Journal of Chemical Technology and Metallurgy, 51, 4, 2016, 379-384

DEFORMATION, STRESS AND FRACTURING OF STEEL IN THE PROCESS OF FLAT ROLLING

Alexandr Bogatov[1], Henryk Dyja[2], Danis Nukhov[1]

[1]*Ural Federal University named after the First President of Russia B.N. Yeltsyn*
19 Mira street, Ekaterinburg, Russia
[2]*Czestochowa University of Technology*
ul. Dabrowskiego 69, room. nr 2,42-201
Czestochowa, Poland
E-mail: danis_nuchov@mail.ru

Received 24 November 2015
Accepted 27 April 2016

ABSTRACT

The plate that is formed during longitudinal rolling out of continuously cast steel is characterized by deformational and structural inhomogeneity by rolling height, presence of stringer-type non-metallic and liquation inclusions, elongated along rolling direction, which reduce mechanical and performance properties of flat steel and its products. This research presents the comparative analysis of deformation inhomogeneity during plate rolling carried out by various methods, and also provides performance estimation of stressed state and fracturing of steel in the process of rolling.

Keywords: plate rolling, simulation, deformation, DEFORM, Q-FORM.

ANALYSIS OF DEFORMATION INHOMOGENEITY DURING PLATE ROLLING

The development of a computer model of plate rolling technological process has been carried out considering the range of product sizes and technological capacity of equipment of rolling mill 5000 at "Magnitogorsk Metallurgical Plant" JSC. Three rolling passes of "MMP" JSC mill 5000, namely first, thirteenth and twenty first passes, were selected for the purpose of this research: initial height of continuously cast slab at the first pass was h^1_0 = 300 mm, at the thirteenth pass - h^{13}_0 = 67,4 mm and – h^{21}_0= 30,5 at the twenty first pass. The values of friction index ψ (as per Shear) for the thirteenth pass varied at three levels: ψ = 0,6; 0,7; 0,8, and at one level - ψ = 0,8 - for the first and twenty first passes. The results of calculation of deformation zone sizes, neutral plane position, measure of deformation for nine particles having various altitude coordinate

$$0 \le \frac{2y}{h_0} \le 1$$

extracted by means of DEFORM-3DandQ-FORM software were compared to analogous properties, extracted with the help of formulas [1-13]. As per the thin section method, the deformation during rolling is considered monotonous and homogeneous, when deformation is defined by final modification of sheet sizes – $\varepsilon_u = \frac{2}{\sqrt{3}}\sqrt{\overline{\varepsilon_2^2} + \overline{\varepsilon_2 \varepsilon_3} + \overline{\varepsilon_3^2}}$ where $\overline{\varepsilon_3} = \ln\frac{h_0}{h_1}$ $\overline{\varepsilon_2} = \ln\frac{b_1}{b_0}$ h_0 and h_0, b_0 and b_1 are initial and final height and width of the sheet respectively. Disregarding broadening we get $\varepsilon_u = \frac{2}{\sqrt{3}}\ln\frac{h_0}{h_1}$.

The velocity profile provided by DEFORM-3D and Q-FORM software presented by isograms in Fig. 1 does not justify the hypothesis of thin sections. It is observed that axial component gradient of particles velocity vector is lower when exposed to friction stress in near-contact zone, than in central part of deformation zone. Deformation inhomogeneity estimationby sheet height was exercised for 9 steel particles: (P1…P9), where P1 is a particle at the area of slab and roll contact (z = h/2); P9 is a particle in symmetry plane (z = 0) (Fig. 3). Average

