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Simulation of accelerated strip cooling on the hot rolling mill run-out roller table

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ABSTRACT. A mathematical model of the thermal state of the metal in the run-out roller table continuous wide hot strip mill. The mathematical model takes into account heat generation due to the polymorphic $\gamma \rightarrow \alpha$ transformation of supercooled austenite phase state and the influence of the chemical composition of the steel on the physical properties of the metal. The model allows calculation of modes of accelerated cooling strips on run-out roller table continuous wide hot strip mill. Winding temperature calculation error does not exceed 20°C for 98.5 % of strips of low-carbon and low-alloy steels

KEYWORDS. Hot Rolled; Wide-strip; Accelerated Cooling; Run-out Roller Table; Polymorphic Transformation; Mathematical Modeling.

INTRODUCTION

In a highly competitive market, each steel group strives to improve product quality. The most important factor affecting the quality of products, ensuring accuracy is a necessary process parameter throughout the production cycle. When thermomechanical processing of metals in the hot rolling mill main controllable parameters are the temperature of the end of the rolling and winding, the thickness, width, profile and flatness of the strip.

At the present time to provide the necessary parameters in a narrow permitted range is not possible without automation of the production process. In this regard, the development of mathematical models, based on which is more precise control of process parameters is an urgent task.

MATEMATICAL MODEL OF THE THERMAL STATE OF THE METAL IN THE COLLECTING ROLLER TABLE

Currently, broadband hot rolling mills for rapid cooling strips on collecting roller table used as a rule, the collector jet (laminar) cooling. When you turn on the system of forced cooling of the heat exchange with the band by exhausting heat out of the jets of water coming from the upper and lower reservoirs, the layer of water flowing from the upper surface of the strip, and the environment. Temperature monitoring of the end of the rolling and coiling by radiation pyrometers.

The mathematical model of the thermal state of the metal in the collecting roller table is based on the definition of the space-time temperature field strip. The calculated field is found by solving one-dimensional unsteady heat conduction equation (1) the numerical method - the method of finite differences:

$$\rho(T)c(T)\frac{\partial T}{\partial \tau} = \lambda(T)\frac{\partial^2 T}{\partial x^2} + q_V \tag{1}$$

where:
ϱ - density of the metal, kg/m^3;
c - specific heat of the metal J/(kg×K);
λ - thermal conductivity of the metal, W/(m×K);
T - temperature of the metal, K;
τ – time, s;
x - coordinate of the strip thickness, m; qv - power density heat sources, W/m^3.

Heat loss from strip cooling water, radiation, and interaction with the ambient air are described by the boundary conditions of the second and third kind, and for the difference scheme are given in the following form:

$$-\lambda\frac{\partial T}{\partial x} = q + \alpha\left(T - T_{\phi}\right)$$

where:
Tsr - ambient temperature;
q - heat flux, W/m^2;
α - heat transfer coefficient, W/(m^2×K).

The solution of the heat is carried by the sweep method. As a finite-difference scheme is used implicit scheme. The calculation of heat flow and heat transfer coefficient is performed on the dependence presented in [1-3] for the conditions of collecting roller table of continuous strip hot rolling mill (CSHRM).

On cooling the strip to the collecting roller table mill hot rolling the metal undergoes a polymorphic transformation of γ → α, which is accompanied by significant heat release. The vast majority of mathematical models of the thermal state of the band on the collecting roller table, for example, [2-6], does not include a calculation of the polymorphic transformation as transportation for the band collecting roller table, which can lead to substantial error in the prediction of coiling temperature variation of process parameters in a wide range.

To calculate the polymorphic transformation in the collecting roller table to know Ar3 transformation temperature of the beginning and end of the conversion of Ar1. These parameters depend on the chemical composition of steel, the cooling rate, the dislocation density in the crystal lattice, the grain size and strain rate prior to the metal. In constructing a mathematical model of calculation of the critical points Ar3 and Ar1 made only according to the chemical composition of the steel, cooling rate and, indirectly, on the grain size, by choosing for the calculation of thermokinetic decomposition diagrams of supercooled austenite with austenite temperature, similar to the conditions CSHRM.

The density and thermal conductivity of the metal is given according to the reference data. Specific heat of the metal is calculated by the formula:

$$c = Xc_{\alpha} + \left(1 - X\right)c_{\gamma}$$

where: X - the share of the formed α-phase; c_{α} - the heat capacity of α-phase; cγ - the heat capacity of γ-phase.

