D. ĆURČIJA, I. MAMUZIĆ

ISSN 0543-5846
METABK 44 (3) 221-226 (2005)
UDC - UDK 669–122–2:669–418:519=111

OPTIMISATION PROCESS OF STRIP COLD ROLLING

Received - Primljeno: 2004-02-10
Accepted - Prihvaćeno: 2005-02-20
Preliminary Note - Prethodno priopćenje

Solutions of differential equations for smooth surfaces and transversal strip roughness with inertial lubrication forces were analyzed. Ten factors impacting the height of lubrication film at material input deformation zone were systemized through: rheologic lubrication properties, kinematics of technological processes and geometric characteristics of rolling processes. Linear optimization is based on the process of cloning, where two methods are proposed (rotary and step-like) and it contains three variants of adjustment of technological factors. The cloning process disposes of a possibility of the control of differential equations. The cloning is carried out with the Osnup tool that proposes a static and a dynamic method of transmission of similarity criterion over a singular point.

Key words: *cold rolling of strip, Monte-Carlo method, multiple lineal regressions, lineal optimization*

Optimiziranje procesa hladnog valjanja trake. Analizirana su rješenja diferencijalnih jednadžbi za glatke površine i poprečnu hrapavost trake sa utjecajem inercijskih sila maziva. Deset faktora koji utječu na visinu mazivog filma na ulaznom presjeku zone deformacije metala sistematizirani su kroz reološka svojstva maziva, kinematiku tehnološkog procesa i geometrijske karakteristike procesa valjanja. Linearno optimiziranje zasnovano je na procesu kloniranja, gdje su predložene dvije metode (rotacijska i stupnjevasta), i sadrži tri varijante podešavanja tehnoloških faktora. Proces kloniranja ima mogućnost kontrole riješena diferencijalnih jednadžbi kada zahvatni kutovi teže nuli. Kloniranje se vrši preko alata Osnup gdje je predložena statička i dinamička metoda prenosa kriterija sličnosti preko singularne točke.

Ključne riječi: *hladno valjanje trake, metoda Monte-Carlo, višestruka linearna regresija, linearno optimiziranje*

INTRODUCTION

Lubrication flow in Descartes coordinates system for conditions of incompressibility can be described in tensor notation [1, 2]:

$$\left[\sigma_{ij}\left(p,\ t,\ v_i\right)\right],\ j=\rho\omega_i \tag{1}$$

where:

σ_{ij} - components of stress tensor,
P - lubrication density,
ω_i - substance derivation by speed,
t - temperature,
p - pressure in lubrication film,
v_i - lubrication moving speed.

D. Ćurčija, I. Mamuzić, Faculty of Metallurgy University of Zagreb, Sisak, Croatia

For Newton fluid the notation (1) takes the following form:

$$v_j v_{i,j}=-\frac{p}{\rho}+V_k\Delta v_i \tag{2}$$

where:

V_k - kinematics value,
Δ - Laplas differential operator.

Through the expression (2) we reach Reynolds notation of lubrication differential equation :

$$\frac{\partial p}{\partial x}=\mu\frac{\partial^2 v_x}{\partial y^2};\quad \frac{\partial p}{\partial y}=0 \tag{3a}$$

$$\frac{\partial p}{\partial z}=\mu\frac{\partial^2 v_z}{\partial y^2};\quad \frac{\partial v}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial v}{\partial z}=0 \tag{3b}$$

where:

μ - dynamic lubrication viscosity.

Differential equation that takes into account the influence of inertial forces of lubrication at high technological speeds of metal processing has the following record:

$$\frac{\partial p}{\partial x}=6\mu\frac{v_0+v_R}{\varepsilon^2(x)}+C\mu\frac{1}{\varepsilon^3(x)}+ \\ +x\rho\frac{16(v_0+v_R)^2\varepsilon^2(x)-C^2}{120R\varepsilon^3(x)} \quad (4a)$$

$$C=\frac{k}{2}-\sqrt{\frac{k^2}{4}+2(v_0+v_R)\varepsilon_0\left[8(v_0+v_R)\varepsilon_0+3k\right]};$$

$$k=120v\frac{R}{x} \quad (4b)$$

where:

v_0+v_R - speed of movement of rolled strip and operating speed of rolls,
R - radius of rolls,
$\varepsilon(x)$ - geometrical shape of lubricating wedge in front of the entrance into the deformation zone,
x - abscissa,
v - kinematics viscosity,
ε_0 - the height of lubricating film at the inlet cross-section of metal zone deformation.

