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INFLUENCE OF THE RADIATION SHIELD ON THE TEMPERATURE OF RAILS ROLLED IN THE REVERSING MILL

WPŁYW EKRANOWANIA NA TEMPERATURĘ SZYN WALCOWANYCH W WALCARCE NAWROTNEJ

The paper presents a mathematical model of heat transfer during cooling of hot-rolled rails in the reversing mill. The influence of the radiation shield on the temperature of rolled rails has been analyzed. The heat transfer model for cooling a strip covered by the thermal shield has been presented. The two types of shields build of steel and aluminum sheets separated with insulating layer have been studded. Calculations have been performed with self developed software which utilizes the finite element method.

Keywords: radiation shields, rolling of rails, finite element method

W pracy przedstawiono model matematyczny wymiany ciepła w czasie chłodzenia szyn walcowanych na gorąco w walcarce nawrotnej. Analizowano wpływ zastosowania ekranów cieplnych na temperaturę walcowanych szyn. Model wymiany ciepła pasma osłoniętego ekranem opracowano dla ekranu zbudowanego z dwóch warstw metalowych przedzielonych warstwą izolacyjną. Modelowano ekrany wykonane z blachy stalowej i aluminiowej. Jako materiał izolacyjny przyjęto warstwę saffilu. Obliczenia wykonano Autorskim oprogramowaniem z wykorzystaniem metody elementów skończonych.

1. Introduction

Sections hot-rolling is the process of metal forming which is one of the most difficult to model. An important element of the simulation is to determine the temperature field of the rolled product. The results obtained are difficult to verify, the temperature field is usually qualitatively correct and there are difficulties connected with the elimination of less accurate solutions. An important basis for assessing the accuracy of the solution is given by the study of heat balance in the control volume which is a part of rolled strip [1]. Determination of temperature field in the rolling processes is obtained by finite element method with the use of two-dimensional or three-dimensional models [2-5].

The dominant mechanism for heat transfer at high temperatures (above 300°C) is the heat exchange by radiation. The heat loss as a result of radiation has a significant effect on the temperature of the strip rolled in a reversing mill. Excessive cooling of the outer layers of the rolled material can lead to too much uniformity of the temperature field which may lead to surface or shape defects. Prevention the temperature drop at outer layers of rolled products can be achieved by use of adequately constructed heat shields.

2. Heat exchange model

For the determination of strip temperature changes, the heat conduction equation has been solved using the finite element method [6]:

$$\int_V \left[\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + \dot{q}_V - \rho c \frac{\partial T}{\partial \tau} \right] dV = 0 \qquad (1)$$

where:

λ – thermal conductivity, W/(m·K);
ρ – density, kg/m^3;
c_p – specific heat, J/(k·gK);
$\dot{q}_V$ – capacity of the external heat source, W/m^3;
τ – time, s.

Transient heat conduction equation was solved in cross-section of the cooled and rolled material travelling with strip at the speed of v_z. In the subsequent time intervals of $\Delta\tau$, the new boundary conditions were determined in accordance with the current position of the strip cross-section in the rolling line. The internal heat source present in the heat transfer equation includes heat dissipated due to plastic deformation and a latent heat of phase transformations [2].

The boundary conditions were assumed depending on the stage of cooling or rolling. The flux of heat released to the environment by the uncovered strip was determined taking into account the radiation and convection of heat:

$$q = \varepsilon_w \cdot 5.67 \cdot 10^{-8} \left(T_w^4 - T_a^4\right) + \alpha_c \left(T_w - T_a\right) \qquad (2)$$

where:

ε_w – strip surface emissivity [2],
T_w –strip surface temperature [K],
T_a – environment temperature [K].

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In order to calculate the convection heat transfer coefficient α_c for the forced flow, the Nusselt's criteria equations were used:

– for the laminar flow

$$Nu = 0.664 \cdot Re^{0.5} Pr^{1/3} \cdot \varepsilon_T \quad (3)$$

– for the transition and turbulent flow

$$Nu = 0.037 \cdot Re^{0.8} Pr^{1/3} \cdot \varepsilon_T \quad (4)$$

where:

Re, Pr – Reynolds and Prandtl number, respectively

ε_T – coefficient taking into account the change in thermo physical properties of the liquid as a result of difference between the liquid and strip surface temperature:

$$\varepsilon_T = \left(\frac{Pr_p}{Pr_s}\right)^{0.19} \quad (5)$$

Thermo physical parameters of the air are determined for: air temperature (p index) and strip surface temperature (s index).

