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THE NUMERICAL APPROACH TO THE CALCULATION OF COMBINED HEAT TRANSFER COEFFICIENT FOR COOLING PROBE IMMERSED IN AGITATED QUENCHING OIL

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Abstract: *The article deals with the issue of heat treatment. The cooling curve was obtained for Isorapid 277HM by experimental way of temperature measuring and their statistical processing. The experimental method was consistent with the test normative ISO standard 9950th (Wolfson's test). The cooling oil Isorapid 277HM was agitated and had the constant temperature of 50 °C. In the next part of this article was calculated combined heat transfer coefficient from thermal data which were obtained from the experimental measurement. The methodology was based on inverse heat transfer. The interpretation code was software ABAQUS.*
Key words: *quenching, measuring, oil, simulation, ABAQUS*

1. INTRODUCTION

Heat treatment is a multi-parameters process. The selection of appropriate parameters predicts to achieve required behaviors of treated components. The kind of quenching medium, the selection of quenching medium temperature and the selection of the medium state (unagitated, agitated) are determining factors. Quenching oil Isorapid 277HM belongs to cooling oils common in use. Prediction of treated components behavior during a cooling process is possible only in the case if are defined the boundary conditions of the process. Before the application of a cooling process numerical simulation, the heat transfer coefficient on the component surface should be defined quantitatively. The experiment applying, simulation model and numerical solution are able to test the influence of heat treatment parameters on an immediate and final state of a component. The methodology of cooling effect quantification of agitated oil Isorapid 277HM at temperature 50 °C is presented in the article.

2. EXPERIMENTAL SETUP AND MATERIALS

Isorapid 277 HM is fast quenching oil for low, medium and high alloy steel as well as carburized steel. The Isorapid 277 HM is oil with very good evaporation stability and it is been used extensively in atmospheric furnace. The typical oil property is rapid decay of the vapour blanket. Its application reduces smoke and flame formation significantly. The range of recommended working temperatures is from 50 °C to 80 °C. Coefficient of the kinematics viscosity has value 25.10^{-6} $m^2.s^{-1}$ for oil temperature 40 °C (***, 2010).
The experimental equipment consisted of electrical resistance furnace of LM 212.10 type, cylinder-shaped experimental probe, oil Isorapid 277 HM, portable USB-based DAQ for thermocouples NI USB 9211 for digital record of measured temperatures, personal computer and pneumatically manipulator for probe moving. Geometrical and initial conditions of the experiment were based on the Wolfson's quenching test (Bodin et al., 2010). The diameter of the probe was 12.5 mm and its high 60 mm. Before cooling, the probe was heated up to the initial temperature of 850 °C. The temperatures were measured by the encapsulated 304 SS thermocouple of K type with diameter of 1.5 mm located in the centre of the probe. Temperatures were recorded 5 times per second and set of measurement was repeated five times for constant oil temperature 50 °C. The quenching oil was agitated with energy input 1.65 $J.s^{-1}.kg^{-1}$. Temperature measurement started from the moment when the centre of gravity of probe reached the oil level. The temperature records were statistically handled and consequently used for the determination of the cooling rate and the temperature dependence of combined heat transfer coefficient applying the inverse-numerical-correlation (INC) method, created by authors of article.

3. THEORETICAL BASE OF THE SOLVED TASK

The transient temperature field in the quenched probe can be described by the Fourier-Kirchhoff heat diffusion equation (Incropera & Dewitt, 1996)

$$\rho(T)c(T)\frac{\partial T}{\partial t} = div(\boldsymbol{\lambda}\ grad\, T) + q_v \qquad [\mathrm{W.m^{-3}}] \quad (1)$$

where ρ [$kg.m^{-3}$] is the density, c [$J.kg^{-1}.K^{-1}$] is the specific heat, $\boldsymbol{\lambda}$ is the tensor of the thermal conductivity and q_v [$W.m^{-3}$] is the volumetric density of internal heat sources, i. e. the heat generated in the unit volume of material per unit time.

The heat is removed from the cylindrical probe into the cooling oil by the mechanisms of radiation, boiling and free convection. Supposing isotropic material ($\lambda_x = \lambda_y = \lambda_z = \lambda$), the heat extraction from the probe can be described by the boundary condition of the 3rd kind in the form

$$-\boldsymbol{\lambda}(T)(gradT)_s = h_C(T_s)(T_s - T_r) \qquad [\mathrm{W.m^{-2}}](2)$$

where $(gradT)$s denotes temperature gradient at the probe surface, T_s [°C] is the surface temperature of the probe, T_r [°C] is the oil temperature and $h_C(T_s)$ [$W.m^{-2}.K^{-1}$] represents the combine heat transfer coefficient involving the heat extraction by different mechanisms in the dependence on the probe surface temperature.

4. NUMERICAL SIMULATION

Engineering-scientific program code ABAQUS was the interpretation program of numerical simulation (***, 2008). Geometrical model of the probe was the half part of the cylinder. On the outer faces of the cylinder was applied convective boundary condition. Applied elements were axisymmetric with quadratic base function and surface temperature behaviour. Calculation procedure was transient and nonlinear. Thermophysical material model of the probe material is obtained from experimental measuring by laser flash method. The inverse heat conduction problem of heat transfer solving from the probe into the cooling oil was solved by FEM and INC methods (Maniruzzaman at al, 2010)

Through the iterative INC method can find a result witch it is very likely and useful for computer prediction of thermal treatment processes. Task solution by the INC method must meet the following criteria: relative error for measured and calculated temperature in the i-time must be less than 1.0 %, relative error for cooling rates derived of measured and calculated temperature must be less than 5.0 % and the correlation coefficient between measured and calculated temperatures in the cooling time must be greater than 0.99.

