Innovative Descaling Strategies and Their Influence on Heat Losses

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INTRODUCTION

Hot rolling of long products is composed of several steps: reheating, descaling, roughing, intermediate and finishing rolling, heat treatment, etc. Mills strives to increase the efficiency of these processes as much as possible. Product quality is the top priority, and it is directly connected to descaling quality. High-pressure descaling is typically composed of high-pressure nozzles mounted on a fixed spray bar. Key parameters are water pressure, nozzle configuration, size of nozzles, positioning of nozzles, orientation and overlapping and the arrangement of the descaler header related to descaling performance. These parameters have already been studied and optimized concerning descale ability in [1] - [3]. Innovative trends described in this paper focus on different descaling strategies and systems related to descaling quality and heat loss.

Typically, a single row of descaling nozzles is used in a hot rolling process. The first innovative approach was to install a low pressure (20 bar) row of nozzles before the descaling system. The hypothesis was that undercooling of the scale surface could cause microcracks in the oxide layer due to the different thermal expansions of a scale and steel. The next innovative approach was based on placing two descaling rows in opposite directions to improve the descaling process and minimize heat loss caused by reflected water flowing on a workpiece surface. Finally, another two descaling systems were studied. The first one was hydromechanical rotary descaling and shot blasting systems.

The above-mentioned strategies and systems were compared with a focus on heat transfer and descaling efficiency, which is a key factor. Heat transfer tests were performed by Heat Transfer and Fluid Flow Laboratory (HeatLab). The descaling trials were done by Centre de Recherches Metallurgiques (CRM) and numerical simulations by VDEh-Betriebsforschungsinstitut (BFI). Hauhinco Maschinenfabrik produced a descaler and mounted it at a blooming line.

Experimental Equipment and Methodology for Heat Transfer Tests

Linear stand (Figure 1) is a laboratory equipment used for heat transfer tests. It is composed of an 8 m long frame with a trolley that moves the experimental plate with a maximal velocity of 10 ms^{-1} through a descaling zone. The frame is rotatable, so bottom, side and top descaling processes could be studied. The experimental plate, with dimensions of 320 x 300 x 25 mm, was made of austenitic stainless steel 1.4828. It was embedded by thermal sensors. The typical distance between the temperature measurement point and the plate surface was around 0.6 mm. This distance was obtained for each thermal sensor by calibration. Each experiment started by heating a plate to the initial temperature of 910°C. When the temperature was reached, the water pump was switched on and the required water pressure was set. The heater was removed and the plate was moved reversibly through the descaling unit until the final plate surface temperature was reached. The reference movement velocity was set to 1 ms^{-1}. A pneumatically driven deflector was positioned between the plate surface and the nozzle. It prevented the water from spraying the plate surface during backward movement. Finally, the recorded data (temperatures) were transferred to a computer and used during the inverse calculation to achieve the surface temperature, heat flux and heat transfer coefficient.

Experiments with a descaler were done in Hauhinco. The experimental equipment, along with a detailed picture of the experimental plate and descaler, is shown in Figure 2. The experimental procedure was similar to trials done in HeatLab. Just the plate was moved through the descaler only once.

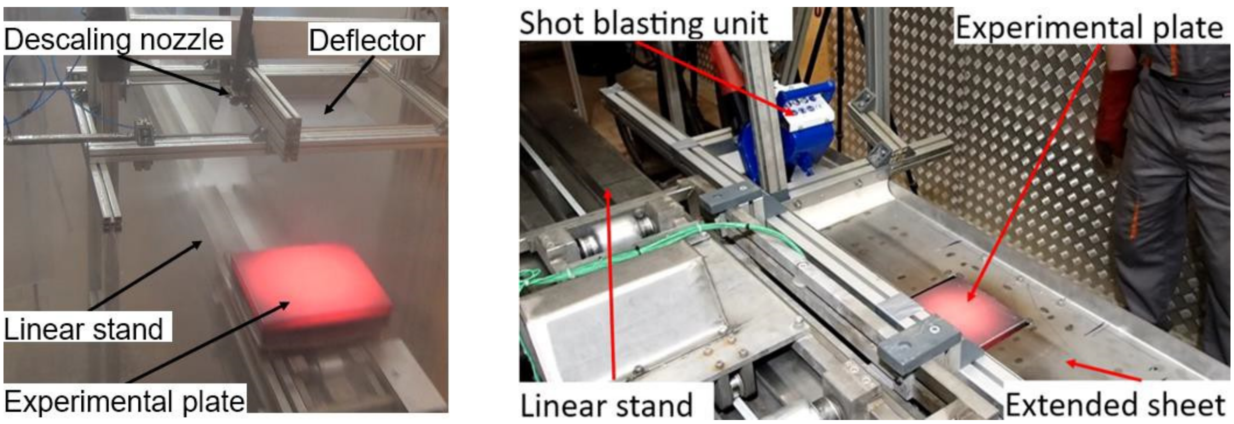

Figure 1. Linear stand used for heat transfer tests. The experimental plate is moved through a descaling nozzle (on the left) and shot blasting descaling system (on the right)

