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The Effect of Discontinued Water Spray Cooling on the Heat Transfer Coefficient

J. Hrabovský, M. Chabičovský, J. Horský

Abstract**—**Water spray cooling is a technique typically used in heat treatment and other metallurgical processes where controlled temperature regimes are required. Water spray cooling is used in static (without movement) or dynamic (with movement of the steel plate) regimes. The static regime is notable for the fixed position of the hot steel plate and fixed spray nozzle. This regime is typical for quenching systems focused on heat treatment of the steel plate. The second application of spray cooling is the dynamic regime. The dynamic regime is notable for its static section cooling system and moving steel plate. This regime is used in rolling and finishing mills. The fixed position of cooling sections with nozzles and the movement of the steel plate produce nonhomogeneous water distribution on the steel plate. The length of cooling sections and placement of water nozzles in combination with the nonhomogeneity of water distribution lead to discontinued or interrupted cooling conditions. The impact of static and dynamic regimes on cooling intensity and the heat transfer coefficient during the cooling process of steel plates is an important issue.

Heat treatment of steel is accompanied by oxide scale growth. The oxide scale layers can significantly modify the cooling properties and intensity during the cooling. The combination of static and dynamic (section) regimes with the variable thickness of the oxide scale layer on the steel surface impact the final cooling intensity. The study of the influence of the oxide scale layers with different cooling regimes was carried out using experimental measurements and numerical analysis. The experimental measurements compared both types of cooling regimes and the cooling of scale-free surfaces and oxidized surfaces. A numerical analysis was prepared to simulate the cooling process with different conditions of the section and samples with different oxide scale layers.

Keywords**—**Heat transfer coefficient, numerical analysis, oxide layer, spray cooling.

I. INTRODUCTION

THE water spray cooling is a successful method of cooling hot steel surfaces and heat treatment of steel. Spray cooling is an essential part of the continuous casting and hot rolling and 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. One problematic factor of cooling process is the oxide scale layer formation on the steel surface. This paper is focused on studying the impact of the oxide scales layers on the cooling intensity at static and dynamic regimes.

During the cooling process of the hot surface the 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 cooling law intensity is defined as the product of the heat transfer coefficient (HTC) and the temperature difference (surface temperature and ambient temperature). The intensity of the heat transfer depends on the surface temperature of the cooled steel. It means that the character of surface is an important parameter affecting 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 vapor layer occurs at the hot surface which insulates the liquid from the hot surface [5], [6]. So called Leidenfrost temperature specifies the boundary between the vapor 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 water impingement density [7]-[9]. Other possibilities to change the cooling intensity trough oxide scale layer are presented in this paper.

II. EXPERIMENTAL MEASUREMENTS

The impact of the oxide scale layer on the cooling intensity during discontinued water spray cooling was experimentally investigated. The different thicknesses of the scale layer were prepared on the test plate made of austenitic stainless steel (EN 1.4828) with dimensions 600 mm x 320 mm x 25 mm (Fig. 1). Two different areas (areas A and B) with different scale layer thicknesses were prepared on the test plate surface (Figs. 2 and 3). The test plate was eight times heated at a temperature 1200°C and then cooled by a mist nozzle to a room temperature. The heating time was approximately 2 hours and cooling time 15 minutes. Thin inhomogeneous scale layer was created on the cooled surface of the test plate after this heating and cooling cycle. Scales from the area A on this test plate were removed by pickling and scales from area B were unchanged before the experiment. Scales layers from

J. Hrabovský is with the Heat Transfer and Fluid Flow Laboratory, Brno University of Technology, Czech Republic (corresponding author to provide phone: +420 541 144 906; fax: +420 541 142 224; e-mail: hrabovsky@fme.vutbr.cz).

M. Chabičovský and J. Horský are with the Heat Transfer and Fluid Flow Laboratory, Brno University of Technology, Czech Republic (e-mail: y100872@stud.fme.vutbr.cz, horsky@fme.vutbr.cz).

area A (pickled) and B (covered by the thin scale layer) before and after the experiment are shown in Figs. 2 and 3.

