DESCALING WITH HIGH PRESSURE NOZZLES

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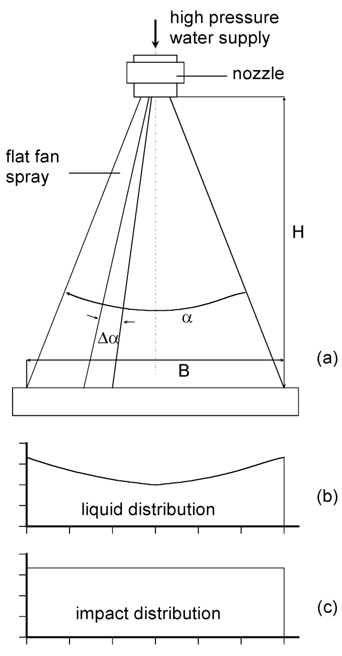
Abstract

Descaling of steel in hot rolling processes is an application of high-pressure spray nozzles. The impact force and pressure of theses nozzles can be determined using Newton's 2nd and 3rd axiom. This allows calculating the impact pressure approximately by a simple formula. Direct measurement of the impact is possible with a force transducer, scanning the area of direct impingement of the spray. Droplet size of the spray jet seems to be a secondary factor, because pure mechanical considerations lead to a sufficient model of the impact. However, measurement of the area, covered by the spray, shows that the water film of the jet has been disintegrated, when impinging on the surface, but has not been atomized completely. This can be proved by short-time photos. Different investigations substantiate the hypothesis, that thermal shock due to high gradients of surface temperature changes under the spray is a dominant physical mechanism of descaling, especially for secondary scale. That is why two additional types of experiments are necessary to characterize the influence of the water jet on the hot surface, which is the measurement of the heat transfer coefficient of the impinging water and the descaling test under laboratory conditions. The study of metallurgical and surface quality parameters of the steel before and after the test allows quantifying the descaling efficiency.

Introduction

Descaling of steel in hot rolling processes is an application of high-pressure nozzles of the flat jet type. Scale is a layer of oxide build up on the surface of the steel due to high temperatures, up to 1250°C, and the presence of oxygen and other gases. It can be created as primary scale in the atmosphere of the oil or gas fired furnace, or as



$$F = \frac{d}{dt}(m \cdot v) = \dot{m}v + m\dot{v} = \dot{m}v = \dot{V}\sqrt{2p\rho} \qquad (1)$$

for constant liquid pressure, i.e. constant v, and using Bernoulli's law for the relation between v and p. The vertical component of dF on the target surface is constant (FIG. 2 c).

$$dF_v = dF\cos\left(\frac{\alpha}{2}\right) \qquad (1a)$$

The area, covered by the spray is:

$$A = 2tH\tan\left(\frac{\alpha}{2}\right) \qquad (1b)$$

This results in the impact pressure I:

$$I = \frac{F}{A} = \dot{V}\frac{\sqrt{2p\rho}}{2tH\tan(\alpha/2)} \qquad (2)$$

FIGURE 1 Definition and calculation of the impact of a flat jet nozzle for descaling purpose