Differential equation that takes into account transversal strip roughness and longitudinal roughness of rolls has the following record:

$$\left\langle\frac{dp}{dx}\right\rangle=6\mu(v_0+v_{Rx})\left[\left\langle\frac{1}{\varepsilon^2(x_0)}\right\rangle-\frac{\left\langle\frac{1}{\varepsilon_0^2}\right\rangle}{\left\langle\frac{1}{\varepsilon_0^3}\right\rangle}\left\langle\frac{1}{\varepsilon^3(x_0)}\right\rangle\right] \quad (5)$$

where:

$\langle\ \rangle$ - symbol for the operator of mathematical hope.

Accidental value of rolls and strip roughness at $R_2 = 6\sigma$ according to GOST is

$\varepsilon(x_0) = \varepsilon_N + [\sigma_v(x_0) + \sigma_{tr}(x_0)]$

where:

ε_N - nominal height of lubrication film when the surfaces of rolls and strip are described by smoothness ($R_2 = 0$).

SOLUTIONS OF DIFFERENTIAL EQUATIONS BY MONTE-CARLO METHOD AND DISCUSSION ON THE RESULTS

Evaluation of the roller cage rhythmicity

Lubrication viscosity depending on rolling pressure is introduced in the formula

$$\mu=\mu_0 e^{\gamma p} \quad (6)$$

where:

μ_0 - dynamic viscosity at atmospheric pressure,
p - roll pressure on metal,
γ - piezocoefficient of lubrication viscosity.

Should viscosity depend on temperature then is:

$$\mu=\mu_0 e^{\gamma D}\cdot e^{\frac{-\Theta(t-t_1)}{B-1}} \quad (7)$$

where coefficients D, B, and Θ are defined on rotary viscosimeters.

If some reliable dynamic lubrication viscosity is available according to (6) and (7) solutions of differential quotations may be presented through technological parameters:

$$A=\frac{1-e^{-\gamma D}}{6\mu_0\gamma(v_0+v_R)} \quad (8)$$

The lubrication height in the area [–a, 0] can be approximated by the following polynomial (Figure 1.):

$$\varepsilon(x)\equiv\varepsilon_N=\varepsilon_0-\alpha x+\frac{x^2}{2R}-\alpha\frac{x^3}{2R^2} \quad (9)$$

For the area of cold rolling it is sufficient to approximate $\varepsilon(x)$ by square polynomials.

In the theoretical analysis a cage rolling composed of 11 roll pairs will be supposed inside of which technological parameter A will fall lineally from A_0 = 1 965 512 m^{-1} down to A_{10} = 898 519 m^{-1} with ΔA = – 106 700. In this process is: $v_0 = 0{,}6v_R$ m/s, vR m/s = 10 m/s, μ_0 =0,024 Pas,

γ = 0,218E–6 m²/N, $p \cdot \gamma$ = 4,36, ε_a = 0,001 m, R_Z = 0, isothermal conditions of technological process t = (20 °C).

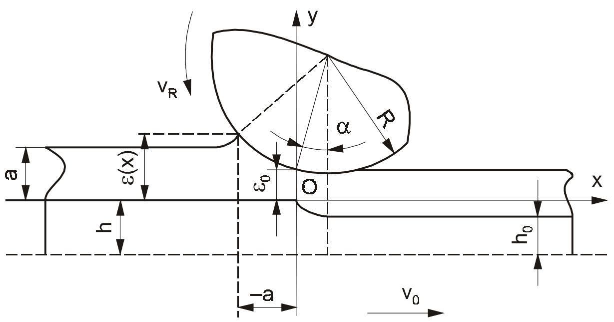

Figure 1. **The scheme of rolling with lubrications**
Slika 1. **Shema valjanja sa mazivima**

Guidelines of analysis will be moving over singular point in which discriminate of square expression in (9) is equal to zero [3, 4].