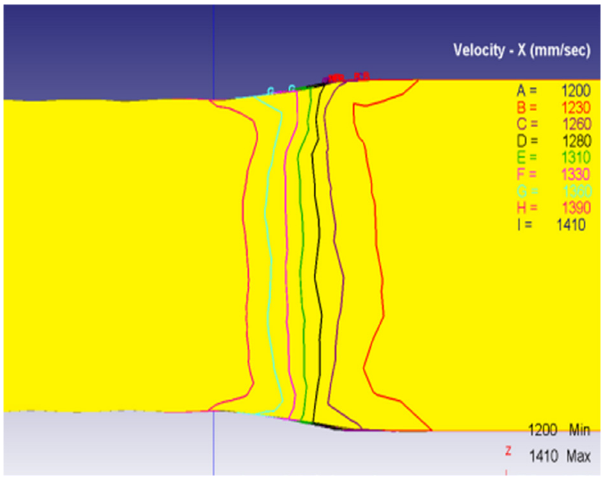

Fig. 1. Velocity profile of axial component of steel particles velocity.

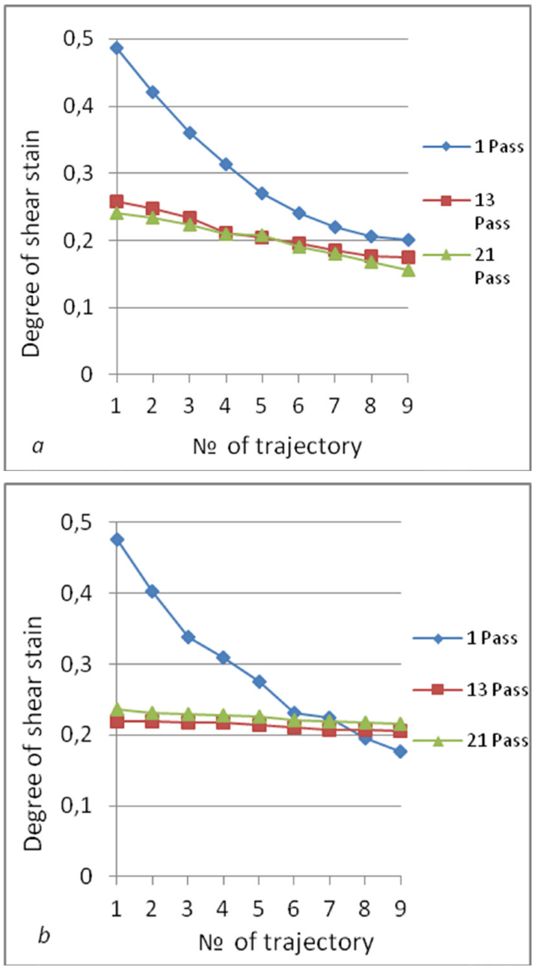

Fig. 2. Distribution of accumulated deformation degree as per DEFORM-3D (a) and Q-FORM (b) software.

deformation value in section after rolling was defined with the help of formula

$$\overline{\varepsilon_u} = \frac{1}{n}\sum_{i=1}^{n}\varepsilon_{ui}$$

i - particle number. The deformation inhomogeneity by sheet height was estimated by means of variation coefficient $S/\overline{\varepsilon_u}$,

where $S = \left[\frac{1}{n-1}\left(\varepsilon_{ui} - \overline{\varepsilon_u}\right)^2\right]^{1/2}$

is average squared deviation. The calculation results for three aforementioned rolling passes are provided in Table 1.

It is observed from Table 1 that the deformation zone parameters (length of deformation zone l, and l/hmedium ratio, gripping angle α and angle of neutral plane γn), calculated by means of DEFORM-3D and Q-FORM software are slightly different from the parameters defined as per the hypothesis of thin sections.

