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THERMAL EFFECTS OF A HIGH-PRESSURE SPRAY DESCALING PROCESS

TOPLOTNI UČINKI POSTOPKA ODŠKAJANJA Z VISOKOTLAČNIM BRIZGANJEM

Mária Čarnogurská[1], Miroslav Příhoda[2], Zdeněk Hajkr[2], René Pyszko[2], Zdeněk Toman[2]

[1]Technical University of Košice, Faculty of Mechanical Engineering, Vysokoškolská 4, 042 00 Košice, Slovakia
[2]VŠB – Technical University of Ostrava, Faculty of Metallurgy and Materials Engineering, 17. listopadu 15, 708 33 Ostrava-Poruba, Czech Republic
miroslav.prihoda@vsb.cz

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The article deals with the possibilities to remove scale from a slab surface by means of a hydraulic spray using pressurized water as well as with an analysis of the influence of the employed removal method on the thermal field of flat rolled products. The effect of spray descaling on the temperature field of the rolled material was established experimentally in a real mill in semi-operational conditions during the process of secondary spray descaling. The experiment was carried out with two sample slabs. The dimensions of a slab were 400 mm × 400 mm × 30 mm and the chemical composition was 0.20 % C, max. 1.4 % Mn, 0.045 % P, 0.045 % S and 0.009 % N. The temperature data for different depths below the surface of the slab being sprayed, obtained during the experiment, were processed using IHCP1D, a software developed on the basis of the Beck minimization-principle algorithm. The obtained values of the heat transfer coefficient represent the boundary condition for a numerical model of the spraying process. Its mean value established in the experiment was 18460 W/(m^2 K).

Keywords: spray, scales, temperature field, heat transfer coefficient, boundary condition

Prispevek obravnava možnost hidravličnega odstranjevanja škaje s površine litih slabov z visokotlačnim brizganjem vode in tudi analizo vpliva načina odstranitve na toplotno polje ploščatih valjancev. Eksperimentalno je bil preizkušen vpliv visokotlačnega odstranjevanja škaje na temperaturno polje valjanega materiala na proizvodni liniji valjarne med sekundarnim odstranjevanjem škaje. Preizkus je bil izveden z dvema vzorcema. Dimenzija valjanca je bila 400 mm × 400 mm × 30 mm, kemijska sestava pa 0,20 % C, maksimalno 1,4 % Mn, 0,045 % P, 0,045 % S, 0,009 % N. Eksperimentalno pridobljene podatke o toploti na posamezni globini pod površino valjanca smo nato obdelali s programsko opremo IHCP1D, ki deluje po algoritmu Beckovega minimalizacijskega principa. Navedeni faktor je hkrati mejni pogoj za numerični model odškajanja. Eksperimentalno določena povprečna vrednost faktorja je 18460 W/(m^2 K).

Ključne besede: visokotlačno brizganje, škaja, temperaturno polje, koeficient prenosa toplote, mejni pogoji

1 INTRODUCTION

The present development of high-quality new compositions of rolled steels combined with the fluctuating furnace atmosphere lead to a formation of scales that are very thin, adhesive and hard to remove from the surface of the rolled material. Descaling issues have been examined by a number of authors presenting the results of their experiments across a wide spectrum of applications. The rolled-in scales that cause defects in a billet, including visual surface faults, are discussed in[1], among other issues. In addition to the other methods, this problem can be resolved with high-pressure spray descaling using modern spray nozzle types, with which a higher operating pressure and force of the water jet per unit of area can be achieved.[2] One object of observations in the steel rolling technology research is the heat transfer coefficient.[3]

Spray descaling has an impact not only on the temperature field of the billet but also on the quality of its surface. The latter is usually associated with the determination of the heat transfer coefficient. The coefficient also represents the boundary condition for a numerical solution model of the spray based on the finite element method (FEM). Article[4] deals with the issue of surface quality of continuously cast slabs. It points to the significant impact of secondary cooling in compliance with the required surface temperature. A new element in the spray descaling theory is introduced in[5]. The paper presents the water hammer effect theory. The author argues that the drops of water falling at a speed of 100 m s^{-1} to 300 m s^{-1} over an extremely short interval (0.1–5 μs) may generate a pulse (peak) impact pressure with the maximum value of 300 MPa. It was proved that a water jet acting this way is able to descale even a cold material.