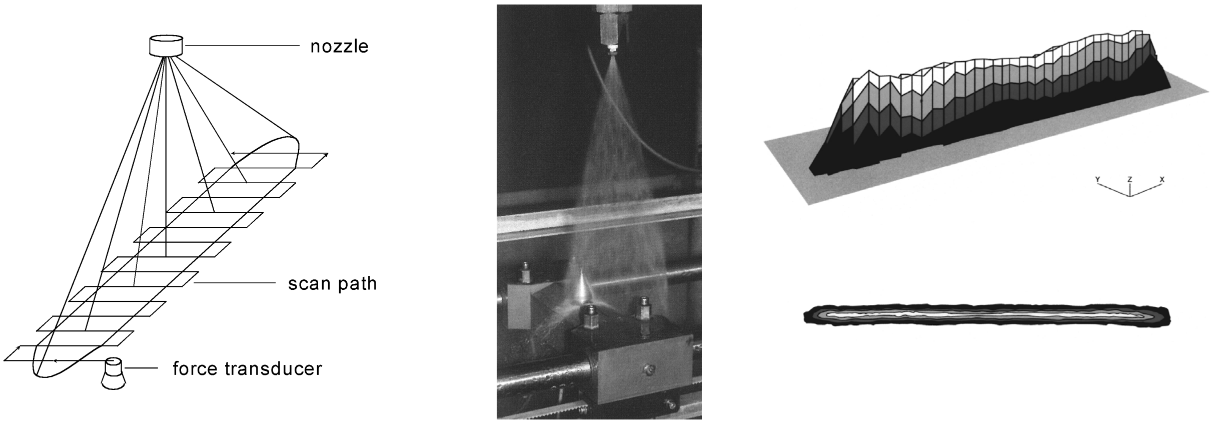


FIGURE 2 Test set-up for impact measurements and example of the test results

secondary scale under ambient conditions during the rolling process. Primary scale has a porous structure and a thickness in the range of 1 to 5 mm, whereas secondary scale has a more compact microstructure and a thickness between 60 and 100 µm [3]. The latter is difficult to remove and usually a layer of 5 to 10 µm remains.

The usage of high-pressure nozzles for descaling in production processes is an indispensable measure for the quality of the steel. In the literature the mechanism of descaling is explained in different ways. Mechanical forces due to high impact pressures of a "razor blade" like jet are hold responsible for removal of the scale from the surface. On the other hand the water jet causes an intensive cooling of the surface and a high temperature gradient in the area close to the surface is created. This can cause break-up of the oxide layer due to different thermal expansion rates of the scale and the steel, i.e. high shearing forces between scale and steel and in the scale as well.

Flat jet nozzles with rectangular impact distribution and spray angles between 22° and 40° are preferred for the generation of high impact pressures at a sufficient working width of the spray. The spray pressure ranges from 80 to 500 bars with flow rates between 10 and 200 l/min. The spray distance typically covers 50 to 200 mm.

Determination of the impact pressure

The impact force F and the impact pressure I of a spray can be determined using Newton's 2nd axiom in the generalized form $d(m \cdot v)/dt = F$ (FIGURE 1). The water jet results in a propulsion force on the nozzle and the same force is acting on a surface perpendicular to the axis of the impinging jet, in accordance with Newton's 3rd axiom *"action = reaction"*. Because the nozzle has been designed to produce an even impact distribution, calculating the impact pressure is possible by a simple formula. For verification of this calculation and quality control of the nozzles the impact pressure can be measured with a force transducer, scanning the area of direct water impingement (FIGURE 2). The measured values confirm the simple mechanical model of the jet impact, but measurement of the shape of the spray fan shows that the spray has not an ideal triangular but a convex shape. This influences the determination of the effective spray width and empirical correction factors for formula (2) are necessary [1].

The impact pressure depends on the nozzle feed pressure, the water flowrate and the impingement area. In order to get a high impact it is necessary to keep the thickness of the spray jet as small as possible. This can be achieved using a jet stabilizer in the nozzle feed tube, which avoids rotation and turbulence of the water flow in the liquid passage. The typical design of a descaling nozzle is shown in FIGURE 3. Another important component of this nozzle is the filter, which is necessary to avoid clogging of the outlet orifice and the stabilizer.

Disintegration of the jet

A droplet-stream theory has been applied to descaling nozzles [5] but measurement of the droplet size of these nozzles has showed to be difficult. Failure rates of a Laser-Phase-Doppler-Analyzer can be in the range of 90% of