The Figure 2. involves the monitoring of inertial lubrication forces according to the differential equation (4a), the influence of roughness according to (5) and normal lubrication height film according to differential equation (3a). The results are obtained by Monte-Carlo numerical method for all three differential equations with the following approximation for $\varepsilon(x)$:

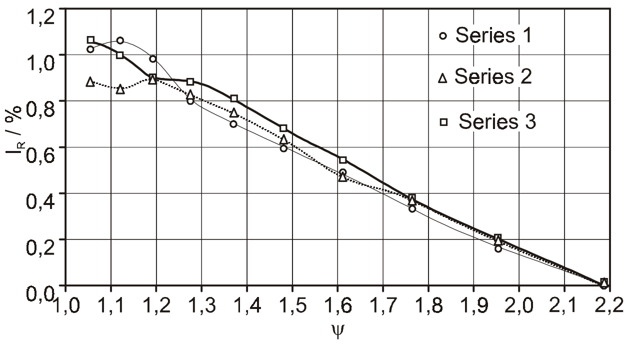

Figure 2. **Deviation of lubrication film height I_R / % at input cross-section of deformation zone in relation to technological parameters ratio ψ**
A_{10} = 898 519 m^{-1}(10th roll pair); R = 0,2 m, α = 0,03 rad, R_Z = 6E^{-6} m, ε_a = 0,0015 m,
Series 1 differential equation (3a),
Series 2 differential equation (5),
Series 3 differential equation (4a)

Slika 2. **Odstupanja visine mazivoga filma I_R/% na ulaznome presijeku zone deformacije u odnosu na omijere tehnoloških parametara ψ**
A_{10} = 898 519 m^{-1}(10. par valjaka); R = 0,2 m, α = 0,03 rad, R_Z = 6E^{-6} m, ε_a = 0,0015 m,
Serija 1 diferencialna jednadžba (3a),
Serija 2 diferencialna jednadžba (5),
Serija 3 diferencialna jednadžba (4a)

$$\varepsilon(x) = \varepsilon_0 - \alpha x + \frac{x^2}{2R} - \alpha \frac{x^3}{2R^2} + \frac{x^4}{8R^3} \tag{10}$$

For roll radius R = 0,2 m, disharmony is contributed by pairs of roller cages 1., 2., and 7. for the series 2. On the abscissa of Figure 2. a ratio of technological parameter in relation to the initial roll pair, that has A_0 = 1965512 m^{-1}, is plotted. In addition to a graphical method of the moving of disharmonic roller cage some other criteria of this estimation can be developed. The easiest one is regression estimation through regression coefficient. So for differential equation (5) and exampled Figure 2. there is a following movement in Table 1. for linear regression analysis.

Table 1. **The movement of the coefficient of linear regression depending on distancing of roller cage ordinary numbers for differential equation (5); α = 0,03 rad**
Tablica 1. **Kretanje koeficijenata linearne regresije u ovisnosti o udaljavanju rednih brojeva valjaka iz kaveza za diferencijalnu jednadžbu (5); α = 0,03 rad**

All present	Removed 1st couple (A_0)	Removed 1st and 2nd couple	Removed 1st, 2nd, and 7th couple	-
R^2 = 0,9882	R^2 = 0,9802	R^2 = 0,9948	R^2 = 0,9955	-

The results of the Figure 2. could be presented by a multiple linear regression in a following form:

$$Y_i = 2,4628 - 0,2896 X_1 - 0,7285 X_2 - 0,3657 X_3 \tag{11}$$

$$X_i = \frac{A_0}{A_{1-10}}; \quad Y_i = \frac{\varepsilon_0(A_{10}) - \varepsilon_0(A_{1-10})}{\varepsilon_0(A_{10})} \% = 1_R \tag{12}$$

where:

X_1 - influence of smooth surfaces (dif. equation (3a)),
X_2 - influence of inertial forces (dif. equation (4a)),
X_3 - influence of surfaces' roughness (dif. equation (5a)).

It can be seen in (11) that the inertial forces have the greatest influence. It is shown in Figure 2., where the solutions of differential equations (4a) are the most balanced.

The coefficient of multiple digression is R^2 = 0,99862, Durbin-Watson Test = 2,15062.

According to Table 1. it is visible that with removing of the seventh roll pair there was no contribution to any great increase to the index of rythmicity for differential equation (5) which is also graphicly visible in Figure 2.