Many solutions to the temperature related heat transfer problems make an intensive use of the so-called inverse problem. In addition to determining the heat transfer coefficient by means of the inverse procedure, the inverse algorithm methodology is also used, for example, in the material defect detection after hot processing as well as in other technical applications.

2 DESCALING PRINCIPLE

A descaling process aims to achieve the best possible quality of the surface with the lowest possible reduction in the temperature of the rolled material and the lowest possible energy consumption in the production of pressurized water. The process requires a generation of large impact pressures at a low water flow rate. The quantity of the water falling to the surface of the material during spraying is evaluated by means of *SIR* (specific impingement rate) indicators defined as:

$$SIR=\frac{Q_V}{v\cdot w} \quad (\mathrm{m^3/m^2}) \tag{1}$$

The hydraulic descaling of hot rolled steel plates with a higher silicone amount can be positively influenced with increased amounts of phosphorus and sulfur. Phosphorus reduces the binary eutectic temperature of a FeO/Fe_2SiO_4 compound. Sulfur forms a eutectic, a low melting point FeO/FeS compound on the metal plate surface.

3 HEAT TRANSFER COEFFICIENT DETERMINATION METHODOLOGY

The hydraulic descaling process involves not only the descaling itself, but also the cooling of the surface of the rolled material. The knowledge of the temperature field of the material is still rather relevant since it allows an optimization of the rolling process in real operational conditions in terms of the dimensional tolerances, the resulting structure and the surface quality of a rolled product. Slabs feature two dimensions substantially larger than the third dimension, i.e., the thickness and, therefore, we can assume a unidimensional thermal transfer in the major part of their volume.

Basically, two methods are available to address the issue of the changes in the temperature fields of rolled materials. They are the *analytical* method and the *numerical* method. The analytical method is based on either the temperature balance or, in the case of an application of an inverse problem, the so-called Beck's minimization principle.[6] The basis of the numerical method is a determination of the heat transferred to an elementary volume per interval of time, $\Delta\tau$, through a transmission from the adjacent volumes. Its undoubted advantage is in that it respects the dependence between the material properties and the temperature.

3.1 Heat balance

A change in the temperature field of a slab being sprayed results from the heat transfer conditions of spray descaling. The heat transfer coefficient, *h,* is an inevitable boundary condition needed for a direct problem calculation. The coefficient calculation procedure using the heat balance method can be summarized as follows.

The total amount of the heat removed by the spray is expressed with the following formula:

$$\Delta Q=\sum Q_{\mathrm{be}}-\sum Q_{\mathrm{af}} \quad (\mathrm{J}) \tag{2}$$

The amount of the heat before spraying can be expressed with the formula below:

$$\sum Q_{\mathrm{be}}=\sum m\cdot c_p\cdot t_{i,\mathrm{be}} \quad (\mathrm{J}) \tag{3}$$

The amount of the heat after spraying can be expressed with the formula below:

$$\sum Q_{\mathrm{af}}=\sum m\cdot c_p\cdot t_{i,\mathrm{af}} \quad (\mathrm{J}) \tag{4}$$

Using the heat transfer theory, the amount of the heat transferred by the spray can be expressed as:

$$\Delta Q=h\cdot(t_0-t_{\mathrm{w}})\cdot S\cdot\tau_{\mathrm{adm}} \quad (\mathrm{J}) \tag{5}$$

The heat transfer formula follows from relations (2) and (5):

$$h=\frac{\Delta Q}{(t_0-t_{\mathrm{w}})\cdot S\cdot\tau_{\mathrm{adm}}} \quad \mathrm{W/(m^2\ K)} \tag{6}$$

3.2 Inverse problem

An inverse problem is based on a direct problem solution. A determination of the boundary conditions of operational experiments is often rather problematic. However, experimental observations of the time behavior of the temperature are available for several points of the examined body. The temperature data serve as the input values for the calculation of the unknown boundary conditions and this approach is referred to as an *inverse problem*. The inverse problem solution procedure is based on the minimization principle. In hydraulic descaling, the temperatures in the given points of a cooled body are measured and the variable sought is the heat transfer coefficient *h*. The accuracy of an inverse problem solution depends primarily on how the amount of the temperature variations observed in a point of the examined body approximates the accuracy, with which the temperatures of that body are measured. The inverse problem calculation result is, thus, affected by a number of factors such as the properties of the measuring instrument, the temperature measurement method, the material composition of the thermocouple employed, etc. An inappropriate selection of the input parameters for an inverse problem may cause an impairment of the required information about the temperature changes occurring on the surface. Measurement errors may induce a situation where the measured value of the temperature in the body being examined is higher than any

