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Influence of the Scaling upon the Heating Process of Steel Slabs in a Pusher-type Furnace

Utjecaj ogorine na proces zagrijavanja čeličnih slabova u peći potisnog tipa

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In the frame of this paper an existing and a proposed more optimal temperature regime for heating of steel slabs in a pusher-type furnace is analysed. The influence of steel oxidation upon the heating process and its influence upon the optimal temperature regime calculation is also investigated.
Key words: pusher-type furnace, scaling, heating of steel.

U okviru ovog rada analiziran je postojeći i predloženi optimalniji temperaturni režim zagrijavanja čeličnih slabova u peći potisnog tipa. Također je istražen utjecaj oksidacije čelika na proces zagrijavanja i njezin utjecaj pri proračunu optimalnog temperaturnog režima.
Ključne besede: peć potisnog tipa, zagrijavanje, oksidacija.

1. Introduction

The intensity of oxidation of the heated steel generally depends on the affinity of the basic material, i.e. of iron and alloying elements towards oxygen, on gas composition above the heated steel, on the temperature of furnace space and the time of exposure to high temperatures. Oxidation doesn't depend solely on the presence of free oxygen in the furnace atmosphere. Aqueous vapour, carbon and sulphuric dioxide also appear as reactants. Results achieved regarding the influence of these factors on steel scaling revealed differences, the cause of which has not been explained adequately so far. Quantitive values regarding the extent of the scaling achieved during the investigation stated in references, are given as medium values of several repeated investigations. Such data can be useful for determining the influence scale has on steel heating, especially due to the changes in scale composition throughout the depth of the scale layer, as stated in references, the layer may significantly influence the coefficient of heat conductivity. However, it should be taken into consideration that iron oxidation in the course of steel heating also introduces heat into the process. Yet, exploitation of such heat is insignificant, as the oxygene necessary for iron oxidation is brought from the furnace surroundings, i.e. with the air required for fuel combustion, therefor a corresponding quantity of nitrogen is present, which is heated to the temperature of waste gases. A part of the heat produced by iron oxidation is lost by this heating. Formation of scale diminishes utilization of heat from waste gases inside the furnace, as the heat source on the steel surface decreases the possibility of heat transfer from the waste gas to steel, and due to the low coefficient of conductivity, heat conductivity is limited as well. The latter indicates the importance of defining the thickness of the scale layer on the surface of the heated steel semiproduct. The thickness of the scale layer in relation to the one obtained by calculation from referential data may be checked by means of plant investigations in actual process conditions of given steel heating. This paper also presents the research results regarding the influence of scale layer thickness on the time required for the low carbon steel heating in a pusher-type furnace of a nominal capacity of 67 t/h.

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2. A pusher-type furnace and the research results

To study the influence scaling has on the rate of charge heating, in other words the temperature regime of the furnace, a temperature profile of the wall and of the upper surface of the charge lengthways of the pusher-type furnace is determined by an optical pyrometre and presented by a diagram in **Fig. 1**. The length of the furnace from the slab charging line up to the front wall is 26,5 m, and the furnace length covered with slabs is 24,4 m. The inside width of the furnace is 4,6 m. A schematic presentation of the furnace profile and of its main dimensions is given in **refer-**

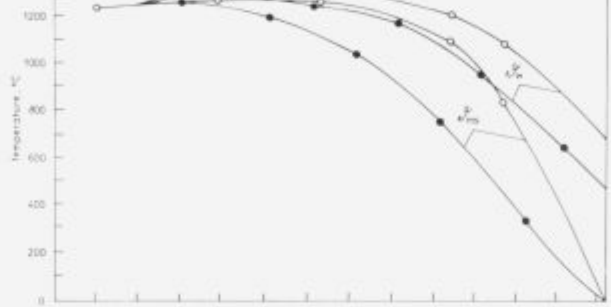

Figure 1: Temperature profile of the wall and of the upper charge surface along a pusher-type furnace

Slika 1: Temperaturni profil zida i gornje površine uloška po dužini peći potisnog tipa

ence 1. In the course of determining the temperature profile slabs of the St 12 (per DIN) quality, with dimensions of 430x190x3800 mm and mass of 2500 kg were heated. The furnace capacity was 31,4 t/h. To be able to estimate the value of the determined temperature regime, due to low furnace productivity, a numerical method was used to obtain an optimal temperature regime in such conditions. The numerical method[2] starts by dividing the calculation into several sections within which variables may be considered constant with regard to temperature. While the material was passing along the section length, the charge was considered motionless and its heating was calculated as such as in a hearth furnace of the same temperature, the temperature flow of the flue gas was determined on the basis of the section heat equilibrium.