A. Experimental Procedures

The experimental procedure consisted of several steps to reach the relevant experimental data of cooling process with oxide scale layers. A laboratory stand developed for testing nozzles applied for continuous casting was used to test the cooling intensity with different levels of oxide layer on the surface (Figs. 4 and 5). A steel frame held three major parts of the stand: the test plate, a moveable mechanism with nozzles and a heater. The test plate was placed into a lift. This allowed the plate to move up, removing the furnace and positioning of the nozzles under the test plate. There were holes drilled into upper side of the test plate where thermocouples were placed (Fig. 1). Shielded thermocouples of type K with a diameter of 1.5 mm were used for temperature monitoring. The temperature was measured 2 mm under the cooled surface. The temperature was measured by eighteen thermocouples (T1-T18) during the experiment. The thermocouples in areas A and B (T4 and T5) were used for the comparison of the scale layer effect. Three flat jet nozzles (S.S.CO. 8006) with typical use in the secondary cooling zone in the continuous casting of the steel were positioned on the moveable mechanism under the test plate. The water flow rate per nozzle at 0.2 MPa was 1.9 l min-1. The distance between the first and the second nozzle was 26 mm and the distance between the second and the third nozzle was 50 mm. The Spray height was 150 mm. Nozzles moved at a velocity 1 m min-1 under static test plate. The first row of thermocouples (T1… T9) was 40 mm far from the nozzles centers.

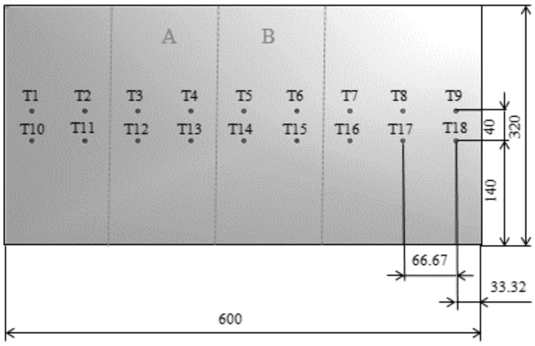

Fig. 1 Dimensions of the test plate with positions of the thermocouples

The test plate was placed in an electric furnace and it was heated in an air atmosphere to the initial temperature 980°C. Deflectors were closed and the pressure of the water was set up at 0.2 MPa. The test plate was moved up to the adjusted cooling position (150 mm) and the furnace on rails was moved out. The moving mechanism with the spraying nozzles with closed deflectors moved to a defined position under the hot test plate, then deflectors were opened and spraying nozzles moved at a velocity 1 m min-1 in one direction under the hot test plate. Nozzles moved in one direction with opened deflectors and returned with closed deflectors. This was repeated until the temperature in all measured points was below 100°C. The data acquisition system recorded the temperatures of all thermocouples, the temperature of the coolant and the position of nozzles with frequency 60 Hz during the whole experiment. The water flow rate (three nozzles) was 0.095 l/s during the experiment and the water temperature was 17°C.

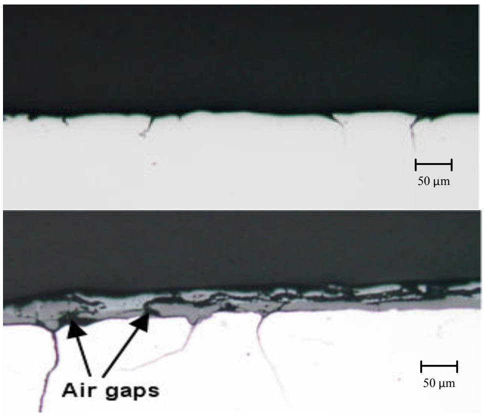

Fig. 2 Steel surface of area A (top-before, bottom – after experiment; black - plastic glue fixing scales for microscope observation, dark gray – scales, light gray – steel)

