HEFAT2007
5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
Sun City, South Africa
Paper number: HJ1

EXPERIMENTAL STUDY OF HYDRAULIC DESCALING

Horsky J.* - Raudensky M. – Vavrecka L.
*Author for correspondence
Heat Transfer and Fluid Flow Laboratory,
Faculty of Mechanical Engineering,
Brno University of Technology,
Czech Republic,
E-mail: horsky@fme.vutbr.cz

ABSTRACT

Experimental work was concentrated on the study of descaling in relation to heat transfer and the quality of removing scale from the surface. Three types of measurements were implemented. The first one is a measurement of impact pressure distribution on spraying surface. The second is a measurement of temperature drop when a product is passing under the nozzle. The third type is a study of the surface quality where a defined layer of oxides is sprayed and its remaining thickness is evaluated. The heat transfer test is evaluated by inverse task and the results are prepared in a form of boundary conditions suitable for using in a numerical model.

INTRODUCTION

Hydraulic descaling is the process of removing oxides layer from a hot (typically steel) surface using high-pressure water jet. This process is essential in the hot rolling. Quality of descaling can strongly influenced final quality of rolled surface. The scale is formed during heating in a furnace (primary scale) and during rolling process (secondary scale). Both types of scale must be removed before entering rolls. High-energy water beam has two effects on a scale layer. The first one is a relatively intensive thermal shock depending on a set of parameters (water pressure, nozzle type, distance from the surface, inclination angle, speed of product moving). The second effect is mechanical caused by impact pressure. There is no acceptable answer to the question – which effect is dominant? A suitable numerical model could give the answer to this question. Realistically working numerical model needs realistic boundary conditions. The knowledge of heat transfer coefficient (HTC) distribution and impact pressure (IP) distribution is necessary.

IMPACT PRESSURE MEASUREMENT

When measuring the pressure distribution (see Figure 1 and Photo 1), the nozzle sprays on a moving plate. This plate is equipped with a pressure sensor that is of circular shape. The active surface of this sensor is size of 1.5 mm in diameter. For a given nozzle configuration, a pressure is measured as position dependent while the plate with the sensor is moving under the spraying nozzle.

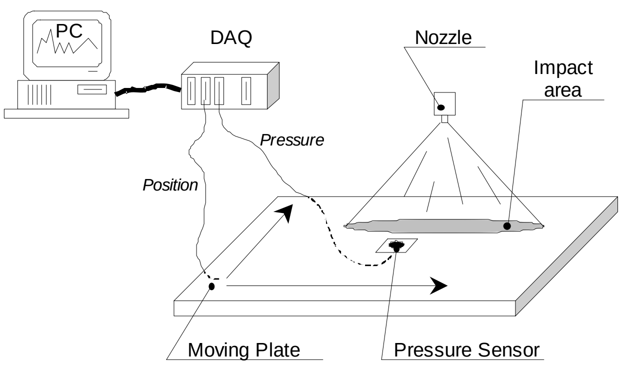

Figure 1 – Pressure distribution measurement

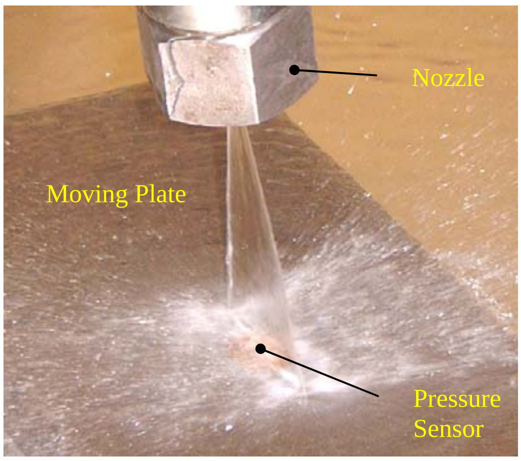

Photo 1 – Nozzle and test plate with sensor

A typical result of the impact force measurement is shown in Figure 2. The result in Fig. 2 was obtained for a spray height of 150 mm, feeding pressure 20 MPa and flow-rate of 2 l/s. The nozzle produces a narrow footprint approximately 6 mm wide and 70 mm long. The result in Figure 2 was obtained by using a relatively high-mass force sensor, which dumps all of the instant force fluctuations caused by non-continuous flow.

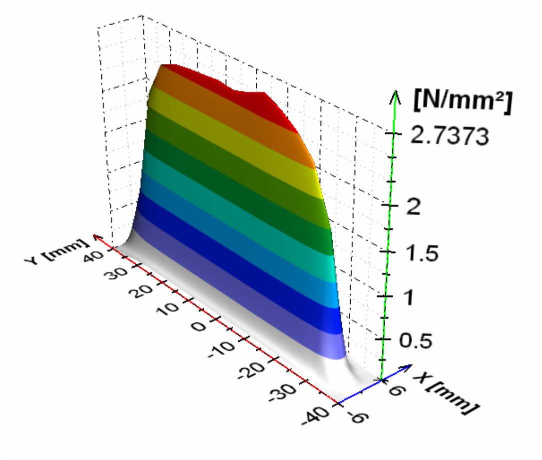

Figure 2 – Example of impact pressure distribution

Influence of feeding pressure on impact pressure is demonstrated in Figure 3. The plotted curves were measured in the position of nozzle axis.

