PREDICTION OF A HEATING PROCESS IN CONTINUOUS FURNACES WITH REGARD TO THE ECONOMY OF OPERATION

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Abstract
Heating of material in continuous reheating furnaces is often accompanied by uneven betting material to the furnace, which has an effect on the resulting parameters of the heated material. Too long heating leads to the exceeding of optimal temperatures and operating inefficiency, too short heating leads to insufficient heating of the material. Deviations from the standard set of parameters hot material may occur with subsequent further processing in successive forming technologies. To determine the optimal heating of the material in the furnace is a complex and difficult task. The aim of the article will examine possible modes of heating in a continuous furnace with respect to establishing the criteria of heating in order to optimize heating process.

Key words:
heating, furnace, model, optimal control, simulation

1. INTRODUCTION
A heating of materials is a common technological process. In the process of metallurgical production this operation is particularly common in hot rolling mills. The whole area of metallurgy is characterized by a high energy consumption. Therefore, even in heating furnace segment it is true, that even a small percentage of a reduction of an energy consumption can lead to very interesting economic benefits. These savings can be achieved in several ways. Below it will be shown only one possible way leading to savings and to an optimized control of own heating unit. In rolling mills, when the heating process is dictated by the rhythm of the rolling mill work, the control of heating furnaces must solve a complex task together with the whole technology of a rolling line. The part of the proposal optimizing of a heating furnace control is a rigorous evaluation of a furnace operation during its normal operation. Data from this operation forms the basis of the optimum control. It has several purposes: to verify models of heating materials, to select of appropriate operational models of heating, to set parameters of the dynamic model behaviour of the furnace technology. These data necessary for the creation and generally the verification of the model is obtained using data mining methods. As a mathematical-physical model of an optimization of heating can be used the model built upon the idea of the Pontragin’s principle of maxima. Using the operating data an example of verification of heating material in a continuous furnace and potential contribution of optimal control will be shown.

2. MATHEMATICAL-PHYSICAL MODEL AND DESCRIPTION OF THE PROCESS OF HEATING AS A DYNAMIC SYSTEM
The technology of the heating furnace can be divided into several parts:
the transport of heated slabs in the furnace during heating; the furnaces heating system; the process of heat transfer from the furnaces atmosphere to the heated slabs; the heat transfer from the surface of the slab
inside the slab and heating of the material of the slab. For mathematical and physical description is based on the common theoretical combustion gas temperature, theoretical calorific value of gas, the amount of heat contained in preheated air. For models of two factors are important: a relationship between the power the furnace and slab surface temperature; a relationship between the temperature of furnace environment and the surface temperature of the slab. Optimality criterion of the fuel consumption can be constructed so that of the relationship between the mean temperature of the material and the fuel consumption for heating is described.

\[ I(t + \Delta t) - I(t) = m \bar{c} [T_S(t + \Delta t) - T_S(t)] = \eta Q, \] (1)

where \( I \) is the enthalpy [J], \( t \) time [s], \( \Delta t \) is the increment of time, \( m \) is the weight of the heated material [kg], \( c \) mean specific heat capacity [J kg\(^{-1}\) K\(^{-1}\)], the mean temperature of the material [°C], \( \eta \) is the efficiency of heating, \( Q \) is the heat supplied to the furnace, thus its input [J].

The relationship between the system and heating efficiency can be determined only with difficulty. In [1] and [4] is described the relationship between the specific consumption and the temperature of the surface of the material in the form of a transfer function of the first order. Relationships using the variable \( p \) are images in the Laplace transform.

\[ T(S, p) = \frac{A}{K_y Q_{cp}(p)} \left( \frac{1}{p \tau_r + 1} \right), \] (2)

where \( T(S, p) \) is the image of the material surface temperature [K], \( K_y \) is the coefficient indicating how much of the total amount of heat is distributed to a place in the oven measuring coordinate \( y \). \( A \) is the amplification of this system [kg K W\(^{-1}\)]. \( \tau_r \) is the transfer time constant [s], \( Q_{cp}(p) \) is the image of the specific power consumption [W kg\(^{-1}\)].

