

LUBRICANTS FOR THE ROLLING AND DRAWING OF METALS

MAZIVA ZA VALJANJE IN VLEČENJE KOVIN

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A survey is given over lubricants for rolling and drawing of metals. Emulsions, suspensions, natural fats and oils and synthetic lubricants are presented. Fluid mechanics Reynolds equations are used for the calculation of the lubricant layer in the entering section of the metals deformation zone. Colloide chemistry is used for the analysis of surface active additions on lubricant properties, lubricant layer thickness and the wetting angle. Lubricants for hot rolling based on suspensions and glass are presented also. Special attention is given to the removing of lubricant from the surface after processing, to measures for the protection of workers and to ecological problems of used lubricants.

Key words: lubricants, emulsions, suspensions, Reynolds equations, lubricants toxicity, surface roughness

Dan je pregled maziv, ki se uporabljajo pri valjanju in vlečenju kovin. Opisane so emulzije, suspenzije, naravna olja in masti ter sintetična maziva. Reynoldssove enačbe iz mehanike tekočin so uporabljene za izračun debeline sloja maziva na prerezu kovine na začetku deformacijske zone. Kolooidna kemija je uporabljena za opis vpliva površinsko aktivnih snovi na lastnosti maziva, na debelino sloja maziva in na kot omočljivosti. Opisana so maziva za vroče valjanje na osnovi suspenzij in stekel. Posebna pozornost je namenjena odstranitvi sloja maziva s površine kovine po procesiranju, ukrepom za zavarovanje delavcev pri delu in okolju.

Ključne besede: maziva, emulzije, suspenzije, Reynoldssove enačbe, toksičnost maziv, hrapavost površine

1 INTRODUCTION

The basic tribological principles presented in ref. 1 for the manufacturing of steel ropes and metal extrusion are enlarged to the use of lubricants for the rolling and drawing of metals. The methods for the deposition of lubricant in the process of working of metals were developed gradually. In **Figure 1** a modern system for lubricant deposition is shown schematically.

Water, water steam and air temperature are adjusted to the type of lubricant by means of thermoregulators. The system is equipped with contact manometers,

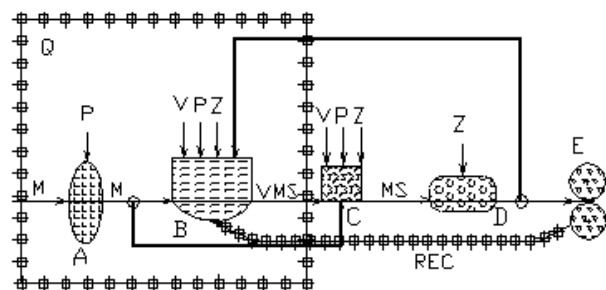


Figure 1: Functional lubrication system. A – Entering collector, B – Preparation of the mixture, C – Mixing of components, D – Feeding, E – Rolls, M – Lubricant, VMS – Water rich mixture, MS – Lubricant mixture, V – Water, Z – Air, REC – Lubricant recirculation

Slika 1: Funkcionalni sistem za mazanje. A – Vhodni kolektor, B – Priprava zmesi, C – Mešanje komponent, D – Dodajanje, E – Valji, M – Mazivo, VMS – Zmes, bogata z vodo, MS – Zmes maziva, V – Voda, Z – Zrak, REC – Recirkulacija maziva

devices for condensation, flow regulators, devices for automatic feeding of lubricant and for the recycling and regeneration of lubricant returned in the processing. Pioneer works in these topics are of Troost A., Roberts W.L., Billigman Y. and Stone M. The hydraulic resistance of emulsions at flowing through the feeding tubes and devices is specific by relation to other liquids. The hydrodynamic findings related to these topics were established by Dans and Rosii, while Darsi and Vejsbah developed the theoretical base.

2 LUBRICANTS FOR DRAWING AND ROLLING

2.1 Emulsions for cold working

Emulsions are of the greatest importance for the cold working of metals. The viscosity of the system can be calculated using Einstein's and the Taylor's equation¹

$$\mu = \mu_d \left(1 + 2,5\varphi \left(\frac{\mu_e + \frac{2}{5}\mu_d}{\mu_e + \mu_d} \right) \right) \quad (1)$$

This equation describes well the viscosity of dispersion systems up to the content of 15-20 %. For greater concentrations emulsions of the type water in oil consist of colloide systems with more phases. Equation (1) can't be applied for boundary conditions where the viscosity changes rapidly and also using optical microscopy reliable informations on the colloide systems can not be obtained. These areas of colloide systems limit the technological use of emulsions, since, the

friction force does not depend on emulsion concentration due to possible inversions of phases in the emulsion. These problems were approached with investigations of sedimental characteristics of half dispersed concentrated emulsions and modelling of their layering². The simulation is performed on the base of electrostatic fields.

The layering rate is defined as

$$U = -\frac{dH}{dt} = k_1 (H - H_{df}) \quad (2)$$

and calculated using the following solution

$$U = \left(a + \frac{b}{H_{df}} \right) (H - H_{df}) \quad (3)$$

With constants a and b independent of the quantity of dispersed phase in the initial emulsion and on its concentration and k_1 -reaction rate constant. The rate coarsening of emulsion particles (droplets) is calculated using the equations³.

$$d^3 = a_0 + b_0 \tau \quad \text{and} \quad b_0 = \frac{64 \sigma DCv}{9 kT} \quad (4)$$

The decrease of the solubility of soap in emulsions deteriorates their technological properties. For lowering the effect of impurities 0.4 g/L sodium polyphosphate (NaPO_3)_x with $x = 20-200$ is added without effect on the layering, on the viscosity and pH. In place of sodium polyphosphate, stearate and the expensive olein acid also cotton oil can be added to the emulsion, however, this addition decreases the emulsion properties. With change of temperature, also physical properties of emulsions, such as density, adhesion and cooling capacity are modified. The proper use of emulsion can lower down to 10 % the rolling energy used, while the rejection is diminished up to 20 %^{9,10}. The stability of the emulsion is of very great practical importance¹¹, while its inversion causes serious problems for the emulsion treatment. The problem is mostly investigated with the determination of the coalescence of emulsion particles (droplets) in the dispersed medium or determining the life time of a particle on the boundary of two liquids¹².

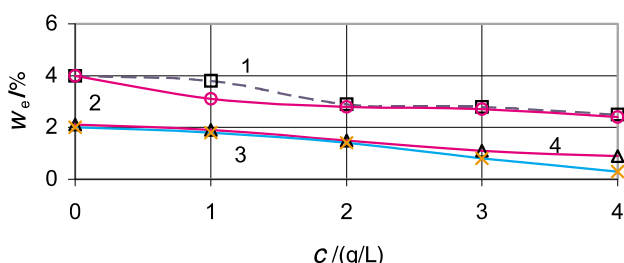


Figure 2: Influence of Ca^{2+} and Fe^{2+} ions $c/(\text{g/L})$ on the destabilisation of the emulsion composition $w_e/\%$. 1,3 – content of Ca^{2+} ; 2,4 – content of Fe^{2+} ; 1,2- emulsion with 4 % of additions; 3,4 emulsions with 2 % of additions

Slika 2: Vpliv Ca^{2+} in Fe^{2+} ionov $c/(\text{g/L})$ na destabiliziranje sestave emulzije $w_e/\%$: 1,3 – vsebnost Ca^{2+} ; 2,4 – vsebnost Fe^{2+} ; 1,2 – emulzije s 4 % dodatkov; 3,4 emulzije z 2 % dodatkov

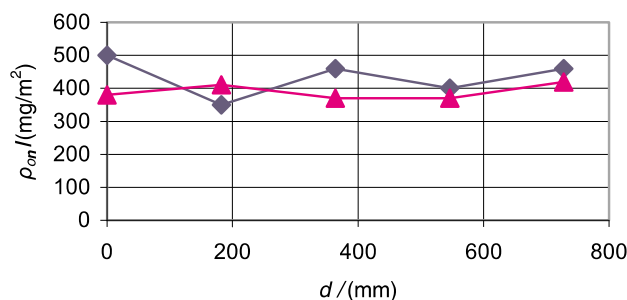


Figure 3: Distribution of the oil quantity $\rho_{on}/(\text{mg/m}^2)$ over the sheet width d/mm for the cooling of rolls with emulsions; – emulsion based on water, Δ – emulsion based on water and lubricant

Slika 3: Porazdelitev količine olja $\rho_{on}/(\text{mg/m}^2)$ na površini traka po širini d/mm pri hlajenju valjev z vodnimi emulzijami; – emulzije na osnovi vode, Δ – emulzije na osnovi vode in maziva

Microflore contamination has a deleterious effect on emulsions and their cooling capacity, it causes also the demulsion and decreases the emulsion concentration. Such emulsions are faster saturated with mechanical particles and require more addition of fresh emulsion. For this reason, to emulsions 0.1–0.15 % of stabilising antimicrobial substances are added. This addition lowers the consumption of emulsoil, diminishes the sheet contamination, it can however, due to the change of pH, increase the corrosivity. The stability of emulsions is decreased with increased content of ions, f.i. Ca^{2+} , Fe^{2+} and Cl^- . The origin of calcium ions is the used water, while, the sheet surface is the source of iron and chlorine ions. On **Figure 2** the destabilisation of emulsions is shown in dependence of some ions concentration.

