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Experimental study of in-line heat treatment of 1.0577 structural steel

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Abstract

In-line heat treatment is frequently used in rolling mills because it offers a significant improvement of rolled product mechanical properties with costs benefits. This method allows achieving required mechanical properties without necessity of additional alloying and rolled product reheating. Disadvantage of in-line heat treatment is fixed rolling velocity which is typically strong parameter in controlling of final cooling regime. Water flow rate, pressure, type, size and position of nozzles, water temperature are examples of parameters influencing cooling intensity and the Leidenfrost temperature. Laboratory experimental study is needed to design well controllable cooling system which allows keeping required cooling regimes for various product steel grades and dimensions. This paper describes experimental stages of cooling system designing procedure for improving structural steel 1.0577 mechanical properties. First experimental part began with building of cooling intensities (heat transfer coefficients - HTC) database for tested several nozzles configurations. Then required cooling regime was selected according to the continuous cooling transformation diagram. The target was obtaining harder (quenched) material with good ratio between elongation and strength. The final equalization temperature was set to 600 °C in the whole body. Numerical simulations of cooling followed based on the knowledge of heat transfer coefficients from database. Appropriate nozzle configuration was chosen and numerical results were experimentally validated using modified Jomminy test. A hardness was improved significantly up to thickness of 12 mm (275 HV under sprayed surface decreasing to 180 HV in 12 mm). When the required material structure and hardness verified appropriateness of cooling regime by previous tests, the first design of cooling section was done. Full scale sample was heat treated on a new experimental stand (Karusel) which was developed by HeatLab. It enabled to simulate real cooling process in laboratory conditions. The sample was heated to rolling temperature and moved through the intensive spray (surface temperature drop to 300 °C) and then through the soft spray because of water savings. The cooling stopped in required time and the sample tempered to the target equalization temperature of 600 °C in the whole body. Finally, the hardness was measured, tensile and Charpy pendulum tests were done to confirm design of cooling unit. The hardness of the original material was constant along depth – 160 HV. It was improved by heat treatment – decreasing from the sprayed surface (265 HV) to the depth of 12 mm (175 HV). The minimal yield strength of the heat treated material increased from 355 MPa 400 MPa (maximal up to 750 MPa – closed

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to the sprayed surface). The sample was cooled to -20 °C for Charpy pendulum test. The pendulum energy of heat treated material rapidly increased from 50 J to 150 J.

Keywords: Heat treatment; Water quenching; Self tempering; Tensile tests; S355J2; 1.0577; Structural Steel

1. Introduction

Heat treatment of rolled material 1.0577 (S355J2) is more frequently used in rolling mills because of markets demands (e.g. oil country tubular goods, power and mechanical engineering - sections bars) on steel quality, mechanical properties and costs. Heat treatment allows production of required steel grade with increased mechanical properties without necessity of additional alloying [1].

Very important part of a heat treatment is controllability of the cooling process. Cooling strategy should be based on continuous cooling transformation diagram and metallurgist demands. Numerical simulations of appropriate cooling process could follow. Boundary conditions (heat transfer coefficient [$Wm^{-2}K^{-1}$]) have to be found experimentally because of its dependence on various parameters: nozzle type, spray distance, water impingement density, nozzle position, nozzle overlap, movement velocity, scales etc. [1-3]. In addition, accurate material thermos-physical properties are needed also [4].

This article deals with the improvement of 1.0577 mechanical properties and its testing methods (Tensile strength and Charpy pendulum tests).

2. Laboratory research

Heat transfer and Fluid Flow Laboratory (HeatLab) developed a methodology to predict temperature field evolution in the body of heat treated sample [5]. The methodology is divided into 4 stages.

2.1. First stage – hardening capacity tests

The first stage starts by a study of continuous cooling transformation diagram and finding appropriate cooling regime which is verified by modified Jominy tests (Fig. 1(a)) – experimental sample is heated to the initial temperature in a furnace. The furnace is lifted up and the sample is moved under spraying nozzle. Pneumatically driven deflector, positioned between nozzle and sample, could be opened and closed in required time which is useful for simulating of various cooling regimes. Heat treated samples are cut and taken for measurement of hardness profile (Fig. 1(b)).