The quantity of X is calculated as follows according to [7]:

$$X = 1 - \exp\left(-by^{n}\right) \tag{2}$$

$$y = \frac{Ar_3 - t^{j}}{Ar_3 - Ar_1}$$

$$b = -0.009 Ar_3 + 14.521\,, \qquad n = 0.018 Ar_3 - 9.293\,,$$

where:
t^j - metal temperature at the collecting roller table in the j-th time,
°C; Ar_3 and Ar_1 - the critical point, °C.
Ar_1 and Ar_3 temperature, depending on the chemical composition of steel and the cooling rate can be described by the equation [8]:

$$Ar_i = kW - mW^n + A_i\,, °C, \qquad i = 1,\ 3; \tag{3}$$

$$W = \frac{t^{кп}_{масс} - t^j_{масс}}{\tau^j_{тр}}\,,$$

where:
W - the rate of cooling, °C/s;
Ai - isothermal value based on the chemical composition;
k, m, n - coefficients;
$t_{max}{}^{kp}$-averaged temperature at the end of rolling, °C;
$t_{max}{}^{j}$-averaged temperature of the strip in the j-th time;
$t_{mp}{}^{j}$ - transportation time of the calculated cross sections in the j-th moment of time from the end of rolling pyrometer, s.
According to estimates in the demo-version of the Thermo-Calc heat when γ → α transformation of pure iron was 136.93 MJ/m3, then the expression for the power density due to heating of the strip of polymorphic transformation can be written as:

$$q_V = \frac{136{,}93\left(X^j - X^{j-1}\right)}{\tau^j - \tau^{j-1}}\,,\ \frac{MBm}{м^3}\,,$$

where:
τ – time, s.

ADAPTATION OF A MATHEMATICAL MODEL

The mathematical model of the thermal state of the metal in the collecting roller table adapted to the conditions of continuous wide hot-rolling mill 2000 "NLMK", Russia. The existing mill in the accelerated cooling unit consists of 80 upper and lower sections, equipped with reservoirs of jet cooling. The scheme of collecting roller table with the installation of cooling is shown in Fig. 1. The total length of the outlet roller mill in 2000 is 206.6 m

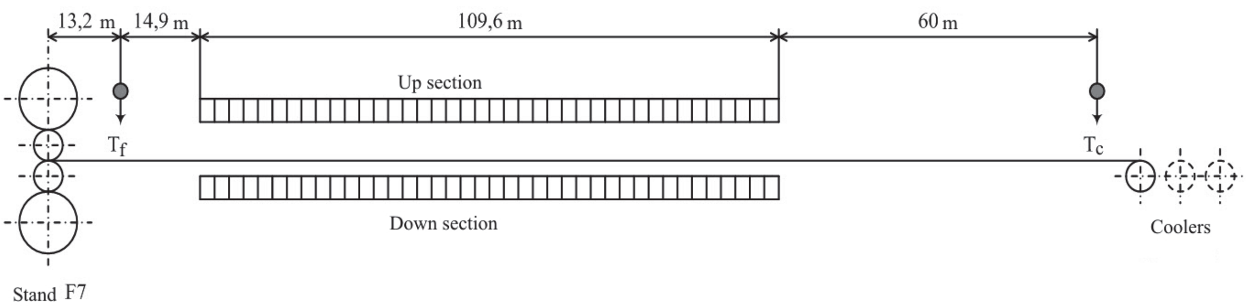

Figure 1: Cooling scheme on outlet roller of mill 2000.

Adaptation of a mathematical model was to minimize the error between the calculated and actual measured temperature coiling. During the first stage adaptation of the method of Nelder-Mida determined the unknown coefficients of the mathematical model (the emissivity of the surface of the strip, the coefficient of proportionality flow characteristics of reservoir cooling, etc.). In adapting the model used two samples of hot-rolled strips of low carbon and low alloy steels: an adaptation and control. Adaptive sampling is designed to find the optimal values of the coefficients of the model, and control - adapted to assess the adequacy of the mathematical model. The total number of bands in the adaptation and control samples was 5441 and 5442, respectively.
In the second phase of adaptation was performed at a rate of iteration n (2) to minimize errors in the calculation, since the coefficient n is obtained only through a thermokinetic diagram of decomposition of supercooled austenite of low carbon steels. As a result, we obtain the following regression equation:

