EXPERIMENTAL DATA AND SIMULATION BY THE FINITE ELEMENT METHOD OF THE CYLINDRICAL STEEL SHAFT QUENCHING IN WATER

ЕКСПЕРИМЕНТАЛНИ ДАННИ И СИМУЛИРАНЕ ПО МЕТОД НА КРАЙНИТЕ ЕЛЕМЕНТИ НА ЗАКАЛЯВАНЕТО НА ЦИЛИНДРИЧЕН СТОМАНЕН ВАЛ ВЪВ ВОДА

Assist. Prof. PhD. Draganov I., Assoc. Prof. PhD. Gospodinov D.
University of Ruse, Bulgaria – Faculty of Mechanical and Manufacturing Engineering

iivanov@uni-ruse.bg, dgospodinov@uni-ruse.bg

Abstract: *In the present work, the process of water quenching of a steel cylindrical body imitating a stepped shaft is considered. The cooling function was determined experimentally, based on which the heat transfer coefficient was determined according to an existing methodology. The results obtained are used as input data for simulation using the finite element method. Results are obtained for the cooling functions at different points in two sections of the shaft. The results of the simulation are compared with the CCT curves and with the measured hardness at these points.*

Keywords: STEEL C45, WATER QUENCHING, FINITE ELEMENT ANALYSIS, COOLING FUNCTION, HEAT TRANSFER COEFFICIENT

1. Introduction

Heat treatment is the most common and most effective method to altering the properties of metals and their alloys [1]. The most commonly thermally treated metal alloys are those of iron, and the most commonly used in the thermal process is quenching. A responsible transition (where more than 90% of the waste is obtained) when quenched is the cooling transition. The reason for this is that during cooling due to the large temperature gradient in the different points of the cooled object and the formation of the final structure and properties of the articles, conditions are created for the occurrence of large internal mechanical stresses. One way to reduce the risk of inadmissible strain or destruction due to an increase in stresses above the yield strength while at the same time achieving total quenching is the right choice of cooling environment and the conditions under which it works.

Appropriate modeling and simulation of different quenching cooling processes can provide reliable information about the temperature distribution of the volume of the objects under investigation as a function of the time directly related to the changes in structure occurring during the cooling process. Due to the flexibility of the method and the possibility of an easy and rapid change of the introduced data on the cooling characteristics of the environments used for quenching, it is possible to simulate different cooling conditions for short time and to choose those which guarantee the highest quality of the heat-treated products [2-7].

The choice of the boundary of the mathematical model is dictated by various considerations: choice of method of soling the mathematical task, knowledge of the physical properties of the volume consideration, knowledge of the specific boundary condition, enc. In this work, only the solid steel body is considered and for the definition of the mathematical model, it is necessary to know the heat transfer coefficient (HTC). It is possible to determine it by lumped-heat-capacity method or by inverse method [8].

The ABAQUS [9] commercial program for finite elements analysis has been chosen for use because it is possible to create custom subroutines.

2. Methodology of Experiment

In the work were used cylindrical test bodies imitating a stepped shaft – Fig. 1, The material of shaft is C45 steel (1.0503, EN 10083-2), and the chemical composition determined by quantum analysis is shown in Table 1.

Two test pieces were made, with the type K thermocouple **(**Chromel**/**Alumel**)** mounted in the geometric center of one. The test piece made in this way serves to obtain the cooling curves (T-t curves), recording and using LabVIEW software application for data process. After obtaining the cooling curves, the calculation of HTC α is made using the equation:

$$\alpha = V.G.\frac{c_p}{(\Delta t.F)}, \quad (1)$$

with dimensionality W/m^2K, where V is the cooling rate in °C/s, G in kg is the mass, c_p in J/kg.K is the specific heat capacity, Δt in °C is the temperature difference between the heated body and the cooling fluid, and F in m^2 is th contact area.

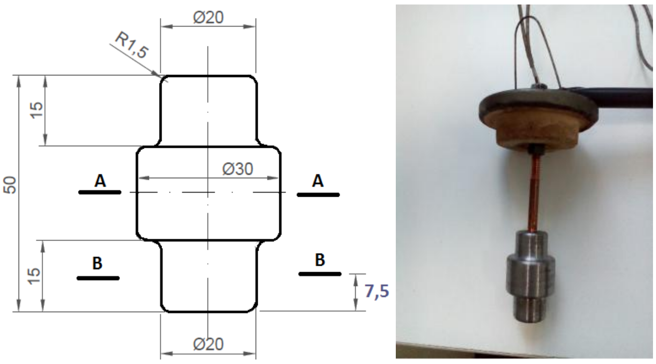

Fig. 1. *Shape and dimensions of the quenched body*

Table 1. *Chemical composition of the quenched body*

Element	C	Si	Mn	S	P
Contents %	0,46	0,35	0,71	0,041	0,04

As a cooling medium, tap water was used with an initial temperature of 15 °C and volume 1 liter.

