

METAL SURFACE QUALITY DRASTICALLY CHANGES COOLING RATE¹Michal POHANKA, ²Pil-Jong LEE¹VUT - Brno University of Technology, Brno, Czech Republic, EU, Michal.Pohanka@vut.cz²The Cooling Inc., Handong University, Startup Incubation Center, Pohang, Republic of Korea,
leepj@thecooling-eng.com<https://doi.org/10.37904/metal.2026.5243>**Abstract**

This study presents new experimental results showing how strongly the surface quality of steel plates influences their cooling rate during continuous production. The investigated phenomena are directly relevant to industrial water-based cooling technologies applied to steel plates on the Run Out Table, during accelerated cooling, and in interstand cooling sections of hot rolling mills. The work focuses on solid jet nozzles operating in a low pressure system, which are commonly used in industrial cooling lines. Three types of surfaces were tested: a slightly oxidized stainless-steel surface, and once oxidized and twice oxidized surfaces on standard low carbon steel. The stainless-steel surface remained homogeneous both after heating and after cooling, forming only a thin and continuous oxide layer. In contrast, the carbon-steel surfaces sometimes developed blister-like defects during heating. When these blisters peeled off during cooling, they left behind a very rough oxide layer that completely changed the cooling behavior of the material. Our results show that this rough and uneven oxide layer can significantly slow down or accelerate cooling, depending on how water flows and breaks on the surface. This behavior is particularly important for controlling cooling uniformity and reproducibility under real operating conditions of continuous rolling and cooling lines. The contribution demonstrates the importance of controlled experimental testing for understanding real cooling behavior in production conditions. These findings are relevant for manufacturers and research organizations seeking to improve product quality, optimize cooling strategies, and increase the efficiency of continuous steel processing lines.

Keywords: Steel plate cooling, water jet cooling, oxide layer, surface roughness, heat transfer coefficient

1. INTRODUCTION

The introduction should provide a clear statement of the study, the relevant literature on the study subject and the proposed approach or solution.

Heat removal during secondary cooling in continuous casting, hot rolling, or during cooling in annealing lines is a key step in steel production. The cooling rate strongly affects the final microstructure, mechanical properties, and flatness of steel plates. In industrial cooling lines, water-based cooling is widely used because it is efficient and flexible. However, achieving uniform and reproducible cooling is still challenging under real production conditions. One important factor that is often underestimated is the surface quality of the steel. Changes in oxidation, roughness, or surface defects can significantly influence how water contacts the surface and how heat is transferred. Understanding this effect is essential for better control of industrial cooling processes.

Surface characteristics such as roughness, oxide scale layers, and surface texture can strongly influence cooling rates because they affect how water interacts with the hot metal surface. Research has shown that even thin oxide layers of just a few microns can significantly modify cooling intensity, with low thermal conductivity oxides sometimes making cooling more intensive than on clean surfaces due to changes in the

Leidenfrost phenomenon [1]. Similarly, surface roughness has been demonstrated to substantially affect heat transfer during quenching operations, with rough surfaces showing different cooling behaviors compared to smooth surfaces when exposed to spray and jet cooling [2,3]. Studies on aluminum alloys have confirmed that surface roughness directly influences heat transfer efficiency during water spray quenching, affecting the final material properties [4,5]. Understanding these surface effects is critical because they directly impact product quality, mechanical properties, and process control in industries ranging from steel rolling mills to aerospace component manufacturing.

Surface conditions influence cooling behavior across various cooling methods and materials. In spray cooling, oxide scale formation on steel surfaces has been shown to change both the heat transfer coefficient and the Leidenfrost temperature, which is the critical point where water shifts from film boiling to nucleate boiling [6,7]. In jet impingement cooling, surface roughness affects the stagnation heat transfer characteristics, changing how efficiently heat is removed from the metal surface [8]. Even surface texturing and nano-structured coatings have demonstrated the ability to enhance heat transfer, with some studies reporting heat flux improvements of nearly 40% through engineered surface modifications [9]. For manufacturing companies and research organizations working to optimize cooling processes, these findings highlight that surface quality is not just a cosmetic concern but a fundamental parameter that must be carefully controlled to achieve consistent, predictable cooling rates and desired material properties [10–12].