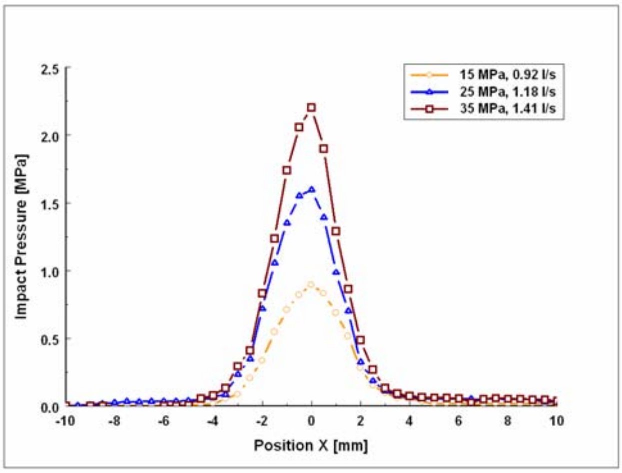

Figure 3 – Influence of feeding pressure on impact pressure

The knowledge about impact distribution and influence of feeding pressure and distance from sprayed surface is basic information for successful descaling system design. Descaler uses a set of nozzles to cover the whole width of rolled material. Nozzles are embedded into a spray header. Geometrical configuration is usually recommended by nozzle producer. Typical, common situation is demonstrated in Figure 4. The nozzles are located at a certain distance in row. Vertical spray height influences value of impact pressure and also important parameter – over lap. The value of over lap can strongly influenced quality of descaling. If this parameter is not designed properly, “tiger strips” can be observed on descaled surface. (Non homogeneity in cooling and descaling intensity).

Impact pressure in direction of moving (x axis) should be constant on the whole width of material (y direction).

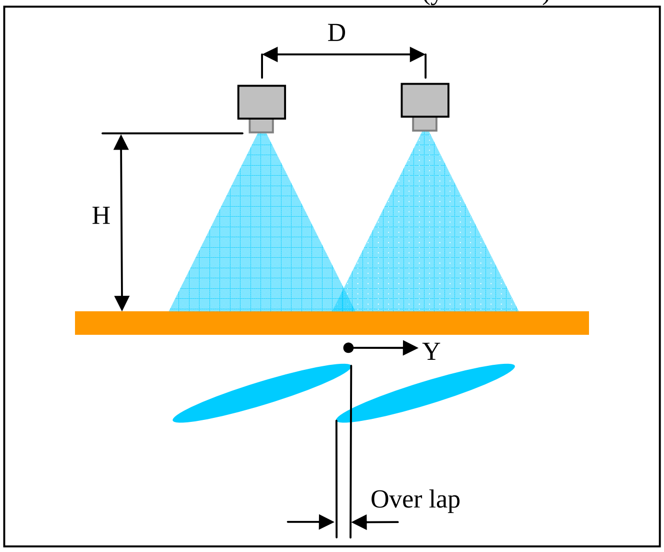

Figure 4 – Typical nozzle configuration

Integral value can give an idea about this situation. The definition of this characteristic is:

$$Integral\ impact = \int_{-X}^{+X} impact\ pressure\ dX$$

For given nozzle distance D, the over lap is in proportion to the height H. If the over lap is too wide then the value of integral impact can reach a maximum in this area. In a case of no or very small over lap a minimum of impact can arise here. An example above mentioned is shown in Figure 5.

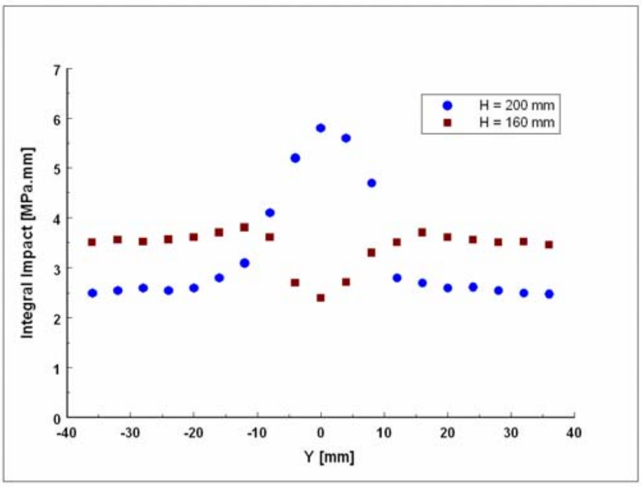

Figure 5 – Integral impact distribution for two spray heights, feeding pressure 15 MPa, flow-rate 0.92 l/s, D=72 mm

Properly designed descaling system should satisfy the basic condition – integral impact is constant over the whole width of rolled material. This situation is demonstrated in Figure 6.

