Int J Adv Manuf Technol (2015) 79:1797–1803
DOI 10.1007/s00170-015-6934-4

ORIGINAL ARTICLE

Energy-saving optimal control over heating of continuous cast billets

B. N. Parsunkin · S. M. Andreev · O. S. Logunova · T. U. Akhmetov

Received: 26 July 2014 / Accepted: 20 February 2015 / Published online: 10 March 2015

Abstract This paper describes a solution to the problem of energy-saving optimal control over heating of continuous cast billets in a transient operation of high-performance hot rolling mills. We set forth a technique for forecasting a total time of heating by the moment of charging billets into a furnace and suggested a technique for prompt calculation and optimal control following the surface temperature of heated billets subject to generation of set points for temperature controllers in heating areas and objective control of a thermal state of every heated billet before its discharge from the furnace and forecast of expected temperature of the feedstock after roughing mills. All studied techniques focus on software implementation entailing insignificant economic costs and guaranteed success.

Keywords Energy-saving mode · Metal heating before rolling · Thermal state of billets · Billet surface temperature · Temperature set points

1 Problems of optimal control over heating of continuous cast billets

Modern metallurgical plants include many processing stages, each of them has tasks of finding an optimal batch composition [1], optimal cooling [2, 3] or heating modes, and assessment of the quality of finished products [4, 5]. All developed measures aim at achievement of maximum performance, energy-saving, and high consumer properties of finished steel products. Billets transferring from steelmaking facilities to high-performance rolling mills should be heated in continuous heating furnaces consuming large volumes of fuel. In view of a current economic situation, reduction of specific fuel consumption during heating of continuous cast billets in a transient operation of high-performance hot rolling mills is a complex problem of current importance. Changes in the quantity of billets rolled per hour on mill 2500 at OJSC Magnitogorsk Iron and Steel Works within 24 h are given in Fig. 1.

Another problem occurring during energy-saving heating of continuous cast billets on hot rolling mill 2000 at OJSC Magnitogorsk Iron and Steel Works is heating of lots of billets, which vary in steel grades and initial thermal states, at the same time. A share of billets having a mass-average temperature of 500°C and over (hot charge) is within a range of 42–87 %.

Energy-saving heating modes are feasible, if heating furnaces do not limit performance of a complete hot rolling complex for products with a specific size, which requires maximum performance of furnaces.

It is justified in theory and proven in practice that energy-saving heating modes minimizing fuel consumption are applied when heating is intensified at a final period of heating time [6–8]. In this case, less heat energy is consumed to maintain the billet temperature at a higher level, waste heat of combustion products is used more efficiently, and metal loss through oxidation is reduced. When mill performance shows variable and unpredictable changes, process personnel reasonably have to maintain a required stock of billets ready for discharge, but in excess. Thus, intensive heating of billets starts almost at the entry of first top and bottom heated zones of continuous furnaces. Moreover, such mode of maximum performance is stipulated by

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B. N. Parsunkin · S. M. Andreev · O. S. Logunova (✉) ·
T. U. Akhmetov
Nosov Magnitogorsk State Technical University, Av. Lenina 38,
Magnitogorsk, Chelyabinsk 455000, Russia
e-mail: logunova66@gmail.com

S. M. Andreev
e-mail: andreev.asc@gmail.com

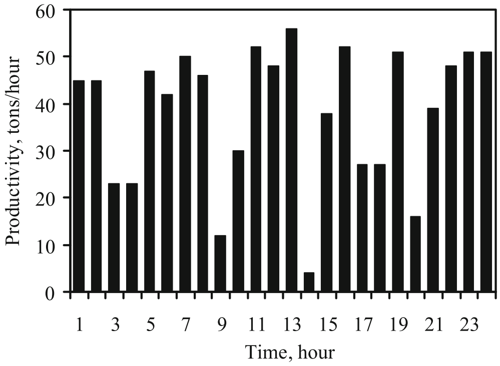

Fig. 1 Changes in the quantity of billets rolled per hour on mill 2500 at OJSC Magnitogorsk Iron and Steel Works

low-powered soaking (holding) zones at the exit of furnaces, i.e., during a final part of total heating time, whose heat load is only 12–15 % of total furnace heat load. These factors cause major problems when applying energy-saving optimal heating modes.