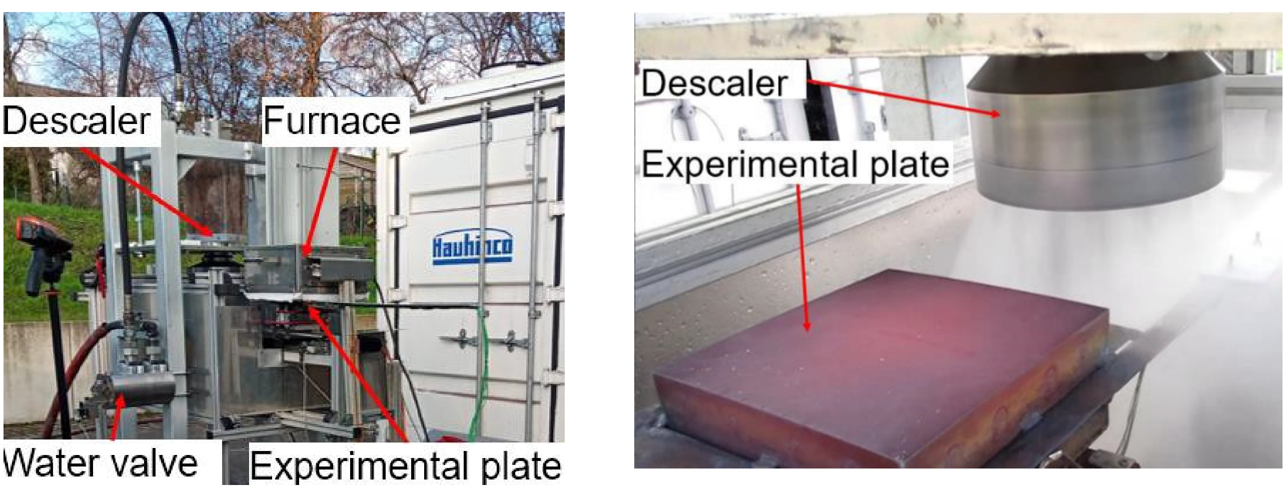

Figure 2. The experimental device used in Hauhinco (on the left) and a picture of a plate entering to the hydromechanical descaling zone (on the right)

Inverse Task for Computation of a Heat Transfer Coefficient

Inverse task calculation is roughly described below. Detailed description is in Chyba! Nenalezen zdroj odkazů. and Chyba! Nenalezen zdroj odkazů. The computational software was developed by Pohanka for the computation of heat transfer coefficient, heat flux, and surface temperature from measured temperature data under a sprayed surface using a 1D inverse task. Estimation of the time varying boundary conditions uses future time step data to stabilize computation. Determination of the unknown surface heat flux at time t^m is estimated by comparison of the measured temperature $T_r^{*,k}$ with computed T_s^k from the forward solver (finite differential method) using n_t future time step

$$SSE = \sum_{k=m+1}^{m+n_t} \sum_{s=r,r=1}^{n_T} (T_r^{*,k} - T_s^k)^2, \tag{1}$$

where n_T is the number of thermocouples. Heat flux q^m in time step m. Using the linear minimization SSE → min, the value of the surface heat flux q^m is

$$q^m = q^{m-1} + \frac{\sum_{\kappa=m+1}^{m+n_t} \sum_{s\equiv r,r=1}^{n_T} \left(T_r^{*,\kappa} - T_s^{\kappa}\right) \cdot \zeta_r^{\kappa}}{\sum_{\kappa=m+1}^{m+n_t} \sum_{r=1}^{n_T} \left(\zeta_r^{\kappa}\right)^2} \tag{2}$$

where T_s^k are the computed temperatures by the forward solver using all previously computed heat fluxes without the current one q^m. The ζ_r^k is a sensitivity coefficient of the r^{th} temperature sensor at time t_K to the heat flux pulse at time t^m. These sensitivity coefficients are partial derivatives of the computed temperature field to the heat flux pulse, but in this case they physically represent the rise in temperature at the temperature sensor location for unit heat flux at the surface. The sensitivity coefficient is defined as

$$\zeta_r^{\kappa} = \frac{\partial T_r^{\kappa}}{\partial q^{\kappa}} \tag{3}$$

Once the heat flux is computed for a time t^m, the corresponding surface temperature and the heat transfer coefficient (h^m) is computed using the following formula

$$h^m = \frac{q^m}{T_{coolant}^m - T_{surface}^m}, \tag{4}$$

where $T_{coolant}^m$ is measured during the experiment. The index m is incremented by one after heat transfer coefficient computation and the procedure is repeated for the next time step.

Reduction of Heat Losses by One Low Pressure (20 bar) and Another High Pressure Row With Nozzles

In these trials, a low pressure flat jet nozzle (20 bar) was applied to the first row. The second row was kept at the same pressure as during the reference trials. Schemes of tested descaling configurations are shown in Figure 3 on the left. Two configurations were tested. The inclination angle of low pressure nozzle was set to 0° and 15° for high pressure nozzle (against the movement direction). Then, the low pressure nozzle was spraying water against the descaling nozzle. The inclination angle was changed to -15°. A distance of 50 mm between the water impact area was maintained for both configurations. A heat transfer coefficient (HTC) dependence on a movement position was obtained for both configurations and compared with HTC for single descaling and flat jet nozzle (averaged on surface temperature interval 700 – 900°C). These results are compared in Figure 3 on the right. The grey line represents HTC for a single flat jet nozzle at low pressure (20 bar) and the yellow represents HTC for a single descaling nozzle at a pressure of 150 bar. Water flowing on the plate surface from the descaling nozzle is "pressed" by the low pressure spray and increases the surface pre-cooling (in position between 350 – 425 mm). The heat transfer under and between the flat jet and descaling nozzles remained the same.

