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VALIDATION OF THE BOUNDARY CONDITIONS IN ON-LINE TEMPERATURE MODEL FOR PLATE ROLLING MILL

WERYFIKACJA WARUNKÓW BRZEGOWYCH MODELU ON-LINE STEROWANIA PROCESEM WALCOWANIA BLACH GRUBYCH

Effective modeling of rolling processes with the finite element method strongly depends on the accuracy of the temperature field computation. Heat transfer while rolling combines radiation and convection. Rolled material also loses heat to the equipment by direct contact. In addition to that heat sources such as work of plastic deformation and heat of phase transformation should be taken into account. All these parameters can be applied in the finite element models, however, computation time increases gradually with the model complexity. A simplified heat transfer model for on-line systems of mill control has been presented in the paper. The model has been validated by measurement curried out at an industrial steel plant. It has been shown that plate cooling due to water falling down from the rolls cooling system is an important factor and water consumption should be recorded to ensure proper temperature predictions in on-line control systems. Heat losses to the rolls and convective heat loses from the strip surface decrease the plate temperature by about 1,3 %. The computation time on typical PC computers of the plate temperature is short and do not exceeds 0.1 s for the hole production line.

Poprawne modelowanie numeryczne procesów walcownia metodą elementów skończonych w dużej mierze zależy od dokładności obliczeń pola temperatury. Strata ciepła w czasie procesu walcowania jest związana z transportem ciepła w wyniku konwekcji oraz radiacji. Walcowany materiał traci ciepło także w wyniku bezpośredniego kontaktu z walcami. Oprócz tego podczas kształtowania metali rozkład temperatury w materiale zależy również od generowanego ciepła w wyniku odkształcenia plastycznego a także występowania przemian alotropowych w stanie stałym. Wszystkie te parametry mogą być zastosowane w modelu elementów skończonych, jednakże czas obliczeń wzrasta stopniowo wraz ze złożonością modelu. W artykule zaprezentowano uproszczony model wymiany ciepła dla sterowania procesem walcowania w systemie on-line. Opracowany model poddano ocenie poprzez porównanie z pomiarami wykonanymi w rzeczywistym procesie walcowania na gorąco blach grubych. Wykazano istotny wpływ wody chłodzącej opadającej z walców na wyniki obliczeń temperatury pasma. Konwekcyjne straty ciepła i straty ciepła do walców spowodowały obniżenie temperatury pasma o około 1.3%. Czas obliczeń opracowanym modelem nie przekraczał 0.1s na komputerze PC.

1. Introduction

Plate rolling mills are automatically controlled and computer controlled production systems play an importent role in the manufacturing processes. Numerical software designed for such systems should be fast enough to work in real time. One part of a software used in such systems is assigned to compute temperature of the rolled material. This temperature is further used to predict the rolling force and torque. It is also an important factor in planning of final product properties. The workpiece temperature is numerically computed starting from the billet heating process and ending on plate cooling. The plate rolling process is composed of several passes and the heat transfer processes are very complex. Heat is transferred by conduction, radiation and convection. The air flows over a plate surfaces under natural or forced convection. The flow can be laminar, transitional or turbulent depending on a strip velocity and a side of a plate. Several heat conduction models can be applied to calculate the heat transfer coefficient. The role of forced convection in the heat transfer was studied in works [1,2]. In the case of plate rolling processes the rolling velocity is limited and forced convection do not affects the heat transfer essentially [3]. Forced convection is important in continuous strip rolling lines, where the rolling velocity is much higher. In the rolling gap the high temperature gradients arise due to heat conduction from the hot strip surface to the cold rolls. In addition

