Tribology

Tribology of machine elements is the new concept of application of tribological knowledge in analysis of operation, design and constructing of machine elements, as carriers of elementary functions in the general structure of machine systems. The common goal and obligation is to obtain "tribologically proper constructions" as the most significant quality indicator.

Keywords: *Tribology, Design, Machine elements*

1. INTRODUCTION

In contemporary mechanical engineering, machine elements represent the irreplaceable group of general or special purpose of many machines and mechanisms, that, in many cases are determining the value of technical parameters of the machine systems into which they are being built. Regardless of that whether the machine element is a part, sub-assembly, assembly, or a group, its role in performing the elementary functions is irreplaceable in the general structure of the machine system.

Tribology, as the new science on friction, wear, lubrication and mutual interactions of the surfaces in contact during their relative motion, has found its practical application in machine elements very fast. Nature of tribological processes and natural inevitability that machine elements wear during exploitation, have caused the necessary need for minimizing this process down to the limit of being possible. The fact that majority of machine elements is being removed from application due to excessive wear have caused that, within tribology as a science, the special area is developing: the machine elements tribology and tribology of design. Their main task is to obtain "tribologically proper constructions", as the important quality indicator of the machine elements and the machine system as a whole.

Present modest results in the area of machine elements tribology and of introduction of tribology in the design process, are the evidence of complexity of tribological processes, and also the evidence of certain opinion that both tribological processes and tribological errors can be corrected later in exploitation. Thus improving of constructions and making of machine elements, development of new highly productive and economical technological processes for increasing the reliability and working life, are directly related to significant introductions of tribology and tribological knowledge. And those are the tasks of the general social importance.

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2. TRIBOLOGY AND DEVELOPMENT OF THE MACHINE SYSTEMS

Historically considering, development of each science is different, but in the final prospective the goal was always the same: development of the new and better product, servicing the society with the new offer, for the sake of increasing both the general and individual standard. Development of each science had always assumed the necessary complex of highly intellectual enterprises, undertaken in the aim of progress of society and the community as a whole.

Existence and development of technical sciences was closely related to production of technical systems, improvements, renewal and manufacturing. Thus, at early stage of development of mechanical engineering, the technical sciences were developing, like: theory of cutting, science about metals, machine tools, technology of machine building, etc. Design, and especially methods of design, came on later. Scientific fundamentals of technical systems development entered the practice of manufacturing companies, and they serve in the basic sources of information of specialists from different groups, only after the batch product development. Typical example of the close relation between the production and science is development, creation and realization of electronic computing machines, as well as development of space science and technology.

Application of tribology in design and constructing of technical systems, and accordingly in development of machine systems, was completely lagging behind the application of other technical sciences. Tribological information were optional for application and use. Constructors were trying to increase working reliability and eliminate failures, and they considered wear as one of other requirements. For a long time constructors were calculating that computation of machine elements for their static strength, permanent strength and stiffness, can be the necessary warrant of reliable and efficient operation of each machine. For individual working conditions of machines it was really the like situation. But the years went by. Technical progress persistently required increase of power, operating speeds and loads, in order to increase the working productivity. Machine elements were operating in more and more severe working conditions. At that point and time distance, the attention was devoted to causes of failures, and sometimes to sudden depleting of their projected working resources. More detailed analyses have shown that the most frequent cause was excessive wear and tribological processes on vital machine elements and assemblies. That was especially obvious in oil and gas industry, mining and agricultural techniques.

Problems of increasing the wear resistance of machine elements and assemblies suddenly became actual. That problem was again solved by increasing the strength. In individual cases, the problem of increasing the wear resistance was solved by choosing the steel of higher hardness. For a long time steel was considered as analogous to wear resistance. Later, materials were substituted by lubricant, thus the problem of decreasing wear were for a long time solved by adequate choice of lubricant.

Long and difficult penetrating of tribology into the science of deign and scientific disciplines like: machine elements, machine tools, etc., can be explained in several ways, and from different points of view. The essence of tribology, as a new scientific discipline, is such that form the beginning it involved: engineers, chemists, technologists, metallurgists, physicists, and others, each from their own aspect. Such a wide ray of possible interests is, certainly, an important characteristics of tribology, since it is, by its nature, interdisciplinary. At the same time, just because of that, it was not, for a long time, applicable, since the information of fundamental research could not sufficiently satisfy practical needs of design and constructing.

Another aspect of insufficient application of tribology in mechanical engineering is absence of coordination in conducting the tribological investigations, regularly planning of publishing the tribological information, noticing priority directions, and unsynchronized development. Thus, even today, there exists several versions of wear types classifications, methods of wear tests, wear evaluations, wear resistance, wear intensity, etc. Certain lack of system in development of tribology as a science has contributed to the fact that majority of information had accidental character, and was in no way related to practical needs of design and constructing.

From these reasons, it turned out that very small number of tribological information is applicable in practical design and constructing, especially in the form of handbook literature. The list of books and handbooks that can be recommended to constructors-designers is very limited. On the other hand, in engineers potential of the largest production companies there is no position of the main tribologist, analogously to the main designer, main metallurgist, main technologist, etc.

The larger devoting of attention to tribology and its application in machine elements and systems in general, started at the beginning of seventies, with the sudden increase of exploitation regimes of machines. The trucks carrying capacity was increased from *1.5* tones to *150-200* tones, the speed of rail road and automobile transportation was increased, the qualitatively new airplanes appeared. Practice of increasing the wear resistance by choosing better steels ceased to be efficient. Development of science about metals apparently was lagging with respect to development of designers requirements in all areas of mechanical engineering.

Today, there is significantly more tribological knowledge about machine systems, or tribology of machine elements and systems is today a very important field in the science of design. The best illustration for that is that the newest ISO recommendations for computation of the gears carrying capacity, out of four criteria for computation, three have wear in their bases: criterion of teeth sides strength, calculation of carrying capacity with respect to scoring, calculation of carrying capacity with respect to wear.

To the fact that tribology has deeply penetrated into the machine systems of the most complex constructions and highest technologies, also testify the efforts that Russia, Japan and United States have put into development of tribology of space technical systems. The fundamental tribo-mechanical systems, into which is put a lot of tribological knowledge, and which are built into modules and components of space stations are: rolling ball bearings, journal bearings, spiral ball mechanisms, gears,... . Lot of tribological knowledge is also built into the special bearings of rocket engines, ball bearings for operation in the outer space conditions (vacuum, wide range of temperatures, zero gravity conditions, radiation), highly loaded gears for positioning in distance control systems of manipulators. etc.

Apparently, the time that is coming, requires larger application of tribology in the area of machine elements and systems, and the number of scientific information from this are is going to be larger. Still remains the problem of their applicability and searching for the shortest way to practical design and constructing.

3. TRIBOLOGICAL PROCESSES IN MACHINE ELEMENTS

Contemporary classification of classical machine elements to: elements for connection, elements for power transmission, elements for rotational motions, and elements of armatures and hydraulic installations, did not diminish the global need for analysis and identification of arisen tribological phenomena and processes. In the frictional contact zone of any machine element appear complex non-stationary physical-chemical and mechanical processes, of stochastic nature, determined by the non-unique influence of numerous factors. Let us mention only the most important ones: physical-chemical and mechanical properties of elements in contact, medium, roughness, manufacturing accuracy, load (magnitude and character of variation), speed and acceleration, temperature of contact surfaces, etc.

Processes on contact surfaces are, by their nature, stochastic and of continuos duration. Non-unique influence of numerous factors leads to ambiguous results: magnitude of the friction force and wear.

Complexity of tribological phenomena in machine elements, especially in elements for power transmission and elements for rotational motions, does not imply that the processes of friction and wear are totally out of control. Modern knowledge and available information of theoretical and application tribology enable partially reliable regulation and control of processes that occurred on contact surfaces of elements in relative motion (the friction couple).

Analyzing the methodology and mechanisms of machine elements operations, and in order to classify the complex processes on contact surfaces, and exploitation cycle systematically decompose, the general picture is formed of the dynamic cycle of machine elements operations, Figure 1. The system analysis of each block enables explanation of complex phenomena in the contact zone, noticing of the order of complex relationships of many factors, and, finally, noticing of their influence on the working life of each machine element. The block-scheme of dynamic cycle makes possible for each researcher to, according to his own preferences, find the area of his own scientific and production work. It is necessary to notice that the scheme of dynamic cycle can be expanded, more detailed decomposed in each block, and in all directions.