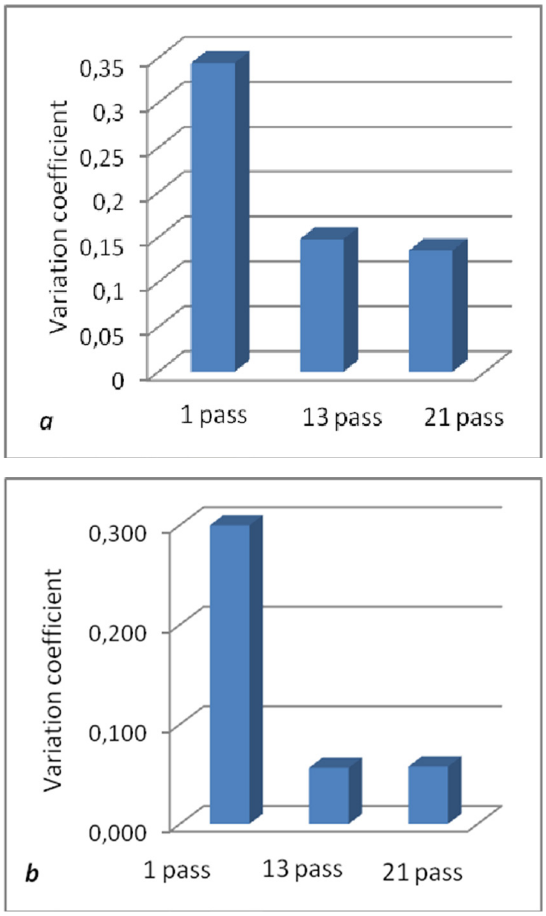

Fig. 3. Variation coefficient $S/\overline{\varepsilon_u}$ for three passes as per DEFORM-3D (a) and Q-FORM (b) software.

Table1. Research results.

Pass number	Calculation method	n, min^{-1}	Δh_i, mm	ψ	T,°C	l, mm	l/h_{med}	b_0, mm	b_1, mm	Δb, mm	α, grad	γ, grad	l_{tim}, mm	ε_u
1	DEFORM-3D	23,7	36	0,8	1172	139,90	0,49	2700	2723,46	23,46	14,61	5,65	54,41	0,320
	Q-FORM					143,15	0,54		2724,07	24,07	15,10	4,26	40,85	0,310
	Thin section method					140,71	0,49		2706,33	6,33	14,66	5,94	50,67	0,256
13	DEFORM-3D	63,1	6,5	0,8	890	59,17	0,92	4490	4495,87	5,87	6,25	2,87	27,62	0,222
	Q-FORM					65,62	0,94		4494,83	4,83	6,85	1,83	20,61	0,226
	Thin section method					59,79	0,93		4492,64	2,64	6,23	2,86	27,51	0,203
13	DEFORM-3D	63,1	6,5	0,7	890	59,17	0,92	4490	4494,15	4,15	6,25	2,84	27,28	0,220
	Q-FORM					64,70	1,01		4494,24	4,24	6,76	1,90	21,84	0,227
	Thin section method					59,79	0,93		4492,59	2,59	6,23	2,84	27,26	0,203
13	DEFORM-3D	63,1	6,5	0,6	890	59,17	0,92	4490	4493,97	3,97	6,25	2,80	26,91	0,219
	Q-FORM					65,23	1,02		4493,95	3,95	6,81	2,15	23,67	0,233
	Thin section method					59,79	0,93		4492,53	2,53	6,23	2,79	26,85	0,203
21	DEFORM-3D	96,2	2,8	0,8	868	39,50	1,36	4490	4492,10	2,10	4,10	1,96	18,87	0,213
	Q-FORM					43,02	1,48		4493,3	3,3	1,48	2,21	21,79	0,225
	Thin section method					39,24	1,35		4491,61	1,61	4,08	1,94	18,79	0,193

The relative broadening of slab established by means of DEFORM-3D and Q-FORM software at the first pass is $\frac{b_1}{b_0}\cdot 100\%$ = 0,87 % and 0,89 %, at the thirteenth - 0,13 % and 0,11 %, and 0,05 % and 0,07 % at the twenty first. Thus, the sheet broadening during rolling can be disregarded in engineering analysis.

The values of deformation by nine particles trajectories are provided in Fig. 2a,b, when the values of variation coefficient $S/\overline{\varepsilon_u}$ which characterizes deformation inhomogeneity by height, are provided in Fig. 3a,b.

It is observed in charts of Fig.4 that the deformation degree at the area of contact with roll is 2.5 times higher for the first pass (l/h ≈ 0,5) than in the symmetry plane.

