An Experimental Study of the Thermal State of a Steel Billet during Hot Rolling

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Abstract. The technology of hot flat rolling is a complex technological process that includes multiple shaping of a steel billet, the temperature of a bullet ranging from 1100 to 900 degrees [1-6]. To deform a workpiece, mill rolls are used. The control over a workpiece thermal state is an important task aimed at the quality of its manufacturing [7-13]. To achieve the goal, a mathematical model is developed for calculating a steel billet thermal state. The model makes it possible to determine a temperature distribution along the whole length of a workpiece. The study results are useful for researchers and developers of the hot rolling technology, and they can be applied in the organization of the rolling process with an allowance for the temperature distribution. Based on the results, the parameters of steel billet production can be adjusted or changed [14-18].

The aim of the study is the development of a mathematical model, describing a steel bullet thermal state during a hot rolling process.

1 Implementation of the mathematical model for calculating a steel billet thermal state

Mathematical modeling of a rolled strip thermal state is based on the numerical solution of the differential equation of thermal conductivity (a thermal conductivity equation).

Modeling of a rolled billet temperature field is based on solving a bidimensional problem of thermal conductivity (1). A calculation model for solving the problem is shown in Figure 1.

$$c\rho \frac{\partial T}{\partial \tau} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (1)$$

Since the rolling speed of a billet is greater than the speed of heat spreading over a working roll [19, 20], the bidimensional modeling problem is simplified to a univariate one:

$$c\rho \frac{\partial T}{\partial \tau} = \lambda \left(\frac{\partial^2 T}{\partial y^2} \right) \quad (2)$$

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where the ratio $\frac{\lambda}{c\rho} = \alpha$ is temperature conductivity coefficient:

λ , coefficient of thermal conductivity of steel, W/m⁰C; c , specific heat capacity of steel, J / kg · ⁰C; ρ , density of steel, kg/m³.

Fig. 1. A calculating scheme for modeling a rolled strip thermal state

Provided $v = \frac{\partial x}{\partial \tau}$ and $a = \frac{\lambda}{c\rho}$, we get

$$v \frac{\partial T}{\partial x} = a \frac{\partial^2 T}{\partial y^2} \quad (3)$$

The work takes into account that in the process of deformation a rolled billet moves with an acceleration. Therefore, each step Δx_i on the x coordinate is characterized by its own speed v_i which is found by the formula:

$$v_i = \frac{v_{i-1} h_{i-1}}{h_i} \quad (4)$$

$$\Delta y_i = \sqrt{R^2 - (l_i - \Delta x)^2} - \sqrt{R^2 - l_i^2} \quad (5)$$

$$l_i = \sqrt{R^2 - (R - \frac{1}{2} h_i (1 - \varepsilon))^2} \quad (6)$$

where R , radius of the working rolls, mm; l , length of the deformation zone arc, mm.
 ε is the drafting value, when rolling an i-strip in the j-th stand, and it is determined by:

$$\varepsilon_{(i;j)} = \frac{h_{i-1}}{h_i} \quad (7)$$

For each of the thermal zones of a rolled strip, we use the following equations:

- provided convective air cooling, which, depending on the character of the movement (laminar or turbulent), is determined according to the calculated value of Nusselt number [21-25]:

$$Nu_{liquid} = 0.33 X^{-0.5} Re_{liquid}^{0.5} Pr_{liquid}^{0.33} \left(\frac{Pr}{Pr_{strip}} \right)^{0.25} \quad (8)$$

$$Re_{cr} = \frac{v X_{cr}}{\nu} = 5 \cdot 10^5$$

- provided radiative heat transfer [21-25]:

$$q_{(i)} = \varepsilon (T_{strip}) \sigma [(T_{strip} + 273)^4 - (T_{air} + 273)^4] \quad (9)$$

where σ is Stefan-Boltzmann constant; T_{air} is an ambient (air) temperature.

According to the works [21-25], the coefficient of radiative heat transfer between the strip and the ambient (air) temperature (for steel) is determined:

- provided an increase in temperature due to a deformation of a strip [21-25]:

$$\Delta T_{(i,j)} = \frac{\sigma_{s(i)} \ln \varepsilon_{(i,j)}}{\rho_i c_i}, \quad (10)$$

where $\sigma_{s(i)}$, is a strain resistance of a rolled i-billet MPa [26];

- provided a heat transfer from the strip to the working roll (heat transfer in the system “strip – roll” in j-th stand, according to [26]:

$$q_{(i,j)}^{\text{strip-roll}} = \frac{\lambda(T_{\text{strip}} - T_{\text{roll}})}{\sqrt{\pi a \tau}} \quad (11)$$

where T_{roll} is a maximum working roll temperature, assumed in the center of a barrel, °C.

2 Numerical implementation of the mathematical model

The mathematical model of a rolled strip thermal state is implemented in the form of a computer program, written in the Delphi 7.0 language. When executing the program, Rez.txt files are automatically created. They contain results of the program execution. The working window of the program is shown in Figure 2.