Analysis of initial conditions influence on tribological processes, friction, wear and working life of machine elements, shows that, until now, the most is done in the area of influence of material, that was, for many years, the basic regulator of increasing the wear resistance. Materials are mainly metals, but the more prominent becomes application of synthetic materials and composites.

Metallurgical problems of making steels and alloys highly resistant to wear are very complex. Steels and alloys resistant to wear must possess, not only high static and permanent strength and hardness, but also stability against heat effects, that are inevitable in tribological processes. According to certain data, the better wear resistance possess steels with carbide hardening. Steels of other structural classes: perlite, austenite, martensite, ferrite, and others, have more than three times lower wear resistance.

Application of non-metallic materials and composites is the new direction in development of machine elements with higher wear resistance. That is especially referred to for journal bearings, where today, besides the classical materials are also used multi-layer material with metallic basis, homogeneous non-metallic materials and non-metallic materials with filament.

Modern trends of introducing the non-metallic materials into the machine elements production are realized also in the manufacturing of plastic chains. They are chemically resistant, non-magnetic, do not require lubrication, and they are resistant to corrosion caused by alkaline materials, acids and salts.

Due to high manufacturing technology of lubricating agents manufacturing, it is justified to state that the significant influence of lubricants on wear and working life of machine elements is evident. Special importance in the lubricants industry is assigned to manufacturing of new and better quality additives, which improve quality of lubricants. From the aspect of tribological processes on machine elements contact surfaces it is of special importance to improve quality of additives for protection against wear and additives for protection against . Combination of different additives shows significant effects, and that is why their application is the way to further development of higher quality and more efficient lubricants.

In past few years especially was noticeable development of solid lubricants for lubrication of machine elements (bearings, gears, spiral shafts) that operate in specific and difficult working conditions. Lubricating layers based on compound of molybdenum disulfide have shown the better tribological characteristics with respect to classical lubricants that were used until now.

Considering application of tribological knowledge in practical design and constructing, it should be stated that the most accepted are information about influence of materials and lubricants on tribological processes and

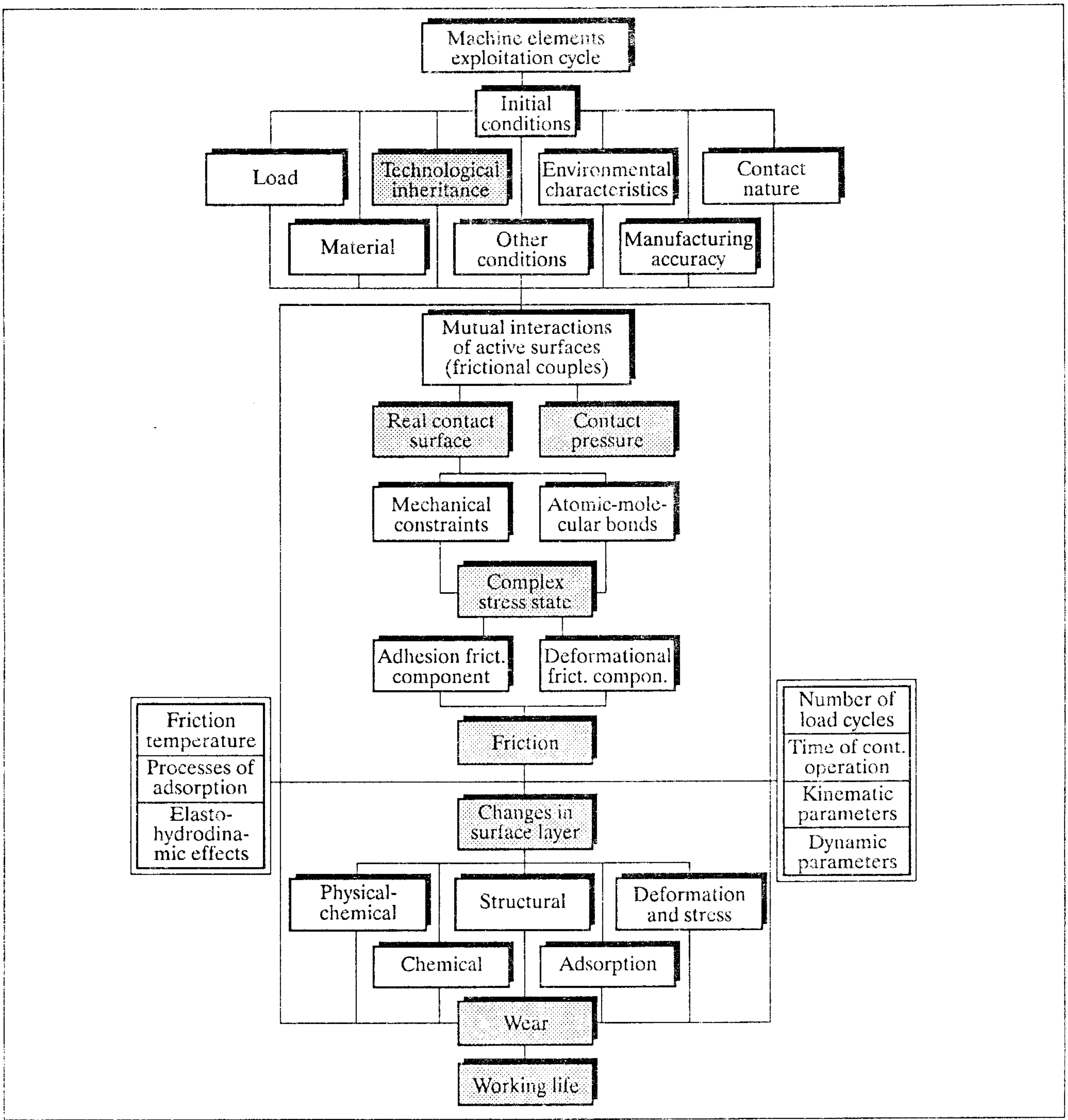

Figure 1. General picture of machine elements exploitation cycles

working life of machine elements. Influence of large number of other factors, that define initial and additional conditions, that appeared in the friction and wear processes, is still poorly investigated, and even less accepted in practice. All these testify about necessity of more intensive development of machine elements tribology, and also point to the fact a long time will pass until the complete definition of tribologically proper construction.

Speaking of further directions of development and influence of numerous factors on tribological processes and working life of machine elements, let us only state that today in technical world is more and more present theory about technological inheritance and its influence on processes of friction and wear. Technological inheritance is relatively new theory on transfer of properties and characteristics of the object from previous to future technological operations. Hereditary information carriers are material and its topography. Inherited properties, in the phase of technological operations, to the significant extent project the type and dynamics of the wear process, exploitation characteristics and working life of machine elements.

Accepting the fact that today in technical world exists inadmissible limited number of information from the area of tribology of the real machine systems, and that influences of numerous individual factors on processes of friction and wear are insufficiently known, let us remark that the similar situation exists when one considers friction and friction mechanisms of machine elements. This is especially expressed in modern mechanical power transmitters by friction (frictional, belt and chain), where the process of opposing the relative motion is used for the basic function and purpose of transmitters. The mechanism of power transmission by the idle friction is still insufficiently understood, and especially are insufficiently known previous displacements, relative micro-displacements, at which theses processes occur.

4. MACHINE ELEMENTS WEAR

Wear is, in general sense, any type of material removal from the contact surfaces. Simultaneously, that is also the natural process, that can not be avoided, and which accompanies operation of each machine element and machine system as a whole. Consequences of wear are changes of system's technical parameters, changes in functioning, and finally, removal from exploitation, or in the extreme case fracture and failure.

Period of functional aging of machine systems is, in principle, significantly longer than the period of permissible wear of machine elements. Physical wear of elements (*1.5* to *2* years) occurs much faster than the functional (moral) aging (*5* to *10* years) of a machine system. Limiting tendency is to reach their equality, since at present time such an accord does not exist. Main task of tribology is to minimize breaks between these two periods, up to the possible limits.