The destabilisation of the emulsion can be prevented with addition non ionic emulgators, with use of pure water and with clean sheet surface. The addition of 10 % of palm oil has a beneficial effect on cooling emulsions and improve the cleanliness of the sheet¹⁴, as shown in **Figure 3**.

Applying the proper droplets size and thickness of the filtering layer, the properties of emulsions are improved and the quantity of mechanical impurities, oxidation products and polymerisation products is diminished. With active additions and fillings, the properties of emulsions can be modified. It is important that surface active additions are stable in the range of temperature of the processing and play a role of plasticators¹⁵ thickening the emulsion¹⁶.

Microemulsions¹⁶ with droplet size below $0.1\text{E-}6$ were not investigated sufficiently for eventual use for plastic deformation of metals. Three types of stable properties are required from these emulsions: sedimentation, flocculation and coalescence. According to Russian standards for microemulsions, the surface active additions Span-80, T-2, Sorbitan-O, Pentol and Stearoks 6 are used, especially in case of greater cooling efficiency.

2.2 Emulsoils

Emulsoils are colloidal solutions of soap and free high molecular acids in mineral oil of average viscosity (20–40) E-6 m²/s stabilised with water or alcohol and with a content of organic acids of 8–12 % and are widely used in metallurgy¹⁷. Their effect on the lubricant layer in the deformation zone can be opposite to that expected from solutions of theoretical equations developed for standard emulsions. Up to now, no explanation was proposed for their effect and the theory was advanced that they represent a special form of the Rebunder effect. Emulsoils based are some alloyed lubricants with the viscosity of 4.19 mm²/s, density of 845 kg/m³ at 20 °C, surface tension of 0.03 N/m² and flash point of 138 °C.

2.3 Graphite lubricants and emulsions

Graphite lubricants combined with emulsoils are frequently used for plastic deformation of metals¹⁸, as shown in **Figure 4**.

On the base of experimental results the following equation was deduced for the wetting angle:

$$\cos \theta = \cos \theta_0 \exp\left(\frac{E}{RT}\right) \quad (5)$$

With: T – temperature, E – activation energy, R – gas constant and θ_0 – wetting angle for the null concentration of the active substance. The wetting angle is decreased with increasing the content of surface active additions and of electrolyte.

The stabilising additions should be adapted to the emulsion type¹⁹. In dependence of pH of the emulsion, cation or anion type emulgators should be used with the hydrophilic-lipophilic number known. The efficiency of the lubricant is increased also using ultrasound in the preparation of the emulsion. Unstable emulsions for plastic working of metals are of the water – oil type and are manufactured by mixing at the rate of 100–200 r/min. Without addition of emulgator, these emulsions are kept at the temperature around 70 °C. According to I.A. Buchbinder, the turbulent flow occurs in emulsions with fat oils in content of 20 % for a Reynold's number of

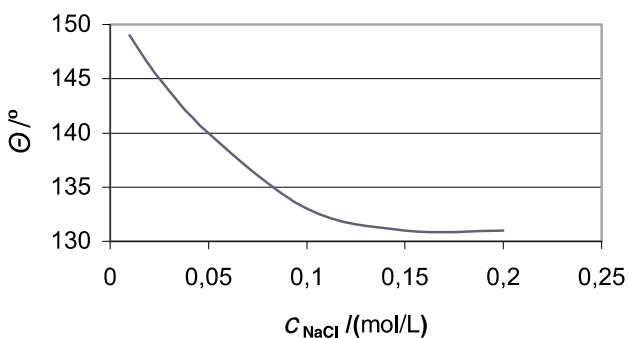


Figure 4: Wetting angle $\theta / ^\circ$ of emulsions on graphite in dependence of the concentration of NaCl (mol/L)

Slika 4: Kot omočljivosti $\theta / ^\circ$ na grafitu v odvisnosti od vsebnosti NaCl (mol/L)

1400–1600, thus earlier than for pure water. The Reynold's number is generally determined using potential functions frequently called also as "catastrophe theory".

Synthetic oil emulsions are stable due to the presence of glycol monoether and more atomic alcohols acting as emulgators. By mixing, it is necessary to consider the product $n^{1/2}d_m^{0.8}$ which value should be between 0.7 and 10 and the Weber number: $We = \rho n^2 d_m^3 / \sigma$. In the gravity field this number is deduced as: $d/d_m \approx We^{-0.6}$ with ρ – emulsion density, n – frequency of rotation and d_m – mixer diameter and d – the average size of emulsion droplets: $d = \Sigma N_i d_i^3 / \Sigma N_i d_i^2$; σ – surface tension on the boundary of both phases solid (T) and liquid (P), N_i – number of droplets of diameter d . The surface tension can be deduced using the Džirifalc relation: $\cos \theta = 1 - 2 \sqrt{\delta_T / \delta_P} - \varpi / \delta_P$, with ϖ as correction⁴ because of the absorption of liquid vapour on the solid surface.

The distribution of particles of dispersed phase follows the law of normal distribution in emulsion of the type "oil in water" and "water in oil". However, the normal distribution is not met always²³ and other types of distribution occur also, f.i. Rosin-Rammler, normal-logarithmic and Pearson distribution. In **Figure 5** the Pearson distribution is shown²³.

Also the size decreasing of droplets in turbulent field using mechanical, ultrasound and vibrational mixer is modelled mathematically. For the size decrease of droplets a determined time is required which can be evaluated using the Navier-Stokes equation: $t \approx \rho v d / \sigma$ considering fluid density, kinematical viscosity, droplets size and surface tension. The proces was investigated

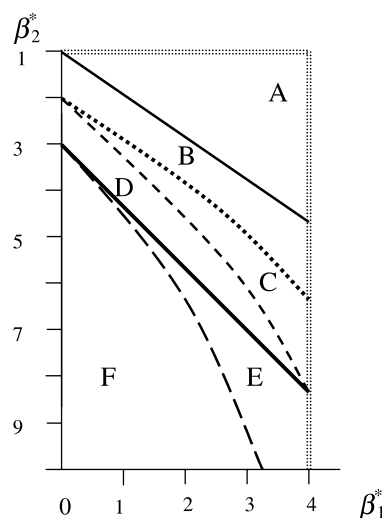


Figure 5: Pearson's diagram. β_1 – index of normal square of asymetry, β_2^* – index of the normal square of peaked distribution, A – critical area, B – U area of beta distribution, C – area of J distribution, E – gamma distribution and F – normal logarithmic distribution.

Slika 5: Pearsonov diagram. β_1 – indeks kvadratov normalne simetrije, β_2^* – indeks normalnih kvadratov žagaste distribucije, A – kritična površina, B – U površina β distribucije, C – površine J distribucije, E – gama distribucija, N – normalna logaritmična distribucija

little and several theoretical and empirical relations have been proposed for its generalisation.

2.4 Natural oils and fats

For the plastic working of metals natural and synthetical oils and fats are used²³. Of natural oils the ricinus oil consisting of hydro acids is mostly used (it is used the most for lubrication of aircrafts engines). Also palm and cocos oil are widely used. Natural oils have an agreeable scent, are oxydation resistant, dry slowly in air and are classified according their yodine number, which is indicator the drying and polymerisation rate. For use in plastic working these oils are hydrogenised and their yodine number is diminished to below 80. The palm oil consists of groups of oleine and linoline acids.

Cattle and sheep tallow and whale oil are the most used of animal products. Fats of animal origin are more propensive to bacterial activity than plant oils and are easier oxydised and contaminated. The addition of whale oil increases the emulsion viscosity by three times. Fat oils should be used only in a very thin layer, since, thanks to the polarity of fat molecules, form a layer of molecular thickness²⁶. Sulphurised fat oils are added to cutting oils to increase their stability to a higher temperature, as the formed iron sulphide prevents the direct contact of two clean metal surfaces. Technical fats of soaps origin are classified by the length of soap thread 1–100 μm and are used for the lubrication of reductors and rolling stands. Oils decay with formation of CO_2 by atmospheric oxydation and are carbonised if the working temperature is increased above a limit characteristic for the oil. All degeneration processes are inhibited by keeping the lubricant in vacuum or in nitrogen.

