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IMPACT OF THE OXIDE SCALE ON SPRAY COOLING INTENSITY

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ABSTRACT

Heat treatment of steel is attended by oxide scales growth with various physical properties. The most common and most dominant impact of the oxide scale layers is on the surface quality and mechanical properties of steel. This paper is focused on study of influence of the oxide scale on cooling intensity. Spray cooling is a typical technique used in heat treatment and other metallurgical processes where controlled temperature regimes are required. Cooling intensity is primarily affected by spray parameters as pressure and coolant impingement density. It is not frequently reported but even thin layers of oxides can significantly modify the cooling intensity. This effect is dominant in the cooling of steel surfaces at high surface temperatures. Study of the influence of the oxide scale layers on cooling intensity was carried out by experimental measurements and numerical analysis. Experimental measurements compare the cooling of scale-free surfaces and oxidized surfaces. Experimental investigations show a difference in the cooling intensity. Numerical analyses were prepared to simulate cooling of the samples with different oxide scale layers and different thermal conductivity of scales. Even a scale layer of several microns can significantly modify the cooling intensity. A low thermal conductivity of the oxides can make the cooling more intensive.

The paper provides experimental evidence of this fact and numerical study of the oxide scale layer thickness and thermal conductivity on the influence on the spray cooling with boiling. The Leidenfrost phenomenon and change in surface temperature provides key to the explanation why the hot surface covered by the oxides is sometimes cooled more intensively than the clean surface.

INTRODUCTION

The most widely used method of cooling at heat treatment of steel is water spray cooling. Spray cooling is an essential part of the continuous casting and hot rolling an integral part of production and heat treatment of steel [1,2]. Method and cooling intensity can significantly affect the quality of the steel or final steel product [3]. The cooling intensity affects important parameters and mechanical properties of steel such as grain size, yield strength, ultimate strength and so on. Method of spray cooling and its intensity can be designed according to the specific applications with focus on the best quality of steel or steel products. In order to prepare the specific cooling it is necessary to consider, study and include all relevant aspects of the process. Cooling process is affected by many factors. This paper is focused on studying the impact of the oxide scales layers on the cooling intensity.

In the cooling process of the hot surface intensive heat transfer from the hot surfaces occurs. The heat transfer is mainly realized through the convection mechanism. This mechanism can be described by Newton´s cooling law [4]. Newton´s law of cooling intensity is defined as the product of the heat transfer coefficient (HTC) and the temperature difference (surface temperature and ambient temperature). The intensity of heat transfer depended on the surface temperature of the cooled steel. It means that the character of the surface is an important parameter with impact on the cooling intensity. The cooling intensity is defined by Leidenfrost effect. The Leidenfrost effect slows down the heat transfer from hot surface due to physical fundamentality which is evident in the impact of liquid on the hotter surface than the liquid´s boiling point. In this case the vapour layer at the hot surface occurs which insulates the liquid from the hot surface [5,6]. So called Leidenfrost temperature specifies the boundary between vapour layer creation (low intensity heat transfer) and intensive cooling. The Leidenfrost temperature can be affected by several parameters such as the type of spray nozzle, water pressure, temperature and so on. Other possibilities to change the cooling intensity trough oxide scale layer are presented in this paper.

Oxide scale formation occurs under a variety of morphological and chemical conditions. All changes can be sorted into three basic groups, depending on the phase of the manufacturing process. In the first phase of the process, primary scales form; the second phase forms secondary scales; and the final phase forms tertiary scales [7].

The issue of cooling process is more complicated when we consider oxide layer that are an essential part of the heat treatment of steel. Effect of oxide layer on cooling intensity was studied by R. Wendelstorf et al [8,9]. This author presented experimental measurements of different thicknesses of oxide scale layers and their impact on the heat transfer. Based on the experimental experiences and the results presented by experimental measurements numerical analyses for identifying and understanding the impact of scale layers on cooling intensity was prepared.

