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TRIBOLOGICAL ASPECTS OF THE USE OF LUBRICANTS FOR THE PLASTIC FORMING OF METALS

TRIBOLOŠKE ZNAČILNOSTI UPORABE MAZIV PRI PLASTIČNEM PREOBLIKOVANJU KOVIN

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In this paper the analysis of the effects relating to lubricants used for the cold working of metals, with the emphasis on steel ropes and extrusion is presented. Also matters related to colloidal chemistry and the mechanics of fluids are discussed. In addition, the paper addresses issues such as contact and fluid wear and the corrosion stability of lubricants.

Key words: lubricant, wear, emulsions, corrosion, fluids mechanics, stability of lubricants

V članku so opisani pojavi, povezani z uporabo maziv pri plastičnem preoblikovanju kovin s poudarkom na ekstruziji in na izdelavi jeklenih vrvi. Tudi pojavi, povezani s koloidno kemijo in mehaniko fluidov, so obravnavani. V članku se obravnavajo tudi kontaktno trenje, trenje tekočin in korozijska stabilnost maziv.

Ključne besede: maziva, obraba, emulzije, korozija, mehanika fluidov, stabilnost maziv

1 INTRODUCTION

The Egyptians are known to have used a mixture of olive oil and lime[1] for the lubrication of cart axis. Greases and oils – mostly olive[2], rape and whale oils as well as pig tail and grease[3] – were also used as lubricants in the second half of the 19th century[4], until the development of mineral oils with additions of potassium, calcium and sodium soaps[5]. The first base oils manufactured with vacuum distillation of earth oil and the first solvents were manufactured in1910 with the Edeleanu process.

The evolution of modern machines[6] has brought lubrication problems that cannot be solved with mineral oils, e.g. aircraft gears. This has led to the development of synthetic mixtures[7], the properties of which depend on those of their basic components, the synthesis process and the additives. These types of mixtures were classified into nine groups by Gunderson.

In 1881, Mendelejev manufactured the first synthetic lubricants in Russia. He also developed the theory of the boundary layer. By the end of the 19th century Petrov had further developed this theory, and he is considered to be the founder of the theory of hydrodynamical lubrication. Leonardo da Vinci should also be mentioned as one of the early tribologists, thanks to his association with tribological tools that were based on the work of Archimedes. However, tribology as a technical science was first defined by Jost, in 1966, who brought together theory and practice.

Special synthetic lubricant mixtures of ferrocene derivates, aromatic amines and heterocyclical compounds of nitrogen, boron, phosphates and urea were developed[8].

The first use of additives dates from the middle of the 19th century, when Raecz and Little introduced the use of mixtures of mineral oils and soaps for the manufacturing of lubricants. Brown added red phosphorus to mineral oil as oxidation inhibitor. For plastic forming the use of additives that increase the viscosity (polyzobutenes, styrenes, copolymers) and additives for high pressure based on sulphur, chlorine and phosphor are of vital importance. Extreme[9] pressure additives, e.g. sulphurised metal-esters of natural grease acids, are used in oils for the machining of metals because of their small effect on the coagulation of oils. Additives based on phosphor and chlorine are sensitive to hydrolysis, whereas those based on sulphur react with non-ferrous metals, especially copper alloys. Additives, as emulsifying and antifoaming agents are used for emulsions. For hydraulic systems mineral hydraulic oils were developed, and these actually constitute about 12 % of all the lubricants[10] in use.

The regeneration of technological lubricants[11] is performed using mechanical[12] and chemical[13] methods. Centrifuging is effective because the lubricant structure is not changed. The purification of emulsions[14] is performed using flotation and electrodynamical methods. The lubricants used in industry[15] can be classified into the following groups:

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- liquid emulsions for cold rolling, high-speed drawing and the rolling of aluminium and its alloys,
- greases and mixtures of mineral and plant oils for the cold rolling of metals with high deformation resistance;
- consistent lubricants, colloidal solutions with soap additions for the cold rolling of zinc and aluminium foils;
- glass lubricants, special salt eutectica, with a small change of viscosity over wide temperature intervals, which increase the corrosion of metals;
- powders used as mixtures and suspensions (graphite lubricants);
- metallic lubricants, such as lead or copper coatings.

2 FLUID MECHANICS AND THE THEORY OF LUBRICATION

The flow of fluids[16] is laminar or turbulent with a transition area in between defined with the Reynolds number. The friction in the fluid changes the regular (theroretical) or Poisell flow. In the studies of Burgers, Haegge-Zienem and especially Nikurades the presence of a standstill layer of fluid in contact with the solid surface was confirmed. This layer is the origin of the friction in the fluid. The mutual mixing of layers is at the origin of the turbulence, and for a complete physical description it is necessary to consider for this layer[17]:

- the continuity equation;
- the Navier-Stokes equations;
- the energy equation including the Fourier law of heat conductivity, the dissipation functions and the conservation of energy;
- the equations of state considering a stable chemical composition of the lubricant during the process.

Sometimes constitutional equations whithout universal significance are added[18], and visualisation methods are used. It is important to mention that the Navier-Stokes equation was developed ab initio for elastic solids and later used in fluid mechanics. If the viscosity is omitted in this equation the Euler equation is obtained, which for stationary flow and constant density evolves into the Bernoulli equation. From this equation the Torricelli equation, which is used in the regeneration processes of lubricants, is deduced:

$$\beta = (2\ g\ H)^{1/2} \tag{1}$$

If the analysis is reduced to a stationary flow in the Descartes system, the boundary layer is introduced and if the mass[19] force is neglected the Reynolds differential equations are obtained:

$$\partial p/\partial x = \mu \partial^2 v_x/\partial y^2 \tag{2}$$

$$\partial p/\partial y = 0 \tag{3}$$

$$\partial v_x/\partial x + \partial v_y/\partial y = 0 \tag{4}$$

The relation (4) is the continuity equation, the relation (3) reflects the basic property of isobarity requiring that the pressure is considered to be constant over the section of the boundary layer. In this case relation (2) becomes a shortened Reynolds equation. This equation was established in 1886 in the original form (figure 1):

$$\partial/\partial x\ (h^3/\mu\ \partial p/\partial x) + \partial/\partial z\ (h^3/\mu\ \partial p/\partial z) =$$
$$= 6\ (v_0+v_1)\ \partial h/\partial x + t\ h\ [\partial(v_0+v_1)/\partial_x] + 12\partial h/\partial t \tag{5}$$

The right-hand side of equation (5) contains three elements with different physical meaning. The first represents the flow shape (the wedge effect), the second the dynamic load and the third the extrusion of the fluid (the pressure effect). In this case the equation is reduced to its most frequently used form:

$$\partial/\partial x\ (h^3\partial p/\partial x) + \partial/\partial z\ (h^3\partial p/\partial z) = 6\mu\ (v_0+v_1)\ \mathrm{d}h/\mathrm{d}x \tag{6}$$

Reynolds and Sommerfeld[20] suggested several data for the solution of the equation, the integration of which is possible if the geometry is functionally connected over the section of the thickness of the lubricant layer[21] between the contact surfaces. The hydrodynamic equation[22] (6) can be adapted to lubricants with different aggregate state and also for rheodynamic lubrication when the properties[23] of the lubricants correspond to those of Bingham fluids. To obtain the simplest analytical solutions[24] the following simplifications are introduced:

- external forces do not act on the fluid;
- the pressure over the section of the lubricant layer is constant;
- the radius of the surface is great in comparison to the thickness of the lubricant layer;
- the lubricant slip is absent;
- the lubricant is a Newtonian fluid;
- the flow is laminar;
- the force of inertia and the weight of the lubricant are neglected;
- the viscosity of the lubricant is constant.

