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Simulation of metal forming during multi-pass rolling of shape bars

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Abstract

In this paper, the mathematical model of the multi-pass rolling is proposed. The problem of non-isothermal metal forming during multi-pass rolling in grooved rolls had been solved with using of the finite-element method. As example the computer modeling results of the angle steel 150 mm × 100 mm during rolling for 6th passes are discussed. To take into account the changes of plastic properties of the rolled metal during its deformation in a roll gap as well as in the time between passes the rheological model have been developed on the base of the dislocation theory of plastic deformation.

Keywords: Multi-pass rolling; Dislocation; Finite-element method; Rheological model

1. Introduction

Performing the analysis of the hot shape rolling process with the use of the finite-element method is a complicated task, because the process is not always carried out in all consecutive passes. In most simulation studies using the finite-element method during rolling in the three-dimensional strain state successive passes are considered separately [1–3]. To eliminate the accumulation of error resulting from successive passes, it is necessary to apply such mathematical models to multi-pass rolling, which will be of higher accuracy compared to the models used for single-pass rolling. Problems that arise when attempting to apply a model to the multi-pass rolling technology—from the first pass to the last pass, can be divided into the two following groups:

1. Solving algorithmic problems associated with rebuilding the finite-element grid, transferring metal properties from one pass to another, computation automation and result analysis.
2. Recording the principal deformation non-monotony, the processes of strain hardening and removal effects of hardening in each point of the metal volume during deformation in passes and in breaks between them.

There are a number of studies on this subject in the world. Attention should be given to one of the first publications [4], which describes the results of the simulation of multi-pass rolling of shapes by using the finite-element method. In that and several other studies, most of consideration is given to the algorithmic component of the problem. In subsequent studies, attempts were made to take advantage of the latest achievements of the physics of metals, including the theory of dislocation, for recording the processes of strain hardening and removal effects of hardening during multi-pass rolling [5,6]. The authors of those studies analyzed sheet and shape rolling processes. The above-mentioned and other studies have proved that dislocation equations can be used for solving the problem of the rheological properties of metal during non-monotonic hot deformation. On the other hand, there is an opinion [7] of the possibility of applying the dislocation equation in the case of strain rate other than zero. However, relevant data collected so far suggest that satisfactorily good results can already be obtained at low strain rates (in the order of $0.005\,s^{-1}$) [8].

Thus, the presently available studies provide premises for solving the problem raised in this study—developing a mathematical model for multi-pass shape rolling, considering the processes of strain hardening and removal effects of hardening occurring in the rolled band. For this purpose, the equations of the theory of dislocation will be used. Breaks between successive passes are considered as a special case of deformation non-monotony, and the properties of material between passes and during deformation are described by the same equations. The effect of the presented rheological model on the results of the modeling of three-dimensional forming during rolling has also been analyzed in the study.

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A basis for solving this problem is the model of metal deformation in the passes, implemented in the form of the SortRoll computer program [9] relying on the finite-element method.

2. Mathematical model of metal deformation during rolling

References [10–12] describe developing and testing of a mathematical model for the solution of the three-dimensional problem of metal deformation determination during rolling in passes by using the finite-element method. To obtain the solution, the theory of the non-isothermal plastic flow of an incompressible non-linearly viscous medium must be applied.

Boundary conditions are taken into account by using the method proposed in reference [11]. The idea o the method involves the use of penalty function for taking into account the conditions of interaction of the metal with the tool in a complex spatial configuration. Solution should be sough for from the stationary condition of the modified Markov functional:

$$J=\frac{1}{2}\int_V \mu\dot{\varepsilon}_i^2\,\mathrm{d}V+\int_V \sigma\dot{\varepsilon}_0\,\mathrm{d}V+K_\tau\int_F (V_\tau)^2\,\mathrm{d}F + K_n\int_F (V_n-W_n)^2\,\mathrm{d}F, \quad (1)$$

