# HEAT TREATMENT OF TUBES

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**Abstract**

This paper describes a design procedure of cooling sections for the heat treatment of tubes. Two experimental stands used for cooling studies of steel samples were built at Brno University of Technology. The first experimental stand allows researchers to simulate a variety of cooling regimes and evaluate the final structure of test samples. These samples have installed a set of thermocouples, which indicate temperature history of the tested material. The second experimental stand is used for the design of the cooling sections which can obtain a desired heat treatment procedure and final structure of a real sample.

**Keywords:** Heat treatment, spray cooling, heat transfer, tube

## 1. INTRODUCTION

The microstructure and nature of grains, grain size and composition determine the overall mechanical behaviour of steel. Heat treatment provides an efficient way to manipulate the properties of steel by controlling the cooling rate. The method of heat treatment depends on many parameters. One of the most important parameters is the amount of production. Another important parameter is the size of products. We focus on large productions, such as cooling of tubes at the exit of a rolling mill. This treatment is called in-line heat treatment of materials and has become quite common in hot rolling plants. However, many of the topics discussed can be applied to smaller-scale production as well.

The design procedure for cooling sections which obtain the desired structure and mechanical properties is an iterative process involving several important steps [1]. It begins with the Continuous Cooling Transformation (CCT) diagram for the selected material. Next, numerical simulation of the cooling is used to find the appropriate cooling intensity and its duration. With this information, a new cooling section is designed and tested under laboratory conditions. From laboratory experiments, boundary conditions are obtained and tested using a numerical model [2]. When the optimal solution is found, it is tested on a real sample and the resulting structure is studied. In most cases, the process must be repeated as the CCT diagram is aimed at a different sample size and the cooling rate in the designed section is changed.

## 2. EXPERIMENTAL DETERMINATION OF SPRAY COOLING INTENSITY AND THE CREATION OF A DATABASE OF NOZZLE SPRAY COOLING INTENSITIES

Sprays are commonly used for product cooling in metallurgical industry nowadays. There are several types of nozzles like full cone, flat fan or mist nozzles, which produce wide range of sprays. The cooling intensity of a spray is a function of several parameters, including nozzle type, flow rate [3], [4], pressure, water temperature [5], surface temperature of a material, and velocity of a material movement under the spray [6]. There is no function available which describes cooling intensity using all of the aforementioned parameters and so measurement is the only way to determine the spray cooling intensity. Measurements of the cooling intensity for different nozzles types, pressures and positions of nozzles headers lead to creation of a database of nozzles cooling intensities. This database is useful for the suitable choice of a size of the nozzles, feeding pressure and positions of nozzle headers for next step, the quenching tests.

The determination of the spray cooling intensity consists of several steps: preparation of the experiment, experimental measurement, calculation of boundary conditions and evaluation of computed results.

### 2.1. Experiment

The experimental procedure starts with the manufacture of the test sample and the embedding of thermocouples within the test sample. The test sample is mounted to the experimental apparatus (**Fig. 1**) and is then heated to the desired temperature. Once the test sample is heated, the spray is started. When the cooling conditions are adjusted the data-logger begins to record temperatures at the thermocouples and the sample, which is mounted on a trolley, passes through the cooling section repeatedly. When the sample is cooled, recorded data is transferred to a computer and evaluated. After measurement, the inverse heat conduction problem is used to compute time-dependent boundary conditions: the heat transfer coefficient (HTC), heat flux and surface temperature. Beck's sequential approach is used ([7], [8]). This method uses a sequential estimation of the time-varying boundary conditions and future time steps.

