IN-LINE HEAT TREATMENT OF LONG PRODUCTS

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Abstract

An in-line heat treatment of rolled materials is becoming frequently used by hot rolling plants. This method achieves the required material structure without the necessity of reheating.

This paper describes a design procedure of cooling sections for obtaining the demanded structure and mechanical properties.

An experimental stand, applied for the cooling study of steel samples, was built at the Brno University of Technology. The stand carries a movable trolley with a tested sample. The sample moves under the spray by a given velocity. The sensors indicate the temperature history of the tested material. This experimental stand enables to simulate a variety of cooling regimes and evaluate the final structure of the tested samples. The same experimental stand is a tool for the design of the cooling sections which can ensure obtaining demanded heat treatment procedure and demanded final structure. The HTC history at the surface is reached as an output of inverse task. Cooling examples of rails and tubes are presented in the paper.

Keywords: Heat treatment, hot rolling, spray cooling, heat transfer coefficient, final structure

1. INTRODUCTION

Microstructure and nature of grains, grain size and composition determine the overall mechanical behavior of steel. Heat treatment provides an efficient way to manipulate the properties of steel by controlling the cooling rate. The way of heat treatment depends on many aspects. One of the most important parameter is the amount of production. Another important parameter is the size of products. We focus here on large production such as cooling of long products at the exit from a rolling mill, cooling of rails, tubes and special profiles. Such a treatment is called in-line heat treatment of materials and has become frequently used by hot rolling plants. This method achieves the required material structure without the necessity of reheating. In-line heat treatment is characterized by running of hot material through the cooling section. However, many of discussed topics can be applied on smaller production as well.

The design procedure of cooling sections for obtaining the demanded structure and mechanical properties is iterative research involving several important steps. We begin with the Continuous Cooling Transformation (CCT) diagram for the selected material. Numerical simulation of cooling follows to find appropriate cooling intensity and its duration. Knowing the desired cooling intensity new cooling section is designed and tested under the laboratory conditions. From the laboratory experiments boundary conditions are obtained and tested using a numerical model [1]. When the best solution is found it is tested on the real sample and the result structure is studied. In most cases the process must be repeated as the CCT diagram is aimed at a different size of the sample and the cooling rate in the designed section is not constant.

2. STRATEGY OF DESIGN

When preparing a design of the cooling system for the continuous heat treatment, we should know the optimum cooling regime for the material and the product [2]. Any continuous heat treatment process needs to vary the cooling intensity with time. Moreover, the practice has shown that the results obtained by using small samples (usually for the CCT diagram) are usually different from the results achieved when using real products of a large cross-section because it is not possible to achieve the identical temperature regimes in the whole volume due to the low diffusivity. We cannot expect same behavior on product as on the small sample. There are varieties of technical methods for hot steel cooling; one of them uses the spray cooling. The cooling section should ensure reaching a required temperature history in the cooled piece prescribed by the metallurgists. The nozzles applied allow controlling the cooling over a wide range.

3. THE MAIN PARAMETERS INFLUENCING COOLING INTENSITY

3.1 Leidenfrost effect and its impact

It should be understand that intensity of cooling strongly depends on the surface temperature. So called Leidenfrost effect can be observed above certain temperature. During this effect a liquid, which is near significantly hotter object than the liquid's boiling point, produces vapor layer which insulates the liquid from the hot object and keeps out that liquid from rapid boiling. This is because of the fact that at temperatures above the Leidenfrost point, the part of the water, which is near hot surface, vaporizes immediately on contact with the hot plate and the generated gas keeps out the rest of the liquid water, preventing any further direct contact between the liquid water and the hot plate. The temperature at which the Leidenfrost effect begins to occur is not easy to predict. It depends on many aspects. Ones of them are velocity and size of droplets. As a rough estimate, the Leidenfrost point might occur for quite low temperatures such as 200 °C. On the other hand for high water velocity the Leidenfrost point can be even above 1000 °C. 0 shows measured heat transfer coefficients (HTC) for water-air mist nozzle.