According to this, a preheating and heating zone was divided into five sections, the soaking zone itself consisted one of the sections. The calculation presumes that heating effects from below were equal to those from above in the heating and preheating zone which was confirmed during determination of the temperature regime. The calculation starts with the required final temperature of the material and is successively carried out for each section up to the beginning of the preheating zone. The initial temperature was always the final temperature of the material of the preceding section. The calculation was considered to be completed when the obtained initial temperature of the material in the first preheating zone section was app. 20°C. If, however, the initial temperature of the material differed considerably from the one stated, the calculation would be repeated. **Table 1** presents values for some calculated variables and the results of the temperature regime calculation for a 31,4 t/h productivity of the pusher-type furnace. The wall temperature and the charge temperature along the furnace during heating were obtained by calculating on optimal temperature regime that is presented in a diagram form in **Fig. 1**.

Table 1: Some variables and the results of the pusher-type furnace temperature regime calculation

Number of section	Length of a section (mm)	Θ_f °C	h W/m²K	λ W/mK	N_{Bi}	τ	c_p kWs/kgK	Θ_{ms} °C	Θ_m °C	$\Delta\Theta_m$ °C	Θ_s °C
1.	4066	1300	269	29,2	8,88	0,74	0,71	1225	1228	4	1230
2.	4066	1450	308	29,2	1,03	0,73	0,71	1260	1270	18	1303
3.	4066	1400	292	27,4	1,01	0,73	0,71	1171	1200	37	1260
4.	4066	1350	252	26,8	0,90	0,75	0,71	1004	1050	70	1190
5.	4066	1200	198	33,9	0,55	0,84	0,62	713	760	64	975
6.	4066	800	91	51,3	0,17	0,97	0,51	318	330	15	650

Due to the effect of the furnace atmosphere an oxide film (scale), consisting of the Fe_2O_3, Fe_3O_4 and FeO bound more or less tightly onto the iron base, is formed on the white hot steel surface. On the basis of the accepted steel scale composition: consisting of 5% Fe_2O_3, 10 % Fe_3O_4 and 85 % FeO[3,4] and density ranging from 5200 kg/m³, 5100 kg/m³ for Fe3O4 and 5900 kg/m³[3,5], a correspoding scaling density of 5785 kg/m³ is determined. The density and the scale composition enable the calculation of the percentage of steel burn off in regard to the heated charge. **Fig. 2** shows diagrams of the dependence of the scale layer thickness in regard to the percentage of steel burn off and slabs thickness heated both sidedly in a pusher-type furnace.

The amount of burn off steel per unit of steel charge surface may be calculated according to the temperature and duration of detainment at that temperature, as stated in **reference 6, 7, 8** when fuels of higher heating values (coke-oven gas, natural gas and heavy fuel oil) are used the generated flue gases have a similar effect upon the formation of scale. The quantity of the steel burn off per unit of the heated charge surface is presented in the references quoted in a form of a table and diagram in regard to various air factors during fuel combustion, i.e. from 0,6 to 1,1.

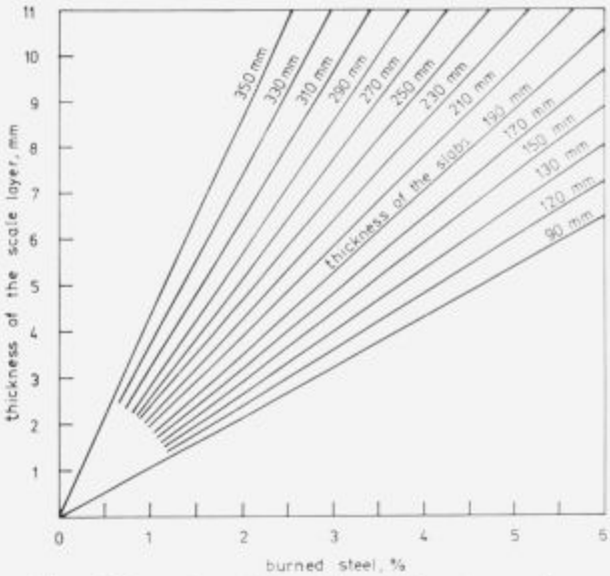

Figure 2: Dependence of the scale layer thickness in regard to percentage of steel burned off and the slabs thickness during heating from both sides