In case of the use of thermal shield, the heat flux was determined in accordance with the following equation:

$$q = \alpha_{se}(T_w - T_a) \quad (6)$$

Effective heat transfer coefficient was determined using a two-dimensional heat conduction model in a plate. In the air gap between the strip and the shield it has been assumed that heat exchange is a result of heat conduction and radiation while on the outer side of the shield, the effective heat transfer coefficient was assumed of 10 W/(m^2·K). Calculations were performed for a shield made up of three layers: the inner metal casing, saffil layer (λ – 0.12 W/(m^2·K), c_p – 1000 J/(kg·K), ρ – 160 kg/m^3) and an outer metal screen. Two shields were modelled: one with the steel plate screen (λ – 50 W/(m^2·K), c_p – 480 J/(kg·K), ρ – 7800 kg/m^3, ε = 0.9) and the second with the screen made of aluminium sheet (λ – 150 W/(m^2·K), c_p – 420 J/(kg·K), ρ – 2650 kg/m^3, ε = 0.03). The obtained results of the effective heat transfer coefficient α_{se} as function of strip temperature within the range of 600°C to 1150°C for both shields were approximated by a polynomial of the second, shown in the Figure 1.

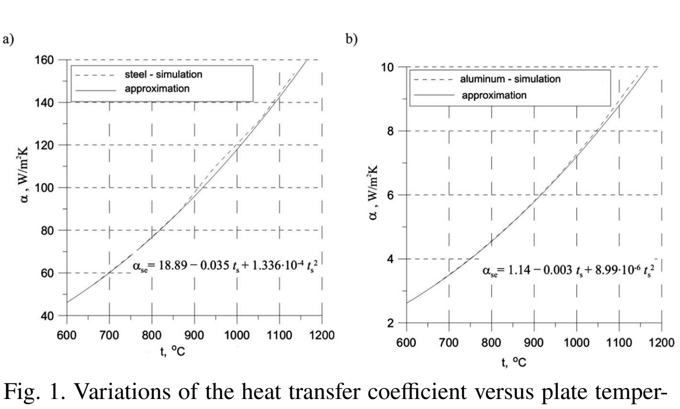

Fig. 1. Variations of the heat transfer coefficient versus plate temperature covered with radiation shield made of steel (a) and aluminum (b) sheets

During rolling, the heat transfer coefficient between the deformed strip and the rolls is determined from the following equation:

$$\alpha_w = 36400 - 74 \cdot t_w + 0.04 \cdot t_w^2 \quad (7)$$

where: t_w – strip surface temperature [°C]

3. Numeric calculations

Numerical simulations were performed for the rolling process of S49 rail, produced under conditions of Huta Królewska. The composition of the steel rail, in accordance with PN-84/H/84027.07 is given in Table 1. Charge to the process of rolling was a slab with cross-sectional dimensions of 175×260 mm, preheated to a temperature of 1150°C. The time of transport from the furnace to the rolling mill was assumed as 19 s. After rolling, the rail was transported on the roller table for 5 s. Times of subsequent rolling passes are presented in table 2. They include both the period of transport and contact with the rolls. Rolling was carried out in two-roll assemblies. After the 4th rolling pass, the strip was rotated by 90°. The rolling process was carried out in D815 rolling assembly, composed of two-frame trio and duo mill, laid out in a linear arrangement. Trio mill is equipped with rolls with the nominal diameter of 815 mm.

TABLE 1

Chemical composition of steel

C	Mn	Si	P	S
[%]				
0.4-0.75	0.6-2.1	<0.5	<0.005	<0.005

TABLE 2

Times of subsequent roll passes for the rolling process of S49 rail

Pass no.									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Pass time [s]									
12	6	9	11	8	27	18	8	14	21

Using finite element method for the calculation requires the division of the strip cross section into elements. The square elements have been used in a study. An example of division into elements is shown in the Figure 2.