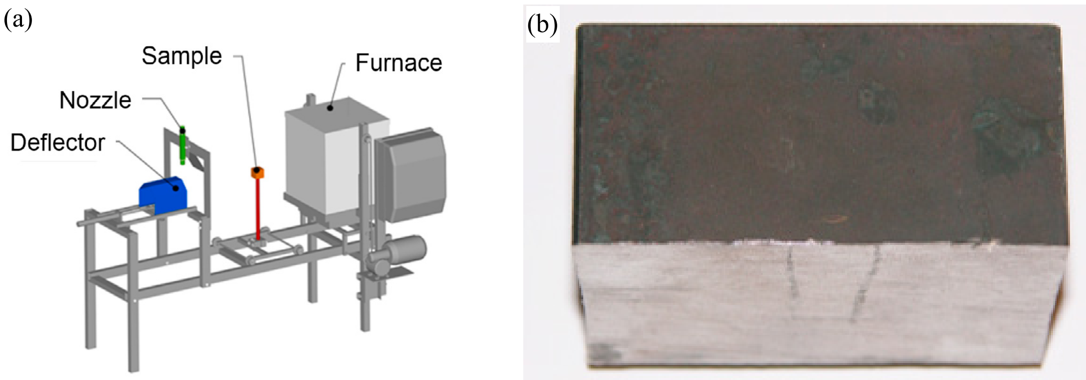


Fig. 1. (a) Scheme of modified Jominy experimental device; (b) cut experimental sample (dimensions 60 x 30 x 40 mm).

2.2. Second stage – heat transfer coefficient measurements

The cooling regime and precision of continuous cooling transformation diagram was verified by static tests (Jominy) during the first stage. Second stage is focused on dynamic experimental study of heat transfer coefficients for various cooling parameters. A linear stand testing device (Fig. 2(a)) is used for these tests. An austenitic steel experimental plate of dimensions 300 x 320 x 25 mm is embedded by thermocouples. A reason of usage austenitic steel plate is simple – no phase changes during cooling and good protection against scales. Boundary condition (heat transfer coefficient) is dependent on the surface temperature so it can be used for any simulation of carbon steel material cooling. This sample at a required temperature was passing through the cooling section repeatedly until it was cooled down under 100 °C (Fig. 2(b)). Various types of nozzles, water pressures (flow rates) transport velocities nozzles positions, etc. were tested. The measured temperatures were used for calculating corresponding heat transfer coefficients as a function dependent on the surface temperature and position of the sample in the cooling section.

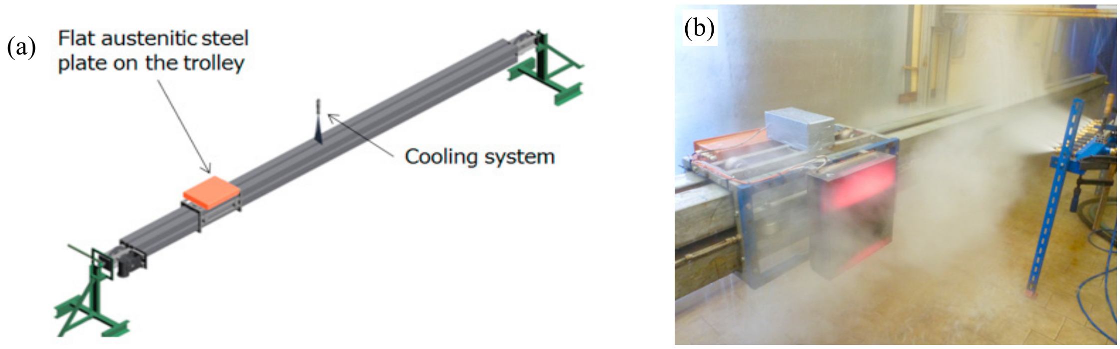


Fig. 2. (a) Scheme of Linear stand; (b) experimental plate after passing through cooling section.

2.3. Third stage – numerical simulations and first design of cooling section

HTC database was created for various cooling parameters during the second stage. Example of heat transfer coefficient dependence on the surface temperature and position of the product in the cooling section is shown in Fig. 3 (a). It was used for numerical simulations of real cooling process (Fig. 3(b)). Results of these simulations were used to determine minimal cooling length (dependent on the rolled product material, thickness and velocity), cooling intensity and also homogeneity. Afterwards the first design of cooling section could be done.