Process optimization

The Figure 3. presents a technological chart as regards the optimization of the results in Figure 2. It would be more appropriate to suppose that the roller cage should not be removed but their technological parameter adjusted so that

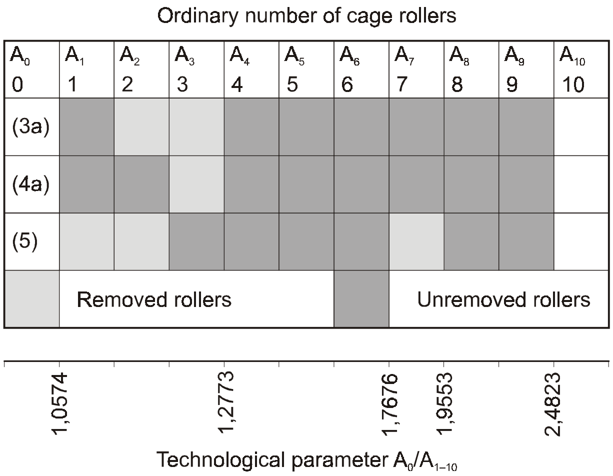

Figure 3. **Optimization of index of cage rhythmicity in the area of technological parameter**
$A_L \in [1,2773 - 1,7676] \cup [1,9553 - 2,4823]$
(3a)-diff. equation for smooth surfaces
(4a)-diff. equation with inertial forces
(5)-diff. equation for rough surfaces $R_z = 6E^{-6}$ m

Slika 3. **Optimizacija indeksa ritmičnosti kaveza u području tehnološkog parametra**
$A_t \in [1,2773 - 1,7676] \cup [1,9553 - 2,4823]$
(3a)-dif. jednadžba za glatke površine
(4a)-dif. jednadžba koja uključuje inercijske sile
(5)-dif. jednadžba za hrapave površine $R_z = 6E^{-6}$ m

they follow the general regression line (11). The separated area of optimization A_L €[12773 – 1,7676] U[1,9553 - 2,4823] according to the technological parameter , presents a concatenated case that has no need for switching over to new values of technological parameters. Rhythmicity indices for linear optimizing may hold on their values together with unchanged value of technological parameter, inside of which there is possibility for the change of kinematical and rheological characteristics according to the law of hyperbole. Consequently for the fourth roller cage, A_4 = 1 538 714 m^{-1} gives an initial product for $\mu_0 \cdot v_R$ = 0,030657×1,6×10 = 0,49051 Pam (values of A_0 stayed on). Should the rolling speed be increased to 11 m/s, then the new value for dynamic lubrication viscosity amounts μ = 0,02787 Pas.

However, if we are outside the area A_t, then it is good to change the index of rhythmicity through the change of constructive characteristics; engaged angle or radius of rolls. Another and more difficult case of optimization proceeds by change of technological parameter A_2. According to A_2 = 1 752 113 with change of only m_0 proceeds the value μ_0 = 0,0269231 Pas (other parameters are equal as for A_0). With a small addition of increment of μ_0 = 0,027 the height of lubrication film will increase and rythmicity index amount lg = 0,9869. In the Table 2. the review of calculation results is given.

Table 2. **The results of iteration for differential equation (3a), variable A**
Tablica 2. **Rezultati iteracije za diferencijalnu jednadžbu (3a), varijabilan A**

A / m^{-1}	α^* / rad	α_0^* / m	α_1^* / m	α = 0,03 rad ε_0 / m	Index of rhythmicity
A_0= 1965512	0,011058	12,227E^{-6}	15,827E^{-6}	7,223E^{-6}	
A_2= 1752112	0,011483	13,198E^{-6}	17,083E^{-6}	8,013E^{-6}	
A_{10}= 898519	0,0143357	29,551E^{-6}	26,600E^{-6}	14,471E^{-6}	
New A_2 = 1747122 comes with the new μ_0 = 0,0267 Pas. The consequence is correction of Osnup.					
A_2=1747122	0,0115137	13,257E^{-6}	17,157E^{-6}	8,0338E^{-6}	2,0853
There follows linear interpolation					
	I_R	μ_0			
	1,060	0,0269231			
	2,0853	0,027			
	0,9869	0,0026917			

In dynamic lubrication viscosity the result of optimization changes on the 4th Figure of calculation and, in this case, has a theoretic meaning for the cloning processes if they should be transmitted on engaged angles about 0,05 rad. for an differential equation (3a). The high value of correlation coefficient for regression direction (11) indicates that the cage has a good hydrodynamic work stability, so insignificant shifts on l_R require small shift on dynamic lubrication viscosity.

