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SCHEMES OF METAL-WORKING PROCESSES AND THE RELATED TRIBOLOGICAL EQUATIONS OF FLUID MECHANICS

SHEME PROCESOV PREDELAVE KOVIN IN TRIBOLOŠKE ENAČBE MEHANIKE FLUIDOV ZANJE

Dušan Ćurčija, Ilija Mamuzić
University of Zagreb, Faculty of Metallurgy Sisak, Aleja narodnih heroja 3, 44000 Sisak, Croatia
mamuzic@simet.hr

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We present a survey of the most frequently used equations for applications in cold drawing and rolling, for smooth and rough surfaces, for the effect of lubricant inertial forces, for more advanced theoretical solutions as well as the equations for cold drawing with a solid lubricant and the combination solid lubricant-emulsion. The compression processes are described using cylindrical coordinates. Also, the basic equations for the flowing of the lubricant on inclined planes related to screw rolling and for the forming of metals with fluids are given.

Key words: lubrication, metal forming Reynolds differential equation, Monte-Carlo method

Podan je pregled najbolj pogosto uporabljenih enačb pri hladnem valjanju in vlečenju, za gladke in hrapave površine, za vpliv vztrajnostnih sil, za bolj napredne teoretične rešitve in enačb za vlečenje s trdnim mazivom in kombinacijo trdo mazivo – emulzija. Tlačni procesi so opisani s cilindričnimi koordinatami. Podane so tudi osnovne enačbe za tok maziva na nagnjeni površini, ki se nanašajo na navojno valjanje in za oblikovanje kovine s fluidi.

Ključne beside: mazanje, preoblikovanje kovin, Reynoldova diferencialna enačba, metoda Monte Carlo

1 INTRODUCTION

The investigations and development of modern plastic working technology covers the following topics: physical modelling and simulation, computer simulation and characteristics and the behaviour of the material during processing.

The gradients representing the changes of temperature and mechanical stresses are greater for a greater per-pass (partial) deformation. In **Figure 1** the compression force ***F***, the heat flow ***H***, the deformation direction ***D*** and the rolling direction ***K*** for simple rolling are shown. The physical simulation, as a laboratory representation of the process, is based on the law of similarity and allows only a limited extrapolation. The simulation of the rolling process occurs by applying the principles of viscoplasticity and the use of analytical solutions increases with the rapid development of modern theoretical and experimental methods for the investigation of the plastic deformation of metals. A torsional plastometer was applied with success for the determination of the rolling force (**Figure 2**) and the obtained data can be applied for the correction of the

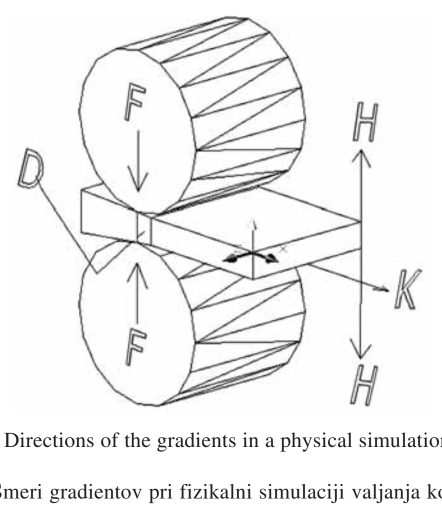

Figure 1: Directions of the gradients in a physical simulation of metal rolling[1]
Slika 1: Smeri gradientov pri fizikalni simulaciji valjanja kovin[1]

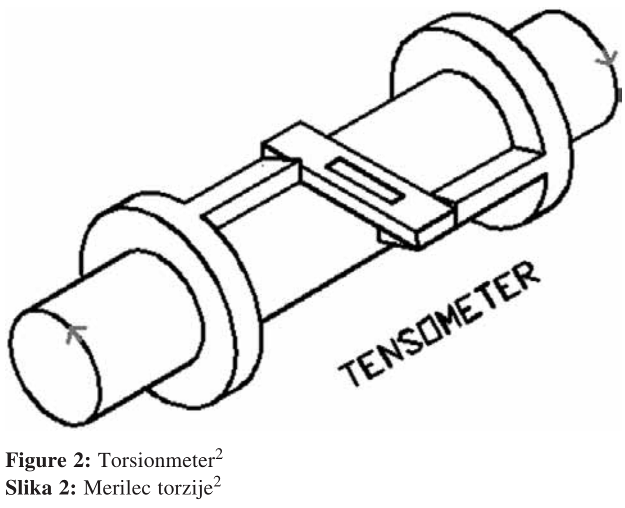

Figure 2: Torsionmeter[2]
Slika 2: Merilec torzije[2]

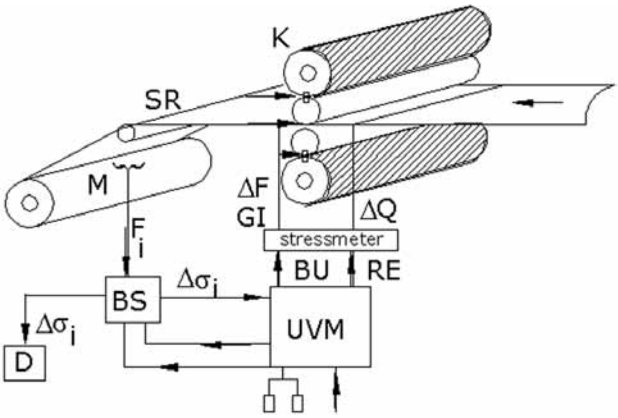

Figure 3: Measuring the surface stresses on a sheet's surface
Slika 3: Merjenje površinskih napetosti na traku

calibration as well as the regulation of the rolling gap for continuous rolling stands.