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to that, the heat is generated inside the workpiece as an effect of the work of plastic deformation. The conduction heat transfer coefficient in the roll gap is affected be the lubricant, strip and roll temperature, deformation gradient, scale formation and other factors which may have influence on the strip or roll surface. These problems have been addressed in work [4] where the values of the heat transfer coefficient varying from 4 kW/(m^2·K) to 465 kW/(m^2·K) have been reported. The strip surface is also cooled by water used in the roll cooling systems and while descaling process. The heat transfer by water cooling is an separate problem discussed in many works [5,6,7,8]. It would be appropriate to mention that the heat convection coefficient for water cooling depends on strip surface temperature, strip thermal conduction coefficient, water pressure, water flux and factors which may have influence on the strip surface roughness. In works [5,6] the strip surface temperature on the convection heat transfer while water cooling was presented in details. There is no simple method to select an appropriate value of the heat transfer coefficient. In works [7,8] 6000 W/(m^2·K) have been used for water spray cooling and 1200 W/(m^2·K) for laminar water cooling of a hot strip.

The temperature drop of the steel strip during rolling leads to phase transformation, when the temperature and the rate of temperature change have reached an appropriate level. It has an influence on the heat balance and can be taken into account as an internal heat source [9]. All these factors can be applied in the finite element models, however, computation time increases gradually with the model complexity. The factors mentioned above cause that the development of fast computer models suitable for real time calculations is mainly based on experience and models should be dedicated for a particular steel plant. In the paper simplified heat transfer model for on-line systems of mill controls has been presented. The model has been validated by measurement curried out at an industrial steel plant.

2. Heat transfer model

The heat transfer model is based on the finite element solution to the transient heat conduction equation. Two dimensional model is employed and the workpiece temperature is computed from the equation:

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

where:

T – temperature, K,

τ – time, s,

λ – thermal conductivity, W/(m · K),

q_V – internal heat source, W/m^3,

c – specific heat, J/(kg · K),

ρ – density, kg/m^3.

The solution to Eq. 1 is possible if the boundary conditions are specified on the surface of the deformed steel plate. The boundary conditions on the plate surface cooled in air are combined of radiation and convection and can be given in a form of the heat flux:

$$q = \varepsilon_w 5.67 \cdot 10^{-8}(T^4 - T_a^4) + \alpha_a(T - T_a), \tag{2}$$

where:

ε_w – steel surface emissivity,

α_a – convection heat transfer coefficient for air cooling, W/(m^2 K),

T_a – air temperature, K.

Radiation heat loses strongly depend on the emissivity of a cooled surface. In the case of hot rolling of steels, surface of the deformed material is covered by the secondary scale and the emissivity can be computed from the empirical equation [10]:

$$\varepsilon_w = 1.2 - 0.52\frac{T - 273}{1000} \tag{3}$$

The Eq. (10) has been developed based on the experimental data published in [11]. The sample temperatures cooled in air have been measured and simulated by the finite element method. The measured and simulated temperatures have been compared in order to calculate the coefficients in Eq. (3). The equation is valid for temperatures greater than 400°C. The secondary scale thickness varies in time, however it has little influence on combined heat flux given by Eq. (2). Some inaccuracy in the heat transfer description by Eq. (2) is expected for plate cooling in air before descaling process. The emissivity of the plate given by Eq. (3) is very close to the results published in [12]. The Nusselt number is employed to compute the convective heat transfer coefficient α_a for laminar and turbulent flow. The Nusselt relations used in the model are given in Table 1. The transition from laminar to turbulent flow is based on the Reynolds number calculated for fluid flow over a flat plate [13]. The coefficient ε_T in the Nusselt number is used to evaluate the change of fluid temperature near the steel surface and has the form:

$$\varepsilon_T = \left(\frac{\mathrm{Pr}_p}{\mathrm{Pr}_s}\right)^{0.19}. \tag{4}$$

TABLE 1
Average values of the Nusselt number during parallel flow over a flat plate

L.p.	Type of flow		Nusselt number
1.	$Re < 5 \cdot 10^5$	laminar	$Nu = 0.664\ Re^{0.5}\ Pr^{1/3}\varepsilon_T$
2.	$5 \cdot 10^5 < Re < 10^7$	turbulent	$Nu = 0.037\ Re^{0.8}\ Pr^{1/3}\varepsilon_T$

Subscript p denotes that the Prandtl number Pr should be calculated for the air bulk average temperature. The subscript s indicates that the Prandtl number Pr is to be calculated at the steel surface temperature. For other stages of a plate cooling, the boundary conditions are specified in the form:

$$q_i = \alpha_i(T - T_i). \tag{5}$$

Subscript i indicates cooling stage number, α_i is the heat transfer coefficient and T_i represents ambient temperature for the cooling stage i.