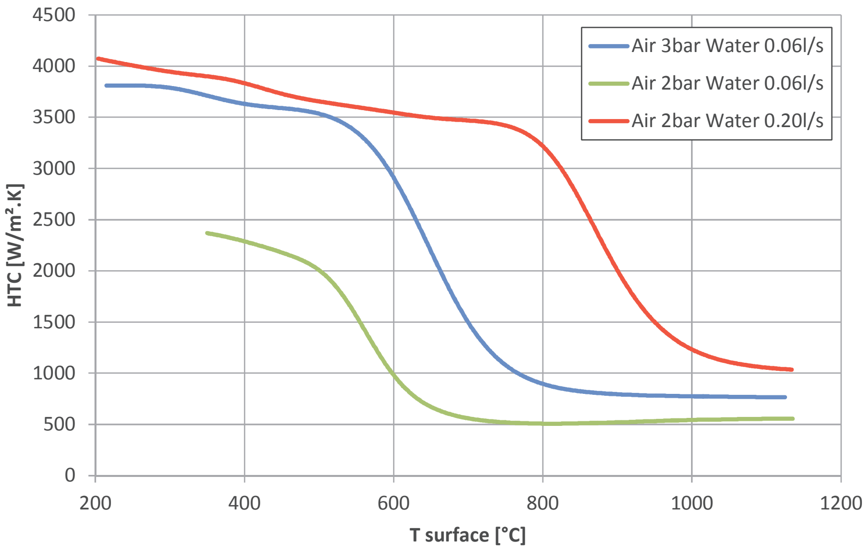


Fig. 1 Moving Leidenfrost point for water-air mist nozzle and various water and air conditions

Graph shows three measurements for same nozzle using varying water and air parameters. Three regimes can be found. The first one is for low temperatures when the HTC is relatively high and decreasing slowly. This part is below Leidenfrost point. From certain temperature HTC decreases rapidly. This is a transient regime in which some droplets are above Leidenfrost point and some are below that point. For the last regime HTC is relatively low and is constant or may be increasing due to the increasing radiation with the increasing surface temperature. Designed cooling section should work in the first regime for low temperatures or in the third regime with almost constant HTC. It is strongly recommended to avoid the second transient regime as the product surface temperature is not usually at uniform temperature. Due to the strong dependency of HTC on surface temperature non homogeneous cooling is achieved and causes distortion of the product.

3.2 Nozzle types and controllability

Nozzle produces usually one of three typical sprays: flat-jet, full-cone, and solid-jet. However, other shapes can be found such as hollow-cone, square, spiral etc. An important parameter is controllability of the cooling section and intensity of cooling. The water-air mist nozzles can be used for a soft cooling and a wide controllability range (see **Fig. 2**).

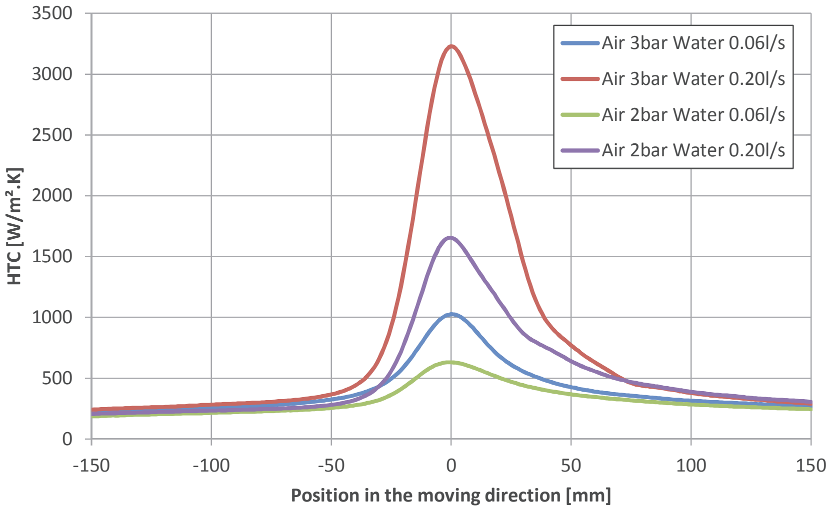


Fig. 2 Controllability of water-air mist nozzle for surface temperatures 1000 °C

The HTC can vary from several hundreds of W/m².K up to several thousand of W/m².K. Water-air mist nozzles are not the cheapest ones and also the pressurized air is expensive in terms of power consumption. Water-only nozzles can often provide a lower cost solution. Small full-cone nozzles with high pressure and bigger distance from surface can provide also very soft cooling. On the other hand with high pressure flat-jet or solid-jet nozzles at small distances HTC over 50000 W/m².K can be obtained even for high surface temperatures (see **Fig. 3**). This results in enormous heat flux above 50 MW/m². The distance of the nozzle form surface is very important in this case for flat-jet nozzles because for 100 mm the HTC can be 50000 W/m².K but for 1000 mm it can be similar to water-air mist nozzle.