For the transmission of similarity criterion (cloning process) $R^2 \rightarrow 1$ is required and will be explained later in the text.

The scheme of the tool for determining index of rythmicity and solution of cloning of differential equations

The past analysis was made with a tool the algorithm of which will be presented. The principled scheme is given in the Figure 4. where two methods can be observed:

I) Transfer of similarity criterion from the etalon A_0 over guides $A_{1\text{-}10}$ in relation to the fixed roller cage A_{10} is made by hyperbole,
II) Transfer of similarity criterion in the cage is made over rotating OSNUP.

Example application for differential equation (3a) is shown in Table 3. In this connection R = 0.2 cm, α_a = 0,001 m, without influence of inertial forces.

From the Table 3. it is visible that both methods give the same result so in fact they control each other. The high value of the correlation coefficient for the tool in Figure 4. which can be seen in the equation (11) also enable some

Table 3. **Example for the application of tool presented in the Figure 4.**
Tablica 3. **Primjer primjene alata sa slike 4.**

<table>
<tr><td>A_i / m^{-1}</td><td>α* / rad</td><td>α_0^* / m</td><td>α_1^0 / m</td><td>α = 0,03 rad</td></tr>
<tr><td>A_0= 1965512</td><td>0,0110580</td><td>12,227E^{-6}</td><td>15,827E^{-6}</td><td>7,223E^{-6}</td></tr>
<tr><td>A_1= 1752112</td><td>0,0112649</td><td>12,689E^{-6}</td><td>16,425E^{-6}</td><td>7,597E^{-6}</td></tr>
<tr><td>A_{10}= 898519</td><td>0,0143357</td><td>20,551E^{-6}</td><td>26,600E^{-6}</td><td>14,471E^{-6}</td></tr>
<tr><td colspan="5">Evaluation of index of cage rhythmicity</td></tr>
<tr><td colspan="2">Method I (Static)</td><td colspan="3">Method II (Dynamic)</td></tr>
<tr><td colspan="2">$A_0 \therefore A_1$
$\Delta\varepsilon_0$= 3,74E^{-6} Δ_0= 6,060E^{-6}
Δ_1= 6,476E^{-6}
$\Delta_1 - \Delta_0$= 4,16E^{-7}
φ_0= $(\Delta_1 - \Delta_0)/\Delta\varepsilon_0$= 1,1123

$A_{10} \therefore A_1$
$\Delta\varepsilon_0$= 6,874E^{-6} Δ_{10}= 1,394E^{-5}
Δ_1= 6,476E^{-6}
$(\Delta_{10} - \Delta_1)_2$= 7,465E^{-6}

$(\Delta\varepsilon_0)^C$= $(\Delta_{10} - \Delta_1)_2/\varphi_0$= 6,711E^{-6}

ε_0= 7,597E^{-6}+6,711E^{-6}=
= 14,308E^{-6}
Index = 1,126 %</td><td colspan="3">$A_0 \therefore A_1$
$\Delta\varepsilon_0$= 3,74E^{-7} Δ_0= 6,060E^{-6}
Δ_1= 6,476E^{-6}
χ= $(\Delta_1 - \Delta_0)$ = 4,16E^{-7}
$\chi - \chi/\varphi = \Delta\varepsilon_0 \longrightarrow \varphi$ = 9,905

$A_{10} \therefore A_1$
$\Delta\varepsilon_0$= 6,874E^{-6} Δ_{10}= 1,394E^{-5}
Δ_1= 6,476E^{-6}
$\chi_2 = \Delta_{10} - \Delta_1$= 7,465E^{-6}

$(\Delta\varepsilon_0)^C$= $\chi_2 - \chi_2/\varphi_0$= 6,711E^{-6}

ε_0= 7,597E^{-6}+6,711E^{-6}=
= 14,308E^{-6}
Index = 1,126 %</td></tr>
</table>

estimation of lubrication film for the case when differential equations are difficult to solve. In this connection it is necessary to know the indices of cage rhythmicity and removing those roll pairs that make it worse. Such a refined cage may be a good base to find out approximate solutions for the areas of other engaged angles. In Table 4. such an evaluation (cloning) for differential equation (4a) whose solutions are presented in Figure 2. is given.