where

$$K_\tau^{(p)}=\frac{\tau^{(p-1)}}{V_\tau^{(p-1)}}, \quad (2)$$

$$\mu^{(p)}=\frac{2\sigma_s^{(p-1)}}{\sqrt{3}\dot{\varepsilon}_i^{(p-1)}}, \quad (3)$$

p is the number of current iteration; V_τ the overall velocity of metal slip over the tool surface; V_n the normal metal velocity; W_n the projection of the velocity of point lying on the surface of contact with the normal; τ the friction stress (in the considered case, the law of $\tau = m\sigma_s$ was adopted; m the friction factor); σ_s the material yield stress as a function of the parameters of metal deformation in a given point; σ the mean stress; $\dot{\varepsilon}_i$ the strain rate intensity; $\dot{\varepsilon}_0$ the strain rate in triaxial compression; K_τ the penalty coefficient for the velocity of metal slip on the tool surface (accurately computed from formula (2) by the iteration method); K_n the penalty coefficient on metal penetration into the tool; μ the apparent metal viscosity is computed from formula (3) by the method of hydrodynamic approximation.

If the penalty constant K_τ is increased, the slip of metal over the contact surface will be hampered. When $K_\tau = 0$, then we have a frictionless variant of deformation.

In the discrete formulation of the surface integrals in Eq. (1), the following relationships vary:

$$K_\tau\int_F (V_\tau)^2\,\mathrm{d}F=K_\tau\sum_{i=1}^{N_{pov}}V_\tau^2F_i, \quad (4)$$

$$K_n\int_F (V_n-W_n)^2\,\mathrm{d}F=K_n\sum_{i=1}^{N_{pov}}(V_{ni}-W_{ni})^2F_i, \quad (5)$$

where N_{pov} is the number of grid nodes in contact with the tool; F_i the metal–tool contact surface area per ith node.

3. Description of the rheological model based on the theory of dislocation

Presently available studies on the theory of dislocation enable one to use a number of assumptions underlying this theory as a basis for the calculation of yield stress during rolling. The basics of the approach taken in the present study were originated in the studies of Taylor [13], who formulated in 1934 the first special theory of hardening. The main concept of Taylor's theory supposes that the yield stress depends on internal stresses disturbing the movement of dislocations. Without going into details, it should be noticed that Taylor obtains the following dependence of yield stress on dislocation density:

$$\sigma_s=\alpha Gb\sqrt{\rho}, \quad (6)$$

where G is the shear modulus; α the factor accounting for the interaction of dislocations (according to Taylor, it is equal to 0.1); b the Burgers vector (its value is in the order of 10^{-8} s m); ρ the dislocation density, s m^{-2}.

As follows from formula (6), the yield stress depends directly on the current value of dislocation density. This value can be determined from one of the known models of dislocations generation. A more detailed description of some existing models of dislocation generation during hot deformation is given in references [7,14]. Putting aside other models, we will focus on the approach adopted in reference [14], which, in our view, has the best grounds, and is based on the following equation:

$$\frac{\mathrm{d}\rho}{\mathrm{d}\tau}=\frac{u}{bl}-k_2\rho(\tau)-\frac{A_3}{D}\rho(\tau)r\left[\rho(\tau)-\rho_{cr}\right], \quad (7)$$

where u is the strain rate; l the mean length of the free propagation of dislocations, which, for large deformations is determined from the formula of $l = A_0Z^{A_1}$ (for small deformations, we have $l = A_2\rho^{-0.5}$); A_3 the coefficient of grain boundary mobility:

$$A_3=A_{30}\exp\left(\frac{Q_m}{R(t+273)}\right), \quad (8)$$

Q_m is the activation energy of grain boundary motion; R the universal gas constant; t the temperature in a given point of the metal; Z the Zener–Hollomon parameter:

$$Z = u \exp\left(\frac{Q_{\mathrm{def}}}{R(t+273)}\right), \tag{9}$$

Q_{def} is the activation energy of the plastic deformation process; k_2 the self-diffusion coefficient:

$$k_2 = k_{20} \exp\left(\frac{Q_{\mathrm{s}}}{R(t+273)}\right), \tag{10}$$

Q_{s} is the activation energy of self-diffusion; ρ_{cr} the critical dislocation density, above which dynamic recrystallization processes begin to apply; r the function is equal to zero, when $\rho < \rho_{\mathrm{cr}}$ otherwise, it is equal to $\rho - \rho_{\mathrm{cr}}$; D the grain diameter; A_0, A_1, A_{30}, A_2, k_{20} the empirical material coefficients.