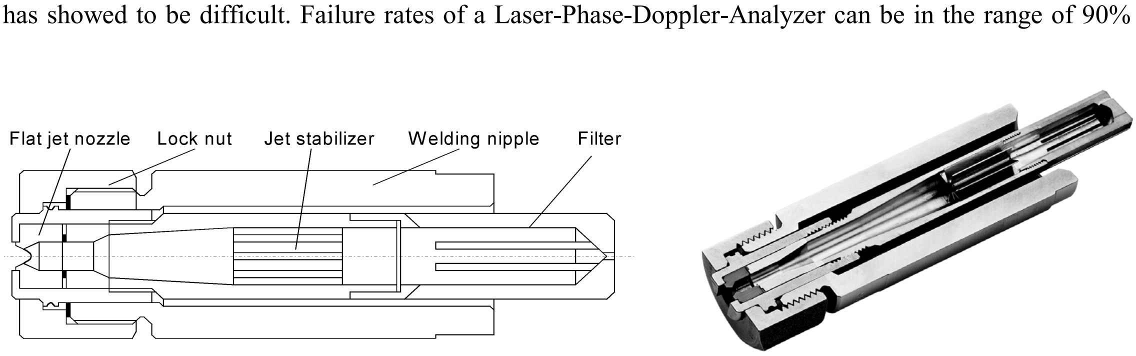
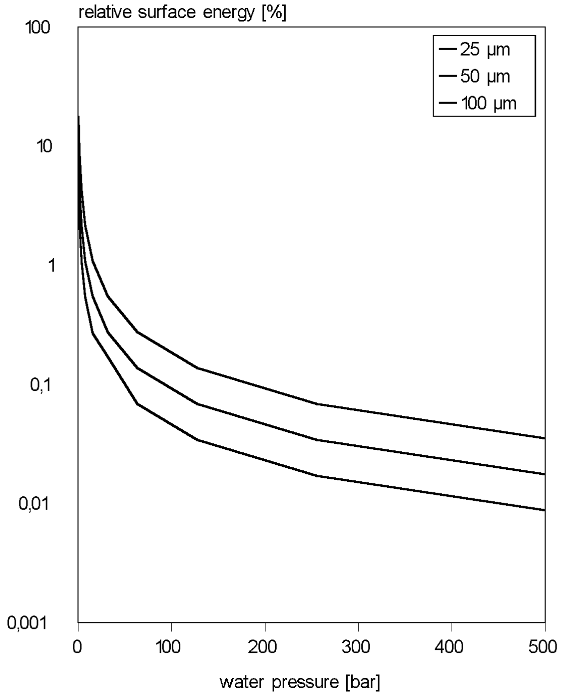


FIGURE 3 Basic design principle of a descaling nozzle system and photo of a sectional view



$$\dot{E}_{sur} = \sigma \cdot \dot{A} = \sigma \cdot \pi \cdot D_{20}\dot{N} \qquad (3a)$$

$$\dot{E}_{sur} = 6\sigma \cdot \dot{V}\frac{D_{20}^{2}}{D_{30}^{3}} = \frac{6\sigma \cdot \dot{V}}{D_{32}} \qquad (3b)$$

The power of the pump has to produce the kinetic energy of the jet and the surface energy. This results in (3c). The specific kinetic energy of the jet, thus, is given by (4).

$$p\dot{V} = \dot{E}_{kin} + \frac{6\sigma \cdot \dot{V}}{D_{32}} \qquad (3c)$$

$$\frac{\dot{E}_{kin}}{\dot{V}} = p - \frac{6\sigma}{D_{32}} \qquad (4)$$

With σ = 0,0729 N/m for water at ambient temperature this results in the diagram on the left side.

FIGURE 4 Calculation of the surface energy of a spray in comparison to the total energy of the jet

all detected liquid particles. Reliable result could be obtained, for example, at 100 bar and 500 mm spraying distance for a nozzle with 18,2 l/min flowrate. D_{32} was 180 µm, but typical values for the full range of descaling nozzles can be estimated to cover 100 to 1000 µm depending on the spray conditions and the distance from the nozzle, which is necessary for a valid test result. Atomization of the jet seems to be a secondary factor for descaling and pure mechanical considerations, as shown before, lead to a sufficient model of the impact. This can be confirmed by calculation of the energy, which is necessary to atomize the liquid, i.e. to increase its surface (FIGURE 4). The Energy per second, which is necessary to create a spectrum of N droplets with the total surface A is given in (3a) and (3b). The original surface of the flat jet is neglected. Only for very small drops and low feed pressure the energy of atomization is a considerable amount of the total energy of the jet. However, comparison of the measured thickness of the spray jet in comparison with the dimension of the small axis of the outlet orifice (exit gap) and the theoretical thickness t_min of a true laminar sheet (using the equation of continuity) shows, that the water film has been disintegrated when impinging on the surface (FIGURE 5 for two nozzle sizes). But it can be shown, that the momentum and kinetic energy of the jet is transferred completely to the target surface (FIGURE 6). Computed and measured values of the impact force show - within measuring tolerances - a strong linear relationship.