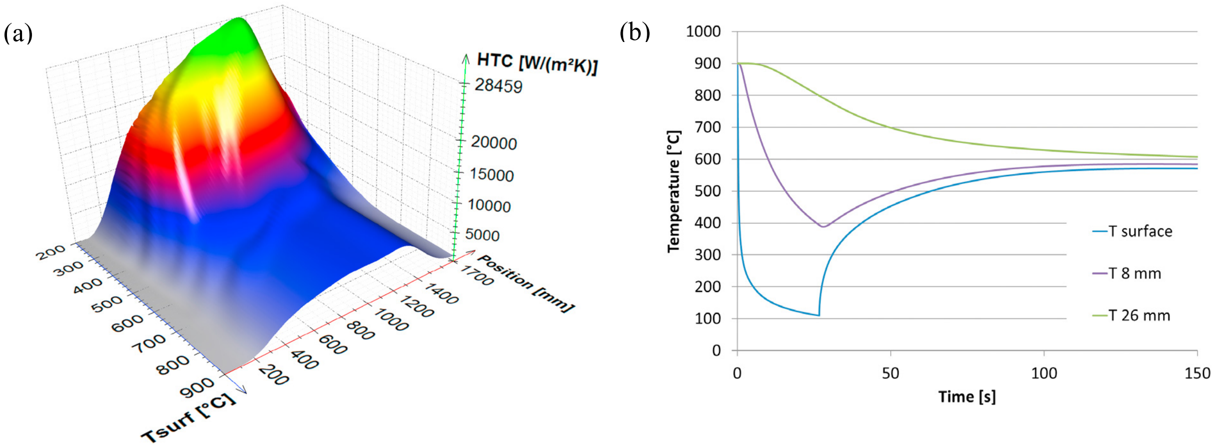


Fig. 3. (a) Example of heat transfer coefficients boundary condition (HTC) as function of surface temperature and position; (b) Example of simulated temperatures in various depths from sprayed surface.

2.4. Fourth stage – verification of the simulations in laboratory or mill conditions

The design of cooling section is known so the last stage of laboratory research is verification of obtained results. HeatLab developed an experimental device termed Carousel (Fig. 4). This device allows simulating the full scale heat treatment proces in laboratory conditions. The linear movement of real product (in steel mill) is converted to the rotation movement. Carousel testing device is compound of heater, rotating arm, which holds the sample, and cooling section, which enables spraying with two different nozzle sizes (hard cooling and then soft cooling).

An experiment starts with heating of the real material sample (typical dimensions for flat product are 100 x 100 x 5 - 20 mm) to the initial temperature higher than A_{C3}. Then this temperature is hold for required time. Nitrogen is blown to the furnace during heating and soaking to prevent scales occurring. Afterwards the heater is opened and the sample is moved to the cooling position. The rotation velocity is set. Pneumatically driven deflector is removed and the water sprays on the sample surface. Two nozzle sizes could be used during this experiment. Bigger size nozzles simulating hard cooling and smaller size nozzles simulating soft cooling. When the surface temperature is lower than 200 °C the cooling is immediately switched from hard to soft cooling. Heat treated samples are taken for measurements of hardness and other mechanical properties – tensile tests, Charpy pendulum tests, etc.

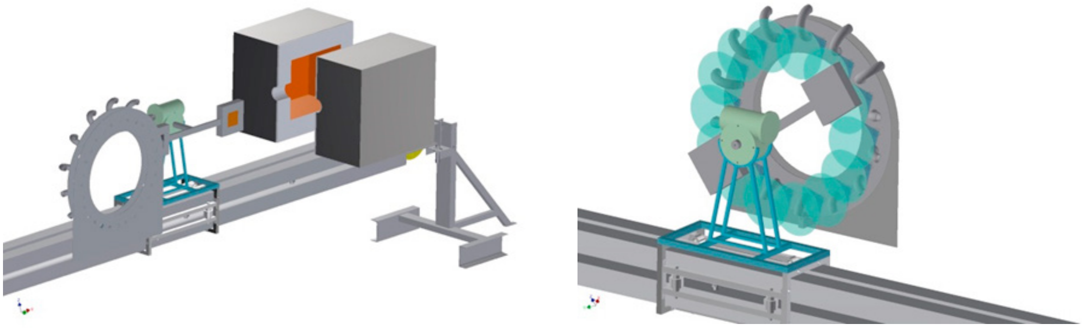


Fig. 4. Scheme of Carousel testing device.