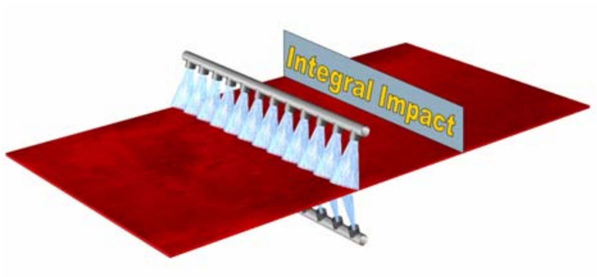

Figure 6 – Ideal integral impact pressure distribution

HEAT TRANSFER TESTS

Temperature drop is measured during the pass of hot instrumented sample under the descaling nozzles. The experimental conditions were prepared in such way, which resembles as close as possible to the real mill conditions. There are two basic parameters, which should be kept. The first is the initial temperature of a tested sample and the second is the speed of sample motion. A special experimental stand was developed for these tests.

Experimental stand

The experimental stand was built to study the cooling of linearly moving objects. A six-meter-long girder carrying a movable trolley and a driving mechanism (see Figure 7) forms the basic part of the experimental device.

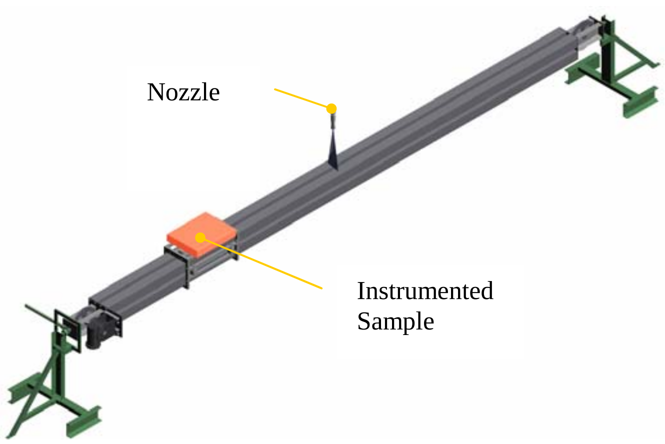

Figure 7 – Principle of linear stand

An electronic device measuring the instant position of the trolley is embedded in the trolley. The driving mechanism consists of an electric motor controlled by a programmable unit, a gearbox, two rollers and a hauling rope. The girder is divided into three sections. The marginal sections are used for the trolley's acceleration or deceleration. The velocity of the trolley is constant in the mid-section and it is here where the spray nozzles quench the measured sample.

Procedure of the experiment

- An electric furnace (heater) heats the test plate to an initial temperature of the experiment (typically 950 ^{o}C).
- The plunger pump is switched on and the pressure is adjusted.
- A driving mechanism moves the test plate under the spray. After recovering the temperature field in the plate, the movement of the plate under the spray is repeated.
- The sensor measures the temperature in nozzle axis position at a certain depth from the cooled surface and the temperature is recorded into datalogger memory.
- The positions of the test plate and the sensors (in the direction of movement) are recorded together with the temperature values. The record of instant positions is used for computation of instant velocities while moving under the spray.

Experiment evaluation

The pass under the nozzle causes a temperature drop in the material sample that is indicated by a temperature sensor. An example of temperature record is plotted in Figure 8.

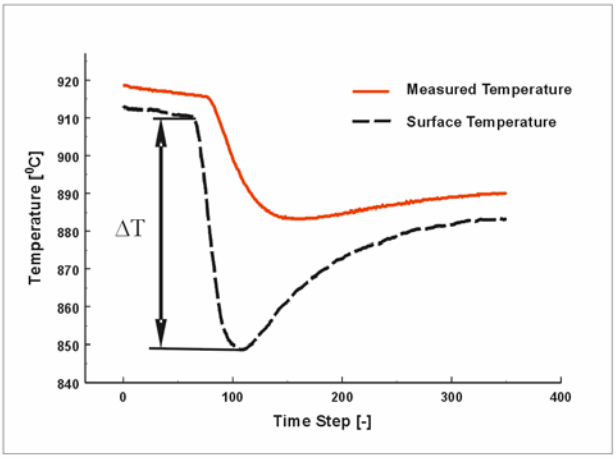

Figure 8 – Temperature drop during the pass under nozzle

This information together with material properties and calibration characteristics of temperature sensor is used as input of inverse heat conduction task.

Inverse heat conduction task

Temperature distribution inside test specimen is described by a differential equation.Direct solution of this equation can be done relatively easily when using a numerical technique, with the knowledge of thermo physical material properties and boundary conditions. Inverse task means, in this case, finding the heat transfer coefficient on the surface body. One or more temperature records at points (sensor positions) inside the body are obtained from the experiment. The method used here is based on a minimization principle [2]. The results of computation are surface temperature, heat flux and heat transfer coefficient. An example of inverse computation output is plotted in Figure 8 (surface temperature - black line) and Figure 9 (HTC).