Disintegration of the jet can be visualized with 18 nanosecond short-time exposures (FIGURE 7). The photos have been taken at 200 bar in a distance of 50 and 100 mm from the nozzle outlet orifice. The flowrate at this pressure is 25 l/min, which represents the lower range of nozzle sizes for descaling applications. FIGURE 8 and 9 show results of measured impact values for descaling nozzles versus the flowrate and for different feed pressures respectively spray distances. The dependence of the impact on the water flowrate is not linear. The larger the nozzle flowrate, the larger the dimensions of the outlet orifice, and this results in an increasing thickness of the liquid film escaping the nozzle, i.e. in some reduction of the impact pressure as a result of an increased impingement area.

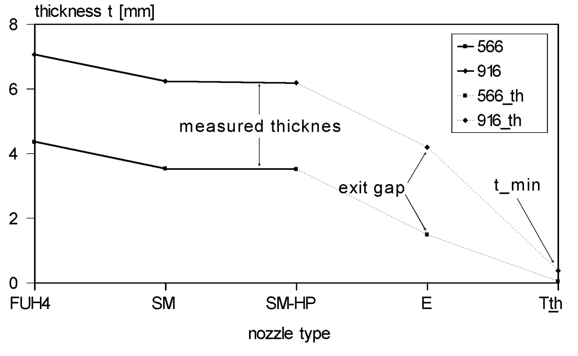


FIGURE 5 Thickness of the spray jet (FUH4 = standard nozzle; SM = nozzle with stabilizer)

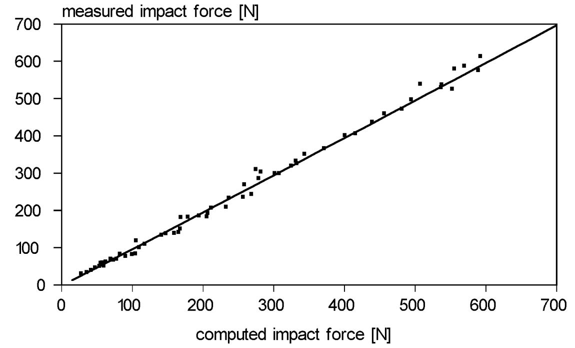
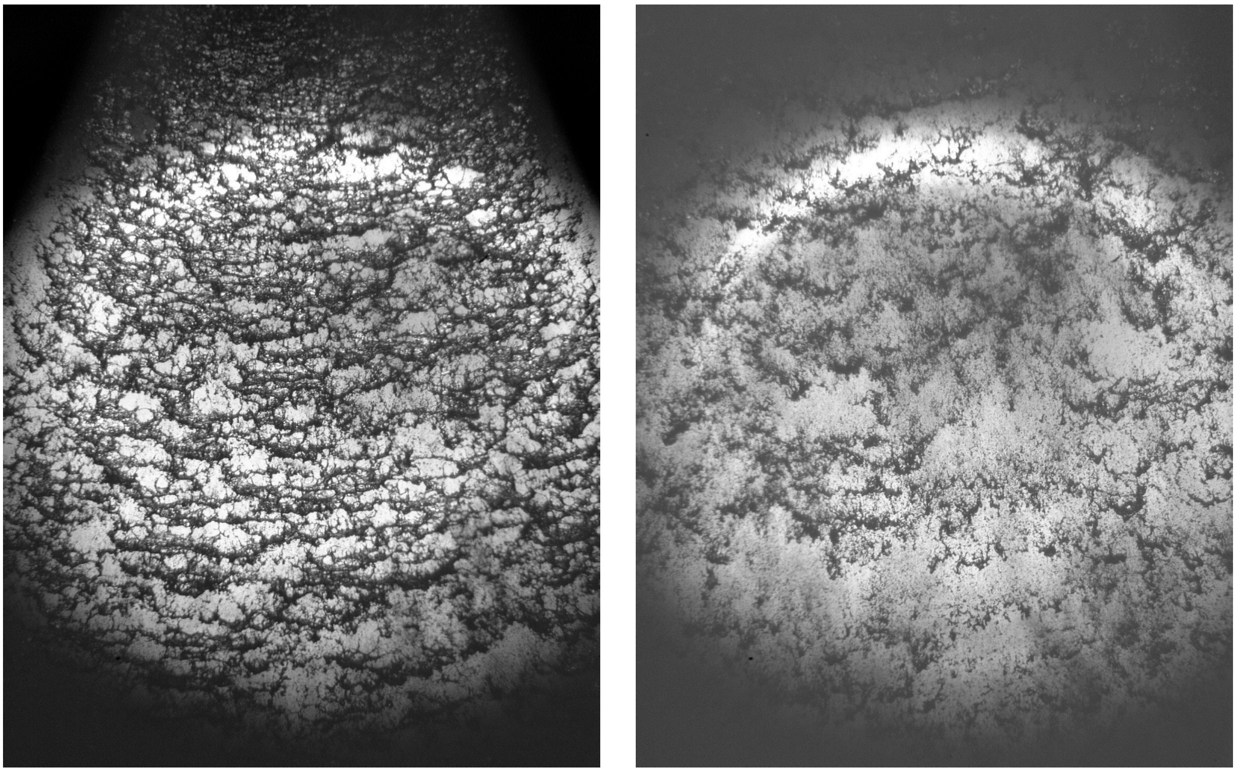


