Journal of Achievements in Materials and Manufacturing Engineering
Volume 66 • Issue 1 • September 2014
International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

FEM-simulation of plate rolling process, analysis of inhomogeneous deformation and indexes of stress state in the deformation zone

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Received 28.06.2014; published in revised form 01.09.2014

ABSTRACT

Purpose: This paper contains a comparative analysis of the computer simulation results and calculation results on engineering techniques used to estimate the parameters of the stress-strain state, as well as the efficiency of FEM plate rolling process modelling application.

Design/methodology/approach: Development of a computer model of the rolling process was carried out considering assortment of produced steel and technological capabilities of the plate rolling mill 5000 JSC „MMK" equipment.

Findings: Analysis of the stress state in DEFORM-3D software showed that FEM-simulation of plate rolling does not give reliable data on the index of the stress state because they do not satisfy the boundary conditions at the input and output of the deformation zone.

Research limitations/implications: Use of DEFORM-3D and Q-FORM software packages allowed to reveal patterns of inhomogeneous deformation change, stress state index, the velocity field on the geometric parameters and modes of deformation zone rolling. As a criterion of deformation inhomogeneity in the deformation area a coefficient of variation is used, which is convenient for analysis and forecasting quality of the structure during rolling.

Originality/value: The work contains comparative analysis of the data received on the extent of the backward and forward slip zones, as well as according to the nature of the inhomogeneity of stressed and strained state while sheet rolling.

Keywords: Math modelling; Hot-rolled plate; Stressed and strained states; Strained state parameters; Degree of shear deformation

Reference to this paper should be given in the following way:

A. Bogatov, D. Nukhov, K. Pyankov, FEM-simulation of plate rolling process, analysis of inhomogeneous deformation and indexes of stress state in the deformation zone, Journal of Achievements in Materials and Manufacturing Engineering 66/1 (2014) 31-38.

ANALYSIS AND MODELLING

1. Introduction

There are the results of calculations of the deformation zone geometry and kinematics of the plate rolling process, obtained via the software complexes of DEFORM-3D and Q-FORM. The work contains comparative analysis of the data received on the extent of the backward and forward slip zones, as well as according to the nature of the inhomogeneity of stressed and strained state while sheet rolling. As the criteria of the strain discontinuity in the working zone it is used the coefficient of variation S/Λ_{mean} where Λ_{mean} – is the mean value of the deformation level of the shear deformation on the strip height, and S – is the mean square deviation. The state of stress was evaluated in accordance with the index of the stress state of mean square deviation $\frac{\sigma}{T}$. The development of a mathematical model of the technologicalprocess of rolling was carried out taking into account the mix of the produced steel and technological capabilities of the equipment of the plate rolling mill 5000 OJSC "MMK".

2. Analysis of deformation discontinuity at plate rolling at programs of DEFORM-3D and Q-FORM

Analysis is performed using DEFORM-3D and Q-FORM software for rolling of the first (initial strip thickness h^1_0 = 300 mm), the thirteenth (initial strip thickness h^2_0 = 67.4 mm) and the twenty-first (initial strip thickness h^3_0 = 30.5 mm) passes the table rolling mill 5000 OJSC "MMK". St45 steel was chosen as the work piece material. This steel is applicable for the simulation of hot deformation process at temperatures of 900-1200°C. The results of calculations of the deformation zone size, the position of the neutral plane, the degree of shear strain for nine particles having different altitude coordinate $0 \leq \frac{2y}{h_0} \leq 1$, were compared inprogramswith similar characteristics, obtained with formulas well-known in the theory of plate rolling [1-3]. The degree of shear strain, defined by a finite change of the sheet size was calculated according to the formula $\Lambda_0 = 2\sqrt{\bar{\varepsilon}_2{}^2 + \bar{\varepsilon}_2 \cdot \bar{\varepsilon}_3 + \bar{\varepsilon}_3{}^2}$, where $\bar{\varepsilon}_2 = ln\frac{b_1}{b_0}; \bar{\varepsilon}_3 = ln\frac{h_1}{h_0}$. If there is no broadening, then $\Lambda_0 = 2ln\frac{h_0}{h_1}$.