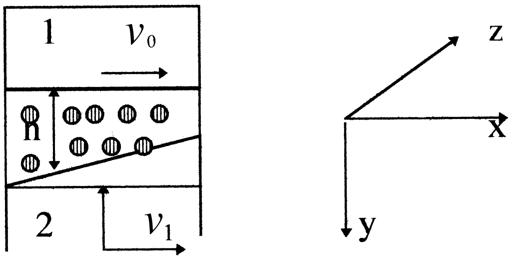


Figure 1: The geometry of the lubricant layer between two contact surfaces. The Reynolds equation was deduced for surface 2 at standstill, h_1 and h_2 are the thickness of the lubricant layer for the entry and the exit edges.

Slika 1: Geometrija sloja maziva med dvema stičnima površinama. Reynoldsova enačba je bila razvita za stoječo površino 2, h_1 in h_2 sta debelini maziva na vstopnem in na izstopnem robu.

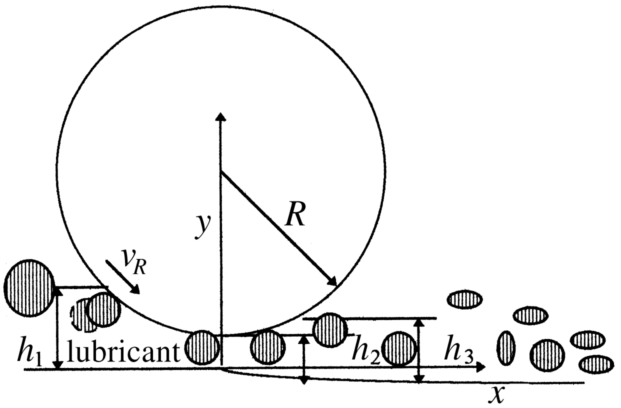


Figure 2: Scheme of the rolling with lubricant, $v_R + \Delta R$ the rolled sheet

Slika 2: Shema valjanja z mazivom, $v_R + \Delta R$ valjanec

Based on these assumptions[25] the maximal pressure according to **Figure 1** for the case of standstill surfaces is:

$$P_{\mathrm{max}} = p_{\mathrm{a}} + [3\mu l v_0 \,(h_1 - h)/2h_1h_2\,(h_1 + h_2)] \tag{7}$$

These conditions are close to those that occur during cold rolling.

The maximum friction for the mobile surface is:

$$T_{\mathrm{max}} = 0.75\ \mu\ l\ v_0\ /h_2 \tag{8}$$

The rolling process[25] is, according to **Figure 2**, described[26] with the differential equation[27]:

$$\mathrm{d}p/\mathrm{d}x = 12\mu v_R\ [(h_2 + x^2/2R) - h_3)/(h_2 + x^2\,/2R)^3] \tag{9a}$$

According to **Figure 2** the rolling force is:

$$(\delta_{\mathrm{x}} + \mathrm{d}\delta_{\mathrm{x}})(h_{\mathrm{x}} + \mathrm{d}h_{\mathrm{x}}) - \delta_{\mathrm{x}}h_{\mathrm{x}} = 2\ (p_{\mathrm{x}}\,\mathrm{tg}\zeta_{\mathrm{x}}\mathrm{d}x + \tau_{\mathrm{x}}\mathrm{d}x) \tag{9b}$$

Several solutions of the equation (9b) are known. These solutions do not differ significantly in terms of mathematical simplifications used; they differ more in terms of postulation of the frictional force τ_{x} and the selection of the analysed criterion. For **Figure 2** two interesting cases are possible: for $V_R \rightarrow 0$ the equation is used for cold rolling, whereas in the case of $(v_R + \Delta R) \rightarrow = 0$ it is used for the case of the hydrodynamic lubrication of slip bearings.

3 CONTACT FRICTION

Friction is the force that hinders the movement of two surfaces that are in mutual contact. In Ancient Egypt the dragging of heavy statues mounted on sledges was assisted by a slave who watered the road ahead of the sledge. Ball bearings[28] made with bronze balls, dating from about 50 B. C., were found in lake Nemi in England The first treatises on friction are attributed to Herodotus, from the Alexandrian school (484-425 B. C.), who improved the bearings for different mechanisms. Aristotle also wrote a treatise on the reduction of friction by rolling. The first scientific treatise was by Leonardo da Vinci, who defined the frictional force two centuries before Amonton. Newton was the first to formulate the laws of internal friction in fluids, which were later completed by Stokes. Euler, Coulomb and Stefan performed the first investigations of the friction that occurs between dry surfaces. Desaguliers' explanation of friction, based on molecular adhesion forces, was improved by W. B. Hardy and I. K. Hardy in 1919, and investigated after the first world war by Bowden and Tabor. Contact friction during the plastic deformation of metals complicates[29] the problem, since the contact surfaces are plastically deformed. For this case Nadaia proposed the following relation:

$$t_{\mathrm{x}} = \mu\ (v_R - v_0)/\varepsilon \tag{10}$$

with the frictional force inversely proportional to the thickness of the lubricant layer and proportional to the difference in the velocity. Dry friction is only obtained in the laboratory, where friction coefficients of more than one can also be achieved. During the plastic deformation of metals mostly boundary friction occurs between the surfaces separated by the lubricant layer of thickness $(0.1\text{-}0.5)\cdot10^{-6}$ m, and with a friction coefficient of 0.005 to 0.01. The boundary friction[30] for non-ferrous metals is approximately constant over the area of rolling deformation.

By using sodium soaps for dressing[31] soft steel sheets of thickness (0.7 to 1) mm the drawing force can be reduced by 24 % for a drawing rate of 10.8 m/min and a drawing angle of 10°. The drawing force can be decreased additionally for 19 % if the lubricant solidol is used. The intensity[32] of the contact stresses is discernible for a small rolling rate; with a higher rolling rate the stresses are increased. When[33] rolling tubes of corrosion-resistant steel the surface is covered with a thin layer of copper or brass, which protects the surface against elaboration defects. The covering layer is obtained at a temperature of 60 °C to 75 °C in a sulphate solution with mass fraction (24 to 28) % of H_2SO_4, (0.1 to 1) % $CuSO_4.H_2O$, (0.5 to 0.2) % NaCl and with the addition of (0.05 to 0.2) % of inhibitor. With electrolytic deposition of zinc a layer with a high adhesion to the steel surface is obtained which can support forging and complex stresses without failure. Soaps with sulphur powders produce better results than graphite: fewer surface defects occur and the deformability is increased. However, graphite lubricants are ecologically more friendly.

Elasto-dynamic friction, defined by the Hertz contact conditions, occurs between the working and the supporting rolls. The contact surfaces are elastically deformed and the contact geometry is changed. The high contact stresses significantly increase the lubricant viscosity via the change in the lubricant's rheological properties. In this case the lubricants are important for the increase in the productivity of rolling stands and the prolongation of their exploitation time. The mathematical solution is given as[34]:

$$\varepsilon_k = 3.17\ (\mu_0)^{0.75}\ (v_p+v_{op})^{0.75}(\gamma)^{0.6}\ /$$
$$/\ [p_p{}^{0.15}\ (1/R_p + 1(/R_{op})^{0.4}] \qquad (11)$$

Compressor oil with 5 % of oleine acid can be successfully applied for cold drawing and its use seems to be very promising because an increase in the drawing speed brings the decrease in the amount of energy used and a reduced wear. Small gaps during drawing can lead to pulsing of the lubricant, thus the hydrodynamic wear can be characterised as balancing of the pressure in the lubricant with the deformation resistance of the metal. With an increase in the rolling speed the reverse flow of the lubricant (the tunnel effect) is diminished. Experiments have shown that the pressure in the lubricant can vary significantly for a low drawing rate. The maximum pressure in the lubricant is observed for a drawing speed in the interval from 100 to 300 m/min, and for different lubricants, e.g. soaps and complex lubricants with activators such as lime, molybdenum disulphide and zinc white.

The lubricant's viscosity[35] should allow laminar flow, good adhesion, the removal of heat from the deformation zone and the easy removal of the lubricant residues. The effect of the dynamical viscosity is not constant and it decreases the roughness of the rolled sheet to a minimum before increasing it again.