This study presents new experimental results showing that the surface quality of steel plates has a strong influence on their cooling rate during continuous production. These effects are directly relevant to industrial water-based cooling technologies used on the Run Out Table, during accelerated cooling, and in interstand cooling sections of hot rolling mills. The study focuses on solid jet nozzles working in low-pressure systems, which are widely used in industrial cooling lines [13].

2. COOLING EXPERIMENTS

To investigate cooling process of hot steel plate the equipment shown in Figure 1 was used. It consists of heated test plate which is surrounded by extension plates to simulate large surface which is in continuous cooling lines. These plates are attached to trolley which is moving on supporting frame from left to right and back repeatedly until the test plate is cooled down to 600 °C by water spraying from cooling header. The dimensions of the heated test plate were 300 x 320 x 25 mm (L x W x H). Two materials were used for the test plate: S235JGR2 (regular low carbon steel) and 1.4845 (high-alloy stainless steel with high-temperature resistance). Each test plate was equipped with 5 K-type thermocouples arranged in one row across the plate width. The thermocouple pitch was 25 mm, and they were welded to the test plate 2 mm under the cooled surface. The movement velocity of the trolley with the test plate and extension plates was 2 m/s which is typical for many roughing mills. The temperature of the test plate was 1100 °C at the beginning of spray cooling. Low pressure solid multi-jet cooling with water density 30 l.s⁻¹.m⁻² was used. First the test plate was heated to prescribed temperature. Next the spray was adjusted. When everything was ready the trolley with the test plate and extension plates was moving through the cooling section repeatedly. High speed data logger recorded temperature history and position of the trolley with the test plate during the whole experiment. Recorded data were downloaded to computer after the experiment for further evaluation. Three experiments are evaluated. Experiment E1 and E2 were made with S235JGR2 test plate. It was the same test plate used twice. Experiment E3 was made with 1.4845 test plate. Initial temperature, velocity, movement range, and cooling conditions were same for all experiments.

3. DATA EVALUATION

Data from the experiments are temperature histories for each thermocouple and position of the trolley. Two types of data were evaluated from experimental data: cooling rates and thermal boundary conditions. Cooling rates were evaluated from recorded temperature histories for temperature range 1100 °C – 800 °C.