The variation coefficient $S/\overline{\varepsilon_u}$, calculated with the help of DEFORM-3D and Q-FORM software equals 0,315 and 0,30 respectively. These values indicate significant inhomogeneity of deformation in strip section. As for the thirteenth pass (l/h ≈ 0,9) and the twenty first pass (l/h ≈ 1,35–1,48), the deformation degree in near-contact zone and central part of the sheet is 1,10 - 1,5 times different, when variation coefficient equals 0,13 and 0,12, respectively, as per DEFORM-3D and 0,06 for both passes as per Q-FORM. Calculation comparison of average deformation degree by height $\overline{\varepsilon_u}$ as per the DEFORM-3D and Q-FORM software and formula

$$\varepsilon_u = \frac{2}{\sqrt{3}} \ln \frac{h_0}{h_1}$$

indicates that assumption of monotonous and homogeneous character of deformation by height during rolling provides underestimated results.

ESTIMATION OF STRESSED STATE IN DEFORMATION ZONE DURING PLATE ROLLING

For providing conditions of plain deformation and fulfilling the hypothesis of thin sections the stressed state is characterized as follows: σxy = σyz = 0, σyy = (σxx +σzz)/2= σ, where σ = $\frac{1}{3}$ σii - average normal stress. Based on yield criterion considering value of normal contact stress [8]:
for backward slip zone

$$p=\frac{2\tau_s}{\mu}\frac{tg\alpha}{2}\left[(\delta-1)\left(\frac{h_0}{h_x}\right)^{\delta}+1\right]-\sigma_{x0} \tag{1}$$

and for forward slip zone

$$p=\frac{2\tau_s}{\mu}\frac{tg\alpha}{2}\left[(\delta+1)\left(\frac{h_{x1}}{h_1}\right)^{\delta}-1\right]-\sigma_{x1} \tag{2}$$

where μ is the friction coefficient;

$$\delta=\frac{\mu}{tg\alpha/2}$$

h_0, h_1 and h_x are initial, final and current value of rolled strip thickness, σ_{xo}, σ_{x1} are stress of back and forward tension. It is necessary to find respective formula for σ_{xx} =-p+2τs. Then stressed state index

is $\frac{\sigma}{T}=-\frac{p}{\tau_s}+1$.

There is no $\sigma_{xo} = \sigma_{x1} = 0$ for plate rolling of forward and back tension, then stressed state index at the entrance and exit of deformation zone equals $\frac{\sigma}{T}$ = -1 when Lode index is $\mu_\sigma = 0$ (Fig. 4a,b). The stressed state index for 21st pass in neutral plane is σ/T = –2,71, and for 1st - σ/T = –1,5. While increasing friction index from 0,6 to 0,8 in 13th pass, stressed state index reduces from (–1,91) to (–2,11).

FEM problems solution –that is the process of modeling of plate rolling for three passes (the first, thirteenth and twenty-first) in the program of DEFORM-3D for the assessment of the stress state determined the stress state factors of σ/T and μ_σ in the deformation zone of the cross sections for the input, output, and neutral section