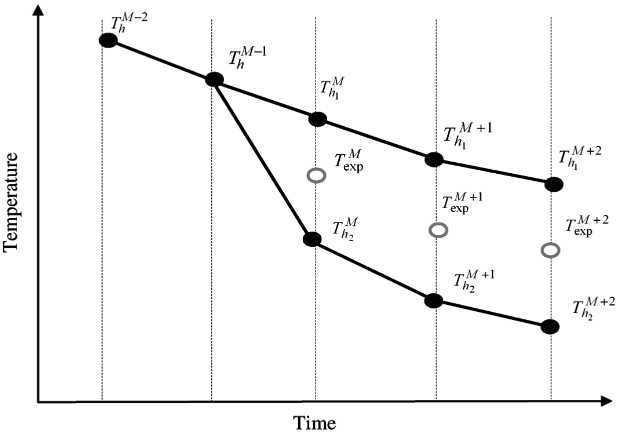

Figure 1: Inverse-calculation diagram
Slika 1: Inverzni računski diagram

temperature caused by any change in the boundary condition of the body, or the time derivative of the temperature is higher than any derivative caused by any swift change in the boundary condition. In such a case no solution to the inverse problem can be found. An inverse calculation diagram is shown in **Figure 1**.

The inverse problem solution is based on an assumed derivative of the temperature, *D,* which is defined as follows:

$$D^i=\frac{\partial T^i_h}{\partial h} \tag{7}$$

where *i* is a forward time step and *h* is the corresponding designation of the heat-transfer coefficient at a given temperature. The calculation of the actual heat transfer coefficient h^* (for point *M*) relies also on the coefficient values for points $M+1$ and $M+2$. The calculations for the initial point $M-1$ will be made using the estimated values of h_j, where $j = 1, 2, \dots r$ (*r* is the number of forward steps).

The result of the calculation is temperature $T^i_{h_1}$ where the upper index *i* designates the time step and the lower index *h* designates the heat transfer coefficient. In **Figure 1**, the temperatures from the experiment are designated as T_{exp}. The heat transfer coefficient value h^* minimizes the mean square deviation between the calculated $T^i_{h_1}$ and the temperature obtained in the experiment, T^i_{exp}, according to relation (8):

$$F=\sum_{i=1}^{r}(T^i_{\mathrm{exp}}-T^i_{h_1})^2 \tag{8}$$

Let us assume that the derivative of *F* with respect to h_j is zero and replace h_j with the h^* being sought:

$$0=\sum_{i=1}^{r}(T^i_{\mathrm{exp}}-T^i_{h^*})^2\cdot D^i \tag{9}$$

The calculation may also be made using a time consuming method based on calculating three temperature branches for the estimated values of h_1, h_2 and h_3. These calculated values are then used to calculate the coefficients of the second degree polynomial that can be easily derived.

Numerical tests showed that a simpler approach would be a substitution of the derivation with a differentiation, in which only two branches would be needed to obtain a sufficiently accurate result:

$$D^i=\frac{T^i_{h_1}-T^i_{h_2}}{h_1-h_2} \tag{10}$$

The temperature field in time step *i* can be characterized with the Taylor development around h_j*:*

$$T^i_{h^*}=T^i_{h_j}+(h^*-h_j)\frac{\partial T^i_{h_j}}{\partial h_j}+\frac{(h^*-h_j)^2}{2!}\frac{\partial^2 T^i_{h_j}}{\partial h_j^2}+\dots \tag{11}$$

In equation (9), we can substitute the first two Taylor development elements and consider only one estimated value of coefficient *h*; the outcome is:

$$0=\left[\sum_{i=1}^{r}(T^i_{\mathrm{exp}}-T^i_{h_1})^2-(h^*-h_1)\cdot D^i\right]\cdot D^i \tag{12}$$

Formula (12) can be translated into the following heat transfer coefficient (h^*) equation:

$$h^*=\frac{\sum_{i=1}^{r}h_1\cdot(D^i)^2+\sum_{i=1}^{r}(T^i_{\mathrm{exp}}-T^i_{h_1})\cdot D^i}{\sum_{i=1}^{r}(D^i)^2} \tag{13}$$

The determination of the heat transfer coefficient using the inverse procedure is a non-linear problem even if the thermo-physical properties of the material are temperature independent. The calculation should be carried out by way of iteration and stopped at the point where the predefined number of iterations has been reached or the condition for the maximum deviation between the new solution and the previous one has been fulfilled.

