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Mathematical modelling of controlled cooling and properties of hot rolled steel

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Abstract. Numerical model of controlled cooling in the production of steel hot rolled bars was developed. The numerical model and algorithm are completed to solve problems in controlled cooling of hot rolled bars in cooling beds. The controlled cooling is performed by special placement of hot rolled bars on cooling beds. By numerical model of controlled cooling is possible to predict a transient temperature field, microstructure evolution and hardness of round steel bars during their cooling in cooling beds. The numerical model of transient temperature field is based on control volume method. The hardness and microstructure distribution in steel bars has predicted by using equations of austenite decomposition kinetic. The algorithm for prediction is based the real chemical composition. Numerical model and computer program were experimentally verified by experimental work in a real industrial production of low-alloyed steel bars. The verification of developed numerical model was performed by comparison of simulated with experimentally evaluated results hardness and cooling curve.

1. Introduction

Continuous casting is the process whereby molten steel is solidified into a semi-finished products for subsequent rolling in the finishing mills. Steel from the furnace is tapped into a ladle and taken to the continuous casting machine. Solidification begins in the mould and continues through the zone of secondary cooling and strand guide. In this configuration, the strand is straightened, torch-cut, then discharged for intermediate storage or hot charged for finished rolling. The product end-use dictates the quality, grade and shape of the cast product (billet, bloom, slab, beam blank, and/or round). After straightening, the strand is transferred on roller tables to a cut off machine, which cuts the product into ordered lengths. Sectioning can be achieved either via torches or mechanical shears. Then, depending on the shape or grade, the cast section will either be placed in intermediate storage, hot-charged for finished rolling or sold as a semi-finished product. Prior to hot rolling, the product will enter a reheat furnace to adjust its thermal conditions to achieve optimum metallurgical properties and dimensional tolerances. After the hot rolling the mechanical properties of products can be adjusted by controllable cooling of products in cooling beds [1, 2].

Rate of steel specimen cooling essentially depends on workpiece geometry and characteristic physical properties of cooled steel and way of cooling. Relevant physical properties about which cooling rate depends are specific heat capacity of steel, heat conductivity coefficient of steel, steel density and heat transfer coefficient of steel body surroundings. For precise mathematical modelling these variables must be precisely estimated. These variables can be predicted by inversion method based on achieved cooling results and qualitative analysis of cooling curve [3-7].

Mechanical properties and microstructure distributions can be calculated by using both, the CCT diagram and thermo-kinetic equations for evaluation of kinetic microstructure transformations [1, 2]. For more precise prediction of adjustment of mechanical properties of products by controllable cooling of products in cooling beds, the additionally experimental work and development of computer program is needed to be done.

2. Mathematical modelling of heat transfer and microstructure evolution

The transient temperature field in an isotropic rigid body with a coefficient of heat conductivity, λ/Wm^{-1}K^{-1}, density, ρ/kgm^{-3} and specific heat capacity, c/Jkg^{-1}K^{-1}, without heat sources can be described by Fourier's law of heat conduction:

$$\frac{\delta(c\rho T)}{\delta t} = div\lambda\, gradT \tag{1}$$

The characteristic boundary condition is:

$$-\lambda \left.\frac{\delta T}{\delta n}\right|_{\mathrm{s}} = \alpha\left(T_{\mathrm{s}} - T_{\mathrm{f}}\right) \tag{2}$$

where α/Wm^{-2}K^{-1} is heat transfer coefficient of body surroundings, T_{s}/K is surface temperature, T_{f}/K is a temperature of body surroundings. Calibration of input data should be done according to achieved experimental results. If the variables ρ and c were accepted from other literature, variables λ and α must be estimated, i.e., calibrated according to variables ρ and c, based on experimental results. The input values of heat transfer coefficient can be optimized using Crafts-Lamont diagrams [8, 9].