EXPERIMENTAL MEASUREMENTS

Experimental measurements have general aim to define cooling intensity and identification of the Leidenfrost temperature for different cooling parameters (nozzle, fluid flow and so on). To present the impact of the cooling parameters on the cooling process and Leidenfrost temperature determination the Figure 1 with dependency of the HTC and surface temperature was prepared. This figure clearly demonstrates the diversity of the cooling intensity and shifts of the Leidenfrost temperature and thus vapours layer formation [10].

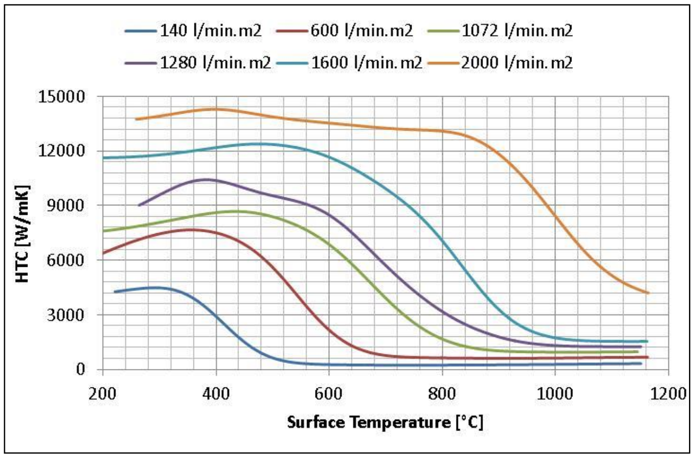

Figure 1 Heat transfer coefficient for mist nozzle in dependence of surface temperature for increasing flow rate

Experimental measurements of the intensity of cooling with oxide scale layer on two types of specimens were carried out. For the first measurement the austenitic steel plate (type 1.4828) with size 300x300 mm was used. The steel plate was covered by about 60 μm layer of oxides. During one hour of oxidation in air at temperature 1000 °C the oxide scale layer on austenitic steel plate was prepared. After oxidation process the steel plate with oxide layer was heated to 800 °C. In the next step the steel plate was sprayed by water nozzle and temperature decrease was measured. For experimental measurements the full cone nozzle with 3.15 l/min flow rate at 2.0 bar air pressure was used. The distance between the water nozzle and the steel plate was 150 mm. As a function of surface temperature heat transfer coefficient (HTC) was computed from temperature measurement. Obtained results are presented in Figure 2. The used test plate was mechanically brushed from oxides. After cleaning by steel brush the surface looks like shiny steel. Microscope analysis of a sample from the test plate shows that the scale was removed only partially and on the steel surface remains in average 20–30 μm layer of sticky scale (see Figure 3). The plate after brushing was heated again in protective atmosphere to 800 °C and the experiment was repeated. The experiment with brushed test plate heated under argon was repeated several times and the results are shown in Figure 2. The results show that cooling intensity with thick oxide layer is higher than with thin layer.

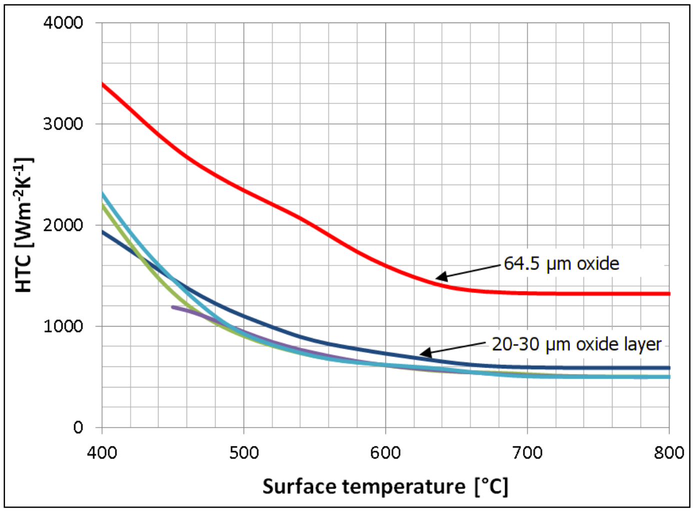

Figure 2 Measured cooling intensity for surface with original thickness and reduced thickness