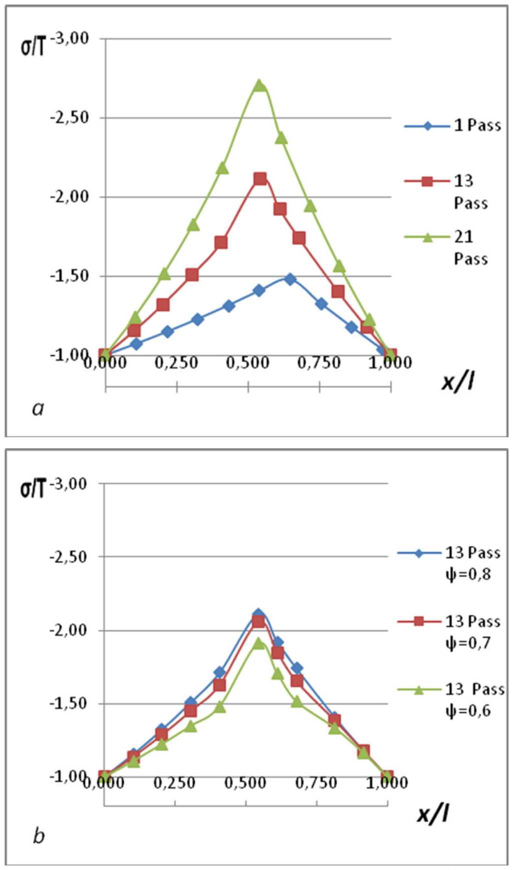

Fig. 4. Distribution of stressed state indexes σ/T along the deformation zone x/l (a) for three rolling passes and for one pass with various friction conditions (b).

along the trajectories of contours of axial velocity of the metal (see. Fig. 1). Graphics of the change of the stress state factor for the five trajectories along the deformation zone are shown in Fig. 5 and Fig. 6.

The values of Lode factor ($\mu_\sigma=2\frac{\sigma_{22}-\sigma_{33}}{\sigma_{11}-\sigma_{33}}-1$), found by the program of DEFORM-3D, are close to 0 (the values from 0,01 to 0,09) and do not contradict the theory - when sheet rolling there is the plane strain (μ_σ = 0).

The obtained results of the task solutions, performed by the program of DEFORM-3D, do not satisfy the boundary conditions when the sheet rolling (Figs. 5 and 6).

Taking into account the character of steel yield ability ε_p dependence from σ/T indicator (Fig.7) [9], it is fair to say that higher steel collapsibility is observed during plate rolling rather than during steel sheet rolling.

During plate rolling at the first pass index is σ/T

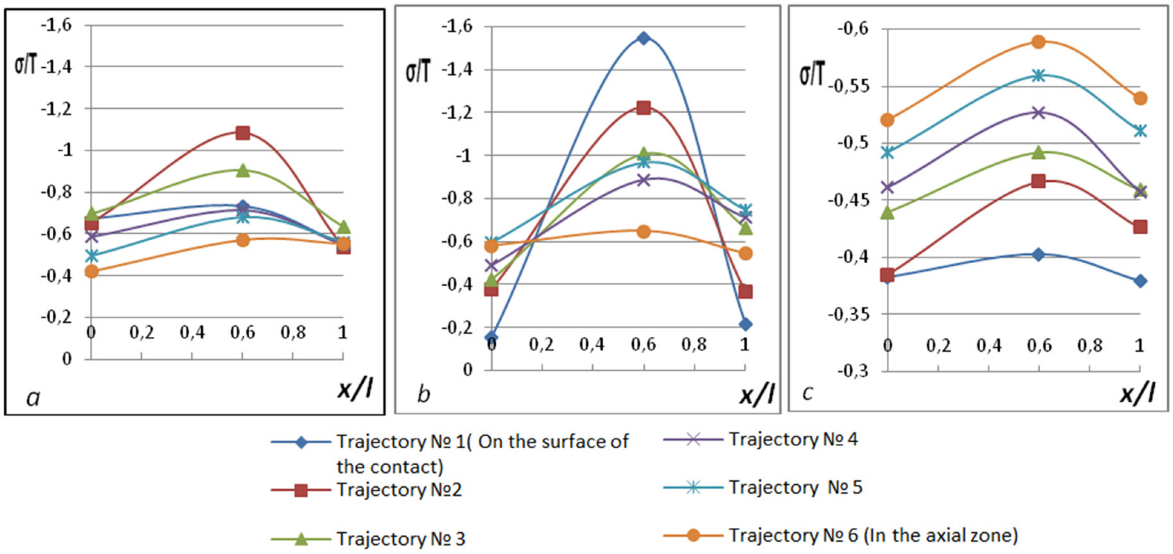

Fig. 5. Indicator of stress state σ/T along the deformation zone x/l for three rolling passes when ψ = 0,8 according to DEFORM-3D (a – first pass; b – thirteenth pass; c – twenty first pass).