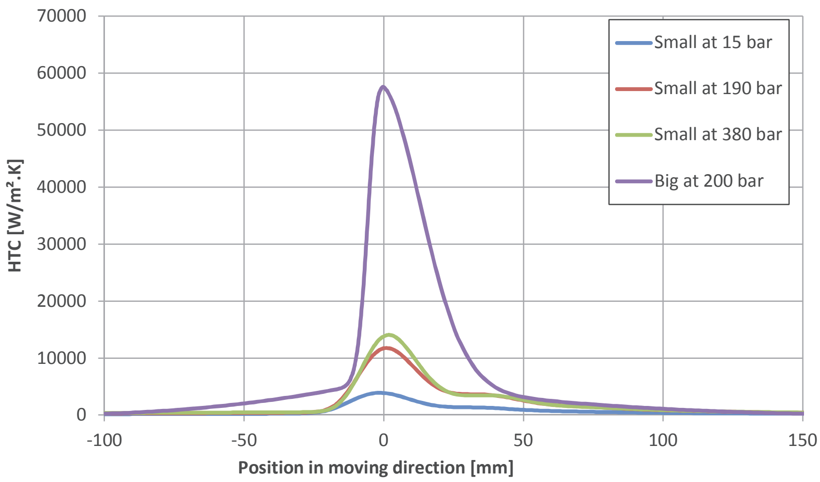


Fig. 3 Distribution of HTC under spray for high pressure flat-jet nozzles for surface temperature 1000 °C

4. COOLING INTENSITY AND NUMERICAL MODELS

In order to design a cooling section, knowledge of the cooling intensity is required for a group of nozzles and nozzle headers. Exact knowledge of the heat transfer coefficient as a function of spray parameters and surface temperature is the key problem for any design work. The cooling intensity is a function of several parameters, mainly, nozzle types, chosen pressures and flow rates, surface temperature of a material, and velocity of a material movement whilst under spray. There is no function available which describes cooling intensity using all the mentioned parameters. This is the reason why real measurement is absolutely necessary. An example of numerical simulation for different cooling strategy is demonstrated in **Fig. 4**.

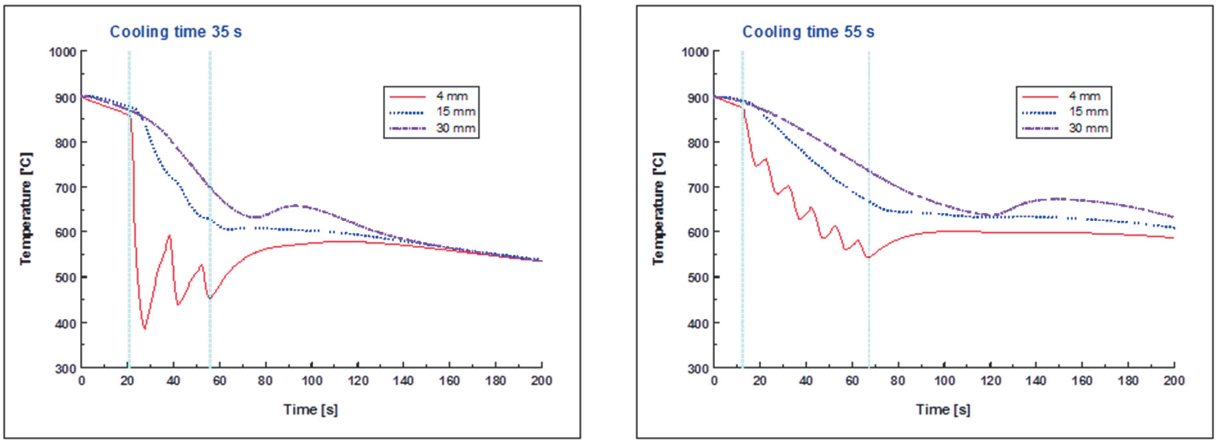


Fig. 4 Results of numerical model - temperature on the depth of 4, 15 and 30 mm, two different cooling times

5. DESIGN OF COOLING SECTION

Based on previous measurement of nozzle cooling characteristics (HTC) and numerical simulation of various cooling strategies, cooling section can be designed. **Fig. 5** shows design of laboratory cooling unit used for rail head cooling.