$$n = 1984.74 + 0.0144 Ar_3 \text{-} 5204.1\left(\frac{t_{кп}}{Ar_3}\right) + 2918.4\left(\frac{t_{кп}}{Ar_3}\right)^2 2854.6\left(\frac{t_{кп}}{Ar_3}\right)^3 - 3596.9\left(\frac{t_{кп}}{Ar_3}\right)^4 + 1035.6\left(\frac{t_{кп}}{Ar_3}\right)^5$$

where:
t_{kp} - temperature of the end of rolling, controlled by the radiation pyrometer, °C.
The comparison of the calculated and actual values of temperature coiling after adaptation of the mathematical model is presented in Fig. 2. The number of bands with an error of calculation of more than 20 ° C for adaptation and control samples was 1.43% and 1.16% respectively. The result of calculation of the mathematical model for the length of the collecting roller table for a design section is shown in Fig. 3.
The result is presented for a strip of steel St3sp standard size 4x1500 mm, the filling speed of 7.2 m/s.

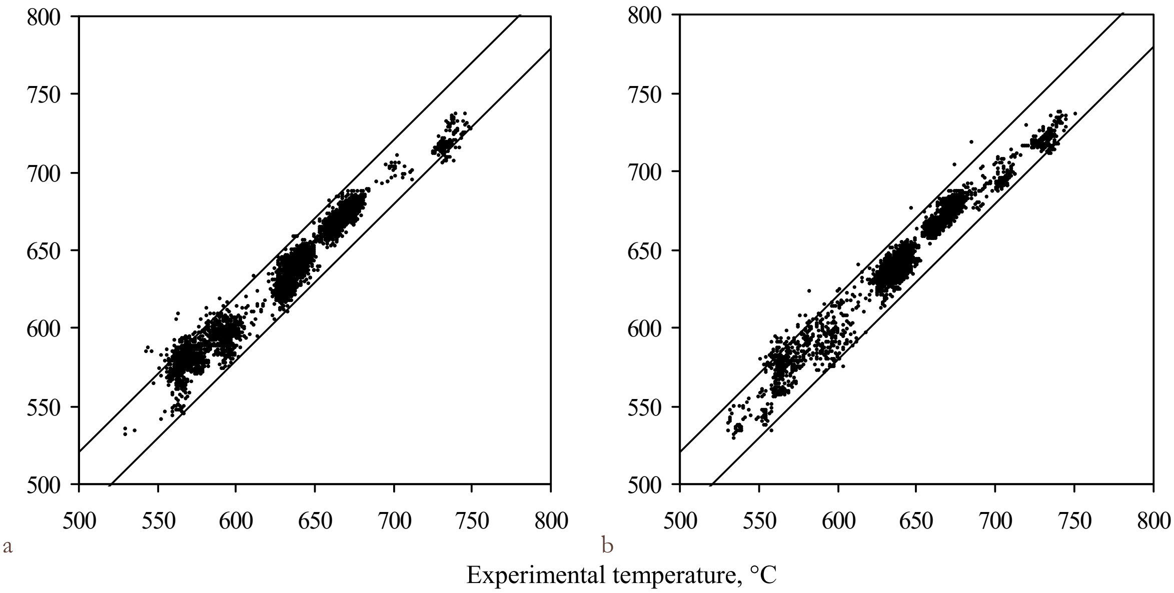

Figure 2: Comparison of calculated and measured values of the winding temperature: a) adaptive sampling; b) the control one.

To compare the calculated and actual distributions of temperature along the length of coiling were selected band of low-carbon steels (Fig. 4).
The mathematical model allows to calculate the number of cooling sections, which should be included to ensure the desired temperature, depending on the coiling temperature and rolling speed mode and cooling strategies.
Fig. 5 shows a comparison of estimated and actual number of cooling sections of mill 2000 when rolling strip 3.5 x1300 mm of steel St1ps with increased acceleration and application between standing cooling in the finishing group (rolling speed 10-13.4 m/s, acceleration 0.056 m^2/s, the flow of water in the cooling system 960 m^3/h, coil weight 26 tons)