FIGURE 6 Measured and computed impact force at 200 bar



50 mm

100 mm

FIGURE 7 Short time photos of the spray fan at 200 bar; spray distance 50 and 100 mm; image size 30 x 50 mm

Mechanism of hydraulic descaling

The physical mechanism of descaling still is subject of controversial discussions [2], [3]. Scale is a layer of iron oxides, a material with the characteristic of a ceramic, i.e. a low thermal expansion coefficient and good heat insulation properties. The steel on the other hand has a high thermal expansion coefficient. FIGURE 10 shows results from a REM analysis of a layer of primary scale - typically Fe_2O_3 – on the steel. When a high-pressure water jet hits the surface of a scale/steel compound, not only a sharp peak of mechanical pressure is induced but also a high gradient of the surface temperature change, due to intensive cooling by the water jet. This creates enormous shear forces between steel and scale and in the scale itself. It can be observed under laboratory conditions that secondary scale breaks up explosion-like. Estimations of the mechanical stress, induced by the impact of the jet, and the shear stress, created by the thermal shock, show that the latter can be about 500 times higher and, thus, is dominating the process [3]. This substantiates the need for thermal measurements in addition to the pure mechanical determination of the impact pressure.

Heat transfer measurements

Spraying water on hot steel surfaces with scale causes heat transfer from the solid material to the coolant. The thermal influence of the water jet on the hot surface can be studied with laboratory experiments [4]. This allows not only determining the temperature gradient, which is a dominant parameter for the descaling process, but also to measure peak and mean values of the heat flux and the heat transfer coefficient. Both parameters are important for