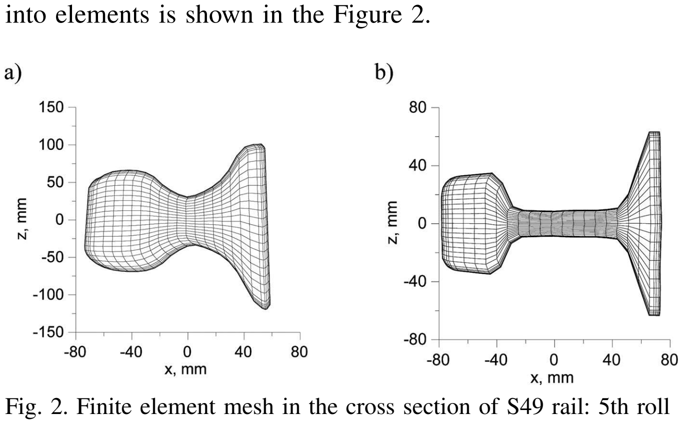

Fig. 2. Finite element mesh in the cross section of S49 rail: 5th roll pass (a); 10th roll pass (b)

In order to verify the developed heat transfer boundary conditions, the measurements of strip temperature in the subsequent stages of the hot working using a thermal imaging camera were performed (Fig. 3). From the measurements carried out for the D815 rolling assembly it was read the strip surface temperature after leaving the chamber furnace heating the strip up to 1187°C.

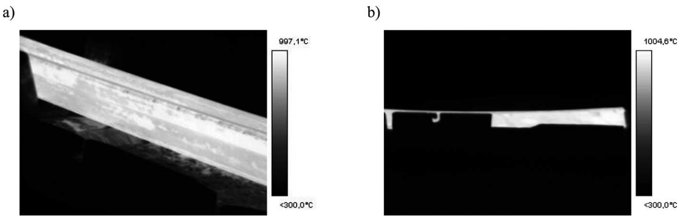

Fig. 3. Thermal photography of S49 rail before (a) and at the end (b) of rolling

In the Figure 4 there is a comparison of the maximal temperature of the top surface of the rolled rail with the maximal temperature recorded by the infrared mapping camera during rolling process. The registered strip surface temperature distribution was carried out for the passes of 1, 3, 5, 7, 9 and after leaving the finishing pass.

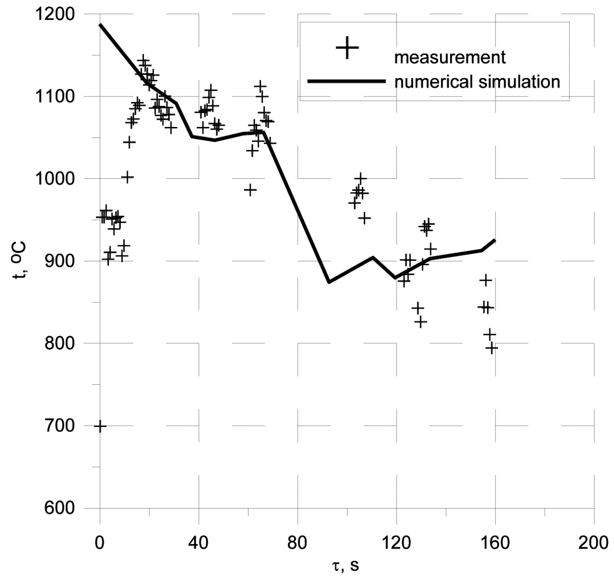

Fig. 4. Comparison of the maximum temperature of the rail upper surface with infrared camera measurements for each roll pass

It results from the comparison of the simulation with thermographic measurements shown in Figure 4, that the developed numerical model provides correct temperature values during the entire rolling process of the S49 rail. The differences arise from the nature of the infrared mapping measurements. Please note, that the measurement made with infrared mapping camera may be affected by a large error. In addition, the location of the measuring point, forced by technological and safety issues concerning staff performing the measurements may have had some influence on the obtained results. Considering all the above mentioned factors, it should be assumed that the validation of the model confirmed its correctness.

Further numerical calculations were done for the temperature of strip surface after leaving the furnace heating the band up to 1150°C. Preliminary calculations have shown that this temperature is quite sufficient for subsequent working processes. Too high temperature of strip heating may result in lowering the quality of the final product, i.e. excessive oxidation and decarburization of the surface layer. The three variants of calculations were analyzed: strip cooling in the air, shielding with steel and aluminium shield. It was assumed, that the thermal shielding is mounted on the roller table which transport the charge from the furnace into the D815 rolling assembly.