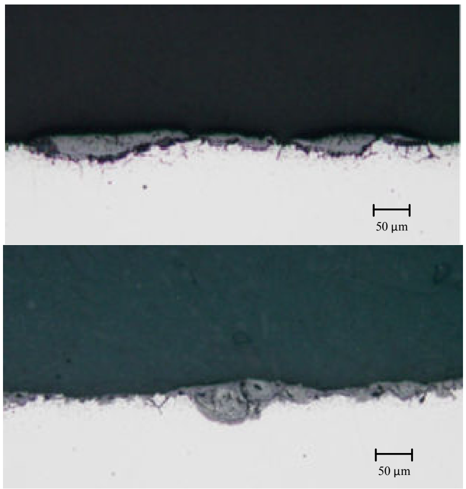

Fig. 3 Steel surface of area B (top-before, bottom – after experiment; black - plastic glue fixing scales for microscope observation, dark gray – scales, light gray – steel)

B. Experimental Results

The thickness of the scales was measured after the experiment. Two scales samples were taken from test plate after the experiment. One from area A and one from area B. Positions of both samples were between the thermocouples. Photos of the scale layers from area A and B are shown in Figs. 2 and 3. The scale layer, which grew during heating on the pickled area (area A) and was partly removed during cooling, was much thicker than the scale layer in the area B. The scale layer which grew on the pickled area was approx. 50

µm thick and was very porous (30% of the air). The scale layer in the area B was not so homogeneous as in the area A and the thickness differs from 0 µm to 50 µm.

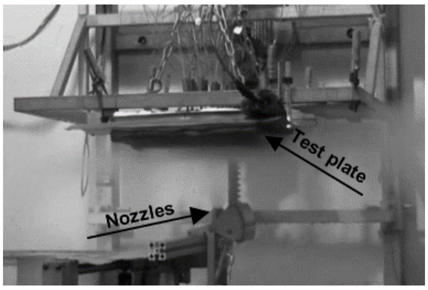

Fig. 4 Schematic illustration of the experimental apparatus

Fig. 5 Bottom view of the test plate cooling

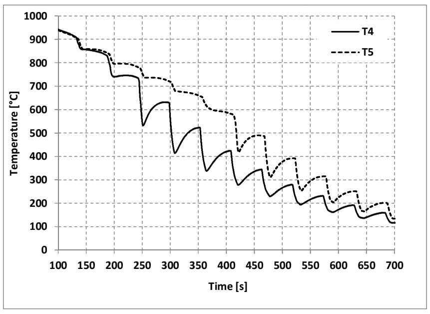

Fig. 6 Measured temperatures through the thermocouples T4 and T5

An inverse task [5], [6] was used to re-compute measured temperatures (see Fig. 6) to surface temperatures in order to obtain the heat transfer coefficient. The model for computing inverse task did not contain the scale layer. Computed time dependent surface temperatures are shown in Fig. 7 and the dependence of the heat transfer coefficient on the surface temperature is shown in Fig. 8 for thermocouples T4 and T5. The Thermocouple T4 was located in the area A (area with thick porous scale layer and thermocouple T5 was located in the area B (thin inhomogeneous scale layer).

The heat transfer coefficient is almost the same for thermocouples T4 and T5 for surface temperatures higher than Leidenfrost temperature (840°C). The Leidenfrost temperature was significantly higher for the thermocouple T4, which was located in the area with thick porous scale layer. The Leidenfrost temperature was 840°C for thermocouple T4 and 600°C for thermocouple T5.