2.5 Soaps

Soaps are widely used as lubricants for the drawing of metals. The first informations on the nature of soaps and water-soap emulsion of MacLennon date from 1923. Soaps don't have a crystal structure and exist in different phases: izotropic solutions, soaps kernels and threads. Mc Bain and Langdon discovered the half soaps, which according to Voldo, do not contain liquid crystals but soap mycelia and are called also "boiler soap". After McMahan discovery that the Gibbs rules apply also for soap phases, the treatment of soaps changed from empirical to scientific. More informations on soap phases are obtained with calorimetric and dilatometric investigations than with X ray diffraction. The Kraft point defines the boundary between the isotropic solution and the thread. The phase behaviour of soaps was relatively little investigated up today. Harkins and Langmuir investigated the orientation of soaps molecules on free surfaces and Rayleigh showed that the orientation depends on static and dynamic tension. Christopherson and Naylor²⁷ were the first to investigate the use of soaps in metallurgy, while Perlin²⁸ applied as first the fluid mechanics to soap emulsions.

2.6 Synthetic fats and oils

The use of synthetic fats and oils dates from the end of the second world war and actually are used for the range of temperature from $-60\text{ }^\circ\text{C}$ to $300\text{ }^\circ\text{C}$. With antifricition additions the rheology and colloidal stability of fats are improved. As additions, graphite and molybdenum disulphide are used, mostly. The addition of polymers increases the resistance to mechanical and thermal loading. More frequently used polymer additions are polyisobutylene, poymetacrilate, plaxol and lubtisol. Also powder lubricants are a useful addition, f.i. polyetilene with high and low density, polytetrafluoretilene, polyvinyl chloride etc. With appropriate thermal treatment at the temperature of $150\text{ }^\circ\text{C}$ the fat resistance is increased up to four times. Fat lubricants are able to support heavy loading in hard working conditions. They decrease the contact friction due to the absorption of molecules on the metal surface. The absorbtion strength is determined by measuring the exit work for electrons applying the method of contact potential difference *KRP*. The absorption of radicals and molecules on the metal surface can decrease or increase *KRP*. With longer metal immersion in oil also the absorbtion is increased and the friction is diminished. The absorbtion is affected by pitch products containing oxygen, sulphur, nitrogen and polycyclic aromatic hydrocarbons. The absorbtion rate is defined as: $\Delta KRP/\Delta\tau \cong d\phi/d\tau$ with the exit work inversely proportional to the immersion time. The rate of the exit process depends on the donor and acceptor mechanisms³².

Also surface active substances, mostly oleine acid, are added to fats. According to Rebinder, surface active additions inhibit in absorbtion time the formation of a structural skeleton and increase, in this way, the fat fluidity. The origin on the anomaly of litium soap is in the formation of eutectic mixtures by crystallisation. The hermetic capacity of fats depends on the type and the dispersion of the filler.

Fat lubricants for steel ropes are controlled also for the resistance to cold. The rope is covered with lubricant, loaded and cooled to $-40\text{ }^\circ\text{C}$. The adhesion work is than determined measuring the electrical resistance³³ of the lubricant layer, which increases with increasing pelling.

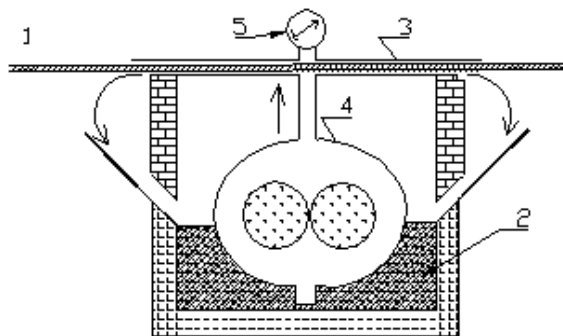


Figure 6: Device for the pressure impregnation of steel rope
Slika 6: Naprava za impregnaciju jeklene vrvi pod pritiskom

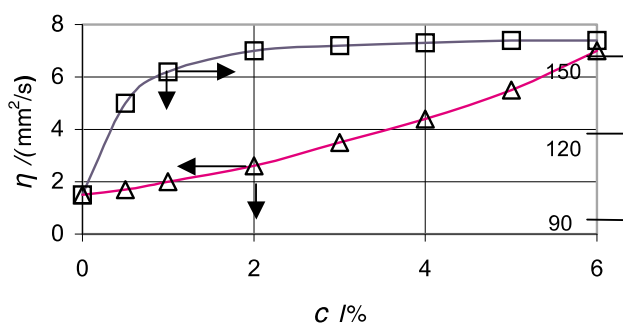


Figure 7: Dependence of kinematical viscosity (Δ) $\eta/$ ($\text{mm}^2 \text{s}^{-1}$) and of the viscosity index (\square) for a synthetic oil on the content of copolymer $c/$ %.

Slika 7: Vpliv vsebnosti kopolimera $c/$ % v sintetičnem olju na kinematično viskoznost (Δ) $\eta/$ ($\text{mm}^2 \text{s}^{-1}$) in na indeks viskoznosti (\square).

The surface cleaning can also be included in the finishing operation of the manufacturing process, as shown in **Figure 6**, where the scheme of pressure impregnation of steel wire with a hydromechanical gate is shown.

The steel rope (1) is covered with a protective layer from the vat (2), it is then lead over the toothed pump with a pressure gauge (4), through the pressure tube (3) and through the switch point (5). Fats for steel ropes are improved with addition of zinc³⁴ up to the mass fraction (1-7)E-2 %.

Catalisators and additions increasing the viscosity are important also for the properties of synthetic oils. **Figure 7** shows the influence of the copolymers³⁵ vinipol+stirol on kinematical viscosity at the temperature of 100 °C. The lubricants are checked for the critical loading³⁶ in dependence of the gliding rate and for the load capacity³⁷ in dependence of the friction coefficient.

Polyphenylethers are aromatic compounds particularly resistant to higher temperature. The lubricant properties of these compounds in temperature range 200 °C to 300 °C are similar to those of mineral oils and better than those of silicon oils and aromatic hydrocarbons, they have, however, a lower load supporting capacity than mineral oils. Perfluorinepolyethers developed in 1968 as lubricant for space technology³⁸ are resistant also to thermal and oxidation loading above 260 °C.

2.7 Clay suspensions

For the seamless tube technology the proper selections of lubricants³⁹ for tools and accessories is of the greatest importance. The best performances are obtained using powdered slags and graphite as oil suspensions⁴⁰ which could be used also for the drilling of tubes. Clay suspensions are used in petrol drilling technology⁴¹. **Figure 8** shows the effect of additions on the stability of the montmorillonite in water suspensions.

For the content above 0.2 g-eq./L of KCl in suspension the clay is less stable than for suspensions

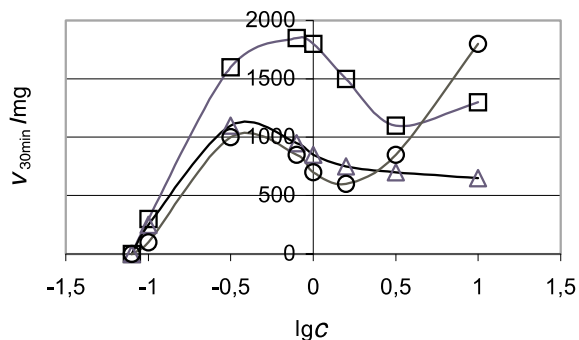


Figure 8: Stability of montmorillonite as rate of clay decomposition (in v mg for 30 min) in dependence of the log. value of the content of salts \square – KCl, Δ – CaCl₂ and O – NaCl in water suspension

Slika 8: Stabilnost montmorillonita kot hitrost razgradnje gline (v mg na 30 min) v odvisnosti od logaritma vsebnosti soli \square – KCl, Δ – CaCl₂ in O – NaCl v vodi.

with other salts. By increasing the content of salt up to 0.5-0.8 g-eq./L the stability is increased. This is explained in terms osmotic pressure preventing the capillary absorption of water in clay.

2.8 Glas as lubricant

Glas lubricants form by hot working a protective layer⁴² which prevents the surface oxidation, as shown in **Figure 9**.