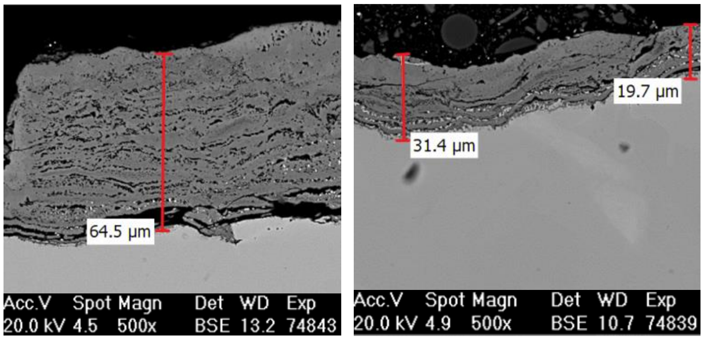

Figure 3 Layer of porous oxides on austenitic steel (left), steel surface after brushed (right)

The second experimental measurement was also prepared on steel plate but with and without oxide layer. The first sample was cleaned by pickling (Figure 4, at the top). The second sample was covered by compact layer of oxide scales of average thickness of 15 μm (Figure 4, at the bottom). Spray conditions were identical for both samples. Both samples were initially heated in protective atmosphere to 500 °C and then cooled by water nozzles. The results are shown in Figure 5. This test confirmed that the cooling intensity for perfectly clean surface is lower than for surface covered by oxides. The temperatures in all test plates were measured through the thermocouples with diameter 0.5 mm. The thermocouples were located 0.5 mm under the surface of the test plate. All experiments have dynamic character because during the cooling process the test plate drives under the water nozzle with velocity 1 m/s. The cooling process was considered as transient process. Described experimental procedures were used as a starting motivation for numerical analysis of the impact of the oxide scale layer on the heat transfer and cooling intensity.

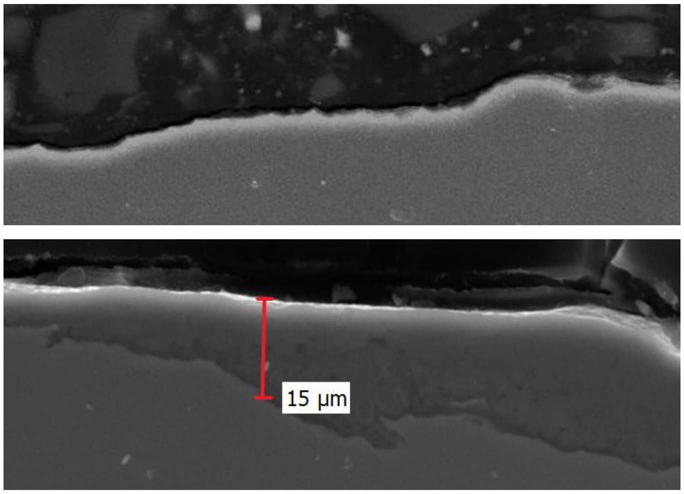

Figure 4 Steel surface after pickling, steel surface with about 15 µm layer of oxides (oxides – dark grey area)