In **Figure 3** a scheme is given for measuring the stresses on the sheet surface with a stressmeter[3].

2 FLUID MECHANICS

The concept of the boundary layer (**Figure 4**) was proposed by Prandl in 1904. The thickness of the fluid layer (δ_x) can differ significantly from the flowing line **2**. The layer has, however, a constant flow velocity. Below the laminar part of the layer **3,** the flowing velocity (**v**) decreases and on the solid surface the fluid is at a standstill, ϕ is the boundary laminary layer, ω is the transition area and κ is the turbulent part of the boundary layer **1**. The representation in **Figure 3** shifts the Navier-Stokes and Reynolds equations in the domain of velocity.

The use of emulsions for the plastic working of metals led to a significant lowering of production costs and to savings with expensive natural oils. In **Figure 5** the equilibrium is shown for the surface tension of a drop of light liquid on the surface of a heavier liquid:

$$\sigma_{12} = \sigma_{13}\cos\theta_2 + \sigma_{23}\cos\theta_1 \qquad (1)$$

For θ_2 --> 0 the adhesion work (W) is calculated using the Jung-Dupre equation

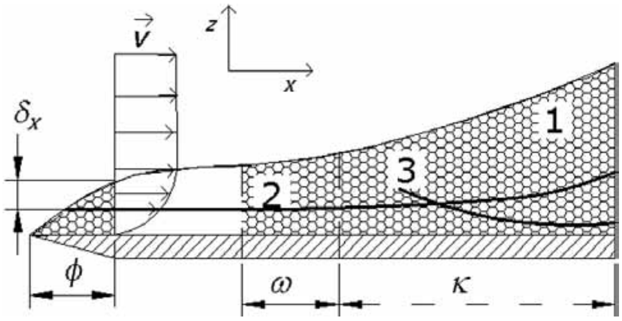

Figure 4: Boundary layer for the flow of fluid on the flat plane[4]
Slika 4: Mejni sloj za tok maziva na ravni površini[4]

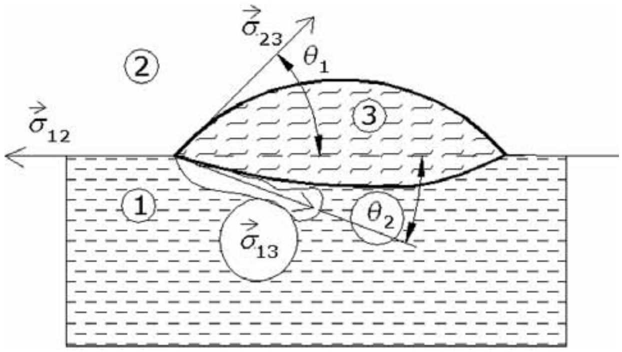

Figure 5: Equilibrium of the surface tension σ for a light liquid (**3**) on a heavier liquid (**1**) in air **2**[5]
Slika 5: Ravnotežje površinske napetosti σ za lahko tekočino (**3**) na težji tekočini (**1**) in na zraku (**3**)[5]

$$W = \sigma_{23}\,(1 + \cos\theta_1) \qquad (2)$$

Investigations of the use of equation (2) in metallurgy were carried out by Ju. P. Abdulov[6]. In a fluid mechanical metallurgical investigation different equations are used for the flat (**Figure 5**) and for the inclined plane (**Figure 6**).

The case of lubrication of a surface with vertical movement is met, also (**Figure 7**).

In this work we will examine the fluid friction (friction with hydrodynamic lubricant), for which Newton's law is applied:

$$F = z\,S\,v\,/\,h \qquad (3)$$

where ***F*** is the friction force, z is the flowing capacity, ***S*** is the sliding surface, ***v*** is the velocity of the relative transfer, and ***h*** is the thickness of the lubricant layer.

For a description of the case of liquid friction in the plastic deformation of metals the Nady equation is used. Let us start with an analysis on the basis of **Figure 8**. The sheet of thickness ***h*** is covered with the lubricant layer $\varepsilon(x)$ ahead of the section entering the deformation zone, for a wedge-shaped rolling gap ***a*** with the gap

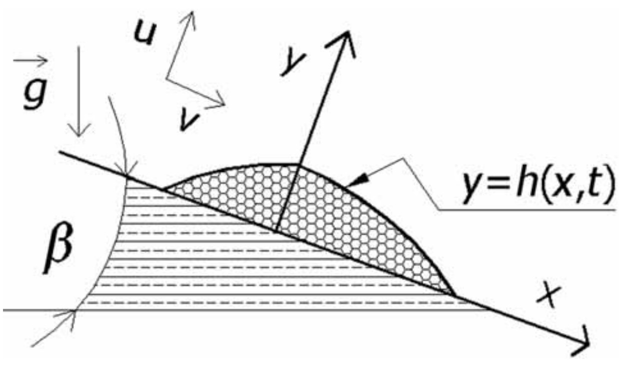

Figure 6: Shaping of a drop of liquid on an inclined plane[7]
where ***x***, ***y*** are the Descartes coordinates; ***u***,***v*** are the corresponding flowing velocities; ***t*** is the time; ***g*** is the acceleration due to gravity; and β is the angle of inclination
Slika 6: Oblikovanje kapljice tekočine na nagnjeni površini
x, ***y*** Descartesove koordinate; ***u***,***v*** hitrosti pretokov; ***t*** čas; ***g*** konstanta gravitacije; β kot nagiba