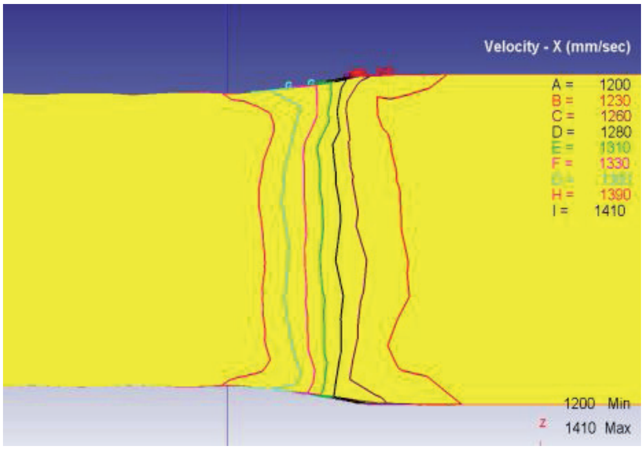

Fig. 1. Distribution of contour lines of axial velocity component of metal

Velocity field, determined by the program of DEFORM-3D, represented by contour lines in Figure 1 do not support the hypothesis of plane sections. It is seen that in the contact region under the influence of the frictional constraint the gradient of axial velocity component of the particles is smaller than for the central region of the deformation zone. To evaluate the no uniformity of deformation on the sheet height the calculation of the cumulative degree of particles shear deformation was performed on nine trajectories: P1 – trajectory of a particle along the contact with the roll (*z=h/2*); P9 – trajectory of a particle on the symmetry plane (*z=0*) (Fig. 2). Mean shear strain level on the height is $\Lambda_{mean} = \frac{1}{n}\sum_{i=1}^{n}\Lambda_i$, i – number of the particle trajectory, n =8.5. Non-uniformity of deformation on height of the sheet can be estimated using the coefficient of variation S/Λ_{mean}, where $S = \left[\frac{1}{n-1}\sum_{i-1}^{n}(\Lambda_i - \Lambda_{mean})^2\right]^{1/2}$ – mean square deviation. The calculation results for the three above mentioned rolling passes are shown in the Table 1 and Figures 3a,b. Note that for the thirteenth passage the calculations were performed for three different friction conditions ψ = 0.6; 0.7; 0.8, and for the first and twenty-first passes – ψ=0.8, where ψ – is Zybel friction factor. The table shows that the calculation of the parameters of the deformation zone: length *l,* relative length l/h_{mean} entering angle α and angle of neutral plane γ_n, via programs of DEFORM-3D and Q-FORM produces the same result with the calculation according to the known formulas in the theory of rolling. Relative broadening of the work piece, found via the program of DEFORM-3D and Q-FORM, in the first pass is $\frac{\Delta b}{b_0} \cdot 100 = 0.87\%$ and 0.89%, in the thirteenth it is – 0.13% and 0.11%, and in twenty first it is –0.05% and 0.07%. Thus in engineering calculations the broadening of the sheet during rolling can be neglected.

Figure 3a,b shows the calculations of the cumulative degree of shear stain Λ for nine particle trajectories, and Fig. 4a,b shows values – of the variation coefficient S/Λ_{mean}, which characterizes the non-uniformity of the shear deformation level on height.