The nature of the wear process, possibility of indirect and direct identifications, as well as possibility of measurement, have caused that today wear of machine elements is used as the most natural criterion for evaluation of the operating condition during the exploitation period. Furthermore, wear is now even more used also in criteria for machine elements computations. The best example for this are computations of gears. The calculation of chain transmitters is based on permissible change of the chain step due to elements wear ($\Delta h = 3\%$), at nominal working life of *15000* hours.

In Table 1 are presented results of many years long analysis of the most characteristic phenomena and the most frequently present types machine elements wear. At the same time are presented the fundamental recommendations for minimizing the wear process and slowing down its further development. Possibilities exist in design, technology and exploitation domains.

Fatigue wear (pitting) is the most frequent, and at the same time the most characteristic form of machine elements wear. Some information indicate that the phenomena of pitting represents about *90%* of all wear phenomena on industrial and ship gears. Today, this type of wear is studied relatively good, and the general principles of its appearance, development and influence on the machine elements working life and reliability are known. However, besides that, there are still some unanswered questions in the phenomenon of pitting, like the appearance of cyclic destructive pitting, influence of technological inheritance, relationship between pitting and working life, etc.

Abrasive wear is the frequent form of wear of machine elements that operate both in conditions of open and closed systems. The majority of available information exist and the most is known about abrasive wear of gears (investigations of Tonn, Hrušov, Babičev and others). There are significantly less information about other machine elements (especially rolling bearings and belt transmitters). Especially are needed investigations about the influence of concentration of abrasives in lubricant, influence of number of revolutions, slipping, etc.

Scoring is the type of wear of relatively recent times, and contemporary trends of designers to transmit as large as possible loads with sizes that are as small as possible. This natural discord leads to increase of mechanical and thermal stresses and destruction of the integrity of the limiting lubricating layer. Scoring can appear in several different forms (cold welding, scuffing, seizing, galling, etc.), what renders more difficult identification, removing and slows down further development. Especially interesting area of further investigations is influence of roughness on appearance of scoring, since in technical literature, for now, there is no unique opinion.

Corrosion, as characteristic form of tribo-chemical wear, is frequently present in exploitation of machine elements. Present interests of researchers are directed towards development of new oxidation inhibitors, investigations of influence of composition and degree of machining of contact surfaces, as well as influence of straining structure.

Fretting and fretting corrosion are types of wear that are recently identified, and that appear in exploitation of specific machine elements (groove connections, clutches, ...). Today, in specialized technical literature can already be found impressive number of information about their appearance and development. Due to their reliable identification, they are convenient for evaluation of contact surfaces condition in exploitation, and preventive maintenance (chains for instance). Directions of further investigations are aimed towards possibilities for minimizing wear by constructive improvements, towards new damping materials, and new technology of surfaces protection against corrosive-fatigue processes.

Table 1. The most frequent types of machine elements wear

Type of wear	Machine elements	Main causes of appearance and development	Main recommendations for removing and slowing of further development	
			On elements	In lubricant
FATIGUE WEAR (PITTING)	• Gears • Rolling bearings • Belts • Journal bearings • Frictional trans-mitters (lubricated) • Seals	Cyclic straining during the longer period Material inclusions Overloads and stress concentrations	Reduction of contact stresses and frequency of cyclic strains Application of high quality materials Application of the adequate machining regime (hereditary characteristics)	Application of cor responding oils of higher viscosity and adequate additives
ABRASION		Solid particles contained in oil Insufficient material hardness Hard, rough metals in contact with the softer material	Removal of abrasives by improving the air and oil filters Seal improvement Addition and more frequent oil replacement Increase of metal surfaces hardness	Application of oil clean of abrasive particles Application of more viscous oils
SCORING	• Gears • Chains • Journal • Bearings • Rolling bearings • Metal seals • Puey	High loads, speeds, and temperatures Application of stainless steels or aluminum Insufficient lubrication Lack of additives Operation without running in Abrasive wear	Reduction of loads, speed and temperature Cooling improvement Application of compatible materials Application of surface coatings (e.g. fosfatizing) Surface modification (e.g. ionic transplantation)	Application of more viscous oils Application of "extreme pressure" additives (anti-scoring additives)
CORROSION	• Bearings • Gears • Belts • Seals	Corrosive environment Corroded metals High temperatures Corrosive lubricants	Application of non-corrosive materials Lowering of working temperatures Removing of corrosive contamination sources	Application of corrosion resistant lubricants Avoiding of high pressure oils Application of fresh oils
FRETTING CORROSION	• Grooves, wedges • Clutches, flanges • Chains • Bearing outer ring	Vibrations and small oscillatory displacements in conditions of corrosive environmental actions	Increase of assemblies strength Application of damping materials Surface protection against corrosive fatigue process Preventing of intermolecular bonding	Application of lower viscosity oils More frequent lubrication Application of the oxidation inhibitors

5. CONCLUSION

Tribology of machine elements is the new concept of application of tribological knowledge in analysis of operation, design and constructing of machine elements, as carriers of elementary functions in the general structure of machine systems. The common goal and obligation is to obtain "tribologically proper constructions" as the most significant quality indicator.

Present modest results, especially in practical applications, are not satisfactory, but the encouraging is the fact that the knowledge has matured that the time that is coming will require larger application in area of machine elements and construction as a whole. The growing number of scientific information from this area and their practical application are promising.

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RESEARCH

M. BABIĆ

Tribology and Energy

Fundamental problem that humanity is facing with comes from opposite requirements that are enforced simultaneously, for providing sufficient amount of energy for the growing needs, for preserving the non-restorable energy resources and for decreasing ecological loads of the environment.

Urgent need to minimize this problem is apparent in view of the powerful development of the new, so called environmental technologies, like energy savings, clean energy, renewable energy resources, waste management, recycling, and environment monitoring. Considering the scenarios for the 21st century about the exponential growth of the energy consumption, it is clear that the most important place belongs to energy savings. Having in mind the dissipative nature of the two basic tribological phenomena - friction and wear, tribology today, as the multidisciplinary concept, is accepted as one of the most important chances for contribution to general efforts for both direct and indirect savings of energy.

1. INTRODUCTION

Fundamental problem that humanity is facing with comes from opposite requirements that are enforced simultaneously, for providing sufficient amount of energy for the growing needs, for preserving the non-restorable energy resources and for decreasing ecological loads of the environment. The degree of systematic dealing with this problem is directly related to the degree of the country's development.

In developed countries efforts for decreasing this problem result in development of the new, so called environmental technologies, like the energy savings, clean energy, renewable energy resources, waste management, recycling, and environment monitoring [1]. Considering the scenarios for the 21st century about the exponential growth of the energy consumption and further dominant part of fossil energy resources, it is clear that the most important place belongs to energy savings. Having in mind the dissipative nature of the two basic tribological phenomena - friction and wear, tribology today, as the multidisciplinary concept, is accepted as one of the most important chances for contribution to general efforts for both direct and indirect savings of energy and ecological protection of the environment.

In many countries (England, Germany, USA, Japan, Canada, China) large funds were and are invested today into research that have as a goal to identify areas of largest "tribological sinks" and to economically express losses and potential savings, as well as to define main directions of research, development and education in order to realize estimated savings [2-8]. Taking into account the world experiences in this area, it can be expected that paying the adequate attention to tribology will result in savings (of energetic character) of up to 2% of the gross national product. Up to 20% of these effects can be achieved without significant investments.

A topic like energy savings through tribology, assumes a broader approach to tribology as a science and technology. That approach should highlight direct easier to spot, but also indirect-hidden, relations between the contact phenomena during the relative motion, that are of the dissipative nature, and their effects on different macro levels of expressing. Just the existence of such relations represents the basic power of the exponential development of tribology in the last thirty years.

In this paper is given the global approach to problem of energy savings through tribology. It enhances relations between micro-dissipative contact phenomena of friction and wear, and negative effects that are expressed as direct or indirect energy losses, as well as the estimate of basic tribological sinks and possible energy savings through tribology.

2. DISSIPATIVE NATURE OF FRICTION AND WEAR

Friction and wear represent fundamental processes during the relative motion of solids, liquids and gasses, that are of stochastic nature, and that are manifested by dissipative, nonlinear dynamic effects in the contact zones.

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On the micro level, friction is occurring through interaction of micro-roughness, i.e., through dissipative process of forming and breaking of micro-contacts. The total resistance to relative motion, i.e., the friction force represents the sum of the resistance micro-components (resistance to elastic deformation, plastic deformation, jamming of micro-roughness, and breaking of adhesive bonds) on the total real surface, and dissipation of energy is a sum of elementary dissipation processes.