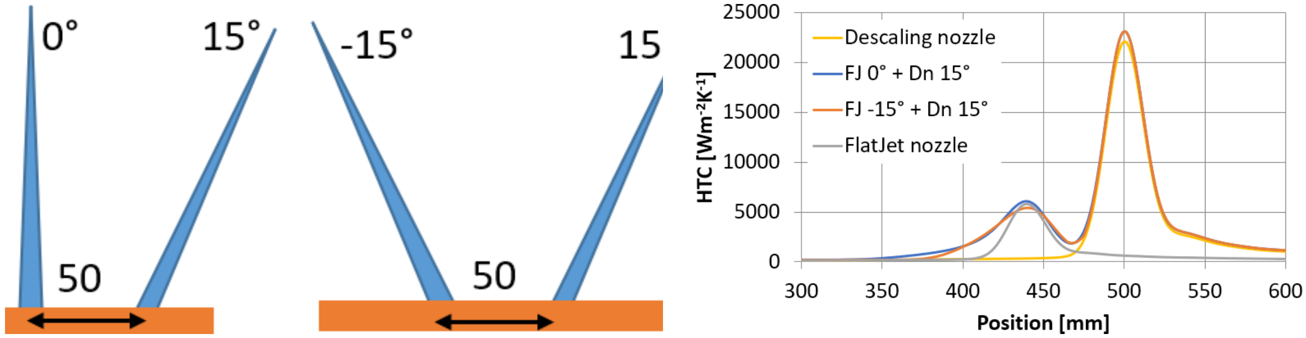

Figure 3. Scheme of nozzle orientation (left nozzle at low pressure - 20 bar, right nozzle at high pressure 150bar) and the average heat transfer coefficient dependence on the position during the descaling on the right (average on a temperature interval of 700 – 900°C)

Reduction of Heat Losses by Opposite Descaling

The objective was to study the HTC of descaling where two nozzles are spraying in opposite directions. Various distances between the spray footprints were studied. They were 50, 10, -10 and -50 mm (cross spray). Schemes of tested configurations are shown in Figure 4. The nozzle inclination angle was set to -15° for nozzle B and 15° for nozzle A. Both descaling nozzles were tested separately (green and blue lines, Figure 5 on the right). It is visible that the nozzle inclination angle does not affect heat transfer significantly. The grey line represents HTC for two descaling nozzles spraying oppositely with a footprint distance of 50 mm. The heat transfer coefficient slightly increased under the second nozzle (A) because the plate surface is at a lower temperature under the second nozzle compared to the first. The temperature decrease is caused by cooling from the first nozzle and water flowing on the surface between nozzles. The heat transfer coefficient increases with the decrease in the nozzle footprint, even for cross spray. The reason is shown in the left picture in Figure 5. The water collides above the plate and sprays with quite high impact pressure on a wider area than the configuration with the spray footprint distance of 50 mm.

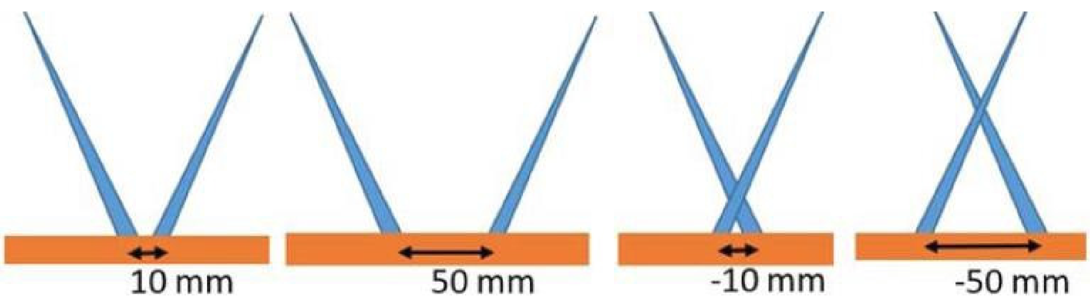

Figure 4. Scheme of four tested configurations – descaling nozzles spraying against each other (opposite descaling), nozzle A is on the right side and B on the left sid e

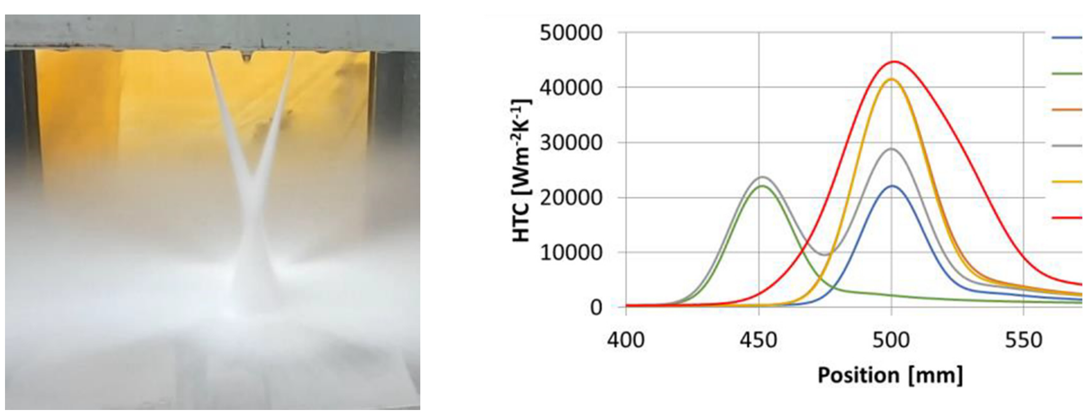

Figure 5. Two descaling nozzles spray water on a cold surface – cross spray -50mm on the left and comparison of a heat transfer coefficient for all experiments with opposite descaling on the right

Reduction of Heat Losses by Shot Blasting

Shot blasting unit Blastrac 1-5 HH was used for heat transfer tests (Figure 6). The device shoots metal grains (diameter around 0.5 mm) against the plate surface with a velocity of 70 ms^{-1}. Impacting grains remove the scales from the surface, which are moved together with dust into the sorting chamber. A vacuum cleaner sucks the dust and shots fall into a hopper. They are re-shot against the surface again. Four different plate movement velocities were tested – 0.1, 0.3, 0.6 and 1 ms^{-1}. The results are shown in Figure 7. These HTCs, unlike the others, were evaluated excluding the radiation part of the heat transfer. The radiation part could be computed using the following formula:

$$HTC_{radiation} \equiv \varepsilon\, \sigma\, (Ts + Tsur)\, (Ts^2 + Tsur^2), \tag{5}$$

where HTC is a radiation heat transfer coefficient [W m^{-2} K^{-1}], σ is Stefan-Boltzmann constant = 5.67 10^{-8} [W m^{-2} K^{-4}], ε is emissivity, Ts is surface temperature [K] and Tsur is a surrounding temperature [K].

