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Inverse hardness distribution in quenched steel specimen of complex form*

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Influence of the shape complexity on quenching results was investigated by using the computer simulation. An algorithm of computer simulation of transient temperature fields is based on finite volume method. The prediction of specimen hardness is based on *Jominy* test results. Hardness in specimen points was calculated by the conversion of calculated characteristic cooling time for phase transformation $t_{8/5}$ to hardness. Heat transfer coefficient and heat conductivity coefficient values involved in mathematical model have been calibrated by inversion method.

1. INTRODUCTION

Heat treatment automation made the steel quenching simulation actual. Quenching used to be called the black hole of heat treatment processes [1]. Model would not be considered representative of one process if all mechanisms of the actual process are not well known and if the appropriate mathematical methods are not used. Although very simple on first sight, quenching is physically one of the most complex processes in engineering, and very difficult for understanding. Simulation of steel quenching is a complex problem, dealing with estimation of microstructure and mechanical properties, and dealing with evaluation of residual stresses and distortions after quenching.

The mechanical behavior of as-quenched or quenched and tempered steel directly depends on steel hardening degree [2]. Research of numerical simulation of hardening degree, i.e. hardness distribution in quenched steel specimen is one of with high priority research in simulation of phenomena of steel quenching.

As-quenched hardness distribution in steel specimens with complex form can be predicted by approximating the complex form by simple one. Evaluation of hardness depth in approximated simple model is not precise enough. Much better, modern approach for prediction of as-quenched hardness of steel specimen with complex form is based on mathematical modeling and computer simulation appearances that exist during the steel quenching.

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2. THE ALGORITHM FOR NUMERICAL SIMULATION OF STEEL QUENCHING

Quenching of complex axially symmetrical bodies, as complex cylinders, cones, spheres can be described as 2-D problem. Knowing the initial condition for cooling and characteristic boundary condition transient temperature field in an isotropic rigid body with in 2-D final volume formulation in cylindrical coordinates can be defined by discretization equations, i.e., algebraic equation system [3][4]. The number of equation is equal to number of final volumes in domain. Temperature field change is solved by solving the discretization system for any time step. The result of transient temperature field is directly influenced of physical properties involved in the model. Specific heat capacity (c), density (ρ), heat conduction coefficient (λ) and heat transfer coefficient and α have to be known. Variable α was calibrated by inversion method using the *Crafts -Lamont* diagrams [5]. Calibrated values of heat transfer coefficient (α) of oil with severity of quenching, i.e., *Grossman's* to H-value equal to 0.3 vs. surface temperature is shown in Figure 1.

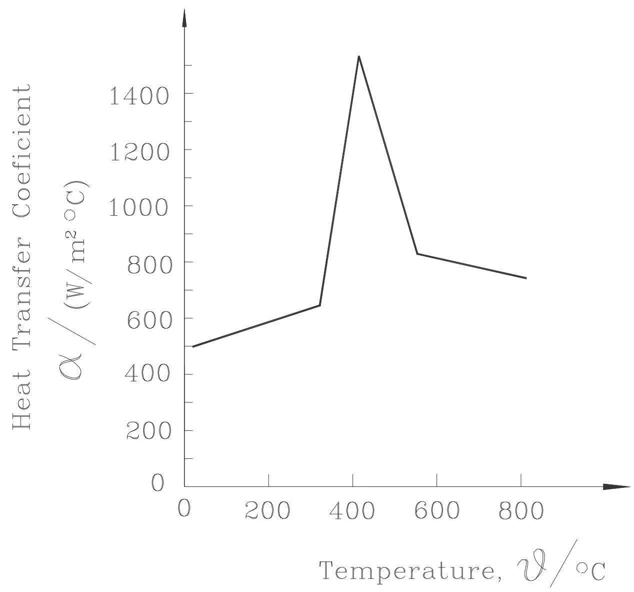

Figure 1. Calibrated values of heat transfer coefficient vs. surface temperature for quenching medium with severity of quenching H=0.3

The hardness at grid-points can be estimated by the conversion of calculated time of cooling from 800 °C to 500 °C ($t_{8/5}$) to hardness. The conversion can be done by using both, the relation between cooling time and distance from the quenched end of *Jominy*-specimen and the *Jominy*-hardenability curve [6][7].