The Equation (1) can be solved by using the finite volume method [10-12]. For example, 2-D finite volume formulation of the transient temperature field in an isotropic rigid body can be defined by [10]:

$$\begin{gathered} T_{ij}^{1}\left(\sum_{m=1}^{2} b_{\mathrm{I}(i+n)j} + \sum_{m=1}^{2} b_{\mathrm{J}i(j+n)} + b_{ij}\right) = \sum_{m=1}^{2}\left(b_{\mathrm{I}(i+n)j}T_{(i+k)j}^{1} + b_{\mathrm{J}i(j+n)}T_{i(j+k)}^{1}\right) + b_{ij}T_{ij}^{0} \\ i = 1,2,\dots,i_{\max}, \quad j = 1,2,\dots,j_{\max}, \quad n = 2-m, \quad k = 3-2m \end{gathered} \tag{3}$$

where T_{ij}^{0}/K is the temperature in the beginning of time step Δt/s, T_{ij}^{1}/K is the temperature in the end of time step Δt/s, $b_{ij} = (\rho_{ij}c_{ij}\Delta V_{ij})/\Delta t$, ΔV_{ij}/m^3 is the volume of the control volume, $b_{\mathrm{I}(i+n)j} = W_{\mathrm{I}(i+n)j}^{-1}$ and $b_{\mathrm{J}i(j+n)} = W_{\mathrm{J}i(j+n)}^{-1}$, where variables $W_{\mathrm{I}(i+n)j}$ and $W_{\mathrm{J}i(j+n)}$ are the thermal resistances for x axis. For example, $W_{\mathrm{I}(i+n)j}$ is thermal resistance between ij and $(i$-1$)j$ volume for n=0, and for n=1, $W_{\mathrm{I}(i+n)j}$ is equal to thermal resistance between ij and $(i$+1$)j$. The same nomenclature exists for y axis.

Discretization system has N linear algebraic equations with N unknown temperatures of control volumes, where N is a total number of control volumes. Time of cooling from T_{a} to a specific temperature in particular volume of cooled specimen is determined as the sum of time steps, and in this way, the diagram of the cooling curve in every grid-point of a specimen is possible to found out.

$$t_M = \sum_{m=1}^{M} \Delta t_m \tag{4}$$

where M is the number of time steps to the specific temperature. Fractions of ferrite, x_{F}, pearlite, x_{P}, bainite, x_{B}, martensite, x_{M} and austenite, x_{A} at some temperature can be estimated based on calculated time of cooling from 800 to 500 ºC, $t_{8/5\mathrm{e}}$. Relation between critical temperatures of austenite decomposition and hardenability properties are found out in Ref. [13].

Kinetics of transformations can be calculated by Avrami's isothermal equation. For purpose of numerical analysis by computer, it is convenient when kinetics of austenite decomposition is defined in an incremental form. The volume fraction, Δx of austenite transformed in the time interval Δt_i at temperature T_i can be calculated as follows [14]:

$$\Delta X_{(m)} = nk^{\frac{1}{n}} \left(\ln \frac{1}{1 - X_{(m-1)}} \right)^{1-\frac{1}{n}} \left(1 - X_{(m-1)}\right) \Delta t_{(m)} \tag{5}$$

In accordance to the Scheil's additivity rule, characteristic microstructure transformation is completed when transformed part of microstructure, $\Sigma\Delta x$ is equal to one The non-isothermal transformation kinetics can be described as the sum of a series of the small isothermal transformations. Kinetic parameters k and n from Eq 5 can be determined inversely [14].

Characteristic time of isothermal transformation was found out by using IT diagram of steel with standard chemical composition. IT diagram were additionally adjusted based on Jominy test results for applied steel [15]. The martensitic transformation relation can be expressed by Koistinen - Marburger general equation prescribing the extent of the austenite-martensite transformation [16]:

$$x_{\mathrm{M}} = \left(1 - x_{\mathrm{F}} - x_{\mathrm{P}} - x_{\mathrm{B}}\right)\left(1 - \exp\left(-0.011\left(M_{\mathrm{S}} - T\right)\right)\right) \tag{6}$$

where x_F, x_P and x_B represent ferrite, pearlite, and bainite, respectively. Increment of martensite in temperature depth delta $\Delta T = T_m - T_{m\text{-}1}$ is equal to: $\Delta x_M = x_M(T_{m+1}) - x_M(T_m)$.