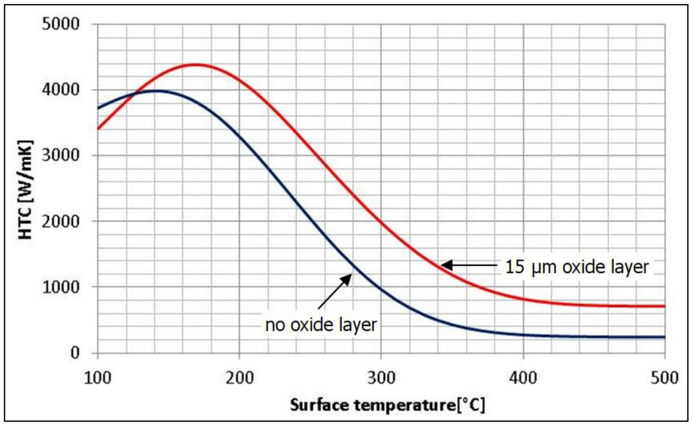

Figure 5 Measured cooling intensity for clean surface (blue) and for surface with oxides (red)

In the study of heat transfer through the oxide scale layer it is necessary to keep several facts in mind, which have fundamental impact on this process. The first fact is that the oxide layers at steel surface have much lower thermal conductivity (0.1–3 W/mK) than is the conductivity of steel (15–60 W/mK). The second fact is that the scale layer is not compact with the number of voids and the contact between basic steel material and oxide layer may not be perfect. Physically, from the point of heat transfer, scale can be considered as thermally resistant layer which will reduce the cooling intensity. It could be expected that spray cooling of clean surface would be more intensive than cooling of steel surface covered by oxide layers. This conclusion was not confirmed by experimental measurements, contrarily the samples with oxide scale layer reached more intensive cooling. To verify and clarify experimental results, numerical simulation of the cooling process of the samples with variable thickness of oxide scale layer was prepared.

NUMERICAL SIMULATION

The main goal of numerical simulation was to study and simulate the impact of the oxide scale layer on the cooling process. The results of numerical analysis should lead to discovery of oxide layer behaviour at heat transfer and clarify experimentally measured data. The numerical simulation was based on the experimental measurements and suspicious results. To solve this problem two dimensional finite element (FE) model was created. The FE model included the base material and variable thickness of oxide scale layer. The oxide scale layers in the numerical model in the range from 0 µm (only the base material) to 1000 µm were considered (see Figure 6). For the base material the physical properties of structural steel were applied (see Table 1). For the oxide scale layer the physical properties from literature were used which occur in large dispersion (0.1–3 W/mK). To comply with conservative approach in terms of cohesion and defects in the oxide layer the value of the thermal conductivity 0.17 W/mK was applied. The basic material and oxide scale layer as a continuous and homogenous were considered. The contact between the base material and the oxide scale layer was modelled as perfect.

Table 1 Physical properties of the used materials

Thermal conductivity		Specific heat		Density	
[W/mK]		[J/kgK]		[kg/m^3]	
scale	steel	scale	steel	scale	steel
0.17	60	970	434	5700	7850

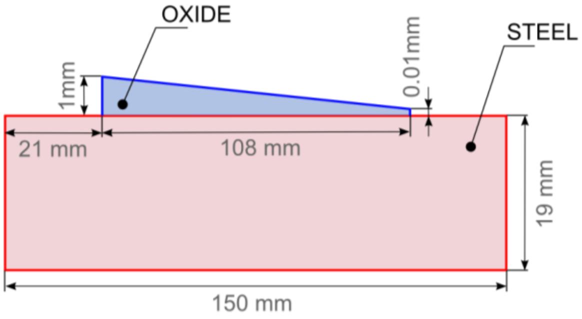

Figure 6 Schematic illustration of model with dimensions

As mentioned in the previous chapter, the cooling intensity is strongly affected by dependency of the HTC and steel surface temperature. To confirm this statement two cases were considered. In the first case the constant value of HTC was applied. In the second case HTC depending on surface temperature was applied. Applied dependence of cooling intensity (HTC) on surface temperature used in numerical model is presented in Figure 7. This HTC curve was experimentally measured and corresponds to one curve with defined conditions presented in Figure 1. The constant value of HTC during cooling process is not real and it is used only for comparison with real conditions. In the FE model the ambient temperature 22 °C was used. This temperature corresponds with temperature of the cooling water. In the FE model initial temperature 1000 °C was applied.