4 EXPERIMENTAL WORK

The methodology of the experimental research into the heat transfer coefficient carried out in semi-operational conditions does not allow the accuracy of the measurements made in laboratory conditions. However, it is able to produce the temperature data that correspond to the real spray descaling process.

The product selected for the experiment was a heavy metal plate (slab) with the dimensions of 400 mm × 400 mm × 30 mm and the material grade in line with the CSN 11 375 standard, whose chemical composition was 0.20 % C, max. 1.4 % Mn, 0.045 % P, 0.045 % S and 0.009 % N. Thermocouples were installed in the plate (**Figure 2**) according to the layout diagram in **Figure 3**. The distances of the thermocouples from the sprayed surface were (4.8, 8, 15, 22 and 25.6) mm. The thermocouple installation depths in the sample were verified with a Krautkramer USN-2 ultrasonic probe. In order to provide a unidirectional thermal field of the test speci-

Figure 2: View of the experimental slab sample
Slika 2: Videz eksperimentalnega valjanca

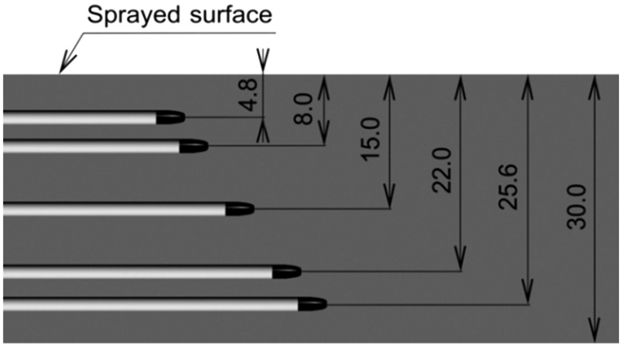

Figure 3: Layout diagram of the thermocouples installed in the sample
Slika 3: Prikaz razporeditve termoelementov v vzorcu

men, its lateral walls were insulated with a fibrous material.

The thermocouples were routed through a milled groove to the surface of the test plate. The thermocouples were protected from the mechanical effects of pressurized water with a thick wall tube. The thermocouple cold ends were routed through the protective tube to the terminal board. The signals from the thermocouples were transmitted to an OMEGA 180 recorder with the Pronto application software. The temperatures were measured with the shielded K-type Ni-NiCr grounded-end thermocouples with 3 mm diameters. The accuracy of this type of thermocouple is ± 2.2 °C at 0 °C.

The test sample (heavy metal plate) was fitted for heating in a pusher furnace and heated to 1000 °C. After the heating, the plate was transferred onto an accessory slab with the dimensions of 2360 mm × 1500 mm × 240 mm and then placed in a structure securing its stability during the spraying. Six sprays were applied during the experiment with the plate moving underneath the nozzles at a speed of 1 m s^{-1}. The spraying was performed only with the upper secondary descaling nozzles. Two thermocouples, out of the total of five, were damaged during the experiment. These were the thermocouples placed at the depth of 8 mm and 25.6 mm.

The graphical presentation of the time behavior of the temperature during the spraying (**Figure 4**) indicates that the temperature of the temperature field at the depths of 15 mm and 22 mm from the sprayed surface ceased to fluctuate with the motion of the plate underneath the spray nozzles. Only a slow, gradual decrease in the temperature was observed.