The mode of heat load distribution along the length of an operating area and a design of the operating area should be universal in the future as distinguished from current continuous furnaces; it means that they should provide for switching from the maximum performance mode into the energy-saving mode and backward depending on actual processes.

In view of existing conditions, a main objective of the energy-saving mode is prompt and task-oriented adjustment of fuel consumption in first heated zones subject to the current furnace capacity and an initial thermal state of charged continuous cast billets to ensure absolutely guaranteed quality of their heating even at a maximum capacity of the mill and minimum fuel consumption.

2 Test methods under production conditions

Under production conditions in heating furnaces of high-performance hot rolling mills up to several hundreds of continuously cast billets are heated following an individual temperature—time curve and the length of the operating area of the furnace. Transient heating conditions require an increased promptness of control actions in case of an optimal energy-saving heating mode. A generally accepted and standard temperature parameter used for automatic control is the operating area temperature of the furnace or the heating medium temperature measured by platinum-containing thermocouples in carbide and ceramic protection sheaths. This method for collecting information about the current temperature mode of heating billets in steady operating conditions of the furnace gives an ambiguous characteristic of the current state of heated billets [9]. Dynamic parameters of the information channel when measuring the operating area or heating medium temperature by different means are given in Table 1.

Lifetime of the Type S thermocouple is 2 months which is also unacceptable. An experimental transient response curve of the heated billet surface temperature measured by the total radiation pyrometer in the first heating zone of the continuous furnace on mill 2500 at OJSC Magnitogorsk Iron and Steel Works is given in Fig. 2.

Table 1 Dynamic parameters of the information channel

Parameters	Symbols	Values	Unit of measurement
Platinum-containing thermocouples [5]			
Time delay	τ_d	40÷60	s
Time constant	T_0	210÷252	s
Transfer ratio	K_0	0.14÷2.8	$^\circ C/\%$ of the stroke of the actuator
Total radiation optical pyrometer			
Time delay	τ_d	35÷40	s
Time constant	T_0	145÷150	s
Transfer ratio	K_0	2.0	$^\circ C/\%$ of the stroke of the actuator
Type S thermocouple in a standard ceramic sheath			
Time delay	τ_d	16÷18	s
Time constant	T_0	85÷96	s
Transfer ratio	K_0	2.8÷3.2	$^\circ C/\%$ of the stroke of the actuator

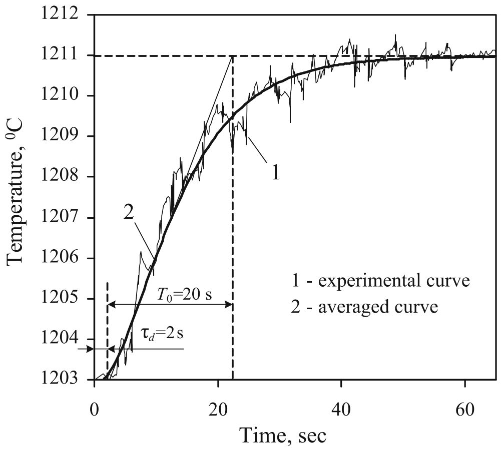

Fig. 2 Transient response curves of the heated billet surface temperature in the first heating zone of the continuous furnace on mill 2500 at OJSC Magnitogorsk Iron and Steel Works

High-frequency components of the information measuring signal were averaged by means of software ensuring double averaging of the information signal. Dynamic parameters of the billet surface temperature were $\tau_d = 1.5 \div 2.3$ s; $T_0 = 15 \div 22$ s; $K_0 = 2.0 \div 2.5$°C/% of the stroke of the actuator depending on installation of a sensor along the furnace length.

A main deterrent to the use of the billet surface temperature measured by the optical pyrometer is a theoretically justified objective statement on a significant error occurred when measuring the billet surface covered with scale through a selective radiating layer of combustion products influenced by a reflected radiation of a flame and lining of the operating area. Steps aimed at reducing an error of billet surface temperature measurement on the site and experience of using the billet surface temperature for efficient control over fuel consumption in first heated zones of the furnace by means of prompt and task-oriented adjustment when changing the operating speed of the rolling mill and the initial thermal state of heated billets are described in papers [7, 8, 10, 11]. Perhaps, thermocouples may provide for quite accurate measurement of the operating area temperature or the heating medium temperature, but the thermocouple tip temperature in dynamically transient modes being main operating modes of the furnace does not give an objective and prompt evaluation of a current thermal state of heated billets [6, 9]. Given a complex and critical problem to be solved, we have developed efficient information application and software for successful performance of the control task following values of billet surface temperatures in real time to perform optimal energy-saving control over continuous cast billets when mill performance is variable.