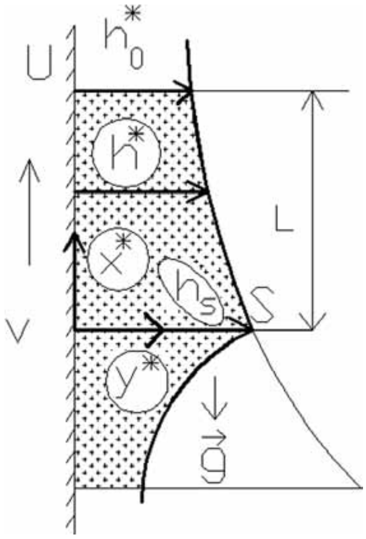

Figure 7: The dragging of fluid on a vertically moving metal surface[8] where h_s is the thickness of the fluid layer on the stagnation line of a metal surface moving with the constant velocity of U, h^*_0 is the the thickness of the dragged fluid layer on the metal sheet, and v is the sheet velocity

Slika 7: Vlečenje maziva na površino s pokončnim gibanjem[8]
h_s – debelina sloja maziva na mirujoči točki metalne površine, ki se premika s stalno hitrostjo U, h^*_0 – debeline sloja maziva, ki ga vleče kovinska površina, v – hitrost traka

angle α, sheet velocity v_0, rolls velocity v_R and rolls radius R.

The Reynolds' differential equations of fluid mechanics describing the representation in **Figure 8** are:

$$\mathrm{d}p/\mathrm{d}x = 6\mu(v_0 + v_R) / \varepsilon^2(x) - 12\mu Q/ \varepsilon^3(x) \qquad (4)$$

$$\tau = \mu(v_R - v_0) / \varepsilon(x) - (\varepsilon(x)/2)\, \mathrm{d}p/\mathrm{d}x \qquad (5)$$

For $x = 0$ we have $\varepsilon(x) = \varepsilon_0$ in the entering section of the deformation zone. For the change of pressure gradient $\mathrm{d}p/\mathrm{d}x = 0$ the tangential stress in the lubricant layer (τ) is:

$$\tau = \mu(v_R - v_0) / \varepsilon(x) \qquad (6)$$

In equation (6), attributed to Nady, μ is the lubricant dynamic viscosity, Q is the lubricant flow, $\varepsilon(x)$ is the lubricant layer thickness ahead of the section entering the deformation zone and **d*p*/dx** is the pressure gradient in the lubricant.

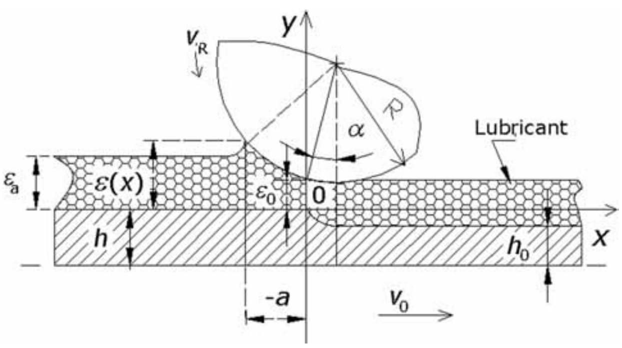

Figure 8: Cold rolling with a lubricant[9]
Slika 8: Hladno valjanje z mazanjem[9]

3 TECHNOLOGY OF THE PLASTIC WORKING OF METALS

This technology depends strongly on the quality of the technological lubricants used that:
- diminish the contact friction,
- remove the heat, cool the tool and diminish the wear,
- diminish the deformation resistance and the deformation work,
- diminish the sticking to the tool and keep the surface of the product clean.

The basic groups examined in this work are:
- liquid emulsions,
- fats and compounds,
- consistent lubricants,
- transparent – glass lubricants,
- powder lubricants,
- metallic lubricants.

The friction in cold deformation is, in principle, of the boundary type, and it is characterised with a great working pressure. The approaches in the development of the theory of friction are:
- geometrical, with the friction coefficient μ = tgα,
- molecular, with attraction based on a kinetical conception,
- deformation, based on the deformation work for a determined volume,
- a combination of different approaches.

The first calculations for the lubricant layer were by Mizuno[10]. According to Figure 8, the thickness of the lubricant layer is:

$$\varepsilon_0 = 3\mu_0\gamma(v_0 + v_R) / \alpha(1 - \exp(-p_0\gamma) \qquad (7)$$

with γ being the piezocoefficient lubricant viscosity, p_0 the rolling pressure, α the rolling angle, μ_0 the lubricant viscosity at atmospheric pressure, v_0 and v_R the working velocities of the tool and the rolling.

Also, new solutions were suggested, for example, Perlina, Grudeva and Kolmogorova for the technology of the cold drawing of metals,[11] according to **Figure 9**. The tube **3** moves with a velocity v_0 through the matrix **1** with the entering gap ψ; it is covered with the lubricant **2** of thickness ε in the entrance section of the deformation zone.