2.1 Transportation of heated slabs in the furnace

Common slab heating furnaces have slabs placed at certain predetermined locations in furnaces. The number of these positions is up to several tens. In the text below it will be considered the furnace with by positions. The first position is the inlet position; the last 56th position is the outlet position. As it was mentioned in the introduction, the material shift from one position to the next position is determined by the rhythm of rolling. Slabs always remain in the designated position some time and after removing the heated material from outlet position the step of a furnace may occur when slabs shift one position toward to the furnace outlet. Despite the fact that their motion is irregular, we consider the movement of slabs as a fluent motion from the oven inlet to its outlet.

2.2 A furnace heating system.

A furnace heating system burns the heating medium. Furnace combustion burner burn heating mixture of a gas with usually preheated air using more or less optimal ratio of combustion. The burners are located in different zones of the furnace. The inlet area usually is not heated. A common method of heating and movement of material is counterflow, material moves opposite the direction of movement of combustion gases. This fact is very relevant in the sense that if power consumption is increased in any of the zones at the end of the furnace, the temperature rises not only in this area but in all zones that lay back from this area. The temperature of furnace atmosphere is measured by thermocouples.

2.3 Heat transfer from the surface of the slab inside the slab

The behaviour of this system can be described by a simple transfer of the first order. To determine the degree of heating of the material is possible to use the mean temperature of the material. The relationship
between surface temperature and the mean temperature of the material is once again given by a simple first order transfer function.

From the above description would suggest that the behaviour of systems described by simple equations for proportional integral system of first and second order, the solution is easy. But the problem is that the dynamic behaviour of the system depends on the temperature of the heated material. Thermo-technical properties of steels vary significantly in the temperature range, which reaches the material in heating furnaces. A change in these parameters, which are the specific heat capacity of steel, thermal conductivity, specific density and coefficient of thermal expansion, leads to the changes in the time constants.

3. THE POSSIBILITIES OF MODELING OF HEATING.

For the modelling of the behaviour of dynamic systems the Matlab and Simulink serve well. Based on the selected operating data of reheating furnace the identification of the dynamic behaviour of systems was made, i.e. the determination of their time constants was made. For a description of the dynamics behaviour of system power of the furnace – the furnace environment temperature changes and the surface slabs temperature changes amplification $A$, factor $K_y$, time constant $\tau$, and specific power $Q_{cp}$ were calculated.

To evaluate the economy of heating burn is an important parameter consequently surface oxidation of heated steel. To calculate the relation for specific surface burn the dependence on the surface temperature of the material can be used in the form

$$a_y = \sqrt{\frac{2K}{B} \frac{e}{T_{pov}}}.$$  

(3)

In accordance with the reality at the beginning heating we consider zero mass scale. The values of coefficients are $K = 76233 \text{[kg}^2\text{Km}^{-1}\text{s}^{-1}]$ and $B = 17057 \text{[K}^{-1}]$ [1], [2]. An oxidation process may be solved using artificial intelligence, too. [3], [4].

4. THE MODEL STRUCTURE

Major block structure of the model is shown in Fig. 1.
The meaning and features of inputs, outputs, signals and blocks is as follows. Current simulation time Sim_time is an input signal of the block Position, which of the current simulation time determines the position of the simulated material in the furnace. Indication of the position of the input block T_furn that is based on the current position determines the temperature in the furnace above the designated point. This value is passed to the output of its T_furn.

The block T_surf provides calculation of the surface temperature T_surf using signals T_furn and Position. From the surface temperature T_surf the block T_surf_T_mean determines the mean temperature of the material T_mean, and the block T_surf_Spec_burn calculates the specific surface burn Spec_burn. Based on the temperature in the furnace T_furn and the current position Position block T_furn_Qcp calculates instantaneous specific fuel consumption and integral specific fuel consumption from the start of heating. Another case of using simulations is described in [5]

5. THE PURPOSE AND RESULTS OF SIMULATIONS

The purpose of described above model is the verification optimal heating strategies for the walking beam furnace. Here only the selected simulation is shown. Characteristics of the different simulations are summarized in the table 1. Time of heating is 18000 s.