New structural antifriction materials based on Teflon and polyamides are not subjected to dry wear and can be successfully applied for couplings with hydrodynamical lubrication. These materials are particularly interesting for a slip velocity close to zero and cannot be replaced in vacuum and space technology. Furthermore[36], relatively good combinations of slip couples can be obtained with two mutually insoluble metals. For steels, such metals are lead, tin, indium and to a smaller extent also cadmium, germanium, antimony and bismuth. The wear properties can be modified with surface treatments, e.g. with plastic deformation and heating, chemical conversion (phosphating, Tufftridiing and Sulfinuzov processing) and different methods of surface deposition, e.g. plasma processing, ionic implantation, CVD methods and electro-deposition).

For dry wear the wear force is described by the dependence of the wear and the material properties using the Coulomb law:

$$T_s = f \cdot N_0 + F_{0M} \qquad (12)$$

The molecular force F_{0M} is difficult to determine and it is habitually omitted for dry wear. The Bowden and Tabor adhesion theory cannot be applied for very hard (diamond) and elastic materials (rubber).

Oscillatory movements 'stick-slip' are characteristic for tool machines. A larger contact wear is useful for hot rolling because it increases the per-pass deformation. The friction coefficient is greater for rolls' grasping than for rolling. There are several explanations for the difference:

- the specific pressure (Grudev),
- the presence of the oxide layer (Chekmarev),
- the surface of the rolls (Preshnjakov),

The technology affects the wear coefficient, which is greater for rolling in vacuum and is significantly smaller for indirect extrusion than for direct extrusion. All alloying elements that decrease the melting point of the scale and increase it softening diminish the coefficient of friction. In the presence of scale the addition of graphite decreases the friction. Also, slags have been investigated as potential lubricants.

To deduce the frictional force various empirical relations were developed:

– for a rolling speed from (0.15 to 0.6) m/s

$$T_S = t_p\ [0.7/(v_s + 0.28) + 0.36] \qquad (13)$$

– for a rolling speed from (1 to 10) m/s

$$T_s = t_p\ [1 + 0.001\ (v_s - 1)^2]$$
$$v_s = v_H\ (\lambda - 1)/3] \qquad (14)$$

Experimental measurements have shown that the thickness of the lubricant layer in the deformation zone increases with the rolling speed. The frictional force is smaller by a thicker lubricant layer. This force and the quality of the lubricant significantly influence the surface finish of the sheet. Surface-active additions hinder the sticking sheet-rolls and increase the content of impurities in the lubricant. This effect is known as pat, and it intensity is determined from the reflection index of the rolled surface.

The frictional force affects also the transmission of the rolls' surface roughness onto the sheet's surface. The transmission is greater for rolls with a small radius. In the presence of oleine acid as pat the content of impurities in the lubricant is increased leading to the formation of metal complexes that increase the abrasion. The regeneration of such emulsions requires the use of magnetic separators for the separation of larger particles and the use of flotation for the removal of very small particles.

The minimum thickness of the rolled sheet depends on the frictional force. According to [35,36] it can be calculated as:

$$h_{min.} \approx 3.4 \cdot 10^{-4} f\, R\ (K_{sr.} - \delta_N)$$
$$K_{sr.} = 1.15\ \delta_T + 2/3\ (\Delta_0) - 1/3\ (\delta_1) \qquad (15)$$

The value of the coefficient $3.4 \cdot 10^{-4}$ includes the effects of the elasticity module on the deformation degree[37] and the type of steel. Equation (15) shows[38,39] that good lubrication facilitates the rolling of thin sheets.

4 FRICTION IN THE FLUID

Viscosity is the most important property of the lubricant. It is generally defined for laminar flow and it represents the resistance[40] of the lubricant to shear deformation. The level of the viscosity depends on the pressure and the temperature and several relations were proposed for the calculation of their effect. For lubricant oils the Walther-Uddeloheda relation is frequently used:

$$\log \log (\nu + c) = K - m \log T \qquad (16)$$

Where ν is the kinematical viscosity, T is the temperature and K and m are slope coefficients. Vogel and Cameron proposed the following equation for the calculation of the dynamical viscosity:

$$\mu = A \exp\,[B/(T+C)] \qquad (17)$$

Where A, B and C are experimental constants. Arhenius and Guzman proposed the relation:

$$\mu = A \exp\,(\Delta E_V/RT) \qquad (18)$$

Where ΔE_V is the activation energy and R is the universal gas constant. For the use of a lubricant for plastic working the viscosity is frequently calculated according to Baruss as:

$$\mu = \mu_0 \exp.\,(\gamma\, p) \qquad (19)$$

where μ_0 is the viscosity of the lubricant at air pressure, γ is the viscosity piezo-coefficient and p is the pressure. The relation shows that the viscosity increases with increasing pressure and decreasing temperature. For non-Newtonian fluids the viscosity also depends on the shear rate (**Figure 3**), which is due to the presence of colloidal particles. Very coarse molecules deform themselves at a great shear rate in the direction of the flow. This deformation is known as structural viscosity. The flow of non-Newtonian fluids is described with the Ostwald and De Waals equation:

$$\ln \mu = \ln \mu_s - (1-n) \ln S/n, \ (p, T \text{ constant}) \qquad (20)$$

$$S = k\, \tau^n \qquad (21)$$

where μ_S is the apparent dynamical viscosity for $S = 1\ s^{-1}$, S is the shear rate, and τ is the shear stress.

A linear dependence of μ versus S was found for stable flow. This was also observed with other materials, which are known as Bingham bodies. The hardening due to the increase[41] of the shear pressure is known as dilatancy, and the related phenomena are known as rheopectical or tyxotropic, depending on the effect of time on the viscosity. The lubricants' elastic properties are characterised with the relaxation period and related to the Weissemberg-Merrington effect.

For the deduction of the rheological properties of lubricant greases several relations were developed. In these relations the apparent viscosity is connected to the gradient of shear rate over a large interval of this property. Sisko's equation is used for the calculation of the apparent viscosity for a shear rate in the interval (10^{-2} to 10^{-4}) s:

$$\mu_S = \mu + bD^{n-1}\ (n < 1) \qquad (22)$$

where D is the gradient of the shear rate, B and n are constants related to the pseudoplastic state. For a large shear rate $n > bD^n$ the flow changes to Newtonian. For grease lubricants the following equation is used:

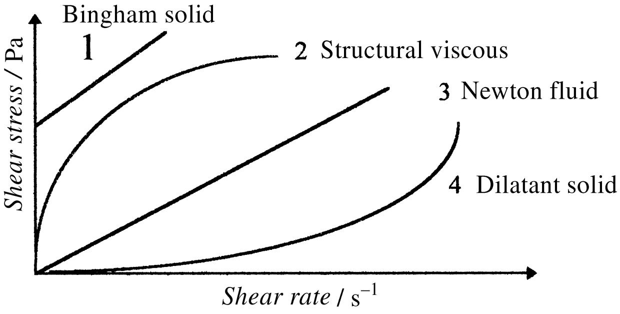


Figure 3: Dependence of the shear stress on the shear rate
Slika 3: Odvisnost med strižno napetostjo in hitrostjo striženja

$$\tau - \tau_0 = \mu D + bD^n \qquad (23)$$

where τ is the shear stress and τ_0 is the boundary threshold of the shear stress when the flow begins. The rheological properties show, according to **Figure 4**, three possibilities[42]:

flow of a Bingham body: $\tau = \tau_0 + \mu\, D$ (24)

exponential pseudoplastic behaviour: $\tau = bD^n$ (25)

Newtonian fluid flow: $\tau = \mu D$ (26)

The flow of Newtonian fluids occurs with the Eiring-Rebinder mechanism. Both external and internal friction dissipate the energy of the moving bodies.