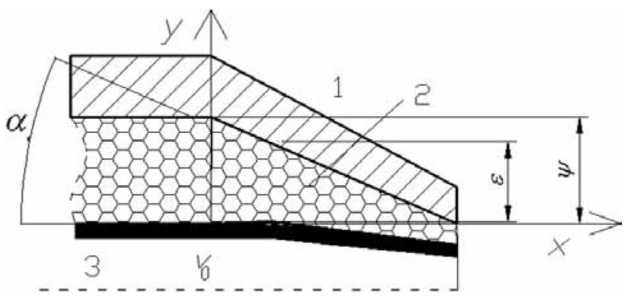

Figure 9: Cold drawing of metals with lubricant[11]
Slika 9: Hladno vlečenje z mazanjem[11]

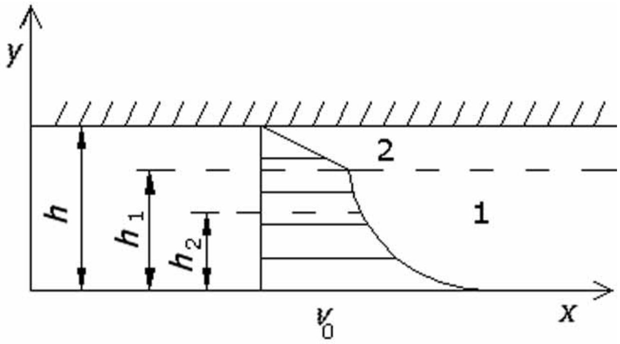

Figure 10: Distribution of velocity for the drawing of tubes with fat lubricant[12]
Slika 10: Porazdelitev hitrosti pri vlečenju cevi z mastnim mazivom[12]

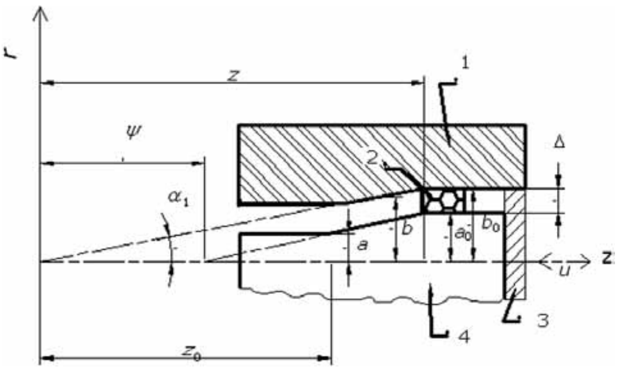

Figure 11: Pressing of metals[13]
Slika 11: Prešanje kovin[13]

The calculation is more complex for the case of combined liquid-solid lubrication. In **Figure 10** the solid lubricant is the part **1** and the emulsion is the part **2**. For the case in Figure 10 the maximum velocity of the emulsion is approximately 0.4 of the rolling velocity[12].

The pressing plastic deformation would be impossible without lubricant. The mathematical modelling in cylindrical coordinates is based on the scheme in **Figure 11**, with **1** being the round matrix, **2** the lubricant, **3** the mandrel, **4** the pressed metal and ***u*** the pressing velocity.

The forming with hydraulic fluid at the pressure **2** occurs over the membrane **1** (**Figure 12**). The liquid can have the role of either the matrix or of the extractor. For this process, a smaller number of toolings is used, the production costs are lower and complex forms are achieved more easily than when using conventional deep drawing.

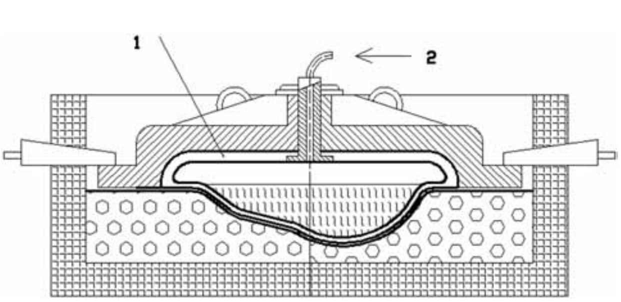

Figure 12: Hydraulic forming of a sheet
Slika 12: Hidravlično oblikovanje traka

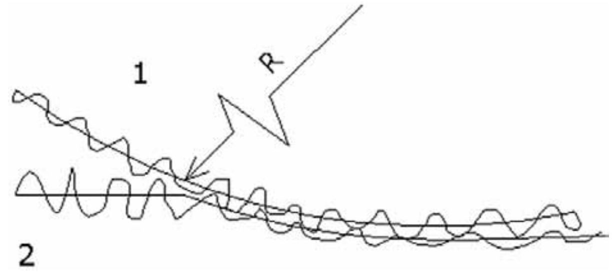

Figure 13: Uniform roughness of the rolls **1** and the sheet **2** surface[14]
Slika 13: Enakomerna hrapavost površine valja **1** in površine traka **2** [14]

The use of computers enabled us to also consider the surface roughness in the calculations (**Figure 13**) and the inertia of the lubricant with a great metal deformation velocity. In **Table 1** are the differential equations for the average roughness.

The development of mathematical calculations for Pilger rolling are in the initial phase because of the complexity of the working surface of the Pilger rolls (**Figure 14**).

