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Modern trends in improvement of steel heating technology in continuous furnaces

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Abstract. The principles and approaches in the development and improvement of steel heating technology in the furnaces of rolling manufacture of various structural design, based on the systematic study of thermal physical and technological processes, including mathematical modeling, industrial experiments, development of rational temperature-thermal modes.

1. Introduction

This paper contains the results of the research we have been carrying out for many years in the field of technology of metal heating in the continuous furnaces. This study is based on the experience and knowledge obtained within the Ukrainian (Dnepropetrovsk) and Ural-Siberian metallurgical schools founded by the leading theoreticians and practitioners in the field of metallurgical heat: Semikin I.D., Taits N.Yy., Nevsky A.S., Timofeev V.N., Nazarov I.S., Kavaderov A.V., Kitaev B.I., Samoylovych Yu.A. et al. [1].

It is noted that in fact the trendsetters in the field of investigations of thermal performance of rolling mill furnaces today are the Ural, Siberian and Belarusian schools.

The purpose of this paper is to summarize the research for the last 10-15 years, performed by the scientists of Siberian Industrial Institute and the Belarusian National Technical University.

The study is focused primarily on experimental methods for studying the thermal operation of the furnaces, which functions in the lines of modern high productive rolling and tube mills (walking beam furnace of mill 850 and a furnace with walking hearth and walking beams of mill 320/150 of the Belarusian Metallurgical Plant, furnaces of pusher-type of mill 810 at Novosibirsk Metallurgical Plant, annular furnace axis-rolling mill 250 and continuous furnaces of mill 900/750 at Dneprovsky Metallurgical Combine n.a. F.E. Dzerzhinsky, pusher furnaces of mills 600 and 2250 at Alchevsk Metallurgical Combine [2-5], pusher furnace of mill 2800 at Orsk-Khalilov Metallurgical Combine, furnace with walking beams of mill 2000 at JSC “Severstal” [6], etc.).

The important role is played by theoretical studies of heat- and mass-transfer processes in fuel furnaces, including mathematical modeling and numerical methods for calculations of heating furnaces of modern design, first of all, with walking beams and crown heating, as well as of pusher-type for medium- and heavy-section mills [2-4, 6-10].

It should be noted that the Belarusian scientists and experts paid great attention to the study of nonlinear thermal and thermo-mechanical processes using different mathematical apparatus (different versions of numerical methods, approximate methods (method of equivalent sources)). Of course, these researchers made a significant contribution to the formation in effect of a new fundamental metallurgical science – nonlinear thermal mechanics and thermal physics of metallurgical production (Postolnik Yu.S., Timoshpolskiy V.I. et al.) [8].

The scientists of the Siberian scientific school paid much attention to the creation of resource saving thermal technological processes during the heating of large slabs and blooms in the continuous furnaces of various designs [6, 9, 10]. In detail they studied the mass-transfer processes with regard to the processes of decarburization and scale formation, as well analyzed numerical methods for solving nonlinear tasks and generalized the obtained results to ensure high performance of furnaces.

As an example, we provide results of the research aimed at improvement and development of energy and resource saving thermal technological processes in the heating furnaces of different structural design.

2. Research and results

In accordance with the system approach, in which the obligatory component was the experimental study of temperature fields inside the heated blanks during their displacement in heating devices, we conducted numerous experiments in conditions of real production in order to analyze the thermal operation of the furnaces, to evaluate the possibility of productivity increase and heat-transfer enhancement.

Figures 1 and 2 show the results of experimental studies of thermal treatment of special steel grades (for example, steel ShH15SG) during organization of blanks hot charge in the furnace of tube-rolling mill 850 (with walking beams) at the Belarusian Metallurgical Plant (BMP) and during heating in the furnaces of pusher-type mill 810 at Novosibirsk Metallurgical Plant [3].