5. RESULTS AND DISCUSSION

In Fig. 1. are cooling curves for agitated oil Isorapid 277 HM at 50 °C as the result after statistically processing and the numerical simulation. The temperature curve fitting is than very close. This fact can you see in Fig. 1. It is not possible represents graphically both curves. Value of the correlation coefficient between calculated and measured temperatures was obtained 0.9998. In Fig. 2 are plotted the both cooling rate curves. The compliance rate of curves for the cooling rate indicates the quality of the task processing. Maximum cooling rate was reached 111.0 $K.s^{-1}$ at thermocouple temperature 669 °C. Combination of experimental cooling curve and numerical simulation using INC method give the following values of average relative errors between:

-measured and calculated temperature is 0.43 %,
-measured vs. calculated cooling rates is 3.7 %.

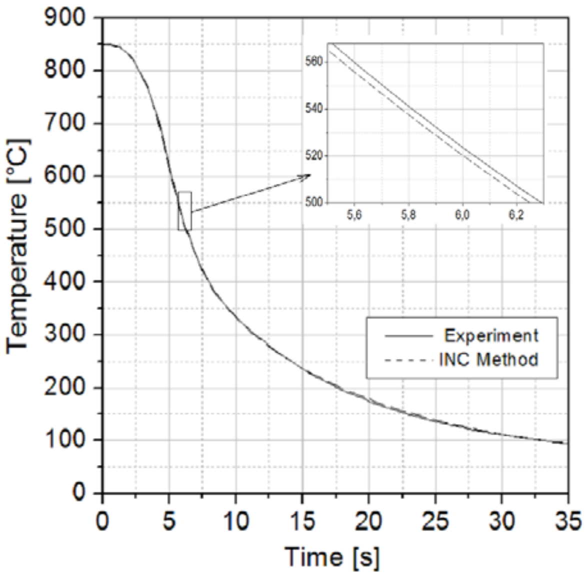

Fig. 1. Cooling curves for agitated oil Isorapid 277HM at 50 °C

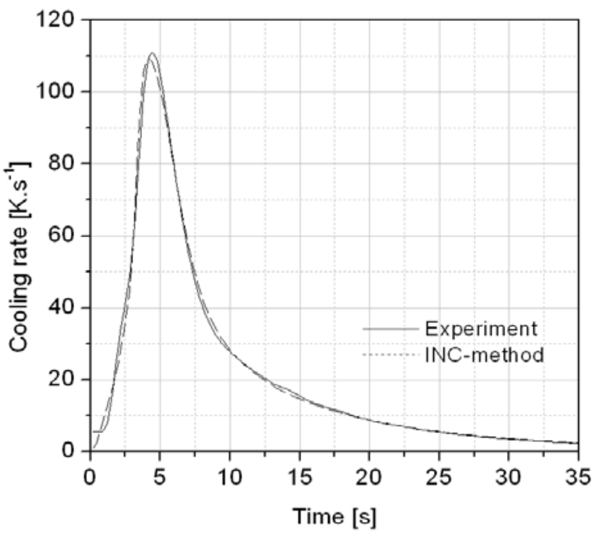

Fig. 2. Plot of both cooling rate curves

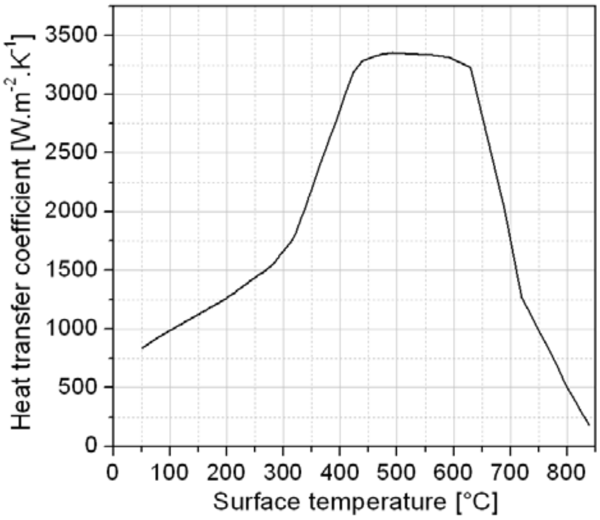

Fig. 3. Combined heat transfer coefficient as a function of probe surface temperature

Combined heat transfer coefficient dependence of probe surface temperatures for agitated oil and generally oriented walls is the main result of INC method and is shown in Fig. 3.

6. CONCLUSION

With combination of experiment and numerical simulation is able in qualitative and quantitative way to analyze the influence of cooling fluid on the heat transfer from the probe into unagitated or agitated oil at different temperatures. The obtained results of the combined heat transfer coefficient can be used as boundary condition of 3th kind in thermal transient analyses as the base for stress-strain state prediction.

The next research will be oriented on exploring of the heat transfer from the oblique surfaces for the chosen oil temperatures and various intensity of the agitation. The calculated results will verify by different tests like C-test. Obtained knowledge will be used on the creation of the simulation models for parts behaviour prediction in heat treatment processes.

7. ACKNOWLEDGEMENT

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