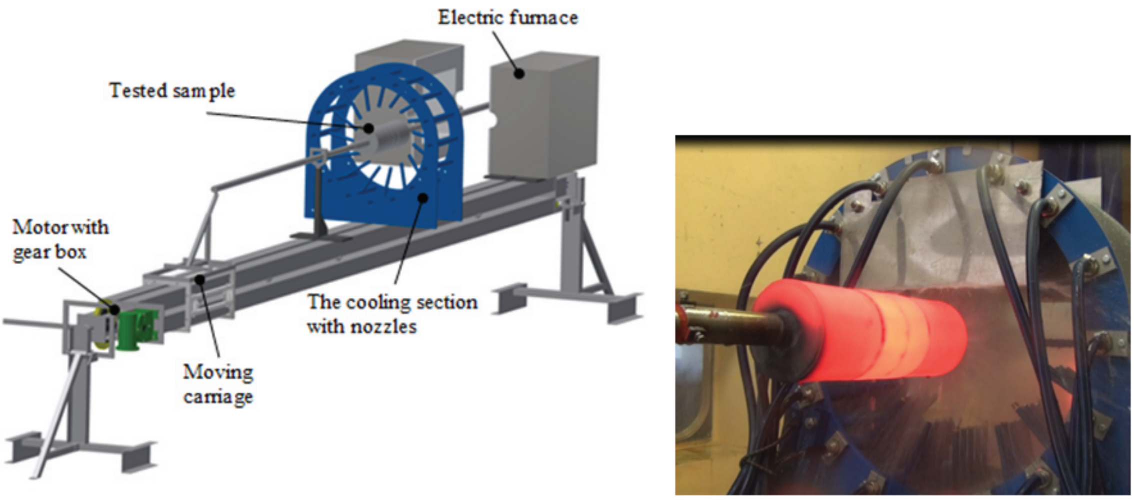


**Fig. 1** Laboratory test bench and a photo of a tube running to the cooling section

### 2.2. Results

The measured time-dependent temperature is used as input for the inverse heat conduction problem and the time-dependent surface temperature, heat flux and heat transfer coefficient are obtained (**Fig. 2**). Furthermore, the dependence of the heat transfer coefficient on the surface temperature and position in the cooling section is obtained. The average value of the heat transfer coefficient along the position (between first and last nozzle) is shown in **Fig. 3**.

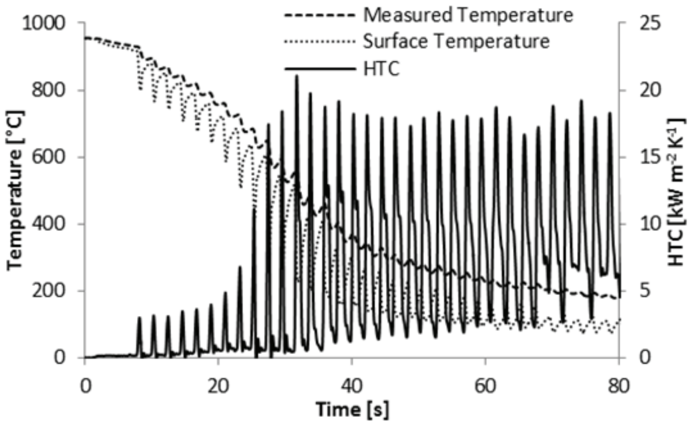


**Fig. 2** Example of measured temperature, computed surface temperature and heat transfer coefficient (HTC) depending on time