Figure 5 shows a comparison of the maximum temperature of the top surface of the strip for the analyzed calculation variants. Figure 6 shows the temperature distribution in the cross section of a rolled rail after selected roll passes in case of air cooling and the use of an aluminium shield.

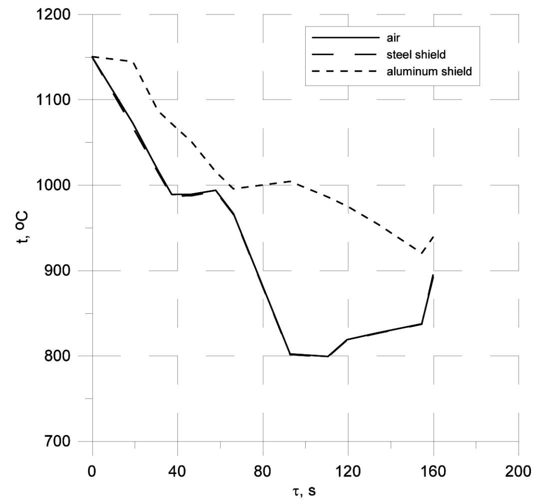

Fig. 5. Comparison of the maximum temperature of the rail upper surface for different cooling variants of S49 rail

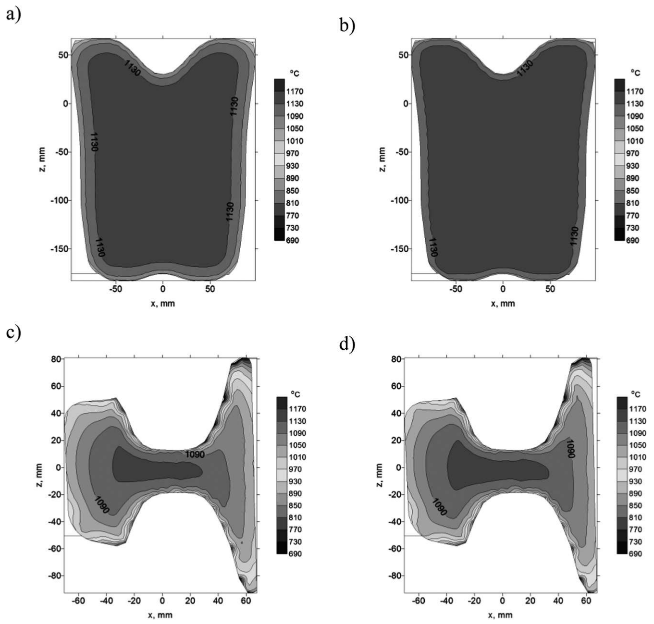

Fig. 6. Temperature field of S49 rail for rolling pass: no. 1- air cooling (a); no 1- aluminum radiation shield (b); no. 7- air cooling (c); no 7- aluminum radiation shield (d)

The highest values of the maximum temperature were observed in case of shielding the slab with aluminium shield for the practically entire period of the rolling process. After 90 seconds of the process, they are even 200°C higher in comparison to the air cooling or using the steel shield. Covering the strip with the steel shield did not bring any effect.

The temperature of the top surface of the charge is analogous to the case of air cooling. Probably the steel shield received excessive amounts of heat from the charge, which in turns did not give the expected insulation results. In contrast, aluminium shield reflected a large part of the radiation energy and finally, the radiation heat exchange was low and the charge maintained high temperature on the roller table.

In case of using an aluminium shield in the surface layer, the temperatures within 1090÷1130°C range are dominant – Figure 5b. Air cooling results in a reduction of the surface layer temperature to a value of 1050÷1090°C – Figure 6a. After successive passes, only minor differences within the zone of temperatures above 1130°C can be observed – Figure 6c and 6d.

For the purpose of the analysis, also considerations concerning the installation of thermal shields directly downstream and upstream rolling frames were carried out. On the basis of measurements on the real object, the time of contact between strip and rollers was calculated. Again calculations were performed for the variant of covering strip on roll tables with aluminium shield and for air cooling. Figure 7 shows a comparison of the maximum temperature of the top surface of the strip for the analyzed calculation variants. Figure 8 shows the temperature distribution in the cross section of a rolled rail after selected roll passes in case of cooling in air and the covered with an aluminium shield.

