DEVELOPMENT OF THE TUBE QUENCHING PROTOTYPE UNIT

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Abstract
This paper describes the stages of applied research and development leading to a functional prototype of a quenching unit. It became a part of a closed facility of process equipment for thermal treatment by refining and other methods of annealing of seamless steel tubes for the OCTG industry (Oil Country Tubular Goods), power engineering and mechanical engineering in Třinecké Železárny. The development of the prototype has been divided into several stages: mapping of the current state and critical assessment of the technical and technological level of the existing equipment in the Tube Mill, laboratory testing of tube samples cooling, including numerical simulations with the prediction of the initial settings of the process parameters for the recommendation of the technological configuration of the quenching unit prototype and finally a comprehensive technical design of the prototype quenching unit. The design of the prototype technical solution served as the basis for the creation of the detailed engineering documentation with the subsequent construction of the prototype quenching unit. The paper summarizes the procedures and results of individual development stages, including the results of measured temperatures of tubes during actual operation of the prototype and the results of additional numerical simulations of its actual cooling capacity.

Keywords: quenching, tube, simulation, CCT diagram, optimization

1 Introduction

The production base in the area of refined tubes production in Trinecke Zelezarny in response to market demands (OCTG, power engineering and partly mechanical engineering) is broad not only in terms of chemical composition of steels (currently 5 groups of microalloyed and low-alloy steels including 34 steel grades), but also in terms of dimensional variability with tube diameters of 168 - 406.4 mm and a wall thickness of 6.3 - 60.5 mm. The aim of the project was to design and manufacture a prototype QUENCHING UNIT that will ensure quenching of tubes along the length of the quenched tube with a minimum HRC range across the thickness of the tube wall (max. 3 - 5 HRC) and achieving a uniform homogeneous hardening structure and required mechanical properties after refining. The prototype design for pipe quenching is iterative research that took place in the following stages:

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A. Mapping of the current condition and assessment of the technical and technological level of the existing equipment in the Tube Mill operation based on the operational measurements of the process parameters of quenching (thermocouple measurement of temperatures during the process of heating to the quenching temperature and the quenching itself with the prediction of mechanical properties using the QTSteel software), evaluation of the required mechanical properties and microstructure before and after individual refining operations on the selected representatives.
B. Laboratory tests and numerical simulation of tube sample cooling in the Heat Transfer and Fluid Flow Laboratory (Heatlab) of FME BUT including the design of the initial settings of the quenching unit process parameters. Suitable types of nozzles, their placement and distances around the circumference of the collectors of the individual quenching sections have been designed and the effect of cooling on hardenability has been assessed. To support subsequent heat and metallurgical computer simulations, a heat transfer coefficient (HTC) has been determined for different cooling conditions.
C. Technological study prepared by ITA Ltd., Ostrava, which summarized the results of the calculations of the final metallurgical properties of the cooled tubes with the assessment of the effect of the transport speed on achieving the desired homogeneity and hardness range after quenching including the recommendations for the technological configuration of the prototype of the quenching unit [1].
D. Implementation of the final scheme of the technological configuration of the prototype of the quenching unit as a comprehensive Technical Design of the prototype QUENCHING UNIT in cooperation with BKB Metal. The new technical solution included the improvement of the furnace heating parameters, automatic control of heating of tubes to the quenching temperature in conjunction with the control of the quenching process itself, automatic hydraulic alignment of the hardening equipment and cooled tubes axes and implementing a closed water management system ensuring purity and stable temperature of cooling water. The technical design of the prototype served as the basis for the creation of the production documentation, followed by the construction of the prototype QUENCHING UNIT and its launching into trial operation in November 2016.
E. Testing of functionality and reliability of the QUENCHING UNIT. Currently the QUENCHING UNIT is in the stage of optimization of the technology of quenching of the established steel grades and development of the technology for the introduction of new steel grades and dimensional series for refining together with the development of the HT_TUBE_SETUP calculation model.

2 Laboratory research

The main task of the laboratory phase was to design a cooling ring configuration with a selected type of nozzles as a basic element of the quenching unit with respect to the dimensional variability of tubes and properly distribute the rings inside the quenching unit. To accomplish this task, Jomini tests with measurement of boundary conditions and calculation of the cooling curves and distribution of water on the pipe surface were carried out.