Table 1. Temperatures in zones (°C)

<table>
<thead>
<tr>
<th>Sim. No.</th>
<th>Zóna 1</th>
<th>Zóna 2a</th>
<th>Zóna 2b</th>
<th>Zóna 3a</th>
<th>Zóna 3b</th>
<th>Zóna 4a</th>
<th>Zóna 4b</th>
<th>Zóna 5a</th>
<th>Zóna 5b</th>
</tr>
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<tr>
<td>1</td>
<td>300</td>
<td>400</td>
<td>400</td>
<td>1100</td>
<td>1100</td>
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<td>400</td>
<td>400</td>
<td>900</td>
<td>900</td>
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<td>1320</td>
<td>1260</td>
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<tr>
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<tr>
<td>4</td>
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<td>724</td>
<td>779</td>
<td>900</td>
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<td>1320</td>
<td>1260</td>
<td>1260</td>
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<tr>
<td>5</td>
<td>599</td>
<td>724</td>
<td>779</td>
<td>820</td>
<td>820</td>
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<td>1320</td>
<td>1260</td>
<td>1260</td>
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<tr>
<td>6</td>
<td>599</td>
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<td>1320</td>
<td>1320</td>
<td>1260</td>
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</tr>
</tbody>
</table>

The table shows that the simulation focused on three method of heating:
- a slow heating with subsequent fast heating;
- a medium heating with faster heating rate in the middle of the furnace;
- a fast heating with the reducing the heating temperature at the end.

Specific objectives are total specific fuel consumption, specific burn, reaching the target surface temperature and the mean temperature of the material.

Fig. 2 Specific fuel consumption
Fig. 3 All over specific fuel consumption
Figure 2 shows the progress of immediate and specific fuel consumption and figure 3 shows summary specific fuel consumption, i.e. specific fuel consumption from the beginning of heating. Data 1 corresponds with the simulation No. 1, simulation Data 2 with the No. 2, etc.

Figure 4 shows a plot of the specific burn during heating.

In the fig. 5 the temperature of the furnace environment furnace \( t \) above the slab, the surface surface \( t \) and the mean temperature mean \( t \) are shown. For clarity they are shown only simulation waveforms for No. 2 and No. 6 simulations here.

For the evaluation of the optimality of the course of heating conditions are taken at the end of heating time. Fig. 6 shows the reached temperature of slabs; the mean temperature T mean, surface temperature T surf and the temperature of the furnace environment T furn at the end of the furnace [6].

Fig. 7 shows a summary of specific consumption for heating Sum of spec. consumption and total burn Specific burn and value of \( C \times B \), which is the product of specific burn and specific consumption, which determines the profitability of the particular strategy of heating. Multiplication of both criteria leads to more easily to determine the optimal strategy.

6. CONCLUSION

Designated space does not allow summarize the overall optimization problems of continuous heating furnaces. The presented results are based on validated models that have been verified on real operational data. The results demonstrate that the preferred modelling method of the thermal processes in continuous furnaces is sufficiently accurate to be able to evaluate different strategy of heating.
As mentioned earlier in the introduction, the operation of these furnaces strongly influenced by subsequent operation of the technology that determines the performance of the furnace. Here chosen simulations were performed just for one rate of heating. However optimization algorithms must be able to choose as a strategy for various heating rate of the material, as well as irregular operation of the furnace, where the passage of material through the furnace stops for a shorter or longer time[7]. Here it is necessary to look for a strategy responding to the power the furnace, to a furnace environment temperature, so that at the end of downtime and subsequent smoothly furnace work to reach required parameters of the heated material on the one hand, and to minimize losses and fuel consumption during downtime on the other hand.

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LITERATURE