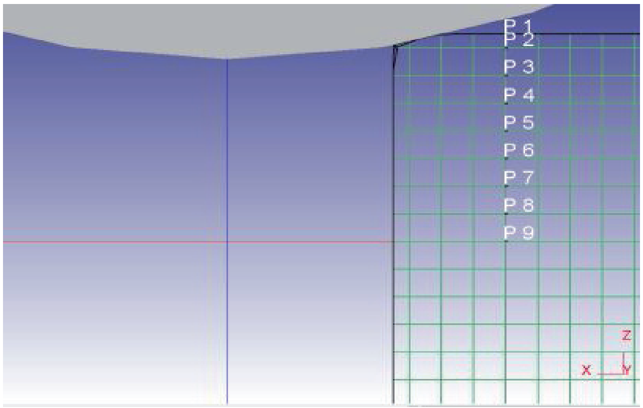

Fig. 2. Positions of sections in nine trajectories

Table 1.
The results of mathematical modelling

Pass №	Calculation method	$D_в$, mm	n, rev/min	Δhi, mm	ψ	T,°C	l, mm	l/h_{mean}	b_0, mm	b_1, mm	Δb, mm	α,°	γ,°	$l_{оп}$, mm	Λ_{mean}
	DEFORM-3D	1110	23.7	36	0.8	1172	139.90	0.49	2700	2723.46	23.46	14.61	5.65	54.41	0.320
1	Q-FORM	1110	23.7	36	0.8	1172	143.15	0.54	2700	2724.07	24.07	15.10	4.26	40.85	0.310
	Rolling theory	1110	23.7	36	0.8	1172	140.71	0.49	2700	2706.33	6.33	14.66	5.94	50.67	0.256
13	DEFORM-3D	1110	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	1110	63.1	6.5	0.8	890	65.62	0.94	4490	4494.83	4.83	6.85	1.83	20.61	0.226
	Rolling theory	1110	63.1	6.5	0.8	890	59.79	0.93	4490	4492.64	2.64	6.23	2.86	27.51	0.203
21	DEFORM-3D	1110	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	1110	96.2	2.8	0.8	868	43.02	1.48	4490	4493.3	3.3	1.48	2.21	21.79	0.225
	Rolling theory	1110	96.2	2.8	0.8	868	39.24	1.35	4490	4491.61	1.61	4.08	1.94	18.79	0.193
13	DEFORM-3D	1110	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	1110	63.1	6.5	0.7	890	64.7	1.01	4490	4494.24	4.24	6.76	1.90	21.84	0.227
	Rolling theory	1110	63.1	6.5	0.7	890	59.79	0.93	4490	4492.59	2.59	6.23	2.84	27.26	0.203
13	DEFORM-3D	1100	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	1100	63.1	6.5	0.6	890	65.23	1.02	4490	4493.95	3.95	6.81	2.15	23.67	0.233
	Rolling theory	1110	63.1	6.5	0.6	890	59.79	0.93	4490	4492.53	2.53	6.23	2.79	26.85	0.203

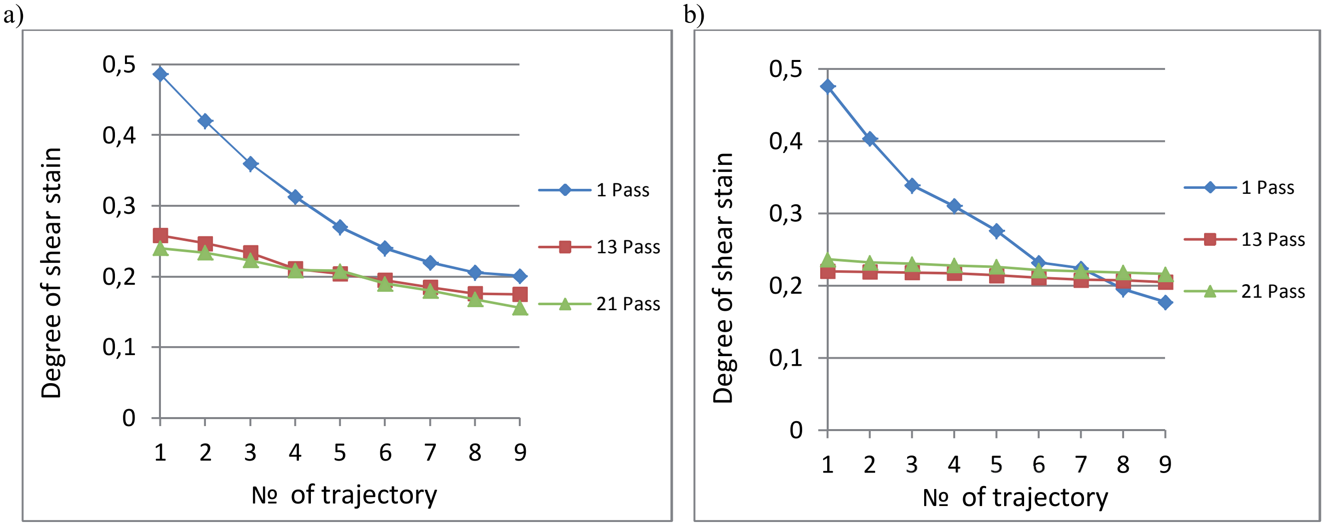

Fig. 3. Graphs of the distribution the degree of shear strain according to the programs DEFORM-3D (a) and Q-FORM (b)