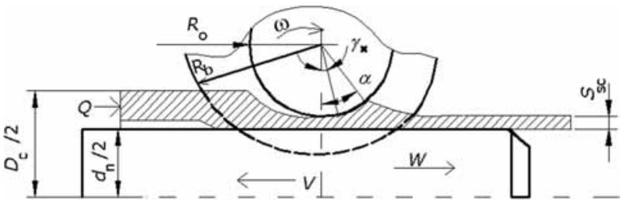

Figure 14: Scheme of Pilger rolling[15], where ***v*** is the rolling direction, ***w*** is the direction of the tube $\mathbf{D_C}$ movement, α is the gripping angle, ω is the constant angle rotation of the Pilger rolls, γ_x is the angle of the neutral section, R_0 and R_b are the radii of the rolls' calibers, $d_n/2$ is the mandrel radius, S_{SC} is the thickness of the tube wall and Q is the direction of the material flow.
Slika 14: Shema Pilgerjevega valjanja: ***v*** – smer valjanje, ***w*** – smer cevi, D_C smer gibanja, α – kot prijema, ω – constantna kotna hitrost Pilgerjevih valjev, γ_x – kot nevtralnega prereza, R_0 in R_b – polmera kalibrov valjev, $d_n/2$ – polmer trna, S_{SC} – debelina stene cevi in Q – smer toka materiala

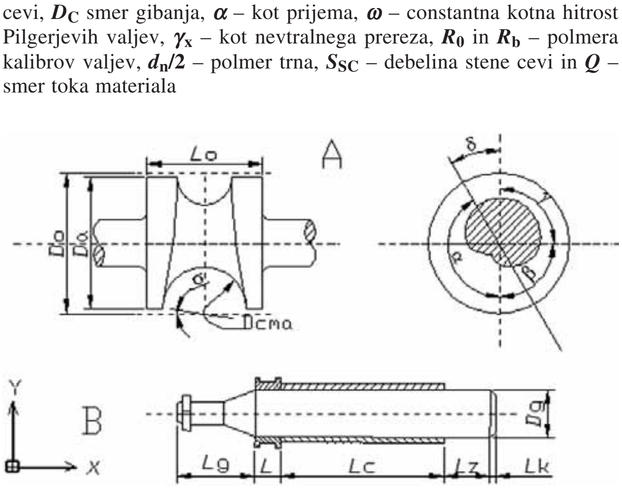

Figure 15: Elements of the Pilger stand: **A** is the roll, **B** is the mandrel[16]
Slika 15: Elementi Pilgerjevega ogrodja: **A** – valj, **B** – trn[16]

Table 1: The most frequently used differential equation of fluid mechanics applied for the description of the lubricant behaviour for different metal working processes
Tabela 1: Najbolj pogosto uporabljene enačbe in mehanike loma za opis vedenja maziva pri različnih procesih preoblikovanja kovin