The test body is heated to a temperature of 857 °C (temperature recommended for quenching of the used steel) in a laboratory furnace and oxidation medium and then transferred to the cooling bath. Three attempts were made, and after each attempt, the test body was cleaned with sandpaper. The recorded cooling curves are averaged and the results is used as the starting point for calculation of HTC.

The second sample is heat treated in a manner identical to that described above. After cooling for quenching, it is cut in the manner shown if Fig. 1. The determination of the hardness distribution in its volume was made after polishing the surfaces by the Vickers method with load of 10 kg. The results obtained for the hardness were convered to Rockwell hardness scale “C” (HRc).

Due to technical limitations, no cooling data has been taken of the surface of the body, but only at the central point.

3. Mathematical and numerical models

The quenching of steel in water is considered as a problem for transient heat transfer [10], in which using the temperature equilibrium condition and the Fourier law, the following equation is obtained:

$$\operatorname{div}\left(\boldsymbol{\lambda} \cdot \operatorname{grad}(T)\right) + Q = V\rho\dot{U} \cdot \qquad (2)$$

In this equation, $\boldsymbol{\lambda}$ is a symmetric second-order conductivity tensor, T is a temperature, Q is an internal heat volumetric source, V is the volume of the body, ρ is the density, and $\dot{U}$ is the variation over time of the specific enthalpy.

The boundary conditions are described by the equations for the heat flux on the outer surface and the heat flux of the convection of the body, respectively:

$$q = q(\mathbf{x}, t), \qquad (3a)$$

$$q = \alpha\left(T - T^0\right), \qquad (3б)$$

where the vector x describes the position in time t, and T^0 is the temperature of the cooling fluid.

The initial condition is:

$$T(x, t = 0) = 857\ °C. \qquad (4)$$

The solution of equation (2) under conditions (3a), (3b), and (4) was done using the finite element method [10]. Spatiol discretization is realized through standard Galerkin approach for energy balance:

$$\int_V \rho\dot{U}\delta T \mathrm{d}V + \int_V \frac{\partial \delta T}{\partial \mathbf{x}} \cdot \boldsymbol{\lambda} \cdot \frac{\partial T}{\partial \mathbf{x}} \mathrm{d}V = \qquad (5)$$

$$= \int_V \delta T r \mathrm{d}V + \int_{S_q} \delta T q \mathrm{d}S,$$

In this equation δT is the variation of the temperature, satisfying the boundary condition in outer surface and the volume.

The body is discretized with finite elements with shape functions and functions of temperature:

$$T = N^n(\mathbf{x})T^n, \qquad (6)$$

where n is the node number in discrete element, and N is the interpolating functions, dependent from the type of the finite element.

The integration of the time, τ, is done by equation:

$$\dot{U}_{\tau+\Delta\tau} = \left(U_{\tau+\Delta\tau} - U_{\tau}\right) / \Delta\tau. \qquad (7)$$

4. Finite element model

A 3D geometrical model of the body was created in ABAQUS. The discretization is made with 20013 tetrahedral elements with one nod in the middle of the edges (typ DC3D10 in ABAQUS). This number of elements is enough for convergence according Draganov at all. [11].

The heat conductivity coefficient and the specific heat capacity are non-linear temperature functions set out in Table 2. For dhe density of the steel, a value of 7850 kg/m^3 is adopted.

Table 2. Physical properties

Temperature, °C	300	400	600	800	1000
Specific heat capacity, J/kg.K	469	506	521	660	616
Conductivity, W/(m.K)	48	47	41	37	32

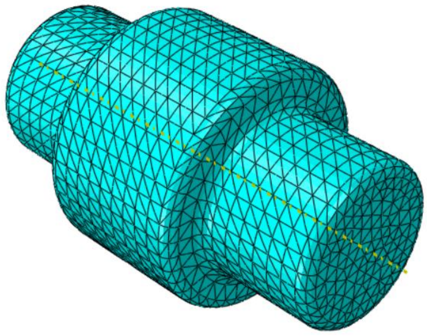

Fig. 2. *Discretization*

The initial temperature of the shaft is 857 °C. The temperature of the cooling fluid - T^0, is 15 °C, and the HTC is a non-linear function of the temperature (time) and is tabled in 1000 steps, according to the experiment – Fig. 3.

