IMPACT OF OXIDE SCALE ON HEAT TREATMENT OF STEELS

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Abstract

Oxidation is an inherent aspect of steel production and heat treatment. Oxide scale layers commonly impact surface quality and material loss during steel processing. This paper is focused on the study of the influence of the oxide layer on cooling intensity. Spray cooling of a hot steel surface is considered. Typical examples are secondary cooling in continuous casting, interstand and run-out table cooling at hot rolling, and heat treatment and other metallurgical processes where controlled temperature regimes are required.

Cooling intensity is primarily affected by spray parameters such as pressure and coolant impingement density. Though not frequently reported, even thin layers of oxides can significantly modify cooling intensity. This effect is prevalent when cooling steel surfaces at high surface temperatures. The influence of oxide scale layers on cooling intensity was studied using 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 sample cooling with different oxide scale layers and thermal conductivity. Even a scale layer of several microns can significantly modify the cooling intensity.

Keywords: scale, oxide, Leidenfrost temperature, spray cooling, cooling intensity

1. INTRODUCTION

Oxidation is an inherent aspect of steel production and heat treatment. Oxide scale layers commonly impact surface quality and material loss during steel processing. The scale layer also affects the cooling process. As reported in [1] and [2], the oxide layer can significantly influence the cooling intensity. Oxide scales covering a steel surface have a much lower thermal conductivity than steel (15-60 W m^{-1}K^{-1}). The thermo-physical properties of the scale layer depends on the percentage of different types of oxides present (FeO, Fe_2O_3 and Fe_3O_4) and the compactness of the scale layer. Thermal conductivities of different type of oxides are shown in **Fig. 1**. The thermal conductivity of a scale layer is approximately 3 W m^{-1}K^{-1} [1] or lower, due to the presence of air voids (0,062 W m^{-1}K^{-1} air at 900K) in the scale layer. Scales on a steel surface act as an insulation barrier, decreasing the heat exchange between the steel and surrounding area. This "insulating" effect of scales can be easy to describe mathematically using the analogy of heat transfer through a wall with insulation. Let Qs $[Wm^{-2}]$ be a heat flux from an oxide-free steel surface at temperature Ts $[K]$ to the surrounding temperature T_∞ $[K]$. This is described by Newton's Law of Cooling:

$$Q_S = HTC(T_S - T_\infty), \qquad (1)$$

where HTC $[Wm^{-2}K^{-1}]$ is a heat transfer coefficient. The heat flux from the oxidized surface Q_P at oxide surface temperature T_P is:

$$Q_P = HTC(T_P - T_\infty), \qquad (2)$$

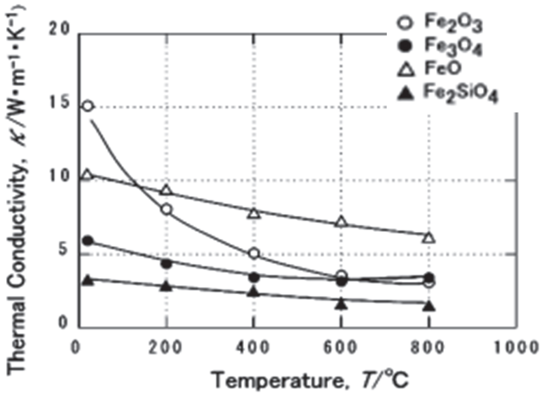

Fig. 1 Thermal conductivity of different type of oxides created on the silicon steel [3]

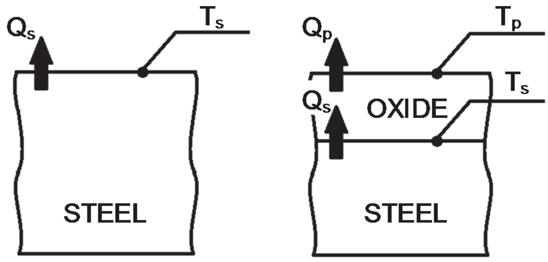

Fig. 2 Illustrative diagram of heat transfer from an oxidized steel surface

For the scale layer on the steel surface, we define the effective heat transfer coefficient (HTC_{eff}) as:

$$HTC_{eff} = \frac{Q_S}{(T_S - T_\infty)} \qquad (3)$$

The effective heat transfer coefficient contains all the effects of the scale layer on heat transfer and it can simplify numerical simulations of cooling processes, because the numerical model does not consider a scale layer. A scale layer is very thin compared to the thickness of the steel, and so the heat accumulated in the scale layer can be neglected ($Q_S = Q_P$). Using Fourier's Law