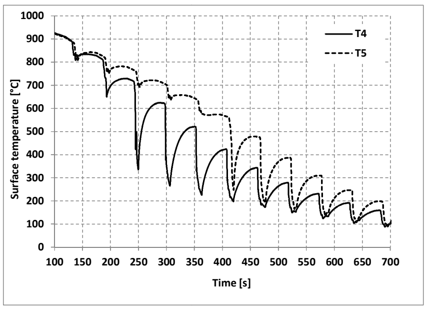

Fig. 7 Calculated surface temperature in position of thermocouples T4 and T5

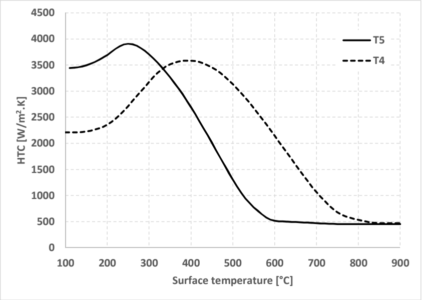

Fig. 8 Calculated HTC in positions of thermocouples T4 and T5

The temperature at which the maximum heat transfer coefficient occurs was higher for thermocouple T4. The maximum heat transfer coefficient occurs at 400°C for thermocouple T4 and at 250°C for thermocouple T5. There was no significant difference between thermocouples T4 and T5 in the value of the reached maximum heat transfer coefficient (approx. 3600 W m-2 K-1 and 3900 W m-2 K-1).

III. NUMERICAL SIMULATION

The numerical simulation was prepared to study the oxide scale layer on the cooling process at two different regimes. The first regime represents the static cooling process. The test plate is without movement. The static regime is characterized by continues cooling conditions. The second regime was described as dynamic. The dynamic cooling process is typical by moving of the test plate. Due to moving of the test plate the cooling process is discontinues. The cooling process and recovery of the temperatures are alternated. The numerical simulation was based on the experimental measurements described in previous chapter.

A. Numerical Model

To perform the numerical simulations two dimensional finite element (FE) model was created. The two simple cases of the FE model were created. The first case composed only from the base material (structural steel). In the second case, the FE model included the base material and defined oxide scale layer. The three thicknesses of the oxide scale layers in the numerical model were considered (30, 50, 100µm). The FE models with defined dimensions and thickness of the oxide scale layer (T) are presented in Fig. 9. For the base material the physical properties of structural steel were applied. For the oxide scale layer the physical properties from literature were used which occur in large dispersion (0.1-3 W/mK). The thermal conductivity 0.2 W/mKwas applied. This value of thermal conductivity was estimated based on measured oxide layers from experiments described in the previous chapter. The physical properties of steel and oxide scale applied in FE model are presented in Tables I and II. The material of the steel and oxide scale as a continuous and homogenous was considered. The contact between the base material and the oxide scale layer was modelled as perfect ("bonded").

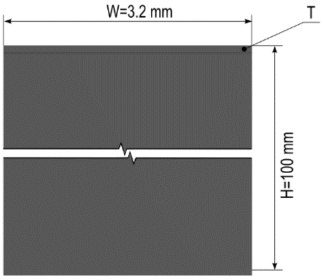

Fig. 9 FE model with dimensions

For the numerical analysis only one HTC vs. surface temperature curve for all considered variants was applied. Heat transfer coefficient used in numerical modelling is plotted in Fig. 8 (line T5). 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 900°C was applied. This temperature was started in experimental measurement. The numerical analysis of static regime was loaded by HTC curve. The cooling time in numerical simulation was defined to 370 s. The applied loads were the same in the whole time. In the dynamic regime two load cases alternate. The first load case consists of cooling (HTC curve was applied) and in the second case the radiation was used. The load profile is presented in Fig. 10. The radiation was considered between the surface of the plate and the ambient temperature. The value of emissivity was defined to 1 and the ambient temperature was 22°C. The first load case was defined on 10s and duration of the second case was 15s. The total time was also 370s as in the static regime. In numerical simulation of dynamic regime, the first load step was applied fifteen times and the second load step fourteen times.