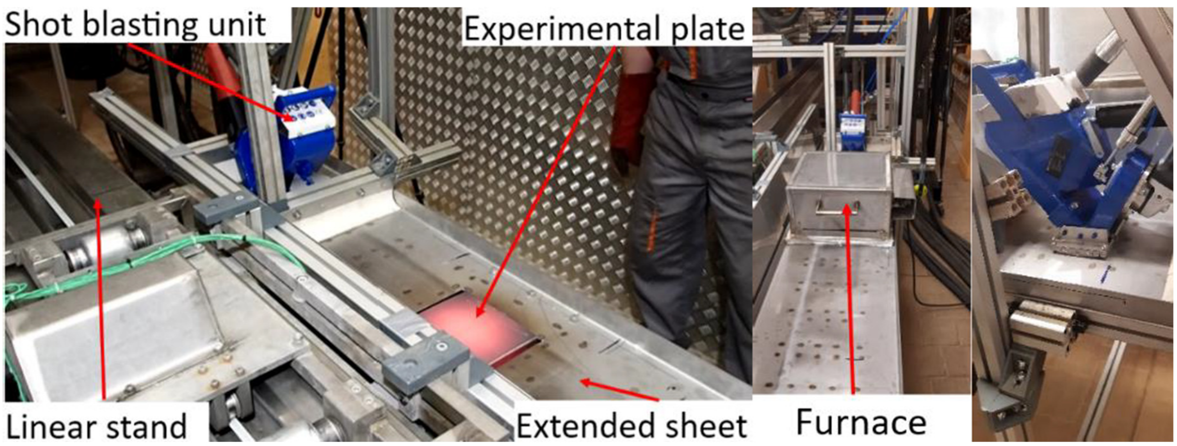

Figure 6. The linear stand holds the experimental plate and moves it together with the extended sheet through the shot blasting unit

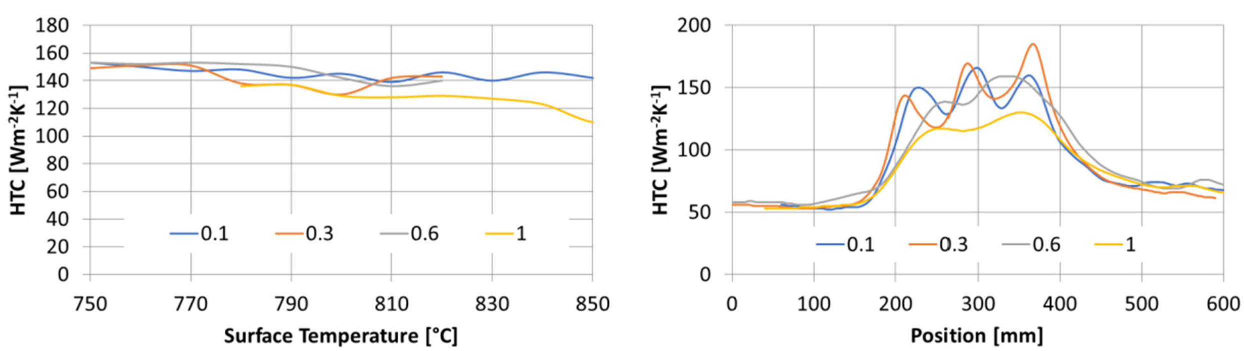

Figure 7. Heat transfer coefficient dependence on the surface temperature (on the left) and on the position (on the right) for different movement velocities, the data does not include radiation

Reduction of Heat Losses by Hydromechanical Descaling

Trials with hydro mechanical descaler were done in Hauhinco Maschinenfabrik (Figure 2). Heat transfer coefficient was studied for several optional parameters. They were water pressure (50 – 250 bar), descaler revolution (500 – 1000 rpm), descaling distance (65 – 165 mm) and number of nozzles (6 – 18 pieces). The descaler allowed mounting different nozzle types, so all the above-mentioned parameters were tested with flat and full stream nozzles. The experimental plate was embedded by 8 thermal sensors aligned perpendicular to a movement direction. Computed heat transfer coefficients (examples are shown in Figure 8) were obtained by averaging HTCs from all 8 sensors. These trials proved that the heat transfer coefficient increases with increasing water pressure, number of nozzles and spray distance. The rotation speed (revolution) does not influence the HTC.

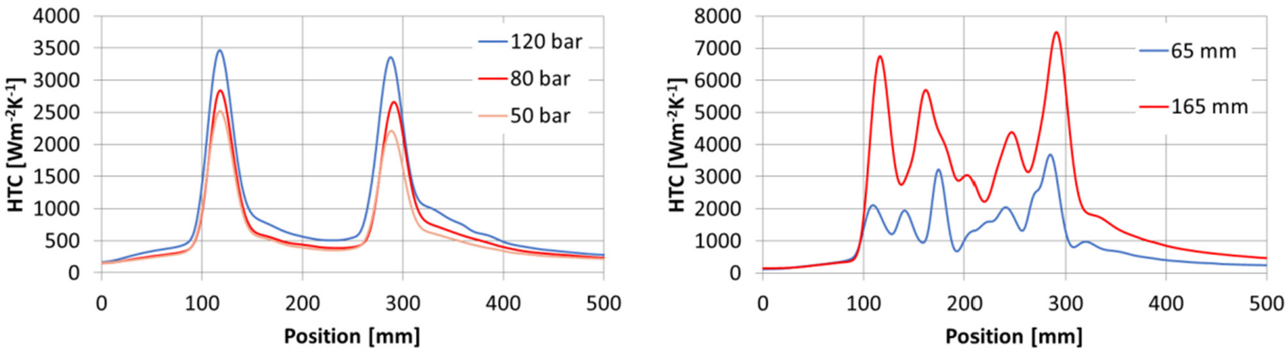

Figure 8. Examples of computed heat transfer coefficients dependent on a movement position for flat stream nozzles with various water pressures (on the left) and full stream nozzles with different descaling distances (on the right)