Energy dissipation occurs through increase of contact temperature and heat losses, increase of internal energy of contact layers materials (defects, dislocations) and emission (photons, Cramer's effect, photo-luminescence).

The sliding friction is accompanied by complex wear process - forming of surface layer interacting with the environment, adhesive transfer between the contact surfaces, and generation of the wear products (basic material, reaction products and transferred material), that is happening through mechanisms of surface fatigue and abrasion.

These processes of prominent scientific importance, though on academic level sometimes neglected due to the complexity of the problem, have unavoidable technological consequences, and are manifested in the most various systems that are performing:

- Kinematic functions (generation, guidance, transmission, restraining of motion)
- Dynamic functions (forces transfer through contact surfaces)
- Work and mechanical energy (transfer and transformation of mechanical energy)
- Transportation functions (transport of solids, liquids and mixtures)
- Machining and material forming (manufacturing of components, products and functional surfaces)
- Information technologies (generation and signal transmission), etc.

Table 1. Tribomechanical systems

Input	Output	Primary technical function	Examples
Motion + Work	Motion	Motion guidance Motion transmission Motion restraining	Bearings Clutches Brakes
	Work	Power transfer (mechanical, hydraulic, pneumatic)	Gears Cylinders
	Information	Generation of information	Cam gear
Motion + Material	Material	Reproduction of information	Sensors and carriers of information
		Transport	Wheel/track
		Machining	Metal cutting

All these systems represent the so called "tribomechanical systems", of more or less complex structure, with input and output variables. There, as the input variables usually appear motion+work and motion+material, and as output variables motion, work, information and material, depending on the primary function the system is performing (Table 1).

In the process of tribomechanical systems functioning friction is manifested the most directly and obviously, causing direct energy loss (Figure 1), affecting in that way the input/output relation and powering the system's efficiency ratio.

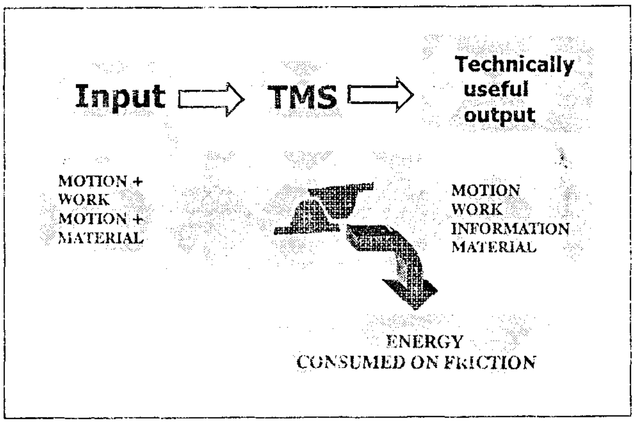

Figure 1. Energy losses of a tribomechanical system

Wear is timewise irreversible process, that has clear and characteristic dependence on time, known as the wear curve (Figure 2). Worsening of different aspects of technically useful output corresponds to this curve. Namely, wear primarily causes change of the system structure (condition of the contact surfaces and layers, forms and clearances), what negatively affects different aspects of functioning, and leads to failure. For friction there is no such a clear relation, though one can speak about existence of correlation between the increase of wear and increase of losses due to friction.

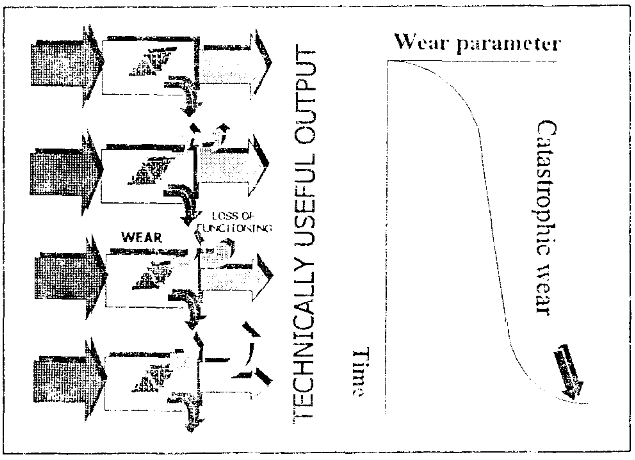

Figure 2. Tribological consequences of friction and wear

3. TRIBOLOGICAL ENERGY LOSSES

Tribological processes, thus, inevitably cause direct energy and material losses, and with time this becomes apparent as worsening of the system's functionality and failure. In order to decrease, prevent and eliminate negative consequences of friction and wear, different maintenance activities are being undertaken. On the other side, tribologically shorten working life of technical systems, contained in various equipment, manufacturing means, transportation means, etc, as a consequence has a need for new investments. Considering that, the negative consequences of tribological processes (tribological losses) can be identified on different levels (Figure 3).

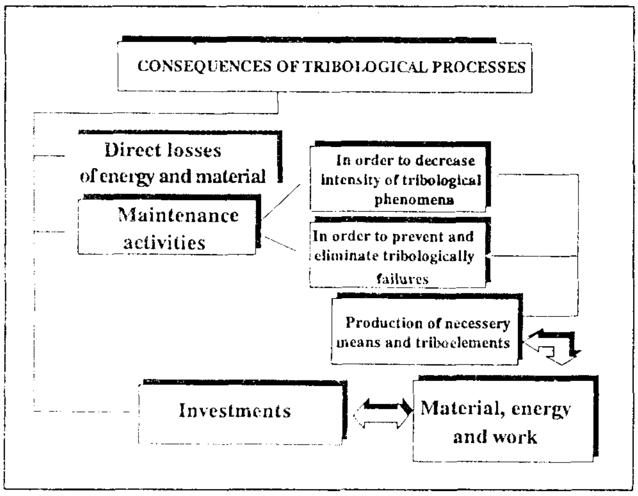

Figure 3. Global consequences of tribological processes

The most globally considered, they can be of direct and indirect character (Figure 4) with respect to tribological processes [2].

Direct losses are immediate energy loss due to friction, and material loss of contact elements due to wear, as well as losses related to maintenance. It combines different activities, like monitoring of changes in conditions of both components and systems, diagnostic of their functions, as well as definition and undertaking of concrete actions of cleaning, lubrications, regeneration, repair, elements replacement, etc., what is, however, related to production of necessary means for maintenance and spare parts.

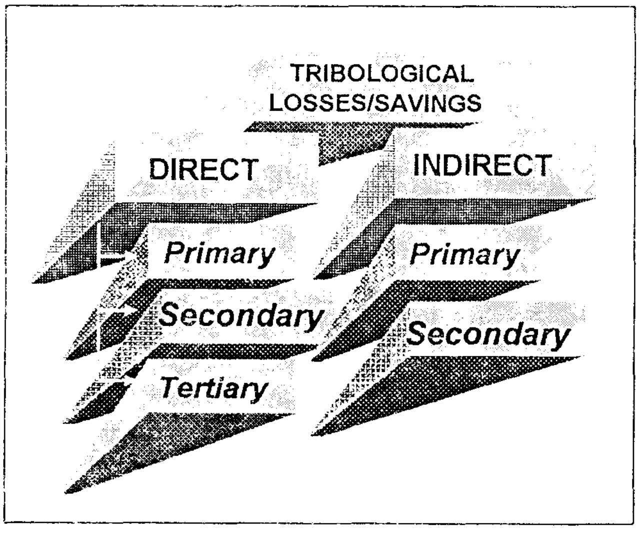

Figure 4. Global classification of tribological losses/savings

Direct energy losses due to friction are marked as primary direct losses. These losses are the easiest to spot, and in superficial approach to the problem they are assumed as equal to total losses of tribological nature. The truth is that in total lost energy, in technical systems functioning, the large share belongs to losses due to friction. Thus, friction is the important cause of low efficiency ratio of technical systems.

The secondary direct losses are mainly related to necessity of producing and replacement of the worn critical elements of the tribomechanical systems, and lubrication in order to decrease intensity of friction and wear. With that it should be kept in mind that the requirement for simultaneous decrease of friction and wear is not always present, what is compatible. Sometimes is present the requirement for increase of friction and simultaneous decrease of wear (wheel/track, car tires/road, brakes, frictional transmissions, etc.). Material machining for replacing the worn elements assumes set of technologies in which the energy is consumed, what can also be quantified energetically.

