FEM MODELING AND EXPERIMENTAL RESEARCH OF THROUGH-THICKNESS STRAIN DISTRIBUTION DURING HOT PLATE ROLLING

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Abstract

One of the main features of rolling process is the inhomogenity of strain in the cross section of slab. It is especially important to know strain distribution in case of massive slabs multipass rolling. Shear stress has a significant contribution in accumulated equivalent strain due to a change of sign in roll bite which is difficult to estimate assuming only the final result after pass is done. In case of physical simulation of hot rolling conditions Gleeble may be advisable to use as a separate sample imitation of a specific layer in thickness . Thus it is necessary to use the values of the equivalent strain derived from calculations using mathematical modeling. For a better understanding of the processes occurring during rolling , the FEM model has been created. In order to check stress distribution along the plate thickness, an experiment was made using a slab with staked pins. The pin located near the surface was more deformed than others and it almost didn't have cavities around. The deeper pin is located, cavities become longer and higher, which means smaller compressive stresses along the axis Oy and larger tensile stresses along the axis Ox. The verification of madel was made by comparison of expirement results with modelled ones.

Keywords: Flat rolling, finite element method, plate mill, strain distribution

1. INTRODUCTION

One of the main features of rolling process is the inhomogenity of strain in the cross section of slab. It is especially important to know strain distribution in case of massive slabs multipass rolling, since properties of metal are being formed due to deformation in each pass, which later are being inherited in subsequent passes and, finally, determine the characteristics of final product. Researchers' attention to this issue is caused due to the need in development of rational rolling schedules, ensuring the required structure of metal, its physical, mechanical and other properties [1].

When rolling slabs with a large ratio of width to bite arc length ($b_{avg}/l > 4$) peace spread is caused by means of slabs' edges spread and most of the slab is not deformed in the width direction . Neglecting minor peace spread common for wide plates, equivalent strain of slabs' center line cross-section can be considered as plane deformation. Equivalent strain equation for the plane problem [2] has the following form:

$$\varepsilon_e = \frac{2}{\sqrt{3}}\sqrt{\varepsilon_x^2 + \frac{1}{4}\gamma_{xy}^2} \qquad (1)$$

In above equation $\varepsilon_x = -\varepsilon_y$ is linear tensile and compressive strain along the corresponding axes, γ_{xy} - shear strain. Under linear deformations for plane problem is considered compression along axis Y - and compression along axis X, which are equal in magnitude but different in sign. Shear strain means deformation of a cell by means of velocity difference in different layers of rolled metal. Accumulated equivalent strain is determined by integrating equivalent strain over time where t_Π - total time:

$$\varepsilon_\Sigma = \int_0^{t_\Pi} \frac{d\varepsilon_e}{dt} dt \qquad (2)$$

Paper reports the study of stress-strain state of the metal analyzed in the finite element method software package DEFORM, experimental studies on the quantity of recrystallized grain measured by Gleeble 3800 and experiments in industrial plate rolling mill.

2. MODEL DEVELOPMENT

Modeling of rolling process was implemented in DEFORM program complex for roll with diameter of 1200 mm, slab with initial thickness of 300 mm at a temperature of 1150 °C, which was rolled in one pass with a reduction of 10 % and a roll peripheral speed of 1.5 m/s. The material used for slab was steel grade X70, designed for the production of large-diameter pipes. Plastic model of slab was formed by 4- node bilinear elements, roll was simulated as rigid body. Pusher was used to ensure a stable bite of a slab. Pusher speed was 0.1 m/s, so that he was left behind after the capture of the slab and had no effect on the further deformation process (**Fig. 1**). To describe the contact between roll and slab was used Coulomb friction model $\tau = \mu p$, where τ - shear stress, μ - coefficient of friction, p - contact pressure. Heat transfer coefficient between roll and slab was 20000 W/m^2/K [3].