The analysis of this model, partially performed in work [8], shows that the process of choosing the coefficients in formulae (7)–(10) is made very difficult because of the introduction of the discontinuous function r to Eq. (7). However, the introduction of this function means the simplification of the dislocation generation model proposed originally by Sandstrom and Lagneborg in publication [15], where the discontinuous function is not used. On the other hand, the analysis of Eqs. (8) and (10) shows that as the temperature increases, the value of coefficients A_3 and k_3 in Eq. (7), responsible for the removal of hardening effects, decreases. This is contrary to the physical sense of the removal hardening effect, which accelerates with increasing temperature.

These and other shortcomings of the existing models of dislocation generation have led to developing a new model which is better adjusted to the identification procedures of this model. We will write the proposed model in the following form easy for identification:

$$\frac{\mathrm{d}\rho}{\mathrm{d}\tau} = C_1 u - C_2 \rho^2, \tag{11}$$

$$\sigma_{\mathrm{s}} = \left(C_3 + C_4\sqrt{\rho}\right) \exp\left(\frac{K_t}{\bar{t}}\right), \tag{12}$$

$$K_t = 0.333 \times 10^{-2} K_{t\,1100}(t - 900), \tag{13}$$

where C_1 is the empirical model coefficients; $\bar{t}$ the convergent temperature (ratio of point temperature t to the solidus temperature of a given alloy); K_t the temperature coefficient; $K_{t\,1100}$ the temperature coefficient at a temperature of 1100 °C.

Solving of Eq. (11), in the case of identification and during its subsequent use, is done by the Adams numerical method. The identification procedure for a similar model is described in a greater detail in reference [8].

To perform further comparative analysis of both rheological models and corresponding results of the computation of band flow in passes, the approximation of plastometric examination was made according to the following formula:

$$\sigma_{\mathrm{s}} = a_1 \varepsilon^{a_2} \exp(a_3 \varepsilon) u^{a_4} \exp(a_5 t), \tag{14}$$

where a_1–a_5 are the empirical coefficients.

Table 1
Chemical composition of the St3S carbon steel (%)

C	0.10
Mn	0.50
Si	0.21
P	0.014
S	0.027
Cr	0.10
N	0.10
Cu	0.24

4. Experimental investigation of yield stress and the identification of the rheological model

St3S steel, whose chemical composition is given in Table 1, was used in the tests.

For the determination of particular coefficients occurring in Eqs. (11)–(13), the results of the plastometric examinations of St3S steel, performed on a plastometer–dilatometer, type DIL 805 A/D, manufactured by BAHR Thermoanalyse GmbH Company was used. These examinations were carried out in a temperature range of 800–1100 °C, and at a deformation rate of 0.001–10 s^{-1}. As a result of model identification, the following coefficients of Eqs. (11)–(13) were obtained:

$$C_1 = 65985.22, \quad C_2 = 0.001571648,$$
$$C_3 = 18.51890, \quad C_4 = 1.762224,$$
$$K_{t\,1100} = -0.587.$$

Based on the same experimental data, approximation with Eq. (14) yielded the following values of coefficients a:

$$a_1 = 11499.2, \quad a_2 = 0.408167,$$
$$a_3 = -1.02130, \quad a_4 = 0.123986,$$
$$a_5 = -0.00378090.$$

Fig. 1 shows experimental work-hardening curves and curves computed according to the model from Eqs. (11)–(14).

In order to verify the operation capability of the rheological model in the presence of breaks between deformations, the following experimental tests were carried out. A standard specimen ($h = 10$ mm, Ø5 mm) was upset on a plastometer at a deformation rate of 3 s^{-1} up to a deformation of 0.3. Then the process was discontinued, and after a break of 0.4 s the specimen was upset again to reach a total deformation of 0.6. The tests were conducted at 900 °C.