2.1 Modified Jomini tests

CCT diagrams (using literature sources as well as diagrams based on the chemical variability of the steel grades produced in TZ as outputs of earlier research tasks) were used to initially estimate cooling regimes with respect to the required mechanical properties. A suitable size and

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type of nozzle were selected based on the knowledge of the desired cooling intensity [2]. Hardness, cooling regimes and selection of nozzles were confirmed by numerical simulations and by a number of modified Jomini tests. The Jomini experimental equipment is shown in **Fig. 1**. The 40x40mm samples in **Fig. 2** with holes for thermocouples, manufactured from tubes of microalloyed steel grades (20MnV6), HSLA steels (X65Q) and low-alloy steel grades (42CrMo4) were tested in two regimes: outer surface cooling only and cooling on outer and inner surface of the tube. Samples were heated to 930°C and held at this temperature for more than 10 minutes. Heated samples were positioned under the nozzle and covered with a deflector until the required water pressure was set. After cooling to the required time the samples were covered with the deflector again. The hardness and microstructure of each sample was analyzed (Example shown in **Fig. 3)**.

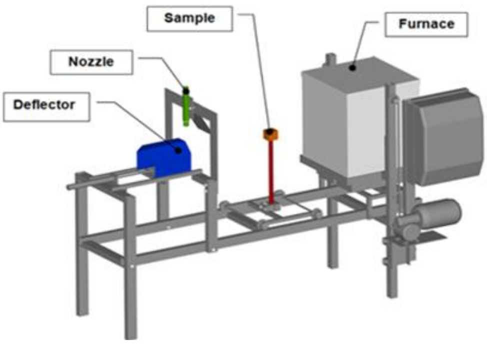

Fig. 1 Jomini experimental device

Fig. 2 Example of X65 sample after testing

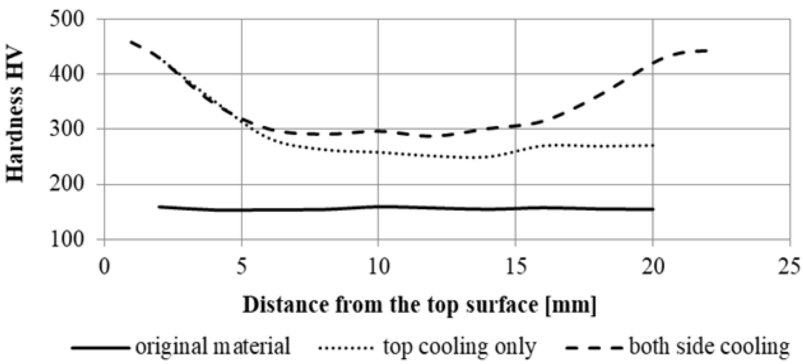

Fig. 3 Example of measured hardness – material X65Q

2.2 Boundary conditions measurement

A very important parameter to be considered is the homogeneity of cooling along the cross-section and the tube length. Non-homogeneous cooling could lead to heterogeneous mechanical properties and dimensional distortions of seamless tubes [3]. The HeatLab has developed a special analytical software to evaluate the distribution of water spray on the surface of the product, see **Fig. 4**. This analysis was also used for the preliminary design of the cooling part of the prototype quenching unit.

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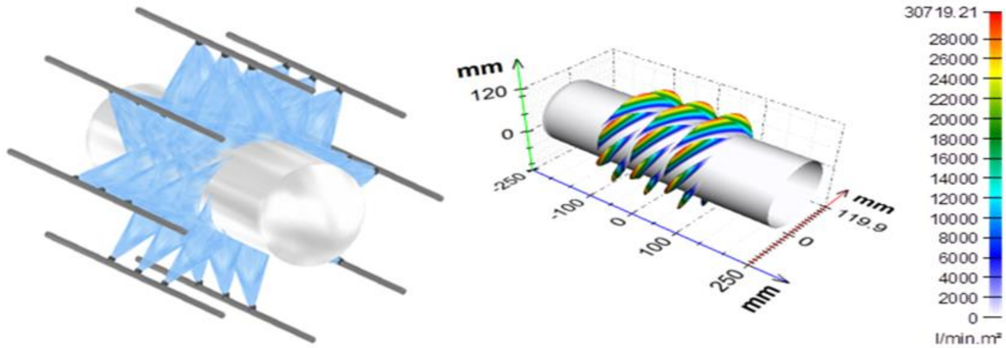

Fig. 4 Example of visualized (on the left) and computed (on the right) water distribution

To determine the HTC, a linear stand equipped with the segment of the designed cooling ring was used (**Fig. 5**). Two 400 mm long tube samples of a 160 and 300 mm diameter were covered by thermocouples. The sample at the austenitic temperature was passing through the cooling portion repeatedly until it was cooled down to the temperature M_f. Various types of nozzles, water pressures, transport speeds and ring configurations were tested. The measured temperatures were used for calculation of corresponding HTCs, see **Fig. 6** [4].