Heat Loss Comparison for all Tested Configurations
The measured heat transfer coefficient was used as a boundary condition for numerical simulation. Standard structural steel was moved once through a descaling system, and extracted heat at an interval of 0 – 500 mm was computed (in the movement direction, purple rectangle in Figure 10 on the left). The scale layer was not considered in these simulations. Results are shown on the bar chart in Figure 10 on the right. Different descaling systems are compared and value of 100% was chosen for a single row of descaling nozzle. It is clearly visible that the lowest heat was extracted for shot blasting nit. The almost 50% of heat loss was achieved for HIDROD.

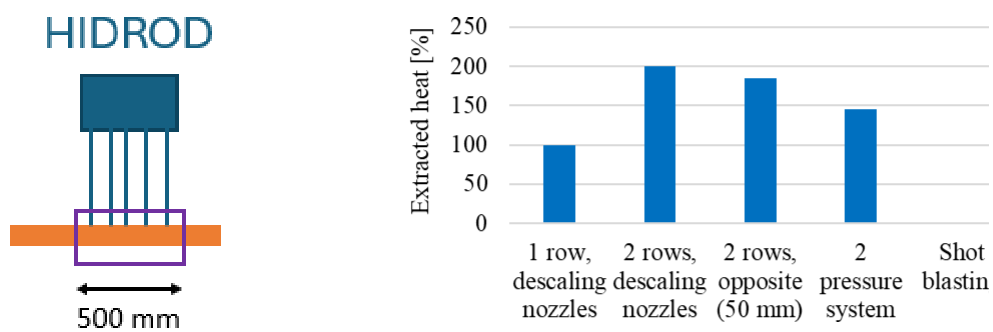

Figure 9. Comparison of simulated extracted heat on an area of 500 mm for all tested systems

ASSESSMENT OF DESCALING EFFICIENCY FOR INNOVATIVE DESCALING SYSTEMS

Experimental Equipment and Methodology in Descaling Tests
Descaling tests were performed on a pilot descaler in CRM (Figure 10). CRM has built this system and designed it for high-pressure water descaling tests. It is a pilot system where a heated sample of typical dimensions 100 x 100 x 30 mm is moved through the descaling system. Two rows of descaling nozzles could be placed at different angle rotations and distances. Descaling can be performed on the top and bottom sides with water pressures up to 360 bar. The speed in the descaler can be increased up to 3 ms^{-1}.

Figure 10. CRM pilot descaler (on the left), two nozzles mounted on the descaler and spraying oppositely (in the center) and shot blasting unit mounded on the descaler (on the right)

Descaling Performance by Opposite Descaling

Trials have been studied on cast material from AM Gijon, heated up to 1250°C, for 2 hours. Descaling nozzle orientation: 15°, with a distance of 70 mm from the surface at 200 bar. The descaler was equipped with a Pyrometer CW2 and a surface temperature was measured after each descaling trial. The movement velocity was set to 1 ms^{-1}. After descaling, the blocks were placed in a nitrogen freezer -50°C for 30 minutes to freeze the scale formation. Samples were then taken for surface and cross section analysis using an optical microscope and SEM. The different trial setups are illustrated in Figure 11.

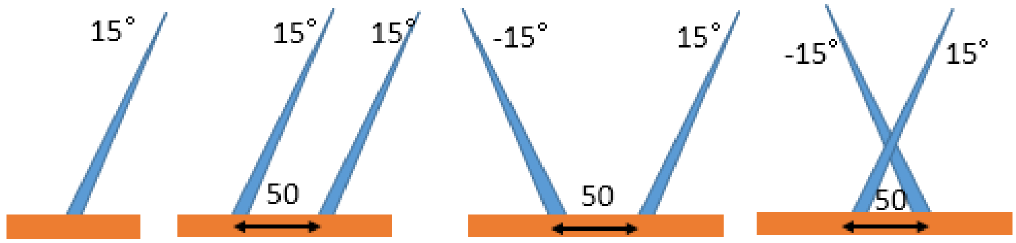

Figure 11. Scheme of descaling configurations

The descaling performance can be observed in Table 1. Each time, the bottom part of the sample was descaled. At this location also a cross section was taken by optical microscopy. Visually, it can be observed that two rows in opposite directions result in the best descaling practice (trial 2 rows – opposite direction). This observation is also confirmed by a measurement of the remaining scale thickness after cooling down (see Remaining scale layer in Table 1 and Figure 12). Trial with 2 rows in the opposite direction gives the best result. The worth result was obtained for trial with the single nozzle.

Table 1. Measurement of remaining scale thickness after each descaling test

Experiment	Measured surface temperature after descaling	Remaining scale layer
	[°C]	[µm]
1 row	1 147	97
2 rows – same direction	1 128	74.1
2 rows - opposite direction	1 143	68.5
2 rows – opposite direction cross spray	1 124	84.3