Table 4. **Rotary and step-like cloning of the solution of differential equation (4a) for α = 0,03 rad**
Tablica 4. **Rotacijsko i stupnjevito cloniranje riješenja diferencijalne jednadžbe (4a) za α = 0,03 rad**

Technological parameter / m^{-1}	ε_0 /(E^{-6}m) for unchanged cage (rotary)	ε_0 /(E^{-6}m) when 2nd and 3rd roll pairs are removed (rotary)	ε_0 /(E^{-6}m) when 2nd and 3rd roll pairs are removed (step-like)	ε_0 /(E^{-6}m) calculated according to the method Monte - Carlo
A_1= 1858812	-	-	-	7,831
A_2= 1752113	8,088	-	-	8,238
A_3= 1645414	8,561	-	-	8,694
A_4= 1538714	9,092	9,206	9,207	9,209
A_5= 1432015	9,693	9,786	9,788	9,795
A_6= 1325316	10,381	10,449	10,453	10,469
A_7= 1218617	11,176	11,215	11,219	11,469
A_8= 1111917	12,104	212,115	12,122	12,172
A_9= 1005218	13,210	13,179	13,188	13,271
A_{10}= 898519	14,548	14,468	14,479	14,607

Removing 2nd and 3rd roller cage pair principally enhances cloning although only the 3rd roller cage could be removed. Here we can mention the characteristics of this cloning. According to the Table 3. it is necessary to know three successive technological parameters A_0, A_1, A_2 with

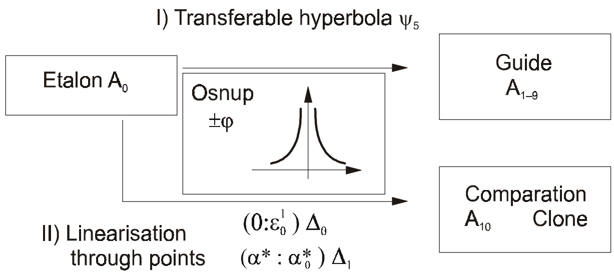

Figure 4. **The tool for determining index of cage rhythmicity**
Slika 4. **Alat za određivanje indeksa ritmičnosti kaveza**

all initial solutions except solutions for α = 0,03 rad from A_2 (9.088E–6). It is cloned on the base of known values for α = 0,03 rad from A_0 and A_1. Then the technological parameter A_1 turns to A_0, and A_0 turns to A_1, however A_3 is

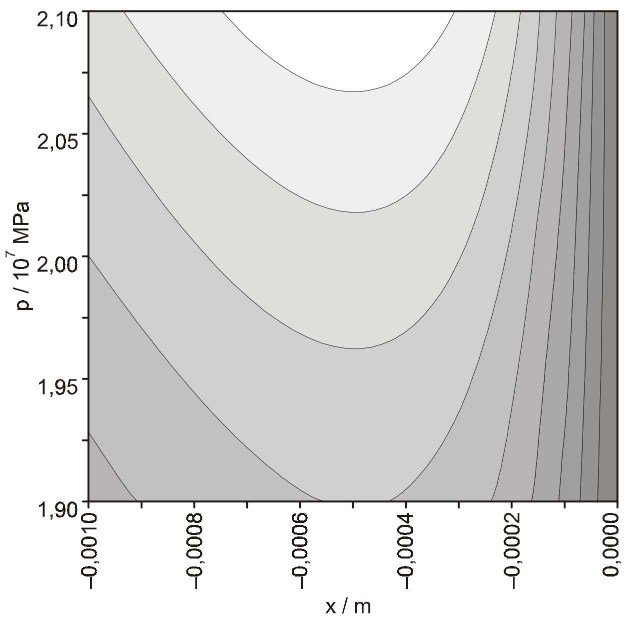

Figure 5. **Pictures aimed at the pressure gradient of differential equation (3a) in seeking its maximum for A_0: R = 0,2 m, α = 0,011058 rad. ε_a = 0,001 m; x = (–0,001m down to 0,0001m), p = 19 to 21 Mpa**
Slika 5. **Ciljani snimci na gradijent tlaka diferencijalne jednadžbe (3a) u traženju njegovog maksimuma za A_0: R = 0,2 m, α = 0,011058 rad. ε_a = 0,001 m; x = (–0,001 m do 0,0001m), p = 19 do 21 Mpa**