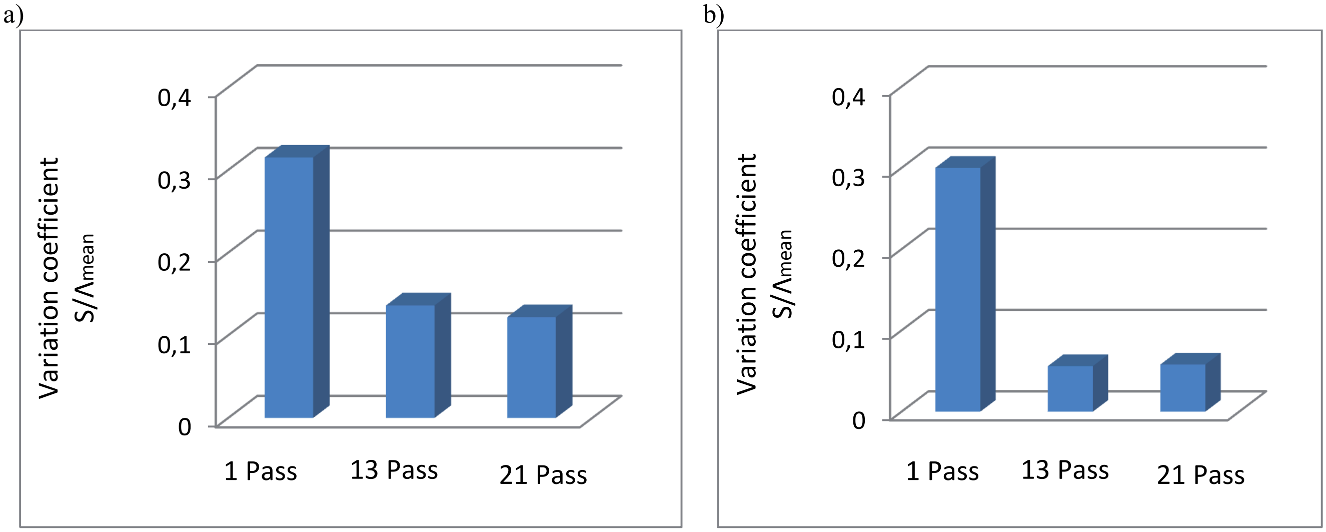

Fig. 4. Variation coefficient S/Λ_{mean} for three passes according to programs DEFORM-3D (a) and Q FORM (b)

According to the graph in Figure 3 we see that for the first pass (l/h_{mean}≈0.5) the cumulative degree of shear stain is 2.5 times greater at contact with the roll than in the plane of symmetry. The coefficient of variation, calculated by the programs DEFORM-3D and Q-FORM, is S/Λ_{mean}= 0.315 and 0.3. These values indicate a considerable discontinuity of strainacross the whole section of the strip. For the eleventh (l/h_{mean}≈0.9) and twenty first (l/h_{mean}≈1.35-1.48) passes the cumulative degree of shear stain the contact region and in the axial zone differ for about 1.10-1.5 times, and the coefficient of variation is 0.13 and 0.12 according to DEFORM-3D and 0.06 for both passes according to Q-FORM. Comparison of the results of the calculation of mean value of the shear strain on height Λ_{mean}, executed according to programs DEFORM-3D and Q-FORM and by formula $\Lambda_0 = 2ln\frac{h_0}{h_1}$, suggests that the assumption of a monotonic nature of strain gives low results.

3. Assessment of the stress state in the deformation zone when plate rolling

The next stage of the study was the evaluation of the state of stress in the deformation zone during rolling of the sheet for three passes: first, thirteenth and twenty-first; for the thirteenth pass it was studied the process with the friction factors ψ = 0.8; 0.7 and 0.6. According to the theory of rolling at a drafting of the sheet the planar sheet deformed state is realized, wherein$\sigma_{xy} = \sigma_{yz} = 0$, $\sigma_{yy} - \sigma = 0$. Since the mean normal stress is $\sigma = (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/3$, то $\sigma_{yy} = (\sigma_{xx} + \sigma_{zz})/2 = \sigma$. For the plane deformedstatethe yield criterion has the form of $\sigma_{11} - \sigma_{33} = 1.15\sigma_s = 2\tau_s$. Applying the engineering method, the following assumptions were used: $\sigma_{xx} = \sigma_{11}$ and $\sigma_{zz} = \sigma_{33} = -p$, where $p -$ normal contact stress [4]. Contact stress was determined by the known formulas [3]:

for backward slip zone

$$p = \frac{2\tau_s}{\mu} \cdot tg\alpha/2 \cdot \left[(\delta - 1)(\frac{h_0}{h_x})^{\delta} + 1\right]; \quad (1)$$