The tertiary direct losses, namely savings, are mainly related to material for manufacturing the worn elements. Amount of losses/savings is proportional to energy equivalent of material and price. Every loss/saving on the primary level of lowering the friction and wear most frequently results in even higher effects on the secondary and tertiary level.

Same as primary and secondary losses, the tertiary losses also have dimension of energy. Namely, the metal machining procedures, as well as the material itself that is used for manufacturing the triboelements, have their own energy equivalent [2].

Indirect losses/savings come as a consequence of direct ones of any kind. Losses due to delays (primary indirect losses) are economically very important, but they do not have the energy dimension. The secondary indirect savings of tribological nature reflect on the capital investments plan, and not only through money, but also through energy and material. Here we think of investments that are consequence of tribologically decreased working life of equipment, as well as the need for increasing the efficiency.

4. POSSIBLE TRIBOLOGICAL ENERGY SAVINGS

In view of very large tribological direct and indirect losses, it is essential to answer the following basic questions:

- In which areas are possible the most significant tribological savings?
- What is the structure of changes with respect to their tribological origin?
- How large are the global savings?
- In what way can the savings be realized?

Although the tribological processes are present everywhere, it is clear that the largest savings can be realized in areas of largest energy consumers. Based on analysis of several reports in this area, for industrially developed countries, industry, transport, and households can be singled out as the individual largest energy consumers. Their shares in the total consumption are:

- industry with *30-38%*
- transport with *20-26%*
- households with *21-27%.*

From the standpoint of the energy balance, there should be kept in mind that only *65.9%* of the energy, on the average, reaches the final consumer, while *27.7%* is lost still in the production phase [4]. Energy that is available to final consumers, is thus spent mainly in the three enumerated areas.

Tribologically relevant is only that energy which is spent on realization of relative motion in all kinds of tribomechanical systems, what can conditionally be identified as the driving energy. In view of the fact that in households the available portion of energy is primarily spent on various other needs (heating, lights, etc.), it is clear that industry and transport are the areas of primary tribological interest, and before all:

- road transport
- energetics
- extractive industry
- metallurgy
- metal working industry
- cement manufacturing industry.

To realistically consider energy that is spent tribologically (whose part that can be saved) it is necessary to have at one's disposal data on balance of energy that is spent by consumers in the areas of the largest consumption.

Based on results of investigations reported in published reports, it can be concluded that the useful energy amounts to little over *50%* in the area of industry, and below *20%* in the area of transport. There, the share of the driving energy (power) in the used energy is estimated to somewhat over *10%* in industry, and about *99%* in transport. Having this in mind, it is obvious that the greatest chances for energy savings through tribology are in the area of transport.

As an illustration for the energy consumption on overcoming the friction resistance and for potential savings, can serve some of the examples in the mentioned critical areas. Thus, in the case of energetics, that in the general sense includes obtaining of the energy carriers (coal mines, petroleum exploitation, etc.), and its production, energy losses on friction are *8 - 10%*, what in FR Germany in 1982. was equivalent to *1.1* to *1.6* billions of German Marks (DEM), [4]. In industry losses due to friction, in the driving energy portion, vary, depending on the production processes technology and used equipment, from *8-15%* in mining to *5-8%* in food producing industry. In the area of traffic the largest portion of energy is consumed in road traffic. Out of that, *80%* are tribological losses.

How important total energy losses through friction are in all areas speaks the data that on the annual level in 1978. in USA they were estimated to 4.22×10^6 *TU*, what is equivalent to *20* billions US $, [3], what is exactly equal to total annual energy needs of city of New York.

Table 2. Losses caused by friction and wear in FR Germany [4]

	Annual losses (billions DEM)	
	Due to friction	Due to wear
Industry	1.60-2.70	6.77
Households	0.20-0.40	0.16
Traffic	5.96-10.73	13.26
Small consumers	0.20-0.50	4.80

Tribological losses due to wear of critical elements in tribomechanical systems of various technical systems, surpass direct losses due to friction several times. This is illustrated by indicators for FR Germany (1981/82) for the group of final consumers shown in Table 2.

By their nature, they include direct costs of maintenance and indirect costs due to delays in functioning of equipment and transportation means. Calculations show that about *2.6%* of the energy consumed in USA refers to maintenance, repair and production of spare parts of vehicles. As an example of "tribological sinks" can serve metallurgy, where tribological losses caused by wear contribute with *40* to *50%* to maintenance costs. Losses caused by tribological reasons, mainly wear, are particularly severe in the so called heavy sector of this industrial branch, i.e., in ore preparation, manufacturing of raw iron and coke, casting and primary rolling.

Voluminous investigations of economical importance of maintenance in Japan, conducted in eighties, have shown that the total costs of maintenance of mechanical systems in 1979. were $8.x10^{12}$ Yen, what represents *3.73%* of total national gross product [7]. There, mechanical systems were defined as equipment and machines in mining, production, transport, communication, energetics, and civil engineering.

Percentage share is different for different branches of industry, and it amounts to 5% for textile industry, metallurgy and paper producing industry, and 2% for food producing industry. Contribution of annual maintenance costs in the purchasing price of more important investment goods, according to data form investigations in Germany, amounts to 1.5 to 15%, and usually is about 6%, same as for industry [4].

Totally spent funds in the maintenance process certainly relate only partially to tribologically caused maintenance. However, data from practice show that in the total number of failures share of tribologically caused ones is quite large. Thus, for instance, out of total maintenance costs for 1982. in Germany in the amount of *46.93* billions DEM portion of *68.9%* (amount of *32.24* billions of US$) is related to maintenance activities that are eliminating consequences of wear.

Enormous tribological losses (1976./77. in USA 100 billions of US$, 1981./82. in FR Germany *32* to *40* billions of DEM, [4]), expressed by economic indicators represent serious motivation for undertaking all possible measures for savings through tribology.

Savings through tribology can be basically reduced to energy, apart from investments in technical means for the sake of extending their working lives. The savings can be realized by improving the tribomechanical systems with respect to lowering the friction and wear. Improvement refers to all the elements in the structure, thus, the contact elements and lubricant (and in certain cases the environment), their tribologically relevant characteristics and interactions.

Fundamental potential in that regard, at this moment, is assigned to tribo-design (construction with implementation of the existing tribological knowledge) of critical tribomechanical systems and to improvement of the lubricants' properties.

Tribological improvements can result in savings in several basic ways:

- By decreasing the amount of energy consumed by friction
- By decreasing the maintenance costs through preserving the functionality and extending the working life
- By decreasing the lubrication costs through better lubrication process and longer working life of lubricants
- By decreasing costs through decreasing delays
- By lowering investments through longer working life of tribomechanical systems.

Possible effects of savings through tribology can be estimated both in particular areas and on the global level. Thus, for example, only in producing of electrical energy in USA annual really possible savings of energy was estimated for 1981. to be *2.8%* of consumption, what corresponded to amount of 4.4 billions of US$ [3]. Also, out of 98 billions of US$ (*107 TU* of energy), that are in this country spent annually for driving in the area of traffic, possible savings on the account of introducing the tribological improvements in road vehicles were estimated to *14.3* billions of US$ (*18.6%* of energy consumed by these vehicles). In FR Germany potential annual savings (1981./ 1982.) trough tribological measures were estimated to be *6.4* billions of DEM (*0.239* in the sector of energy production, *0.298* in industry, and *2.395* in traffic).

So, decrease of friction and wear, through different ways of tribological improvement of tribomechanical systems, i.e., by savings through tribology, are possible on all levels of direct and indirect losses. Energetically expressed, savings are, according to data from 1980./81. in USA, estimated to about *11%* in the group of main consumers (traffic, industry and electrical energy production), what is equivalent to *16.2* billions of US$ per annum.

Example of potential savings according to types of losses, is presented in Figure 5, based on research in Great Britain, [2]. It can be seen that the largest part of them (over *90%*) is directly or indirectly manifested through costs of the corresponding maintenance.