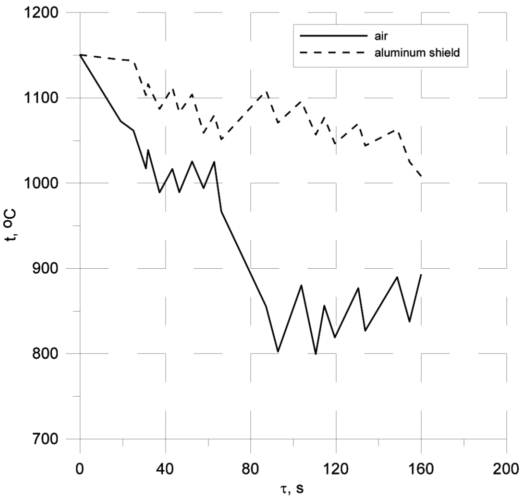

Fig. 7. Comparison of the maximum temperature of the rail upper surface for the different cooling variants of S49 rail

Comparison of the maximum temperature of the top surface of the strip has allowed observing quite significant differences between the variant of rolled rail cooling in air and the variant related to the aluminium shield. Covering the rolled rail with the aluminium shield downstream and upstream the rolling frames allows to obtain slower cooling of the rail, which in turn can result in better quality of the final product and reduction of power consumption for strand reheating. Differences in temperatures above 90 seconds of rolling process reach 200°C and they are maintained at that level until the end of the process – Figure 7.

The use of aluminium shield downstream and upstream the rolling frame results in significantly lover cooling of the rail in the entire production cycle, Figure 8. In case of the 7^{th} pass, the temperatures above 1090°C occupy most of the cross-section of a rolled rail, covered by the aluminium shield (Fig. 8b), while for air cooling, the temperature are above 1010°C (Figure 8a). More clearly, these differences can be observed after finishing the rolling process. In case of an aluminium shield, the temperature range of 1050÷1090°C is present both at the bottom and top part of the rail, whereas in the air cooling this is only the top part, Figure 8 c,d.

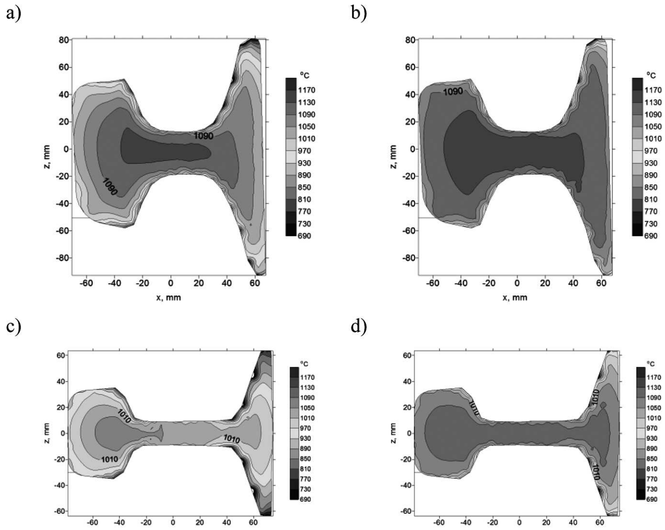

Fig. 8. Temperature field of S49 rail for rolling pass: no. 7- air cooling (a); no 7- aluminum radiation shield (b); no. 10- air cooling (c); no 10- aluminum radiation shield (d)

4. Summary

This paper analyzes the influence of the use of heat shields on the temperature distribution in the rolling process of S49 rail. Preliminary simulations were carried out for the heat shields made of steel sheet and aluminium sheet, mounted on a slab transporting roller table to the D815 rolling assembly. The use of aluminium screen even for such a short distance allowed maintaining the maximum surface temperatures above 900°C. There were no benefits from the use of a steel shield. This is a consequence of the high emissivity of the shield surface, whereby a significant part of the radiation energy contributes to the shield heating. The material from which the heat shield will be constructed should be characterized by low emissivity of the surface, thanks to which the flux of radiant energy is reflected from the surface of the shield and goes back to the surface of the rolled rail.

The best results were observed when using an aluminium shield throughout the entire rolling line, upstream and downstream the individual frames. The maximum value of the temperature does not drop below 1000, which in turn may result in a much higher quality of the final product by ensuring much slower cooling of the rail. As a result, some savings from energy demand in the process of reheating and rolling should be obtained. This option may be difficult to implement, because this will require additional technical solutions related to the possibility of damaging the shield by the rail coming from the roll frame.

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