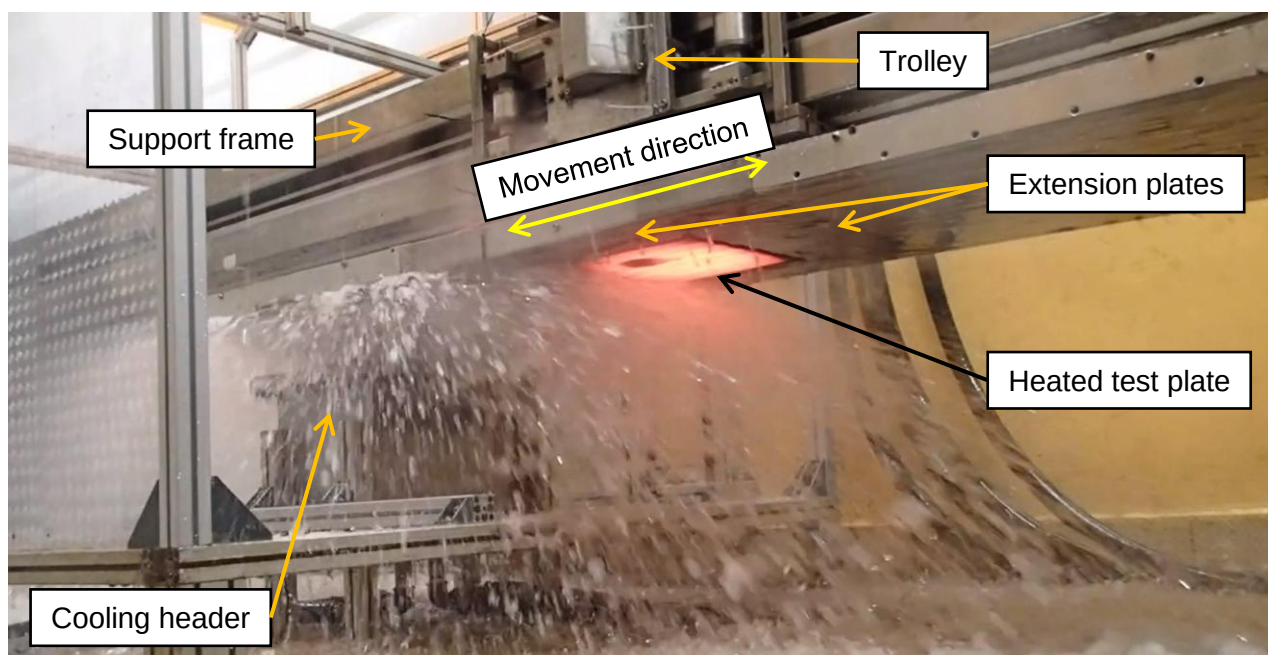


Figure 1 Cooling experiment with low carbon steel

Heat Transfer Coefficients (HTC), heat fluxes, and surface temperatures, were computed using an inverse task method from measured temperature histories [14]. Computed HTC, surface temperatures, and information about the trolley position were combined together to form detail information about the cooling. An example of such result is shown in Figure 2. Such results were obtained for each thermocouple. The green lines represent surface temperature of the test plate during the cooling experiment. A higher line density provides a better description of the HTC. With such detailed boundary conditions, highly accurate numerical predictions of cooling in cooling lines are possible.

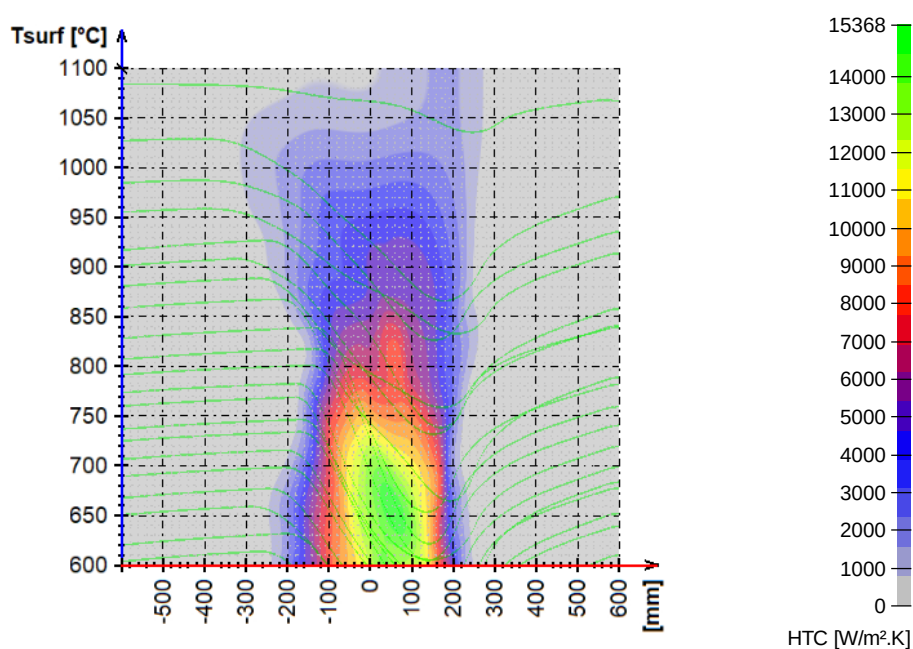


Figure 2 Evaluated HTC as function of position in cooling section and surface temperature during experiment E2 for thermocouple T3

4. RESULTS

The experiments E1 and E2 were exactly the same with same test plate. The only difference was that one large blister was formed on the surface of the test plate during the experiment E1 while during the experiment E2 only small blister was formed and it was not directly in the place where thermocouples were installed (see Figure 3). Experiment E3 was without blisters because high-alloy stainless steel was used. It was found that the surface has significantly higher roughness in places where blisters were formed and peeled off. Figure 4 shows temperature records from all five thermocouples during experiment E2. Temperature drop is higher for thermocouple T1 because it was slightly hitting the small blister.