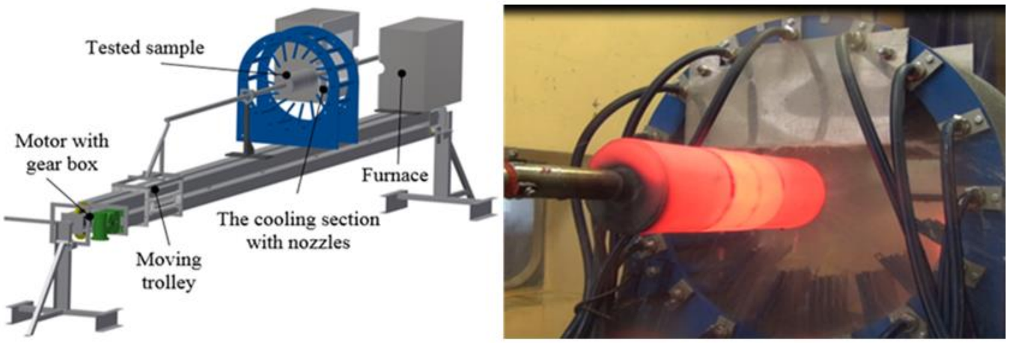

Fig. 5 Scheme of Linear stand (left) and tube sample moving to the cooling ring (right)

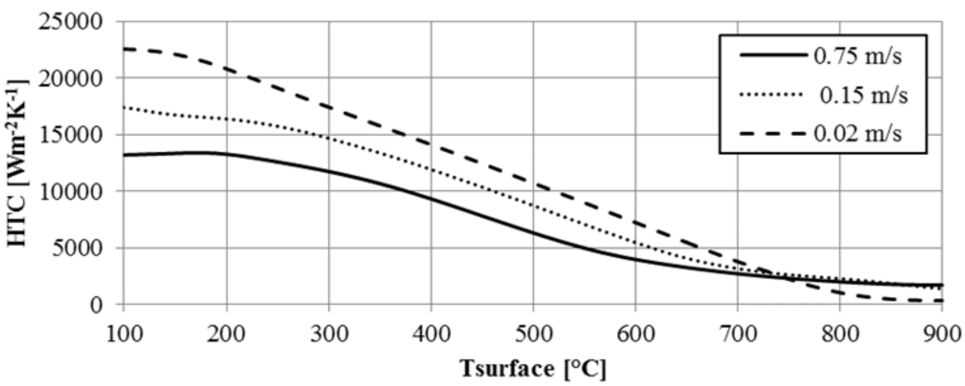

Fig. 6 Example of HTCs for different tube samples velocities

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3 Technological parametric study

With reference to the results of the laboratory tests, numerical simulations of different cooling strategies were carried out for the technical design of the quenching unit. Thermal and metallurgical predictions were made using the QTSteel software [1]. The results were summarized in a technological study containing clarified parameters of the quenching equipment and various technological strategies of optimal cooling of tubes of various sizes with the required properties. The Jomini test results described in Chapter 2.1 were used to verify the metallurgical prediction. The measured cooling curves were imported in the QTSteel software. Comparison of the predictions of the respective hardness was compared with the laboratory-measured values. An example for the sample made of 20MnV6 steel presented in **Fig. 7** confirms a good match.

To model the cooling capacity of the designed quenching unit QTSteel calculations were performed for tubes of given dimensions and grades to find out the number of active cooling sections and transport speed. The 1D FEM temperature module implemented in QTSteel with measured boundary conditions, see **Fig. 7**, was used for temperature calculations. An example of such numerical simulation for quenching of a tube 229x60 mm made of 20MnV6 steel cooled by two active zones and moved at a transport speed of 30mm.s^{-1} is shown in **Fig. 8**.