Simulation of as quenched hardness is estimated by the conversion of the calculated cooling time, $t_{8/5e}$ to the hardness using the CCT diagrams [17]. Differences between the actual chemical composition of steel and chemical composition of standard steel for which CCT diagram was prepared should be taken into account by using Equation (5).

Mechanical properties of steel depend on degree of quenched steel hardening. Relevant mechanical properties, yield strength, R_e, modulus of elasticity, E, strain-hardening coefficient, K and strain-hardening exponent, n was estimated from hardness HRC [7, 18]. The dependences of true stress-strain diagram on temperature is found out [19].

3. Experimental work

The experiment was performed on two steel bars of 60 mm in diameter and 6000 mm long made of steel EN 20MnCr5. The chemical composition of steel EN 20MnCr5 was: 0.19 %C, 0.25 %Si, 1.21 %Mn, 0.001 %P, 0.001 %S, 1.13 %Cr, 0.15 %Ni, 0.04 %Mo.

Table 1 shows the comparison of the experimental and computer simulations results of cooling curves for studied bars. The results of the transient temperature field were measured at rolling bed which was adjusted for the numerical model needs. The range of pyrometer is from 700 °C up to 2000 °C. For lower temperatures, thermocamera can be used.

Table 1. Cooling curves of studied bars.

EN 20MnCr5		
Temperature/°C	Time/s	
	Experimental	Simulation
927	0	0
926	1	0
898	32	12.4
827	107	84.4
798	135	117.9
771	182	154.0
725	232	237.8
Hardness HV	218	219.4

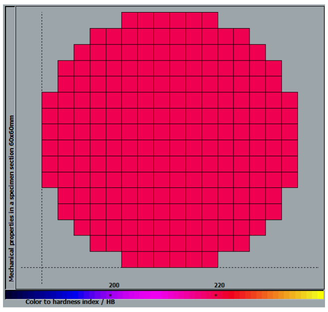

Figure 1. The result of simulation of hardness.

Numerical simulations are made by using the computer software BS-QUENCHING [10]. The result of simulation of hardness is shown in Figure 1.

4. Application

The developed model was applied in computer simulation of two cases of cooling of round bars made of steel EN 20MnCr5 with same chemical composition as was used in experimental work. The dimension of steel bars were of 40 mm in diameter and 6000 mm long. Numerical simulation was done for a case when one, separated bar was cooled alone and for case when two bars were cooled together, placed next to each other. Starting temperature, T_{start} of the steel bars in cooling bed was equal to 921 °C. For packed bars time step t_{step} when the second bar was placed to the cooling bed was equal to 25 s. The temperature of air, T_{air} was equal to 30 °C. The hardness and microstructure distributions of the steel bars after cooling and packed in different ways are shown in Figure 2 to 11.

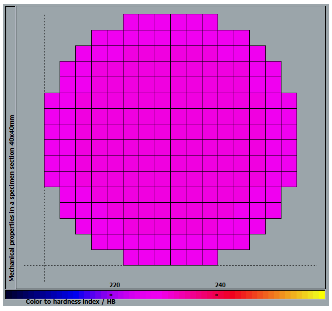

Figure 2. Hardness distribution of steel bar of 40 mm in diameter.

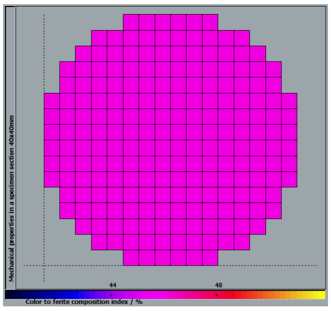

Figure 3. Ferrite distribution of steel bar of 40 mm in diameter.

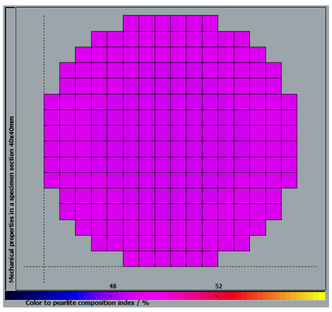

Figure 4. Pearlite distribution of steel bar of 40 mm in diameter.

