

## IMPACT OF OXIDE LAYER ON SPRAY COOLING INTENSITY AND HOMOGENEITY DURING CONTINUOUS CASTING OF THE STEEL

Martin CHABIČOVSKÝ<sup>1</sup>, Ondřej RESL<sup>1</sup>, Miroslav RAUDENSKÝ<sup>1</sup>

<sup>1</sup>Brno University of Technology, Faculty of Mechanical Engineering, Brno, Czech Republic, EU

[Martin.Chabicosky@vut.cz](mailto:Martin.Chabicosky@vut.cz)

### Abstract

Formation of oxide layers on the surface is inherent part of steel production. The presence of the oxide layer primarily influences the surface quality and material losses during steel processing. The influence of the oxide layer on the cooling intensity and homogeneity is not frequently reported but even thin layers of oxides can significantly modify the cooling intensity. Although the cooling intensity is primarily affected by spray parameters as pressure and coolant impingement density, the influence of the oxide layer should be also considered for optimal setting and regulation of the secondary cooling zone. The influence of the oxide layer on the heat transfer coefficient and Leidenfrost temperature is investigated in this paper. Laboratory measurement compares the spray cooling of oxide-free steel surface and oxidized steel surface. Results of measurement also show the impact on the spray cooling homogeneity due to local breaking up of the oxide layer.

**Keywords:** Scale, oxide layer, heat transfer coefficient, spray cooling, Leidenfrost temperature

### 1. INTRODUCTION

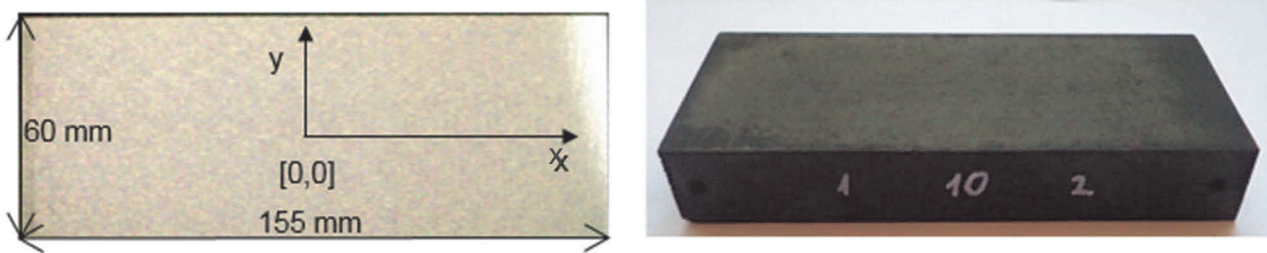
Water spray cooling is a common cooling method used in many high temperature industrial applications, such as metal processing or electronics cooling. Continuous casting of the steel includes the formation of oxides on the surface. These oxides form a porous layer on the steel surface. The oxide layer has a very low thermal conductivity compared to the steel and acts as a thermal barrier. This thermal barrier lowers the heat flux from the metal surface to the surroundings when it is cooled by the air but the use of water can cause a shift of the Leidenfrost temperature and intensify the cooling for a short time period [1,2].

The heat transfer coefficient and the Leidenfrost temperature (temperature at which the minimum heat flux occurs) are mainly influenced by the water impingement (spray) density and by the surface temperature [3]. The influence of the oxide layer is not as significant as previous factors, but it shouldn't be neglected for better control of the temperature in a secondary cooling zone which can minimize surface defects during the continuous casting process of the steel [4].

This paper deals with the influence of the oxide layer on the spray cooling heat transfer coefficient and Leidenfrost temperature. Results of spray cooling laboratory measurement in which oxidized steel samples were cooled by flat jet nozzle with typical use in a secondary cooling zone are presented.