for forward slip zone

$$p = \frac{2\tau_s}{\mu} \cdot tg\alpha/2 \cdot \left[(\delta + 1)(\frac{h_x}{h_1})^{\delta} - 1\right], \quad (2)$$

where μ – is a friction coefficient; $\delta = \frac{\mu}{tg\alpha/2}$; h_0, h_1 and $h_x -$ initial, final, and the current value of the thickness of the rolled strip. Applying the perfect yield criterion $T = \tau_s$, the factor of the stress state is defined by the formula $\frac{\sigma}{T} = -\frac{p}{\tau_s} + 1$. Calculated by the formula (1) and (2) the contact stress factor, indicators of the state of stress of the metal were determined for eleven sections along the deformation zone, depending on the parameter of $\frac{x}{l}$. The results of the calculation are shown in the graph (Fig. 5). Strain resistance σ_s is found via the hardening curves [5], taking into account the temperature and speed conditions for different rolling passes (see. Table 1).

Calculations showed that the index of the stress state has the minimum value in the neutral section and depends on the number of passes and the coefficient of friction; for the last pass it is $-\frac{\sigma}{T} = -2.71$ and it is maximum for the first pass $-\frac{\sigma}{T} = -1.4$. With a decrease of the index of friction in the thirteenth passage a slight increase in the stress state occurs (from -2.11 to -1.91).

FEM problems solution –that is the process of modelling 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 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 Figure 6 and Figure 7. 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 and have the values from 0.01 to 0.09, do not contradict the theory – when sheet rolling there is the plane strain ($\mu_\sigma = 0$).

a) b)

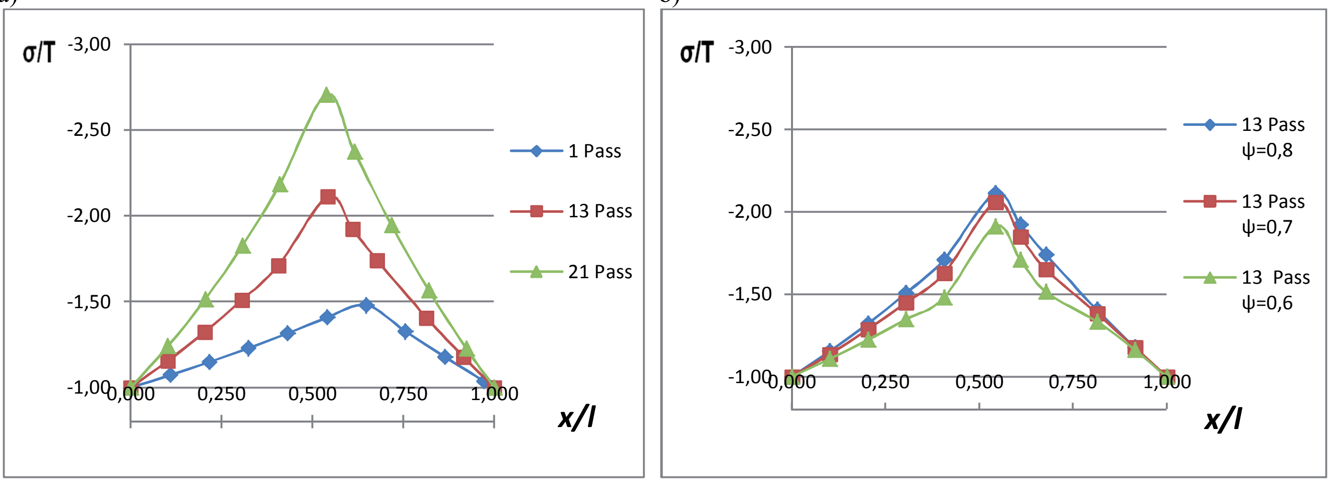

Fig. 5. Distribution of indices of stress state *σ/T* along the deformation zone *x/l* (a)for three rolling passes and for one pass with different rates of friction (b)