The friction of colloidal systems[43] was investigated later. In 1906 Einstein developed, on the basis of a hydrodynamical approach, the equation relating the viscosity of the system μ and the content of the dispersed phase φ.

$$\mu = \mu_0\,(1 + 2.5\,\varphi) \qquad (27)$$

The equation can be used for small contents of dispersed phase and in the absence of the mutual effect of spherical particles. If the shape of the particles is ellipsoidal the value of the coefficient φ is greater. The Brownian motion increases with the square of the ratio greater over smaller axis of the particles. It is described with a kinematical approach based on Fick's diffusion low:

$$\Delta_0^2 = R_0 T \chi \,/\, (3\,\pi r N_A\, \mu) \qquad (28)$$

With the increase in the content of the dispersed phase, equation (28) becomes less reliable, due probably to the solvation of particles, and it should not be used in the case of linear viscosity.

A greater viscosity is related to the effect of the structural viscosity. The colloidal systems as electrolytes were investigated by Smoluchovski, who defined the specific viscosity as:

$$\mu_F = 2.5\,\varphi\,[1 + (\varepsilon_d\,\xi/2\pi)^2 \,/\, \mu_0\,\gamma_L\, r^2] \qquad (29)$$

Where γ_L is the specific electrical conductivity, r is the radius of the particle, ε is the dielectric constant and ξ is the electrokinetic potential. Buuts investigated the connection between ξ and r.

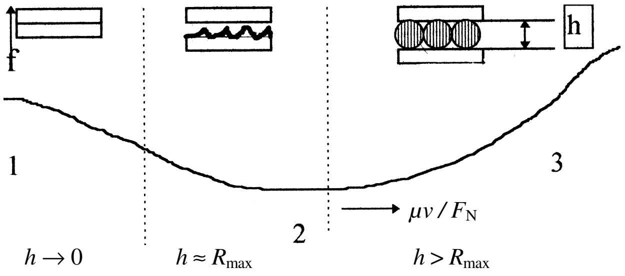


Figure 4: The Stribeck curve
Slika 4: Stribeckova krivulja

Table 1: Composition of some water emulsion
Tabela 1: Sestava nekaterih vodnih emulzij

Compound	Water emulsion	Emulsion "Ukrinol 5/5"
Sodium soap	5-6 g/L	5 g/L
Olein acid	3-4 g/L	3 g/L
Vaseline acid	2-3 g/L	–
Sodium carbonate	0.5-1 g/L	0.5 g/L
Oil I-8A	–	0.5 g/L

The hydrodynamical theory of lubrication was investigated by Stribeck, and his studies were used as a basis for the theoretical investigations of Sommerfeld and Gumbel. It is accepted that the Stribeck[44] curve (**Figure 4**) represents the general characteristics of lubrication. Three areas of lubrication can be distinguished:

- boundary lubrication, with a lubricant layer approaching the thickness of one molecule,
- mixed lubrication,
- hydrodynamic lubrication.

F_N is the load force, v is the peripheral speed, μ is the dynamical viscosity, f is the coefficient of friction. Stable hydrodynamic lubrication occurs in area 3.

The surface tension and the viscosity are connected with the rheohor. This connection is very complex, since the surface tension is an equilibrium property, while the viscosity depends on different influencing factors. The rheohor is defined with:

$$R_h = m\ (\mu / \rho)^{1/2} \tag{30}$$

The cleaning of metal surfaces involves the thermal destruction of lubricants and their decomposition to pitchy substances that plug the filters. The collected impurities are mostly particles of metals, phosphate, undisolved soaps and calcium stearate compounds. The last of these are formed during the drawing, with the reaction:

$$2C_{17}H_{35}COOHNa + Ca(OH)_2 \to$$
$$\to (C_{17}H_{35}COO)_2Ca + 2\ NaOH$$

The decrease of the soap content in the lubricant lowers its technological properties. To lower the impurity level, sodium polyphosphate $(NaPO_3)_x$ is added with $X = 20$ to 100. The addition hinders the layering of the emulsion, while the viscosity and pH remain practically unchanged. The addition of polymerised cotton oil in the emulsion has a beneficial effect on the drawing of surfaces covered with a layer of zinc or phosphate. During the drawing of metals the zinc layer hinders also the sticking. The compositions of some water emulsions generally used for drawing[45] are shown in **Table 1**.

The substitution of the expensive olein acid and sodium stearate with the less expensive cotton oil impairs the emulsion; in this case sodium polyphosphate is a good alternative. The diminished influx of lubricant in the deformation zone by great per-pass strain is prevented with the use of a lubricant with a lower viscosity. The influx of scale particles between the rolls is prevented with the selection of the proper lubricant. The water emulsions of petroleum in combination with local electrical fields can destroy the pat. Plant oils are more stable and cotton oil is used with success for the rolling of hard steels. Every oil performs best at a particular rolling speed, when uniform roughness of the sheet surface is also achieved. For palm oil the optimum speed is around 13 m/s, while for coriander oil it is 18 m/s. The pH for the emulsion is from 7.8 to 8.2, the content of phosphate is (500 to 700) mg/L and the content of chloride is around 300 mg/L.

The stability of the emulsion is improved with addition of stabilisers, and it is investigated by checking the coalescence of droplets dispersed in the liquid phase or by measuring the lifetime of an emulsion droplet situated on the boundary of the phases. The rate of the layering process η, in dependence on time χ, is:

$$\eta = -d\theta/d\chi = K_1(\theta_1 - \theta_2) \tag{31}$$

Where θ_1 is the quantity of the dispersed phase at the boundary of the emulsion and the clear dispersion liquid, θ_2 is the initial quantity of the dispersed phase and K_1 is the constant of the reaction rate

5 LUBRICATION AS A PROCESS OF COLLOIDAL CHEMISTRY AND SURFACE PHENOMENA

In 1860, Graham introduced lubrication as a process[46] of colloidal chemistry. The pioneering studies were made by Selmi and Bodrin. Perrin divided the colloidal systems according to the mutual effect of the dispersed particles and the matrix liquid. Ostwald proposed the first classification of colloids. The properties of colloidal systems originate in the very large contact area between the colloid particles and the matrix liquid. According to the Fick and Stokes law the diffusivity of the spherical particles is proportional to the third root of the relative mass and inversely proportional to the diameter of the molecule. Investigations of the diffusivity in colloidal systems were also carried out by Einstein and Smoluchovski.

Emulsions for general use in the rolling of metals are dispersive systems with spherical particles of diameter (10^2 to 10^5) nm. Water emulsions are well investigated. The stability of emulsions can be improved with addition of stabilisers that increase the viscosity or the electrical charge of the particles. Surface-active compounds (SACs), such as tenzides, decrease the forces on the boundary surfaces. The lubricant qualities of a SAC depend on the activity of polar groups and decrease in the direction COOH > OH > NO_2 > SO_2.. Pavlov pointed out the colloidal nature of emulsions used in metallurgy. Large molecules are added to complex lubricant, and these support the mechanical and chemical stresses in the deformation zone. Free radicals are formed in this zone, which increases the chemisorption of the lubricant on the metal surface. If, for example, polyetilene is added, atomic carbon and hydrogen, as well as other small molecular compounds, are formed. Atomic hydrogen absorbed onto the metal surface decreases the surface energy, relieves the exit of dislocations on the surface and facilitates the cold-rolling process.