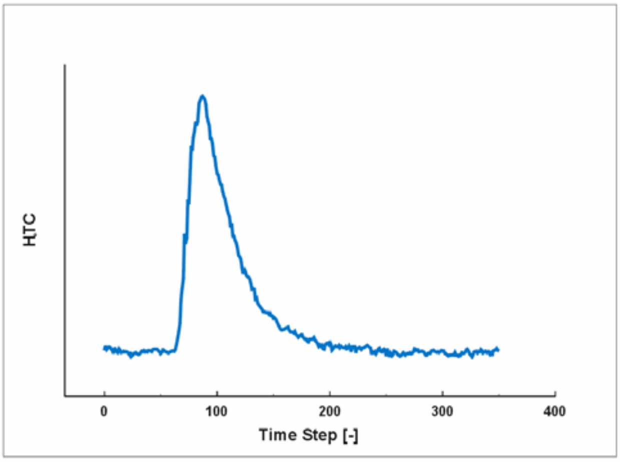

Figure 9 – HTC record, result of inverse computation

HTC distribution over the width of material should be homogeneous as much as possible. That was the reason why investigation of cooling intensity in position of nozzle axis and in overlapping area was done. Test sample was equipped by two calibrated thermal sensors indicating temperature at a certain depth from cooled surface (see example of temperature record in Figure 8, red curve). Geometrical configuration of one and two nozzles is obvious from Figure 10.

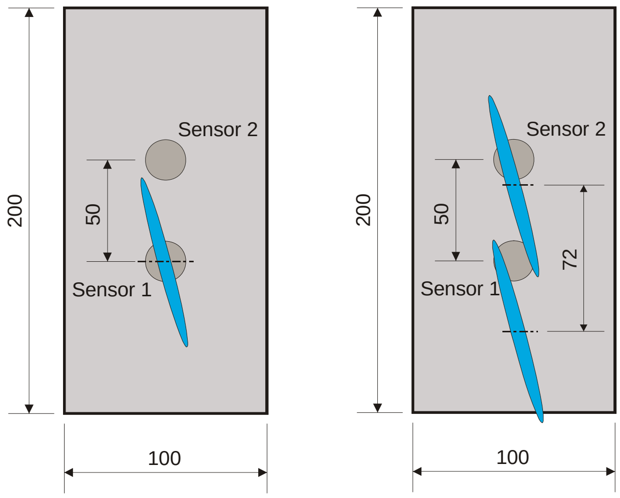

Figure 10 – Test sample dimension and nozzle configuration for HTC tests

Nozzle spray height is 200 mm and all other parameters are the same as in the case of impact pressure measurement (see Figure 5, blue circles). Surface temperature drop is recorded in Figure 11. Cooling intensity corresponds to integral impact pressure distribution – overlapping area is more intensively cooled than the area in surrounding of nozzle axis. The difference in surface temperature loss is about 40 °C in this case.

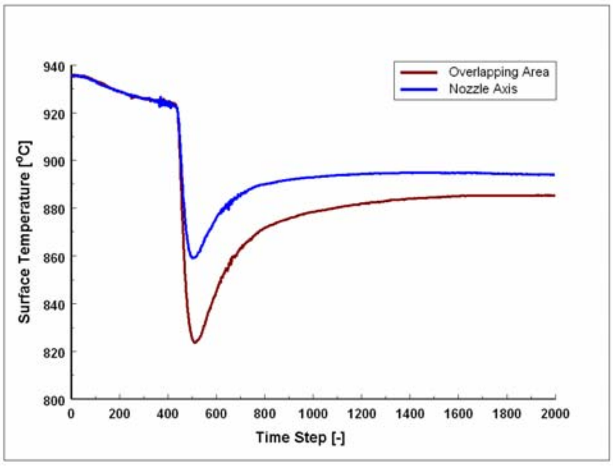

Figure 11 – Temperature drop in over lap and nozzle axis area

QUALITY TESTS

Experiment preparation

Optimal layers of scales for steel materials were reached at the oxidation temperature of 1060 - 1090 °C.

Dimension of the test plate is 250x250 mm; thickness 30 mm. Surface quality of the prepared plate is essential for experiments. The surface is fine grinded. The surface roughness must be less than the thickness of fine oxides remaining after spraying. The heating of the plate is done in an electric furnace. Covering plate of similar thickness during heating covers the test plate. Ceramic paste is applied on the plate edges to prevent air penetration.

The covering plate is removed as soon as homogeneous temperature field in the test plate is achieved. The oxidation time is counted after the covering plate is removed. The test plate stays in the furnace during oxidation to hold the constant temperature. The test plate is moved to the track and placed on the test bench before elapsing the time for oxidation. As soon as the oxidation time elapsed, the test plate starts to move under the descaling nozzle (see Photo 2).