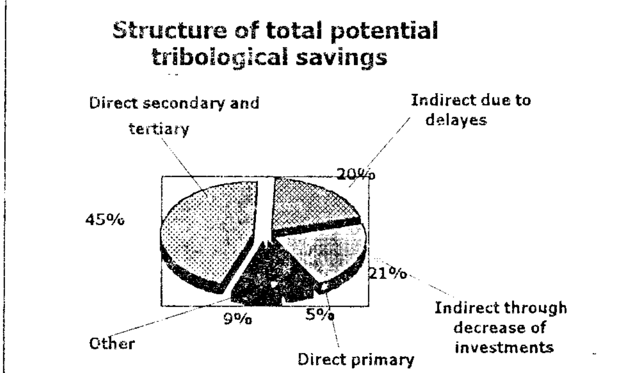

Figure 5. Possible savings through tribology

Total savings, expressed economically, or energetically, are certainly results, primarily of savings in the mentioned areas of largest tribological sinks. However, it should be kept in mind that tribology is of the generic nature, and that the sum of small effects at many places represents significant effect. Thus, for instance, though agriculture, and within it farming, on the global level has a place at the bottom of the energy consumers, data from the report A strategy for Tribology in Canada point to the possibility for annual savings in this area in Canada at the level of *337* millions of dollars.

In the structure of savings through tribology, one can differentiate between savings without research-development work and savings that require research-development work, that can be of medium term or the long term character.

The first group of savings (short term ones) can be achieved by application of the existing tribological knowledge, through increase of motivation, level of education, training and information. Economic effects of such savings can be mainly expected in the period of *3* to *5* years. The second group of savings requires R&D actions accompanied by education, training and information, for the period of up to *5* years. Their effects are expected within the *5* to *8* years period. The third group of savings assumes long term systematic R&D work, where economic effects have now certain prospective. It should be kept in mind that by investments into research and development multifold effects can be achieved (*1:64* [9], *1:40* [9]).

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 *2%* of Gross National Product. Up to *20%* of these effects are achieved without significant investments. The largest part of such savings has their origin in decreasing the costs of technical systems maintenance, replacement of worn elements, and delays due to tribological consequences.

5. CONCLUSION

Tribological processes inevitably cause direct losses of energy and material, with time they disrupt the system structure, what reflects as worsening of its functionality and failure.

In order to prevent, decrease or eliminate negative consequences of friction and wear, different activities of maintenance are being undertaken. On the other hand, tribologically decreased working life of technical systems contained in different equipment, manufacturing means, transportation means, etc., what has as a consequence new investments.

All these consequences of the processes of friction of wear are manifested as the causes of very significant tribological losses, of both direct and indirect character. Consequences of losses can be considered, starting from individual tribological systems, through technical systems, production systems, etc., all the way to consequences on the levels of national economies.

The largest part of these losses can be expressed as the energy loss at the level of the driving energy, and energy that is indirectly and directly consumed in the sector of maintenance.

Decrease of friction and wear through different forms of tribological improvement of tribomechanical systems, i.e., by savings through tribology, can be realized on all the levels of direct and indirect losses. The level of estimated energy savings requires unavoidable organized systematic action, primarily in the field of implementation of existing knowledge in practice, but also on the plan of research and development.

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RESEARCH

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Tribological Behaviour of Surfacing Layers for Continual Casting Rolls

Production of rools for continual casting and rolling mills and their renovation represents a phenomenon which is economically very significant for metallurgists. It can be simply proved that the roll as a tool significantly affects the quality of rolled products and also continuity of production related to its life.

The Welding Research Institute is devoted to these problems for more than 40 years.

Keywords: Tribology, regeneration, surface layer, hardening

1. INTRODUCTION

Production of rools for continual casting and rolling mills and their renovation represents a phenomenon which is economically very significant for metallurgists. It can be simply proved that the roll as a tool significantly affects the quality of rolled products and also continuity of production related to its life.

In the world we ever more often encounter the metallurgical rolls with two, or even more surface layers, where the quality of working surface can be separated from that of base body of the roll. Such is also the principle of rools where the working surface is obtained by welding technologies.

Moreover, the new types of teel rolls [1,2], which were first succesfully used in Japan in 1986 (HSS rolls), have shown great possibilities of their renovation but also their production by welding technologies.

The Welding Research Institute is devoted to these problems for more than 40 years.

We shall indicate what is now available for the mentioned purposes.

2. CURRENT APPLICATIONS

The main advantage of surfacing technology application is a good comtrol over the process micrometallurgy and consequentnly improved quality and purity of the deposited layer, and most recently also fabrication of composite weld overlays.

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The mostly used surfacing technology is submerged arc process (SA). It is used for deposition of block rolls, billet rolls, prefinishing rolls and for the rolls of continual casting lines.

2.1 The parent material

The base metal of surfaced rolls is selected from the following steel types:

1. 0.6%C; 1%Cr; 0.3%Mo - steel in accordance with STN 42 2866.5 (Slovak Standard)
2. 0.8%C 1.%Cr, 0.3%Mo - steel in accordance with STN 42 2865.9
3. 0.5%C; 1%Cr - forged steel in accordance with STN 14 161
4. 0.6%C - forged steel in accordance with STN 12 060.9
5. 0.5%C; 0.8%Cr - steel in accordance with STN 42 2739.5

The choice of base metal depends on overall loading of roll and its dimensions.

2.2 Filler materials

For submerged are surfacing of the rolling mill rolls and rolls for continual casting, the following types of tubular wire and flux cored strip electrodes, including the flux combination from the production of Welding Research Institute Bratislava, the types given in Table 1 are used. [4,6]

In addition to submerged arc surfacing of the continual casting rolls, also open arc self-shielding process is applied. The used type of tubular wires are shown in Table 2. [5]

Table 1: Chemical composition of weld deposits fabricated with flux cored wire (RD) and flux strip electrodes (PP)

No	Mark/ Application	Flux	Chemical composition [%Wt]		
			C	Mn	Si
1	VUZ-RD500 buffer layer	VUZ-F54	0.06	1.30	0.20
2	VUZ-RD503 profile rolls	VUZ-F13	0.14	1.00	0.60
3	VUZ-RD508 blooming	VUZ-F16	0.20	1.00	1.00
4	VUZ-RD522 billet rolls	VUZ-F25	0.20	1.80	0.80
5	VUZ-RD531 hot rolls	VUZ-F13	0.30	1,50	0.90
6	VUZ-RD531 cont. casting rolls	VUZ-F54	0.13	1.30	0,70
7	VUZ-RD534 cont. casting rolls	VUZ-F54	0.12	1.00	0.60
8	VUZ-RD534 cont. casting rolls	VUZ-F54	0.08	0.50	0.50
9	VUZ-RD535	VUZ-F54	0.05	0.50	0.50
10	VUZ-RD537	VUZ-F54	0.08	0.50	0.50
11	VUZ-RD537N	VUZ-F54	0.06	0.50	0.50
12	VUZ-PP531 cont. casting rolls	VUZ-F54	0.13	1.30	0.70
13	VUZ-PP533 cont. casting rolls	VUZ-F54	0.12	1.00	0.60
14	VUZ-PP534	VUZ-F54	0.08	0.50	0.30

Continuation of Table 1

No	Chemical composition [%Wt]					Hard-ness	Type of structure
	Cr	Mo	V(Nb)	W(N2)	Ni		
1	-	0.50	-	-	-	HV-280	B+α
2	0.55	0.45	-	-	-	HV-360	B
3	1.00	-	-	-	-	HV-320	B
4	6.30	1.50	-	1.50	-	HV-450	M+α
5	2.50	-	0.30	7.50	-	HV-500	M+α
6	13.0	1.20	-	0.30	0.80	HV-400	M
7	13.0	0.90	-	0.20	0.80	HV-380	M
8	16.5	0.70	-	-	2.60	HV-250	M+α
9	16.5	-	-	-	-	HV-280	α+M
10	13.0	0.90	-	-	2.50	HV-390	M+α
11	13.0	0.80	(0.1)	(0.14)	3.50	HV-420	M
12	13.0	1.20	-	0.30	0.80	HV-380	M
13	13.0	0.90	-	0.10	0.80	HV-360	M
14	16.50	0.70	-	-	0.40	HV-260	M+α

B - bainite, M - martensite, α - ferrite

Table 2: Chemical composition of weld deposits fabricated with tubular wire by open are process

Mark	Chemical composition [%w]			
	C	N	Mn	Si
Chromecore 410N-O	0.04	0.13	4.0	1.0
Chromecore 414N-O	0.04	0.12	1.2	0.7