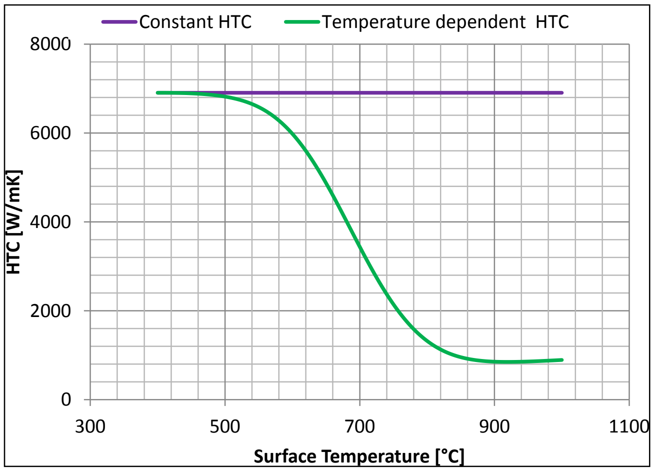

Figure 7 Dependence of the HTC on the surface temperature

To assess the impact of the oxide scale layers on the cooling intensity, the results of the numerical analyses in several important locations were evaluated. These locations with evaluated variables are depicted in Figure 8. Surface temperature of steel is Ts and surface temperature of oxide is Tp. Heat flux through steel surface is marked Qs and through oxide surface Qp respectively. Initial temperature of the samples was 1000 °C. The time of cooling for the first variant (thermal conductivity 0.17 W/mK) was determined to 1.2 s. The evaluated results are presented in Figure 9 and Figure 10.

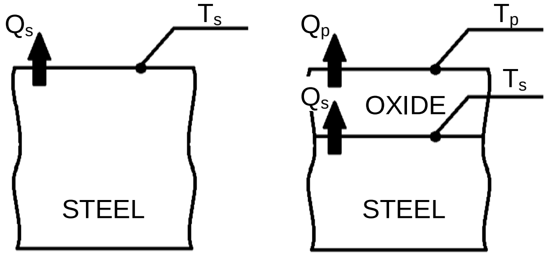

Figure 8 Illustrative scheme of the evaluated locations and variables

The first part of the evaluation is focused on results comparison between application of constant value of HTC and temperature dependent HTC (see Figure 7). This comparison clearly shows how high the real HTC affected the heat transfer at cooling process. The thermal distributions for both conditions are presented in Figure 9 and Figure 10. Evaluation of temperature Ts is depicted in Figure 11. The second part of the evaluation was focused on the temperatures and heat fluxes evaluation for several thicknesses of the oxide layer. This evalution was performed only for real HTC curve. The results are shown in Figure 12 through Figure 14.