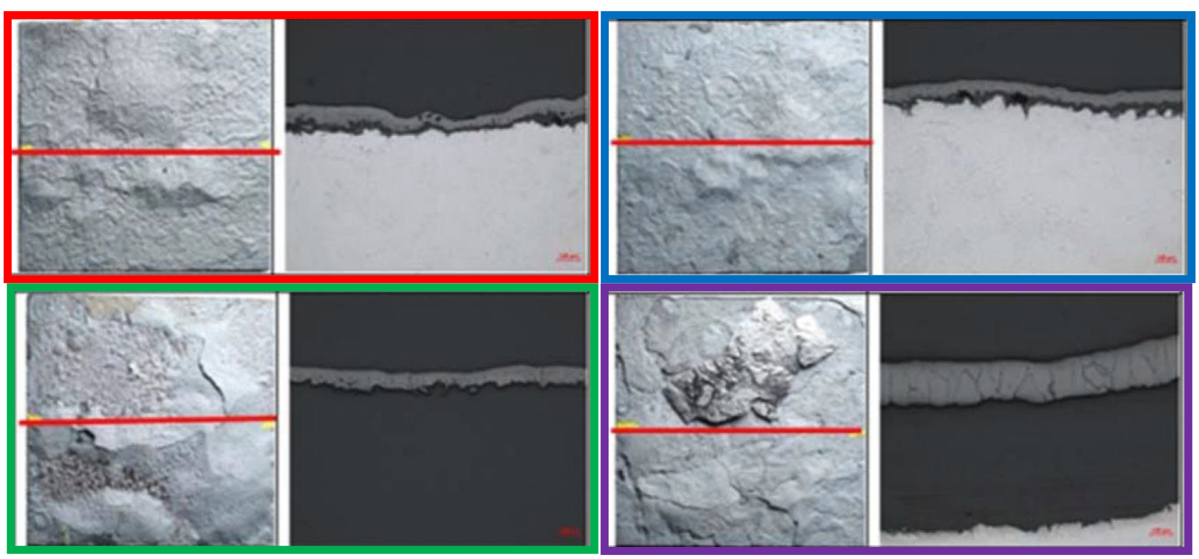

Figure 12. Descaling performance for 4 trials – red – 1 row; green – 2 rows same direction; blue - 2 rows opposite direction; purple - 2 rows – opposite direction cross spray

Descaling Efficiency of Shot Blasting

The shot blasting equipment was mounted on the supporting frame of the high-pressure descaling nozzles (Figure 10 on the right). Below the translation rails, a water basin was installed to collect the shots when no block was situated below the equipment. Three descaling tests were performed with shot blasting at different velocities. The red square indicates the descaled area. It can be observed in the third trial that descaling at 1 ms^{-1}, similar to high-pressure water descaling, is insufficient. Descaling speeds had to be reduced to 0.3 ms^{-1} to obtain an optimum descaling. The remaining scale layer measured after the descaling tests was 144 μm for a velocity of 1 ms^{-1}, 70.8 μm for 0.3 ms^{-1} and 58.7 for 0.1 ms^{-1}. See the results in Figure 13.

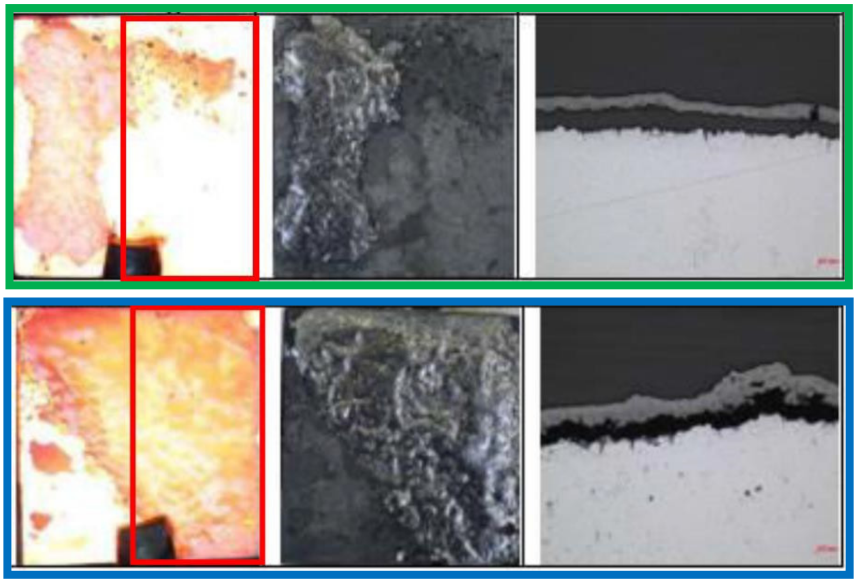

Figure 13. Descaling results by shot blasting (block after descaling (on the left), block after cooling (in the center) and cross section (on the right), two different velocities – green 0.1 ms^{-1} and blue 1 ms^{-1}

Descaling Efficiency for Low Pressure (20 bar) and Another High Pressure Row With Nozzles

The idea of using a two pressure descaling system was to subcool a scale with low pressure spray, which should cause cracks in between scales and then remove it with a pressure descaling spray. Scales' thermal conductivity is very low compared to a steel and they work as a thermal barrier on a steel surface.

First of all, numerical simulations were run by BFI. They developed a model of product descaleability, which was verified by industrial trials. The model is a compound of a scale growth model and a descaleability model. Model inputs are physical material data, slab process dimensions, heating conditions, cooling boundary conditions and temperature field during discharging. An example of a computed porous scale is shown in Figure 14 on the left and in the center together with the example of computed temperature field in a heated block (on the right).