$$Q_P = \frac{\lambda_{sc}}{\delta_{sc}}(T_S - T_P), \qquad (4)$$

where $\lambda_{sc}\ [W\ m^{-1}\ K^{-1}]$ is the thermal conductivity of the scale layer and $\delta_{sc}\ [m]$ is the thickness of the scale layer, we can define the effective heat transfer coefficient as a function of the heat transfer coefficient on a scale free surface, the thickness of the scale layer, and the thermal conductivity of the scale layer:

$$HTC_{eff} = \frac{Q_S}{T_S - T_\infty} = \frac{Q_S}{(T_S - T_P) + (T_P - T_\infty)} = \frac{Q_S}{Q_P \frac{\delta_{sc}}{\lambda_{sc}} + \frac{Q_P}{HTC}} \approx \left(\frac{1}{HTC} + \frac{\delta_{sc}}{\lambda_{sc}}\right)^{-1} \qquad (5)$$

The heat transfer coefficient strongly correlates to the surface temperature during the spray cooling process with high surface temperatures (higher than 100°C), and one must note that the HTC_{eff} is a function of T_s and that HTC is a function of the T_P in eq. 5. If we know the thickness of the scale layer (δ_{SC}), the thermal conductivity of the scale layer (λ_{SC}) and the heat transfer coefficient on an oxide free surface (HTC) at temperature T_P, we can easily evaluate HTC_{eff} at the temperature between steel and oxide layer T_s. The temperature between steel and oxide layer (T_s) can be obtained using eq.2 and eq.4:

$$T_S = T_P + \frac{\delta_{sc} HTC (T_P - T_\infty)}{\lambda_{sc}}. \qquad (6)$$

Eq.6 can be used for to evaluate the effective Leidenfrost temperature ($T_{Leid_{eff}}$) - the Leidenfrost temperature accounts for the influence of the scale layer:

$$T_{Leid_{eff}} = T_{Leid} + \frac{\delta_{sc}\alpha_{min}(T_{Leid} - T_{\infty})}{\lambda_{sc}}. \qquad (7)$$

The concept of the effective heat transfer coefficient was also presented in the paper [1]. The main goal of this paper is to compare the concept of the effective heat transfer coefficient with a numerical simulation and experimental measurement. The experiment was performed by spray cooling austenitic stainless steel plates.

2. NUMERICAL SIMULATION

The main goal of the numerical simulation was to study and simulate the impact of the oxide scale layer on the cooling process. The two dimensional finite elements (FE) model was used for numerical simulation. The FE model included the base steel material and a variable thickness of the oxide scale layer. Thermo-physical properties of the base material (structural steel) and oxide scale layer, which were applied in the numerical model, are shown in (**Table 1**). 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 Thermo-physical properties of steel and scale layers

Thermal conductivity		Specific heat		Density	
[W/mK]		[J/kgK]		[kg/m^3]	
scale	steel	scale	steel	scale	steel
1.7	60	970	434	5700	7850

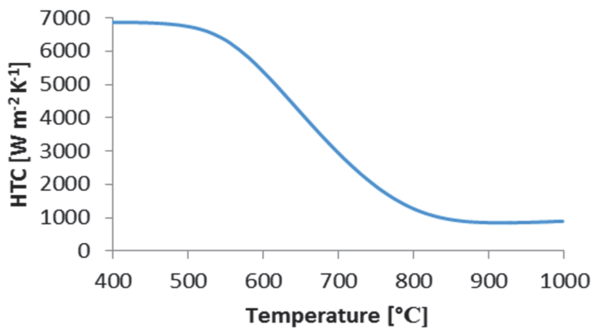

Fig. 3 Dependence of the HTC on the surface temperature

The typical dependence of the HTC on the surface temperature was used as a boundary condition on the oxidized surface (**Fig. 3**). This HTC is typical for the mist nozzles used in a secondary cooling zone in continuous casting of steel. Other surfaces were considered as insulated in the numerical model. A constant water temperature (T_{∞}) of 22°C and an initial steel sample temperature of 1000 °C were applied to the FE model. Results of the numerical simulation were time dependent temperature on the oxidized surface (T_p), time dependent temperature between the steel and scale layer (T_s) (**Fig. 4**) and heat flux from the steel (Q_s) and scale surface (Q_p) (**Fig. 5**). Thus, the presence of a scale layer can cause both an increase and decrease in cooling intensity.