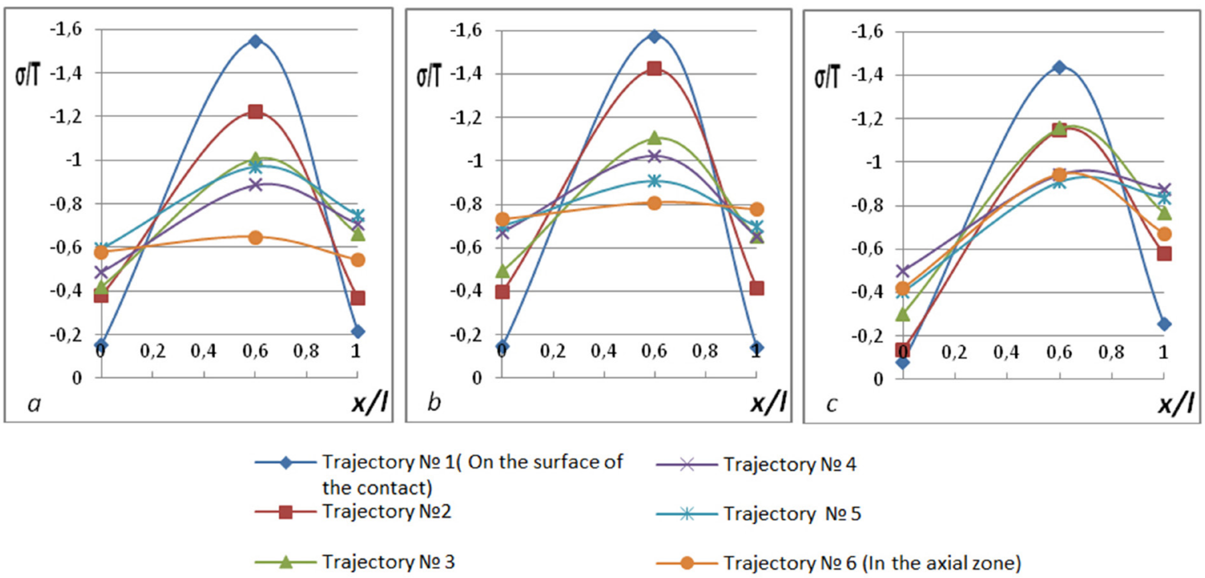

Fig. 6. Indicator of stress state σ/T along the deformation zone x/l for three rolling passes according to DEFORM-3D (a - ψ = 0,8; b - ψ = 0,7; c - ψ = 0,6).

= -1,5, when steel yield ability is ε_p = 4,00. During sheet rolling (21stpass) the stress state index equals σ/T = -2,71, and yield ability equals ε_p = 9,6, i.e. 2,4 times higher than at first pass.

CONCLUSIONS

The quantitative characteristics of deformation inhomogeneity by rolling height depending on sizes of deformation zone and rolling modes were identified and established with the help of DEFORM-3D and Q-FORM software complexes. Index of accumulated deformation degree inhomogeneity in the form of $S/\overline{\varepsilon_u}$ variation coefficient was proposed for comfortable analysis of steel structure inhomogeneity during rolling. It was shown that during rolling of high slabs at first passes the variation coefficient equals $S/\overline{\varepsilon_u} = 0.3$, as there is high variability of deformation degree at the surface and