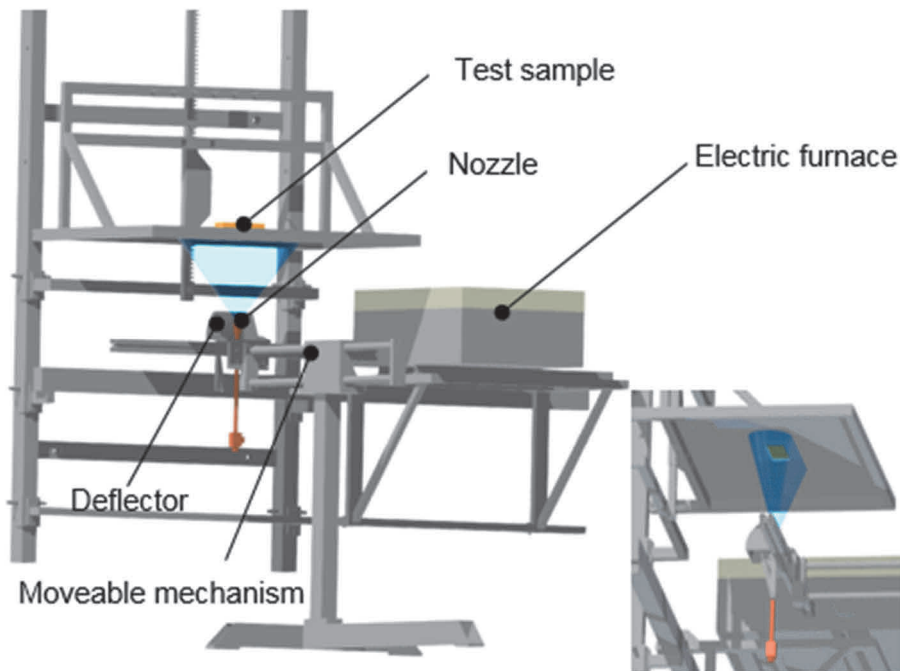
### 2. HEAT TRANSFER COEFFICIENT MEASUREMENT

Four test samples with dimensions 155x60x25 mm were prepared from the spring steel 54SiCr6 (1.7102). Two holes for thermocouples (diameter 1.5 mm, type K) were drilled from the top side in the positions [-30,0] and [30, 0] to each sample. The position [0, 0] is in the centre of the sample (**Figure 1**).



**Figure 1** Test samples: clean (left) and oxidized (right)

The test bench is shown in **Figure 2**. It consists of an electric furnace, covering sheet, hot test sample, moveable mechanism with nozzle and nozzle's deflector. The flat jet nozzle (SS.CO 8006) with spray angle  $80^\circ$  was positioned 300 mm under the test sample. The water pressure was set at 2 bars during the experiment and measured flow rate was 0.0317 l/s.