Photo 2 – Test plate moving under the descaling nozzle

Moving trolley is stopped after the first descaling pass. A box with nitrogen covers the test plate after the spray.

Scale thickness measurements

The testing plates show two areas: the area of the nozzle trace and the area outside the nozzle trace. An electro magnetic probe measured scale thickness and some of the measurements were verified by an electron microscope. The probe calibration was done for each experimental plate. Then, a few measurements were done in various areas of the plate.

Measurement of areas in nozzle trace

Areas with various thicknesses of scales remain in the nozzle trace after spraying. Figure 12 shows clearly noticeable areas with different thicknesses of scale. Upper is the photo of a testing plate and bottom is the same picture coloured when using image analysis program for the measurement of the area size. Each experiment is evaluated and the parameter characterizing the quality of descaling - “Percentage of remaining scale” (PRS) is calculated. The parameter is defined as follows:

$$\left(\frac{h_1 S_1 + h_2 S_2 + ... + h_n S_n}{h_{max} S_{SUM}} \right) \times 100 = PRS(\%)$$

where h_1 … h_n is the thickness of scale, h_{max} is maximum thickness of scale, S_1 … S_n are the areas of the scale, S_{SUM} is footprint (total area below the nozzle).

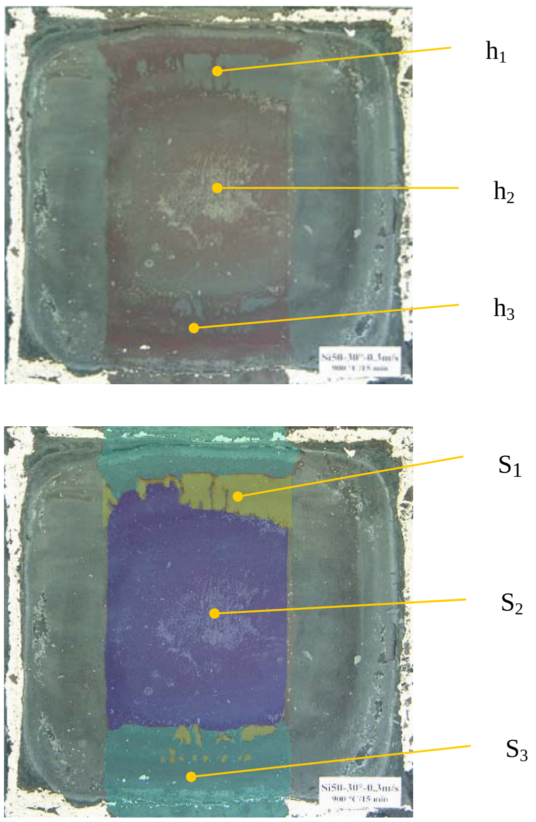

Figure 12 – Original photo of test plate (upper) and coloured pictures showing the areas with different thickness of scale (bottom)

An example of results is summarized in Table 1. In this case, the influence of feeding pressure on the quality of descaling was investigated

Table 1 - Results of quality tests

Feeding pressure [MPa]	Flowrate [l/min]	PRS [%]
5	32	29.6
15	55	23.2
45	95	19.3

NUMERICAL MODEL

This part of paper describes development and principal structure of finite element models of a layer of oxide scales on steel material. In Model 1, there are applied experimentally obtained boundary conditions needed for the evaluation of tensile stress in a layer of scales and in the basic steel material. In Model 2, creation of the crack in scales layer and growth of this crack from scale surface to boundary between oxide scales and steel material are simulated. Both models were developed to understand the process of hydraulic descaling and to get the tool necessary for the optimization of spraying parameters. The investigated process consists of two aspects; the heat aspect (high thermal stresses at the thermal shock) and the mechanical aspect (direct influence of water jet pressure). Mathematical model enables considering the influence of both aspects that finally determine the surface quality.

Input expectations

Uniform distribution of water jet in direction of axis **z** is expected. This condition determines constant parameters of HTC values in the direction of this axis. As HTC is constant in the direction of axis **z,** the temperature gradient is zero for this model. Thereby, the problem can be solved as 2-D task.

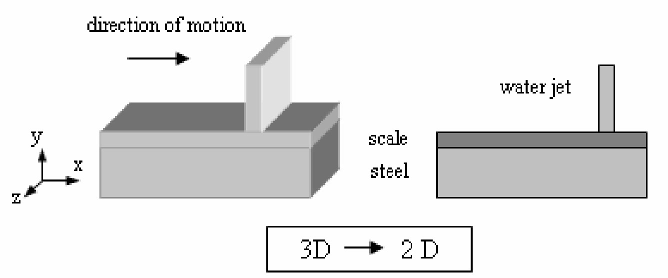

Figure 13 – Geometrical expectations

Oxide scale layer is composed of three different layers of oxides of iron (FeO, Fe_2O_3, Fe_3O_4) with different thickness. These layers are inhomogeneous and can contain some discontinuities as cracks, etc. In this model, one layer of scales was created and homogenous material characteristic was subscribed. These material characteristics are considered according to publication [6]. For a layer of the steel basic material, material characteristics of steel with 4% of C are used. This layer is also modelled as homogenous.