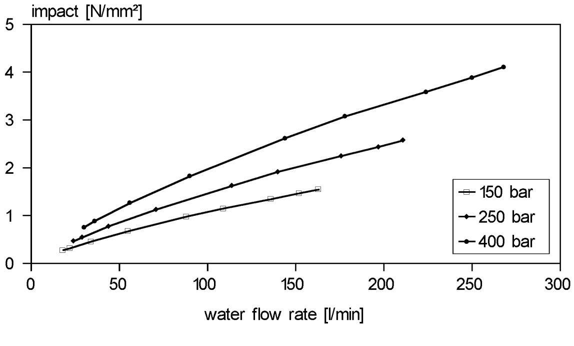


FIGURE 8 Spray impact for different pressures

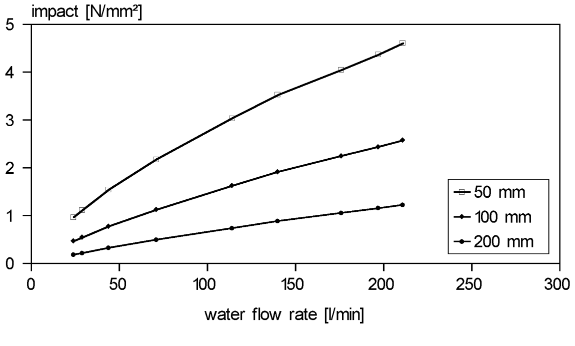
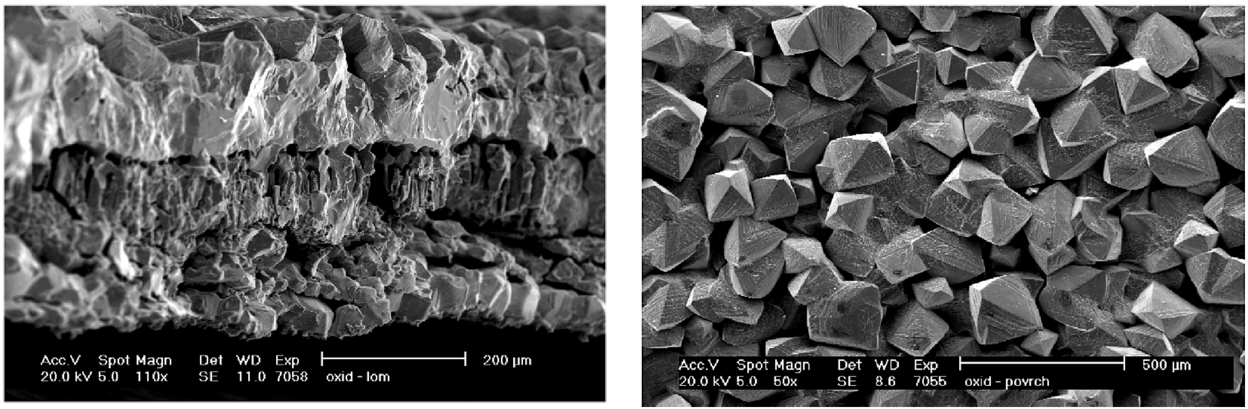