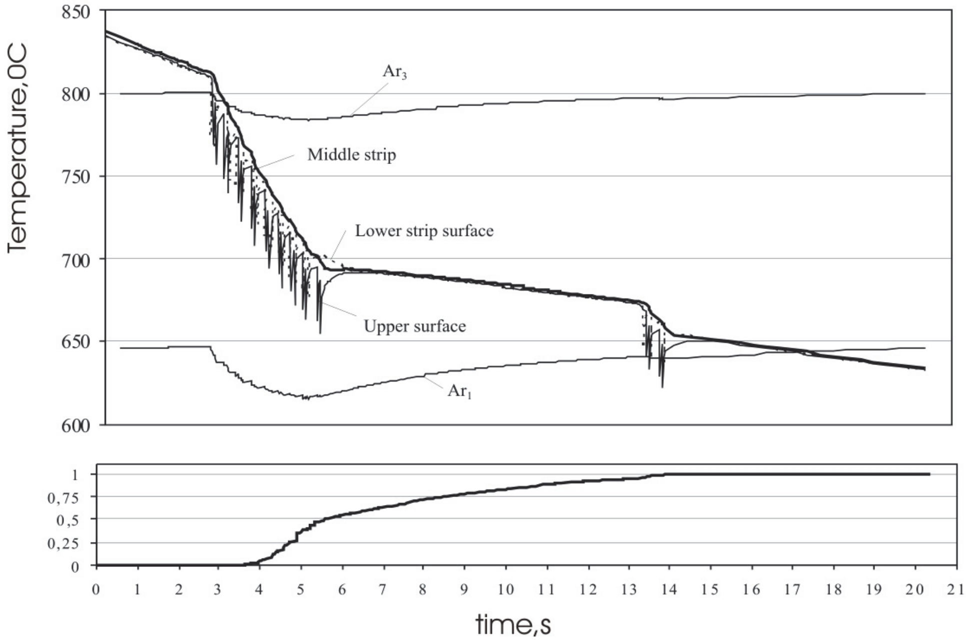

Figure 3: Cooling of the calculated cross stripes on the different rollertable

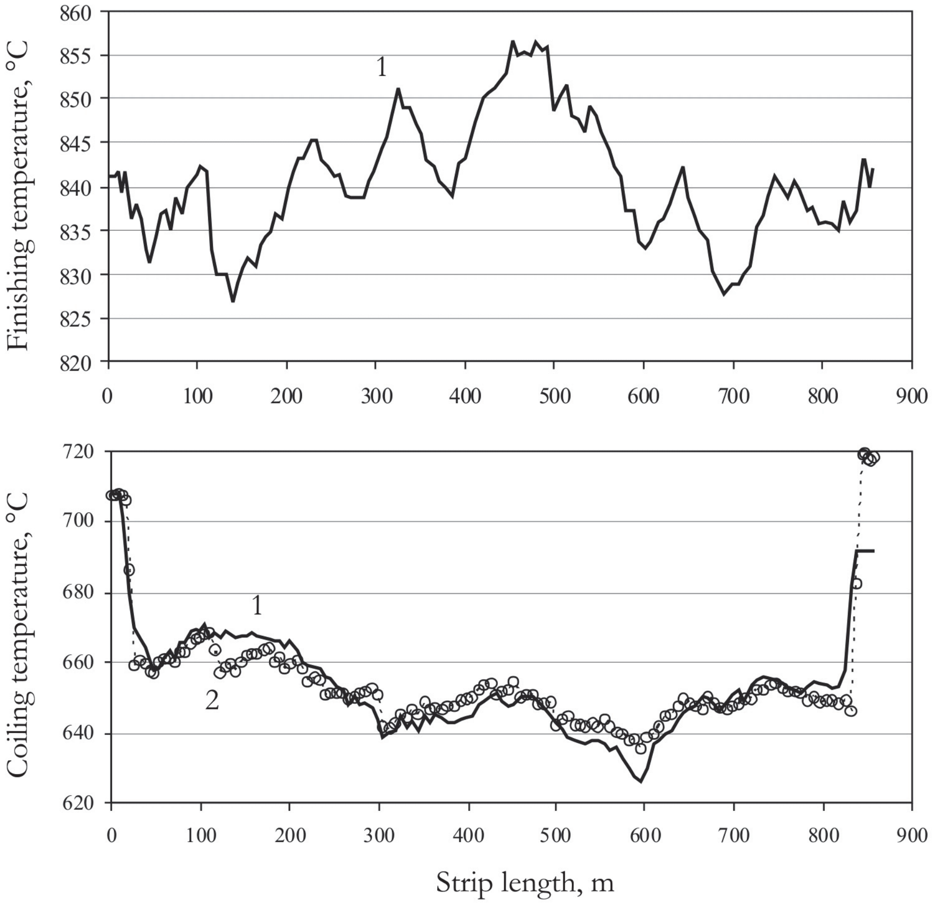

Figure 4: The temperature regime of rolling strip 08ps, 2,7 x1290 mm: 1) the actual value, and 2) the calculated value