Continuation of Table 2

Chemical composition [%wt]			Hardness HRc	Application
Cr	Ni	Mo		
12.7	0.5	0.5	44-47	cont. casting rolls
12.5	4.0	0.4	42-44	- " -

3. TRIBOLOGY OF IRREGULAR WEAR OF WELD OVERLAYS [8]

In SA weld overlays irregular wear of surface layer occurs during the hot rolling process [3]. A view on cross section of the worn working surface of a weld overlay after 4-day service, is shown in Fig. 1. Irregular projections with a network of cracks caused by thermal fatigue can be seen on the worn surface. Such appearance of worn surface is typical for weld overlays fabricated by SA process. In this case the sample was extracted from the roll of continual billet train with the following chemical composition: *C=0.29%, Mn=1.0%, Si=0.4%, S=0.012%, P=0.013%, Cr=0.9%.*

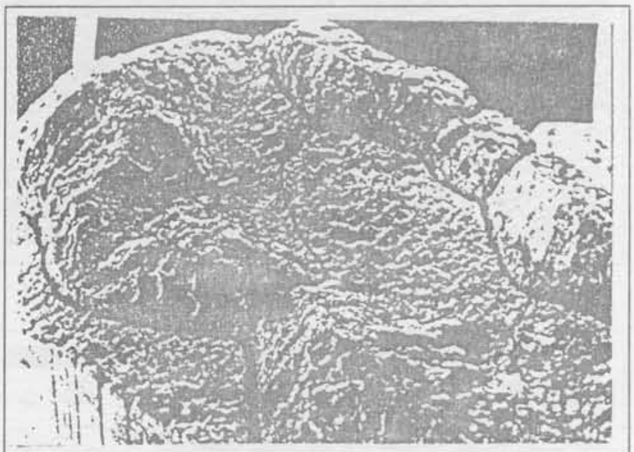

Fig. 1. Irregular wear of weld overlay

Microstructure is ferritic-bainitic while the zone with variable ferrite content occurs.

Non-metallic inclusion with variable size of globular type can be seen in weld overlay microstructure. Microanalysis showed that this is manganese-silicate and it originates in the surfacing process.

Distribution of these inclusions was studied in detail and described in work [9]. Most inclusions were observed in the mentioned projections of the weld overlay close to surface while forming whole agglomerates.

The results from the study of samples in the zone of two adjacent projections surface, as the result of rolling process (relative movement of hot and working surface of the roll), can be seen. At greater magnification (Fig. 2,3) spheroidized carbidic particles, as the result of thermal impacts in rolling and plastic strain of the surface layer,

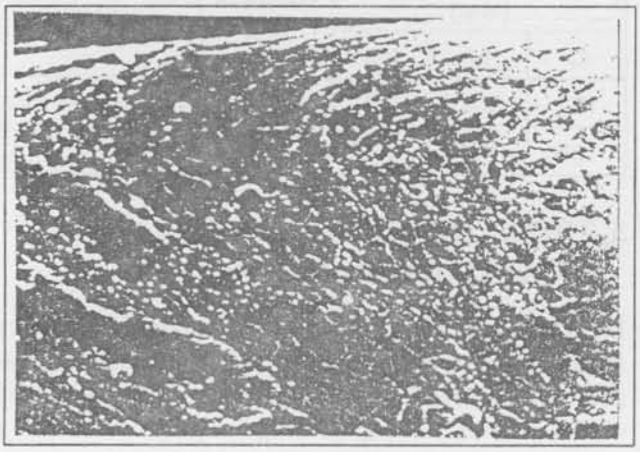

Fig. 2. Plastic deformation of the surface layer

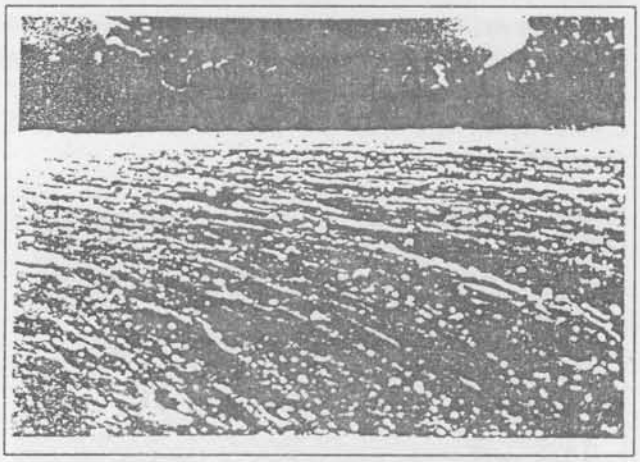

Fig. 3. Plastic deformation of the surface layer

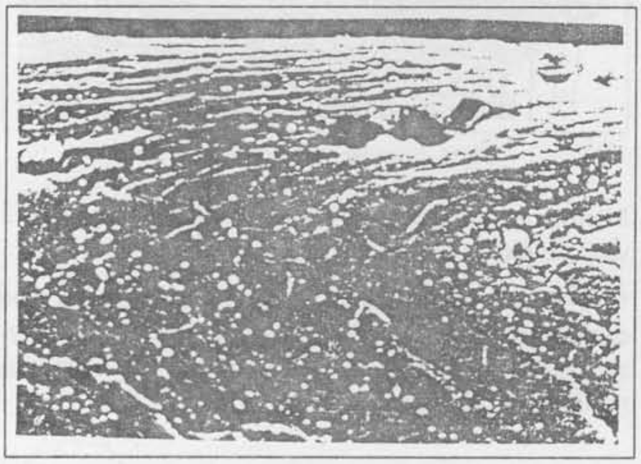

Fig. 4. Nucleation of the crack

and also agglomerates of inclusions of manganese-silicate type can be observed.

Thus in formation of plastic strain barriers we encounter two phenomena, namely the presence of carbidic globules distributed non-uniformly through the weld overlay thickness and also clusters of inclusions of manganese-silicate type.

Plastic crack strain around the inclusions causes nuclei which due to cyclic temperature variations grow and form thermal fatigue craks (Fig. 4).

4. SURFACING OF WORKING ROLLS FOR CONTINUAL CASTING OF SLABS

Besides the rolls for forming of metals, also the rolls for continual casting of slabs are deposited in Slovakia. The working rolls serve for drawing of slabs, their support and colling. Fig. 5 shows the position of the rolls in the continual casting line.

The working rolls are arranged in separate sections and their diameters are graded as follows: *⌀250, 270, 300, 370* and *380 mm*, with weight from *800* to *1960 kg*. Material of rolls is forged lowcarbon steel with following chemical composition:
$C=0.17\div0.27\%$, $Mn=0.3\div0.7\%$, $Si = 0,15\div0,4\%$, $Cr=1.2\div1.6\%$, $Mo=0.25\div0.5\%$, $V=0.4\div0.7\%$.
Roll hardness after treatment is 250HB. [7]

In order to prolong their life the rolls are surfaced by use of SA process with tubular wires in combination with fluxes according to table 1.

The laboratory tests of weld metals against wear from various tubular wires on the abrasion and on the pin-on-disc machine are given in table 3.

Table 3. The results of wear coeficient, friction coeficient and hardness of hardfacing materials from tubular wires [7]

Mark of electrode	ψ_{abr}	ψ_{adh}	μ coef. of friction	Hardness HV
VUZ-RD522	1,81	6,36	0,386	440
VUZ-RD531	1,70	5,08	0,388	314
VUZ-RD533	1,78	5,44	0,388	418
VUZ-RD535	1,62	2,05	0,470	260
VUZ-RD537	1,36	3,57	0,390	280
Base material 15 236	1,28	1,57	0,580	210
Etalon 11 523	1,0	1,0	0,680	175

Practical tests of roll life have shown that after production of *200 000 t* of slabs, the wear on forged rolls without surfacing was *6 mm* from the roll surface with fatigue

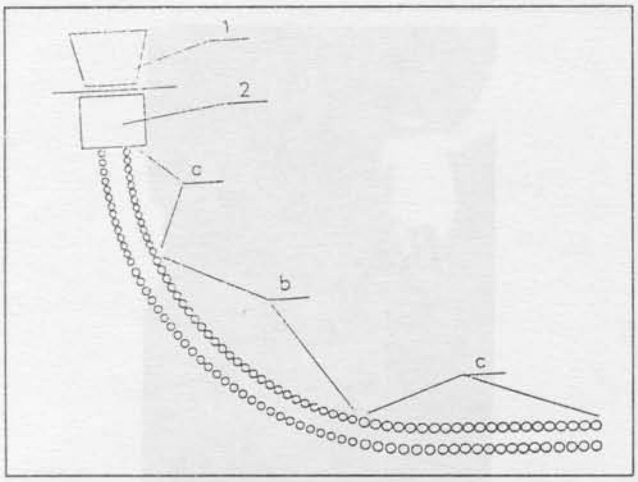

Fig. 5. The scheme of continual slab casting
a - upper part, b - curved central section, c - lower part

cracks up to *15 mm* in depth, and wear on weld overlay was *0.1 ÷ 0.2 mm* without fatigue cracks formation.