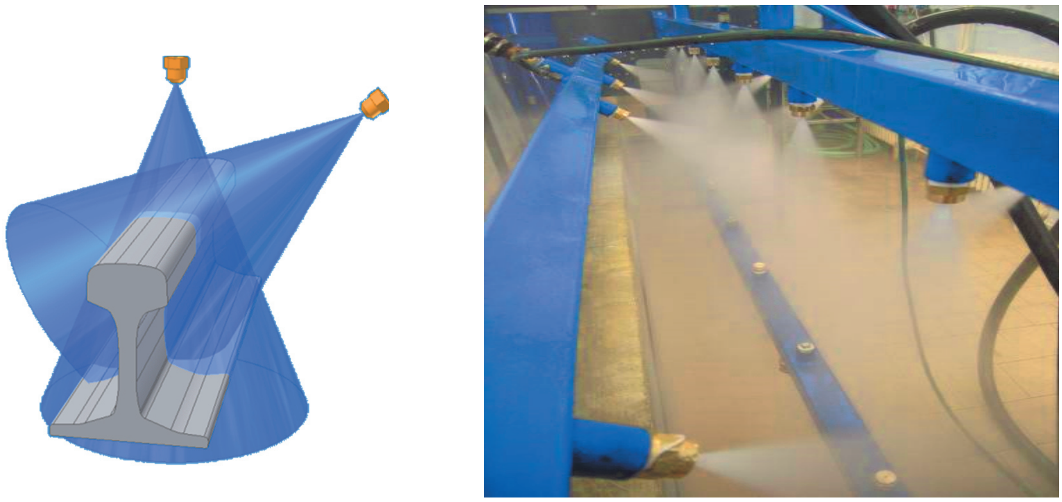


Fig. 5 Laboratory cooling unit used for rail head heat treatment

6. VERIFICATION AT A PILOT TEST BENCH

A pilot laboratory test bench is designed for full-scale material samples [3, 4]. A piece of tube, rail, wire or plate of real dimensions is instrumented with thermocouples and the cooling is tested. The length of a laboratory test bench (**Fig. 6**) is limited, hence the sample must be accelerated at the test start, to a velocity normally used in a plant, and after reaching the end of its run under the cooling section, direction of movement is reversed. In this way, the sample moves several times under the cooling sections. This process of cooling is controlled to simulate running under the long cooling section used normally in the plant. Nozzles, pressures, and header configurations are tested. The design of cooling and the pressures used are modified until the demanded temperature regime is obtained. The full-scale material samples are then cut for tests of material properties and structure.

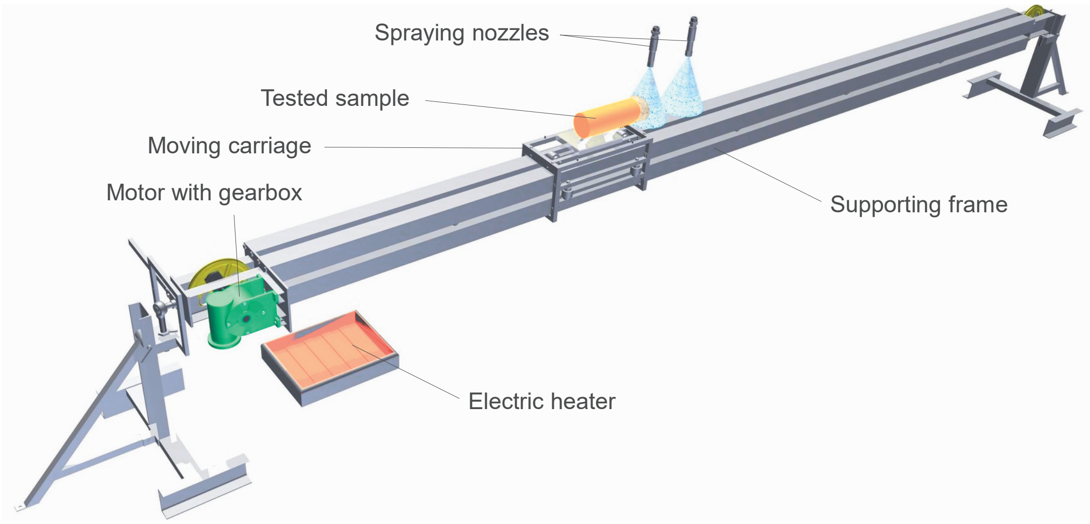
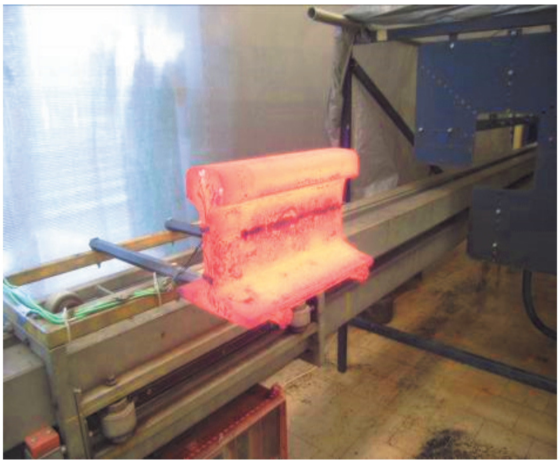