By metal plastic deformation the scale can have also a lubricant action⁹¹. At high temperature a three layer scale is formed, an internal layer of FeO, an intermediate layer of magnetite and a layer of hematite in contact with the atmosphere. By air cooling FeO is decomposed to iron and magnetite. By low temperature the scale consists of two layers, a layer of magnetite in contact with the metal and a layer of hematite.

Experimental data show that the average oxidation rate of steel in an atmosphere containing oxygen and water vapour ($p_{\text{H}_2\text{O}} \approx 40 \text{ kPa}$, $T = 1273 \text{ K}$) is of 270 $\text{mg}/\text{cm}^2 \text{ h}$. If the steel surface is covered with a 0.2 mm thick layer of 0,33 Na₂O 0,67 SiO₂ glas the oxidation rate is diminished by 5 times and for a layer thickness of 2.5 mm by 55 times. The bare metal surface is oxidised according to the reactions:

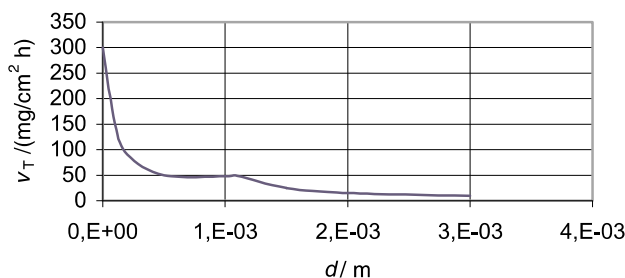
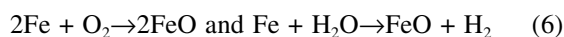


Figure 9: Influence of the thickness $d/$ mm of the glas layer on the oxidation rate $v_T/$ ($\text{mg}/\text{cm}^2 \text{ h}$) of a steel

Slika 9: Vpliv debeline sloja stekla na površini $d/$ mm na hitrost oksidacije $v_T/$ ($\text{mg}/\text{cm}^2 \text{ h}$) površine jekla

By surface oxydations blistering may occur. The crushing of blisters shell lays the metal surface bare and accelerates the oxydation rate. The crytical radius of the blister in the scale layer is calculated using the equation:

$$r_0 = \frac{2\sigma_z \sin \theta \sqrt{2\rho g}}{1/3(\rho g(6 + 3 \cos \theta - \cos^3 \theta))} \quad (7)$$

Using appropriate data a radius of 0.52 mm is calculated. Soda water with the SiO₂ : Na₂O₂ ratio of 2 -2,5 was used as lubricant in the past.

3 FLUID MECHANICS BY WORKING OF METALS

For the simple die design⁴³ in **Figure 10** the process of cold drawing can be described with the Reynold's equation

$$\frac{dp}{dx} = \frac{6\mu v_0 (h_0 - h(x))}{h^3(x)} \text{ with } \mu = \mu_0 \exp(\gamma p), h(x) = h_0 - x \tan \alpha \quad (8)$$

The solution of this differential equation allows to calculate the pressure in the lubricant layer in the matrix;

$$p = -\frac{1}{\gamma} \ln \left[1 - \frac{3\mu_0 \gamma v_0}{h(x) \tan \alpha} \left(2 - \frac{h_m}{h} \right) \right] \quad (9)$$

Introducing $p = p_m$; $h = h_m$ the Mizun-Grudev equation is obtained

$$h_m = \frac{3\mu_0 \gamma v_0}{[1 - \exp(-\gamma p_m) \tan \alpha]} \quad (10)$$

A die of more complex design⁴⁴ is shown in **Figure 11**.

The proces is divided in two phases and for each of them the Reynold's equation is applied separately. The connection of the lubricant layer between the areas of thickness ε_2 and ε_1 is given by the following relation:

$$\varepsilon_2 = \frac{\varepsilon_1}{2} + \frac{\varepsilon_1^3 (1 - \exp(-\gamma p_0))}{12\mu_0 \gamma v_0 l_k} \quad (11)$$

By increased drawing rate in the Reynold'e equation also the effect of inertia⁴⁵ is considered in the following way:

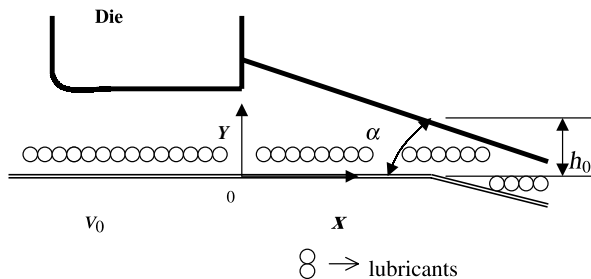


Figure 10: SHEME of die drawing with lubricant
Slika 10: Shema vlačénja z votlico z mazivom

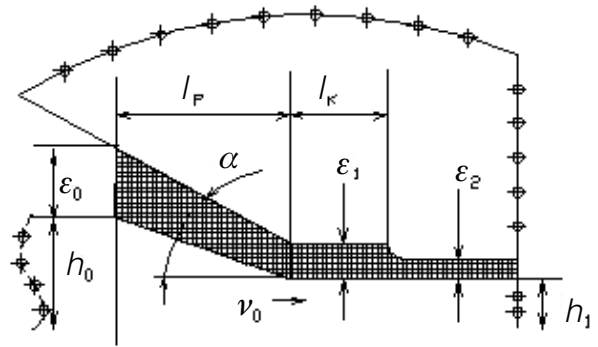


Figure 11: Sheme of drawing with a more complex die
Slika 11: Shema vlačénja z bolj kompleksno votlico

$$\frac{\partial p}{\partial x} = \frac{6\mu v_0}{h^2(x)} + \frac{C_1 \mu}{h^3(x)} + \frac{\tan \alpha \rho}{120h^3(x)} (16v_0^2 h^2 - C_1^2) \quad (12)$$

$$\text{with } C_1 = \frac{k_1}{2} - \sqrt{\frac{k_1^2}{4} + 2v_0 h(8v_0 h + 3k_1)}; \quad k_1 = \frac{120v}{\tan \alpha}$$

For an actual technological processing, the calculations according to equation (12) gives an increase of the pressure gradient in the lubricant layer on the die entering section for a few %. In the lubrication equations also the effect of diffusion forces can be introduced⁴⁶ as result of the interaction between the lubricant and the solid metal surface: $\Theta(x,y) \approx \xi (\tan^2 \theta - \theta^2) / \varepsilon^3$ with: $\xi \approx 10^{-20}$ J, θ – equilibrium wetting angle and ε – lubricant layer thickness.

An analogous treatment can be evolved also for the rolling of metal, only the linear projection of the rolls vector is to be added to the rolling rate, as shown in **Figure 12**.

The proces is described with the simplified version of the Reynold's equation⁴⁷:

$$\frac{\partial p}{\partial x} = \mu \frac{\partial^2 v_x}{\partial y^2}; \quad \frac{\partial p}{\partial y} = 0; \quad \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0 \quad (13)$$

The solutions of this equation are different and for the case of calculation the roll jump⁴⁸ and the lubricant back rate before the rolling gap the following solution is used:

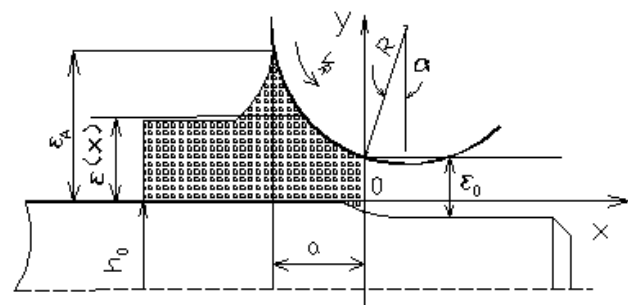


Figure 12: Sheme of rolling with lubrication
Slika 12: Shema valjanja z mazanjem

$$\frac{\partial p}{\partial x} = \frac{2\mu\omega(R - \sqrt{R^2 - x^2})}{(y_0 - H)^2 - (y_0 - y_v)^2}; \quad (14)$$

$$y_v = \varepsilon_0 + R - \sqrt{R^2 - x^2}$$

With: ω – rolls angular velocity, ΔH – decrease of sheet thickness, R – roll radius, μ – lubricant dynamical viscosity, y_0 – lubricant layer thickness in the gap section with the maximal rate of back flow of metal, ε_0 – lubricant thickness in the entering section of the deformation zone, v_x ; v_y – lubricant rate in Descartes coordinates.