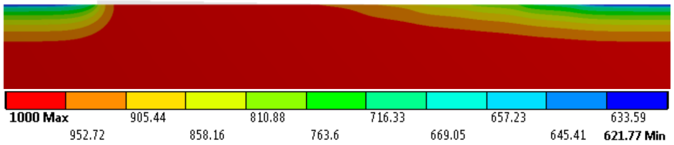

Figure 9 Temperature distribution for constant HTC

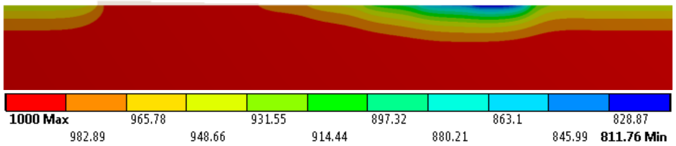

Figure 10 Temperature distribution for HTC dependent on temperature

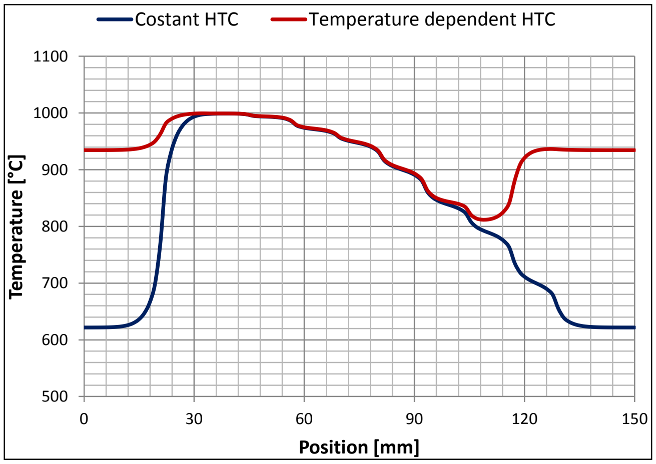

Figure 11 Evaluation of Ts temperature along full length

A comparison of the results presented in Figure 11 with applied constant and thermally dependent values of HTC approved the difference in temperatures along the full length of model. The largest differences in Ts temperatures are at clean steel surface and small thickness of oxide layer. In the area with higher oxide layer the Ts temperatures are the same for both cases. Effect of HTC temperature dependency applied on high thickness of oxide layer is negligible. It is due to high thermal resistance of oxide layer, which creates a barrier to heat flow from hot steel and acts as an insulator. In the small thickness of scale and clean steel surface the temperature dependency of HTC is significant. The boundary between small and high thickness of oxide layer which has essential impact on the cooling intensity (decrease of temperature Ts) depends on the thermal conductivity of scales, homogeneity of scales, initial temperature and other factors. The results of impact of the oxide layer on cooling intensity for defined thickness of oxide layers and temperature dependency of HTC are presented below.

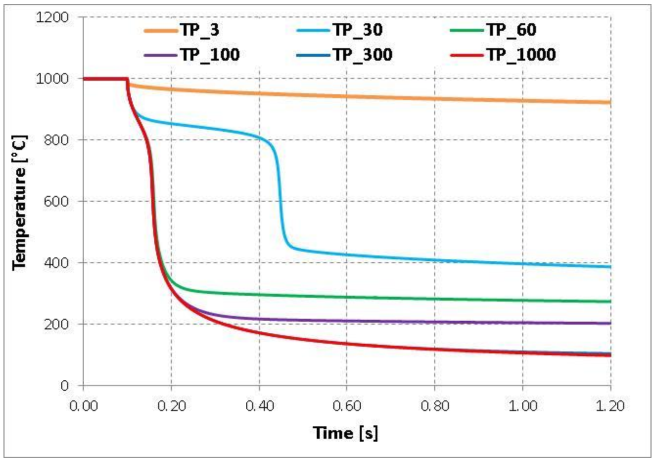

Figure 12 Tp evaluation for thermal conductivity 0.17 W/mK and defined thicknesses of the oxide layers

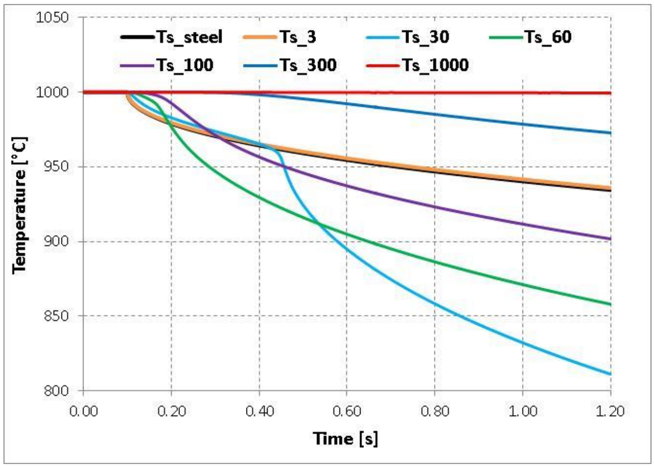

Figure 13 Ts evaluation for thermal conductivity 0.17 W/mK and defined thicknesses of the oxide layers