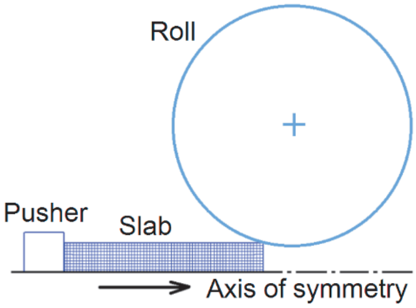

Fig. 1 Model overview

Friction coefficient was calculated from industrial data from plate mill. Calculation was made by evaluating a proper value of rolling force to make it equal to a measured value. Celikov's equation was used:

$$P_{cp} = F \cdot 1.15 \cdot \sigma_{\text{тек}} \cdot \frac{2 \cdot h_H}{\Delta h \cdot (\delta - 1)} \cdot \left[\left(\frac{h_H}{h_1} \right)^{\delta} - 1 \right] \tag{3}$$

$$h_H = h_1 \cdot \left(\frac{1 + \sqrt{(\delta^2 - 1) \cdot \left(\frac{h_0}{h_1} \right)^{\delta}}}{\delta + 1} \right)^{\delta} \tag{4}$$

where F - contact area, $\sigma_{\text{тек}}$- tensile strength, h_H - height of a strip in neutral point, Δh - absolute strain, $\delta = \frac{2 \cdot \mu}{\alpha}$ - deformation coefficient, μ - friction coeffitient, α - bite angle, h_1 - final strip thickness.

Taking into consideration that the properties of plate were acquired from Gleeble tests, the accuracy of determining flow stress was high enough, this method gives an acceptable results. Data obtained from the above calculation is shown in **Fig. 2**. The findings are consistent with the literature data []. Coefficient of friction - temperature dependence is a second order function with the highest value at the lowest temperature. According to the literature [4], in the range of 750 - 800 ° C the maximum of curve μ(T) occurs, which is not shown in the figure since determination of coefficient of friction at a lower temperatures is significantly complicated due to a phenomenon of work hardening in finishing rolling stage, which has to be calculated with a separate model. According to calculated data, maximum value of friction coefficient is ≈ 0.42, minimum - 0.275.

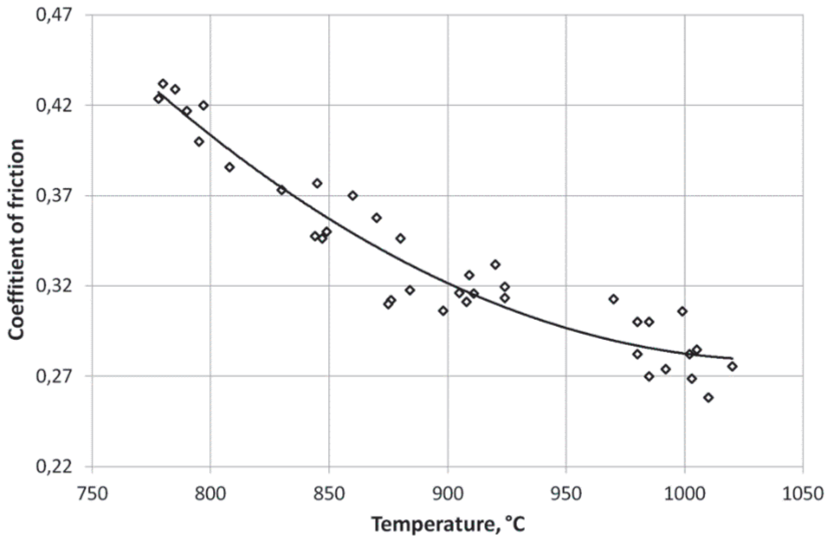

Fig. 2 Coefficient of Friction - Surface temperature curve

3. MODELLING RESULTS

Linear strain after one pass with respect to the initial state decreases towards the middle of slab, but its inhomogenity is negligible. Shear strain in different layers in thickness takes both positive and negative values during rolling, and its inhomgenity is considerably greater than linear. Consequently, shear strain contributes significantly to distribution of accumulated equivalent strain by changing the sign in deformation zone which is difficult to evaluate having only the final values after pass. **Fig. 3** shows that in some layers shear strain changes direction twice during the rolling process, which forms most of the accumulated strain. Other layers (e.g. middle) are practically not subjected to shear strain.

