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Numerical modelling of the metal flow and stock bending during the rolling of unequal angle bar

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Abstract

The rolling of angle bars in closed passes is essentially an asymmetrical process. Therefore, it is advisable to carry out computer simulations of this process in the aspect of stock bending after exit from the roll gap, which depend on the diameters of both rolls. This paper presents the possibility of using numerical modelling for aiding the design of the technology of rolling 150 mm × 100 mm × 10 mm unequal angle bar. For carrying out the simulation the computer programs FEM Forge3® and the authors program SortRoll were used to investigate the thermo-mechanical simulation of this rolling process.

The correctness of prediction of stock delivery after particular passes was verified in the study by comparing simulation results to templates obtained in industrial tests. Then, the effect of roll diameter on the stock bending (turn-up/down) after the exit of the roll, was examined. The examination involves the analysis of how the stock exits the rolls with equal and unequal diameters of rolls, respectively.

Keywords: Unequal angle bar; Stock bending; FEM; Numerical modelling

1. Introduction

The rolling of angle bars in closed passes is essentially an asymmetrical process. Therefore, it is advisable to carry out computer simulations of this process to investigate stock bending after exit from the roll gap, depending on the used diameters of both rolls [1–3].

The paper discusses a possibility of using numerical modelling for aiding the design of the technology of rolling 150 mm × 100 mm × 10 mm unequal angle bar. For carrying out the simulation, the commercial programs Forge3® [4,5] and authors program SortRoll were used [2,6,7]. The programs are based on the finite-element method (FEM) and allow the thermo-mechanical simulation of rolling processes in a three-axial state of strain.

The correctness of prediction of stock delivery after particular passes was verified in the study by comparing the obtained simulation results with templates taken in industrial tests. Then, the effect of roll diameters on the bending of the stock exiting the roll gap was examined. The examination involved the analysis of the way in which the stock exist the roll gap with the identical and different diameters of both rolls, respectively.

2. Mathematical models of the rolling process

2.1. Mathematical model of the Forge3® computer program

The thermo-mechanical simulation of the unequal angle bar rolling process was carried out with the use of a visco-plastic model in the triaxial state of strain by using the Forge3® commercial program, whereas the properties of the deformed material were described according to the Norton–Hoff [4,5] conservation law written in the following form (1):

$$s = 2K(\bar{T}, \dot{\bar{\varepsilon}}, \ldots)(\sqrt{3}\dot{\bar{\varepsilon}})^{m-1}\bar{\varepsilon} \quad (1)$$

where s is the stress deviator, $\dot{\bar{\varepsilon}}$ the strain rate, $\bar{\varepsilon}$ the strain intensity, $\bar{T}$ the temperature, and K and m are the material constants.

2.2. Mathematical model of SortRoll computer program

The FEM mathematical model for the three-dimensional metal flow of unequal angle bar during the rolling in the closed passes has been developed based on principles published in Refs. [6,7].

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To obtain the solution, the theory of non-isothermal plastic flow of incompressible non-linear viscous medium has been applied. Boundary conditions are taken into account by the method proposed in [7]. The essential idea of the method involves the use of a penalty function to model metal–tools interaction in complex spatial configuration. Solution is sought from the stationary condition of the modified Markov functional:

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

$$K_\tau^{(p)} = \frac{\tau^{(p-1)}}{v_\tau^{(p-1)}} \quad (3)$$

$$\mu^{(p)} = \frac{2\sigma_\mathrm{s}{}^{(p-1)}}{\dot{\varepsilon}_i^{(p-1)}} \quad (4)$$

where p is the iteration number, v_τ the slip metal velocity over the tool, v_n the metal velocity normal to the tool surface, w_n the velocity of tool surface point normal to the tool surface, τ the friction stress (according to the law $\tau = m\sigma_\mathrm{s}$, where m is the friction factor), σ_s the yield stress, σ the mean stress, $\dot{\varepsilon}_i$ the effective strain rate, $\dot{\varepsilon}_0$ the volumetric strain rate, K_τ the penalty coefficient accounting the metal slip velocity over the tool (computed from (3) iterations), K_n the penalty coefficient on the metal penetration into the tool, μ the effective metal viscosity computed from (4) by the method of hydrodynamic approaches, V the volume and F is the contact surface.