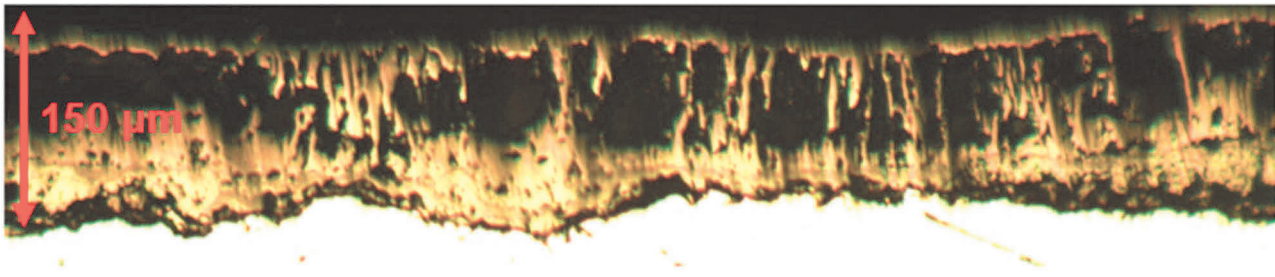


**Figure 2** Test bench

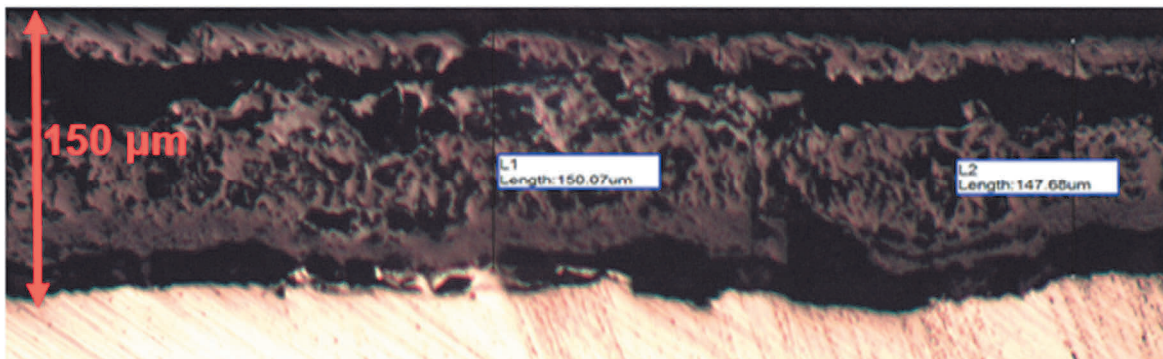
Two samples (A and B) were oxidized in an electric furnace and two samples (C and D) were remained clean (without oxides). The sample A was oxidized at a temperature of  $900^\circ\text{C}$  for 60 minutes and the sample B was oxidized at a temperature of  $1050^\circ\text{C}$  for 30 minutes. Holes for thermocouples were cleaned (the formed oxides were removed) and shielded grounded thermocouples were positioned 2 mm from the bottom (spray cooled) surface before the measurement. Each sample was isolated from the top side and was heated in an electric furnace on the temperature  $760^\circ\text{C}$  in a protective nitrogen atmosphere (avoiding of the oxidation). Then, the sample was removed from the furnace and it was positioned on the test bench. The deflector was opened, and the cooling started.

Samples A (oxidized) and C (clean) were cooled by static nozzle (the centre of the nozzle was positioned under centre of the test sample and samples B (oxidized) and D (clean) were cooled by moveable nozzle. The nozzle passes under the test sample with the velocity 4 m/min. The deflector was opened (the sample was cooled by spray) in one direction and the deflector was closed (no spray cooling) in backwards direction.

The test sample A was cut after the experiment and the oxide layer was observed in a position of thermocouple T2 on the optical microscope (**Figure 3**). The oxide layer was destroyed on the sample B during the experiment. The photos of the oxide layer formed on the same steel sample at same oxidation condition as sample B is in **Figure 4**. The thickness of the oxide layer on the sample A and also on the sample B was approx. 150  $\mu\text{m}$ .



**Figure 3** Oxide layer formed on the sample A



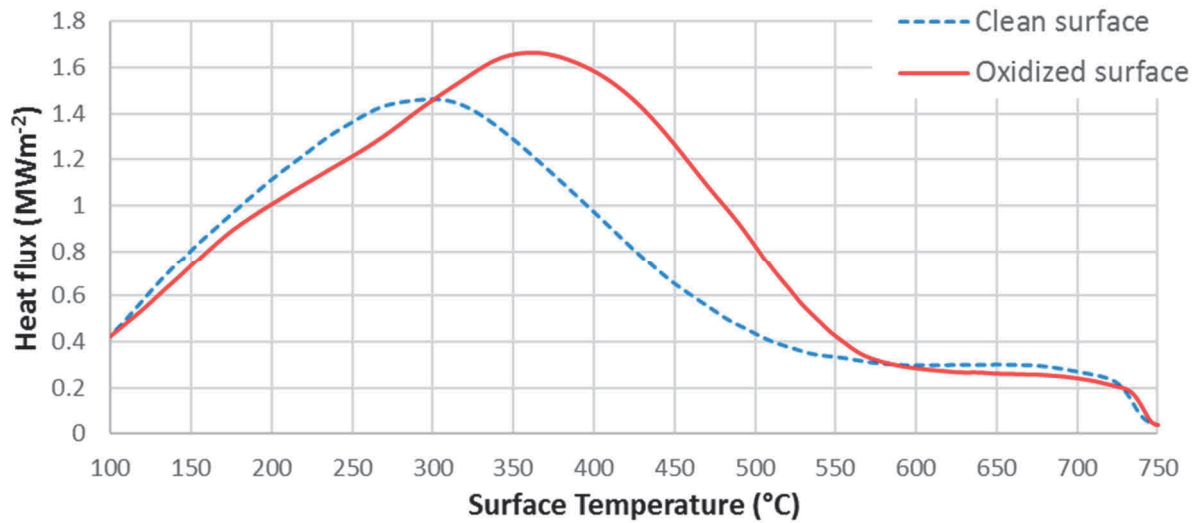
**Figure 4** Oxide layer formed on the sample B