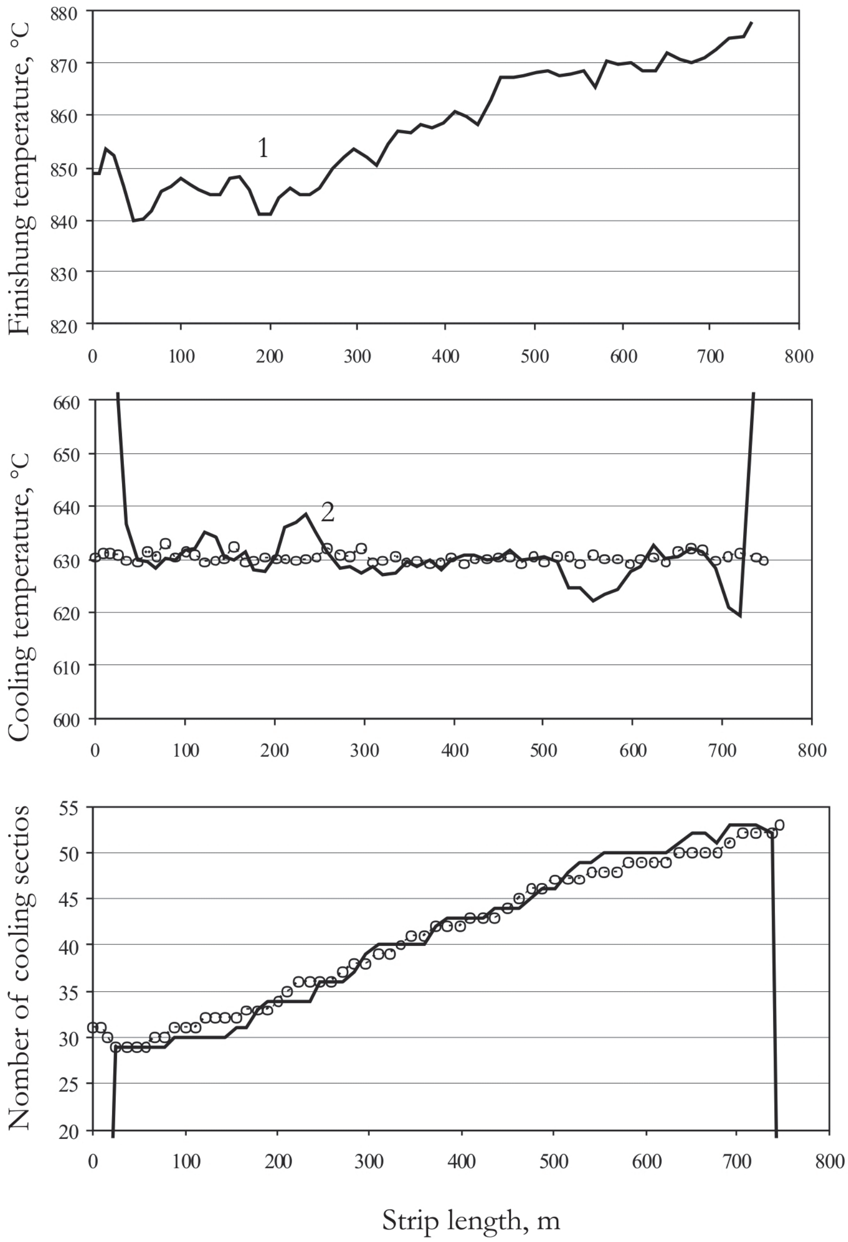

Figure 5: Comparison of estimated and actual modes of cooling on the mill 2000 different rollertable . Strip 3,5 x1300 mm, steel St1ps; 1 - actual temperature, 2 - calculated temperature, 3 - setting management system accelerated cooling the strip to include the cooling sections, 4 - Calculated number of cooling sections.

Conclusion

A mathematical model of the thermal state of the metal in the collecting rollertable continuous wide hot strip mill, which takes into account heat generation due to the polymorphic transformation of supercooled austenite is developed.

The calculate error of cooling temperature does not exceed 20°C for 98.5 % of the strips in a wide range of rolled product of low-carbon and low alloy steels and process parameters of hot rolling.

The developed model can be used in the control system in the construction of algorithms for automatic control by setting the accelerated cooling of the metal in the collecting roller table continuous wide hot strip mill or casting - rolling plant.

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