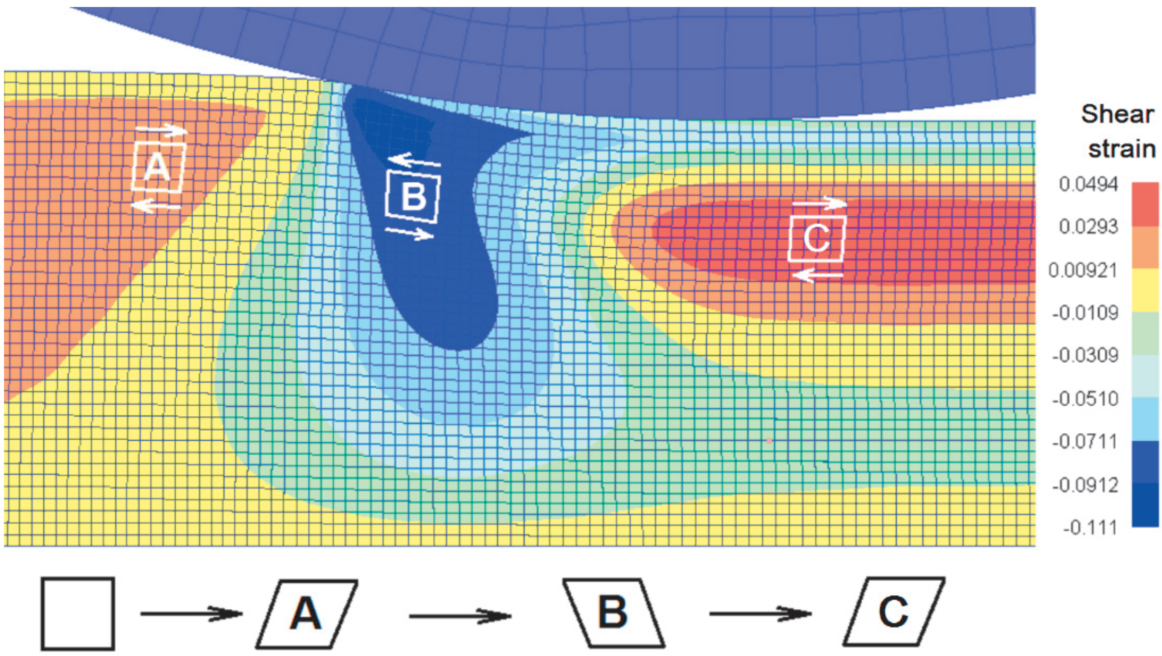

Fig. 3 Shear strain evolution during rolling

Results of mathematical modeling was used in experiments on Gleeble in order to study volume of recrystallization fraction of austenite grains by double compression test 1 second after deformation. This method is based on a strong structure sensitivity of the yield stress and requires two successive deformations with different pause duration between them at a constant temperature. A distinctive feature of this experiment is to use the raw data obtained from FEM simulation for different layers in thickness of slab. This approach allows us to determine the heterogeneity of the recrystallization process in the thickness direction of slab. Input data is presented in **Table 1**.

Table 1 Basic data for modeling on Gleeble 3800

Layer	ε	ε', c^{-1}	T, °C
Middle (№5)	0,136	1,0	1150
3/8h from surface (№4, 6)	0,146	1,0	1150
1/4h from surface (№3, 7)	0,169	1,2	1150
1/8h from surface (№2, 8)	0,207	1,4	1100
Surface (№1, 9)	0,173	1,6	1050

Experimental results demonstrate a significant inhomogenity of recrystallyzed grains in thickness direction of slab (**Fig. 4**). The highest degree of volume of recrystallization fraction observed at ¼ thickness from surface (layer 3 and 7). Thus, zone of maximum deformation is slightly closer to the surface (layers 2 and 8), but recrystallization is impeded due to decrease in temperature. Low temperature promotes almost total absence of recrystallization in slabs surface (layer 1 and 9).