If the penalty coefficient K_τ increases, the metal slip over the contact surface is hampered. $K_\tau = 0$ corresponds to frictionless metal slip.

For velocity calculation the sixth nodes prisms with triangular basis finite elements are used. In the model the algorithm, which transfers temperature field from previous pass to the next, is incorporated. Volumetric solution of temperature field for the billet is built upon the sequent solutions of the plane sections, which correspond to location of cross-section of the billet during the movement through deformation zone and air cooling zone with the rolling speed. Solution of temperature field in rolls is built upon the sequent solutions of the one-dimension tasks in normal direction to the roll surface for every contact points between metal and roll.

3. Conditions adopted for numerical computations

For the computer simulation of rolling 150 mm × 100 mm × 10 mm unequal angle bar on a D600 industrial rolling mill, the following rolling conditions were adopted: rolled material, steel 45 (according to the Polish standard); rolling temperature, 1150 °C; rolling speed, 2.3 m/s. The feedstock was a perform of dimensions of 192 mm × 72 mm; tool temperature, 60 °C; ambient temperature, 20 °C; friction factor 0.8; coefficient of heat exchange between the material and the tool, $\alpha = 13{,}000\ \mathrm{W/K\,m^2}$; coefficient of heat exchange between the material and the air, $\alpha_\mathrm{air} = 100\ \mathrm{W/K\,m^2}$.

In order to determine the effect of roll diameters on stock bending after the exit of the roll, computer simulations were performed, in which the passes were positioned on the rolls according to two schemes: in the first scheme the upper D_u and lower D_l rolls diameters were equal, amounting to 600 mm; in the second scheme, the roll pitch lines coincided with the pass neutral lines, and at that time the roll diameters had different values in each pass (Fig. 1).

4. Numerical computation results and their analysis

In order to determine the accuracy of the rolling simulation, a comparison with industrial rolled bars was made (Fig. 2).

After carrying out numerical modelling, good agreement of the exit bar shape after particular passes with the industrial test

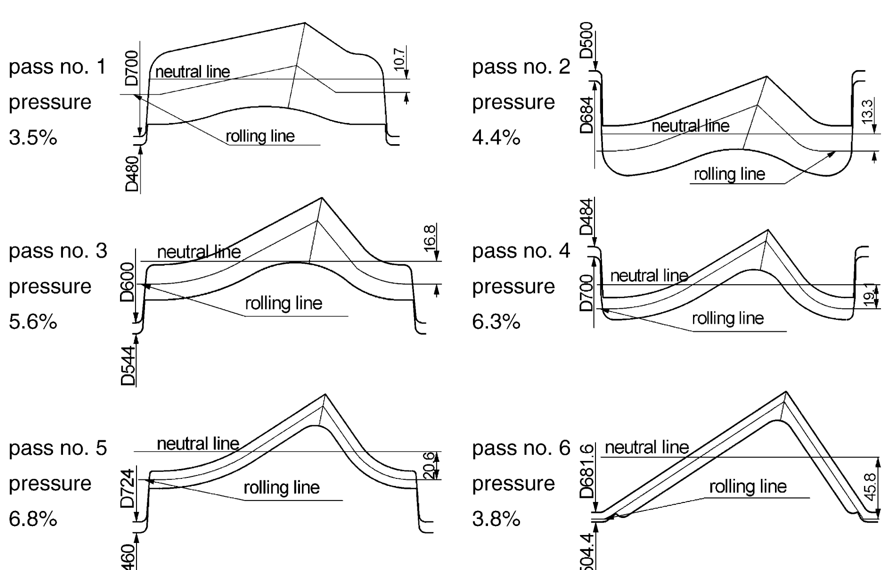

Fig. 1. Position of the neutral and rolling lines of the passes and the calculated values of pressure in individual passes (variant 2).