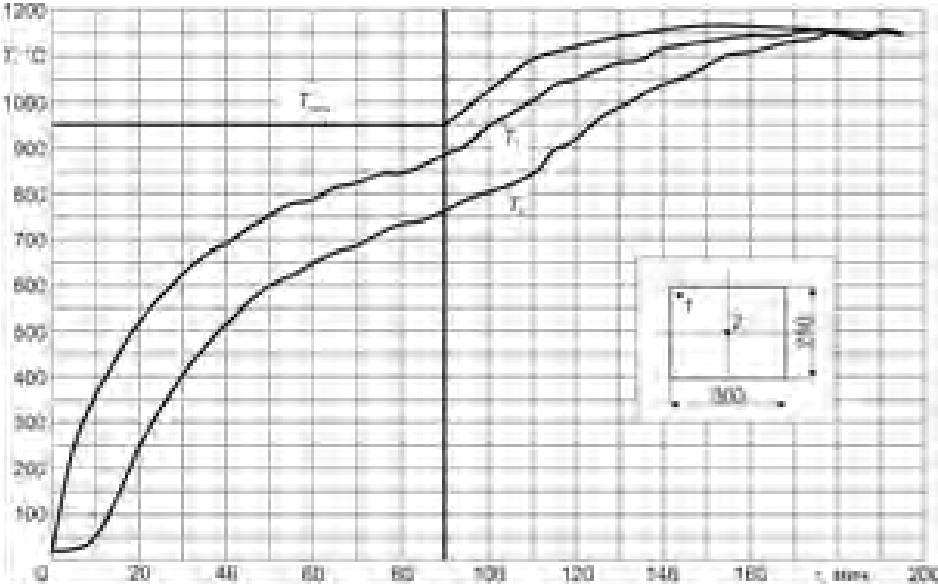


Figure 1. Change in the temperatures during blank heating 250x300 mm (ShH15SG) in the furnace of mill 850 at Belarusian Metallurgical Plant.

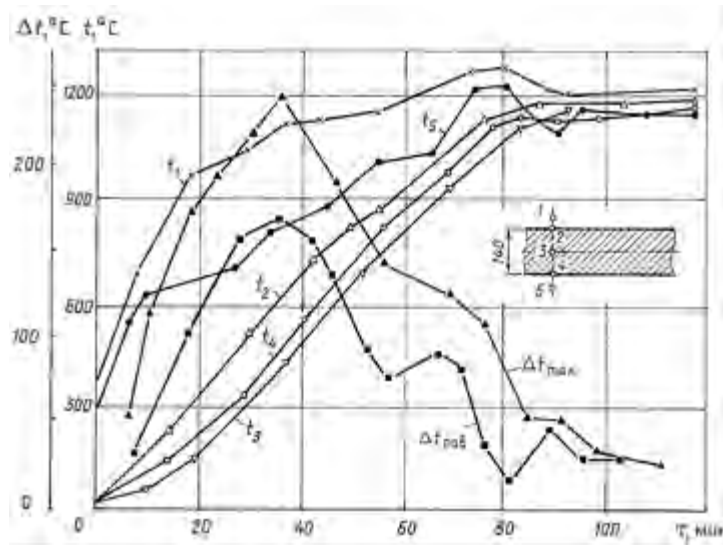


Figure 2. Temperatures change in the characteristic points of cross-section during slab heating (12H18N10T) according to the developed mode in the furnace of mill 810 at Novosibirsk Metallurgical Plant.

Figures 3 and 4 show the results of experimental studies of slab blanks heating in the heating furnace of a pusher-type and the furnaces with walking beams [6].

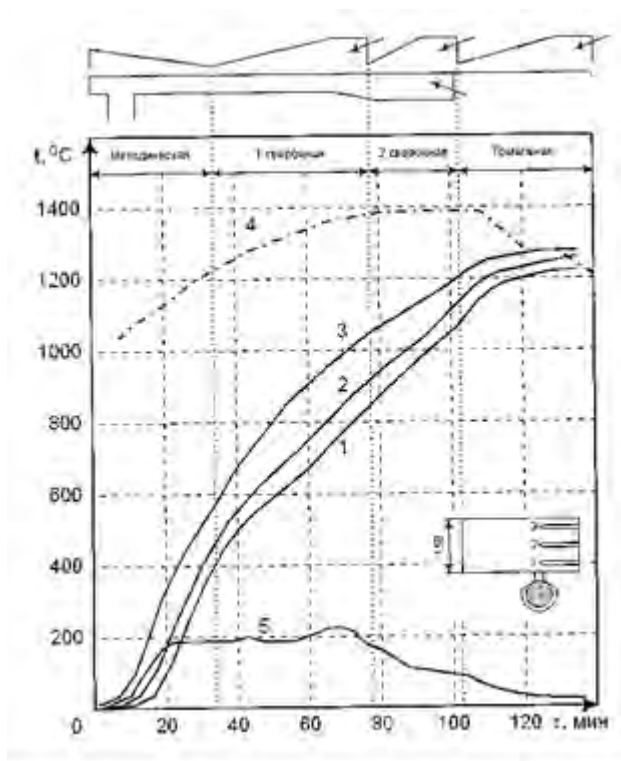


Figure 3. The results of experimental studies of slabs heating in the continuous furnace of plate mill 2800 at Orsk-Khalilov Metallurgical Combine.