FIGURE 9 Spray impact for different spray distances



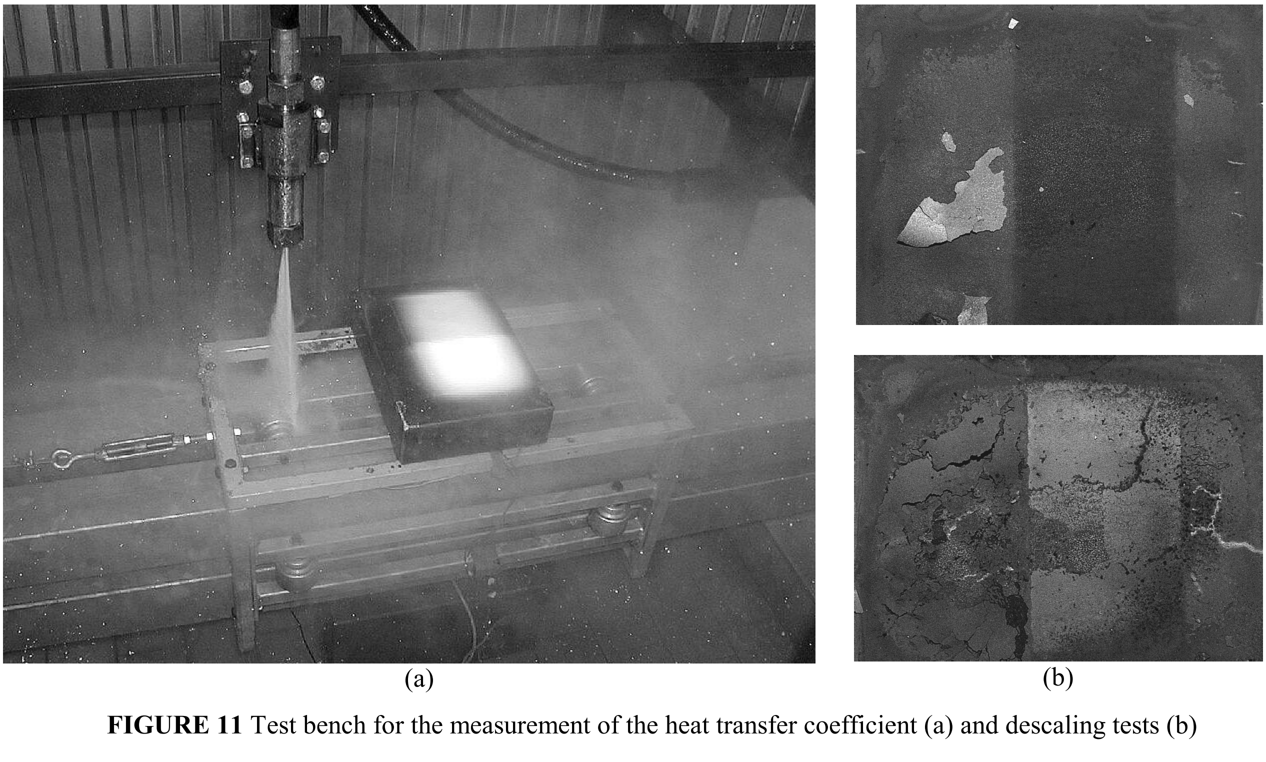
(a) (b)

FIGURE 10 Surface of a steel plate with scale; REM image (a) cross section (b) top view

the design of steel making and rolling processes. Cooling of the steel is a part of descaling, but to intensive cooling is not desired. That is, why a high descaling efficiency is required at a moderate or – at least – a controlled cooling.

A typical test set-up is shown in FIGURE 11 (a). A steel plate is heated up to a temperature of 1250°C and then moved under the spray of a descaling nozzle with the speed of a hot rolling process, typically 1 m/sec. The steel plate is equipped with thermocouples, which allow measuring the temperature at a small distance – 0.5 to 1 mm - to the surface. The temperature signals are recorded with a sampling frequency of 100 Hz and stored in a data logger. After the experiment the recorded temperature data are converted to the heat transfer data via a mathematical model of the steel plate using a so-called *Inverse Task* procedure. Results are: The computed surface temperature, the heat flux from the steel to the cooling water and the heat transfer coefficient. These data allow computations of the thermal and thermo-mechanical behavior of the steel and the scale under descaling conditions.

FIGURE 12 shows the typical characteristic of the descaling process. With a speed of the steel plate of 1 m/sec the mechanical impact covers only 6 milliseconds of the time window, whereas the thermal effect, showed here as heat transfer coefficient HTC, covers about 400 milliseconds. This illustrates, that the thermal influence of the sprayed water is very different from the pure mechanical impact. The water, contacting the steel initially in a region, which equals the area of mechanical impact, afterwards flows over the hot steel surface with high velocity and creates sudden heat transfer in an area, which is much larger than that of direct impingement of the water. FIGURE 13 shows mean values of the measured heat transfer data, averaged over a length of the steel strip of 100 mm. The peak of the HTC, shown in FIGURE 12, creates a rapid dropdown of the steel temperature close to the surface. But this temperature is recovering soon due to heat conducting back from inside the steel plate. For the calculation of the effective cooling of the steel it is therefore better to use the mean values given in FIGURE 13.