### 3. RESULTS OF THE MEASUREMENT

The inverse heat conduction problem was used to compute the time dependent boundary conditions (heat transfer coefficient (HTC), heat flux, and surface temperature) from measured temperatures. Beck's sequential approach, which uses a sequential estimation of the time varying boundary conditions and future time steps, was employed [5]. The dependence of the HTC on the surface temperature is directly obtained from the inverse calculation for static experiments. This dependence is obtained by averaging along the position (interval 10 mm around the thermocouple position) for the measurements with moveable nozzle [3].

#### 3.1. Static nozzle

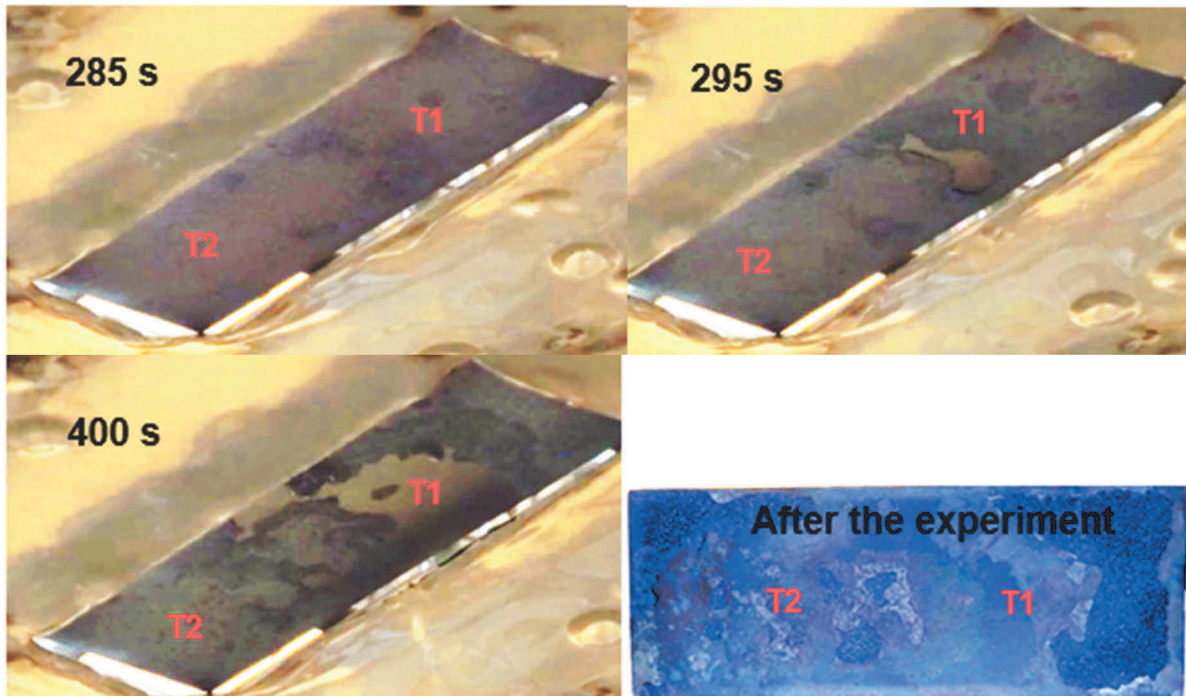
The heat flux dependent on the surface temperature for the clean surface (sample C) and oxidized (sample A) is shown in **Figure 5**. The heat flux values are average values from both thermocouples (T1 and T2). It is evident that the heat flux is slightly higher for clean surface for high surface temperatures (higher than 580 °C). The HF is also higher for clean surface for low surface temperatures (lower than 300 °C). The HF is higher for oxidized surface for surface temperatures between 300 °C and 580 °C. Higher HF for oxidized surface is caused by the shift of the Leidenfrost temperature. The Leidenfrost temperature for the clean surface is around 600 °C and for oxidized sample is 540 °C.