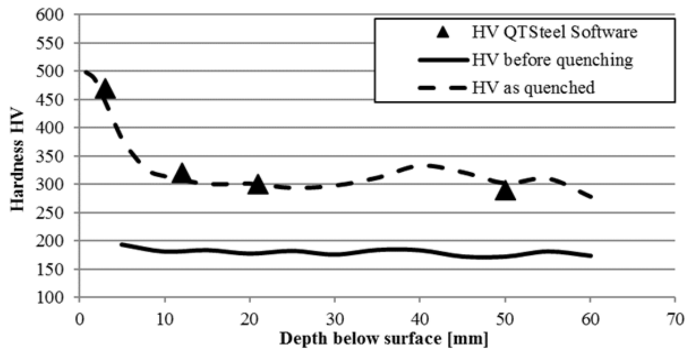

Fig. 7 The comparison of measured and predicted hardness for the 20MnV6 sample

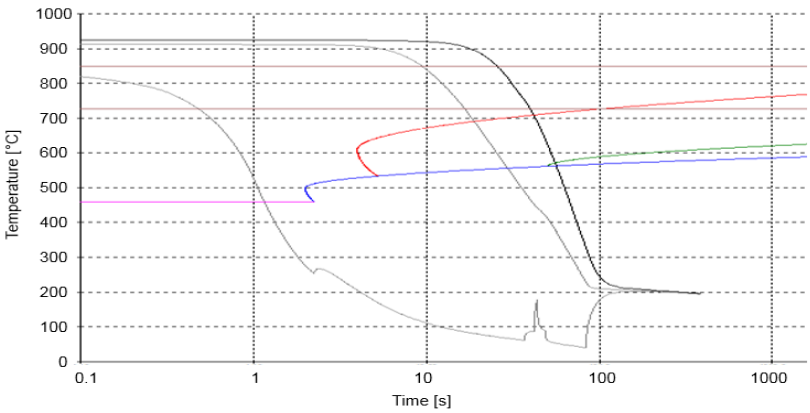

Fig. 8 CCT diagram with cooling curves on the inner and outer surface and in the centre of wall thickness of 20MnV6 tube 229x36mm (transport speed 30mm/s, 2 active cooling zones)

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4 Optimization of quenching parameters in actual conditions of the prototype quenching unit

Trial operation of the prototype quenching unit started in November 2016, a series of optimization tests of the hardening technology began with the consequent optimization of the tempering technology on the established steel grades and with measuring of the temperature during the actual quenching process.

Seamless tubes of various steel grades were fitted with 20 thermocouples (**Fig. 9**) in three different lenghwise distances and three depths. Eight thermocouples were positioned at the beginning of the tube that first entered the furnace, six in the middle and six at the end of each tube. Thermocouples were pulled through the tube to the data-logger which was positioned in the insulation cover which was welded to the rear side of the tube. An example of the measured data is shown in **Fig. 10**. The measured temperatures enable to optimize temperatures in the furnace zones and the heating time. The measurement also showed the cooling intensity and homogeneity which was used for optimization of the water pressure or the transport speed.

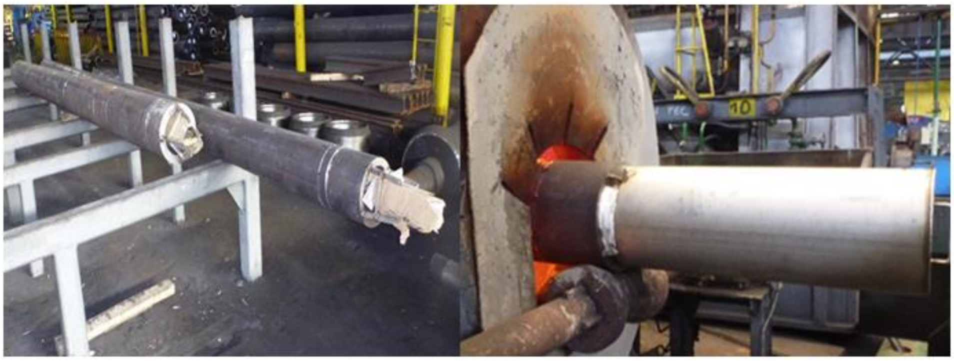

Fig. 9 Tubes embedded by thermocouples (left), end of the tube sample enters to the furnace (right)

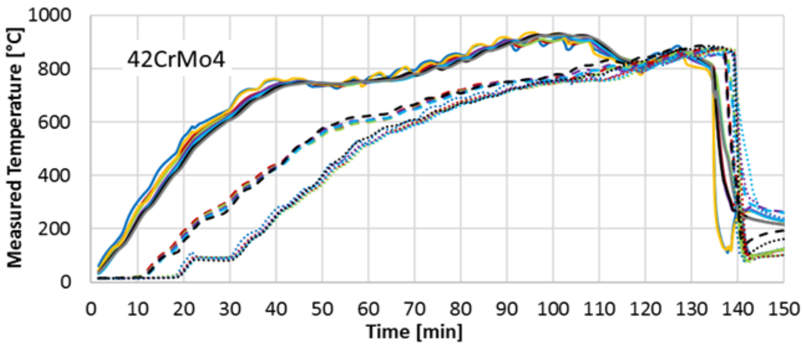

Fig. 10 Example of measured temperatures in various depths and distances from the tube beginning