3. APPLICATION

In order to analyze the performance of proposed numerical simulation method with methods that based on simplifications during the numerical simulation of quenching of steel specimen of complex form the comparison of achieved results by both methods was done. Specimen of complex form which quenching process was simulated is shown in Figure 2.

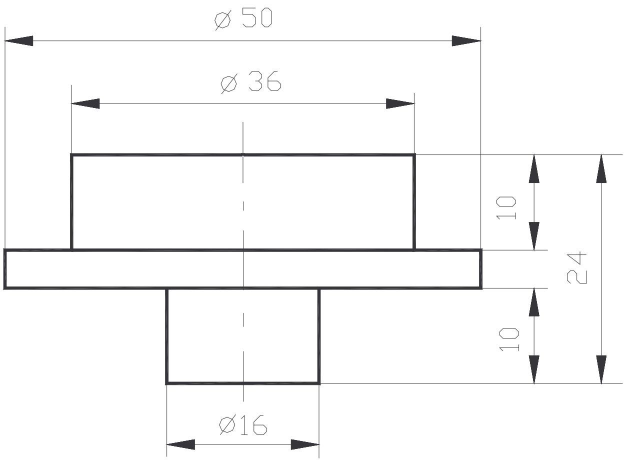

Figure 2. Specimens of complex form

The experiment was done on steel DIN 41 Cr 4. *Jominy* results of investigated steel are shown in Table 1.

Table 1
Jominy-test results

Distance, mm	1.5	3.0	5.0	7.5	10	15	20	25	30	35	40	80
Hardness HRC	55	54	53	52	42	40	38	36	34	33	32	29

Heat treatment was heating to 850 ˚C for 30 min and oil quenching with slow agitation. Severity of quenching, i.e., *Grossman's* H-value was equal to 0.3. The calibrated values of heat transfer coefficient vs. surface temperature of water with severity of quenching H=0.3 are shown in Figure 1. Figure 3 shows computed HRC hardness fields of quenched specimen. The modeling of quenching was performed in two different ways. First, as-quenched hardness distribution in steel specimens with complex form was predicted by realistic approaches without anyone simplification (Figure 3a) and second, by approximating the complex form by simple one (Figure 3b).

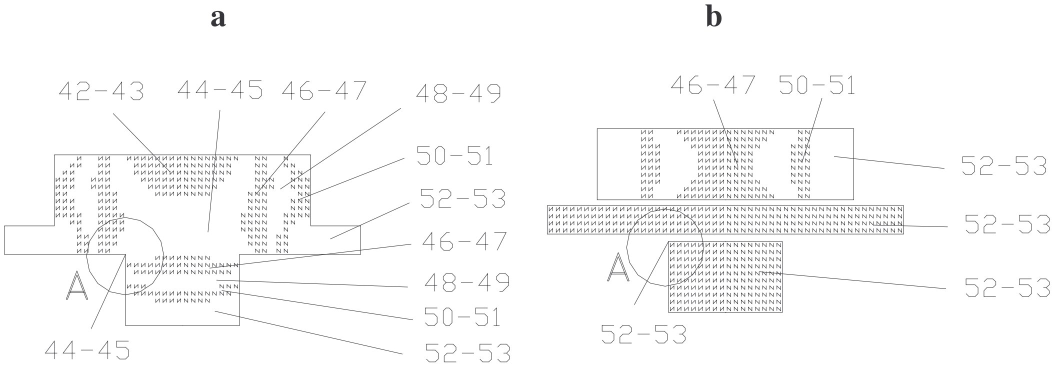

Figure 3. Hardness fields in quenched specimen, (a) modeling without simplification,(b) modeling with simplification

In second way of modeling, specimen was simplified and modeled as three cylinders. Results for three separate cylinders were joined together. The results in two applied models were similar, but in location "**A**" the differences are significant and errors in prediction of hardness in location "**A**" cannot be neglected.

4. CONCLUSION

Computer simulation of hardness distribution in quenched steel shaft was analyzed.

A numerical simulation of quenched hardness in a steel specimen with complex form has been applied to describe the hardness distribution. As-quenched hardness distribution in steel specimens with complex form was predicted by approximating the complex form by simple one and by realistic approaches without anyone simplification.

By the comparison of results hardness simulations it can be concluded that prediction of hardness depth by simplifications is not enough precise.

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