**Figure 5** Comparison of clean surface and oxidized surface heat flux

### 3.2. Moveable nozzle

The oxides on the sample B were destroyed during the spray cooling with moveable nozzle. The oxide surface was perfect until the time approx. 290 s when the oxide layer started to break up close to the position of the thermocouple T1 (**Figure 6**). The oxide layer does not cover the area around thermocouple T1 at time 400 s but the position of thermocouple T2 was still covered by the oxide layer at this time. The oxide layer was largely destroyed around the position of T2 thermocouple after the experiment (**Figure 6**).

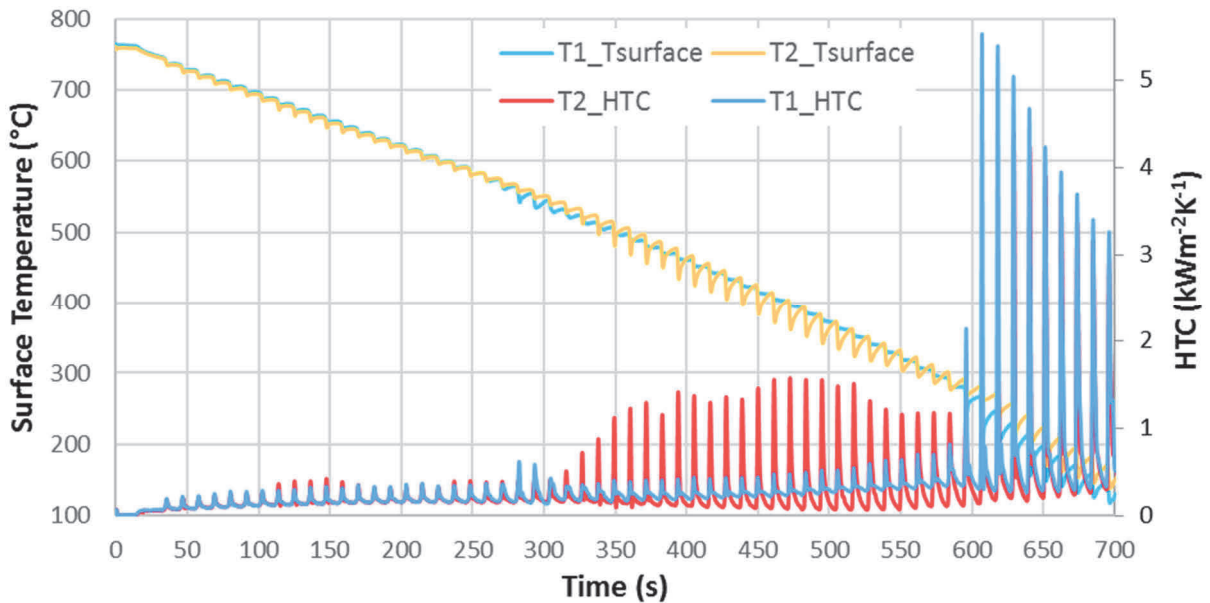


**Figure 6** Cooled surface of the test sample B during the measurement

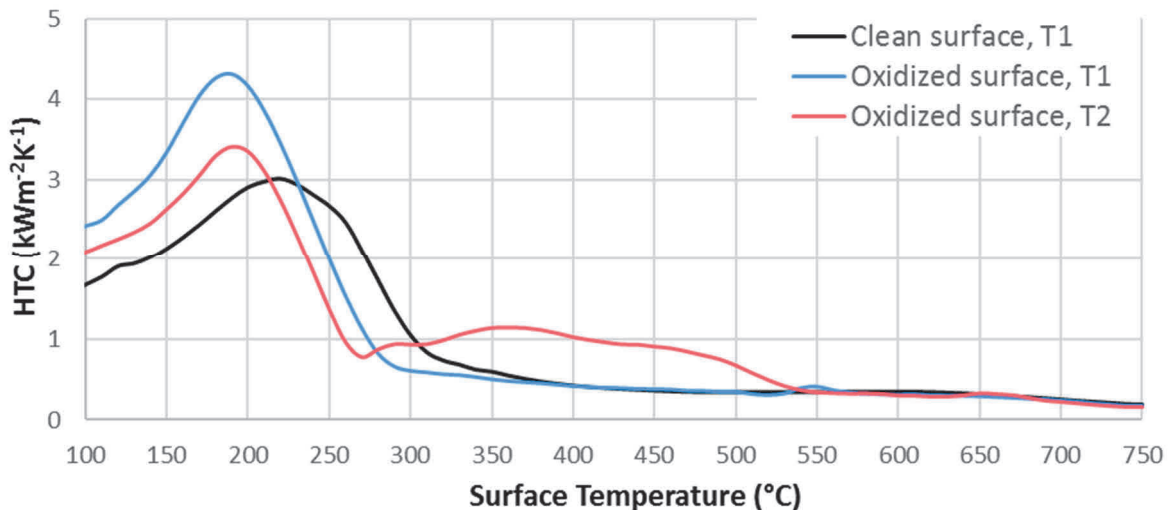
Time dependent HTC and computed surface temperatures for both thermocouples are shown in **Figure 7** for oxidized sample (B). We can see slight increase of the HTC for the thermocouple T1 around the time 290 s. This increase is at the same time in which the oxide layer became broken around T1. There is significant

difference in HTC in positions of thermocouples T1 and T2 at time 400 s. The HTC is significantly higher for T2 (oxidized surface) than for T1 (clean surface - removed oxides). This is caused by the shift of the Leidenfrost temperature. The HTC drops down in position of T2 at time approx. 580 s. This drop is caused by the destruction of the oxide layer in position of T2. The dependence of the HTC on the surface temperature is shown in **Figure 8**.

This measurement demonstrates significant impact of the oxide layer on the cooling homogeneity especially for surface temperatures around the Leidenfrost temperature. The cooling intensity is significantly different on the clean surface than on the oxidized surface at time 400 s.



**Figure 7** Time dependent HTC and surface temperature for oxidized surface (sample B)



**Figure 8** Dependence of the heat transfer coefficient on the surface temperature

#### 4. CONCLUSION

Laboratory measurements showed influence of the oxide layer on the heat transfer coefficient and especially on the Leidenfrost temperature. The presence of the oxide layer shifts the Leidenfrost temperature to higher