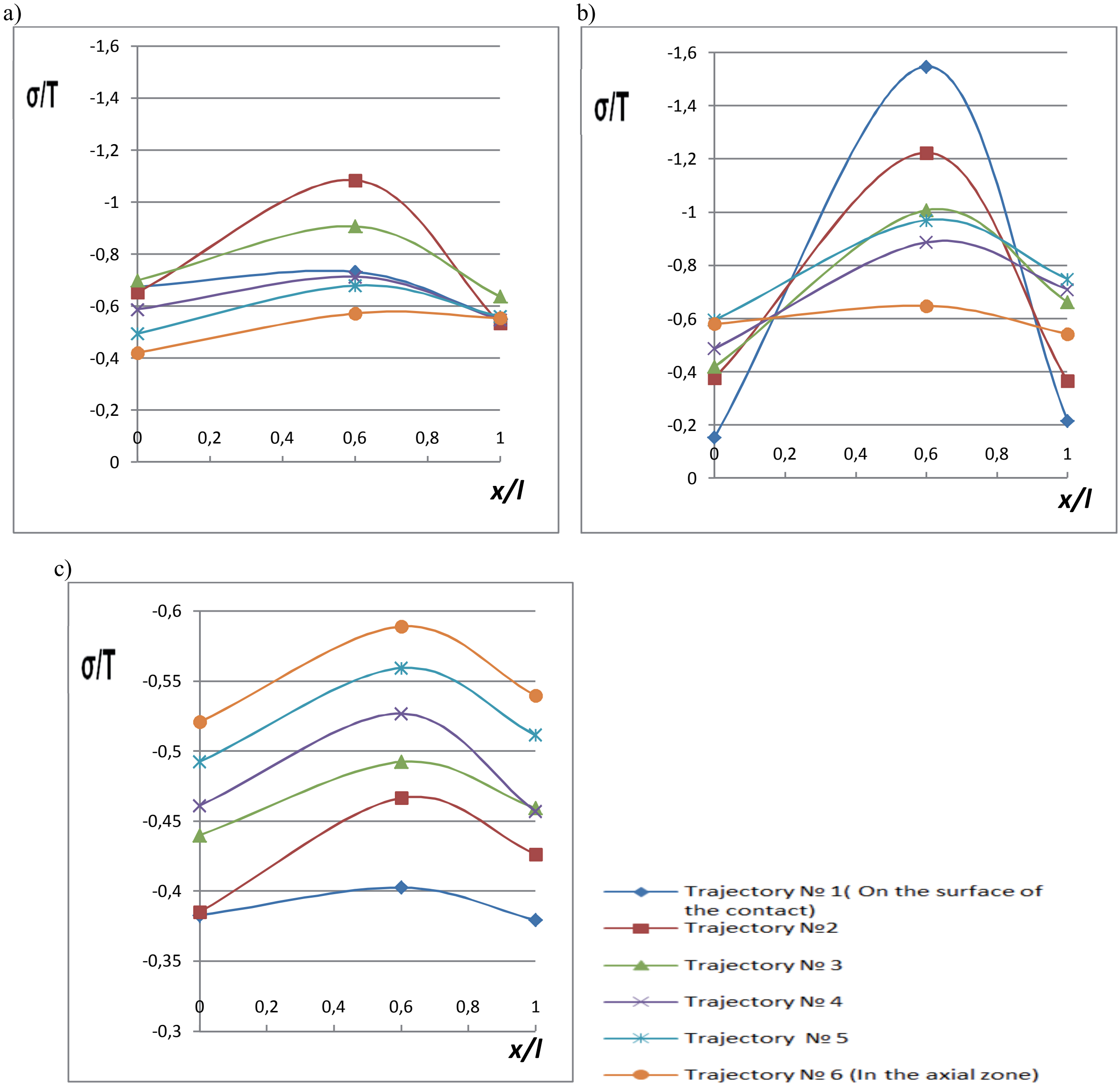

Fig. 6. Indicator of stress state σ/T along the deformation zone x/l for three rolling passes when $\psi = 0.8$ according to DEFORM-3D: a – first pass; b – thirteenth pass; c – twenty first pass

The obtained results of the task solutions, performed in the program of DEFORM-3D, do not satisfy the boundary conditions when the sheet rolling (Figs. 6 and 7).

4. Conclusions

Thanks to the study of plate rolling process with the help of modern software systems of mathematical modelling the size of the deformation zone and the velocity field during rolling were calculated. These data do not contradict the results of the calculation according to the known formulas of the theory of rolling. The new result is the development of a criterion of discontinuity of the deformation in the form of the coefficient of variation S/Λ_{mean}. The values of the coefficient of variation of more than 0.3 indicates that, due to the significant deformation discontinuity on the section of the cast billet, which results in unsatisfactory working of the cast structure.