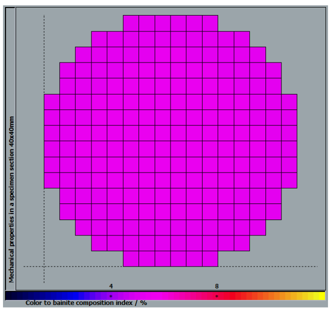

Figure 5. Bainite distribution of steel bar of 40 mm in diameter.

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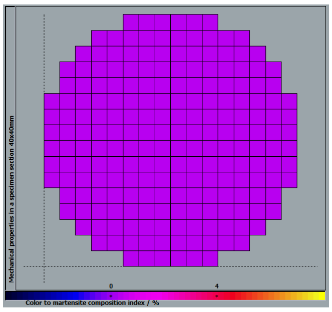

Figure 6. Martensite distribution of steel bar of 40 mm in diameter.

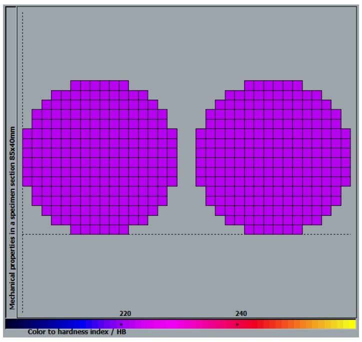

Figure 7. Hardness distribution of steel bars of 40 mm in diameter.

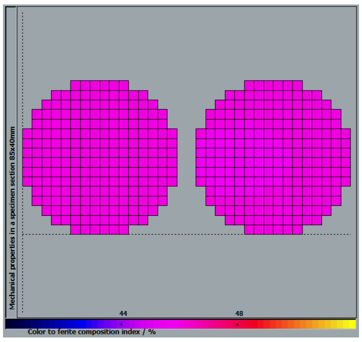

Figure 8. Ferrite distribution of steel bars of 40 mm in diameter.

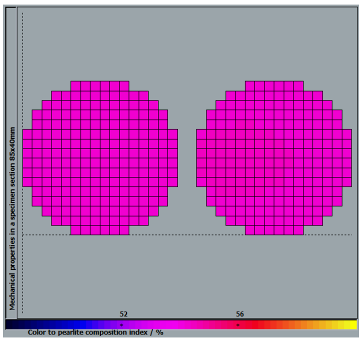

Figure 9. Pearlite distribution of steel bars of 40 mm in diameter.

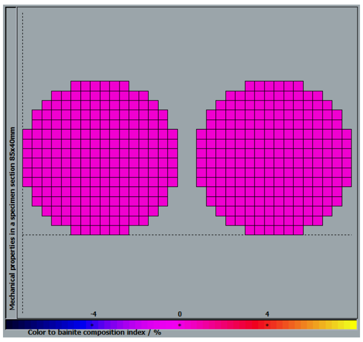

Figure 10. Bainite distribution of steel bars of 40 mm in diameter.

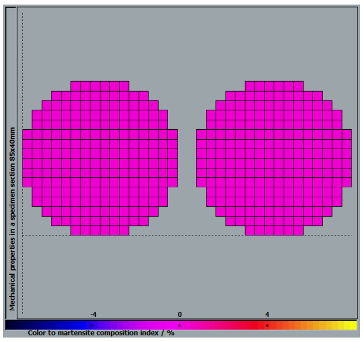

Figure 11. Martensite distribution of steel bars of 40 mm in diameter.

5. Conclusions

The numerical model of controlled cooling of steel bars in cooling beds in a production of steel by continues casting and rolling was developed. The developed numerical model consists of prediction of a transient temperature field, microstructure evolution, and hardness of round and rectangular steel bars during their cooling in cooling beds. The numerical model of the heat transfer is based on finite volume method. The algorithm for prediction of hardness and microstructure distribution in steel bars is based on continues cooling transformation, (CCT) diagrams of steel. The results were be improved by taking in account a real chemical composition of the steel. The verification of developed numerical model was performed by comparison of simulated cooling curves and hardness with experimentally evaluated results. The established model was applied in two cases of controlled cooling of different packed rolling bars in cooling beds. The minimum hardness without a minimum content of bainite and martensite was achieved when two bars were packed together. It can be concluded that by developed numerical model is possible to predict a microstructure composition and hardness distribution of steel bars during them controlled cooling by special placement in cooling beds.

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