TABLE I
PHYSICAL PROPERTIES OF THE SCALE

Thermal conductivity	Specific heat	Density
0.2 W/m·K	970.0J/kg·K	5700.0 kg/m^3

TABLE II
PHYSICAL PROPERTIES OF THE STRUCTURAL STEEL

Thermal conductivity	Specific heat	Density
60.0 W/m·K	434.0J/kg·K	7850.0 kg/m^3

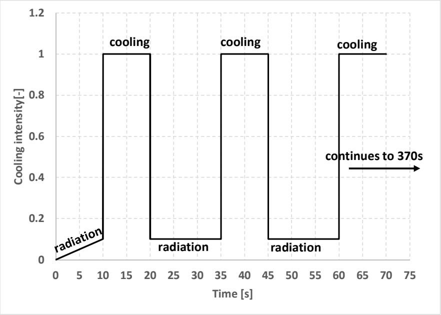

Fig. 10 Applied load profile of dynamic simulation

B. Results

The results were evaluated for both regimes. The evaluation was carried out for surface area and contact between base material and oxide layer. The evaluation of results was performed on surface temperature of steel Ts and surface temperature of oxide Tp. The same symbols were applied on the heat fluxes. Heat flux through steel surface is marked Qs and through oxide surface Qp. The schematic illustration of the evaluated location from numerical simulation is presented in Fig. 11. Based on the evaluated values of the surface temperatures (Ts) and heat fluxes from surface (Qs) the heat transfer coefficient (HTC) was calculated.

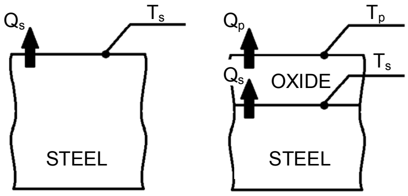

Fig. 11 Schematic illustration of position evaluation

The evaluation of the temperatures for both regimes and different thickness are presented in Figs. 12-15. The presented results of temperature history confirm the impact of the static and dynamic cooling regime and also the impact of the different thickness of the oxide layer. If we apply static cooling regime (without interruption) we can reach the lower temperature earlier than if we use dynamic regime (with interruption). In dynamic regime we need more time to cool down the surface because we apply the cooling only for defined time interval and during time without cooling the temperature is recovered due to thermal energy inside the sample.

In Fig. 12 and Fig. 13 we can see that the cooling in static regime reached temperature on steel surface 127°C (Ts_steel) after 370s. The steel surface (without oxide layer) was considered as reference. The same temperature in dynamic regime is 581°C. This effect is more significant in temperatures obtained from oxide layer (see Figs. 14 and 15). The static regime seems to be more intensive cooling than the dynamic regime. In static regime the intensity of cooling is affected by oxide layer. From Figs. 12 and 14 it is evident, that the thickness of the oxide layer shifted the Leidenfrost temperature in time. Firstly, the Leidenfrost temperature was reached at the thickest oxide layer. On the clean surface it was the latest. This is caused by insulation character of the oxide layer which led to quick cooling of the oxide layer and blocked the flow of thermal energy from steel. The shifting of the Leidenfrost temperature has the same character in the dynamic regime (see Figs. 13 and 15). The intensity of cooling in the dynamic regime is also affected by length of the cooling interval compared to time without cooling (only radiation). The combination of thickness of the oxide layer and cooling interval could have important influence on the cooling intensity and the cooling time. This effect was studied from evaluated heat fluxes and values of HTC. The evaluated heat fluxes for both regimes are presented in Figs. 16 and 17. The calculated HTC are depicted in Figs. 19 and 20.