MODEL 1

Geometry of the model

As seen above, the problem is solved as 2-D task. Model is presented as an assembly of two layers, layer of steel and layer of steel oxides. Steel thickness is 20 mm, scales thickness is 0.1 mm, length of model was set on 6 mm which was considered being sufficient for boundary conditions and does not influence computed stresses according to [7].

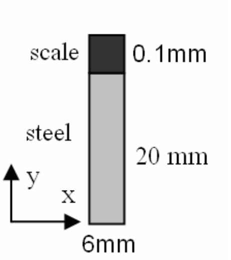

Figure 14 – Model's geometry

Solution

The problem is solved in two consequential steps. First one is 2-D unsteady thermal analysis. During this analysis, temperature of 1100°C was subscribed as an initial temperature of the assembly. Then, the assembly was loaded by HTC(t) with temperature of cooling liquid in magnitude of 20°C. This loading was applied on scaled surface. The principle of computation of HTC is mentioned above in chapter HEAT TRANSFER TESTS. Sides of the model are heat-insulated (Figure 15). Thermal field computed based on this analysis are used as boundary conditions in the next step – thermal stress analysis.

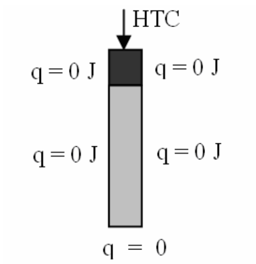

Figure 15 – Thermal boundary conditions

In the next step, thermal stress analysis, the model was loaded with thermal fields. In certain time interval, pressure impulse was applied on scale surface. Values of this impulse match with maximal values obtained during experimental measurements. To find the influence of this pressure impulse on stress fields in the model, two different values were applied – 0 MPa, and 4 MPa. In the model, there were also applied boundary conditions for displacement (Figure 16). The boundary conditions marked as Ux (Uy), subscribes fixation at the directions of axis x(y) and couple Ux unify displacement of nodes at the direction of x axis.

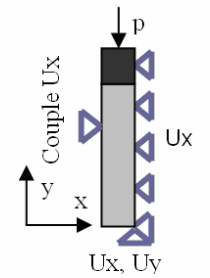

Figure 16 – Boundary conditions for stress analysis

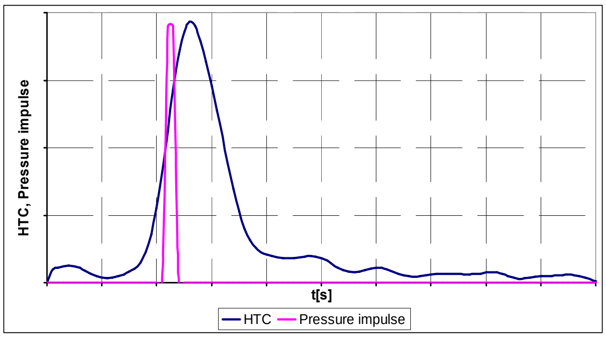

Figure 17 – History of HTC and pressure impulse

Results

After analysing the results, it is obvious, that main component of the stress field is $\boldsymbol{\sigma_x}$ stress – stress in direction of the movement. Other components of stress field, $\boldsymbol{\sigma_y}$ a $\boldsymbol{\tau_{xy}}$ are insignificant to $\boldsymbol{\sigma_x}$. From the results it is obvious, that $\boldsymbol{\sigma_y}$ has same time history as pressure impulse and their maximal values are identical, thus thermal loading has no influence on this component of stress field and its only influence is on $\boldsymbol{\sigma_x}$.