The comparison of effective heat transfer coefficients obtained using numerical simulation and obtained using eq. 5 and eq.6 is shown in **Fig. 6**. It is evident that the effective HTC is almost same for small scale thicknesses. The prediction using eq. 5 and eq. 6 does not correspond to simulated data in the transition between the Leidenfrost temperature and the temperature at the maximum heat transfer coefficient. The prediction of the effective Leidenfrost temperature (eq. 7) and maximum heat transfer coefficient (eq. 5) is similar to the numerical simulation for all scale layer thicknesses. According to numerical simulations, the scale layer thickness influence on the cooling intensity is significant (**Fig. 5**). The thickness of the scale layer mainly influences two variables: the maximum HTC_{eff} decreases when increasing scale layer thickness and the effective Leidenfrost temperature increases when increasing scale layer thickness. Thus, the presence of a scale layer can cause both an increase and decrease in cooling intensity. The comparison of effective heat transfer coefficients obtained using numerical simulation and obtained using eq. 5 and eq.6 is shown in **Fig. 6Fig.** . It is evident that the effective HTC is almost same for small scale thicknesses. The prediction using eq.

5 and eq. 6 does not correspond to simulated data in the transition between the Leidenfrost temperature and the temperature at the maximum heat transfer coefficient. The prediction of the effective Leidenfrost temperature (eq. 7) and maximum heat transfer coefficient (eq. 5) is similar to the numerical simulation for all scale layer thicknesses.

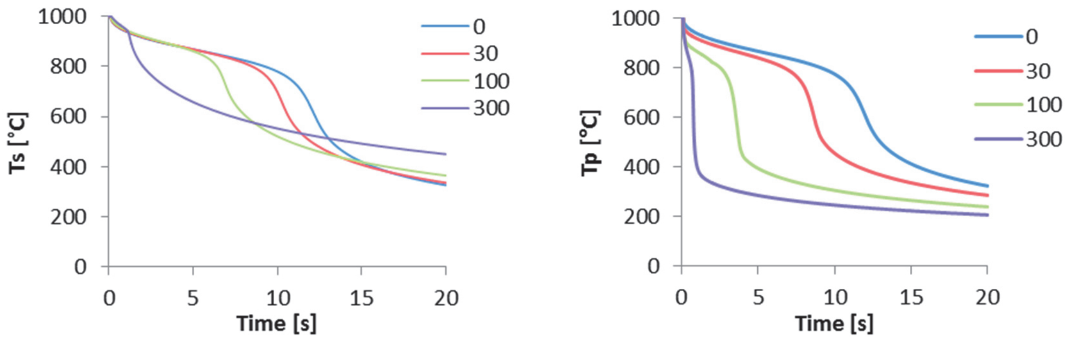

Fig. 4 The time evolution of the surface temperature (left) and temperature between the scale layer and steel (right) for different thicknesses of the scale layer (0 μm, 30 μm, 100 μm and 300 μm)

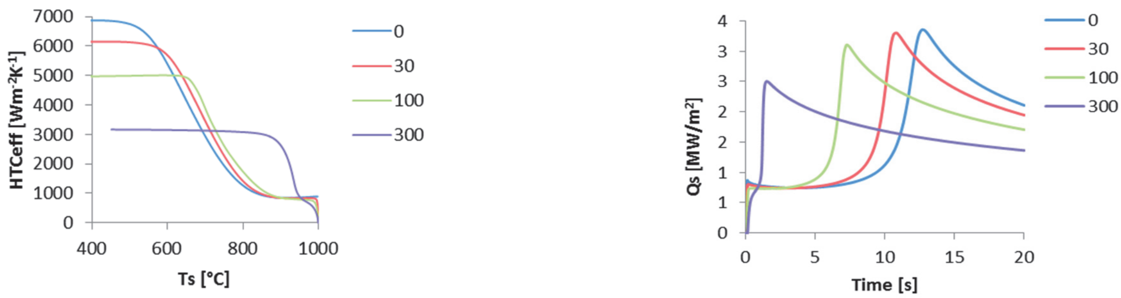

Fig. 5 The time evolution of heat flux from a steel surface for various scale layer thicknesses (from 0 μm to 300 μm) (left) and dependence of the effective heat transfer coefficient on the temperature between the scale layer and steel (right)