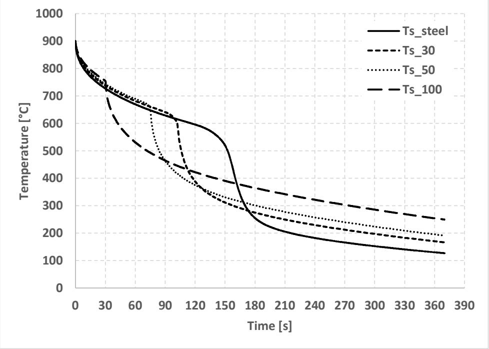

Fig. 12 Evaluation of surface temperatures (static regime)

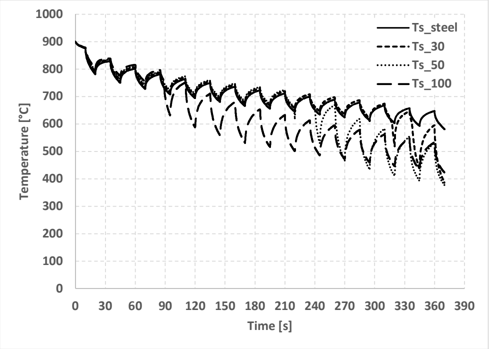

Fig. 13 Evaluation of surface temperatures (dynamic regime)

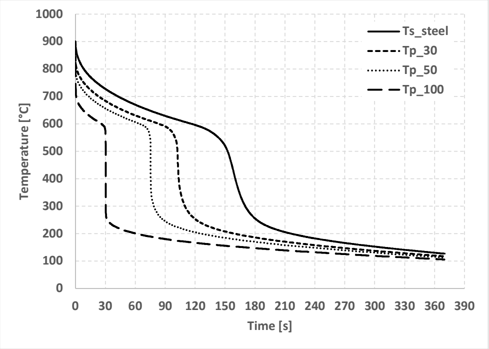

Fig. 14 Evaluation of oxide layer temperature (static regime)

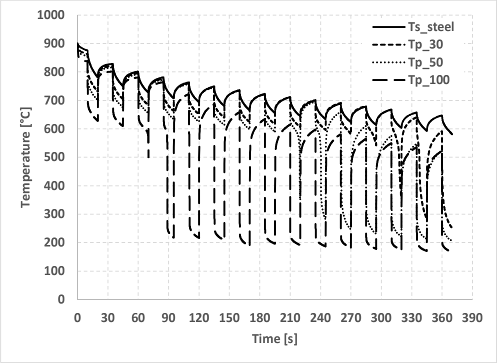

Fig. 15 Evaluation of oxide layer temperature (dynamic regime)

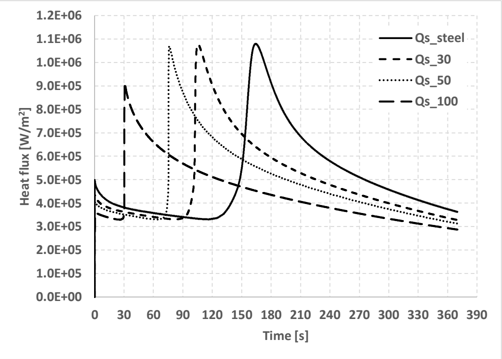

Fig. 16 Evaluation of heat fluxes thorough the steel surface (static regime)

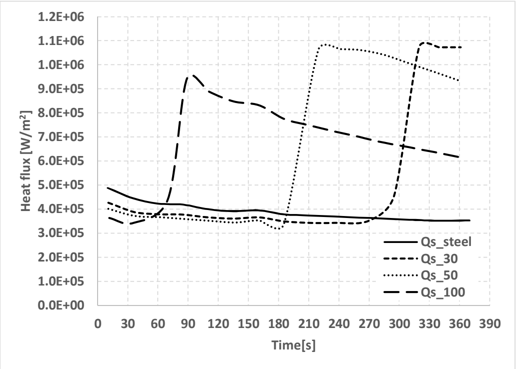

Fig. 17 Evaluation of heat fluxes thorough the steel surface (dynamic regime)

The evaluation of the heat fluxes from steel surface presented in above figures was performed. The heat flux curves for dynamic regime were constructed from maximum values of the heat fluxes of cooling interval (see Fig. 18). For each oxide layer thickness and also for clean steal surface the maximum heat flux in time was evaluated and the heat flux curves vs. time were created (see Fig. 17). These curves can possibly be directly compared with heat flux curves evaluated from the static regime.