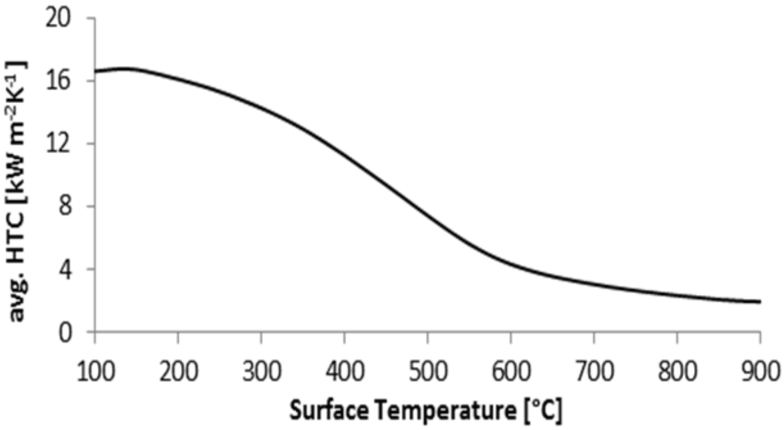


**Fig. 3** The dependence of the average heat transfer coefficient on the surface temperature

## 3. FINDING THE OPTIMAL COOLING REGIME

It is necessary to achieve the desired cooling regime to obtain the required mechanical properties of the final product. The numerical prediction of hardness and microstructure can serve as initial information about the required cooling regime. Tests using industry conditions are ideal for validating the predicted hardness and microstructure. However, tests using industry conditions are very expensive and therefore it is more suitable to conduct tests with smaller samples in a laboratory. The scale factor is important and the sample should have the same thickness and shape as the final product. The type of nozzle and feeding pressure are the parameters used to define the resulting cooling intensity which will create the required material structure. The experimental apparatus is able to cool the sample across a wide range of regimes. The cooling regime can be modified until an optimal material structure is achieved.

### 3.1. Numerical prediction of hardness and microstructure

With chosen nozzles configuration and information about its cooling intensity the prediction of hardness and microstructure after quenching can be done by the CCT diagram or software QTSteel [9]. This software can be used to numerically predict the metallurgical processes running during cooling regimes. It is an off-line tool for calculating the microstructure and mechanical properties of various samples after hardening and subsequent tempering. If the CCT diagram of chosen material is unknown, the quenching tests must be done to obtain the information about the hardness and microstructure. If the prediction of the hardness and microstructure is possible, the quenching experiment should be done to validate the prediction.

### 3.2. Experimental apparatus and experimental process

A test bench was built to find the optimal cooling strategy for a given steel sample (**Fig. 4**). It was composed of an electric furnace, a nozzle, a rail with a moveable steel sample and a deflector. A steel sample with dimensions 50 x 50 x 62 mm was embedded with four thermocouples positioned at 3, 12, 21 and 50 mm beneath the cooled surface. The steel sample was heated to an initial temperature in an electric furnace with an inert atmosphere to avoid oxidation. The heated sample was then moved into the cooling position under the nozzle, a pneumatically-driven deflector was opened and cooling of the hot sample was started (**Fig. 4**). Temperatures at the given positions were measured using thermocouples and recorded by a data-logger during the experiment.

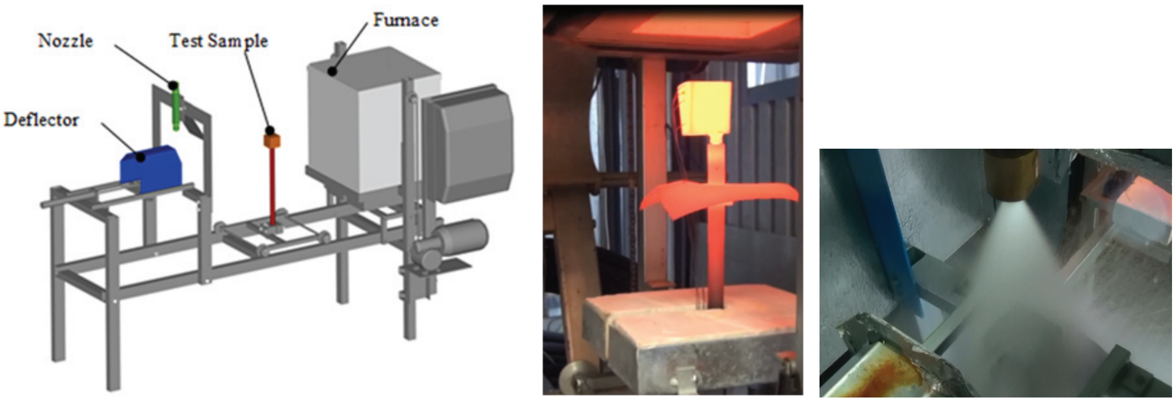


**Fig. 4** Diagram of the experimental apparatus and photos of the test sample after removal from the furnace and during cooling by the nozzle

### 3.3. Measured hardness and microstructure

The sample was cut after cooling and the hardness and microstructure were measured in the axis of the sample. The quenching significantly increases hardness and increases the content of the martensitic structure near the surface (**Fig. 5**). The martensitic structure was observed to a depth of 15 mm. Bainite, ferrite and pearlite were observed deeper in the material. The prediction of the CCT [8] diagram with cooling curves is shown in **Fig. 6**.