Fig. 2 shows the results of experimental tests in stress–strain coordinates in successive stages of deformation.

The results of yield stress computation for conditions corresponding to the tests with two-stage deformation are shown in Fig. 3 (in stress–time coordinates) and in Fig. 4 (in stress–strain coordinates).

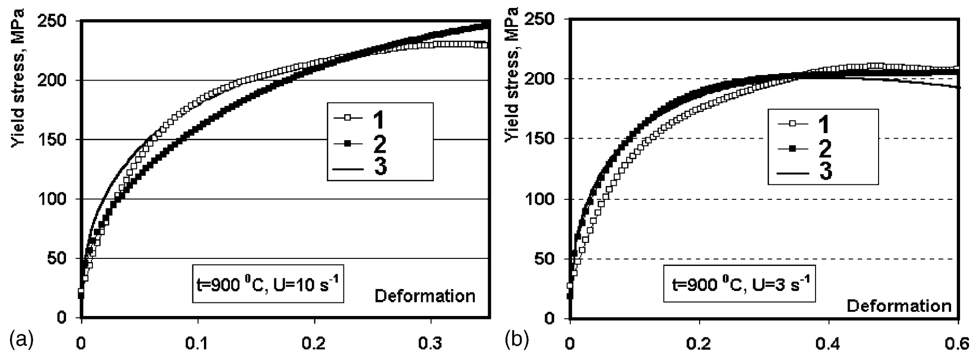

Fig. 1. Results of plastometric test (curve 1), computations according to dislocation model (curve 2) and on the statistical model (curve 3) at a temperature of 900 °C: (a) $u = 10\,s^{-1}$; (b) $u = 3\,s^{-1}$.

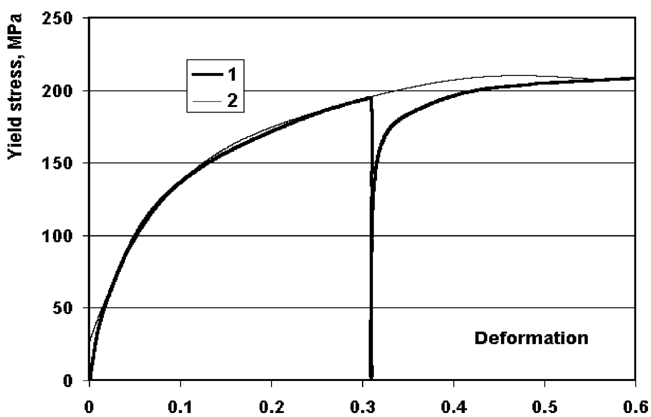

Fig. 2. Results of experimental tests with two-stage specimen deformation at a temperature of 900 °C and a strain rate of $3\,s^{-1}$: (1) two-stage deformation; (2) continuous deformation.

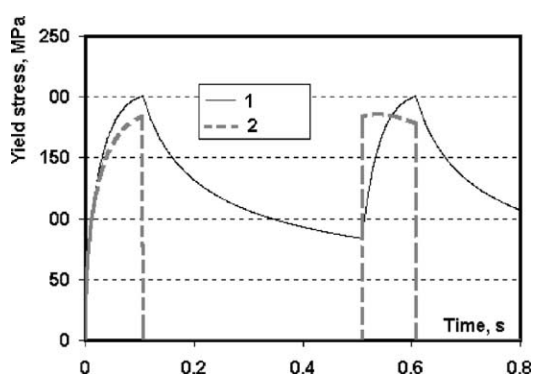

Fig. 3. Results of the computation of yield stress variation in time during two-stage deformation: (1) according to the model based on the theory of dislocation; (2) according to the statistical equation (14).

It should be emphasized that the error of yield stress modeling with breaks between passes, according to the dislocation model, is fairly large (Figs. 2 and 4). However, even with not quite good accuracy, the dislocation rheological model is much better compared to conventional statistical models, such as the one corresponding to Eq. (14). The problem of increasing the accuracy of the rheological model relying of the theory of dislocation will be the subject of further studies by the authors.