Table 5. **Possible methods of cold rolling optimization**
Tablica 5. **Moguće metode optimiziranja hladnoga valjanja**

Area per A_L	Variability	Unchangeableness	Remarks
Within the area A_L	ε_0, v_R, μ_0, γ, p, v_0	A = const α = const R = const	Computation according to hyperbola $v_R \cdot \mu_0$ = const. Solutions are on 3D-surface of expression 8
Outside the area A_2 Figure 3.	ε_0, v_R, μ_0, γ, p, v_0, α, R	A = const	Calculation according to differential equations
Outside the area A_2	ε_0, v_R, μ_0, γ, p, v_0, α, R, ε_a, R_Z, t	-	Iterative method of calculation according to differential equations (3a), (4a), and (5) with the use of Osnup in the Figure 4.

Table 6. **Possible methods of cloning of differential equation**
Tablica 6. **Moguće metode cloniranja diferencijalnih jednadžbi**

Rotationary cloning		To be calculated	Remark
Calibration	A_0	$\alpha^*, \varepsilon_0^*, \varepsilon_0^1$	ε_0 from A_{0+2} follows as the result of cloning
Guide	A_{0+1}	ε_0 for cloning angle from A_0, A_{0+10}	
Clone	A_{0+2}		
Calibration	A_{0+1}	$\alpha^*, \varepsilon_0^*, \varepsilon_0^1$	Now being cloned ε_0 from A_{0+3} chosen angle α
Guide	A_{0+2}	ε_0 from A_{0+1} is calculated	
Clone	A_{0+3}	ε_0 from A_{0+2} is cloned	
Step-like cloning		**To be calculated**	**Remark**
Calibration	A_0	$\alpha^*, \varepsilon_0^*, \varepsilon_0^1$	Two methods of Osnup application are possible and with: 1. statistic φ_0 2. dynamic φ
Guide	A_{0+1}	ε_0 for cloning angle from A_0 and A_{0+10}	
Clone	A_{0+10}		
Calibration	A_0	A_{0+1} is cloned	Recommendation is to recheck the cloning, when φ on Osnap change its direction of rotation over rhythmicity index
Guide	A_{0+2}	A_{0+2} is being cloned	
Clone	A_{0+10}		
Calibration and clone are fixed while the guide climbs along the steps till it reaches A_{0+10}			

a new technological parameter for cloning with known solution in a singular point. As shown in Table 4. this algorithm based on uninterrupted rotation is very useful for the evaluation of the height lubrication film in the areas of engaged angles larger than α^*.

The 2nd cloning type can develop step-like so that A_0 is always a fixed calibration while guides A_{1-10} continually climb along a step until they reach A_{10}. In the Table 4. it is visible that step-like cloning has a insignificant advantage over the rotary cloning. Optimization calculations are accompanied also by changes in pressure gradient within the lubrication film. such a change for A_0 is presented in the Figure 5. It indicates that maximal pressure gradient is at about SE-4 m in front of entry cross section of metal deformation zone.

CONCLUSION

The refining of the region A_L is a good preliminary work for this area of technological parameters to be used for transferring similarity criterion (cloning) of differential equations solutions on larger or smaller engaged angles. Index of rhythmicity showing these features are defined by functions (11). Optimization and cloning could be presented in the Table 5. and Table 6.

Calibration, Guide, and Clone are continuously in a dynamic motion. A good cloning for the angle a_1 requires cutting off roll pairs - at the initial angle a within the cage, which could disturb the accuracy of cloning at a larger engaged angle α_1 (over the index of rhythmicity).

However the process of cloning may also develop backwards - from higher engaged angles down to lower ones, but it can also check the solutions of differential equations when $\alpha \rightarrow 0$ rad.

REFERENCES

[1] D. Ćurčija, I. Mamuzić, Metalurgija 44 (2005) 2, 113 - 117.
[2] G. L. Kolmogorov, A. V. Kovalev, Izv. VUZ. Chernaya Metall. (2003) 1, 40 - 42.
[3] G. L. Kolmogorov, A. V. Fedotov, J. Matev, Process Technology 95 (1999) 1 - 3, 55 - 64.
[4] D. Ćurčija, Materijali in tehnologije 37 (2003) 5, 237 - 251.