Under conditions of variable mill performance, the applied optimal energy-saving heating mode should not be a factor increasing risk of discharging billets which do not accumulate enough heat or entailing negative consequences. Mandatory compliance with technological conditions of billet heating provides for a priority of a reliable forecast of a billet heating period as of the moment of its charging to the heating furnace and adjustment of such period during heating. Under conditions of transient operation of furnaces, available methods for prediction of a heating period factoring into the speed of rolling facilities and consecutive measurement and smoothening of operation of billet transferring mechanisms do not ensure a required accuracy of prediction. To increase the accuracy of the forecast, the authors of the paper suggest methods based on determination of maximum performance of the technological section heating furnaces rolling mill coiler or a maximum period of billet processing during rolling according to the required standard size of a strip [12].

A total period of rolling of all billets which will be discharged from furnaces before the billet is to be charged again to the furnace will be an anticipated period of such billet heating [9, 10, 13]. An unpredictable period of scheduled, emergency, and undetected mill downtimes is a source of errors when forecasting a total heating cycle of billets. Therefore, it is necessary to adjust an estimated period in 10–15-min subject to a mill utilization factor and periods of scheduled and emergency downtimes [13]. The mill utilization factor characterizes a value of undetected downtimes and changes within a range of 0.87–0.95. An indirect indicator of undetected downtimes due to unsteady mill operation is frequency distribution of pauses between rolling of neighboring strips. While a standardized period is 5 s, under production conditions of mill 2000 at OJSC Magnitogorsk Iron and Steel Works, it is 5–60 s [6]. The adjustment procedure for a heating cycle and assessment of the accuracy of forecasts are stated in papers [6, 13]. The analysis of heating of 457 billets within a range of ±3 min revealed a 90.6 % deviation of an estimated heating cycle from the actual one for mill 2000 at OJSC Magnitogorsk Iron and Steel Works, when a heating cycle of cold billets is over 150 min.

3 A mathematical model to describe heating of the continuous cast billet under energy-saving optimal control

At present, significant results have been achieved in a theory of energy-saving optimal control over metal heating. Application of received results on the production site causes difficulties. The reasons are processing limits imposed on heating, design features of the operating area, and the adopted control strategy that focused on achievement of a maximum rate of response. When determining an optimal energy-saving curve of changes in a priority temperature parameter during heating, a main objective is to develop an appropriate dynamic model to calculate optimal temperature paths according to an actual heating process. The dynamics of thermal energy transfer during metal heating may be expressed as a system of equations given in [6]:

$$\begin{cases} \frac{dt_F}{d\tau} = \frac{1}{T_0}\left[U(\tau) - t_F(\tau)\right]; \\ \frac{dt_S}{d\tau} = \frac{1}{T_1}\left[t_F(\tau) - t_S(\tau)\right]; \\ \frac{dt_0}{d\tau} = \frac{1}{T_2}\left[t_S(\tau) - t_0(\tau)\right], \end{cases} \tag{1}$$

where $t_F(\tau)$, $t_S(\tau)$, $t_0(\tau)$ are the temperatures of heating medium, billet surface, and core of a heated billet, $°C$; T_0, T_1, T_2 are the time constants in accordance with channels "control action—heating medium temperature," "heating medium temperature—surface temperature," and "surface temperature—temperature in the billet core" determined during adjustment of the heating model under actual conditions; $U(\tau) = K \cdot V_G(\tau)$ is the control action, proportional to fuel consumption, $V_G(\tau)$, m^3/h; K is the transfer ratio for the channel fuel consumption characteristic control temperature, $°C/m^3$; τ is the current time, s.

As an optimality criterion, we have selected a criterion of minimization of fuel consumption:

$$J = \int_0^{\tau_h} \left[U(\tau)\right]^2 d\tau \rightarrow \min, \tag{2}$$

where τ_h is the estimated heating time, s.

It is necessary to select a control that upon expiration of the heating cycle, temperature of the heated billet transfers from an original state to a final set one, and the functional J takes on the lowest value.