A more used form of the equation⁴⁹ is:

$$\frac{\partial p}{\partial x} = 6\mu(v_0 + v_R) \left[\frac{\varepsilon_0 - \varepsilon(x)}{\varepsilon^3(x)} \right]; \quad \varepsilon(x) = R \cos \alpha - R \cos \varphi_0 + \varepsilon_0 =$$

$$= \frac{1}{2R} [x^2 - R(\Delta H - 2\varepsilon_0)] \quad (15)$$

If in equation (13) also the sheet and rolls surface roughness are considered⁵⁰ the solution for the case of an average roughness is:

$$\left\langle \frac{dp}{dx} \right\rangle = 6\mu(v_0 + v_{Rr}) \left[\left\langle \frac{1}{\varepsilon^2(x)} \right\rangle - \frac{\left\langle \frac{1}{\varepsilon_0^2} \right\rangle}{\left\langle \frac{1}{\varepsilon^3(x)} \right\rangle} \right] \quad (16)$$

With $\varepsilon(x) = \varepsilon(x_{smooth}) + [\delta_v(x) + \delta_T(x)]$. For the solution for a smooth surface the lubricant layer thickness related to the roughness of the rolls and sheet surface is added. The influence of the roughness was carefully checked empirically. It was established that the longitudinal roughness decreases the layer thickness in the entering section of metal deformation, while the transverse roughness increases the lubricant layer thickness in the deformation zone and it is, therefore, usefull. The lubricant layer thickness at the initial section of the plastic deformation zone depends on the thickness on the sheet and it was established that the thickness of 1 mm is sufficient. It is, however, in surplus and necessary only as boundary condition $x = \infty$ required for the solution of the equation (16).

The physics of the proces can be explained considering tangential stresses⁵². In this case the equations are written as follows:

$$\frac{dp}{dx} = \frac{1}{h} \frac{d(2kh)}{dx} + \frac{2\pi}{h}; \quad \frac{dp}{dx} = \frac{6\mu(v_0 + v_R)}{\varepsilon^2(x)} - \frac{12\mu\Omega}{\varepsilon^3(x)},$$

$$\tau_s = \frac{\mu(v_R - v_0)}{\varepsilon(x)} - \frac{\varepsilon(x)}{2} \frac{dp}{dx} \quad (17)$$

The equation taking in account also the longitudinal surface roughness is written as:

$$\frac{1}{6\mu(v_0 + v_R)} \left\langle \frac{dp}{dx} \right\rangle = \frac{\varepsilon(x) - \varepsilon_0}{\langle \varepsilon^3(x) \rangle};$$

$$\langle \varepsilon^3(x) \rangle \approx \varepsilon^3(x) + 3\delta^2 \varepsilon(x) \quad (18)$$

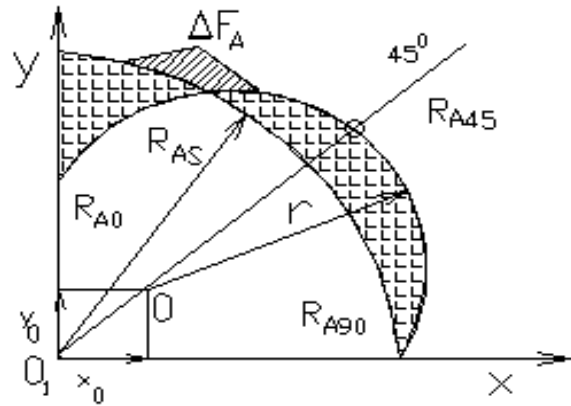


Figure 13: Graphic determination of the average roughness R_{AS}
Slika 13: Grafična določitev povprečne hrapavosti R_{AS}

The surface roughness is of very great practical importance⁵³. Its anisotropy⁵⁴ on the cold rolled sheet depends on the rolling rate, the reduction and the lubricant quality. In Figure 13 the method of determination of the roughness of the cold rolled sheet is shown.

The surface of a specific roughness area can be calculated considering the coordinates of it center (x_0 ; y_0) and radius (r) using the equation:

$$x_0 = \frac{R_{a90}^2 - R_{a45}^2 + \frac{R_{a45}}{\sqrt{2}} (R_{a0} - \frac{R_{a90}^2}{R_{a0}})}{2R_{a90} - \sqrt{2}R_{a45} (1 + \frac{R_{a90}}{R_{a0}})}$$

$$y_0 = \frac{R_{a0}^2 - R_{a90}^2 + 2x_0 R_{a90}}{2R_{a0}} \quad (19)$$

$$r = \sqrt{y_0 + (R_{a90} - x_0)^2}$$

considering the following relations:

$$(0 : R_{a0}); (R_{a45} / \sqrt{2} : R_{a45} / \sqrt{2}); (R_{a90} : 0)$$

The specific area of the roughness shape is:

$$F_a = \frac{R_{a90}y_0 + R_{a0}x_0}{2} + \frac{r^2}{2} \left(2\pi - \arctan \frac{y_0}{x_0} - \arctan \frac{x_0}{y_0} - \arctan \frac{R_{a90} - x_0}{y_0} - \arctan \frac{R_{a0} - y_0}{x_0} \right)$$

The center of the isotropic roughness is then:

$$R_{AS} = \sqrt{\frac{4F_a}{\pi}} \quad (20)$$

On Figure 14 the roughness⁵⁶ of the cold rolled sheet in dependence of its initial roughness and on Figure 15 the solutions of the equation (17)⁵⁷ are shown. The roughness decreases with the increasing number of rolling passes. The rough surface of rolls can be obtained either mechanically⁵⁸ or, as it is presently achieved, with electropolishing. For the case of boundary lubrication, the roughness of the sheet could be greater than that of the rolls. In this case, the rolls require a suitable surface

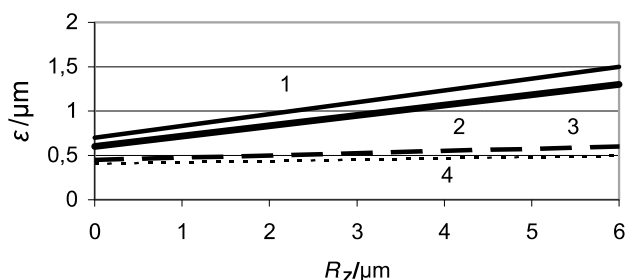


Figure 14: Influence of the sheet roughness $R_z / \mu\text{m}$ on the lubricant layer after $\varepsilon / \mu\text{m}$ cold rolling. The numbers designate the pass number
Slika 14: Vpliv hrapavosti $R_z / \mu\text{m}$ pločevine na sloj maziva $\varepsilon / \mu\text{m}$ po hladnem valjanju. Številke so oznake za valjalniške prehode

treatment. Small sheet roughness smaller than $1,0E-6$ m is not recommended, since it related to sheet micro welds by the annealing of coils. The use of unproper lubricants, especially those containing graphite, can produce sooth stains which, according to Howkins and Mecallan, contain carbon, iron, oxygen or iron carbide. The coefficient of roughness transmitted from the rolls to the sheet is in case of lubrication of 0.6–0.7 and by dressing it is of 0.5. Inaccuracies of solutions of the equation (17) can result from the slippage of lubricant between the rolls and the sheet because of the to small adhesion work. The forced slippage decreases the pressure gradient in the lubricant in relation to its complete adhesion to the rolls and sheet surface(*) of: $\text{grad } p / \text{grad } p^* = 1 / (1 + 6\mu\beta_c / \varepsilon_0^2)$ with β_c as coefficient of forced slippage. This relation was not yet experimentally confirmed.

4 LUBRICANTS FOR HOT ROLLING

The metal resistance to deformation is smaller by hot⁵⁹ than by cold working and other lubricants are used, also, for hot rolling. Earlier, lubricants were used resistant to oxidation and producing smoke⁶⁰, f.i. glass,

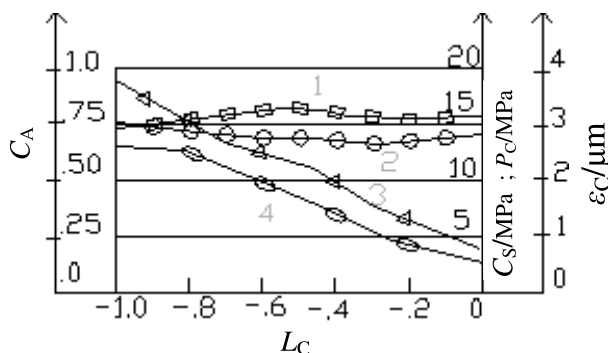


Figure 15: Change of contact stresses P_C / MPa , C_S / MPa , lubricant layer $\varepsilon_C / \mu\text{m}$ and wear coefficient C_A along the deformation zone L_C . 1-pressure, 2-lubricant layer, 3-tangential stress, 4-wear coefficient

Slika 15: Sprememba kontaktnih napetosti P_C / MPa , C_S / MPa sloja maziva $\varepsilon_C / \mu\text{m}$ in koeficienta obrabe C_A vzdolž zone deformacije L_C . 1-pritisk, 2-sloj maziva, 3-tangencialna napetost, 4-koeficient obrabe.

graphite and eutectic salts. The use of colloidal graphite was investigated in Russia already by the 1930-thies and it is investigated also presently due to the great importance of graphite as lubricant for mechanical, metallurgical and electrical industry.