Inside the descaling machine, plate is cooled by water sprays and the convection heat transfer coefficient α_s can be calculated from [14]

$$\alpha_s = 3.15 \cdot 10^9 \dot{w}^{0.616} \left[700 + \frac{t - 700}{\exp(0.1t - 70) + 1}\right]^{-2.455} \left[1 - \frac{1}{\exp(0.025t - 6.25) + 1}\right], \tag{6}$$

where:

t – plate surface temperature, °C,

$\dot{w}$ – water spray flux rate, $dm^3/(m^2\ s)$.

Interface between the workpiece and rolls can be characterized by the thermal contact conductance and the value of the heat transfer coefficient α_c is expressed by the empirical equation, developed based on experimental data published in [11]

$$\alpha_c = 36400 - 74t + 0.04t^2. \tag{7}$$

In the deformation zone heat is generated due to plastic deformation of the workpiece. It is possible to compute dissipation of the plastic work using the finite element method, however, the computation time is large and such solutions are not possible in applications running in a real time. In the presented model heat of deformation is computed as an average value resulting from the plate deformation. In order to accomplish that we need to calculate:

– plate reduction in height Δh, mm

$$\Delta h = h_1 - h_2 \tag{8}$$

– length of the arc of contact l_d, mm

$$l_d = \sqrt{R\,\Delta h} \tag{9}$$

– average logarithmic strain φ

$$\varphi = \ \mathrm{lm}\ \frac{h_1}{h_2} \tag{10}$$

– deformation time Δt, s

$$\Delta t = \frac{l_d}{v_w}1000 \tag{11}$$

– average rate of deformation $\dot{\varphi}$, 1/s

$$\dot{\varphi} = \frac{\varphi}{\Delta t}. \tag{12}$$

As a result of these calculation, the average rate of the internal heat source is given by:

$$q_v = 10^6\sigma_p\dot{\varphi}, \tag{13}$$

where:

h_1 – plate thickness at the entry to the roll gap, mm,

h_2 – plate thickness at the exit from the roll gap, mm,

R – roll radius, mm,

v_w – rolling speed, m/s,

σ_p – yield stress, MPa.

The yield stress of steel can be calculated from the Shida formule [15].

Eq. (1) describes the energy balance of steel passing through the roll gap and the internal heat source q_v represents not only heat generation due to plastic work. If a steel temperature drops below the phase transformation temperature, the heat of the phase transformation should be included in the model. Heat generation due to phase transformations can be calculated from:

$$q_v = Q_s\frac{f_s^{\tau} - f_s^{\tau-\Delta\tau}}{\Delta\tau} \tag{14}$$

where:

Q_s – heat of phase transformation, 100 10^6 J/m^3,

f_s – volume fraction of a new phase.

New phase fraction f_s as a function of temperature, cooling rate and the transformation limiting temperatures can be determined from

$$f_s = 1 - exp\left(K_s\frac{T_s - T}{T_e - T_s}\right), \tag{15}$$

where:

K_s – constant with a value between 2 and 10,

T_s, T_e – limiting temperatures of the phase transformation, K.

If the node temperature drops below T_e temperature, Eq. (14) is used to calculate the rate of the heat generation at the element node. Constant K_s is used to model the influence of the rate of cooling on the rate of heat generation due to phase transformation. For slow cooling in air K_s =4 is employed in computation. In this case heat generation is similar to phase transformation under equilibrium conditions. In case of fast cooling higher values of K_s should be used. It should be pointed out that the rate of heat generation has minor influence on the heat balance. Rate of heat generation is important factor in analysis of local temperature changes in models used to compute microstructure development. Thermophysical properties of steel and air are assumed to be functions of temperature. Properties of air used in computations are listed in Table 2.