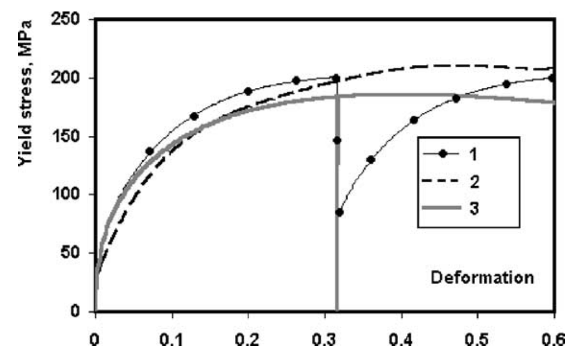

Fig. 4. Results of the computation of yield stress variation as a function of deformation during two-stage (1) and continuous deformation (experimental test) at a deformation rate of $3\,s^{-1}$ (2); (3) results of computations according to Eq. (14).

5. Modeling of the three-dimensional deformation of the St3S steel during rolling in two passes

After introducing the developed rheological model to the three-dimensional model of rolling in passes, the experimental verification of the accuracy of the model of rolling in many passes and the comparison of the results of computation by using dislocation equations (11)–(13) and statistical model (14) was made. For this purpose, the results of the tests of rolling in two passes in the following conditions were used: a rolling speed of 0.5 m/s; an initial stock temperature 920 °C; and a break between passes of 1 s. The shape and dimensions of passes are shown in Fig. 5. The stock diameters

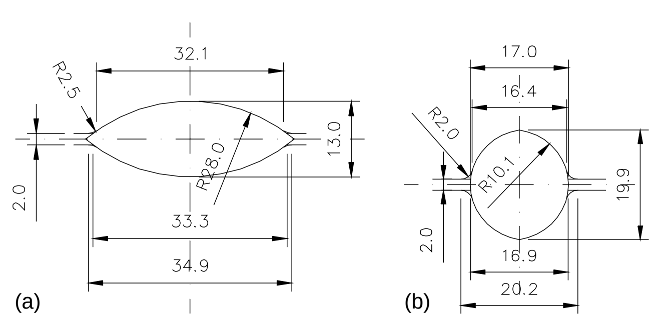

Fig. 5. Shape and dimensions of passes employed in the tests: (a) first pass; (b) second pass.

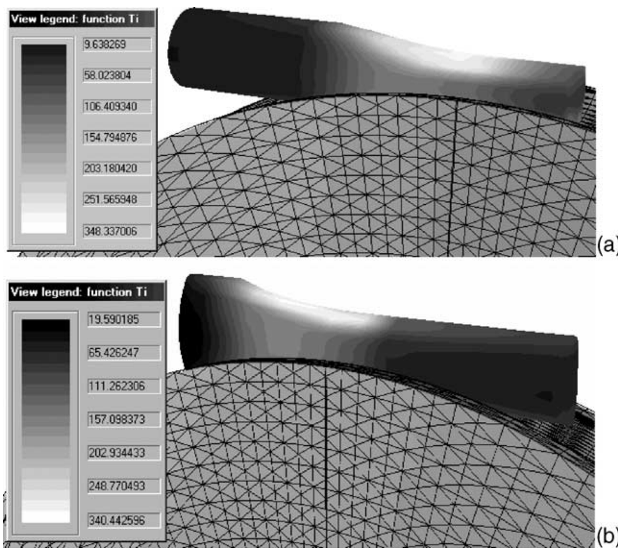

Fig. 6. Results of the computation of the yield stress in the first pass (a) and the second pass (b) with the use of the statistical model according to Eq. (14).