The use of appropriate lubricant for hot rolling has prolonged the working life of rolls from 2600 t to 3200 t.⁶² The use of synthetic lubricant decreased the pressure of metal on rolls by 17 % and the coefficient of contact friction by 35 % when compared to the rolling using cooling water only⁶³. A greater decrease of contact friction is obtained using⁶⁴ synthetic lubricants than with castro oil and masut. The fat addition⁶⁵ to the lubricant is by hot working greater than by cold working and it does not exceed 8 %. Also surface active substances⁶⁶ are added, such as IS-20 and P-20, both increasing the adhesion in the range of boundary friction⁶⁷ by a surface roughness of (0.04–0.06) E-6. The perspective for hot rolling⁶⁷ seems to be the use of solid fats, mixtures of fats and synthetic additions and of lubricant in form of air suspension.

At high temperature fat and oils are not stable, f.e. palm oil is decomposed in several products which, mixed with wear products and oxide particles, contaminate the sheet surface. The process of decomposition is slowed by proper additions and in **Figure 16** the effect of sodium polyphosphate on the layering of palm oil is shown⁶⁹.

The maximum is by the addition of 0.15 % of sodium polyphosphate for the water emulsion with 1/7 of palm oil and for the temperature of 70 °C. As lubricant and cooling agent for hot working⁷⁰, it is possible to use also water with soap addition, even sea water with soap addition.

Lubricant emulsions used for hot working are rapidly degraded because of the effect of microorganisms, such as aerobic and aneorobic bacteria and mildew spores all causing earlier ageing and lowering of chemo-physical, technological and hygienic properties. The degradation can be slowed with bactericide additions. A strong antimicrobic effect is obtained by addition of thrisodiumphosphate and soda in the content of 30-60 g/L of

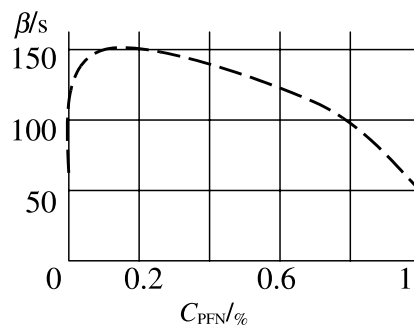


Figure 16: Layering time for the emulsion β / s in dependence of the content of sodium polyphosphate $C_{PFN} / \%$

Slika 16: Čas za razslojenje emulzije β / s v odvisnosti od vsebnosti natrijevega polifosfata $C_{PFN} / \%$

emulsion and of 0.4–0.5 % of phormacide. The exploitation time can be increased up to 4-6 times and the quantity of used additions significantly lowered.

The dilatation of emulsion lubricant because of the increased temperature is calculated using the equation:

$$V_1 = V_0 [1 - C \ln(1 + p/D)]; V_1 = V_0 [1 + C(t - t_0)] \quad (21)$$

With: V_0 as initial lubricant volume by the pressure p_0 and C and D empirical constants, the volume expansion coefficient: $C_0 = 0,0006 - 0,0008 \frac{1}{^\circ C}$, $-t, t_0$ rolling temperature and temperature of softening of the solid lubricant. From equation (21) it is possible to develop the Barussa's equation, which gives the dependence of viscosity on temperature.

$$\mu_t = \mu_0 \exp \gamma D \left[\exp \left(-\frac{C_0}{C} (t - t_0) \right) - 1 \right] \quad (22)$$

Very good effects are obtained by hot working using suspensions, which differ from colloide solutions being more finely dispersed. If resistant to coarsening and sticking, suspensions are stable agregates. The stability is affected⁷³ by absorption of electrically charged particles, which promote the hydratising of their surface. The measure of hydratising is the electrokinetic potential ψ , which is shown in **Table 1** for some compounds.

Table 1: Effects of the electrokinetic potential of some elements on clay suspensions

Tabela 1: Vpliv elektrokinetičnega potenciala nekaterih elementov na suspenzije gline

Absorbed ion	ψ /(mV)	Coagulation threshold KCl eqvi./((mg/L)
Li ⁺	-58,8	21,6
Na ⁺	-57,6	11,2
K ⁺	-56,4	7,8
NH ₄ ⁺	-56,0	5,4
Ca ⁺²	-52,6	3,0
Sr ⁺²	-51,8	2,6
Ba ⁺²	-50,8	2,3
La ⁺³	-45,5	0,86

The clay electrokinetic potential⁷⁴ and the clay suspension stability decrease with the increase of the valence of the compensating ion and a greater stability is found f.e. for lithium clay and a smaller for the lantan clay. The suspension is stabilised also with addition of isopolychromate, K₂CrO₄ and polyakrilamide. The montmorillonite and caolinite clays are stabilised and their properties improved with addition of lime.

The heat conductivity of suspensions increases linerly with the clay content and the heat capacity is, in the range of working temperature, independent of the mineral type. The viscosity of suspensions⁷⁵ in homogeneous field of gradient G and by gliding flowing for an elipsoide shape of suspension particles is:

$$\mu^* = \mu \left[1 + \varphi_v (V_F - S_F G^2 / D^2) \right]; D = \delta_F kT / \mu V_0 \quad (23)$$

With: F – shape index, V_0 – the specific volume of the suspended particle, φ_v – the volume content of particles, D – coefficient of diffusion by rotational mixing, k – Stefan-Boltzmann constant, T – temperature in K, μ^* ; μ – the effective suspension viscosity and the viscosity of the medium (solvent). The flowing of the suspension is described with the Fokker-Planck equation. However, the analytic solution are far from experimental findings and acceptable agreement was found only for diluted suspensions.

For the cleaning of suspensions with filtering⁷⁶ the following equation was derived:

$$W = \frac{dq}{d\tau} = \frac{W_p}{\left[\frac{1}{(1 - K_1 q)} + K_2 q \right]} \quad (24)$$

With: W and W_p – momentary and initial filtering rate (m/s), q – specific volume of the filter, τ – filtering time and K_1 and K_2 – constants characteristic for the filtering process, first of all plugging and deposits.

Good properties, as f.e. low friction coefficient and longer layer stability at all temperatures are characteristic also for the fluorocarbon (CF)_n. By reaction of fluorine with graphite or carbon at determined temperature the compond (C₂F)_n is obtained⁷⁷. The fluorinating time is of 60 h and in graphite up to 14,4 % of fluorine is dissolved without effect on particle integrity although the specific volume is increased.

For the hot working of metals also glas based lubricants can be used. A very important property of glas used for hot working lubrication is the viscosity for which the following equation was derived:

$$\mu = A \exp(H_\mu / RT) = A_T \exp(E_\mu / RT) \quad (25)$$

In the left relation the activation enthalpy is included and in the right the activation energy. A_T depends on a number of factors, first of all the temperature range⁷⁹. Eyring connected A_T theoretically with the molar volume. The activation energy is than deduced from the equation:

$$E_\mu = 2,303RT(\lg \mu - \lg A_T) \quad (26)$$

The driving force for the flowing of a drop of molten glas on a hard and flat surface is calculated using the Truton equation:

$$f_s = 3\mu \frac{dv}{dx} \quad (27)$$

The driving force is proportional to the dynamic viscosity and to the gradient of flowing rate in the direction of the force. The wetting of the metal surface by hot working is not in thermodynamical equilibrium, since by high temperature also oxydes are formed and decomposed and films of water steam and oxyde vapour are chimisorbed on the metal surface. On more impure areas, the kinetics of the process can cause greater

equilibrium differences. Investigations have shown that in temperature range 550–600 °C the equilibrium wetting angle is achieved only after 10 min when the adhesion force is increased sufficiently. By lower temperature the equilibrium wetting angle is not achieved even after one hour. This is however without theoretical and practical interest⁸⁰.