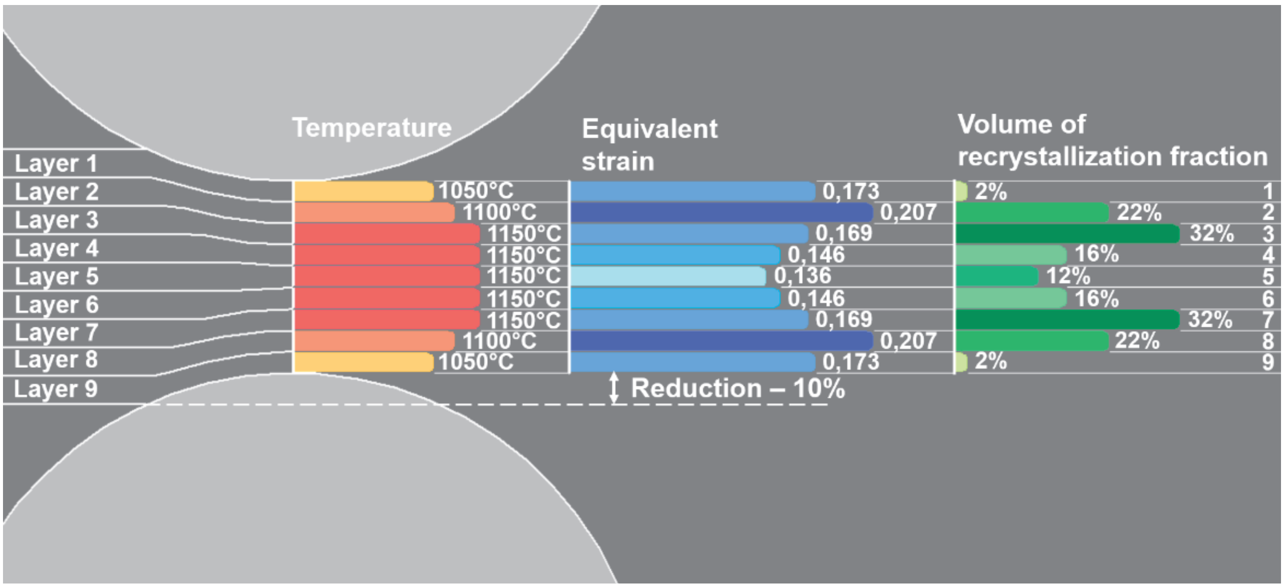

Fig. 4 Recrystallization of different layers in thickness direction

4. MODEL VERIFYING

In order to verify strain distribution along slabs thickness, experiment was conducted with pins staked into the slab, which were of same material as the slab itself - steel grade X70. Pins layout is shown in **Fig. 5**. Slab with sizes 140 * 2500 * 4000 was rolled on plate mill according to the schedule, represented in **Table 2** with constant rolling speed 2 m / s. Reheating temperature was 1150 °C.

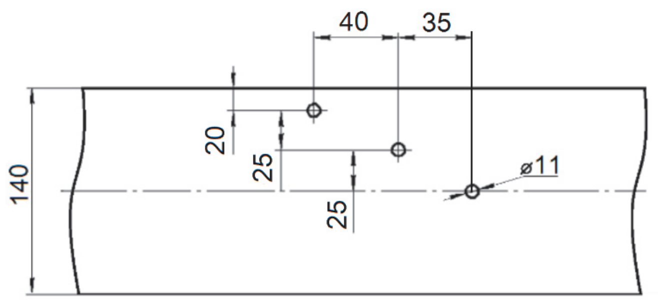

Fig. 5 Pins layout

Table 2 Rolling schedule for experiment with pins

№ pass	Thickness, mm	Strain,%	l, mm	l/H_{avg}
0	140			
1	135,0	3,6%	54,8	0,40
2	130,0	3,7%	54,8	0,41
3	125,0	3,8%	54,8	0,43
4	120,0	4,0%	54,8	0,45
5	115,0	4,2%	54,8	0,47
6	110,0	4,3%	54,8	0,49

After rolling slab was rejected from roller table and sample was cut from it. Results of the experiment are shown in **Fig. 6**. It can be seen from the figures that pins got different strain. Pin located near the surface was compress more than others, without cavities around. The deeper the pin is located, the longer and higher cavity becomes, which means smaller compressive stresses along Oy axis and larger tensile stresses along Ox axis.