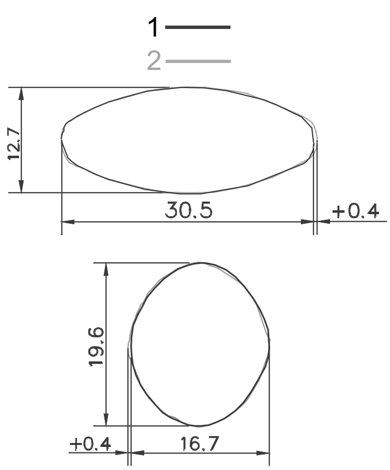

Fig. 7. Results of experimental tests (1) and MES simulation (2).

was 22 mm. The computation results are given in Fig. 6a and 6b. During modeling, the computation results from the first pass were used as input data for the second pass.

The results of the template taken after the first pass were not utilized in modeling. The comparison of cross-sections obtained from the tests with computed models is illustrated in Fig. 7. The results of the shapes and dimensions of the band cross-section allow one to state that the presented model can be used as a tool for the analysis of the process of rolling in stretching passes in many roll passes, because no significant error accumulation was found during two passes.

Fig. 8 shows the results of the computation of yield stress distribution on the cross-section in the plane of exit from the deformation region of the first rolling stand. The distribution corresponding to the dislocation model exhibits a significantly greater value of yield stress (13–60%) compared to the conventional model, as a result of inertia features that are specific for the dislocation model (Fig. 9). A change in rheological properties, in turn, leads to slight changes in the value of widening (0.3 mm) and lead. As the widening value is equal to 8.5 mm, the relative widening change does not exceed 3.5%. In the second pass, the relative widening change is already 19%. Besides, decreasing widening when using the dislocation model leads to a decrease in the difference between the measured and computed values of widening.

6. Simulation of the multi-pass angle bar rolling

In this section, computations were performed with the use of the developed model for a larger number of passes. For this purpose, data from the industrial tests of rolling 150 mm × 100 mm × 10 mm even-armed angle bar of St3S steel carried out on a D600 rolling mill in 6 passes were used. The initial stock temperature was 1100 °C, and the rolling speed was 2 m/s. The shape and dimensions of passes are shown in Fig. 10.

The results of the tests of rolling the angle bar and the computer simulation of the band on exit from the deformation region are shown in Fig. 11. When performing computations, simulation results in the form of band cross-sections from the first pass were supplied to the second pass, then second pass results were supplied to the third pass, an so on, up to the last pass. The test data on the shape of the band cross-section in successive passes were not used for computations. The analysis of the results has shown that, despite a satisfactory agreement between the results of computer simulations and experimental tests, in some cases the flow of metal cannot be predicted with the necessary accuracy. For

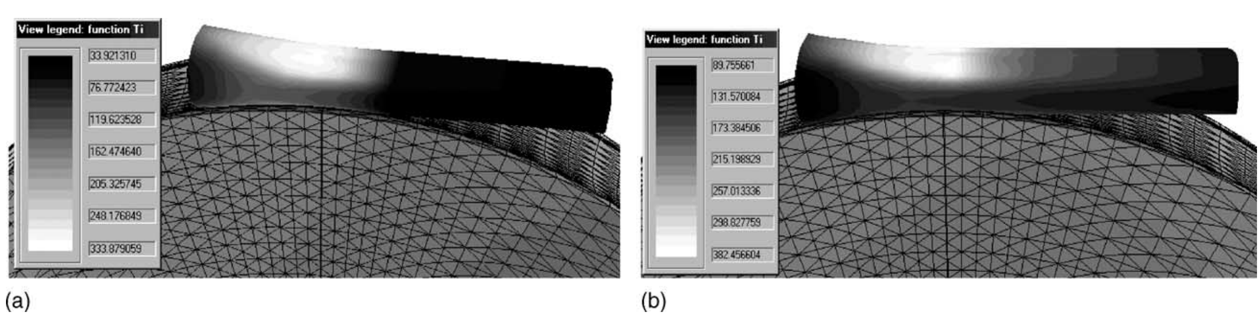

Fig. 8. Distribution of yield stress in the rolled band, determined from the statistical model (a) and the dislocation model (b).