To solve the problem of minimization, Pontryagins maximum principle was used [14]. When applying the maximum principle, it is important to select original values of the function of conjugate variables. In this case, to perform optimal energy-saving control over heating of many billets in the furnace in real time, it is required to increase computing power of control hardware. Therefore, to reduce the required computational resources, we have developed an analytical interpolation method for determination of original values of conjugate variables [6]. Calculated paths of temperature at optimal unrestricted energy-saving heating of a slab with a thickness of 120 mm, an original surface and core temperature of 0°C to a set final surface, and core temperature of 1250°C for a set heating time of 70 min are given in Fig. 3.

The result proves a basic statement. In case of available time for heating, it should be intensified at the end of the set time. The developed model of optimal control may be used to calculate the path subject to compliance with all processing restrictions [6].

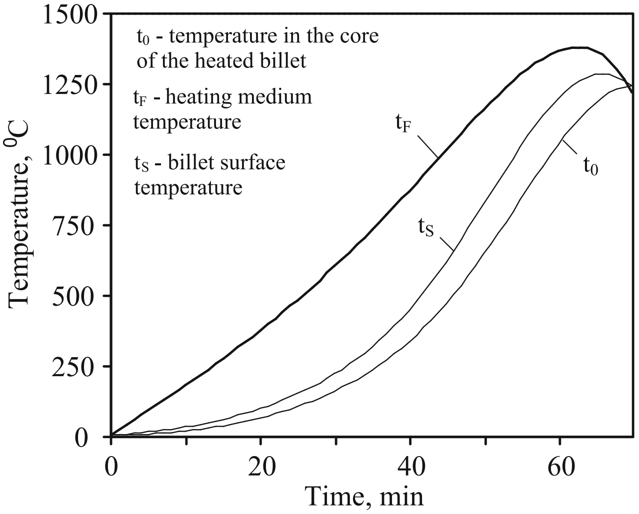

Fig. 3 Heating curves in compliance with processing restrictions

Ideally, every heated billet requires calculation and implementation of the individual temperature curve. At a fixed length of heated zones, all billets located in the zone has one control action fuel consumption determined by a temperature controller. To ensure the guaranteed quality of heating, it is feasible to control temperature according to the temperature curve of the coldest billet in the zone and at the same time to control the surface temperature of hot billets to avoid melting of scale. For this reason, determination of set points by a local controller in individual zones is critical.

The temperature set point for the heating controller in the zone is meant to be a set temperature of the billet surface or the operating area of the furnace along the zone length determined by location of a temperature sensor. To determine an optimal energy-saving distribution of heat loads along the length of the operating area, subject to a known time-temperature change, it is necessary to replace $d\tau$ with dl in used equations according to the expression:

$$\frac{dt_F(\tau)}{d\tau} = \bar{V}\frac{dt_F(l)}{dl} \tag{3}$$

$$\frac{dt_S(\tau)}{d\tau} = \bar{V}\frac{dt_S(l)}{dl} \tag{4}$$

$$\frac{dt_0(\tau)}{d\tau} = \bar{V}\frac{dt_0(l)}{dl} \tag{5}$$

where $\bar{V} = \frac{L}{\tau_h}$ an average speed of conveying billets along the furnace length L for the estimated time τ_h.

The current position of the billet in the furnace from the charging place in a current moment is:

$$l = \bar{V} \cdot \tau = \frac{L}{\tau_h} \cdot \tau \tag{6}$$

The calculated path of temperature distribution along the furnace length should be divided into several parts, each of them corresponds to the length of a specific zone. Temperature in parts of every individual zone is calculated as a weighted mean value along the zone length according to the expression for temperature sensor set points in the center of the zone:

$$\bar{t}_{\mathrm{SP}}\left(l\right)=\frac{\int\limits_{l_1}^{l_2} t_i\left(l\right)dl}{l_2-l_1} \qquad (7)$$

where $\bar{t}_{\mathrm{SP}}\left(l\right)$ is the weighted mean value of temperature; $t_i\left(l\right)$ is the calculated temperature of billets located in the zone; l_1, l_2 are the coordinates of the beginning and the end of the zone; $0 < i \leq n$ is the number of billets in every zone.