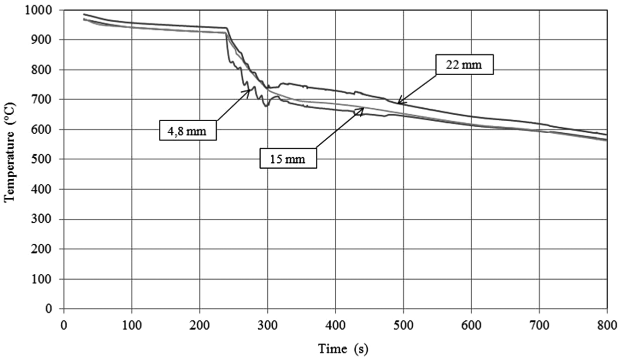

Figure 4: Time behavior of the temperature during the spraying
Slika 4: Časovna odvisnost temperature med brizganjem

It follows from the inverse problem solution principle that it is not possible to use any arbitrary point under the sprayed surface for the temperature measurement in the body being sprayed. The experiment indicates that as the distance from the sprayed surface grows, the information about the changes in the temperature diminishes. The reason for this is the fact that the material has a lower temperature gradient in the depth than on the surface. In view of this finding, the experiment was repeated with a new metal plate sample of the same steel grade but with a double thickness.

The second temperature measurement was done with a model slab with the dimensions of 400 mm × 400 mm × 60 mm. The thermocouples were prepared and routed towards the sensing apparatus in the same manner as for the first measurement. Eight K-type thermocouples were installed in the slab, out of which six were exposed-end (open-end) thermocouples with a diameter of 1.58 mm. The other two (grounded-end) thermocouples had a diameter of 3.0 mm. The distances of the thermocouples from the sprayed surface are summarized in **Table 1**. Two thermocouples were installed at the depth of 2 mm. Like in the first measurement, the thermocouple position depth was controlled by means of a Krautkramer USN-2 ultrasonic probe.

Table 1: Distances of the thermocouples from the sprayed surface
Tabela 1: Oddaljenost toplotnih senzorjev od površine, na katero se brizga

Hole diameter	Thermocouple type	Distance from the sprayed surface (mm)				
1.6 mm	Exposed-end	2.0	3.0	4.0	5.0	7.5
3.0 mm	Grounded-end	10.0	20.0			

The reason for using the exposed-end thermocouples in the measurement was the assumption that the temperature response is faster during the spraying. The prerequisite for their proper functioning was a precise installation of the open connection in contact with the measured material. A 1.58 mm thermocouple diameter was chosen because of a lower effect on the homogeneity of the measured material and improved measurement accuracy. The thermocouples at the depths of 10 mm and 50 mm were of a classic, grounded-end type, like for the first measurement, since the response to the pressurized water spray was assumed not to be equivalent to that occurring in the top layers. This assumption was confirmed with the measurement.

The temperature measurement was performed during eight passes of the slab sample under the spray nozzles. The slab moved at a speed of 1 m s^{-1}. The time interval between two sprays was 100 s.

Only the two thermocouples at the depth of 2 mm and those at the depths of 4 mm and 50 mm survived this difficult experiment without any damage. The thermocouples installed at the depths of (3, 5, 7.5 and 10) mm

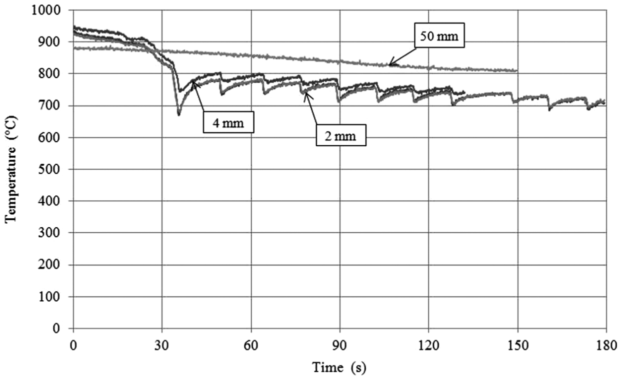

Figure 5: Time behavior of the temperatures in the slab sample during the spraying