Fig. 2. A program window to implement the mathematical model of a rolled strip thermal state

Parameters of a mill and a strip are necessary for the calculations. Mill parameters include: “a roll radius”, “a roll temperature”, “a distance between stands”, “a number of stands” (a maximum number of stands), “drafting for each j-th stand”. Parameters of a strip include: thermophysical properties (“thermal conductivity”, “heat capacity”), mechanical characteristics of a rolled strip (“yield strength”, “density”), initial temperature, initial speed, thickness. The parameters: “Grid spacing along the x strip length” and “Number of pixels in the y thickness” are the characteristics of the computational grid, their decrease improves the accuracy of mathematical calculations.

The computational result in the form of a diagram is displayed in the major window of the program (Figure 3).

The computational results allow constructing a diagram of temperature distribution along a strip when rolling in the direction of a sheet movement for the contact surface of a strip ($y = 0$ or $y = h$); and in the thickness of a strip: at 10% distance from the surface ($y = 0.1h$), at 25% distance from the surface ($y = 0.25h$), at 50% distance from the surface ($y = 0.50h$), as well as the average value.

The work provides with a theoretical study of temperature distribution along a rolled strip. The material of a rolled billet is steel St3kp. Figure 3 shows the results of the study.

Fig. 3. The temperature distribution along a strip when rolling

Initial parameters: speed 2 m/s, thickness 12 mm, temperature 1100 °C, reduction 30%.

final parameters: speed 4,8 m/s, thickness 4,1 mm, temperature 1037 °C.

The analysis of the received data makes it possible to conclude that at the contact of a strip with working rolls there is a drop in temperature at a strip surface. It can be explained by the effect of the maximum heat takeoff (heat transfer) from a strip to the working surface of a tool. When passing subsequent stands (Fig.3) the drop in temperature at the surface ($y=h$) decreases. It can be explained by an increase in speed of a rolled strip when drafting, when a contact time between a strip surface and working rolls decreases. In spite of the fact that a strip transfers some of its heat to working rolls, one can observe an increase in temperature (temperature perturbation) in deeper layers of a strip at the moment of plastic deformation. The heat, released at the moment of deformation, is evenly distributed through the volume, and it results in an average temperature increase (deformation perturbation) by 20...50 °C. The received results correlate well with similar studies by the authors [21-25].

3 Assessment of the reliability of the developed mathematical model of a rolled strip thermal state

The study is carried out with the use of a thermal camera «SDS-Infrared HotFind-DXT» (the range of measurements is from -20 °C to +1500 °C, the minimum distinguishable temperature difference is 0,10 °C (at 30 °C), the measurement accuracy is $\pm 2\%$ of the reading values).

Measurements of temperature of strip surfaces and working rolls are carried out in a certain sequence. Measuring a strip thermal state is carried out immediately before a billet's entering a stand. The results of the measurements are shown in Fig. 4. Measurements of the surface temperature of working rolls are taken at five points: directly in the process of rolling, after finishing the rolling and when rolls being out of a stand.

Fig. 4. An example of temperature measurement with the use of a thermal camera at mill “2000”PJSCMMK

Assessment of reliability of the developed mathematical model of a rolled strip thermal state is carried out by comparing the experimental and the computational data. The comparative analysis is conducted on two “2500” and “2000” sheet hot rolling mills of PJSC MMK. The analysis involves comparing simulation results with control measurements used in production:

- when a strip leaves a roughing train:
 - T_3 (°C) for 2500 mil;
 - T_6 (°C) for 2000 mill;
- when a strip leaves finishing train;
 - T_{11} (°C) for 2500 mill;
 - T_{13} (°C) for 2000 mill.

The experimental temperature values are received from a shop data logging program. The analysis involves 300 hot rolling strips. Some of the results are shown in Table 1.

Table 1. Comparison of computational results of the mathematical model of a rolled strip thermal state with experimental data

Material of a rolled billet/thickness , mm	Temperature values of a rolled billet				Discrepancy, %	
	Roughing train		Finishing train			
	measured T ₃ °C	computational T ₃ °C	measured T ₁₁ °C	computational T ₁₁ °C	Roughing	Finishing
Boiling steel 08, Calm steel 08 h=2,0 mm	1080	1190	830	950	-10,19	-14,46
11кп, 08Ю h=3,2mm	1065	1172	862	989	-10,05	-14,73
SAE1008 h=1,8mm	1085	1184	820	950	-9,12	-15,85

The analysis of the received results (table 1) shows that the discrepancy range between experimental and theoretical data is 8...21%. It allows us to conclude that the developed mathematical model of a rolled strip thermal state is valid.

4 Conclusions

A mathematical model of a rolled strip thermal state is developed and numerically implemented. It takes into account the influence of the following technological features of the hot sheet rolling process: heat exchange of a strip with rolls; volumetric heat generation during plastic deformation of a strip; change in the thermal state of a strip regarding the performance of technological systems: hydraulic descaling, inter-stand cooling, as well as forced cooling of a strip before it enters a deformation zone.

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