TABLE 2

Physical properties of the air used in simulation

Property (unit)	**Function of temperature**
Thermal conductivity W/(m · K)	$\lambda_p = 2.4667929106 + 0.00709356182t - 1.35668205 \cdot 10^{-6}t^2$
Specific heat J/(kg · K)	$c_{p_p} = 1.008 + 0.00016312t$
Kinematic viscosity m^2/s	$v_p = 1.534172819 \cdot 10^{-5} + 9.132714259 \cdot 10^{-8}t + 7.534172819 \cdot 10^{-11}t^2$
Dynamic viscosity kg/(m · s)	$\mu_p = 1.720296626 \cdot 10^{-5} + 4.330544281 \cdot 10^{-8}t$ - $1.115753405 \cdot 10^{-11}t^2$

The heat transfer model is the finite element solution to the problem of cooling the plate cross section under variable boundary conditions. The boundary conditions are defined for separate stages of the manufacturing process. The model can be also used to calculate the cooling time τ_{sr} necessary to reduce the plate temperature to the balk average temperature T_{sr}.

$$T_{sr} = \frac{2}{h}\int_{x=0}^{x=\frac{h}{2}} T(x)dx. \qquad (16)$$

The cooling time τ_{sr} is a sum of time increments $\Delta\tau$ until the balk average temperature T_{sr} has reached the prescribed value.

3. Validation of the heat transfer model

The developed finite element model and software make possible fast calculation of temperature in the plate cross section. The plate can be cooled in air, in water or it can exchange the heat with the rolls. The model is two dimensional, however, for on-line calculations the number of elements in the direction of the plate width can be reduced to one. In this case it is possible to calculate the plate surface temperature, the plate bulk average temperature and the temperature distribution along the plate thickness. These parameters are sufficient for the effective control of the mill.

The model and software validation have been performed for the plate rolling parameters presented in Table 3. The results of computations have been compared to the measurements of the plate surface temperature carried out at the industrial steel plant [16]. The surface temperature measurements have been made with the use of the optical pyrometer. The model validation has been extended to the following numerical tests:

– plate temperature drop due to water falling down from the rolls cooling system,
– plate temperature drop due to heat exchange with the rolls,
– plate temperature rise due to plastic work,
– plate temperature drop due to convective heat transfer from the plate surface.

TABLE 3

Input data for the boundary condition validation test

L.p.	Plate height for subsequent cooling and rolling cycles, mm	Time of cycle, s	Roll radius, mm	Rolling speed m/s	Boundary condition
1.	225	8	–	–	Eq. (2)
2.	225	1	–	–	Eq. (6)
3.	225	5	1085	2	Eq. (2&7)
4.	201	12	1085	2	Eq. (2&7)
5.	171.6	14	1085	2	Eq. (2&7)
6.	143.9	15	1085	2	Eq. (2&7)
7.	116.2	15	1085	2	Eq. (2&7)
8.	88.3	16	1085	2	Eq. (2&7)
9.	66.4	19	1085	2	Eq. (2&7)
10.	32.5	72	949	2.5	Eq. (2&7)
11.	18.4	19	949	3	Eq. (2&7)
12.	13.6	19	949	3.5	Eq. (2&7)
13.	11.3	19	949	4	Eq. (2&7)
14.	9.8	34	–	–	Eq. (2)