Another possibility of verification simulations is measurement in mill conditions. The real sample (e.g., eight meters long tube) is embedded by thermocouples in defined positions (Fig. 5(a)). It is heated to the prescribed temperature and moved through the prototype of cooling section (usually in pilot mill – Fig. 5(b)). Measured temperatures are compared with computed temperatures. This kind of verification is more expensive but it allows optimization of cooling process in real mill conditions with respect to costs, energy and water savings.

(a) (b)

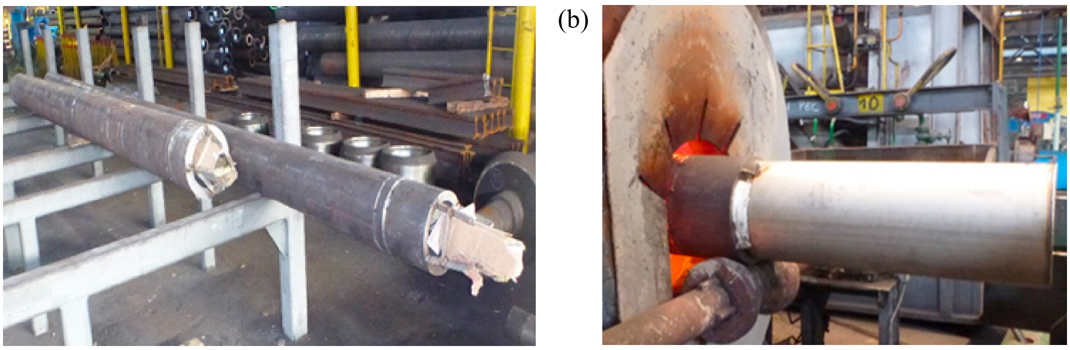


Fig. 5. (a) Example of tube real mill samples embedded by thermocouples; (b) tube sample moving to furnace.

When the cooling process is verified by material properties tests the cooling section could be produced and installed in the steel mill.

3. Improvement of 1.0577 mechanical properties

The target of this project was to improve mechanical properties of 1.0577 (S355J2) mechanical properties by heat treatment with respect to ration between tensile strength [MPa] and elongation [%]. The chemical composition of tested material is written in Table 1.

Table 1. Chemical composition of tested 1.0577 (S355J2) steel in [%].

C	Mn	Si	P	S	CU	Cr	Ni	Al	Mo	V	Ti	CEQ
0.17	1.36	0.36	0.012	0.012	0.05	0.06	0.006	0.031	0.006	0.002	0.0017	0.41

HeatLab methodology described in Chapter 2 was used. The first stage was focused on a study of appropriate cooling regime. The temperature of 600 °C was chosen by metallurgists as a self-tempering equalization temperature. It means that final temperature of the sample in the whole body should be as close as possible to 600 °C. Modified Jominy tests were done to compare the material hardening capacity with hardness obtained by chosen cooling regime. The samples size was 60 x 60 x 40 mm. Comparison of measured temperatures and hardness are shown in Fig. 6.