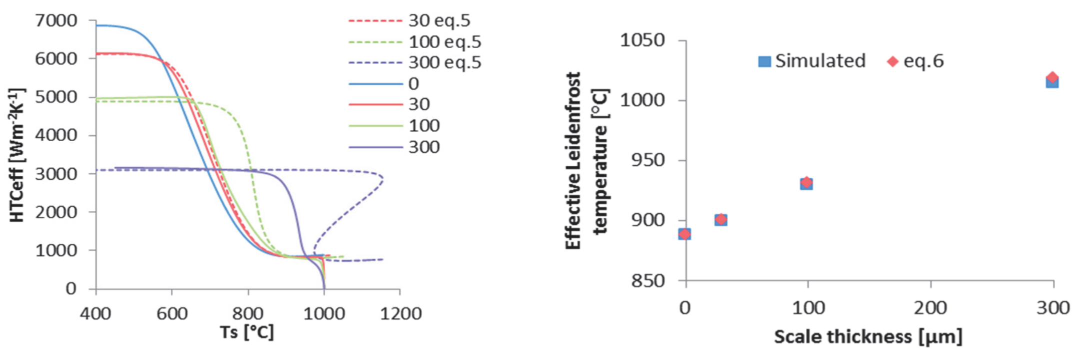

Fig. 6 Comparison of the effective heat transfer coefficient obtained using numerical simulation (solid line) with the effective heat transfer coefficient computed using eq.5 and eq. 6 and using HTC in **Fig. 3** (dashed line) (left). Effective Leidenfrost temperature (right)

3. EXPERIMENTAL MEASUREMENT

Experiments for validating results obtained by numerical simulation were performed on two austenitic steel plates which were cooled using spray nozzles. The experiment was prepared on steel plates with and without an oxide layer. The first sample was cleaned by pickling (**Fig. 7**, left). The second sample was covered by a compact layer of oxide scales of an average thickness of 15 μm (**Fig. 7**, right). Spray conditions were identical for both samples. Both samples were initially heated in a protective atmosphere at a temperature of 500°C and then repeatedly passed with a prescribed velocity through the cooling section, which was composed of water nozzles (**Fig. 8**). The temperature of the test plate was measured during the cooling process. The heat transfer coefficient was computed using the inverse task [4] from measured temperatures. The numerical model for inverse calculation was without an oxide layer and so the obtained HTC is the effective heat transfer coefficient. The results are presented in **Fig. 9**.

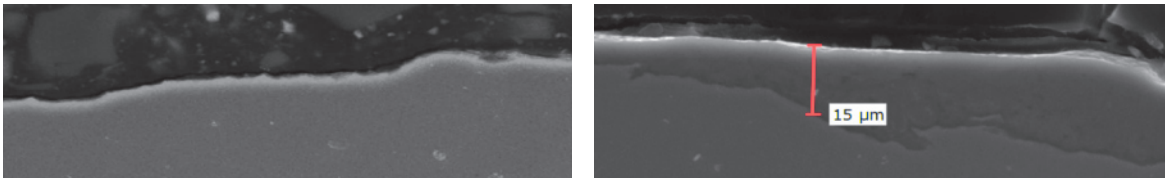

Fig. 7 Steel surface after pickling (left), steel surface with about 15 μm layer of oxides (dark grey is the oxide, light grey is steel, black is a plastic glue fixing scales for microscope observation).

Measurements showed that the effective heat transfer coefficient is higher for a surface covered by a scale layer. The effective Leidenfrost temperature is a bit higher for an oxidized surface. The shift of the Lidenfrost temperature was also predicted by the numerical simulation and by eq. 7. The measured higher effective heat transfer coefficient for an oxidized surface does not match results obtained by the numerical simulation. There are several explanations for this. One is that the increase of the effective heat transfer coefficient of the oxidized surface is due to the higher surface roughness of the oxidized surface. A surface with higher roughness has a higher value of maximum heat transfer coefficient and higher Leidenfrost temperature [5]. Unexpected experimental results can also be caused by differing conditions of cooling and simulation. The cooling in the simulation was continuous, but the experiment was conducted with interrupted cooling due to the movement of the test plate. Experiments conducted with continuous spray cooling of oxidized and non-oxidized steel surfaces [1] and (**Fig. 10**) showed similar scale layer effects as predicted in the numerical simulation. The Leidenfrost temperature increases when increasing the scale layer thickness and the maximum effective heat transfer coefficient decreases when increasing the scale layer thickness.