Fig. 6 Laboratory test bench



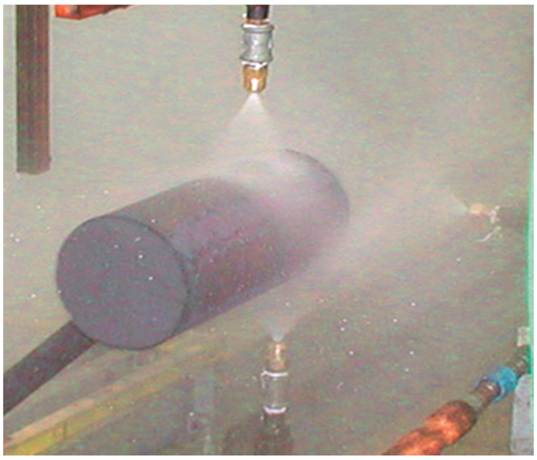
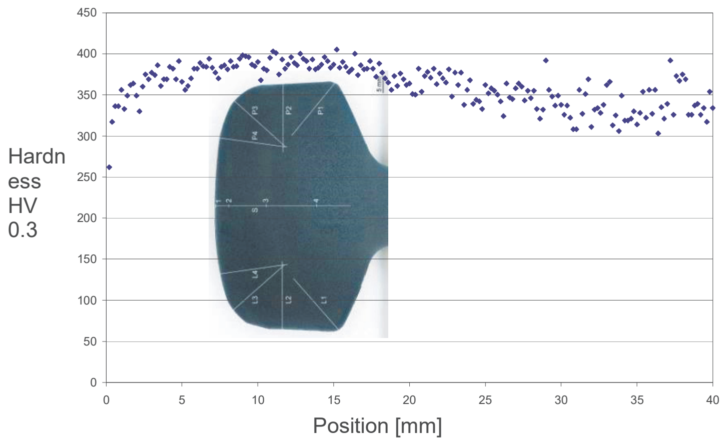


Fig. 7 Samples of rail and tube ale positioned on movable trolley at linear test bench and runs through cooling sections

An example of result after optimization of heat treatment is shown in **Fig. 8**. The material structure is full pearlite - as required for this product.



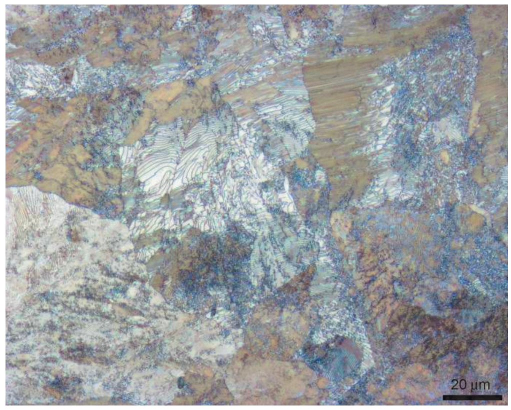


Fig. 8 Measured hardness in axis of rail for optimized cooling strategy and final pearlit structure

CONCLUSION

The design of cooling sections used for in-line heat treatment for hot rolling plants is very extensive work. It utilizes laboratory measurement, numerical modeling, inverse computations, and also pilot mill tests. The first step is the search of the best cooling regime for steels for which this is not yet known. The second step is to obtain a selection of technical means in order to guarantee obtaining the prescribed cooling rates. Nozzle configurations and cooling parameters are selected and controllability of the cooling section is checked. The final step of the design is a laboratory test using a full size sample simulating plant cooling. Design based on laboratory measurement therefore minimizes the amount of expensive experimentation performed directly on the plant. Elimination of potential errors and enabling adjustment of control models in the plant is possible after the cooling process is tested in laboratory conditions.

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