The basic parameter of colloidal systems used as lubricants is the wetting[47] angle (**Figure 5**) between the tangent to the drop curvature in the contact point and the surface where the drop is deposited. This angle is determined with high-speed cameras. Hildebrand first observed the effect of surface tension on the wetting angle and connected this tension to Roult's law of solubility. Also, Stefan's contribution was significant, since he related the surface tension to some thermodynamical functions. The spreading occurs through gravitational, inertial, viscous, transition and surface regimes, and it is described with the Navier-Stokes[48] equation. It is assumed in this equation that the spreading rate is greater in the direction perpendicular to the drop than parallel to its axis.

$$\partial p/\partial r = \mu \partial^2 v / \partial x^2 \qquad (32)$$

The pressure in the drop is:

$$p = p_g - \delta / r \, [\partial/\partial r (r \, \partial h(t,r)/\partial r)] \qquad (33)$$

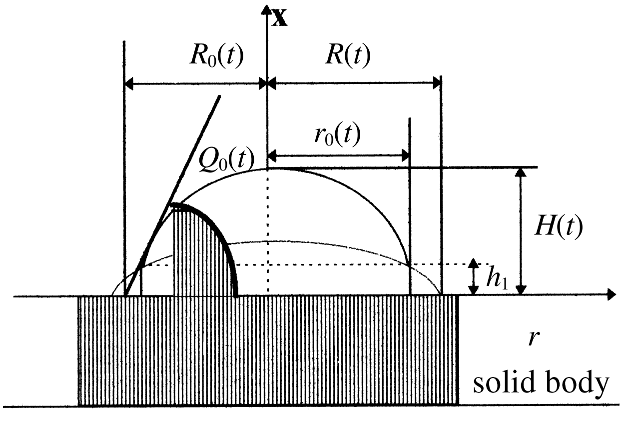


Figure 5: Profile of the spreading drop
Slika 5: Profil kapljice, ki se razliva

with the boundary conditions

$$v\,(t,r) = 0 \text{ and } \mu \partial v/\partial x \,\big|_{x=h} = 0 \qquad (34)$$

Some numerical solutions of the equation are:

$$R(t) \approx 1.6\,(5\sigma V^3/12\pi^3\mu)^{1/10}\, t^{1/10}\ (\text{m}) \qquad (35)$$

$$H(t) \approx 1.1\,(3\mu V^2/40\pi^2\sigma)^{1/5}\, \text{t}^{-1/5}\ (\text{m}) \qquad (36)$$

$$Q_0(t) \approx 0.7\,(27\mu^3 V/2000\pi\sigma^3)^{1/10}\, \text{t}^{-1/5}\ (\text{rad.}) \qquad (37)$$

Where $H(t)$ is the maximum height of the drop, $R(t)$ is the spreading perimeter, σ is the surface tension of the liquid, V is the volume of the drop, $Q_0(t)$ is the wetting angle and t is the spreading time. The use of these relations for mineral[49] oils used for the cold working of metals is very complex and has not been investigated to any great extent. The theoretical analysis is very complex and requires the use of hydrodynamic equations that consider also the capillary forces. The approximate solutions are in the form.

$$R_0 \approx A(t)^n \qquad (38)$$

Where A is the coefficient of proportionality, which depends on the oil, t is the contact time between the drop and the surface, r_0 is the spread circumference and n is a coefficient ($n \approx 0.2$ for mineral oil).

The spreading of the liquid is preceded by the formation of an absorption layer of liquid on the solid surface. The thickness of the layer depends on the liquid's surface tension and requires a correction of the wetting[50] angle and, for example, the relation proposed by Girifalcis:

$$\cos Q = -1 + 2\,(\sigma_\text{T} / \sigma_\text{Ž}) - \pi e / \sigma_\text{Ž} \qquad (39)$$

Where σ_T is the surface tension at the solid–atmosphere boundary, $\sigma_\text{Ž}$ is the surface tension on the liquid–atmosphere boundary and e is the base of the natural logarithm. The ratio $\pi e/\sigma_\text{Ž}$ is the correction required by the presence of the adsorbed layer. Jung and Dupra[51] investigated the relation between the wetting angle and the adhesion work. They established that the wetting angle increases with an increase in the polarity of the liquid, the cohesion energy and the dipole moment. The dispersion conditions depend on the relation between the interphase energy and the kinetic energy of the heat currents. These processes run self-supporting in the presence of pat or in the case of a very lyophilic dispersed phase.

When lubricants are used for cold working the physical adsorption (Van der Waals forces) and the chemical absorption (chemical compound) become very important. The physical adsorption is faster and the desorption is relatively easy. The chemical adsorption is slower and the desorption occurs only at high temperatures and with a considerable activation energy. Also, in some investigations no adsorption effect was found for lubricants applied in the plastic working of metals.

Surface-active substances have shown a considerable effect in rolling processes via the wetting angle and the adhesion work. The adsorption equilibrium of a liquid drop on the sheet surface is achieved for:

$$\sigma_{SL} = \sigma_{SG} - \sigma_{LG} \cos Q \qquad (40)$$

where S is related to the solid phase, L to the liquid phase and G to the gas phase. In **Table 2** the value for σ_{SL} is given for some systems[52].

The spindle and castor oil have a very similar adhesion effect during the rolling of steels and aluminium and give approximately the same values for the elongation coefficient.

If the sheet is held in the lubricant for 3-4 h before the rolling, the friction is decreased by 30 %; whereas after a longer holding of 10-12 h the frictional force is increased[51]. The explanation[53] is that in the first case a physical adsorption and in the second case a chemical adsorption is involved. The time for the physical adsorption is decreased to 35 min if the lubricant temperature is increased to 60 °C. For emulsion lubrication the contact time is three times shorter, and, according to Gardi, the frictional[54] force is lower for a greater number of carbon atoms in the compound chain of the lubricant. The wetting angle is determined in conditions of anodic and cathodic polarisation.

Table 2: Values of adhesion work

Tabela 2: Vrednosti za adhezijsko delo

System	Equation
Zn – Hg	$\sigma_w = 105 - 470 \cos 0 = -365$
Pb – Hg	$\sigma_w = 240 - 470 \cos. 0 = -230$
Al – Hg	$\sigma_w = 860 + 470 \cos 50 = 1160$
Fe – Hg	$\sigma_w = 1360 + 470 \cos 40 = 1720$
Al – spindle oil	$\sigma_w = 860 - 40 \cos 12 = 820$
Al – castor oil	$\sigma_w = 860 - 41 \cos 16 = 820$
Steel – spindle oil	$\sigma_w = 1360 - 41 \cos 30 = 1324$
Steel – castor oil	$\sigma_w = 1360 - 41 \cos 30\ 0\ 1324$

In the analysis of surface-active substances[55] it is also necessary to determine the hydrophilic–lyophilic number (HLN), which is a measure of the quality of the emulsion and of its propensity to inversion. Several methods have been proposed to establish this number. For etheric grease oils and polyatomic alcohols it can be calculated[56] using the relation: HLB = 20 (1–O/K), where O is the soaping number and K is the acidic number. Depending on the pH, in acid emulsions cationic active emulgators and in basic emulsions anionic active emulgators, are used. Care should be taken when using stabilisers, due to their biological activity.

In theory, and according to the Bancroft rule, surface-active agents have[57] either a dominant molecular geometry or a dominant interphase interaction energy. Pauling investigated their geometrical structure.

In **Figure 6** the average thickness of the lubricant[58] layer versus the content of emulsoil ET-2 is given according to Grudnev. Above a content of 2 % the effect of the emulsoil during the cold rolling is not changed. For many emulsions the efficiency is even lower than that in **Figure 6**.

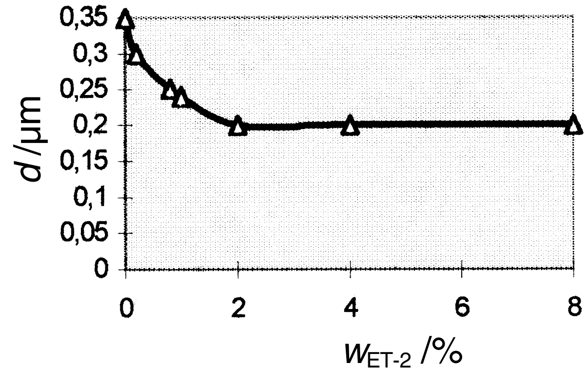


Figure 6: Lubricant layer thickness versus the content of emulsoil in the lubricant

Slika 6: Odvisnost med debelino sloja maziva in vsebnostjo emulsolja v mazivu

The emulsoils are colloidal solutions of soaps and free high-molecular compounds with mineral oils stabilised with 8 % to 12 % of alcohols. Alloyed oils are applied for the rolling of steels with a high deformation resistance. The requirements for these[59] oils are:

- viscosity at 100 °C and a high viscosity index,
- content of coke and sulphur,
- ignition temperature and resistance to thermal oxidation,
- colour, smell and corrosion stability,
- propensity to emulsifying and to froth formation,
- wear decreasing effect and the content of mechanical admixtures,
- acid number.