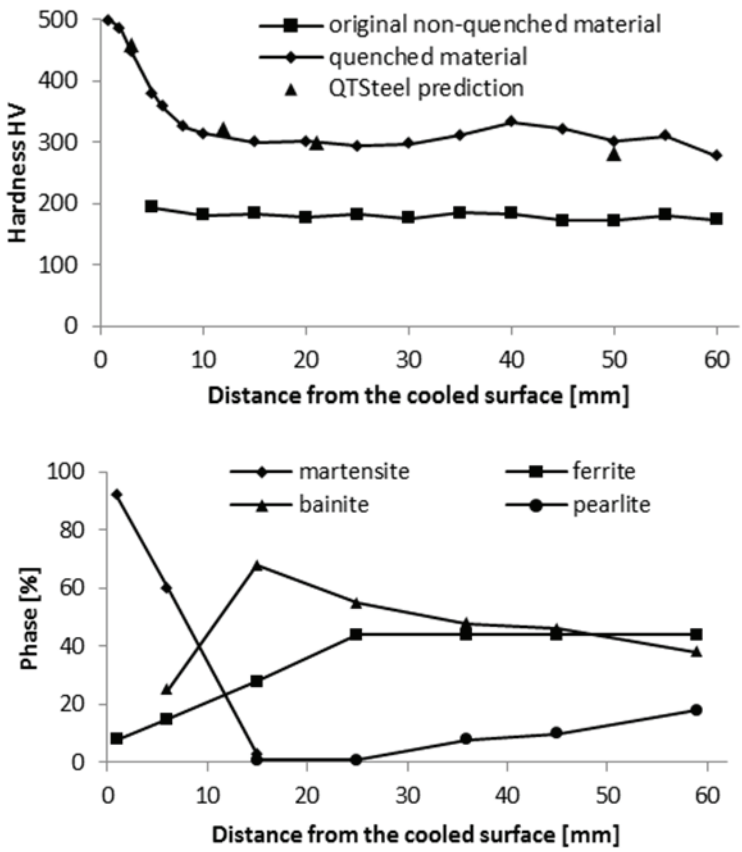


**Fig. 5** Measured hardness (quenched material - HV30, original material - HV 20) and prediction by the QTSteel software [9] (left) and measured microstructure composition (right)

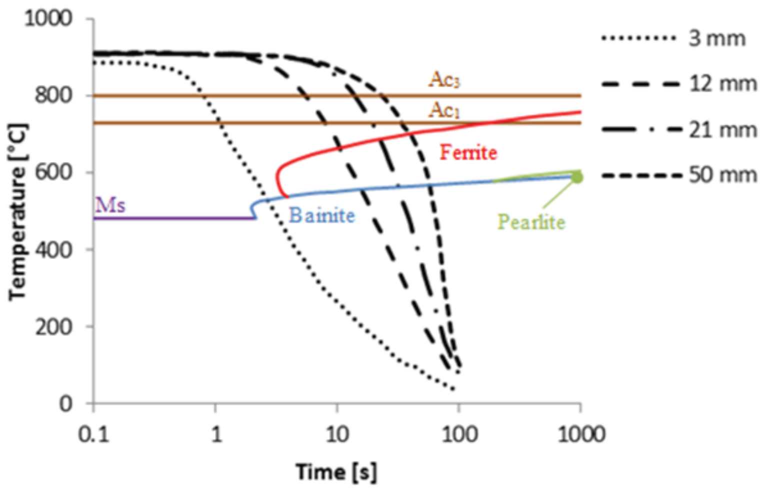


**Fig. 6** Predicted CCT diagram [9] with cooling curves measured 3, 12, 21, 50 mm below cooled surface

## 4. DESIGN OF THE COOLING SECTION

A cooling section can be designed based on previous measurements of nozzles cooling characteristics (HTC), microstructure tests with small samples and numerical simulations of various cooling strategies. An important factor which should be considered in the design of the cooling section is the homogeneity of the cooling. Inhomogeneous cooling can lead to inhomogeneous material properties and deformation of the final product.