It means that actual life attains more then *1 000 000 t* of slabs in dependence on loading and overall conditions.

Caster rolls during operation are subject to a specialy harsch environment. High pressure contact, plastic deformation of roll surfaces at contact areas, severe abrasion by oxides, slags and powders, cyclic mechanical and thermal stresses and above all, corrosion contribute towards the deterioration of caster rolls. To improve the life expectancy of these rolls more noble materials are required. [5]

The very new materials have been developed, where instead of carbon is aded nitrogen into the crhomium alloying tubular wires. First work have been realised with open arc technology [5]. By the chromium nitrides CrN, Cr_2N we can improve the hardness but the carbon is ultra low. Nitrides like hard particles in the matrix blockades the movement of dislocations growth of the grains, creating of the carbides $Cr_{23}C_6$ on the grain bundaries.

Welding Research Institute in Bratislava in cooperation with Metallurgical Plant Košice developed new tubular wire VUZ-RD537N for submerged arc surfacing. We obtained the same Cr_2N chromium nitrides in weld metal and Ms temperature is about *200°C*. [6] The structure is martensitic with hardness *420HV*, practically the same as by open arc technology. Improvement in this case is very high efficiency.

5. MODULAR SYSTEM FOR HARDFACING OF CONTINUOUS ROLLS

This system is prepared for hardfacing and reclamation of worn steel mill components by open arc and submerged arc techniques namely for hardfacing of continual casting rolls.

Model description:

1. Manipulator for rotating of the roll with faceplate and travel carriage.
2. Welding head and power source.
3. Horizontal and vertical beam.
4. Motorised horizontal and vertical lift (X, Y) and Z-axis manual.
5. Computer for carriage and oscillation control enabling computerised control of:
   - Carriage oscilation
   - Oscillation width displayed in mm
   - Step over distance in mm
   - Step over speed
   - Spiralling
   - Off-automatic-manual operation
   - Fine tuning of oscillation width/end stops
   - Dwell at oscillation edges

Parameters:

Diameter of the roll ..... *∅min = 60 mm*
∅max = 450 mm
Total lenght .... *lmax = 2000 mm*
Max. weight .... *Gmax = 1500 kg*

The machine is equipped with single wire open arc or submerged are welding head including automatic flux recirculation and power sources for open arc or for submerged arc hardflacings (Fig. 6).

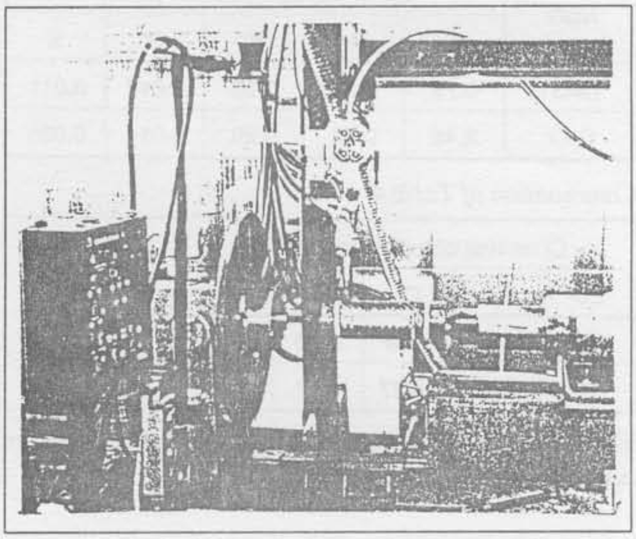

Fig. 6. Hardfacing equipment for open arc and submerged arc surfacing

6. ELECTROSLAG SURFACING OF ROLLS

The third technology, which is concerned in relation to production of renovation of rolls is the electroslag surfacing [3]. Up to now we have surfaced and service tested two types of materials given in table 4. It has been shown

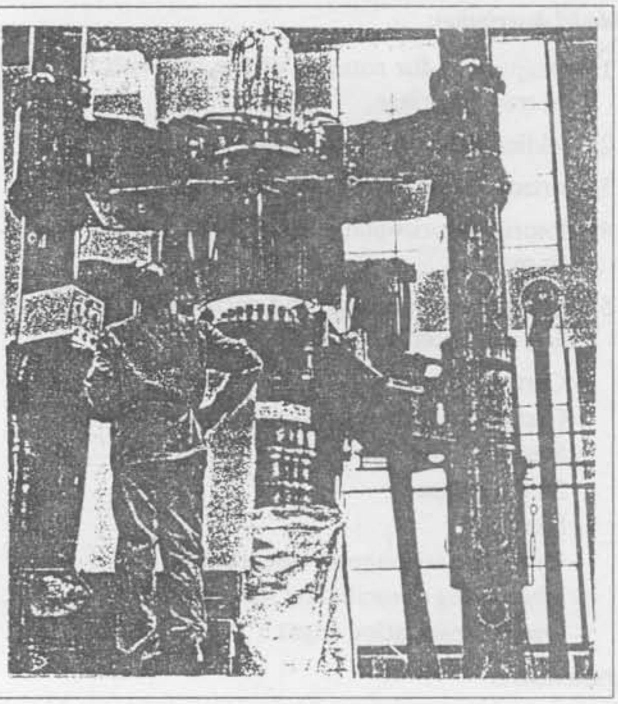

Fig. 7. Detail of electroslag surfacing of flat rolls

that this technology can be applied mainly by the switch from production of rolls of high-chromium alloy to the high-speed steel materials (HSS).

Table 4. Chemical composition of electroslag weld deposits on rolls

Mark	Chemical composition [%Wt]				
	C	Mn	Si	P	S
19431	0,79	0,39	0,26	0,012	0,011
C-Cr	2,46	0,52	0,28	0,014	0,035

Continuation of Table 4

Chemical composition [%Wt]					Application
Cu	Ni	Cr	Mo	V	
0,05	0,31	1,65	0,19	0,01	cold rolls
-	0,43	14,27	0,47	0,05	hot rolls

Electroslag surfacing can be seen in Fig. 7. The roll after surfacing is shown in Fig. 8.

7. CONCLUSION

Submerged arc hardfacing and electroslag hardfacing technology can solve lot of problems with metallurgical rolls and can improve the quality of the rolls and their long life.

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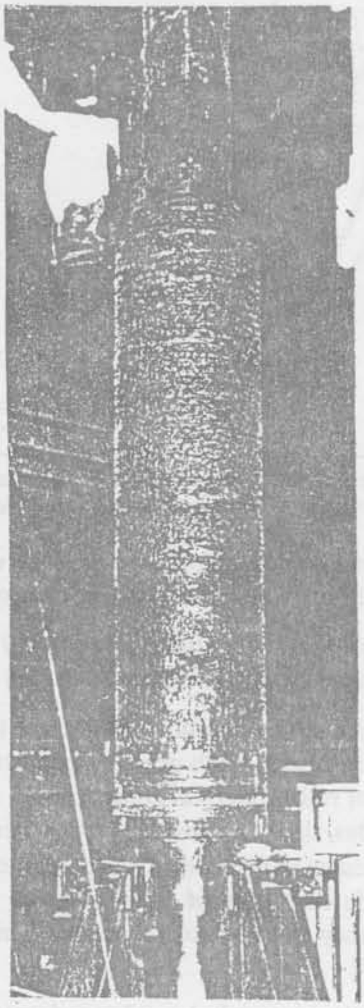

Fig. 8. The roll afret surfacing

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