Equation	Figure
1. Smooth surface of the roll and of the metal worked (rolling, drawing, wire drawing) $\partial p/\partial x = \mu\partial^2 v_x/\partial y^2$; $\partial p/\partial y = 0$; $\tau = \mu(v_R - v_0)/\varepsilon(x) - (\varepsilon(x)/2)\, dp/dx$ $\partial p/\partial z = \mu\partial^2 v_z/\partial y^2$; $\partial v/\partial x + \partial v/\partial y + \partial v/\partial z = 0$ where v_z, v_x are the corresponding lubricant velocities, $\varepsilon(x)$ is the lubricant-layer thickness, dp/dx is the pressure gradient, τ is the tangential stress, μ is the lubricant dynamic viscosity, and v_R and v_0 are the working velocities for the tool and the material	8 9
2. Average roughness of the tool and of the material $\lceil dp/dx \rceil = 6\mu(v_0 + v_R)\{ \lceil 1/\varepsilon^2(x_0)\rceil - [\lceil 1/\varepsilon_0^2\rceil / \lceil 1/\varepsilon_0^3\rceil \cdot \lceil 1/\varepsilon^3(x_0)\rceil \}$ $\lceil\ \rceil$ is the operator of the mathematical probability, $\varepsilon(x_0)$ is the random lubricant layer thickness, depending on the roughness of the tool and of the material, ε_0 is the lubricant-layer thickness in the access section of the zone of metal deformation	14
3. Sheet oiling $H^3 d^3H/Ca dz^3 - (\gamma Ca)^{3/2}(T/5)(H^2 - 2H_s^2/3)\, dH/dz + (3H - H_s - T^2H^3) = 0$ $H_s = 3 - T^2$; $H = 1 + \alpha$; $dH/dz = -c\alpha$; $d^2H/dz^2 = c^2\alpha$; $\alpha = A\exp(-cz)$; $z = x^*/h^*$ $Ca = \mu U/\sigma$; $T = h_0^*(\rho g/\mu U)^{1/2}$; $\gamma = \sigma(\nu^4 g)^{-1/3}\rho$; $H = h^*/h_0^*$ h_0^* is the ordinate of the free liquid surface, H is the dimensionless ordinate of the free surface, T is the dimensionless thickness h^*/h_0^* of the layer dragged on the metal surface, U is the velocity of the sheet withdrawal, z is the coordinate, ν is the kinematical viscosity, and σ is the surface tension	7
4. Lubricant shaping on an inclined surface (inclined bending rolling) $\partial p/\partial x = \mu\partial^2 u/\partial x^2 + \rho g\sin\beta - \partial\Phi/\partial x$ $\partial p/\partial y = -\rho g\cos\beta - \partial\Phi/\partial y$; $\partial h/\partial t + \mu\partial h/\partial x = v$ Shaping of a drop on the horizontal plane (cylindrical coordinates) $\partial p/\partial r = \mu\partial^2 v_x/\partial x^2$ $\partial p/\partial r$ is the cylindrical coordinate system, Φ is the potential of the diffusion forces resulting from the interaction of lubricant molecules and the metal surface $\Phi \approx 10^{-20}((\mathrm{tg}\alpha)^2 - \alpha^2))/h^3$; t is the flowing time for a drop of lubricant; v is the velocity	6 18
5. Metal pressing (extrusion), cylindrical coordinates $(1/r)(\partial/\partial r(r\partial v_z/\partial r) = (1/\mu_t)\partial p/\partial z$ μ_t = the lubricant viscosity, depending on the temperature and pressure according to the Barussa equation.	11
6. Tube drawing with fat lubricant $\tau_1 = -\tau_0 - dp/dx(h_2 - y)$; $\tau = \tau_0 + K\lvert \gamma_0 \rvert^{m-1} \gamma_0$ $v = (h_2 - y)^{c+1}/(c + 1) \cdot (1/K\, (dp/dx))$ τ_1, τ_0 are the critical tangential stresses at the boundary tool and worked piece, h is the gap height between the tool and the worked piece, γ is the worked piece velocity, K, m, c are the rheological characteristics of the fat.	10
7. Effect of inertia and of the smooth tool and worked piece surfaces $\partial p/\partial x = 6\mu(v_0 + v_R)/\varepsilon^2(x) + C_1\mu/\varepsilon^3(x) + \rho\, \mathrm{tg}\alpha(16v_0^2\varepsilon^2(x) - C_1^2)/120\varepsilon^3(x)$ $C_1 = k/2 - (k^2/4 + 2v_0\varepsilon_0(8v_0\varepsilon_0 + 3k))^{1/2}$; $k = 120\nu/\mathrm{tg}\alpha$ $\varepsilon(x) = \varepsilon_0 - \alpha x + x^2/2R - \alpha x^3/2R^2 + ...$ α is the gripping or drawing angle, R is the roll's radius, v_0, v_R are the working velocities for the tool and the worked piece, and ν is the kinematical viscosity	8
8. New approaches to the mathematical modelling (rolling of metals) $dk/d(\varphi/\alpha) = 6W(\Delta h/\varepsilon_0)^2(H_{0S} - H_{HS})/H^3_{HS}e^{Mk}$; $W = \mu_0(v_0 + v_R)/\sigma_T\Delta h\alpha$ $H_{HS} = \Delta h/2\varepsilon_0[(\varphi/\alpha)^2 - 1] + H_{0S}[C_1/\Delta_1(\varphi/\alpha - (1 - \Delta_1)) + k] +$ $+ R_{za}/2\varepsilon_0 \sin[2\pi(\varphi/\alpha - (1 - \Delta_1))/C_{a0}\Delta_1 + C_{a1}] +$ $+ R_{zn}/2\varepsilon_0 \sin[2\pi(\varphi/\alpha - (1 - \Delta_1))/C_{n0}\Delta_1 + C_{n1}] -$ $- (1 + R_{za}/2\varepsilon_0 \sin C_{a1} + R_{zn}/2\varepsilon_0 \sin C_{n1})k + 1$ where C_{a1}, C_{n1} are the roughness of the rolls and the sheet, C_1 is the coefficient considering the shape of the wedge-shaped lubricant gap (zone 1), Δh is the absolute reduction, φ is the local angle in the deformation zone, α is the gripping angle, μ_0 is the dynamical viscosity at air pressure, R_{zn}, R_{za} are the sheet and rolls roughness, $\Delta_1 = \sigma_T/(2\delta E_E)$, σ_T is the module of flowing, δ is the relative reduction, E_E is the module of elasticity, $k = p/\sigma_T$, p is the rolling pressure, $M = \theta\sigma_T$, θ is the piezocoefficient of viscosity, e is the base of the natural logarithm, $H_{0S} = \varepsilon_1 / \varepsilon_0$, $H_{HS} = \varepsilon_2/\varepsilon_0$, ε_0 is the thickness of the lubricant layer at the access of the deformation zone, C_{a0}, C_{n0} are the roughness amplitudes for the rolls and the sheet, v_0 and v_R are the working velocities for the rolls and the sheet	20

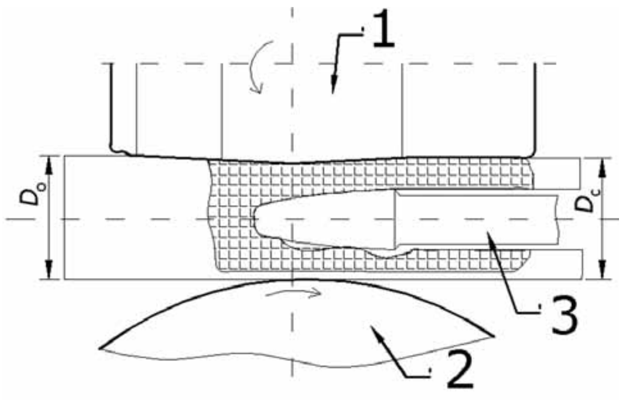

Figure 16: Scheme of the drilling of the rolling in a modern bending stand[17]
Slika 16: Shema prebijanja valjanca v modernem upogibnem ogrodju[17]

Pilger rolling is a periodic process and it is one of the most complex processes of plastics, since it deforms metals and combines the characteristics of rolling and forging with metal forming in the caliber of the changing section (**Figure 15**).

The Pilger rolling stand in **Figure 15** has three parts inside the working caliber:

- the front part, where the basic metal deformation is achieved, α,
- the polishing part, where the final tube size is achieved, β,
- and the longitudinal part, where the transition from the polishing to the final barren part occurs, γ.