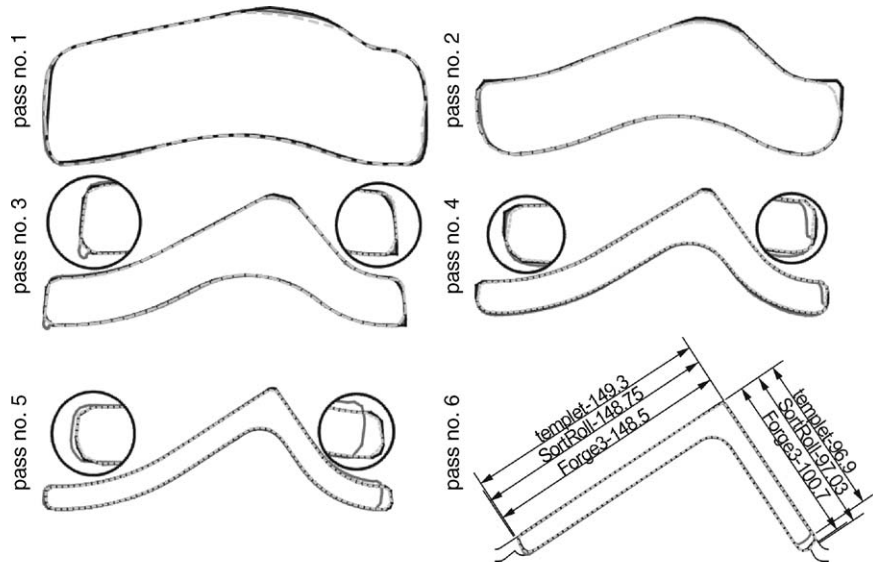

Fig. 2. Comparison of angle bar shapes after particular passes (black color, numerical examination by Forge3® program; grey color, numerical examination by SortRoll program; grey color and dotted line, industrial tests).

Table 1
Cross-section surface area (experimental test and theoretical examination results)

Pass no.	Cross-section surface area (mm^2)			Relative error (%)	
	Experimental test	Theoretical results, SortRoll	Theoretical results, Forge3®	SortRoll	Forge3®
1	11679.6	11485	11522	−1.7	−1.3
2	8734.3	8567	8747.5	−1.9	+0.2
3	6283.4	6242	6244.2	−0.6	−0.6
4	4412.9	4139	4249.4	−6.2	−3.7
5	3301.4	3128	3197.4	−5.2	−3.2
6	2841.3	2929	2979.2	−3.1	+4.9

results could be found. The shapes obtained from the computer simulation in most cases corresponded to the shape of templates taken. The greatest differences in width were observed in passes 5 and 6. The obtained angle bar dimensions conform to the standards.

The results of computation of stock cross-section surface area variations, performed using the Forge3® and SortRoll programs, were compared with the dimensions of templates taken after rolling (Table 1).

The data shown in Table 1 indicate that the differences in cross-section area between the measured values and the obtained from simulation do not exceed +4.9% for the Forge3® and −6.2% for SortRoll.

The subsequent stage of the study was the determination of the effect of the diameters of rolls on stock bending. Fig. 3 shows superposed longitudinal angle bar bands on exit from the roll gap after the following passes, rolled according to two variants, obtained using the Forge3® program.

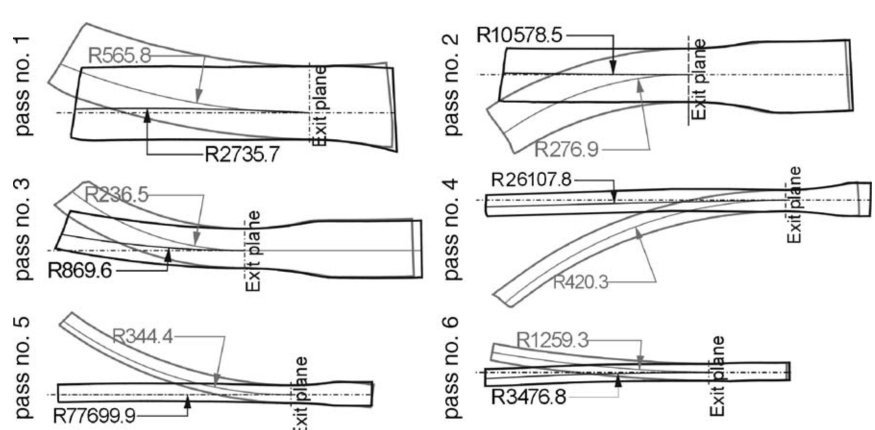

Fig. 3. Stock bending during rolling in (black color) variant 1 and (grey color) variant 2 (the numerical results obtained using the Forge3® program).