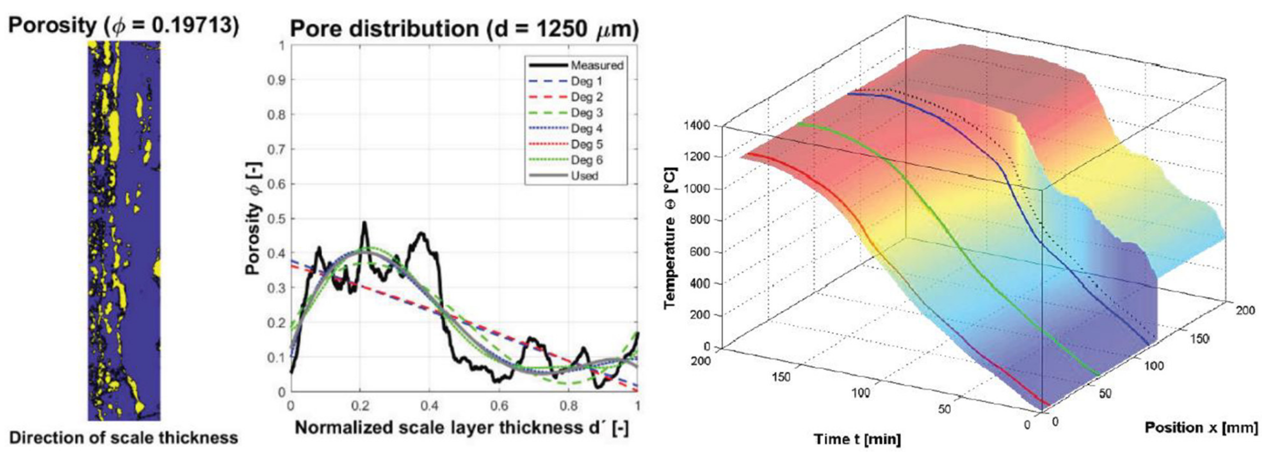

Figure 14. Computed porous scale on a steel surface (on the left and in the center). The blue color is for scale and the yellow for pores. The temperature field of a block after heating.

Simulations were done for material 1.0310 where the scale thickness was 2 mm. Heat transfer and stress analysis showed the original idea was incorrect. The low pressure spray (t = 1.2 s) subcools only a thin layer on a scale surface and no cracks are formed between the oxide and steel (Figure 15 at the bottom). Stress intensity at the point of descaling (t = 7.2 s) is shown on right pictures. These graphs show the stress intensity along the scale thickness. Point 0.05 m is for the scale-steel interface. Regarding this analysis, the descaleability tests were not performed.

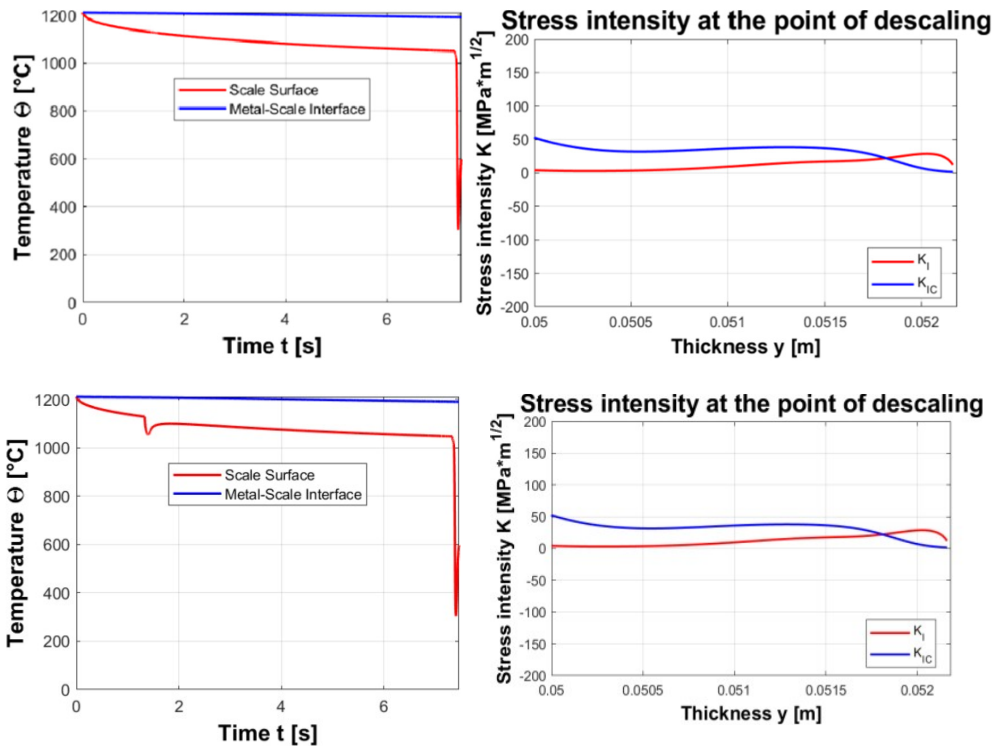

Figure 15 Temperature and stress analysis (simulations) of the oxide and steel surface for one row of descaling nozzles (on the top) and two-pressure system (on the bottom).

Hydromechanical Rotary Descaling

Heat losses and descaling efficiency are mainly influenced by the way water is applied to the hot material. A typical descaling system uses flat stream nozzles, which cover a broad variation of different plate dimensions in steel works. Hydromechanical rotary descaler (HIDROD) enables the use of solid stream nozzles. This allows to achieve much higher local impacts of the water jet with less water consumption. Furthermore, the impact of solid stream nozzles is not as sensitive to the workpiece-nozzle distance as it is when using a flat stream nozzle.

The HIDROD was developed and produced in Hauhinco Maschinenfabrik GmbH & Co in Germany (Figure 16). Various numbers of nozzles could be mounted on the descaler (from 6 to 18) and cover different workpiece sizes and optimize energy consumption (Figure 16 on the right).