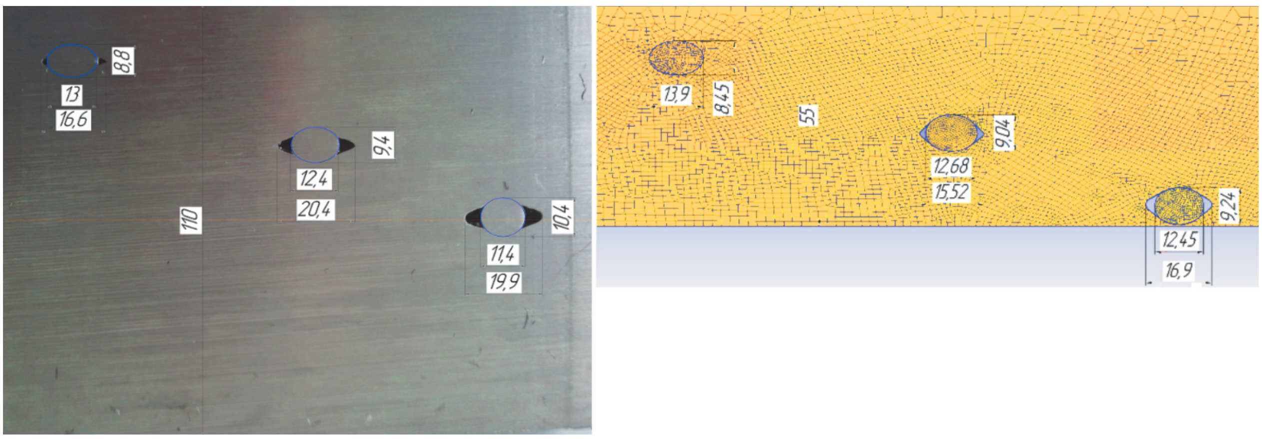

Fig. 6 Experiment and modelling results

For a better understanding of processes occurring during rolling, as well as verification of model, simulation of the experiment was held. Pins were placed in holes with diameter 0.1 mm larger than the diameter of pins. Pin located in the middle of slab was placed 10 mm higher in order to ensure accuracy of modeling. Pins were divided into 500 elements, slab into 15500 elements (**Fig. 6**). All other parameters of the model correspond to the above values. Simulation of one pass took about 4.5 hours with a time step of 0.01 s. Simulation results are shown in **Fig. 6**.

The figure shows that final dimensions of pins are similar to those obtained in the experiment. Maximum difference in total reduction in height is 4.2 % - 9.04/13.68 mm (model) and 9.4/12.4 mm (experiment) for pin located in the middle of slab. Furthermore, the cavity around this pin was somewhat less than in the experiment. Sizes of other pins have also shown good agreement with experiment- 8.45/13.9 and 8.8/13 mm for pin in the surface; 9.24/12.45 mm (taking into consideration the dependence of pins sizes with increasing of depth, it can be assumed that the size of pin in the middle of slab would be 9.8/11.9 mm), 10.4/11.4 mm. Shape and dimensions of cavity around the third pin similar to those obtained in the experiment.

Thus, taking into consideration good convergence of experimental results with modeling, we can make a conclusion about the adequacy of the modeling and possibility of using this data for further investigation or calculations.

CONCLUTIONS

- Shear strain contributes significantly to the distribution of equivalent strain in thickness direction of rolled slab. Shear strain in the middle of slab is practically 0, and maximum values are at a distance of about one eighth of the thickness from surface.
- Volume of recrystallization fraction of austenite grains is minimal on the surface and maximum at about ¼ of slabs thickness from surface.
- During rolling various stress conditions are being formed in different layers in thickness direction. In surface layers dominate compression stress in the vertical axis, in deeper layers - tensile stress along the rolling axis. These conclusions were confirmed by the results of experiments and FEM simulation.

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