Slika 2: Odvisnost debljine sloja ogorine od postotka čelika koji odgori i debljine dvostrano zagrijavanog uloška

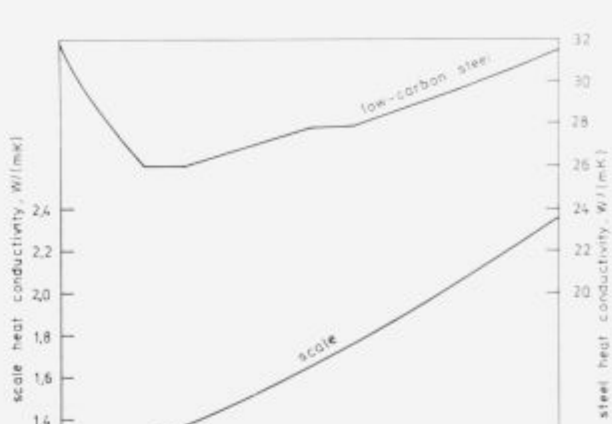

Figure 3: Scale heat conductivity and low-carbon steel in regard to temperature

Slika 3: Toplinska vodljivost za ogorinu i niskougljični čelik u ovisnosti od temperature

Fig. 3 shows diagrams regarding the dependence of scale heat conductivity and low-carbon steel to temperature[5]. From the determined relation it can be seen that the scale heat conductivity is more than ten times lower than that of low-carbon steel, therefor it acts as an isolating layer on the heated steel charge surface. Based on this data a specific heat resistance, depending on the thickness of the scale layer formed during 190 mm thick slabs

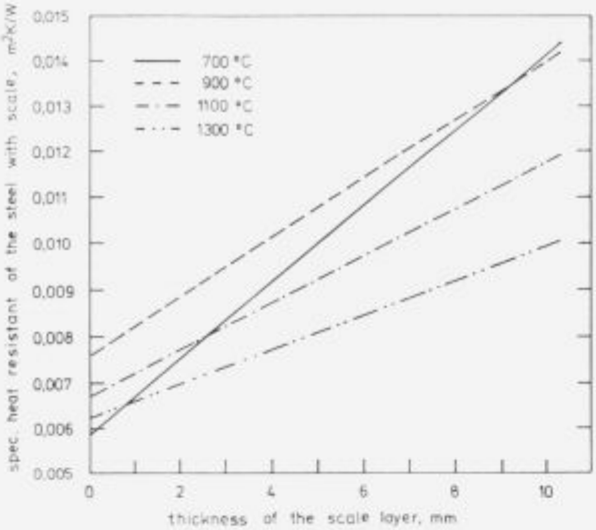

Figure 4: Specific heat resistance of low-carbon steel covered with a scale layer in regard to scale thickness and temperature for 190 mm thick slabs

Slika 4: Specifični toplinski otpor niskougljičnog čelika sa slojem ogorine u ovisnosti od debljine ogorine i temperature za uložak debljine 190 mm

were heated and their temperature, as this is the most common charge of a pusher-type furnace (over 70%), was determing and is presented in a form of a diagram in **Fig. 4**.

However, for the operating conditions investigated, first average temperatures of the charge surfaces in single sections of the furnace were defined from the diagram presented in **Figure 1**, the calculated optimal temperature regime was determined on the basis of data from **Table 1** regarding for the temperature of the charge surface at the end of a single section an average temperature of two neighbouring sections was taken. On the basis of these temperatures and the time of charge detention in single sections along the furnace the parametres regarding scale, as well as the extra time required for charge heating due to scale, were calculated. Natural gas used as fuel (Hu 37300 kJ/m³), the air factor was 1.1, data and methods stated in **reference 8** were used for the calculation. The results of calculation regarding the scaling of the steel St 12 are presented in **Table 2**.