5 CLEANING OF METAL SURFACE AND LUBRICANT TOXICITY

Before further processing or use the, surface of cold worked products has to be cleaned⁸¹ of lubricant residues and impurities⁸². The cleaning could be also included in the finishing operation of the manufacturing process. The quality of the cleaned surface⁸³ depends on the quality and type of the lubricant used. Specific problems are met in case of graphite containing lubricant⁸⁴, since, and especially on the internal surface of tubes, residual sooth bands are found as residues of non removed lubricant. Electrochemical cleaning is frequently used for cold rolled sheet⁸⁵. The removing of fat lubricant is improved applying ultrasound, which may, however, cause cavitation. For a better lustre, surface active compounds are added to the electropolishing solution⁸⁷. The optimal lustre is obtained by a current density of 140–150 A/dm² and the temperature 60–70 °C. Concentrated emulsions leave more impurities on the metal surface⁸⁸, while emulsions with less than 1 % of addition may have even a corrosive effect for the metal surface. Mechanical particles with a diameter below 5.0 E-6 do not leave surface stains if their content is below appr. 5 g/L of emulsion. On **Figure 17** a sheme of the installation for the efficient dry cleaning of sheets is shown.

The steel sheet (2) passes through the storage bin (1), over the guiding wheels (3) and through the powder

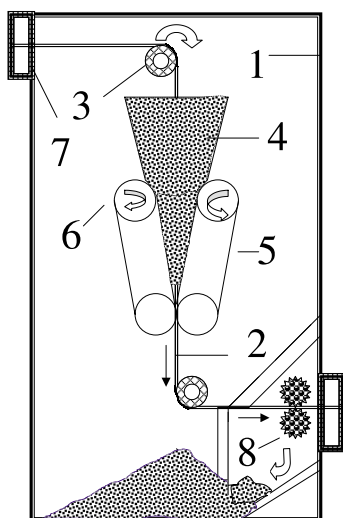


Figure 17: Sheme of the installation for the dry cleaning of lubricant for sheets

Slika 17: Shema naprave za suho čiščenje maziva s površine trakov

store (4). With the belt (5) and the guiding rolls (6) the cleaning intensity is regulated. At the storage bin entry the rough cleaner and at the exit the fine cleaner are set. The circular brushes (8) remove the powder from the sheet.

Dry cleaning has a number of advantages over electropolishing: no evolution of hydrogen, no sheet surface oxydation, no additional treatment with chemicals, no scrap water, no nocive vapour and a smaller use of energy. Circular brushes are manufactured from technical felt. Sheets with thickness 0.15 mm to 1 mm can be cleaned with a sheet motion rate of up to 800 m/min. The relation of the sheet and the belt velocity is 2.5–3 and f.e. by a sheet velocity of 200 m/min the belt rate is of 500–700 m/min. The cleaned sheet has less than 0.2g/m² of impurities. Approximately 20 kg of marble powder is used per t. of sheet and the cleaning capacity is of 3 t/min or more, depending on the sheet thickness.

To decrease the corrosive effect inhibitors are added to lubricants⁹². A direct relation was established between the inhibitor concentration, the stationary potential and the steel corrosion rate. The lubricant MT-16p has no protective capacity and the corrosion current increases from cyclus to cyclus. If 20 % of inhibitor is added the current is strongly diminished and after 1.5 h a constant value is achieved.

Efficient cleaning of fats from the steel surface is achieved using surface active compounds⁹³. The change of surface free energy ΔG due to the removal of fat is:

$$\Delta G = \delta_{Me}^P + \delta_M^P - \delta_{Me}^M \quad (28)$$

The first term in the equation represents the change of specific free energy of the interface metal-liquid, the second the interphase tension and the third the specific energy of the interface metal – oil. In **Table 2** some data on surface active compounds used for the removal of fat from steel surface are given.

Table 2: Effect of some surface active compounds, as wetting angle on the phase boundary, on the removal of fat from steel surface.

Tabela 2: Vpliv nekaterih površinsko aktivnih snovi, kot je kot omočenja na fazni meji, na odstranitev masti s površine jekla

Surface active compound (PAT)	Degree of steel cleanliness	Wetting angle θ degrees	remark
In absence of PAT	0,1	66,6	High efficient PAT
DS-10	0,91	67,5	
NF	0,78	66,7	
TBA	0,4	69,2	Low efficient PAT
NP-3	0,02	112	
Pentadecilovium	-	115	
Spirit	-		
Pentadekanovium acid	-	131,9	

The low fat removing capacity of the solution NP3 is explained assuming that the adhesion is due to the low interface metal-solution and oil-solution activities, it partial solution in oil and to the absorbtion on the

interface oil-metal. For such a case: $\theta \geq 90^\circ$; $\delta_{Me}^P \geq \delta_{Me}^M$. On the other side, DS-10 gives a very clean surface because the surface active compound is adsorbed at the interface metal-solution and oil-solution and does not affect the surface condition at the interface metal-oil.

The property for absorption on metallic surfaces is due to the ionisation potential of surface active compounds⁹⁴. The adsorption is explained in terms of resonant potential⁹⁵. When for an organic compound the resonant potential is achieved, also the maximal adsorption on the metal surface is achieved. The adsorption intensity depends on the length and electronic structure of molecules. The standard free adsorption energy shows a maximum at a determined potential of the surface active compound.

By working with lubricants special attention should be given to fire danger and to hygienic protection of working personal. If systems with oil fog are used, the ventilation system must ensure that the content of oil droplets and vapour in the working place is below 5 mg/m³. Serious harm maybe due to contact with unclean lubricants and polycyclic aromates. Of low toxicity are lubricants containing compounds with low vapour pressure, like white spirit, kerosene and solvents with mucous membrane. By using chlorinised hydrocarbons smoking is dangerous, since, the vapour is oxydised on the burning cigarette and aspired. The maximal toxicity is found by synthetic lubricants, especially triarylphosphates⁹⁶, these having a neurotoxic effect and requiring the use of appropriate protective equipment. Lubricants and additives contain toxic compounds with Zn, Ba, Pb, S and P, for this reason, filters are required for furnaces and chimneys. Emulsion coolants can be treated with vacuum distillation, water dilution and ultra filtering.

According to their cancerogeneity, lubricants⁹⁷ are classified in specific groups. The oils cancerogeneity increases with the temperature. Plant oils and fats are not cancerogeneous and do not affect the skin⁹⁸. The permitted concentration of hydrocarbon vapour is of 300 mg/m³, however, if hydrocarbons are found in air suspension, the permitted concentration is of only 10 mg/m³. The toxicity of spirits increases with the increasing number of carbon atoms in the molecule. Emulsoils are very toxic and already by the concentration of 400 mg/m³ can provoke pathologic changes on internal organs.

Fats are decomposed at high temperature⁹⁹ in complex chemical reactions, which may produce a noisome or even poisonous scent, which may cause eyes burning, dry coughing and headache. The concentration of acroleine, which may form also by the burning of mineral oils, is especially limited. Surface active compounds diminish the human reflexes also by low concentration and are life dangerous by greater concentrations. Non ionised compounds are not dangerous. In

Table 3 the permitted concentration of harmful compounds in air and water is given¹⁰⁰.

Table 3: Allowed limit concentration of harmful compounds in water and air

Tabela 3: Dovoljena mejna koncentracija škodljivih snovi v vodi in v zraku

Compound	Allowed concentration	
	$\rho_{Air} / (\text{mg}/\text{m}^3)$	$\rho_{Water} / (\text{mg}/\text{L})$
Acetone	200	4
Petrol	300	0,1
Kerosene	300	0,3
Hydrocarbons	300	0,3
Petrol acids	200	0,3
Mineral oils	300	0,4
Spirits	2	-
Etylene	1	-
Petrolether	300	-
Ammonia	20	-
Synthetic fat acids	-	4
C ₅ -C ₂₀	-	4
OP-7	-	0,4
OP-10	-	1,5

The content of bacteria in emulsions should be below of 5,0 E5 /mL. In half synthetic amulsions for working of metals the content of microorganisms after 11 h of use my be of 1,0 E9¹⁰¹. In emulsions coolants the formation of N-nitrozodietanolamine (NNDEA) could occur by reaction between NaNO₂ an DEA (alcanolamine) which are cancerogeneous. Also toxic formaldehyde vapours can be formed especially in presence of aerosole and glycole. The most used test for the determination of the biological stability of emulsions is the method CEC-L-33-A-93¹⁰² and the biological decomposition with the CO₂ modified Sturm test.

The properties of lubricants are checked using trybo devices¹⁰³ like that shown in **Figure 18**¹⁰⁴. Also variations with four balls are used¹⁰⁵.

The steel cylinder (8) with the internal ring (7) is placed in the thermostate (6) at the temperature of 180 °C and filled with oil. With the electrical motor (1) the frixion between the metal plate (9) and the ring (7) is achieved. The contact pressure is controlled with the centrifugal regulator (10).The toothed pump (5), driven by the motor (2), pumps the oils through the tubes (4) in contact with the solid inhibitor (3) in the upper part of the device (11). Sprayed with the centrifugal regulator (10) oil falls on the bottom of the steel cylinder to be pumped again in the circular flow (5).