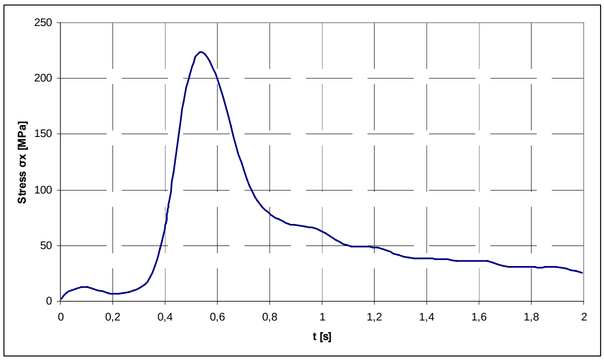

Figure 18 – History of $\boldsymbol{\sigma_x}$ on scale surface

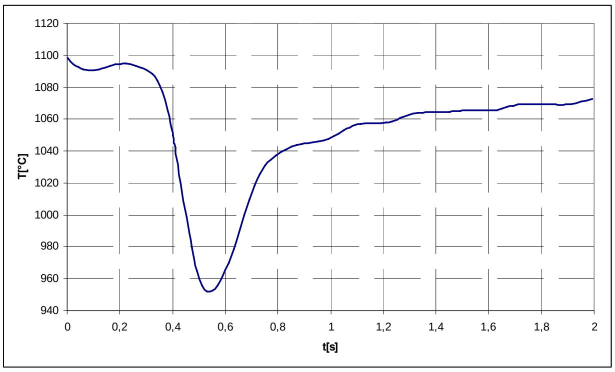

Figure 19 – History of temperature on scale surface

As seen in Figure 18, the course of σ_x follows the course of applied HTC. Maximal value of the σ_x is 224 MPa. The influence of pressure impulse on this component of stress field is very small; the impulse of 4 MPa causes a decrease of σ_x about 0.7 MPa comparing with the analysis without pressure impulse, which is insignificant. This influence of pressure impulse is also confirmed in [8]. The temperature of the surface drops from 1100°C on 951°C and then it recovers on 1073°C.

MODEL 2

Geometry of the model

Geometry is identical with Model 1.

Solution

This problem is also solved in two consequential steps - 2-D unsteady thermal analysis followed thermal stress analysis. At this case, instead of HTC obtained during experiments, just a step change of HTC was applied (Figure 20).

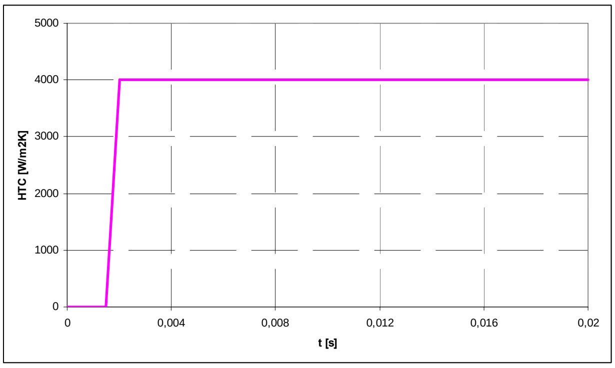

Figure 20 – History of HTC

Others boundary conditions for thermal analysis are similar to Model 1.

Boundary conditions for thermal stress analysis are also similar to Model 1, the only difference is that pressure impulse was not applied because its influence is insignificant according to the analysis with Model 1.

Creation of the crack

Position of crack is in the middle of the model, 3 mm from the edge. Before thermal – stress analysis, contact pairs were created at this position. This contact was defined as bounded.

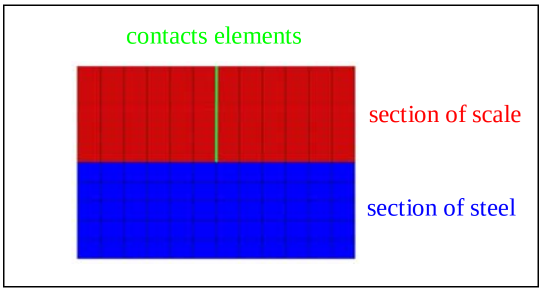

Figure 21 – FEM mesh of Model 2

The creation and growing of the crack are modelled according to a creational value of σ_x – labelled σ_{crit}. At this model we studied influence of three different values of σ_{crit} – 20, 40 and 100 MPa.

The simulation is described in the following steps: during every step of thermal stress analysis, absolute value of pressure between contact elements is obtained. This value is equal to σ_x at this moment $|p_x| = \sigma_x$.

This value is at each step compared with value of σ_{crit}. If

$$|p_x| \geq \sigma_{krit}$$

then status of the contact pair is changed from bounded to standard and cracks can be created and growing toward steel material.

Results

Aim of this analysis is to find a dependence of crack length on the time according to selected σ_{crit}. In Figure 22, this dependence is displayed and it is obvious, that with an increasing σ_{crit} longer time it is required.

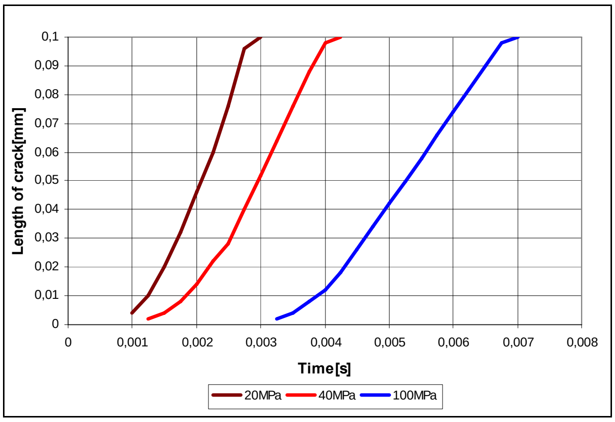

Figure 22 – Growing of the crack in time

As soon as crack is started, σ_x is decreasing on surface of the crack and at the same time shear stress τ_{xy} is growing as displayed in Figure 23. Formation of shear stress probably causes peeling of scales from steel material.