In Fig. 1. the plate surface temperature computed for the data presented in Table 3 has been compared to the measurements. The differences between computed temperatures and measurements are minor for the first 100 s of rolling. The calculated temperature profiles should follow the results of measurements. Some differences can be explained by difficulties with measurements. Optical pyrometers are sensitive to factors which may have influence on the emissivity. Scale dust mixed with water vapor is the main factor which deteriorates the accuracy of measurements. In the finishing line after 150 s of rolling the differences are large and are caused by the water falling down from the rolls cooling system. This factor has not been taken into consideration in the test presented in Fig. 1. In Fig. 2. results with additional water cooling have been presented. Water flux rate of 0.1 $dm^3/(m^2\ s)$ significantly lowers the plate temperature and the results of computation compare well to the measured data. It has been shown that the water consumption is an important factor and must be considered for separate passes to ensure a proper temperature computations. In Fig. 3 model response to heat losses to the rolls as an result of contact with the rolled material in the deformation zone has been presented. It can be seen that this factor is much less important and reduces the average plate temperature by 0.7 % at the end of rolling. Influence of heat generation due to plastic work on the plate temperature has been shown in Fig. 4. In this case plate temperature rises by 3 %. Heat loses to the rolls are lower than heat gained due do plastic work for the analyzed rolling parameters. In Fig. 5 heat loses by convection have been presented. The plate cooling by convection is low mainly due to low rolling speed typical for plate rolling mills. Temperature variations along the plate thickness strongly depend on the heat flux specified on the plate surface, time of cooling and plate thickness. In Fig. 6 temperature field in the plate cross section after rolling is shown. The maximum temperature difference is 6 K.

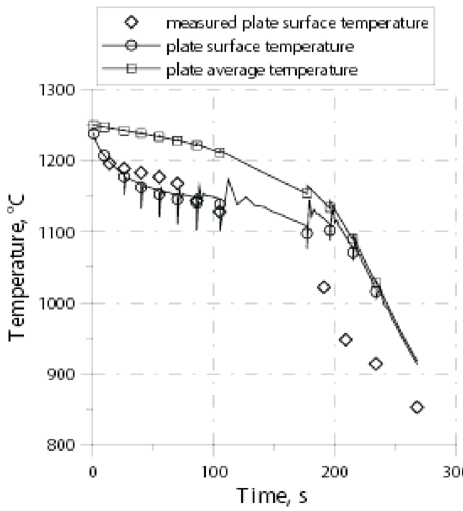

Fig. 1. Computed and measured temperature variations of the plate rolled according to the scheme presented in Table 3

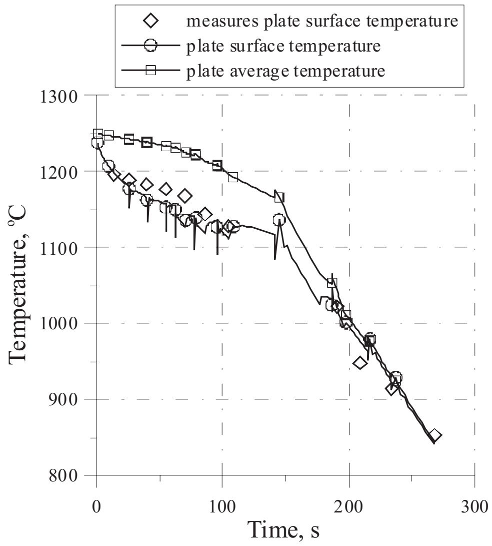

Fig. 2. Computed and measured temperature variations of the plate rolled according to the scheme presented in Table 3 with water cooling in the finishing line taken into account in the finite element model

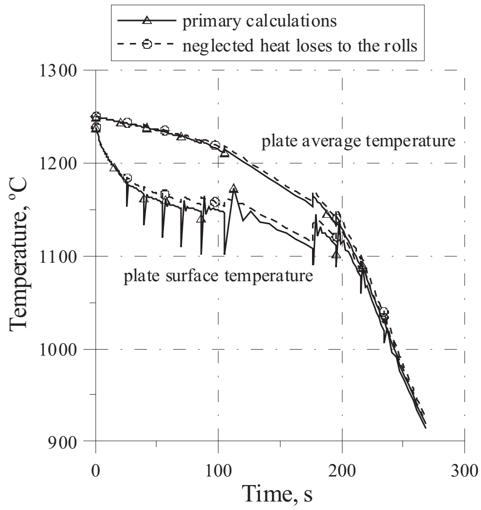

Fig. 3. Computed and measured temperature variations of the plate rolled according to the scheme presented in Table 3. Heat loses to the rolls were neglected in the finite element model