The cooling rates were evaluated from cooling experiments for each thermocouple, and the results are presented in Figure 5. It is obvious that the cooling rate is much higher in the area where blister was formed. The cooling rate during the experiment E3 with stainless steel is more consistent and the inhomogeneity is caused mainly by the design of the cooling (see slightly darker lines in Figure 3 for experiment E3).



Figure 3 Black spots on surface during cooling in experiments E1–E3 (from left to right)

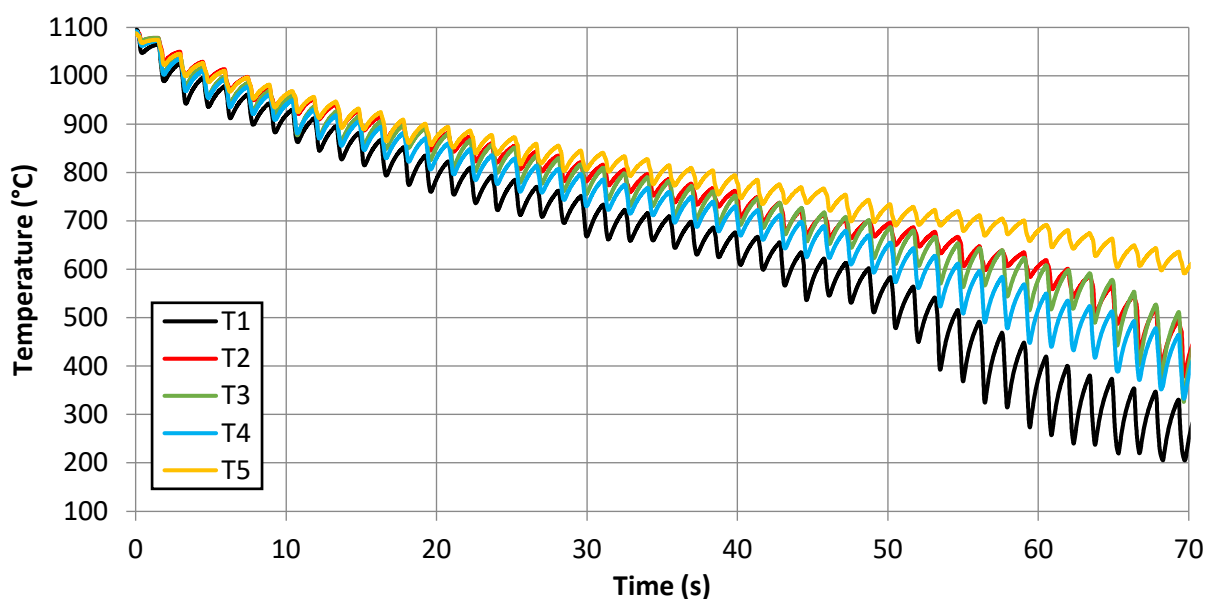


Figure 4 Cooling curves during experiment E2

To demonstrate the effect of inhomogeneous cooling two numerical simulations of cooling were performed using detail HTC data (see Figure 6). Low carbon steel plate 25 mm thick moving 0.5 m/s was cooled from both sides with the same intensity using 10 headers where header pitch was 500 mm. Two cases were picked: the fastest cooling during experiment E1 in thermocouple position T1 and the slowest cooling during experiment E2 in thermocouple position T5. The temperature difference in the center is about 100 °C after 4 m of cooling and it is about 200 °C after 6 m of cooling.