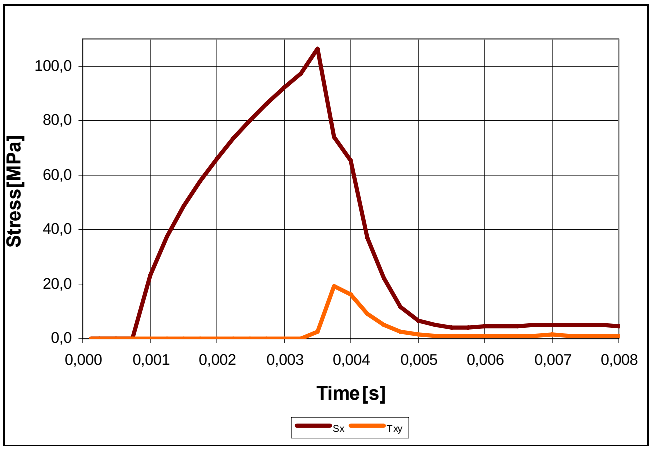

Figure 23 – Stresses on crack surface for σ_{crit}=100 MPa

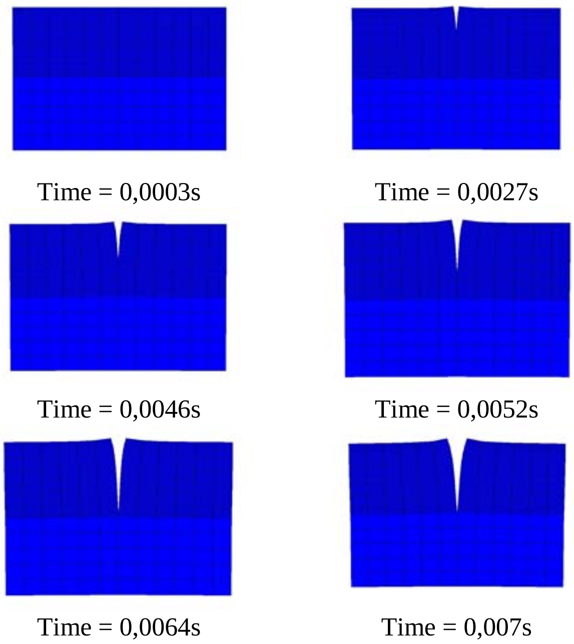

Figure 24 – Growing of the crack for σ_{crit}=100 MPa

CONCLUSION

Complex study of the descaling process using a high pressure nozzle was done in this paper. The aim is to understand the problem and to develop a tool for design and optimization of descaling systems. Experimental work was concentrated on the measurement of impact pressure distribution, heat transfer coefficient distribution and quantitative and qualitative determination of descaling efficiency. Finite element model describing the behaviour of scale layer during descaling was developed. The results obtained from the calculation help to understand the mechanism of descaling. It was confirmed that dominant mechanism, which can causes crack in a layer of scale and then the peeling of scale from the surface, is thermal shock. Mechanical effect (pressure pulse) is of the secondary significance.

ACKNOWLEDGMENTS

This research work was supported by the Czech Grant Agency within the project No. 106/06/0709.

REFERENCES

[1] Blazevic, D. T,: Newton and descaling, 3rd conf. Hydraulic Descaling, London 2000

[2] Raudensky, M.: “Heat Transfer Coefficient Estimation by Inverse Conduction Algorithm,” Int. J. Num. Meth. Heat Fluid Flow, 1993 (3): 257~266.

[3] Bendig, Raudensky, Horsky: Descaling with High Pressure nozzles, ILASS-Europe, Zurich, 2001

[4] Raudensky, Horsky, Pohanka, Tosovsky, Kotrbacek, Experimental Study of Parameters influencing Efficiency of Hydraulic Descaling – Theory of Vapor Explosion, 4th Conference on Hydraulic Descaling, London, 2003, pp. 29-40

[5] Marson, H. F. : Influence of Scale Structure on the Effectiveness of Descaling, Proc. Conference Hydraulic Descaling in Rolling Mills, London, UK, Oct. 1995, pp. 1-10.

[6] M.Krzyzanowski, J.H.Beynon – Modelling the boundary conditions for thermo-mechanical processing-oxide scale behaviour and composition effects, Modelling Simul.Mater.Sci.Eng. 8 (2000) 927-945)

[7] Tosovsky, J., Pohanka, M., Kotrbacek, P.: Stress analysis of scale layer for descaling process, 40.IK EAN Prague, June 2002

[8] N.Mikler, V.Lanteri, V.Leblanc, F.Geffraye – Primary and secondary descaling on low carbon steels, IRSID-USINOR Process Research Center, Maizieres-les-Metz - France