The methods of the plastic deformation of metal between the drawing, rolling, and pressing with already developed calculations of the behaviour of the lubricant layer and the insufficiently investigated Pilger rolling are:

- the drilling on the Diescher disc (**Figure 16**),
- bending (inclined) drilling (**Figure 17**),
- three-rolls rolling stands rolling (**Figure 18**).

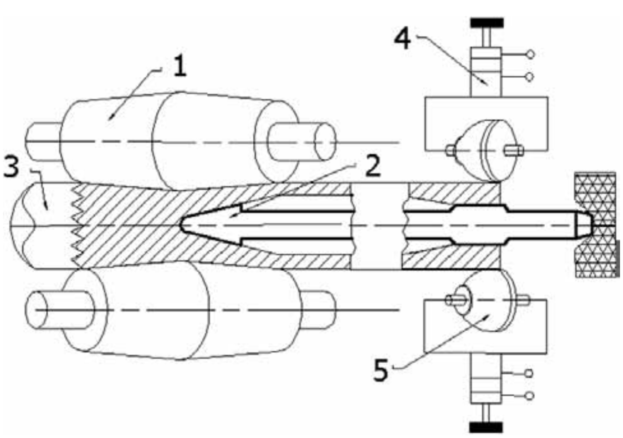

Figure 17: Scheme of the drilling stand for bending rolling with barrel-shaped rolls[18]
Slika 17: Shema prebijalnega ogrodja za upogibno valjanje s sodastimi valji[18]

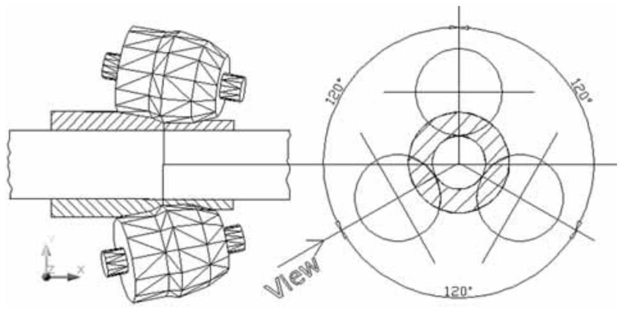

Figure 18: Scheme of the tube deformation in the three-rolls high rolling stand[19]
Slika 18: Shema deformacije cevi v triovaljalnem ogrodju[19]

The drilling mandrel (**3**) advances through the pierced round of diameter $\boldsymbol{D_0}$. Above the rolling is the working stand (**1**) and below it is the Diescher disc (**2**).

The mandrel **2** drills the rolling **3** with the rotation of the barrel-shaped rolls **1** with support from the hydraulic cylinders **4** and the barrel-shaped rolls **5**.

The working rolls of the three-rolls high rolling stand are set at an angle of 120°. The gripping angle is selected in the range 0° to 10° and the rolling angle in the range 3° to 7°. Specific to the stands is the shape of the working rolls that increase the regularity of the metal

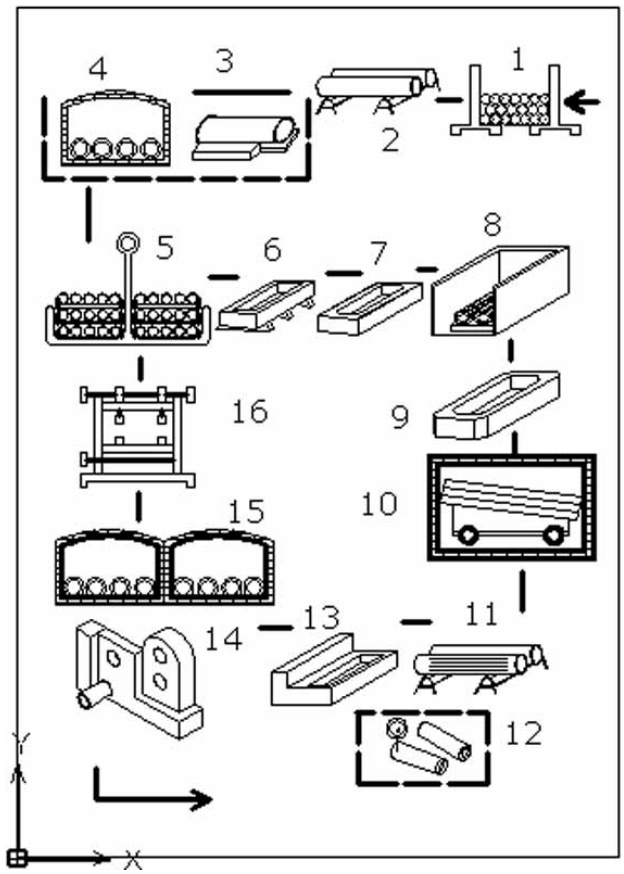

Figure 19: Technological scheme of the manufacturing of tubes with cold rolling[20]
Slika 19: Tehnološka shema za izdelavo cevi s hladnim valjanjem[20]

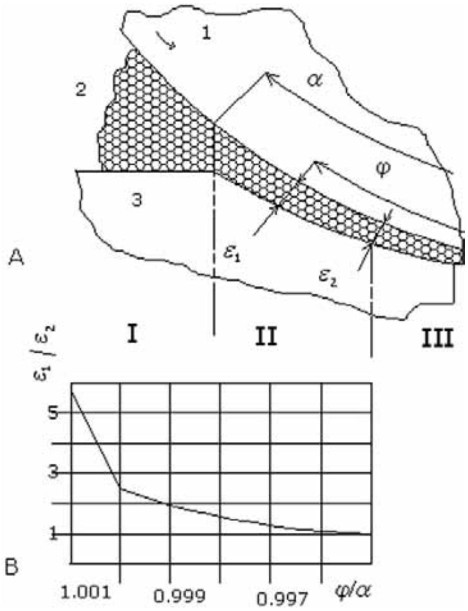

Figure 20: Mathematical modelling of the rolling with lubricant and the approach to the deformation zone[25]
Slika 20: Matematično modeliranje valjanja z mazivom in približek za zono deformacije[25]

flow and the tube quality. (**1**, the gripping cone; **2**, the rolls ridge; **3**, polishing cone; and **4**, the release cone).