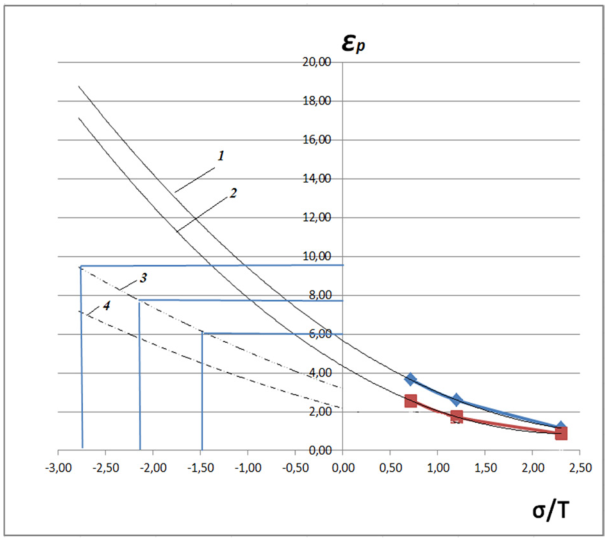

Fig. 7. Yield ability chart for steel of "St 3Sp" grade during hot deformation (1, 3 $-\dot{\varepsilon} =$ 10 c-1; 2, 4 $-\dot{\varepsilon} =$ 100 c-1. Full lines 1 and 2 - $\mu_\sigma = 1$, dashed lines - $\mu_\sigma = 0$).

core zone of the plate. The values of stress state indexes in the deformation zone have been calculated using the thin sections hypothesis and interface conditions of zero equality of forward and back tensions. It was shown that during plate rolling the σ/T indicator is 1.8 times higher and yieldability of steel grade "3Sp" is 2.4 times lower than during sheet rolling.

The modern programs of FEM – modeling allow to evaluate the discontinuity of the deformed state in the deformation zone at plate rolling, while the hypothesis of plane sections, used in the plastic theory of rolling, does not allow to give an accurate estimation. It was shown that in the axial zone there is insufficient work out of structure compared to the contact area. The stress state analysis, made by the program of DEFORM-3D, showed that the FEM-simulation of plate rolling does not provide the reliable data on the index of state of stress, as the boundary conditions at the input and output of the deformation zone are not satisfied.

Acknowledgements

The study was made within the project part of state job in the field of scientific activity No 11.1369.2014/K dated 18.07.2014 (State registration number: 114122470051). The work was supported by Act 211 of the Government of the Russian Federation, agreement № 02.A03.21.0006.

REFERENCES

1. R. Hill, A General Theory of Metalworking Processes, J. Mech. Phys. Solids, 11, 1963, 305.
2. J.M. Alexander, On the Theory of Rolling, Proceedings of the Royal Society of London, 1972.
3. R.D. Venter, A.A. Abd-Rabbo, Modelling of the Rolling Process, Int. J. Mech. Sci., 22, 1980, 83-92.
4. M. Horihata, M. Motomura, Theoretical Analysis of 3-roll Rolling Process by the Energy Method, Transactions ISIJ, 28, 1988, 434-439.
5. P.J. Mauk, Analysis of interacting influence parameters on the tolerances of wire rod and bars in the rolling process, 6thICTP International Conference on Technology of Plasticity, Nuernberg-Erlangen, Germany, 1999, 1529-1536.
6. H.Dyja, A.M.Sałganik, A.M.Pesin, A.Kawałek, Asymetryczne walcowanie blachcienkich Teoria, technologia i nowerozwiązania, Wydawnictwo Politechniki Częstochowskiej, Seria Monografienr 137, 2008.
7. O. Krivtsova, A. Viventsov, V. Talmazan, E. Panin, A. Arbuz, Study of deformation's indexes of rolls of different designs, Applied Mechanics and Materials, 378, 2013, 394-396.
8. V.L. Kolmogorov, Mechanics of metal processing under pressure, Ekaterinburg, Ural State Technical University - UPI, 2001, (in Russian).
9. A.A. Bogatov, The mechanical properties of the metal and the fracture model, Ekaterinburg, Ural State Technical University - UPI, 2002, (in Russian).
10. E.A. Garber, I.A. Kozhevnikov, Theory of rolling: a textbook for students, M., Teplotekhnik, 2013, (in Russian).
11. A.P. Grudev, Theory of rolling, M., Metallurgy, 1988, (in Russian).
12. A.I. Tselikov, G.S. Nikitin, S.E. Rokotyan, Theory of longitudinal rolling, M., Metallurgy, 1980, (in Russian).
13. P.I. Poluhin, G.Ya. Gun, A.M. Galkin, Resistance of the plastic deformation of metals and alloys: refer-