5 HT_TUBE_SETUP – Computational technology model

The model HT_TUBE_SETUP was developed by ITA and currently is developed in cooperation with TŽ to support the setup of cooling strategies providing the required metallurgical properties

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of the quenched tubes. This off-line simulation tool, see **Fig. 11**, is equipped with some special functions:

- the software can connect to the Process Control Database of the Quenching unit where process data of each quenched tube are saved together with results of metallurgical and mechanical laboratory tests performed,
- the software can import process data of selected tube from the Process Control Database and make appropriate temperature and metallurgical simulation very efficiently,
- the software can determine automatically an optimum cooling regime (number of active cooling zones and transport speed) which leads to required hardness in the centre of wall thickness,
- metallurgical model implemented in the software adapts itself according to results of laboratory tests saved in the Process Control Database.

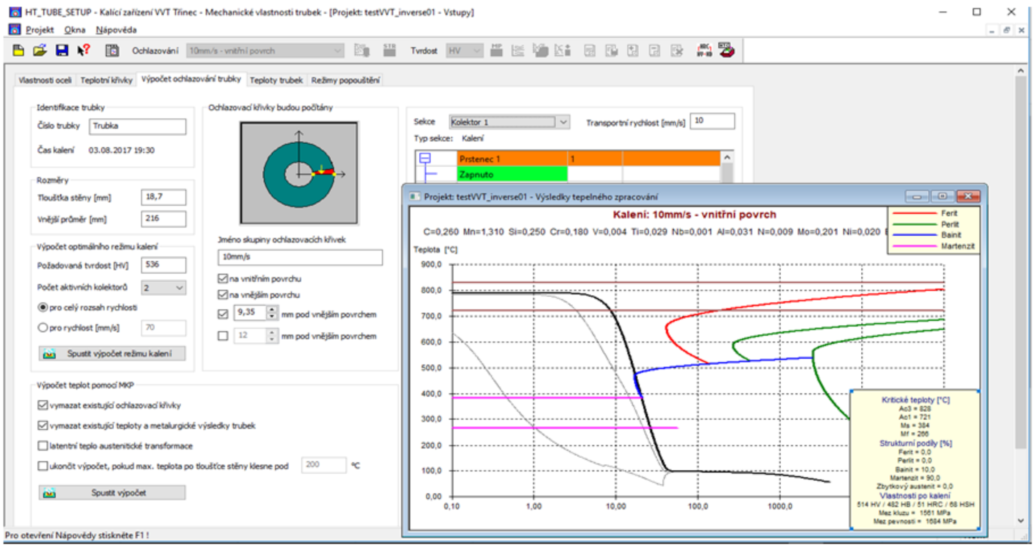

Fig. 11 Graphic User Interface of the software HT_TUBE_SETUP

6 Conclusion

The development of the prototype quenching unit was a long and extensive project involving numerical simulations supported by various laboratory measurements as well as measurements in actual production process of refining. The first stage of the development included mapping of the current state and critical assessment of the technical and technological level of the existing equipment, along with testing of steels in view of the new requirements of the customers. It was decided to develop a functional prototype for the actual conditions of the Tube Rolling Mill operation.

The next stage included a set of laboratory tests of cooling of tube samples performed in the Heat Transfer and Fluid Flow Laboratory (Heatlab) of FME BUT including numerical simulation with the prediction of the initial setting of the technological parameters and the calculation of the final metallurgical properties and the impact of the transport speed on achieving the required homogeneity of the material, and recommendation of the technological configuration of the prototype quenching unit in cooperation with ITA, Ltd. in Ostrava.

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Laboratory and numerical simulations have been used to find appropriate cooling regimes based on the CCT diagrams for the selected materials, to select the appropriate type and size of water nozzles, their placement and distances around the circumference of the collectors of the individual quenching sections impacting hardenability and configuration of the cooling system.
In the final stage, the final scheme of the technological design of the prototype quenching unit was implemented as a comprehensive Technical Design of the prototype quenching unit carried out in cooperation with BKB Metal. The Technical Design of the prototype served as the basis for preparation of the detailed engineering documentation with the subsequent construction of the prototype quenching unit and its commissioning for trial operation in November 2016.
Currently the QUENCHING UNIT is in the stage of optimization of the technology of quenching of the established steel grades and development of refining strategies for the introduction of new steel grades and dimensional series for refining together with the development of the HT_TUBE_SETUP calculation model.

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