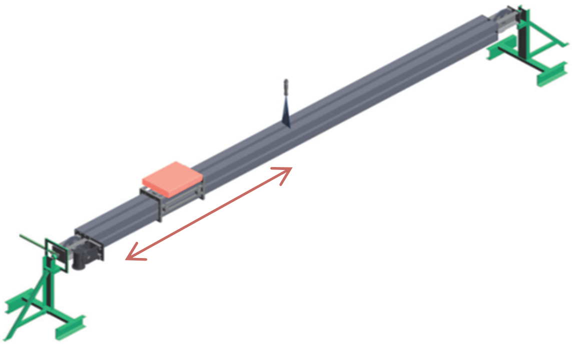

Fig. 8 Experimental apparatus

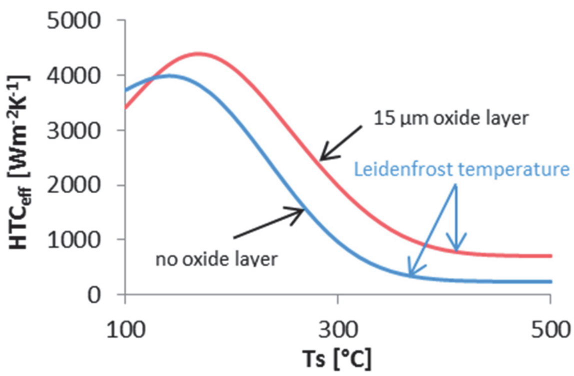

Fig. 9 Measured effective heat transfer coefficient for clean surface (blue) and for surface with oxides (red)

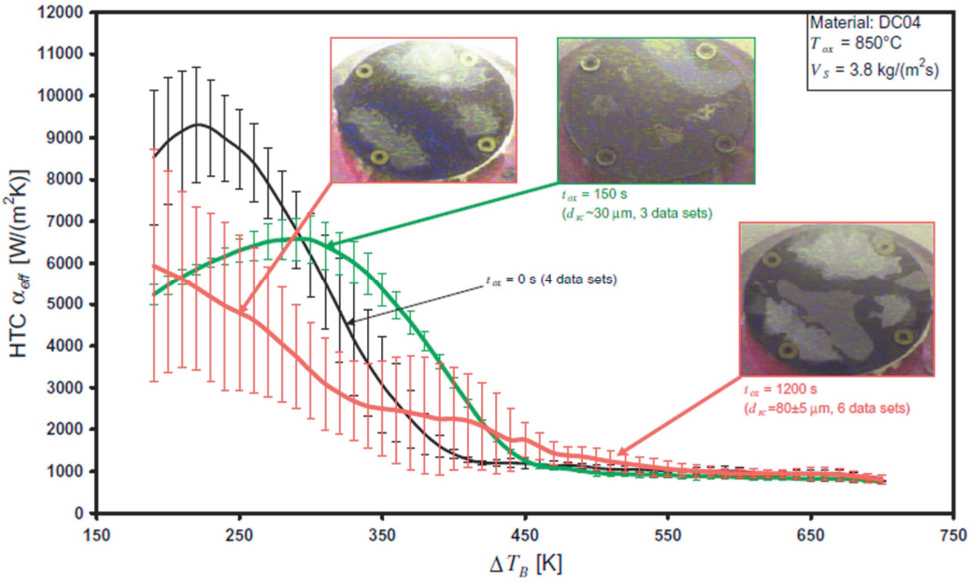

Fig. 10 Experiments with different scale layer thicknesses [1]

CONCLUSION

Numerical and experimental study of spray cooling of hot steel surfaces showed the important role of oxide layers on the cooling. The cooling intensity in these cases strongly depends on the surface temperature. Typical water or mist nozzles have low cooling intensity at surfaces of very high temperature. The cooling intensity suddenly grows about ten times when an insulating vapor layer between the surface and droplets collapsed at the Leidenfrost point. The strong dependence of cooling intensity on surface temperature can cause a surprising effect when a surface covered by oxides is cooled more intensively than a clean steel surface. This effect can be predicted for known thicknesses and conductivity of the scale layer and from the description of cooling intensity as a function of surface temperature.

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