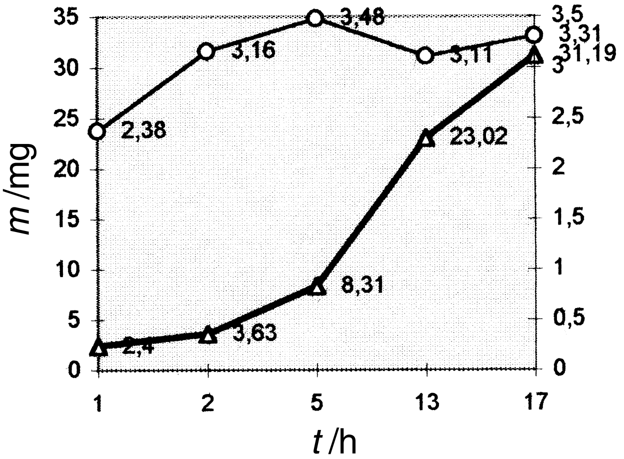


Figure 7: Weight loss of steel specimens[62]

Slika 7: Izguba mase pri jeklenih preizkušancih

6 LUBRICATION DURING THE PLASTIC WORKING OF METALS

Chemical and electrochemical corrosion needs to be considered when using lubricants for the plastic working of metals[60]. The corrosion intensity depends on a number of factors, such as microstructure and texture of the metal, lattice defects, state of the metal's surface, working temperature, contact and residual stresses, lubricant type, working atmosphere, elaboration process[61], etc.

In **Figure 7** the corrosion weight loss is given for a lubricant without addition of inhibitor (O) and with the addition of inhibitor (Δ). The rolling and the pressing increase and the extension decreases the corrosion resistance. The reaction of oxygen with the metal during hot forging and pressing is also a corrosion reaction. The metal has a negative potential compared to that of the scale and therefore the scale residues increase the pit corrosion of the metal.

The chemical corrosion is faster at higher temperatures. Corrosion[63] products are generally solid and compact and increase the metal's resistance to rapid corrosion. Surface roughness and tensile stresses increase the rate of corrosion. At high temperatures lubricants are oxidised and their content in organic acids is increased. The oxidation mechanism involves the formation of basic and peroxide radicals that react with non-oxidised molecules to form hyperperoxides and new radicals. These reactions[64] are suppressed with the addition of oxidation inhibitors (alkilphenoles). In liquid lubricants, hydrogen sulphide and organic compounds of two-valent sulphur react with the metal forming layers of sulphide with a protecting effect. At high temperatures these layers are decomposed to form hard particles that increase the abrasion process of the metal surface.

Mineral oils form hydrophobic layers[65] on the metal surface and have, in this way, a natural anticorrosion effect. These oils can[66] attack the metal surface in the presence of a higher content of protons due to the ageing of the oil or the presence of additives. In spite[67] of the low electrical conductivity, electrochemical corrosion[68] can also occur in oils. This is due to the distribution of cathodic and anodic areas, which makes the effect of the electrical resistance of the lubricant negligible. Active corrosion inhibitors must be efficient in the presence of additives, detergents and emulsifiers in the lubricant.

Tubes used for the exploitation of earth oil and gas are subjected to the corrosive attack of gasses, such as H_2S and CO_2 as well as sulphide and chloride compounds. In addition, stress corrosion may also occur. The resistance to corrosive gasses is increased for alloyed Cr-Mo and NiCr steels, whereas the resistance to stress corrosion is enhanced for the microstructure of tempered martensite[69]. The corrosion resistance is also increased with the decrease of carbon content and vacuum degassing, as well as the deposition of a protective layer of thermoplasts or thermoreactive pitch. Modern theory explains well the corrosion processes of metals in a wet atmosphere, whereas in the presence of lubricants the corrosion processes are more complex and, up to now, poorly understood. Generally, the corrosion process is slower in the presence of layers of lubricant containing organic and inorganic compounds, e.g. by the drawing of wire using soap powder.

The selection of the filler for the lubricant should be made carefully, since it seems that even graphite and molybdenum disulphide can increase the corrosiveness of the lubricant[70]. Also, the change of the process of deposition of the phosphate layer from wet to dry may affect the corrosion resistance[71]. The propensity to corrosion is also increased with the addition of zinc phosphate and borax to powdered sodium soap[72]. Graphite can diffuse in the metal during annealing and form carbide particles that later decrease the corrosion resistance. Graphite also causes black stains, which are avoided with the addition of paraffine and activators based on sulphur and chlorine[73]. Metallic layers can also be used as lubricants. A zinc layer is widely used and it is deposed with the same process on tubes and sheets[74], e.g. with manual spraying or dipping in the molten zinc.

The deposition of a layer of zinc[75,76] is described with the Navier-Stokes equation:

$$\partial p/\partial z = \rho g + \mu \partial^2 u/\partial^2 y \qquad (41)$$

with the boundary conditions:

$$y = 0 \qquad u = u_0$$

$$y = \sigma(z) \qquad \partial u/\partial y = \tau_s/\mu$$

If the inertial forces are neglected the solution of the equation is

$$\sigma_0 = 0.5\,(\mu U_0/\rho g)^{1/2} \qquad (42)$$

where σ_0 is the thickness of the zinc layer, g is the acceleration due to gravity, ρ is the zinc density, μ is the dynamical viscosity of the zinc melt, U_0 is the rate of motion of the sheet through the zinc melt and τ_s is the tangential tension on the sheet-melt boundary.

The diffusional deposition of zinc in powders with appropriate composition is carried out at a temperature 500 °C to 550 °C for (15 to 20) min.

The corrosion process depends also on the deformation level of the metal. The best resistance of cold-deformed tubes to stress corrosion is achieved with a small deformation and with a deformation of 30 % to 40 % for hot rolling.

Lubricant additives are: sulphonic acid, sodium sulphonate with a molecular mass of approximately 500, derivates of phosphoric acid, branched alcohol derivates with 5 to 12 carbon atoms, nitric compounds (these may cause ecological problems), amides, grease acids and others. The corrosivity[77] of water and water emulsions, thus also lubricants, is proportional to the content of chloride and sulphate. The corrosiveness of emulsions prepared with condensate is similar to those prepared with technical water. By increasing[78] in the emulsion the content of soap, and especially oleine soaps, the corrosiveness is decreased, while for a content of 0.5 % of acidol the corrosion is prevented. If the dressing is performed without emulsion it is useful to oil the sheet and deposit a layer of thickness of 1 to 2 g/m^2. The most frequently used anticorrosion lubricants for oiling are lanoline, vaseline, stearates (Al,Ca, Li, Na) and grease oils, sodium nitrates, sulphonates[79], soaps and bentonite. Emulsion inhibitors with a concentration of about 1 % form a finely dispersed stable emulsion of the oil-in-water type with a high anticorrosive efficiency. Emulsion oils with a strong acidic effect can also induce corrosion with a higher content of emulsifiers (15 % to 20 %).

The corrosion currents that are shown in form of cyclogramic diagrams can be determined on the basis of the Tafel coefficients b_A and b_K and the polarisation coefficient R_{pp}.

$$I_{cor.} = [b_A \cdot b_K / (b_A + b_K)]\ (2.303\ R_{pp}) \qquad (43)$$

The data on the high-temperature oxidation of lubricant oils are[80] limited and frequently inconsistent. Evidence of the increased stability of oils at higher temperatures[81] is found especially with additions of powders of copper, nickel and iron oxide. According to ref. 79 iron is the stronger oxidation[82] catalyst.