In accordance with the research methodology further we carried out mathematical modelling of heat- and mass-transfer processes in the heating furnaces, and depending on the research purpose

developed and used a wide spectrum of mathematical models: the traditional metal heating model with boundary conditions of III type [2-6]; model of external heat-transfer [6]; coupled heat transfer (internal and external) [2, 3]; methods of optimal control of heating with a minimum scale formation [2, 4] and under the terms of the heat resistance of the metal [3]; methods for solving the thermal mechanics problems [3, 8]; modelling of interrelated processes of oxidation and decarbonization of steel [6, 9, 10].

As an example, some simulation results of heat- and mass-transfer processes in heating furnaces are given.

In the case of conjugated heat-transfer in the furnaces of pusher-type the system of equations for calculation of zones of II type (heat flows are defined) has the form:

$$\sum_{k=1}^{N_2^{u(l)}} (\alpha_{ki}^{u(l)} T_k^{u(l)} + g_{ki}^{u(l)} T_k^{u(l)}) + g_i^{0u(l)} + Q_i^{u(l)} = 0, i \in N_2^{u(l)},$$

where N – total number of zones;

N_2 – set of zones numbers of type II;

to calculate the heat flows on the metal surfaces (zones of the I type)

$$Q_i^{u(l)} = \sum_{k=1}^{N_2^{u(l)}} (\alpha_{ki}^{u(l)} T_k^{u(l)} + g_{ki}^{u(l)} T_k^{u(l)}) + g_i^{0u(l)}, i \in N_1,$$

where N_1 – set of zones numbers of type I (zones on the upper and lower metal surfaces, where the temperature is given);

$\alpha_{ki}, g_{ki}, g_i^0, Q_i^0$ – coefficients of radiation (effective taking into account the radiation selectivity) and convective heat-transfer, as well as the quantities of volumetric heat generation; “u” and “l” – the upper and lower furnace structure.

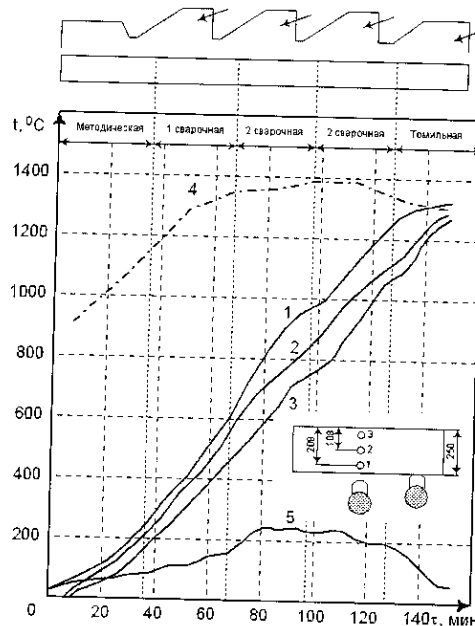


Figure 4. The results of experimental studies of slabs heating in the furnace with walking beams of broad-strip mill 2000 at JSC “Severstal”.

In the furnaces with walking beams and walking hearth at the preliminary stage the solution of nonlinear algebraic equations of heat balance is carried out taking into account the fact that the blank surface is a conventional plane, and at the next stage the calculation results are adjusted with regard to the reradiation between the blanks on the the furnace hearth with a gap [2, 3].

One of the most important aspects of improvement of technical and economic performance of the heating furnaces is the organization of metal hot charge. For this purpose an effective industrial heat technology of through (combined) process “steelmaking – pre-rolling heating” was developed [4] from the standpoint of reducing the specific fuel consumption and increase of furnace units productivity, as well as with regard to the thermal metal strength.