5. Results and discussion

The cooling temperature obtained experimentally is replaced in equation (1) and the HTC function is obtained – Fig. 3 (red color, continuous curve) that applies to the central point of the shaft. In order to be transferred to the border of the body, a iterative procedure was performed. As a proximity criterion, the ratio between the temperature at the center point of the experiment and from the simulation was chosen. A subroutine was created for interpolation of the temperature and HTC values obtained experimentally in the simulation time points. The HTC determined in the manner described above is shown in Fir. 3 with a blue color and a broken line.

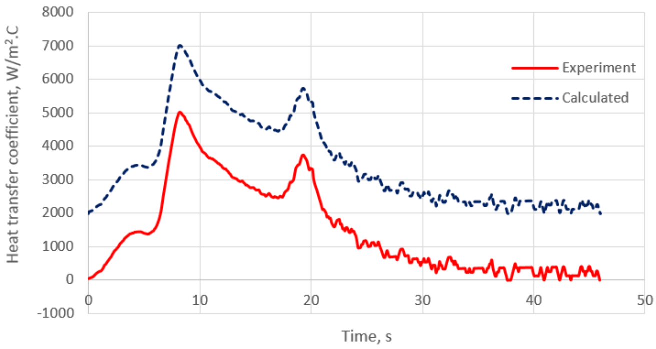

Fig. 3. *Heat transfer coefficient*

In the second iteration step, a satisfactory approximation was obtained, with the maximum difference between the temperature at the center point of the experiment and the simulation at temperature above 300 °C being 2.67%. In Fig. 4 is a diagram of the temperature distribution in 6.026 s.

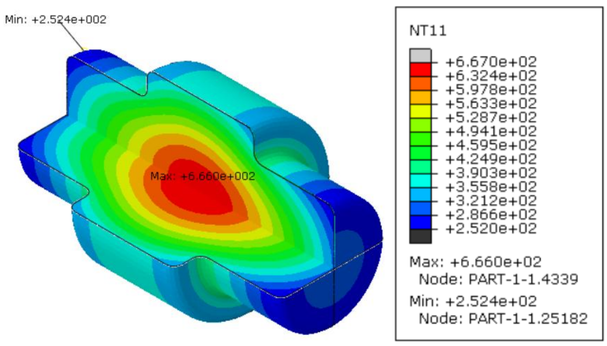

Fig. 4. *Температурно поле в 6,026* ***s***

In Fig. 5 shows the CCT diagram of steel 45 [12] with the cooling curves imposed on it at selected five points in sections A and B obtained after simulation. In the initial comparison of the obtained cooling curves with the thermokinetic diagram, there is a discrepancy between the fields in which they fall and the measured hardness results. For the correct positioning of the cooling curves relative to the conversion curves, the values for the time of curves obtained it the simulations must be multiplied by a factor of 0.5. The coefficient is established after determining the hardness at the selected points – Fig. 6, with 1 being the function of hardness in section B, with 2 – section A, and 3 – hardness in half-martensitic zone

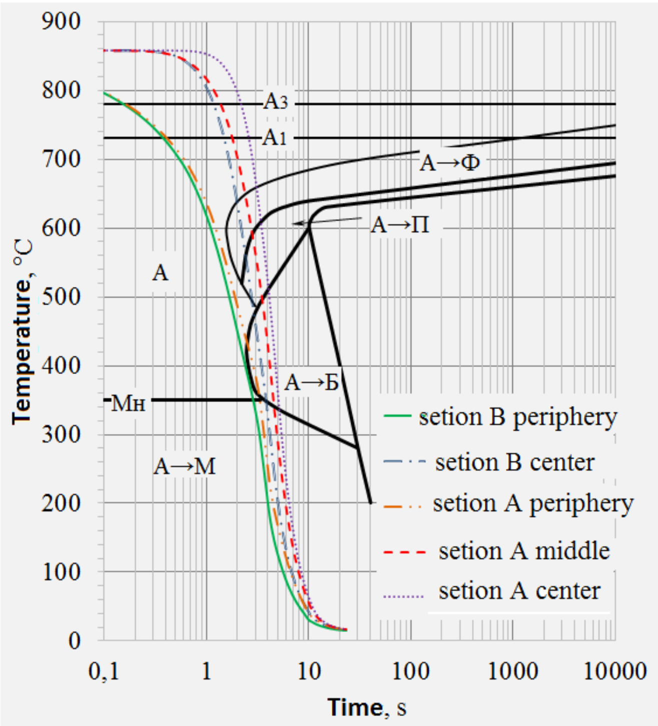

Fig. 5. Thermokinetic diagram for steel 45 and the location to the simulated cooling curves