7 LUBRICANTS FOR THE MANUFACTURING OF STEEL ROPES

Figure 8 shows a device for the vacuum[83] lubrication[84] of steel rope. In the upper part of column 4 a constant concentration of lubricant vapour is maintained. The rope runs from the pulley 1 through the column 4 to the coiling 8. Going up in column 4 the rope passes through zones of increased dilution and gives off moisture. In the vacuum space at the column's top the rope is saturated with lubricant vapour. After this it descends down the column while the pressure in the rope interior increases. The sealant in the entry and the exit of the column maintains a constant lubricant pressure. After exiting from the vat 3 the surplus lubricant is removed [7]. The capacity of the device is (50,000 to 70,000) t/year and it is able to operate economically since lubricant losses are prevented, the consumption of energy is low and the device requires few operators. The speed of the rope is (5 to 30) km/h, the column height H = 11.3 m (it can be decreased easily) and the roll diameter at the top of the column is of 300 mm. The steel rope unwinds from the pulley 1 and before entering the bath it runs through the heating zone 2, where the temperature is increased to 65 °C. In the column the pressure depends on the rope position, thus: $H = (P-p)/\rho$. Where P is the atmospheric pressure, p is the pressure of the saturated lubricant vapour and ρ is the lubricant density.

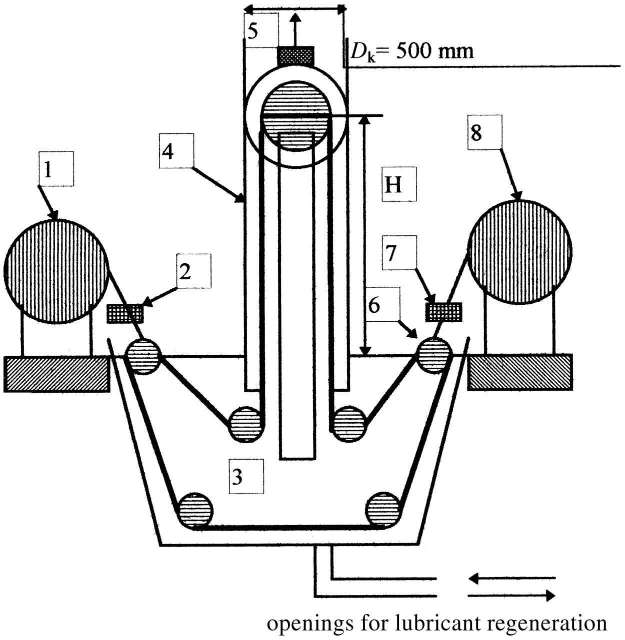


Figure 8: Scheme of the vacuum lubrication of ropes
Slika 8: Shema vakuumskega mazanja vrvi

In this process great attention is given to inhibitors for lubricants, and also molybdenum compounds[85] with the complex chemical formula $[/n\text{-}C_4H_9/_2NOS_2]_2\ Mo_2O_3S$, $[/izo\text{-}C_4H_9O/_2\ PS_2]_2\ Mo_2S_2O_2$ and $[/n\text{-}C_4H_9/_2\ NOS_2]_2\ Mo_2S_4$ are used. The steel rope can also be impregnated with polymers. The impregnation[86] pressure is calculated as:

$$P = \lambda_H\ l_h\ \rho/[2gD_g(Q_p/F_W)^2] \qquad (44)$$

where P is the pumping pressure, λ_H is the coefficient of hydraulic resistance, l_h is the length of the back-pressure tube, D_g is the hydraulic diameter equal to the difference in the diameters of the tube and the rope, ρ is the specific weight of the lubricant, g is the gravitational constant, Q_P is the lubricant current between the ring openings and F_W is the area of the section of the ring channel – smaller diameter.

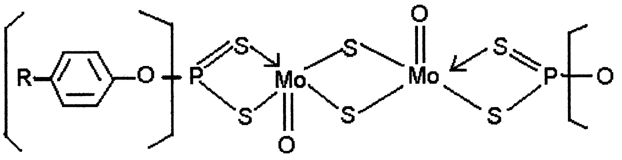
The stability[87] of the process depends on the lubricant quality. The lowest drawing force was found when using soap powder with the addition of molybdenum disulphide[88]. However, the use of soap is not recommended since it decreases the corrosion resistance of rope strands. For this reason, liquid lubricants are more commonly used. In this technology the requirements related to the lubricant quality are stronger than for other applications of cold working of metals. The lifetime of a 15-mm steel rope is decreased in the absence of lubrication by 50 %, and by as much as 70 % if the rope is exposed to sea water. Generally, the lubricant should have a greater specific weight and a better adhesion. Also, liquid lubricants[90] show better performances than those based on soaps, since in the first case the distribution of internal stresses is more favourable. In **Table 3** the characteristics of some lubricants[91] used in the manufacturing of steel rope are given.

Table 3: Chemical and physical characteristics of some rope lubricants
Tabela 3: Fizikalno-kemijske lastnosti maziv

Characteristic	Vaerol	39 Y	Torisol 35B
Dew point, °C (According to GOST 6793-74 it should be above 70 °C)	73	70.5	67
Ignition temperature, °C (According to GOST 4333-48 it should be above 200 °C)	215	240	215
Thermal stability, % (The volatility should be lower than 0.2 %)	0.05	0.19	0.14
Low-temperature characteristic, °C	-30	-14^{VI}	-35
Adhesion, % (Sticking in centrifuge for a distribution factor K_p = 6270 lower than 60 %)	21	99	31
Protective properties, % (Area of the corrosion damage)	30	30	90
Kinematical viscosity at 100 °C, 10^{-6} m^2/s. (higher than $1 \cdot 10^{-6}$ m^2/s after GOST 33-82	10	30	8.5

^{VI} is the loss of elasticity

An experimental investigation has shown that the lubricant[92] Vaerol increased the lifetime of fishing ropes for 35 % in comparison to other lubricants, and the performance of lift ropes was also better. Torisol shows a strong corrosivity. In new investigations of lubricants for steel ropes, in addition to molybdenum sulphide[93] complex molybdenum compounds with the following general structural formula are also being considered:



8 LUBRICANTS FOR PRESSING

Experience shows that during the hot pressing[95]and deep drawing[96] of metals the use of lubricants can improve the quality of the surface and reduce the consumption of energy. By using the right lubricants for pressing[97,98] the coefficient of friction can be decreased for 50 %, and the pressing speed can be increased for 30 to 50 mm/min. When using glass lubricants for hot pressing, problems[99] can arise with the removal of glass residues[100,101] from the surface and a good solution seems to be the simultaneus[102,103] removal of scale and lubricant. In **Table 4** the composition[104] of some glass lubricants for high-temperature use is given.

Table 4: Lubricants based on glasses
Tabela 4: Maziva na osnovi stekla

Chemical composition w /%	Softening or melting temp. °C
68.2 SiO_2, 1.0 Fe_2O_3, 2.1 Al_2O_3, 2.4 SO_3, 7.0 CaO, 4.5 MgO, 14.8 Na_2O_3	700
40.8 SiO_2, 5.1 Fe_2O_3, 2.8 Al_2O_3, 3.0 % CaO, 3.6 PbO_2, 3.2 Cr_2O_3, 9 BaO, 0.07 C and 32.4 compounds of the type R_2O_3	500
NaCl with the addition of salt eutectics	800

The basic problem with the use of glass lubricants is the layer thickness in the case of hydrodynamic lubrication. From the Navier-Stokes equations and based on **Figure 9**, the Reynolds equation was proposed in the form:

$$\partial^2 v_z / \partial r^2 = (1/\mu_t)\, \partial_p / \partial_z \tag{45}$$

and in cylindrical coordinates[105]:

$$(1/r)\, \partial/\partial r\, [r \partial v_z / \partial r] = (1/\mu_t)\, \partial p / \partial z \tag{46}$$

where $\mu_{t} = \mu_0 \exp(yp)$ is the viscosity of the lubricant at the pressing temperature, μ_0 is the viscosity of the lubricant at room temperature, p is the pressure in the lubricant layer, y is the piesocoefficient of the lubricant viscosity, which is deduced for the pressing processes as $y = (41.44 + 11.5 \log \mu_0) \cdot 10^{-9}$.