In **Figure 19** the technological scheme of the manufacturing of tubes with cold rolling is shown with: **1**) billets storehouse; **2**) inspection; **3**) cutting of tube ends; **4**) heat treatment; **5**) collecting of tubes in packets; **6**) decapping; **7**) rinsing with hot water; **8**) rinsing with cold water; **9**) neutralization; **10**) drying; **11**) inspection; **12**) repairing; **13**) lubrication; **14**) rolling on the cold Pilger stand; **15**) intermediate heat treatment; **16**) straightening.

5 DIFFERENTIAL EQUATIONS

In **Table 1** the equations describing the lubricant behaviour for different metal-working processes are given.

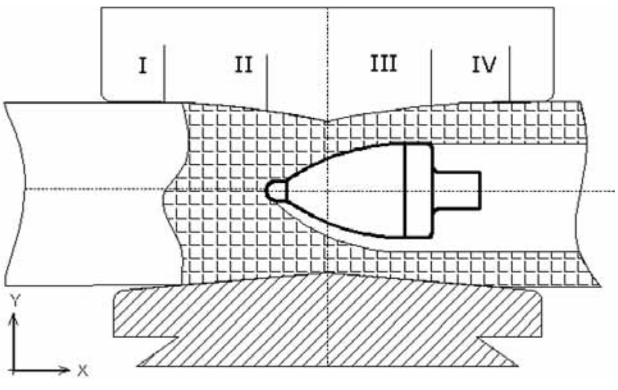

Figure 21: Deformation zone by bending rolling
Slika 21: Zona deformacije pri upogibnem valjanju

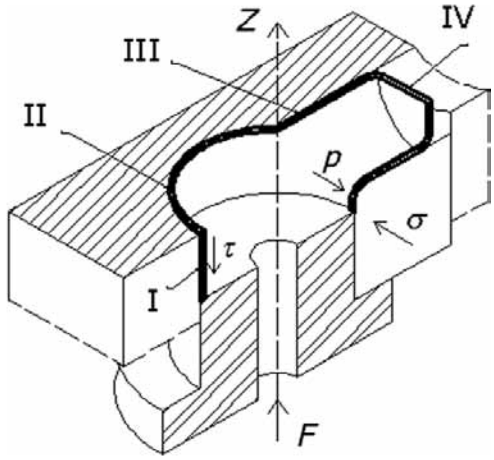

Figure 22: Forming of the T-shaped tube end (*F* is the axial force, *p* is the fluid pressure, σ and τ are the normal and tangential stresses
Slika 22: Oblikovanje konca cevi v obliko T (*F* – aksialna sila, *p* – pritisk tekočine, σ in τ – normalne in tangencialne napetosti

The use of lubricant in the plastic-deformation processes has increased greatly the working velocity, which required a consideration of the inertia effects in the calculations of the lubricant layer[26]. Computer calculations made it possible to also consider the effects of roughness[27,28], the mathematical modelling based on the Fourier series[29] and the reduction in lubricant use, considering the shape of the lubricant wedge ahead of the access section of the zone of plastic deformation[30] (**Figure 20**).

In parallel with the investigations of the lubrication for the plastic working of metals[31,32], more efficient lubricants were also developed[33,34]. It is to be expected that fluid mechanics will also be applied for a description of the lubricant behaviour in the processes of bending rolling, shown in **Figure 21**.

On the longitudinal section of the deformation zone of bending rolling the following zones are distinguished:

1. the drilling zone (from plane I to plane II),
2. the rolling on the mandrel zone (from plane II to plane III),
3. the reduction of the worked piece in the absence of the mandrel zone (from plane III to plane IV).

The application of the Reynolds' differential equation will probably start with the zone of rolling on the mandrel.

New findings of the forming of tubes with a fluid are presented in ref.[36] with the forming of the T- shaped end tubes shown in **Figure 22**.

Four characteristic zones are distinguished:

I – the zone of the main tube (flat stress-state)
II – the zone of the tube translating into drainage (volume stress-strain state)
III – the drainage zone (pressure and stretching stresses)
IV – the drainage peak zone (pressure and stretching stresses)

6 CONCLUSION

The use of fluid mechanics for the calculation of the behaviour of the lubricant layer in the metal deformation zone for most of the metal working processes has greatly increased with the application of computers. In the article a survey is given over the scheme of different metal-working processes and of the differential equations used for the description of the lubricant behaviour. Mostly, the derived equations are based on the Reynolds' differential equation and only some are also based on the Navier-Stokes' equation.

In modern methods of modelling of the lubricated plastic deformation of metals supplementary equations are also included to better consider the parameters of the working process. Actually, the calculations are applied mostly for the processes of the cold drawing and the rolling of metals[35], while for the Pilger processing they are being developed.

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