In practice, temperature sensors are installed for two-thirds of the length, nearer to the end of the zone. In this case, to calculate the weighted mean temperature, we use sections of the path where sensors are installed symmetrically with respect to the beginning and the end. To calculate temperature paths, it is necessary to take a lower limit of the control action at 600°C or higher at the furnace entry corresponding to the temperature of combustion products.

In case of variable performance, to guarantee heating and stock of heated billets which is reasonable according to the process, temperature set points in heated zones are feasible to be set as maximum values out of required calculated average temperatures of billets located in the zone according to the condition:

$$t_{Fi}^{\mathrm{SP}}=\max\left\{\bar{t}_{ij}^{\mathrm{SP}}\left(l\right)\right\}, i=\overline{1,m};\ j=\overline{1,n} \qquad (8)$$

where i is the number of the heated zone; m is the quantity of furnace zones; n is the quantity of billets in the zone as of the moment of calculation of set points; $\bar{t}_{ij}^{\mathrm{SP}}\left(l\right)$ is the required set point in the i-th zone for the j-th billet.

To prevent frequent changes of temperature set points when transferring a new billet to the zone, it is necessary to set a temperature range of 8–10°C as a dead band. Calculation methods for set points of the controller for the temperature of the operating area in bottom zones of the furnace are given in [16]. As practical experience shows, to increase the speed of control relying on the surface temperature, it is feasible to control the heating rate in bottom zones following the scheme of proportioning by volume of fuel consumption in relevant top zones with a proportionality coefficient of 0.85–1.0 depending on the furnace performance.

Calculated set points of the working area temperature in zones of the continuous furnace of mill 2000 at OJSC Magnitogorsk Iron and Steel Works for the optimal energy-saving mode for heating of continuous cast billets with a thickness of 250 mm of the cold charge within 230 min are given in Fig. 4.

4 Implementation of the software-based instrumental control over heating of billets

When using the energy-saving heating mode minimizing fuel consumption (Fig. 4), it is necessary to create a method ensuring objective current control of a thermal state of every billet prior to its discharging from the furnace to the mill. For practical purposes, it is enough to determine the surface temperature and difference in the surface temperature and the core of the heated billet [15]. It is known that there are methods for assessment of the quality of heating by the temperature of the feedstock and load of the rolling mill at first roughing passes which characterize the quality of heating of discharged billets. In this case, it is not practical to correct an error of heating. The developed method of assessment of the current thermal state of the heated billet before its discharge is based on the determination of thermal flows on the surface of heated billets inside and outside the furnace at a constant surface temperature of the heated billet. A full theoretical rationale of the suggested method is given in papers [6]. A flow chart of the software-based instrumental quality control over heating of billets performed on continuous furnace no. 6 of mill 2500 at OJSC Magnitogorsk Iron and Steel Works is given in Fig. 5.

The system includes the following elements:

- heating medium temperature sensors, represented by the thermocouple Type S installed in a side

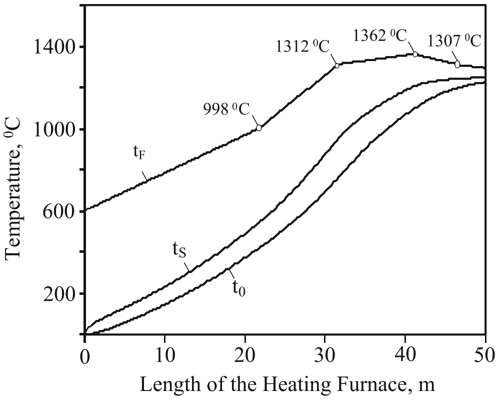

Fig. 4 Temperature set points in zones of the continuous furnace of mill 2000 at OJSC Magnitogorsk Iron and Steel Works for the optimal energy-saving heating mode for the cold charge (*points* indicate set points of controllers in heating zones of the pusher-type heating furnace)