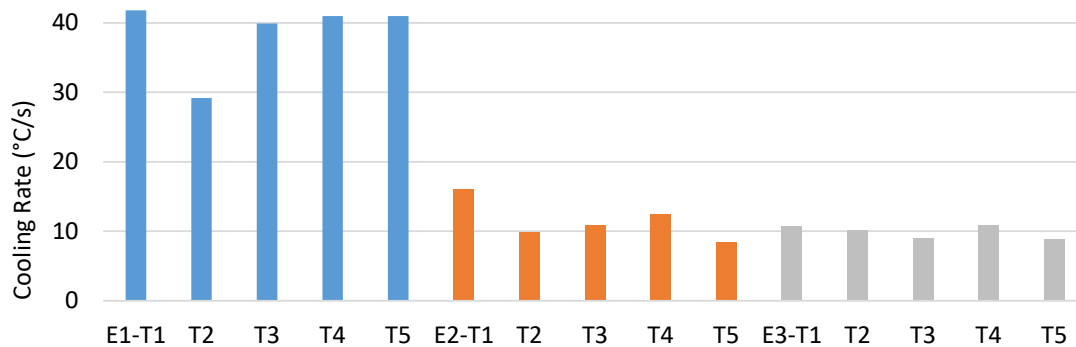


Figure 5 Cooling rates for each thermocouple in all experiments (E1-E3)

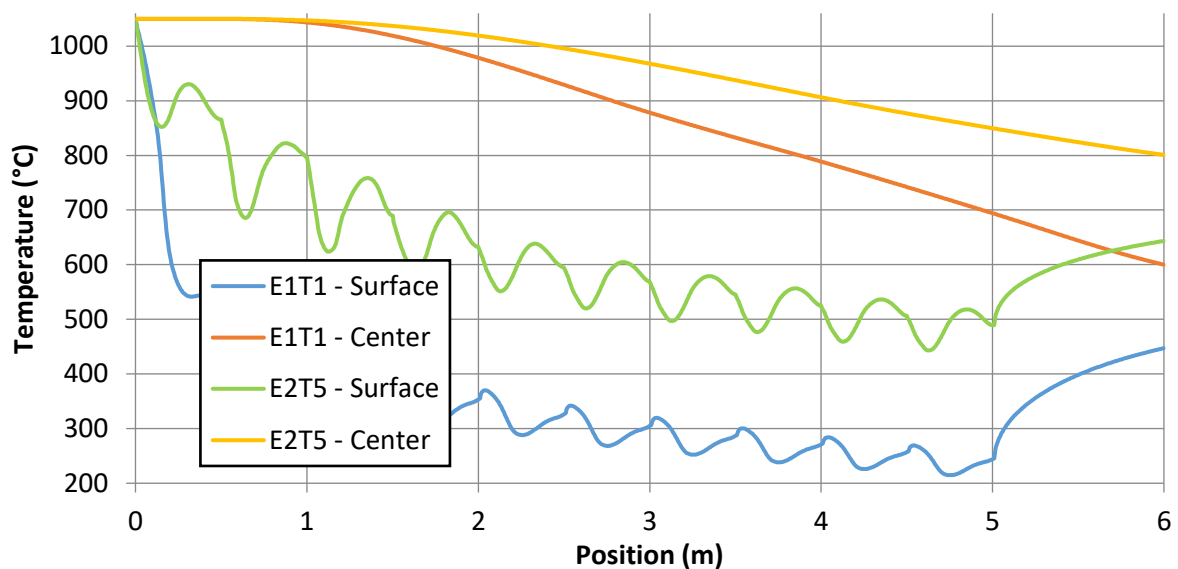


Figure 6 Cooling simulations

5. CONCLUSION

This study clearly shows that surface roughness has a very strong influence on the cooling rate of steel plates during water jet cooling. When blisters formed on the carbon steel surface and later peeled off, a very rough oxide layer remained, and these areas cooled much faster than smooth surfaces. The experiments demonstrated large local differences in cooling intensity even under the same nominal cooling conditions. From measured temperature histories, detailed thermal boundary conditions were obtained using an inverse method, providing realistic input data for numerical simulations. The numerical results showed that, at the end of a 6 m long cooling section, the temperature in the center of a 25 mm thick plate can be up to 200 °C lower if a rough oxide scale is present on the surface. This confirms that surface condition is not a minor effect but a key parameter controlling cooling behavior. The results underline that cooling boundary conditions must be determined by dedicated cooling experiments and that special attention must be paid to the real surface roughness that occurs on industrial production lines to ensure reliable process control and product quality.

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