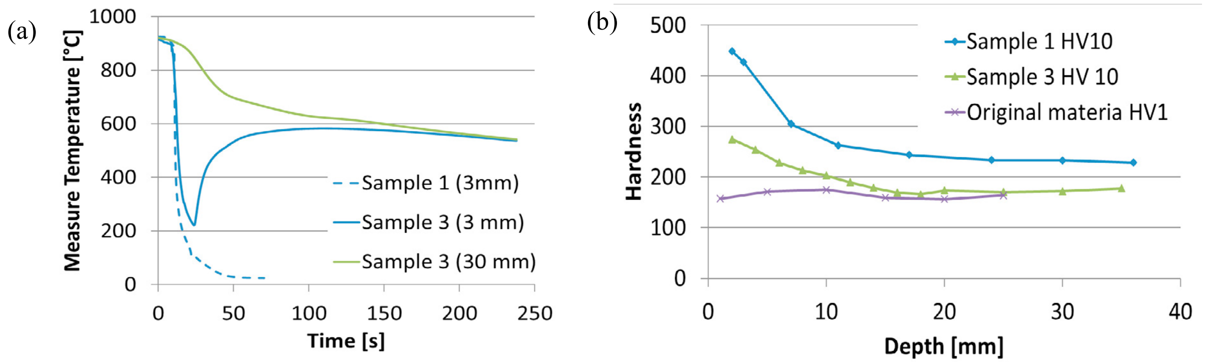


Fig. 6. (a) Measured temperatures in various depths from sprayed surface for various cooling regimes, (b) Comparison of material hardness for original and heat treated samples – static modified Jominy tests.

Second stage was focused on the creation of heat transfer coefficient database for simulation of real cooling process. This procedure is described in chapter 2.2. The example of influence of the water pressure (flow rate) on the heat transfer coefficient is shown in Fig. 7.

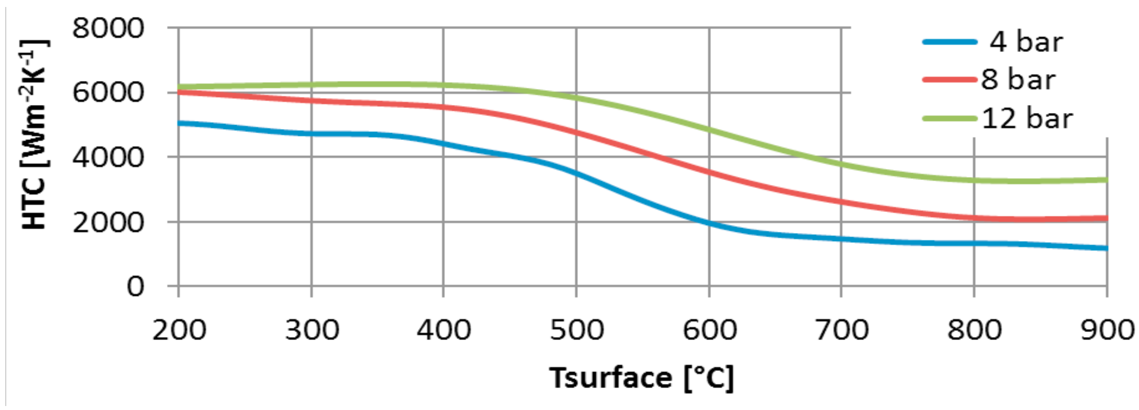
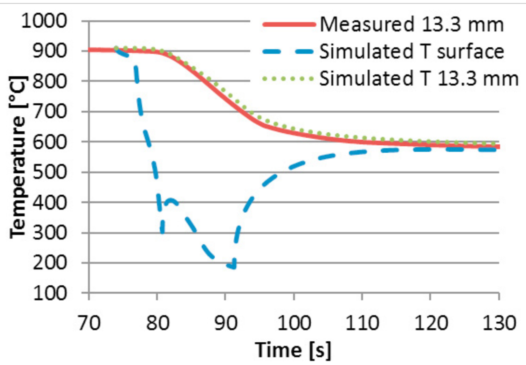


Fig. 7. Example of heat transfer coefficient (HTC) dependence on surface temperature for various cooling pressures (flow rates).

Numerical simulations of required cooling regime followed and first design of cooling section was done (water pressure, nozzles type and sizes were chosen, etc.).

Results of numerical simulations were verified in laboratory conditions using Carousel stand (chapter 2.4). Real (1.0577) samples were produced with different thickness (100 x 100 x 5, 12, 20 mm). They were also embedded by thermocouples. One side of these samples was sprayed by water and other sides were insulated. High cooling intensity was required and the target final temperature in the whole body was around 600 °C. Two nozzle size system was simulated. Hard cooling (big size nozzles) was after 4 seconds switch to soft cooling (small size nozzle) for 10.5 seconds. This test was done twice. Comparison of predicted and measured temperatures of the 20 mm thick sample is shown in Fig. 8(a). A Hardness was measured also using Innova durometer (Vickers). Results are shown in Fig. 8(b). The hardness in depth of 2 mm increased from 160 HV10 (original material) to 260 HV10.