Table 2: Calculation results in regard to steel scaling during charge heating in a pusher-type furnace

Length of a section (mm	For operating conditions					For calculated conditions				
	ϑ (°C)	Burned steel (kg/m²)	%	Layer (mm)	Δt (%)	ϑ (°C)	Burned steel (kg/m²)	%	Layer (mm)	Δt (%)
4066	350	–	–	–	–	–	–	–	–	–
4066	950	0,719	0,09	0,12	2,2	545	–	–	–	–
4066	1150	1,872	0,26	0,32	5,0	905	0,420	0,06	0,07	0,7
4066	1200	2,650	0,36	0,45	7,0	1125	0,907	0,12	0,16	2,5
4066	1230	3,600	0,49	0,61	9,5	1235	2,430	0,33	0,42	6,3
4066	1230	4,372	0,60	0,75	11,0	1249	3,318	0,45	0,57	8,5

Measurements of the scale layer thickness were carried out in the working plant, after the charge was pushed out of the furnace and adequately cooled, data on thickness of the scale layer formed in different working conditions of the furnace with regard to the delays in the working of the furnace due to war circumstances in the country were obtained. **Table 3** shows the results of the measurements of scale layer thickness on slabs with dimensions of 430x190x3800 mm, steel grade St 12, during continuous and discontinuous furnace operation when the slabs were kept too long in the furnace[9].

Table 3: Results of measurements of the scale layer thickness on the surface of steel St 12 during continuous and discontinuous operation of a pusher-type furnace

Working conditions of the furnace	Continuous working of the furnace	Discontinuous working of the furnace			
		Heating	16 h	12 h	–
		Blind firing	8 h	12 h	60 h
Layer thickness	1,0 mm		4,8 mm	7,0 mm	10,0 mm

Slabs were kept in the furnace for 264 min. The calculated optimal temperature regime not only improved the heat flow of the slabs in the initial period, but also shortened the period of slab detention at higher temperatures and reduced scale loss, the growth of the furnace floor and the heat energy consumption.

3. Discussion of the results

In addition to disadvantages that scaling causes such as are reduction of charge mass and defects in products, scale also behaves as an isolating layer on the heating surface of a charge, therefor more energy is required for its heating as the heating capacity of a pusher-type furnace decreases. **Figure 1** shows data aquired from a pusher-type furnace during operation regarding the temperature regime and the calculated optimal temperature regime at a productivity of 31.4 t/h in a diagram form. The influence of the scale layer thickness upon the heating of a charge could be studied and necessary corrections in the optimal temperature regime calculation could be applied from these data. Generally, on the basis of the scale layer thickness, slabs thickness and heating procedures (one or both sidedly), a percentage of steel burn off can be predicted. From the diagram in **Fig. 2** it may be seen that for the scale layer of thickness 2 mm, which does not differ with slab thicknesses in a corresponding furnace atmosphere, the steel burn off at the charge thickness of 350 mm is 0,45 % and at the charge thickness of 90 mm is 1,75 %. As such the percentages of steel burn off increase or decrease in regard to increase or decrease of charge thickness, the specific heat resistance also increases or decreases. From the expounded it may be noted that the oxidation atmosphere of the furnace space contributes a great deal to a formation of scale on the charge surface, and the increase of specific heat resistance was larger when thinner charges were heated.

To what degree scale behaves as an isolating layer can be seen from the diagram in **Fig. 3**. The coefficient of scale heat conductivity, in regard to the temperature level, is more than ten times lower than that of steel. In **Fig. 4** specific steel heat resistance for different scale layer thicknesses of a 190 mm thick charge heated in a pusher-type furnace is presented in a diagram. As the specific heat resistance increases in regard to temperature, it is necessary to correct the calculated heating time of the charge. From the diagram in **Fig. 4** it is also possible to define parametres for the charge of various dimensions when the atmosphere remains unchanged inside the furnace, as already evident in the diagram in **Fig. 2**, increase or decrease of the specific heat resistance parameter presented in diagram, **Fig. 4** for the percentage of increase or the decrease of the steel burn off for the same scale layer thickness.