In this case the boundary conditions are of the form:

$$-\lambda \left(\frac{\partial T}{\partial n} \right)_{n=R_1, R_2} = \begin{cases} \sigma(T_{\text{surface}}^4 - T_{\text{environment}}^4) + \alpha(T_{\text{surface}} - T_{\text{environment}}) - \text{during hardening and cooling} \\ \text{at CCM furnace;} \\ \sigma_{\text{air}}(T_{\text{surface}}^4 - T_{\text{air}}^4) + \alpha_{\text{air}}(T_{\text{surface}} - T_{\text{air}}) - \text{during transportation to the furnace;} \\ \sigma_{\text{furnace}}(T_{\text{furnace}}^4 - T_{\text{surface}}^4) + \alpha_{\text{furnace}}(T_{\text{furnace}} - T_{\text{surface}}) - \text{during heating in the furnace.} \end{cases}$$

In general, the thermo-physical model for calculating temperature fields is supplemented by the expressions to determine the thermal stresses in the growing crust and in fully hardened billet during heating with hot and cold charges. At the same we used different classical theories (of Norton, Maxwell, Boli-Weiner, Parkusa, etc.). During calculation of thermal stresses of the crystallized billet the “building effect” and the stresses relaxation at increased temperatures were taken into account.

Figure 5 shows as an example the results of calculation of the temperature field in the casting process, transportation and heating in the bar furnace applied to the conditions of BMP.

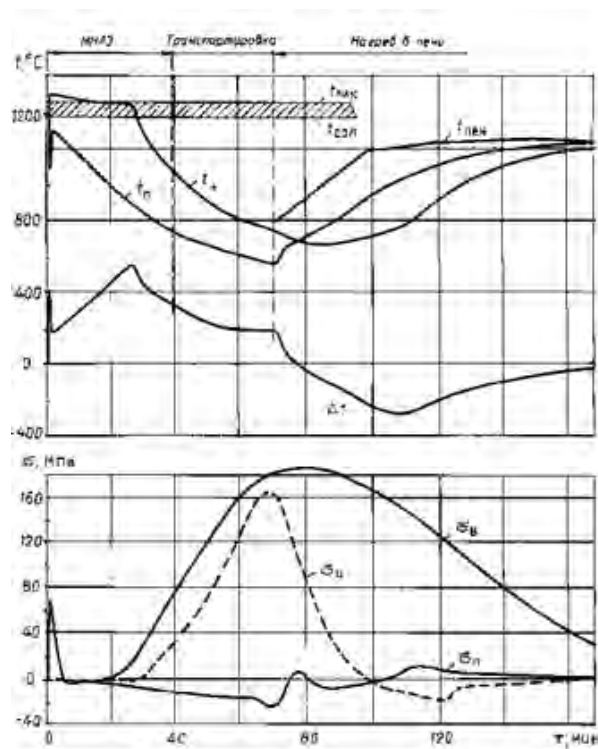


Figure 5. Changes in the temperature and tangential thermal stresses in the centre and on the billet surface 250 × 300 mm from steel 80 K in the through process of CCM – furnace of mill 850.

Much attention is paid to the complex research of thermal-physical processes of metal heating together with the processes of scale formation and decarbonization of blanks and special types of metal-roll [2, 4, 6, 9, 10].

In order to reflect the interconnected processes of scaling formation and decarbonization the deterministic mathematical model during metal heating [6, 9, 10], according to which the temperature change of the metal surface was approximated by the equation:

$$t = t_0 + A_1 \left(1 - \exp \left(-B_1 \frac{\tau_i}{\tau} \right) \right)$$

where t_0 – initial temperature of the metal;

A_1, B_1 – empirical coefficients depending on the heating mode;

τ_i – current point of time from the start of heating;

τ – total time of heating.

The thickness of the metal layer, which transformed into the scale, was determined by the ratio:

$$s = A \exp \left(-\frac{B}{T} \right) \tau^n$$

where A, B, n – empirical coefficients depending on the chemical composition of the steel, the composition of the atmosphere and other factors.

Unsteady carbon concentration fields were found on the basis of differential diffusion equation

$$\frac{\partial C}{\partial \tau} = \frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right)$$

where C – carbon concentration;

D – diffusion coefficient.