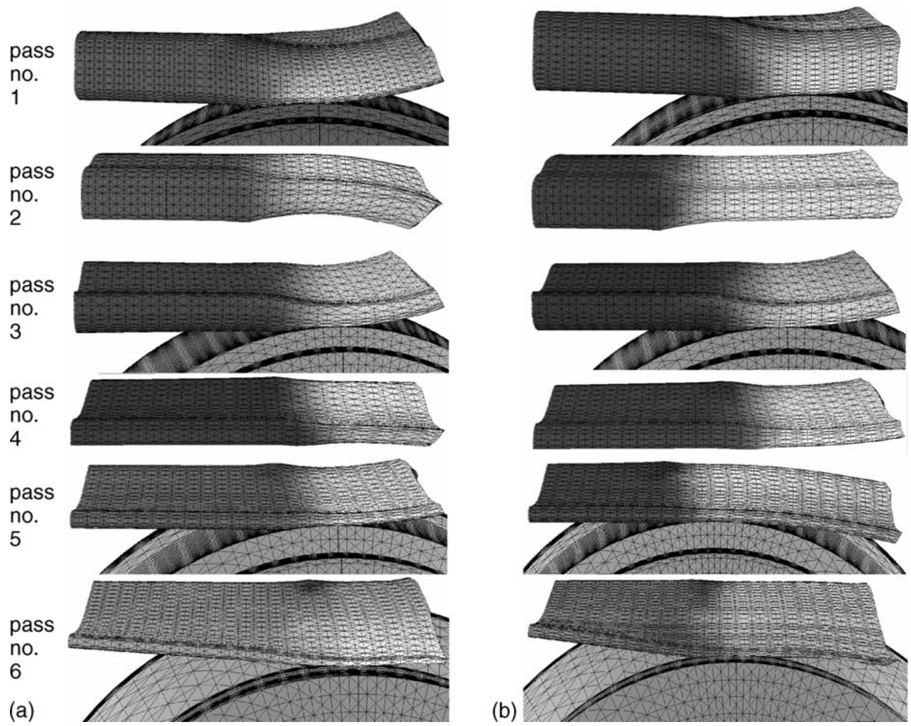

Fig. 4. Examples of stock bending during rolling in (a) variant 1 and (b) variant 2 (the numerical results obtained using SortRoll program).

Table 2
Angle bar bending in particular passes

Pass no.	Forge3®		SortRoll	
	Variant 1, *R* (mm)	Variant 2, *R* (mm)	Variant 1, *R* (mm)	Variant 2, *R* (mm)
1	565.9	−2735.7	315.2	705.2
2	−276.9	−10578.5	−652.5	6090
3	236.5	869.6	177.4	282
4	−420.3	−26107.8	−831.4	606
5	344.5	−77699.9	674.6	−2132
6	1259.3	3476.8	1115.6	1497.5

In Fig. 3, the measured values of curvature are indicated. On the basis of the obtained simulation results it can be stated that the bending of the stock took place toward the roll with the lower active diameter.

In Fig. 4 the numerical results obtained using SortRoll program are presented. In this figure the shape of angle profiles (deformed FEM mesh) is also shown. The direction and value of curvature is found to be similar to the one obtained using the Forge3® program.

A parameter that well reflects the degree of stock bending is the radius of bend curvature *R*. The obtained simulation results are shown in Table 2.

It can be found from the obtained results that in the case of using the first rolling variant considerable stock bending occurs in each pass. The use of the identical diameters for both rolls may prevent the correct rolling of angle bar to be completed. Whereas, for the second variant the stock exits the roll gap correctly. The obtained stock bends in particular passes are negligible (the band exits the roll gap as being straight).

5. Conclusions

One of the main rolling parameters, which has an influence on the way strip exits from the deformation zone is the diameter of rolls. The specific positioning of the grooves on rolls that cause coincidence of the neutral line with the rolling line, assures obtaining straight shaped strip and as well as final product.

The application of the Forge3® and SortRoll programs for the numerical analysis of the rolling process of 150 mm × 100 mm × 10 mm angle bar enables the selection of roll diameters that assures the straight exit of the band from the roll gap and the correct prediction of the shape after individual passes.

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