It was demonstrated that the oil corrosivity and the frixion of the metal surfaces (7) and (9) depend on the type of the inhibitor (3). The device can stay in operation for 20 h with a linear flow rate of 20 m/s and by the oil pressure of 400 N/cm².

The tribological efficiency of oils is very different, also between oils of the same type, as defined in european specifications. All lubricants must be eco-

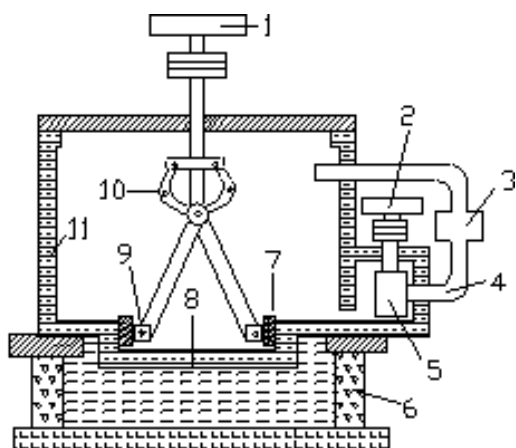


Figure 18: Device for the determination of wear of metal surfaces
Slika 18: Naprava za določanje obrabe kovinskih površin

gically friendly¹⁰⁶. Improvements of oil properties are mostly found with new additives and are used if confirmed as ecologically acceptable¹⁰⁷.

The properties of lubricants of ecological significance are¹⁰⁸: biological stability, low water pollution, low water solubility, low toxicity, absence of heavy metals, high ignition point, low vapour pressure and natural origine like ether, rape, soya and animal oils.

In use and development of lubricants care must be taken for the hygienic protection of workers and for the microclimate in the working location. This warning is confirmed in **Figure 19**¹⁰⁹, which shows that the addition of polymer to an industrial oil affects the formation of oil aerosol in the atmosphere and that already by a small change in polymer content the formation of aerosol is greatly changed.

By hot rolling the lubricants are even more dangerous for the ambient because of the high processing temperature. On **Figure 20** the DTA curve for palm oil and emulsoils OM¹¹⁰ are shown. Emulsoil is less prone to thermal decomposition and to air oxydation and it is also less prone to exo and endothermic reactions, however, it is less stable in temperature range 350 °C to 400 °C. For this reason, natural oils can not be used as lubricants for hot working.

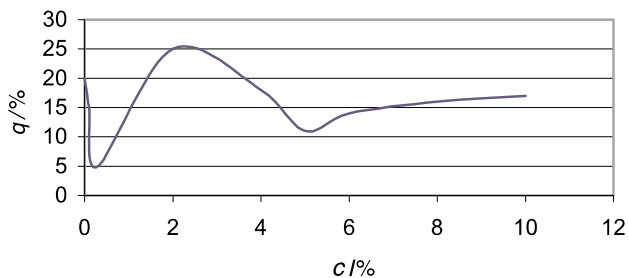


Figure 19: Influence of the content of polyisobutylene *c*% on the loss of aerosol of industrial oil in atmosphere *q*%

Slika 19: Vpliv vsebnosti poliizobutilena *c*% na izgubo aerosola industrijskega olja v atmosfero *q*%

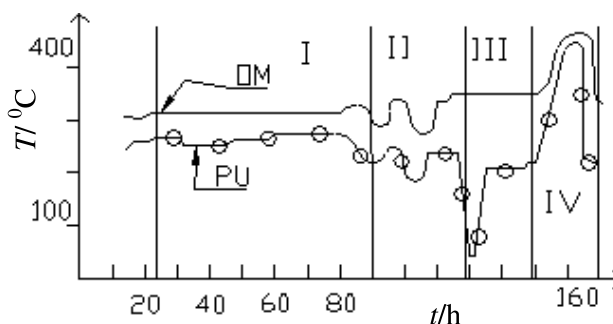


Figure 20: DTA curves *T*/°C for emulsol-OM, palm oil-PU. First range 90–280 °C, second range 280–350 °C, third range 350–400 °C and fourth range 400–500 °C, time *t*/min

Slika 20: DTA krivulje *T*/°C za emulzijsko olje – OM in za palmovo olje-PU. Prvo območje 90–280 °C, drugo 280–350 °C, tretje 350–400 °C in četrto 400–500 °C, čas *t*/min

6 CONCLUSION

Inspite of the great importance of tribology for the plastic working of metals, survey articles are very rare. This article is an attempt to present the more important knowledge on the tribology of use of lubricants for the plastic working of metals. The lubrication and lubricant topics are very wide and include:

1. theory of plastic working of metals
2. fluids mechanics
3. metal corrosion
4. colloide chemistry
5. manufacturing and regeneration of lubricants
6. lubricant devices
7. ecology and hygienic protection.

The author included in this work only some essential of the enumerated topics. From the first paper of Mizumo on fluid mechanics calculation related to the lubricant layer in the rolling deformation zone, through it confirmation by A.P. Grudev in 1966, the volume of investigations has grown very much. In Reynolds equations the following parameters are considered:

1. logitudinal and transversal surface roughness,
2. effect of inertial forces for great drawing rate,
3. potential of diffusion forces as results of the interaction of lubricant molecules with the solid metal surface,

The analytical solutions of equations are complex also in case when they can be obtained, for this reason, numerical solutions are used, especially the Monte-Carlo method.

Colloide chemistry was introduced through equations for the spreading of lubricants on solid surface involving the wetting angle, adhesion work and surface tension. Since a few years, the ionisation potential of organic compounds, surface active compounds and the index of the resonant potential are involved, also, in topics of lubrication.

Automatic lubrication devices were developed with inclusion of processing technology for the deposition and the regeneration of lubricants. Synthetic lubricants of high quality based on animal and plants oils and fats were developed. Systematic investigations on the use of microemulsions were started also with the main aim to improve the cooling efficiency. The use of lubricant shows a number of positive effects and it is estimated that the use of energy in industrial countries can be lowered up to 20 % using lubricants with the best tribological properties and the application of tribological principles

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SYMBOLS EV. NOT EXPLAINED IN THE TEXT

Symbol	Meaning
α	Drawing angle and gripping rolling angle
γ	Piesocoefficient of lubricant viscosity
δ	Eventual lubricant layer thickness determined by the surface roughness
ε	Height layer lubricant on the sheet (1 E-6 m)
ε_c	Height lubricants layer (1 E-6 m = 1 μ m) (Figure 15)
θ	Equilibrium wetting angle
μ	Dynamical viscosity of the lubricant
μA	1 E-6 A Figure 18 .
μ_d	Viscosity of the dispersed phase in form of sphere
μ_e	Effective viscosity of the dispersed phase
ν	Kinematical viscosity
η	Kinematics viscosity copolymers
ρ	Fluid density
σ	Interphase or surface tension
τ	Time
τ_s	Tangential stress in differential equations
φ	Volume concentration of the dispersed phase in equ. (1)
φ_0	Auxiliary reduction angle in equation (15)
$d\varphi/d\tau$	Exits angle of electrons in dependence on the time (τ) of immersion of the metallic plate in oil.
Ω	Consumption of lubricant on the sheet surface
C	Volume solubility in the dispersed phase
C_s	Contact strains (MPa) : $C_s = C_s(L_c)$
C_A	Coefficient abrasion
D	Diffusion coefficient
D	Diameter of the droplet in the coarsening emulsion
exp	Natural log. base
g	Free fall acceleration
h_0	Lubricant layer thickness in the entering section of the deformation zone by metal drawing

H	Distance of the accumulation of the dispersed phase from the boundary emulsion/clear dispersed medium at the time t
H_{df}	Initial quantity of dispersed phase
$h(x)$	Fluid height
$\langle i \rangle$	Mark for mathematical hope
K	Stefan-Boltzmann constant
k_1	Parameter of the kinematical inertial effect
l_k	Matrix deformation zone length according to Figure 10
L_c	Scale length of deformation [-1.0 to 0]
P	Pressure in lubricant layer
P_c	Pressure (MPa): $P_c = P_c(L_c)$
R_z	Initial roughness (1 E-6 m = 1 μ m)
T	Temperature in K
T	Time
U	Layering rate rate for the regimes of compression and coalescence
v_0, v_R	Sheet rate and circumferential rolling rate
v_{Rx}	Projection of the roll rate vector on the ordinate x
v_T	Speed temperature corrosion
q	Loose aerosol (weight %)
∞	Mark for infinite

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