(a) (b)

FIGURE 11 Test bench for the measurement of the heat transfer coefficient (a) and descaling tests (b)

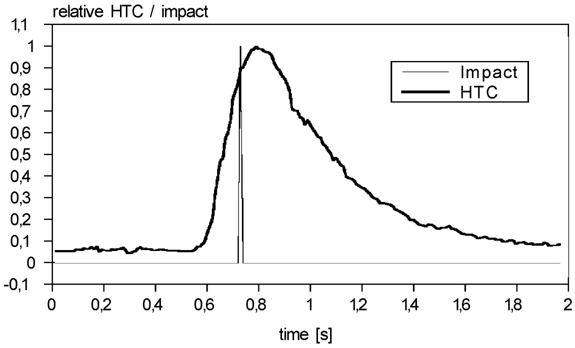


FIGURE 12 Heat transfer coefficient and impact

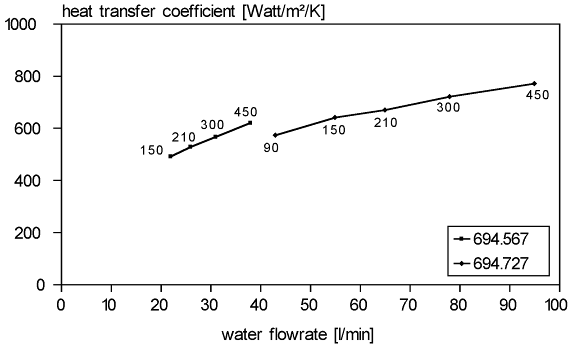


FIGURE 13 Heat transfer coefficient of 2 nozzle sizes

Descaling efficiency

A valid model of the descaling mechanism can only be obtained completing the mechanical (impact) and thermal (heat transfer) experiments by the study of the descaling itself under laboratory conditions. This requires producing scale under controlled conditions and then to perform the descaling process. The latter is similar to the heat transfer test: A hot steel plate with scale is moved under the jet of the high-pressure nozzle and the scale is removed more or less completely. FIGURE 11 (b) shows two steel plates after descaling under different conditions and with different descaling success. The scale has been produced under atmospheric conditions, which equals the so-called secondary scale in the plant. Study of metallurgical and surface quality parameters of the steel allows quantifying the result of the descaling process. In order to get a defined scale quality, heating conditions, surface quality and grade of the steel has to be controlled carefully. Evaluation of the test result, i.e. the quantity of the removed scale and the surface quality of the steel then is done by several methods, as there are: optical or electron microscopy, image analysis, gravimetric methods or magneto-inductive measurements.

Conclusions

Descaling of steel still is a process, which needs intensive research to understand the underlying physical mechanisms. Energy and momentum of the jet of descaling nozzles are dominating spray parameters, which create the impact on the steel surface. Though is can be shown, that the liquid is disintegrating, complete atomization does not take place under descaling conditions and the droplet size is not a parameter which characterizes the descaling process. The counteraction of the liquid and the hot surface is of the mechanical as well as the thermo-dynamical type. The thermodynamics of descaling can be investigated with heat transfer measurements. Heat transfer from the hot surface causes high temperature gradients in the scale/steel compound and is a dominant reason for break-off of the scale. The thermal effect of the spray jet covers a wider area on the surface than the pure mechanical impact. Correlation between mechanical and thermal parameters can only be found by combination of results from mechanical and thermal experiments. The effectiveness of descaling can be studied under laboratory conditions with controlled descaling experiments. This work will be continued in order to get a complete model of descaling.

Nomenclature

A	[m^2]	sprayed area	F	[N]	impact force	V	[m/s]	liquid velocity
E_{sur}	[Nm]	surface energy	H	[mm]	spray distance	V	[m^3]	liquid volume
E_{kin}	[Nm]	kinetic energy	I	[N/mm^2]	impact pressure	α	[°]	spray jet angle
D_{20}	[µm]	Area mean diameter	m	[kg]	liquid mass	ρ	[kg/m^3]	liquid density
D_{30}	[µm]	Volume mean diameter	p	[Pa]	feed pressure	σ	[N/m]	surface tension
D_{32}	[µm]	Sauter mean diameter	t	[mm]	spray thickness			

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