(a)



(b)

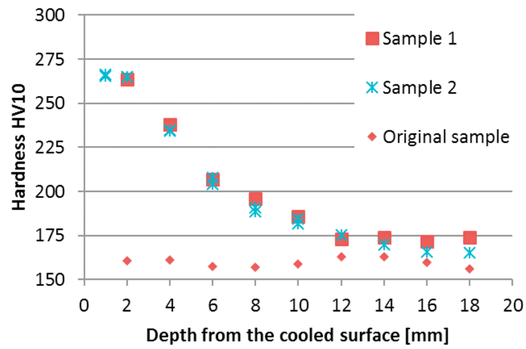
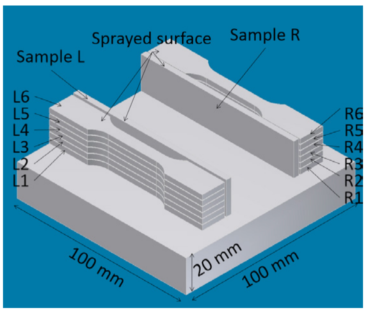


Fig. 8. (a) Comparison between computed and measured temperatures; (b) comparison of measured hardness on heat treated samples and original material sample.

The hardness profile of heat treated materials was heterogeneous – the surface was harder than centre of the sample. First heat treated sample was cut to pieces for tensile testing in various depths (scheme is shown in Fig. 9(a)). Zwick Z250 machine was used for tensile testing. First tested sample was made of original material (sample OL1). The yield strength of this material was around 350 MPa and tensile strength was around 520 MPa. Another heat treated sample termed L was tested. The hardness closed to sprayed surface was 275 and 171 HV10 on the rear side. This sample cracked in tensile test machine jaws (Fig. 9(b)). The yield strength was around 500 MPa for this sample (Fig. 10(a)).

(a)



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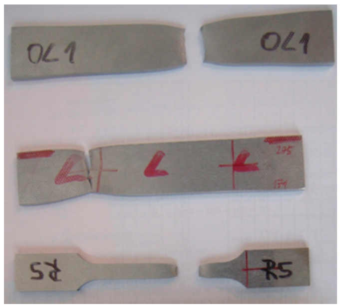

Fig. 9. (a) Scheme of cut heat treated sample, (b) Example of samples after tensile tests.

The heat treated sample was cut again and sliced to 6 pieces. (R1 – R6) - dog bones were made. Sample R6 was the closest to the sprayed surface and R1 was in the centre (Fig. 9 (a)). Results of these dog bones tensile tests are shown in Fig. 10(b). The maximal tensile strength was measured for sample R6 and it was around 825 MPa. The minimal yield strength increased to a value of 400 MPa. The minimal tensile strength increased to a value of around 570 MPa.

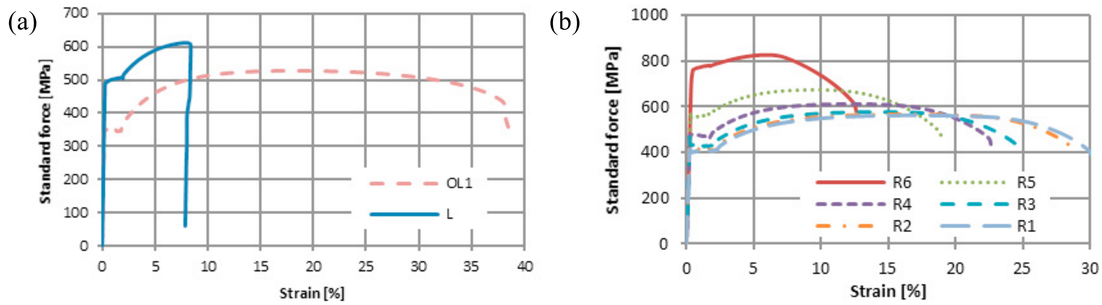

Fig. 10. (a) Tensile tests results, OL1 – original material, L- heat treated sample with heterogeneous hardness; (b) tensile tests results, R1 – R6 heat treated samples (dog bones), R6 – closer to surface, R1 centre of sample.