Table 2 presents quantities of scale determined by calculation following the method referred to in **reference 8** during operation and a calculated optimal temperature regime of a pusher-type furnace. It has been noted that scaling is greater in the temperature regime achieved during operation than that at the calculated optimal one, which can be explained by the higher surface temperature of the charge in the first temperature regime. From the data (Δt) in **Table 3** it may be ascertained that detention at certain temperature sections should be altered, i.e. in a manner that the corresponding temperatures of flue gas and of the walls inside the furnace are higher in the 5^{th} and 6^{th} section in regard to calculated optimal temperature regime, due to the isolating behavior of the scale. However, the temperature regime determined during operation in fact corresponds to the optimal temperature regime of the furnace with a heating capacity of 40 t/h. That increase of capacity would not have an essential influence upon the quantity of scale, as formation due to detention at higher temperatures (which is shortened due to capacity increase) has a significantly greater influence.

Research carried out in a pusher-type furnace has shown that in the operating conditions, with a heat regime obtained by continuous work, a larger quantity of scale is formed in compare with the quantity of scale determined through calculation (**Table 3**). The difference is: (1 - 0,745) 100/0,745 = 34,23 %. The increase of steel burn off may be explained due to a greater oxidation atmosphere inside the furnace due to the air sucking through the openings on the furnace. This was confirmed by additional investigations. Particular attention should be payed to the formation of scale during discontinuous work after longer periods of delay in operation brought about by war circumstances. Five-day operation of the rolling mill train with 12 hours (one and a half) shifts was followed by 60 h delay, which led to a formation of 10 mm thick scale layer on the slabs surface. By normalising of conditions the continuous work was obtained. The result of abnormal conditions was a mass loss of the charge and an increased consumption of energy, because the time necessary for the charge to be heated was more than twice as long as usually. It was noticed that scale formed when the charge was kept in the furnace for over 60 hours, consisted of many layers of probably different composition and microstructure. This might be worth while to investigate in the future due to the influence on heat conductivity and due to great loss of the charge weight.

Research carried out lit the harm that scale makes as an isolating layer on the slab surface, during its heating. A correction of calculated heating time is necessary in the case of determination of proper heating conditions (regime) or by actual heating proces analysis. They can be useful as a ground for further studies of scaling influence on the quantity of air necessary for the start of fuel combustion, or the amount of O2 in waste flue gasses at the end of the furnace.

4. Conclusion

The scale on the surface of a charge behaves as an isolating layer, which enlarged the heating time and increased energy consumption. This is much apparent in the case of thinner charges heating in an oxidating atmosphere. The heating is slower due to the influence of scale. By the determining of an optimal temperature regime is necessary to consider the influence of scale formed. Inaccuracy by the calculation of a temperature regime, due to the increase in specific heat resistance is higher than in the case if no scale is present. A case of a pusher-type furnace with 190 mm thick steel charge heated and with a correction applied in the course of optimal temperature regime calculation, contributing to a better quality of the heated charge is described.

In particular, the influence of a thicker scale layer, formed due to larger stoppage of the rolling mill, the span of the heating time and energy consumption is described. During longer stoppages in a rolling mill multi-layered scale is noticed on a charge surface. A long time a blind fired furnace probably has an influence on scale formation and on its heat conductivity, and also on other parametres connected to charge heating. These investigations may also be useful as a ground for further studies of scale influence on quantity of air required at the beginning of operation and for the determination of fuel to air rate for the automatic regulation of the burners of the pusher-type furnace.

List of simbols

c_p – specific heat of steel, Ws/(kg K)

h – heat transfer coefficient, W/(m^2 K)

k – thermal conductivity of steel, W/(m K)

N_{Bi} – Biot number,

Δt – extention of heating time, %

$\Delta\Theta_m$ – the highest temperature difference in slabs, °C

τ – coefficient for thick-wall bodies

Θ_g – temperature of flue gas, °C

Θ_{ma} – average temperature of slabs, °C

Θ_{ms} – temperature of slabs surface, °C

ϑ_{ms} – medium temperature of slabs surface, °C

Θ_w – temperature of furnace walls, °C

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