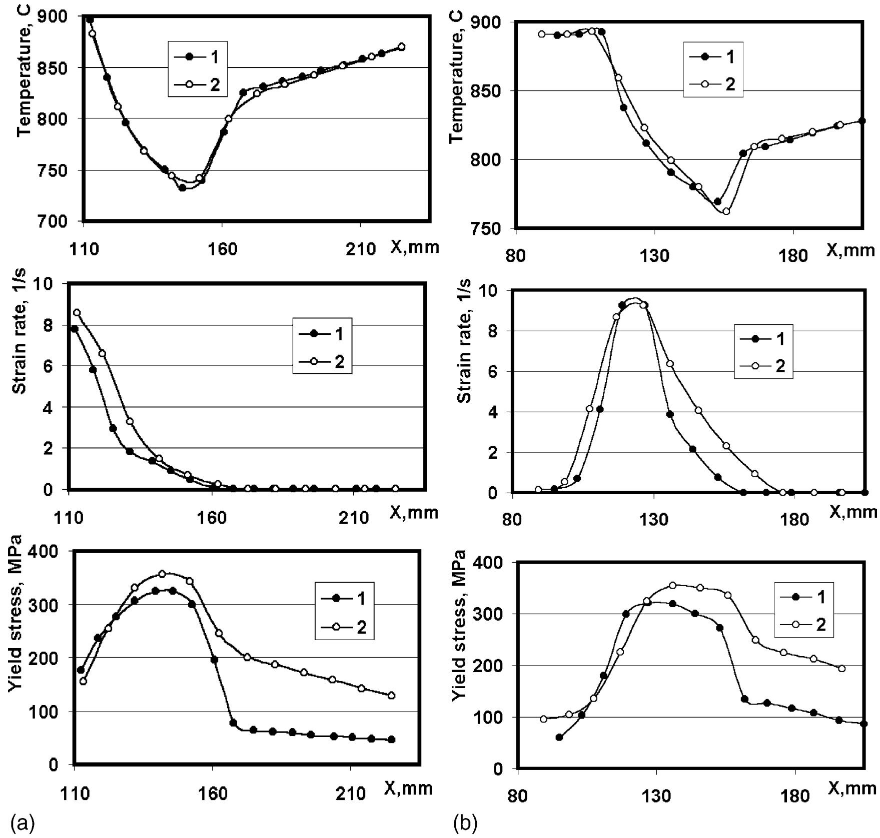

Fig. 9. Distribution of yield stress, strain rate and temperature in the rolled band, determined was used the statistical rheological model (curve 1) and the dislocation model (curve 2); during the first pass (a) and the second pass (b).