Slika 5: Časovna odvisnost temperature v valjancu med brizganjem

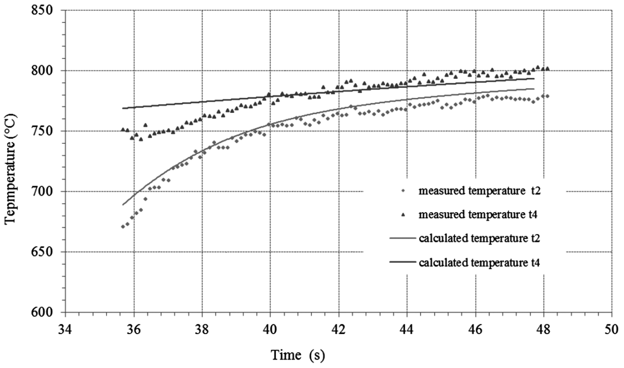

Figure 7: Temperature behavior after Spray 1 obtained from the check calculation

Slika 7: Potek temperatur iz kontrolnega izračuna po brizganju 1

were damaged either during their installation in the slab sample, or while handling the slab sample during the heating, or during the spraying. The first three temperature behavior curves obtained with the measurement were used in the evaluation.

During this measurement, each spray was followed by a short phase in order for the temperatures in the experimental slab sample to balance.

The measurement time step was 0.1 s. The temperature behavior at different measurement depths is shown in **Figure 5**. A detail of the temperature behavior at the depths of 2 mm and 4 mm during the spraying is provided in **Figure 6**.

5 RESULTS AND DISCUSSION

The data obtained through the experiment at different depths below the surface of the sprayed slab were subsequently processed using IHCP1D, a software developed on the basis of the Beck minimization principle algorithm at Beck Engineering Consultants Company.[6] This product is able to perform temperature analyses and cooling related calculations for an unknown heat flow and an unknown heat transfer coefficient based on the inverse solution procedure, using the known material properties of the body being cooled, the properties of the ambient environment and the temperatures experimentally measured in the body. The temperature values obtained in the experiment were applied in the above mentioned algorithm to calculate the heat transfer coefficient h for the first three sprays. Its mean value is 18.46 kW/(m^2 K). The lowest coefficient value was 17.65 kW/(m^2 K) and the highest value was 19.90 kW/(m^2 K).

The heat transfer coefficient values obtained during the spraying were used in the reverse check calculation of the temperature behavior of the experiment slab sample. The calculation results for Spray 1 are summarized in **Figure 7**.

A comparison between the measured values and calculated values indicates that the temperature difference is within a range of 10 °C to approximately 15 °C. The difference is higher for the temperature measured at the depth of 4 mm from the sprayed surface, as compared to the temperature at the depth of 2 mm. This can be attributed to a larger impact of the temperature measurement inaccuracy at the lower temperature levels as compared to the measurements at the depth of 2 mm. For example, for Spray 1 the temperature obtained through direct measurement at the depth of 2 mm below the surface, at the measurement time $\tau = 42.09$ s, was 762.8 °C. The temperature obtained through the calculation using

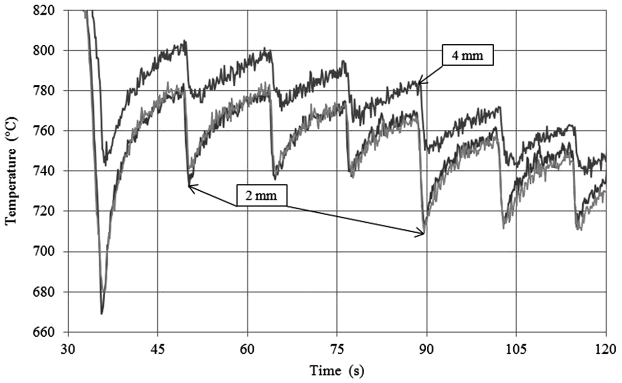

Figure 6: Detail of the time behavior of the temperatures captured by the functional thermocouples

Slika 6: Detajl časovne odvisnosti temperature, zajete s termoelementi

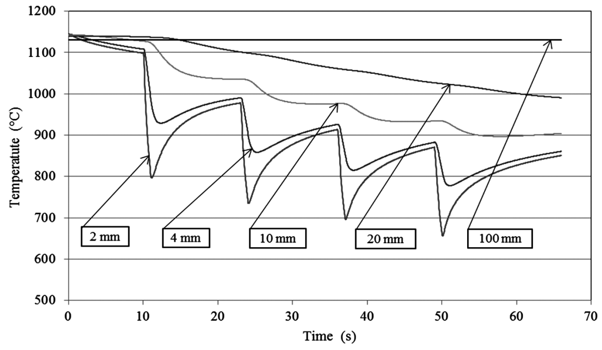

Figure 8: Temperature at the selected points acquired with the numerical simulation