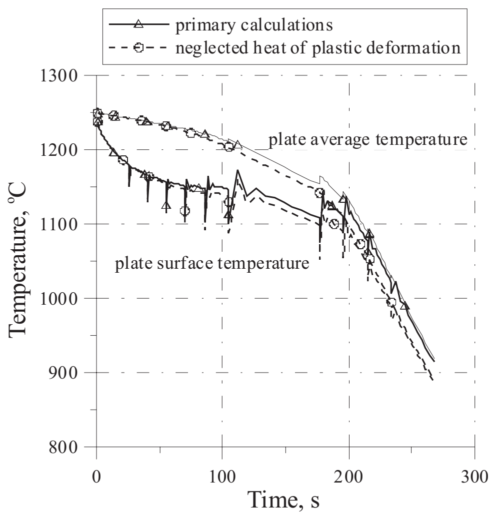

Fig. 4. Computed and measured temperature variations of the plate rolled according to the scheme presented in Table 3. Heat of plastic deformation was neglected in the finite element model

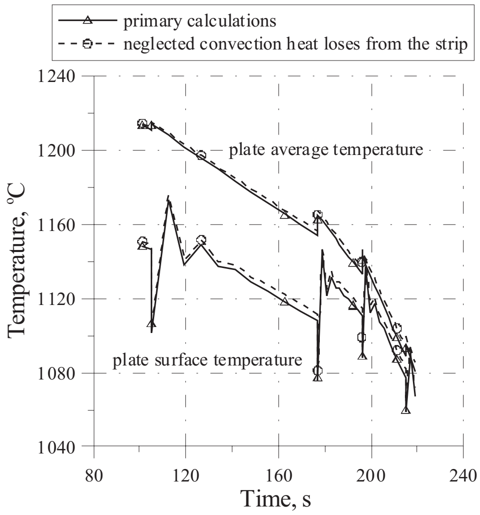

Fig. 5. Computed and measured temperature variations of the plate rolled according to the scheme presented in Table 3. Convective heat loses from the strip surface were neglected in the finite element model

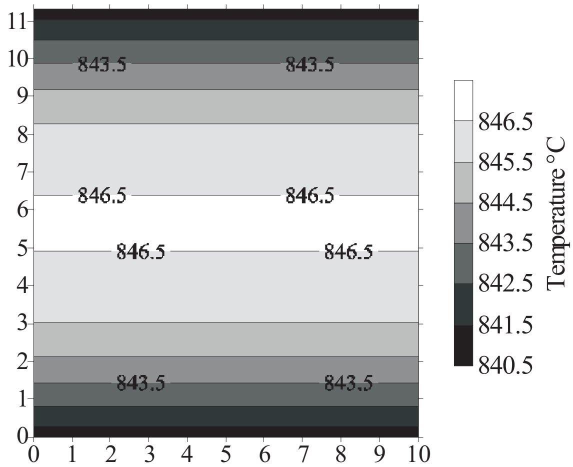

Fig. 6. Temperature field in the plate cross section after rolling according to the scheme presented in Table 3 with water cooling in the finishing line taken into account in the finite element model

4. Conclusions

On-line model for temperature computation during plate rolling has been developed. The model and software have been validated according to five numerical tests. Results of computations have been compared to measurements curried out at the industrial steel plants. The tests have shown very good response of the model to factors which have primary influence on the plate temperature. Heat generation due to plastic work have been included in the finite element model without time consuming computation of the plastic deformation of the workpiece. It has been shown that plate cooling due to water falling down from the rolls cooling system is an important factor and water consumption should be recorded to ensure proper temperature predictions in on-line control systems. Heat losses to the rolls and convective heat loses from the strip surface decrease the plate temperature by about 1,3 %. The computation time on typical PC computers of the plate temperature is short and do not exceeds 0.1 s for the whole production line.

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