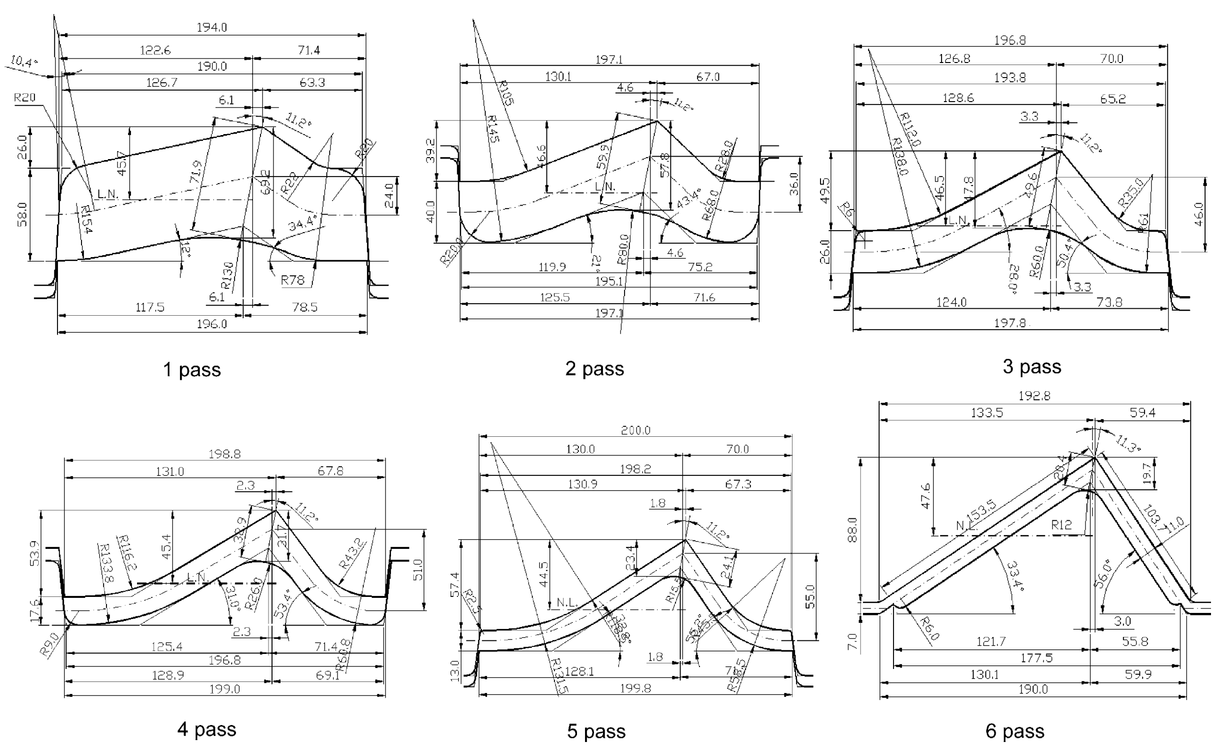

Fig. 10. Shape and dimensions of passes applied in the rolling of 1500 mm × 100 mm × 10 mm angle bar.

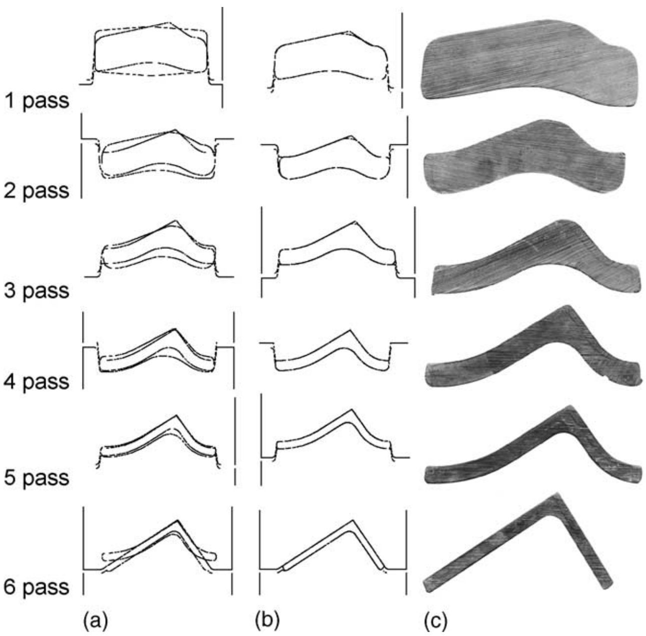

Fig. 11. Initial positioning of rolls and the stock (a); the results of numerical computations (b) and tests (c) of the process of rolling 150 mm × 100 mm × 10 mm angle bar.

example, the pass overfill in the third pass (Fig. 11) did not occur during computer simulations. It can be found from the computation results that most cases of pass fill (passes 1, 2, 4, 5) are correct.

7. Conclusions

The study has demonstrated that the equations of the theory of dislocation describing material behavior during complex deformation, after their appropriate modification, enable the modeling of both the deformation process and the times of pauses between particular passes.

The model of rheological properties, based on the theory of dislocation, was integrated with the finite-element-based SortRoll computer program serving for the computation of metal flow in passes in the triaxial state of strain, which allowed the creation of a multi-pass rolling model involving the removal of the effects of metal hardening in breaks between passes.

A general model of multi-pass rolling in passes was verified against industrial test results for the deformation of St3S steel during rolling even-armed angle bar in 6 passes.

On the basis of the comparison of band cross-sections after successive passes it can be stated that the developed mathematical model and the computer program can be applied to multi-pass rolling in industrial conditions.

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