Water distribution is the main factor influencing the cooling intensity and homogeneity. An example of the computed water distribution of the cooling unit used for tube cooling is shown in **Fig. 7**. Water distribution was computed by software developed in the Heat Transfer and Fluid Flow Laboratory.

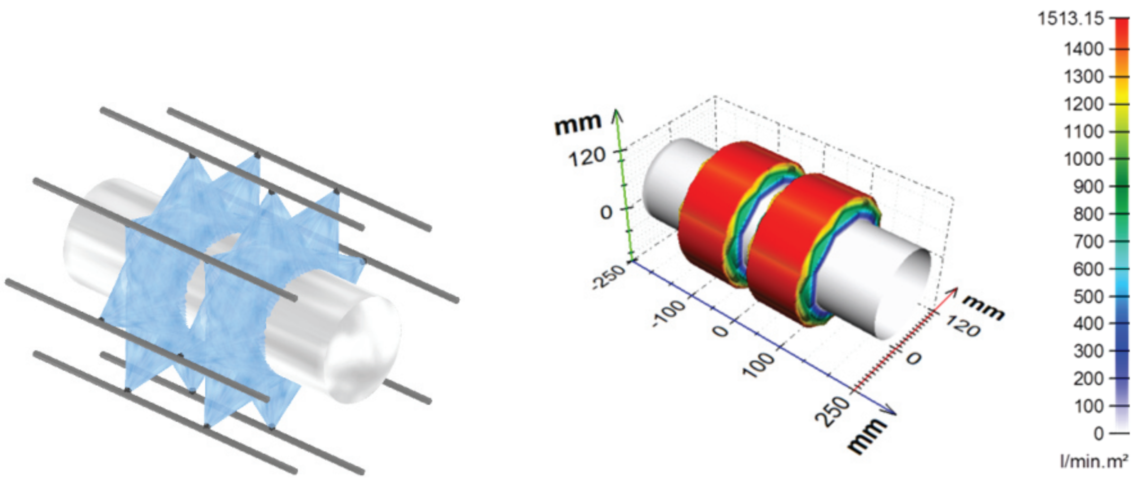


**Fig. 7** Visualization (left) and computed water distribution (right) of the cooling unit used for tube cooling

## 5. FINAL FULL-SCALE EXPERIMENT

A laboratory test bench (**Fig. 1**) is used for the experiment with full-scale material sample. The full-scale material sample of a tube is implanted with thermocouples and the cooling by the designed cooling section is tested. The length of the laboratory test bench is limited, therefore the sample must be accelerated to a velocity normally used in a factory before entering the tested cooling section, and after leaving the cooling section the direction of movement is reversed. In this way, the sample moves several times through the cooling section. This process of cooling is controlled to simulate running through a long cooling section normally used in a plant. The full-scale material sample is cooled by designed cooling section and then cut to test material properties and structures. The design of the cooling section and the pressures used are modified until the required temperature regime, microstructure and hardness are obtained with full-scale material sample.

## 6. CONCLUSION

The design of cooling sections used for heat treatment of tubes requires very extensive work. It utilizes numerical modelling, laboratory measurements and pilot mill tests. The first step is the identification of the best cooling regime for steels, which is not yet known. The second step is to obtain a selection of technical means in order to guarantee obtaining of 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. A design based on laboratory measurement therefore minimizes the amount of expensive experimentation performed directly at a plant.

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