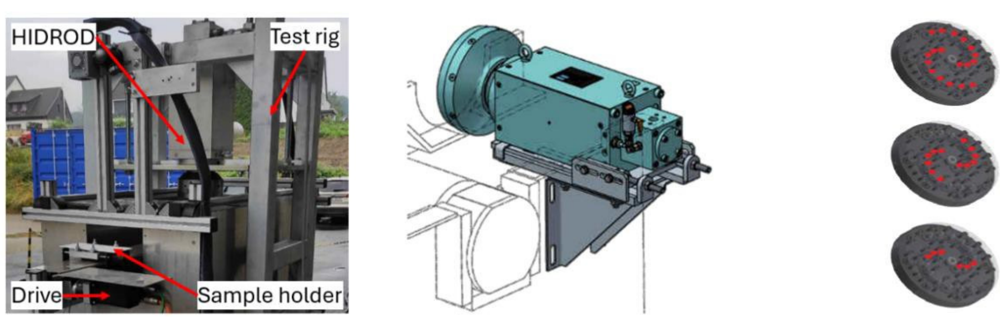

Figure 16. Hydromechanical rotary descaler mounted on test rig for laboratory descaleability tests (on the left), scheme of HIDROD mounted in industrial conditions (in the center) and possible arrangement of nozzles (on the right)

Descaleability tests using HIDROD were conducted. Blocks made of 1.0936 steel with dimensions 100 x 240 x 30 mm were heated in a muffle furnace at 1 200°C. Various parameters were tested – spray distance, water pressure (150 – 300 bar) and type of nozzles. The results of these tests show that a good functional capability concerning the descaling effect was already achieved. All the samples were completely descaled, except for only a few scale spots. The descale ability was higher than 90%. See the example of a result from a descaling trial with a minimal water pressure of 150 bar in Figure 17 (3 pictures on the right).

Figure 17. Experimental sample before descaling (on the left) and pictures of a plate surface from a descaling trial (from left to right): plate surface before descaling, plate surface after descaling and visualized descaled area (blue color)

Finally, HIDROD was installed on the blooming line in Mannstaedt GmbH (MWT, Figure 18). MWT specializes in hot-rolled profiles. The alloys, dimensions and geometries are numerous, so the variation of scale conditions is high. Some of them are adhering slightly, and others are adhering well. In order to respond to this wide range of input conditions, it is therefore necessary to recognize the initial situation and the descaling result. This was solved by camera detection after descaling. In addition, it had to be possible to react to the fluctuating input variable by adjusting the descaling parameters. For this purpose, two descaling motors were installed, one laterally and one vertically to the bloom (Figure 18). The HIDRODs could be parameterized in terms of water pressure, spray distance to the bloom and rotation speed. The parameters were adjusted depending on the descaling result. This adjustment could be done either by manual setting or automatically via the installed OPC interface with an external controller. Control is essential to ensure consistent descaling quality with minimal water application and, therefore minimal heat losses. Several test series were carried out to test the descaling quality in relation to the parameterization of the motors. The results were evaluated and subjectively assessed. It was found that the HIDROD also delivered comparably good to better results than the conventional nozzle bar at same or even less pressure (Figure 19). The advantage of using HIDROD was that it decreased water consumption by 50%. MWT employees subjectively found that descaling produces cleaner surfaces.

Figure 18. HIDORD installation on a blooming line – lateral installation (on the left), vertical installation (in the middle) and complete installation view with housing on the right

Figure 19. The left picture shows a bloom before descaling (very adhesive scales) and the right picture shows the bloom descaled by HIDROD

CONCLUSIONS

Four different descaling approaches were tested and compared with the actual existing descaling system using high pressure nozzles. They were: two pressure descaling system where the first row of flat jet nozzles operated on a pressure lower than 20 bar and a second descaling row at a pressure higher than 100 bar; two rows of high pressure nozzles were oriented to spray oppositely; shot blasting where small metal grains were shot against the scaled surface, hydromechanical descaler produced where high pressure solid stream sprays were rotated.

The two pressure descaling system was based on the idea that the first low pressure spray subcools a scale and causes cracks in between the scale and steel surface, which helps to increase the descaling efficiency of a second high pressure spray. Heat transfer tests and related numerical simulations showed that the original idea was incorrect because the scale works as an insulation on the surface due to a lower conductivity. Only the local thin area of the scale was influenced by low pressure spray without any effect on creating cracks. This finding was the reason for stopping this activity without conducting descaling trials. The second system was based on opposite descaling where the rows of descaling nozzles were inclined by ± 15° and spraying oppositely (against each other). The idea was to decrease heat loss caused by water flowing on the surface from the descaling spray. Various distances between the spray footprints were studied (from 50 to -50 mm - cross spray). Schemes of tested configurations are shown in Figure 4. Descaling trials showed that the best configuration for descaling is opposite spray with a distance of 50 mm, where the remaining scale layer was only 68.5 µm with the lowest heat loss. The remaining scale layer thickness for the reference configuration with 2 rows of nozzles spraying in the same direction was 74.1 µm.

The third descaling system was based on shot blasting. A Blastrac 1-5HH unit was used for these tests. This device shoots metal grains of a 0.5 mm diameter against the scale surface with a velocity of 70 ms^{-1}. Reflected grains together with scales are moved into the sorting chamber where scales are sucked by a vacuum cleaner and grains fall into a hopper. The descaling trials showed that the descaling efficiency rapidly decreases with increasing plate movement velocity. Comparable results with the opposite descaling system were achieved for velocities lower than 0.3 ms^{-1}. Another disadvantage is in changing the surface roughness after the descaling process. The shot blasting system is beneficial from the point of view of heat loss. It was on a level of surface radiation. Compared to the other systems, the heat loss caused by shot blasting is negligible.

Finally, the Hydromechanical rotary descaler (HIDROD) was tested. Descaling trials showed the best descaling performance for HIDROD compared with the other tested systems. HIDROD rapidly decreases heat loss from the material by more than 50%. HIDROD was chosen and installed on the blooming line in Mannstaedt GmbH in Germany (MWT). The descaling trials done in plant conditions showed comparably good or better results than the conventional nozzle bar at the same or even less pressure. However, the water consumption of HIDROD decreased by 50%. Further, the HIDROD descaling parameters were optimized by MWT, and its employees subjectively found that the new descaling produces cleaner surfaces.

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