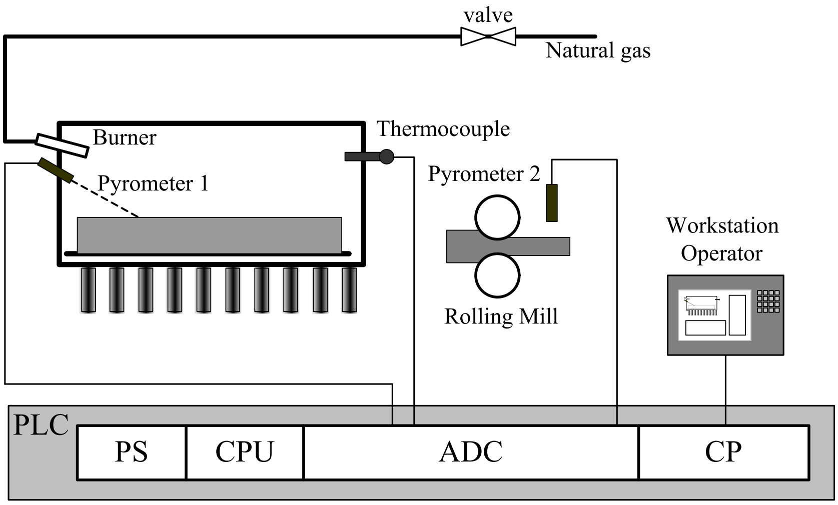

Fig. 5 Flow chart of the quality control system for heating of billets

wall 300 mm higher than the level of the heated billet,

- billet surface temperature sensor represented radiation pyrometer installed in a side furnace wall and aimed at the billet surface and used in a loop of the stabilization temperature in the soaking zone,
- a process interface unit represented by PLC "RK-131" Russian controller which is interfaced with a Workstation via RS-232C ensuring supervisory control over heating of billets in the furnace.

In view of a definite thermal state of every heated billet, actual operating conditions of the mill and location of the furnace with reference to a roughing stand, we developed a program to calculate the expected temperature of the feedstock for every second billet in a sequence of billets discharged from the furnace. To assess reliability and accuracy of the suggested method, we made a research on deviation of the feedstock temperature from the actual value. Heating parameters measured in the fifth zone of continuous furnace no. 6 when controlling the thermal conditions by the billet surface temperature are given in Fig. 6.

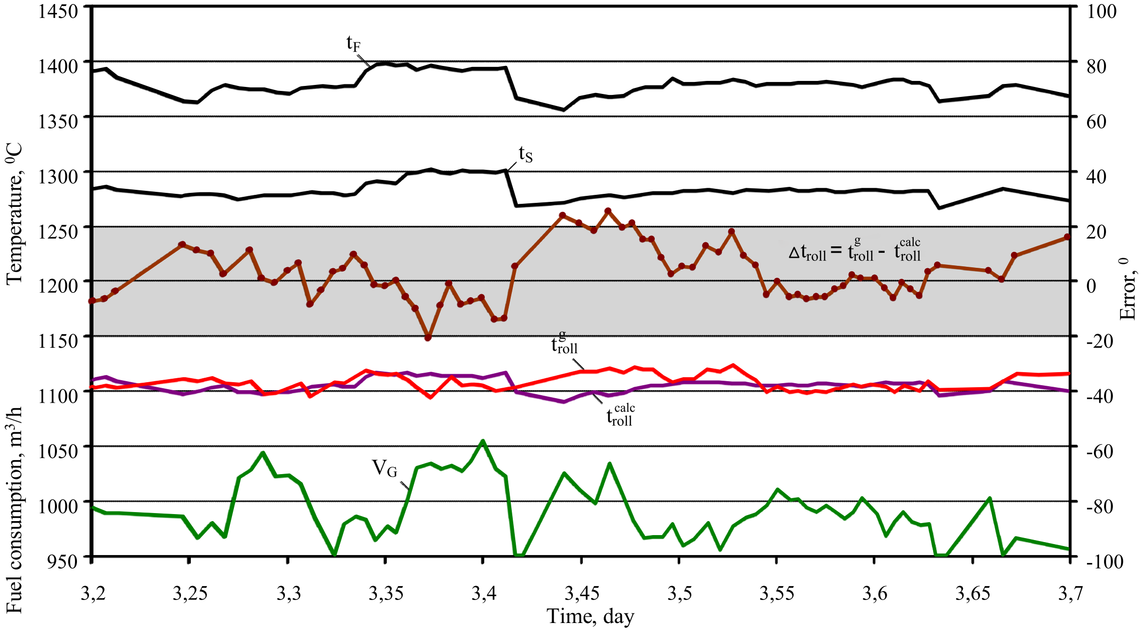

Fig. 6 Heating parameters measured in the fifth zone of the continuous furnace: V_g is the gas consumption; t^{g}_{roll} is the measured temperature of the feedstock after roughing mills; t^{calc}_{roll} is the calculated temperature of the feedstock after roughing mills; Δt_{roll} is the deviation of the calculated feedstock temperature from the measured one