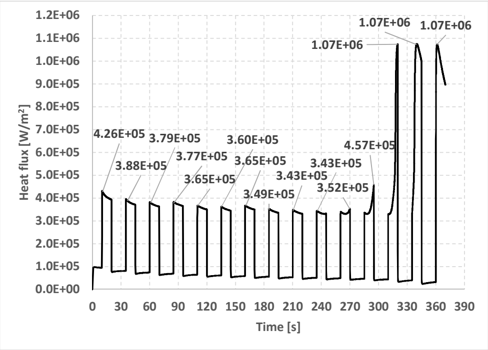

Fig. 18 Heat flux obtained for dynamic regime (Qs_T30)

From comparison of the heat fluxes evaluated in the static and the dynamic regime we can see a very similar character. The impact of the oxide layer on the shifting of the Leidenfrost temperature is also evident. From Fig. 17 it is possible to see, that the Leidenfrost temperature for clean steel surface in defined time was not reached. The maximum values of the heat flux in the static regime for clean surface and oxide layer with thickness 30 and 50 µm are similar. It means that the impact of the relatively low thickness of the oxide layer on the maximum values of the heat flux is not significant. For the thickness 100 µm of oxide layer the maximum of heat flux is lower. It is due to insulation effect of the thick oxide layer. The same character is presented in the dynamic regime. When we compared the absolute maximum values of heat fluxes for clean steel surfaces and the oxide layer thicknesses 30, 50 µm in the static and the dynamic regimes, the values were also very similar, slightly higher in the static regimes. Interesting results for thickness 100 µm are that the maximum value of the heat flux in the static regime (903810 W/m2) is lower than the maximum value in the dynamic regime (943580 W/m2). It means that we intensively cooled in the dynamic regime. This result was confirmed in HTC calculations. The HTC were calculated based on the presented results and the Newton´s law of cooling was applied. The HTC were calculated from steel surface and are presented in Figs. 19 and 20. For the HTC curves creation of the dynamic regime the same methodology as for the heat fluxes was used. The character of HTC curves for the static and the dynamic regimes is similar and corresponds with the character presented in the heat fluxes. The static regime achieves slightly higher absolute values of heat fluxes and also HTC´s for clean steel surface and low thickness of the oxide layer.

The different situation occurred for the highest thickness (100 µm) of the oxide layer. The maximum value of the HTC for this in static regime reached the value 1315W/m2K. For dynamic regime the maximum value is 1563 W/m2K. This difference is more evident for HTC than for the heat fluxes, but this result was observed in both parameters. The difference in HTC between the static and the dynamic regime cannot be neglected.

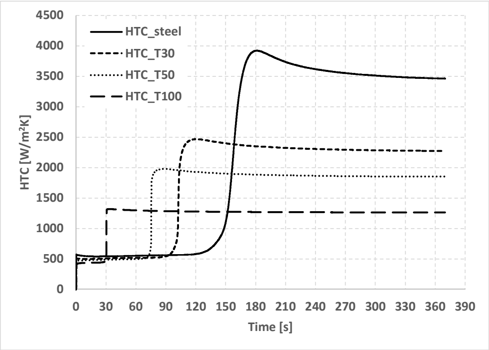

Fig. 19 Calculated HTC from steel surface (static regime)

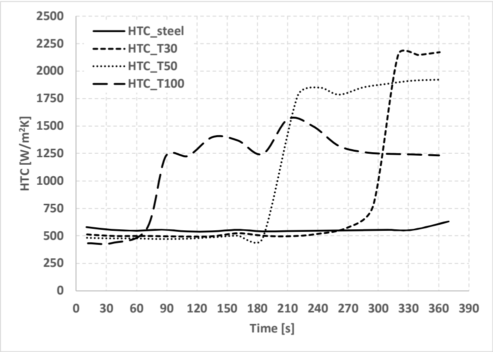

Fig. 20 Calculated HTC from steel surface (dynamic regime)