values and decreases the heat transfer coefficient during film and nucleate boiling regime. The local destruction of the oxide layer can cause different heat transfer coefficient than on the surface which is covered by the oxide layer. This can influence the cooling homogeneity mainly for soft sprays like in a case of the secondary cooling zone during the continuous casting.

## ACKNOWLEDGEMENTS

***The research leading to these results received funding from the MEYS under the National Sustainability Programme I (Project LO1202) and from an internal grant from the Brno University of Technology focused on specific research and development No. FSI-S-17-4346.***

## REFERENCES

- [1] KOHLER, C., JESCHARS, R., SCHOLZ, R., SLOWIK, J and BORCHARDT, G. Influence of oxide scales on heat transfer in secondary cooling zones in the continuous casting process, Part 1: Heat transfer through hot-oxidized steel surfaces cooled by spray-water. *Steel Research*. 1990. vol. 61, no. 7, pp. 295-301.
- [2] WENDELSTORF, R., SPITZER, K.-H., WENDELSTORF, J. Effect of oxide layer on spray water cooling heat transfer at high surface temperatures. *Int. Journal of Heat and Mass Transfer*. 2008. vol. 51, no. 19-20, pp. 4892-4901.
- [3] CHABICOVSKY, M., HORSKY, J. Factors influencing spray cooling of hot steel surfaces. In *METAL 2017: 26th International Conference on Metallurgy and Materials*. Ostrava: TANGER, 2017, pp. 77-82.
- [4] STETINA, J., MAUDER, T., KLIMES, L., KAVICKA, F. Minimization of surface defects by increasing the surface temperature during the straightening of a continuously cast slab. *Materiali in Tehnologije*. 2013. vol. 3, no. 47, pp. 311-316.
- [5] POHANKA, M., WOODBURY, K. A. A Downhill Simplex method for computation of interfacial heat transfer coefficients in alloy casting. *Inverse Problems in Engineering*. 2003. vol. 11, pp. 409-424.