5 Conclusions

In the course of pilot production at various heating control modes, the difference between the measured temperature of the feedstock after roughing mills and the calculated one was within a range of ±20° C. This guarantees prevention of unauthorized discharge of underheated billets to the rolling mill in case of the energy-saving heating control mode. A technology-based mode of control over billet heating subject to the billet surface temperature allowed reduction of specific fuel consumption by 3.5±4 % and increase in the average temperature of the feedstock only due to the increased response rate and focus of control on furnaces of mills 2350 and 2500 at OJSC Magnitogorsk Iron and Steel Works.

Methods for improvement of information and software support of the energy-saving heating control mode suggested in the paper successfully solve the problem of minimization of costs for expensive fuel consumed in variable operating conditions of heating furnaces for high-performance hot rolling mills. All reviewed methods focus on software implementation, including the transfer of the furnace to control by the billet surface temperature and may be used in any pusher-type furnaces of any capacity entailing no significant expenditures, but guaranteed economic benefit.

6 Summary

Having analyzed the received results, we determined feasibility, opportunity of implementation, and efficiency of the optimal billet heating mode in heating furnaces under complex variable operating conditions of high-performance hot rolling mills.

References

1. Logunova OS, Filippov EG, Pavlov IV, Pavlov VV (2014) Multicriterial optimization of the batch composition for steel-smelting arc furnaces. Steel Transl 43(1):34–38. doi:10.3103/S0967091213010051
2. Tutarova VD, Logunova OS (1998) Surface temperature analysis of continuously cast ingot outside air/water cooling zone. Steel Transl 28(8):18–20
3. Tutarova VD, Logunova OS (1998) Analysis of the surface temperature of continuously cast ingot beyond the zones of air cooling. Stal’ 8:21–23
4. Logunova OS (2008) Internal-defect formation and the thermal state of continuous-cast billet. Steel Transl 38(10): 849–852
5. Matsko II, Snegirev YV, Logunova OS (2012) Data acquisition and preparation methods for continuously cast billets quality analysis software. Appl Mech Mater 110–116:3557–3562. doi:10.4028/www.scientific.net/AMM.110-116.3557
6. Andreev SM, Parsunkin BN (2013) Optimization of billet heating modes in pusher-type furnaces. Nosov Magnitogorsk State Technical University, Magnitogorsk
7. Parsunkin BN, Andreev SM, Bushmanova MV (2003) Optimization of controlling the thermal conditions of heating furnaces. Steel Transl 9:65–67
8. Andreev SM, Parsunkin BN (2013) Optimal control system of industrial furnace thermal rate. Russian Internet J Ind Eng 2: 18–29
9. Andreev SM, Parsunkin BN, Zhadinskii DYu (2005) Obtaining reliable information on energy-saving regimes for the heating of continuous-cast semifinished products prior to rolling. Metallurgist 49(9–10):366–371
10. Parsunkin BN, Andreev SM, Obukhova TG, Akhmetov TU (2013) Reduction of specific fuel consumption when controlling heating conditions subject to the surface temperature of heated billets. Comput Aided Technol Manuf 5:302–309
11. Kopelovich AP (1963) Automatic control in ferrous metallurgy. Metallurgizdat, Moscow
12. Parsunkin BN, Fomichev AV, Katasonov SV (1998) Determination of the movement speed of billets in a continuous furnace. Electrical Systems and Complexes 3:156–163
13. Parsunkin BN, Andreev SM (2003) Predicting the heating time of continuous-cast billet in a stepping-beam continuous furnace. Steel Transl 33(1):47–52
14. Pontryagin LS, Boltyansky VG, Gamkrelidze RV, Mishchenko EF (1983) Mathematical theory of optimal processes. Moscow, Nauka
15. Parsunkin BN, Andreev SM, Logunova OS, Akhmetov TU (2014) Assessment methods for a thermal state of heated billets before their discharging from furnaces in an energy-saving control mode. Automation in the Industry 1:52–56
16. Panferov VI (1997) Calculation of set points of temperature controllers in zones of a continuous furnace. News of higher educational institutions. Ferrous Metallurgy 6:20–24