IV. CONCLUSION

The length of the cooling process could have significant effect on the final temperatures and also on the quality of the heat treatment. This paper was focused on the study of the static (permanent-without moving) and the dynamic (moving of the test plate) cooling process. These two regimes were applied on the clean steel surface and on the surface with three different oxide layers (30, 50, 100µm). The experimental measurement of the dynamic regime with different oxide layer was carried out. The results from experimental measurement for numerical simulation of both regimes were used. The initial temperature of specimen, HTC calculated based on the experimental results and properties of oxide layer were applied as initial and boundary condition in numerical simulation.

The numerical simulations for all regimes and oxide layer thickness were performed. The obtained results from steel surface and oxide layer surface were evaluated. The results show several effects. The first effect is shifting of the Leidenfrost temperature in time depended on the thickness of the oxide layer. The cooling intensity for the static regime was slightly higher but very similar compared to the cooling intensity of the dynamic regime. For the highest thickness of the oxide layer the cooling intensity was different. The dynamic regime cooled intensively. These results were evident from calculated HTC. The shifting of the Leidenfrost temperature was described by Wendelstorf, J. [10], [11] in the static regime. The results confirmed positive influence of the oxide layer on cooling intensity in the dynamic regime. The impact could be affected by many parameters, for example: thermal conductivity of oxides, base material, initial temperature, time intervals of load profile and so on. The presented results approved the impact of the oxide layer on the cooling intensity and shown different character in the static and the dynamic regime.

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REFERENCES

[1] Kim, J., Spray cooling heat transfer: The state of the art., International Journal of Heat and Fluid Flow, Vol. 28, 2007, pp. 753-767

[2] Hu, P., Ying, L., Li, Y., Liao, Z., Effect of oxide scale on temperature-dependent interfacial heat transfer in hot stamping process, Journal of Materials Processing Technology, Vol. 213, 2013, pp. 1475-1483

[3] Panigrahi, B.K., Processing of low carbon steel plate and hot strip-an overview, Bull Material Science, Vol. 24, No. 4, 2001, pp. 361-371

[4] Bending, L., Raudensky, M., Horsky, J., Descaling with high pressure nozzles, ILLAS-Europe, Zurich, 2-6 September, 2001

[5] Pohanka, M., Kotrbacek, P., Design of cooling units for heat treatment, Heat Treatment-Conventional and Novel Applications, ISBN: 978-953-51-0768- 2, InTech, 2012, pp. 1-20

[6] Raudensky, M., Horsky, J., Secondary Cooling in Continuous Casting and Leidenfrost Temperature Effects, Ironmaking, Vol. 32, No. 2, 2005, pp. 159-164

[7] S. Yao, T.L. Cox, A general heat transfer correlation for impacting water sprays on high-temperature surfaces. Experimental Heat Transfer, 2002, Vol. 15, No. 4, pp. 207-219.

[8] J. Bernardin, I. Mudawar, ALeidenfrost Point Model for Impinging Droplets and Sprays. Journal of Heat Transfer, 2004, pp. 272-278.

[9] M. Chabicovsky, M. Raudensky, Experimental Investigation of the Heat Transfer Coeficient. Materiali in tehnologije. 2013. 47(3). pp. 395 - 398. ISSN 1580-2949.

[10] Wendelstorf, J., Spitzer, K.H., Wendelstorf, R., Spray water cooling heat transfer at high temperatures and liquid mass fluxes, International Journal of Heat and Mass Transfer, Vol. 51, 2008, pp. 4902-4910

[11] Viscorova, R., Scholz, R., Spitzer, K.H., Wendelstorf, J., Measurement of spray cooling heat transfer coefficient under oxide scale formation conditions, AISTech, Vol. 2, 2006, pp. 519-528.