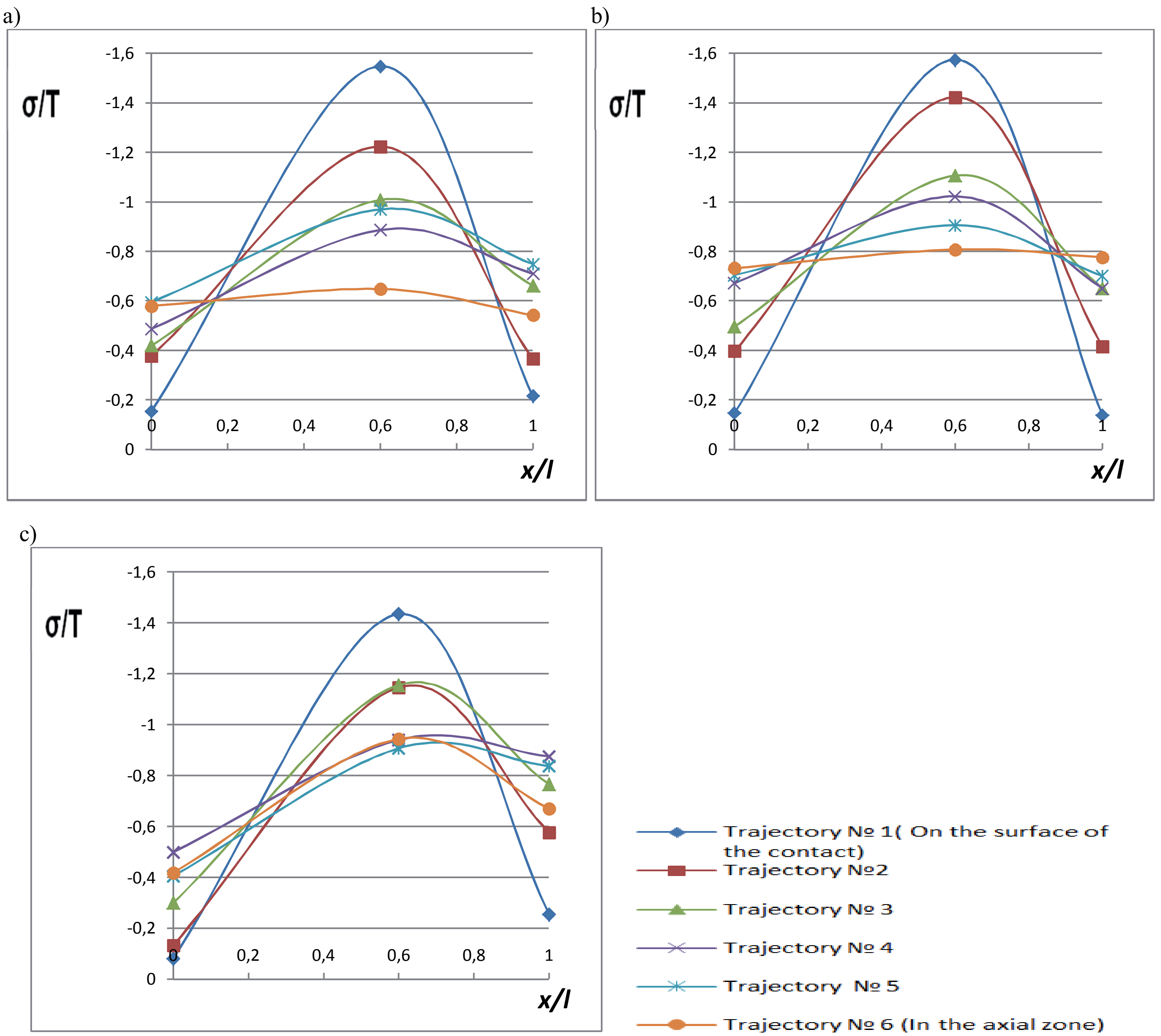

Fig. 7. Indicator of stress state *σ/T* along the deformation zone *x/l* for three rolling passes when ψ = 0.8 according to DEFORM-3D when friction factors are: a – ψ = 0.8; b – ψ = 0.7; c – ψ = 0.6

Modern programs of FEM – modelling 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 the insufficient work out of structure compared to the contact area. Stress state analysis, made in the program of DEFORM-3D, showed that FEM-simulation of plate rolling does not provide the reliable data on the index of the state of stress, as the boundary conditions at the input and output of the deformation zone are not satisfied.

Acknowledgements

This work was done in the framework of the "Young Scientists".

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