With integration for r the lubricant flow is:

$$V_z = [¼\, \mu_0 \exp(\gamma p)]\, \partial p/\partial z\, (r^2) + C_1 \ln r + C_2 \tag{47}$$

Where

$$K = [¼\, \mu_0 \exp(\gamma p)]\, \partial p/\partial z \tag{48}$$

And $\partial p/\partial r = 0$, $\partial p\ \partial z$ = const., K = constant and the boundary conditions

$r = a \qquad v_z = -u$

$r = b \qquad v_z = -u\ [1\text{–}0.25 \ln (b/a)$

The solution for ringform openings is then:

$$K = u\, \{[(\,½)(z - C_3)^2 - C_4 (z^2 - C_3) + \\ + (z^2/8) \ln(z/C_2) + C_7/C_5(z^3 - C_2^3) - (z^2 - C_2^2)/ \\ (\ln z/C_2)[(\ln z/C_2 + C_6)\, z^2/2 + C_8]\} \tag{49}$$

In **Table 5** the relation between the solution of (49) and the Descartes system according to **Figure 9** is given. According to computer calculations* the intensive v change of the lubricant pressure occurs in the range μ =

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* The conditions were: diameter of the blank (0.0035–0.166) m, thickness of the extruded rod (0.01–0.135) m, extrusion speed (0.04–0.4) m/s, deformation temperature (800–2000) °C, coefficient of thermal expansion (volume) $(1 \cdot 10^{-5} - 1.01 \cdot 10^{-3})$ 1/ °C

(200–1000) Pa. Increasing μ 200 to 6500 the lubricant pressure changes from (183 to 135) MPa. With a further increase in the lubricant's dynamical viscosity the change in the lubricant pressure is negligible, especially in the range from (5000 to 6500) Pa. This is explained by the decrease of the coefficient of friction on contact surfaces with the increasing viscosity of the boundary layer, and it is related to the decrease of the pressure in the layer.

Table 5: Relation between the lubricant layer and the geometry of the zone of plastic deformation

Tabela 5: Povezava med slojem maziva in geometrijo zone plastične deformacije

Constants for equation 49	Parameters of the process in **Figure 9**
$T_M = C_1$	$b = T_M z$
$z_0 - \Psi = C_2$	$b_0 = T_M z_0$
$z_0 = C_3$	$a_0 = a$
$C_1 \cdot C_2 /8 = C_4$	$b - b_0 = T_M (z - z_0)$
$C_1/3 = C_5$	$a = T_M (z_0 - \Delta/T_M) = T_M(z_0 - \Psi)$, $\Psi = \Delta/T_M$
$-C_1 \cdot C_2 /2 = C_6$	$b^2 - a^2 = T_M^{\ 2} [z^2 - (z_0 - \Psi)^2]$
$-C^2_3 /8 \cdot \ln (C_3/C_2) = C_7$	$b^2 - b_0^{\ 2} = T_M^{\ 2} (z - z_0^{\ 2})$
$C_1 \cdot C_2^{\ 3} /4 = C_8$	$b/a = z/(z_0 - \Psi)$, $T_M = \text{tg } a$, $b_0/a_0 = z_0/(z_0 - \Psi)$ $b^3 - a^3 = T^3_M [z^3 - (z_0 - \Psi)^3]$, $a^3 = T^3_M (z_0 - \Psi)^3$

Complex pressings, e.g. parts of car bodies, with straight or curved surfaces are manufactured on presses with double action, and with tools having tensile ribs on the holders matrix surfaces. Several significant parameters[106] and the complexity of the drawing make this manufacturing procedure one of the most complicated in the field of metal elaboration with plastic deformation. Criteria relevant to the quality of the lubricant are related to the intensification of the metal elaboration in terms of its boundary deformability. The quantity of lubricant remaining on the withdrawer affects the rate of levelling of the unevenness in the deformation zone. The viscosity of the lubricant is not a relevant characteristic because of the low value of the surface pressure and, according to Shey, in conditions of boundary lubrication the adhesive and chemical properties are more significant than the rheological characteristics of the lubricant.

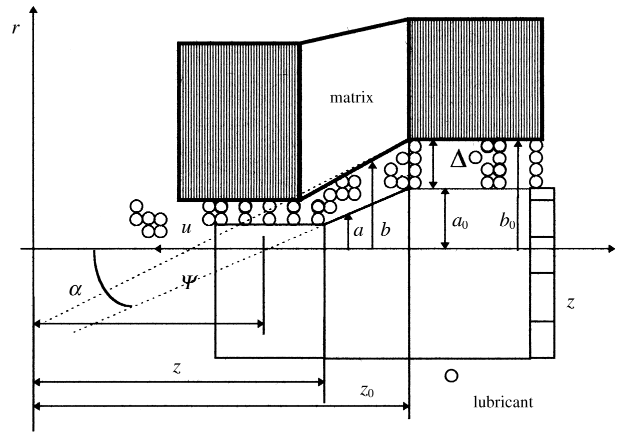

Figure 9: Scheme of the pressing with lubricant

Slika 9: Shema iztiskovanja z mazivom

The small stretching diameter and the narrow zone of lubricant deposition[107] make the Erichsen test, which is frequently used for lubricant selection, useful only for preliminary tests. To eliminate the effect of the state of the contact surfaces it is suggested to use polyetilen foils as a lubricant when checking with the Erichsen test the workability of the material.

9 CONCLUSIONS

Tribology has ancient origins, it was, however, as a branch of the technical sciences, defined only in the 20th century due to its complexity and its interdisciplinary nature. In this survey the plastic deformation of metals with the accent on the processes of colloidal chemistry and the mechanics of fluids is presented. The hydrodynamic equations of lubrication and of the lubricant layer in the deformation zone are reviewed and the relation between the laws of colloidal chemistry (wetting angle and adhesion work) and metallurgical problems summarised.

In the analysis the Reynolds equation for lubrication, which has been used in metallurgy since the development of the third-generation of computers[108], is shown. In the text the newest achievements and the new directions of investigation are discussed.

The effect of lubrication in metallurgy was perceived long before the postulation of hydrodynamic equations for lubricants; however, it use in engineering practice was possible only after a sufficient level of theoretical knowledge was achieved in colloidal chemistry. Visualisation by means of fast cameras enabled the experimental findings to approach the theoretical predictions of the hydrodynamic equations.

Metallurgy rapidly absorbed the positive aspects of this development and the plastic working of metals[109] has greatly profited from a number of tribological achievements, including the possibility:

- to obtain a clean and shiny surface of the deformed metal[110],
- to remove aggressive products in the regeneration process of the lubricant,
- to deposit on the surface different products for corrosion protection or for decoration,
- to reduce the amount of energy used with the right tribomechanical approach,
- to prolong the exploitation time of rolling stands, tools and instruments,
- to obtain a greater per-pass reduction level and a greater coefficient of elongation of the metal,

- to develop a high-pressure cold-rolling process that would not be efficient and economic without the appropriate application of tribology,
- to provide new options in the development of materials and in high-pressure physics,
- to use lubricants simultaneously as cooling agents,
- to obtain special effects in the use of steel ropes for cranes.

The work of Hardy in 1922, where it was demonstrated that the coefficient of friction of paraffin ($C_{24}H_{50}$) was 0.06 in dry air and 0.025 in the presence of water vapour, opened the way to tribological principles in metallurgy and helped to connect the newest findings in colloidal chemistry and fluid mechanics to the plastic working of metals. In a negative context[111] it is necessary to mention the ecological aspects[112] of the regeneration of technological lubricants and of the decomposition of emulsions.

New developments are expected for the application of mathematical tools necessary for the calculation of the lubricant layer in conditions of stable hydrodynamic lubrication with modern computers, which allow the use of differential equations for the analysis of the cold-rolled surface[113,114] roughness. Emulsions are expected to become the next lubricants for the cold-working of metals,[115] and the results of new investigations[116] in this field will increase and change the production of industrial lubricants[117,118] in the next decade.

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