Slika 8: Temperatura v izbranih točkah, ki je bila dobljena z numerično simulacijo

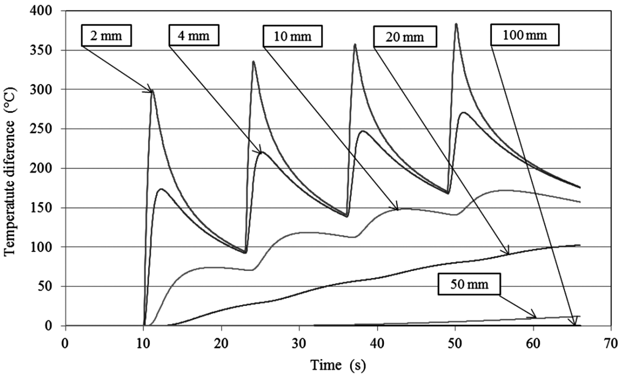

Figure 9: Temperature difference between a freely cooled and a sprayed slab
Slika 9: Razlika v temperaturah med prostim ohlajanjem in pri brizganju slaba

the heat transfer coefficient of 18.46 kW/(m^2 K) was 767.5 °C. The temperature deviation is 0.7 %.

The acquired values of the heat transfer factor was used for the calculation of the slab thermal field with a thickness of 200 mm made from steel with a steel grade identical to the test specimen. The heat transfer theory shows that if the slab length and width are, e.g., 6 m and 2 m, we can then assume a unidirectional heat transfer in more than 75 % of the material volume.

An initial surface temperature of 1145 °C was chosen for the solution, a parabolic temperature distribution was chosen for the cross-section, and the heating non-uniformity was 1.5 K cm^{-1}, while the thermo-physical steel properties depended on the temperature. The thermal field kinetics for the distances of (2, 4, 10, 20 and 100) mm from the slab surface in the course of four subsequent sprays are shown in **Figure 8**.

The numerical simulation has confirmed that the cyclical material temperature changes due to spraying are demonstrated only in the thin layer under the slab surface, approximately up to 10 mm. The temperature fluctuations due to spraying are practically not present in deeper layers. Nevertheless, this does not mean that the spraying does not influence the thermal field of the material in the mentioned areas. The temperature difference for individual spots of a freely cooled and sprayed slab is shown in **Figure 9**. The surface layers show the temperature differences of the order of 10^2 °C. However, at a depth of 20 mm, each spray also causes the temperature to drop by approximately 25 °C, unlike in the case of the freely cooled material. Even at the depth of 50 mm, the temperature drops by 2 °C to 3 °C per each spray. Only in the very centre of a slab the temperature is the same with both cooling methods.

6 CONCLUSION

A high-pressure spray descaling process has a significant impact on the temperature field of a rolled material, closely related to the quality of the final product. The research into the boundary and initial conditions needed for the solution of the temperature field problems, in controlled rolling operations in particular, has not been finished yet, but the results obtained through the on-site observations are precious and relevant for rolled product manufacturers.

An experimental measurement and the subsequent numerical simulations have confirmed that a high-pressure spray descaling process influences, to a significant extent, the surface layers of slabs. The cyclical temperature change due to the spray practically does not affect the remaining volume of the rolled material at a depth of more than 10 mm from the surface. However, the spray influences the speed of the slab cooling down also at larger distances. Only at the depths exceeding 50 mm, the temperature differences between the freely cooled and sprayed slabs are lower than 3 °C per spray.

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Nomenclature

c_p	specific heat capacity J/(kg K)
h	heat transfer coefficient W/(m^2 K)
i	forward time step 1
m	weight of the rolled material kg
Q_V	volumetric flow rate m^3/s
ΔQ	total amount of the heat removed by the spray J
Q_{be}; Q_{af}	heat present in different layers of the material before/after the spray J
S	area being sprayed m^2
$t_{i,\mathrm{be}}$; $t_{i,\mathrm{af}}$	mean temperature in different layers of the material before/after the spray °C
t_0	surface temperature before the spray °C
t_{w}	spray-water temperature °C
v	rolling speed m s^{-1}
w	width of the material being rolled m
τ_{adm}	spraying time s

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