The diffusion coefficient was determined by the formula

$$D = (0.07 + 0.06C) \exp \left(-\frac{32000}{1.99T} \right) f_c^{alloy}$$

where C – carbon content in steel, %;

f – relative activity ratio of carbon in the alloy, taking into account the influence of alloying elements on the diffusion coefficient.

On the metal surface, contacting with the atmosphere, the boundary condition was of III type

$$-D \frac{\partial C}{\partial \tau} = \beta (C_{surf} - C_{atm})$$

where β – mass-transfer coefficient;

C_{surf} – the current concentration on the surface of the solid phase at the moment of time τ ;

C_{atm} – carbon potential of the atmosphere.

Using the given mathematical model implemented by the numerical method, rational temperature regimes for heating the continuous furnaces were developed [9, 10].

The experimental studies of kinetics of scale formation and decarburization of the rail steel were performed that allows us to obtain dependences of oxidation rate of rail steel grades on the temperature [10].

As an example in Figure 6 the nomogram for determining the decarbonized layer of steel during rapid heating is given, which is of great practical value in terms of improvement of furnaces productivity and ensuring the needed heating quality.

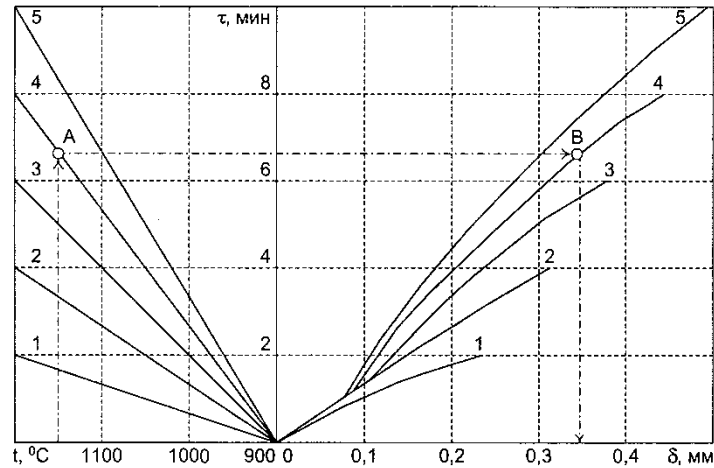


Figure 6. Nomogram for calculating the depth of the visible decarbonized layer during flash heat (heating rates: 1 – 150; 2 – 75; 3 – 50; 4 – 37.5; 5 – 30 deg/min).

The problem of optimal heating in the furnaces with walking beams with a minimal scale formation was formulated and solved [3, 4] using the method of main asymptotic optimization. The internal problem of prism heating is supplemented by the control function, in which the temperature of the furnace is given

$$A_1 \leq T_{furnace} \leq A_2, \quad \tau \in [0, \tau_{final}] \quad (1)$$

where A_1, A_2 – minimum and maximum temperature values of the furnace.

Since at the end of heating the blank should have a temperature distribution over the cross-section as close as possible to the desired uniform one, the restriction was

$$\max |T(x, y, \tau) - T_{final}| \leq \varepsilon \quad (2)$$

The formation of scale on the surface (on the edge) was described by Evans law.

The optimal control problem consists in the choice of the furnace temperature in the class of piecewise continuous functions, which satisfies constraint (1) and during the solution of the temperature problem, satisfying condition (2), gives the minimum value to the scale.

A similar approach is used to solve the optimal control problem by heating the cylindrical billets under the terms of heat strength. In this case as a constraint was taken

$$\sigma_z \leq \sigma_{per}; \quad \sigma_r \leq \sigma_{per}; \quad \sigma_\theta \leq \sigma_{per}$$

where σ_{per} – maximum permissible tensile stress;

$\sigma_z, \sigma_r, \sigma_\theta$ – axial, radial and tangential stresses in the cross-section of the billet.

3. Conclusions

In conclusion, it should be noted that the research team analyzed the thermal performance of continuous furnaces of rolling mills of various designs. The theoretical base of the international Ukrainian (Dnepropetrovsk) and Ural-Siberian scientific schools served as a foundation for the conducted research in relation to the existing equipment. The results of complex theoretical and experimental research allowed us to develop rational temperature-thermal heating modes, implementation of which ensured reduction in specific consumption of equivalent fuel, increase of heating furnaces productivity, improvement of heating quality due to reduction in scale formation and decarburization.

4. References

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