The results obtained from numerical analyses described the effect of the cooling intensity for clean surface of the steel and steel with different thicknesses of the oxide scale layers. The effect of the influence of the steel surface with oxide scale layer on the cooling intensity is evident from the temperature Ts curves (Figure 13). The cooling starts at time 0.1 second. The clean steel surface can be considered as reference (black lines). For the first variant thin oxide layer (3 µm) has almost no influence. Surface temperatures of thick layers (60 to 1000 µm) fall down drastically to 300 °C in 0.1 second but steel covered by thick layer of oxide is hotter than clean steel. In this cases oxides act as thermal insulation. What is interesting is the behaviour of medium-thick oxides. The surface temperature of layer 30 µm thick starts to drop at time 0.4 s when the surface temperature reaches 800 °C. In this case, the oxide scale layer acts as the thermal bridge defined by optimal heat transfer from hot steel to cooled surface.

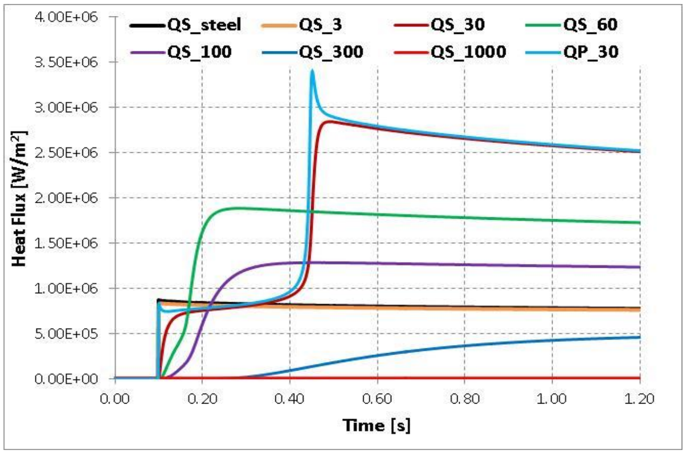

Figure 14 Heat flux evaluation for defined thickness of the oxide layers

All described impacts of the oxide scale layer thickness and thermal conductivity on the cooling intensity are also evident from the heat fluxes evaluation in defined positions. Different cooling intensity represented by the heat fluxes is presented in Figure 14. At the same time temperature of steel under oxides starts to fall. Heat flux from the steel surface covered by 30 µm oxides is 0.5 second after start of cooling about three times higher than heat flux from the clean surface. This result corresponds with the surface temperature dependency depicted in Figure 12 and Figure 13. The results of the second variant confirm the effect of cooling time on the cooling intensity for individual thicknesses. In Figure 14 for the heat flux on the oxide surface (Qp) for the thickness 30 µm was also evaluated and compared with values of Qs. The Qp curves are charaterized by major sharp point, which is caused by the heat capacity of the oxide scale layer.

CONCLUSION

This paper was focused on study of influence of the oxide scale layer on the intensity of cooling on the steel surface. In the first step experimental simulation of a real cooling process of the steel with and without oxide layer was prepared. The experimental measurement shown that the cooling intensity for steel with oxide layer was higher than for steel with clean surface. In the second step numerical analyses of the specimen with variable thickness of oxide layer and constant and surface temperature dependent HTC were carried out. The numerical analyses and presented results definitely confirm the suspiction identified in the experimental masurements and described in the chapter experimental evidence. The cooling intensity of steel surface with specific thickness of oxide scale layer can be higher than cooling intensity of the clean steel surface without oxide layers. All presented results of sprayed hot steel surfaces with scale layer show the enormous influence on the cooling intensity. Based on the presented results the optimum time of cooling for specific case represented by defined oxide layer thickness and thermal conductivity can be chosen. It means that it would be possible to prepare optimal time and form of the cooling process of hot rolled surface for specified oxide scale layer with known thermal conductivity and known dependency of the HTC on the surface temperature.

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