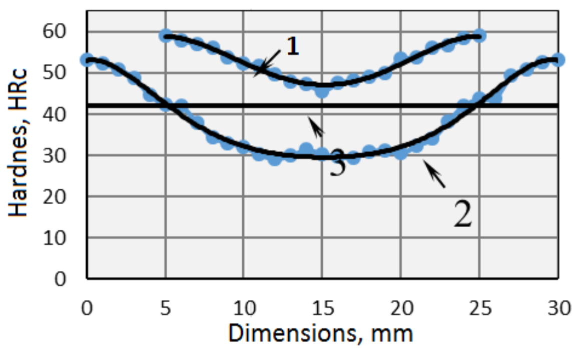

Fig. 6. Hardness

6. Conclusion

The hardness distribution found is logical due to the differences in the studied cross-sections. As can be seen from the figure 6, the cross section of 20 mm in diameter there is a total quenching and when the cross-section increases to 30 mm, the hardened structure (with a hardness greater than HRc 42) is at a depth of 5.5 mm.

The numerical simulation by finite element method based on the transfer of the HTC from central point to the shaft boundary gives a quality plausible result in terms of the expected stiffness that will allow the predictability of the quenching depth in bodies with similar configurations.

The reasons for inconsistency of the experimental cooling curve either the measured hardness may be many, but in this case it is most likely due to poor contact of the thermocouple with the test body. Once the coefficient is established, the resulting simulated cooling curves show a very good match between the expected and hardnesses obtained and can be used to predict the stiffness of bodies with similar shape and size made of different grades of steel for which a thermodynamic breakage diagram of the supercooled austenite.

7. Literature

[1] Данев П. *Термично обработване на металите*. Русе, РУ „Ангел Кънчев“, 2008.

[2] Banka A., J. Franklin, Z. Li, B. Ferguson, M. Aronov, *CFD and FEA used to Improve the Quenching Process*, Heat treating progress, September, pp. 50-56, 2008.

[3] Kobayashi K., O. Nakmura, Y, Haraguchi. *Water Quenching CFD (Computational Fluid Dynamics) Simulation with Cylindrical Impinging*, Jets. Nippon Steel & Suitomo metal technical report No. 111, pp. 101-106, 2016.

[4] Hamouda A., C. Lau, *Finite Element Analysis of Steel Quenching*, Process. Pertanika J. Sci. & Technol. Supplement 9(2), pp. 259-267, 2001.

[5] Ferguson B., Z. Li, A. Freborg, *Modeling heat treatment of steel parts*, Computational Materials Science 34, pp. 274-281, 2005.

[6] Carlone P., G. Palazzo, R. Pasquino. *Finite element analysis of the steel quenching process: Temperature field ans solid-solid change.* Computers and Mathematics with Applications59, pp. 585-594, 2010.

[7] Stavrev D., V. Shtarbakov. *Numerical Modeling and Investigation of Isothermal Annealing Process.* Machines, Technologies, Materials, Year VI, Issue 7,pp. 85-88, 2012.

[8] Narazaki M., M. Kogawara, A. Shirayori, S. Fuchizawa. *Accuracy of Evaluation Methods for Neat Transfer Coefficients in Quenching.* Proceedings of 18th ASM Heat Treating Society Conference Including the Liu Dai Memorial Symposium, pp. 509-517, 1998.

[9] ABAQUS. *Analysis User's Manual. ver. 6.12*, Dassault Systemes Simulia Corp., Providence, RI, USA.

[10] Bergheau J., R. Fortunier, *Finite Element Simulation of Heat Transfer*, John Wiley & Sons, Ins., 2008.

[11] Драганов И., Д. Господинов, Р. Радев. *Числено моделиране на охлаждането на медна сфера.* Топлотехника, брой 13, стр. 18-23, 2018.

[12] A. Rose, *Atlas zur wärmebehandlung der stähle. v. 1*, Verlag Stahleisen mbH, Dusseldorf, Germany, 1954