Second heat treated sample was cut for Charpy pendulum tests. The scheme of samples sizes is shown in Fig. 11 (a). All samples were cooled down to -20 °C and then were immediately broken by the pendulum of PsD 150/300 machine. Results are shown in Fig. 11 (b). Experiments O1 and O2 represents the original material and samples 3 and 4 represents heat treated material. The final pendulum energy was 50 J for original material and 150 J for heat treated material.

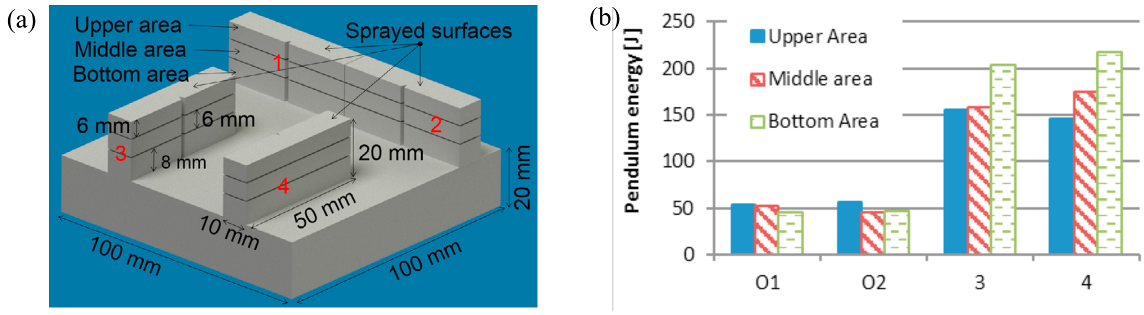

Fig. 11. (a) Scheme of cut samples for Charpy pendulum tests; (b) Results of Charpy pendulum tests for original (O1,O2) and heat treated material (3,4).

4. Conclusion

A material 1.0577 (S355J2) is a standard carbon steel used often in building engineering. The target of this project was to improve mechanical properties of 1.0577 steel by heat treatment with respect to the ratio between yield strength and elongation. Metallurgists chose the temperature of 600 °C as a self-tempering equalization temperature. It means that final temperature of the sample in the whole body should be as close as possible to 600 °C. The HeatLab methodology was used for improving material properties. Results of modified Jominy tests showed significant improve of hardness up to a depth of 12 mm from the sprayed surface. The maximal difference between original and heat treated sample was measured close to the sprayed surface. It was around 100 HV10, increase from 165 HV10 to 265 HV10. Afterward the heat transfer coefficient database was created by extensive dynamic experimental work. Nozzle positions, nozzle sizes, different flow rates etc. were tested. Heat transfer coefficients boundary conditions were used for numerical simulations for wide range of rolled product (different sizes, materials, rolled velocity etc.). First design of cooling section was done based on the cooling simulations results. The cooling regime was verified by another series of full scale tests using Carousel stand. Two 20 mm thick samples were cooled down by spraying water to final equalization temperature of 600 °C. These samples were insulated from sides and rear side so the water sprayed only on the top surface of the sample. Both samples were under metallurgical testing. Hardness of original material was 160 HV10. Hardness of heat treated material was decreasing form the sprayed surface (265 HV10) to the depth of 12 mm (175 HV10) and then was almost constant to depth of 20 mm. Tensile strength tests followed.

Yield strength of the original material was 350 MPa and tensile strength was 500 MPa. Heat treated sample was sliced to six pieces of dog bones along the thickness. The yield strength and tensile strength were improved significantly. The maximal yield strength was around 750 MPa and tensile strength was 825 MPa. The minimal yield strength was improved to 400 MPa and tensile strength was improved to 570 MPa (dog bones near to the center of the heat treated sample). Finally, Charpy pendulum tests were done. The temperature of tested samples was -20 °C. The pendulum energy was around 50 J for original material. Heat treated samples were again sliced to three pieces along the thickness. The pendulum energy increased to 150 J for heat treated samples.

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