MATHEMATICAL MODELLING AND COMPUTER SIMULATION OF STEEL QUENCHING

SMOLJAN Božo, ILJKIĆ Dario, POMENIĆ Loreta

University of Rijeka, Faculty of Engineering, Rijeka, Croatia, EU

Abstract

The objective of design of quenching is to estimate the results of quenching, concerning mostly with the estimation of microstructure and mechanical properties. For the simulation of specimen cooling which is thermos-dynamical problem, it is necessary to establish the appropriate algorithm which describes cooling process, and to accept appropriate input data.

Microstructure composition and hardness will be defined by kinetic equations of prior microstructure decomposition, based on time of cooling from 800 to 500 °C, which is relevant to microstructure transformation. Semi-empirical methods are derived from kinetic equations of microstructure transformation to predict microstructure composition of quenched steel. To determine hardness of high hardenability steels the modified Jominy test (JMC®-test) results can be used.

Keywords: Quenching, mathematical modelling, computer simulation, hardenability, hardness, mechanical properties

1. INTRODUCTION

Quenching of steel is one of the most important factors in production and reliability of engineering components. During the quenching phase transformation, evolution of microstructure, diffusion, heat conduction, and mechanical stressing and distortion are at once taken place inside metal. Computer programs for simulation of the quenching can be developed by considering the issues as are achievement of desired mechanical property distribution, achievement of desired microstructure distribution, achievement of required workpiece shape. Computer simulation of quenching up to has not developed enough [1]. Numerical model of heat transfer and mechanical properties can be based on finite volume method (FVM) [2].

The accuracy of numerical simulation of thermal process directly depends on the applied input variables. Inverse heat transfer problems should be solute to determine heat transfer coefficients for quenching using experimentally evaluated cooling curve results [1].

To solve heat transfer problem using the experimentally predicted cooling curve, all of heat transfer parameters should be similar in simulation of thermal process as was in experimental evaluation of cooling curves [1]. Heat conductivity, heat capacity and other relevant material properties can be estimated based on experimentally evaluated results of quenching of steel specimens [3].

Usually simulations of microstructural transformations are based on CCT diagrams using linear alignment with the actual chemical composition, or on the thermo-kinetic expressions. The first approach is more consistent, but generally does not give accurate results. The second approach gives good results for the chemical composition of the steel, for which expressions have been established.

The structure transformations and hardness distribution can be estimated based on time relevant for structure transformation. Usually it is accepted that cooling time from 800 to 500 °C, $t_{8/5}$, is relevant time for quenching. If the cooling time $t_{8/5}$ is equal for two different specimens, i.e. quenched workpiece and Jominy specimen, the hardness of these two specimens could be equal to each other. By involving the cooling time, $t_{8/5}$, the Jominy test results could be involved into the numerical model of steel hardening if the history of cooling of both, investigated specimen and Jominy specimen are similar [3, 4].

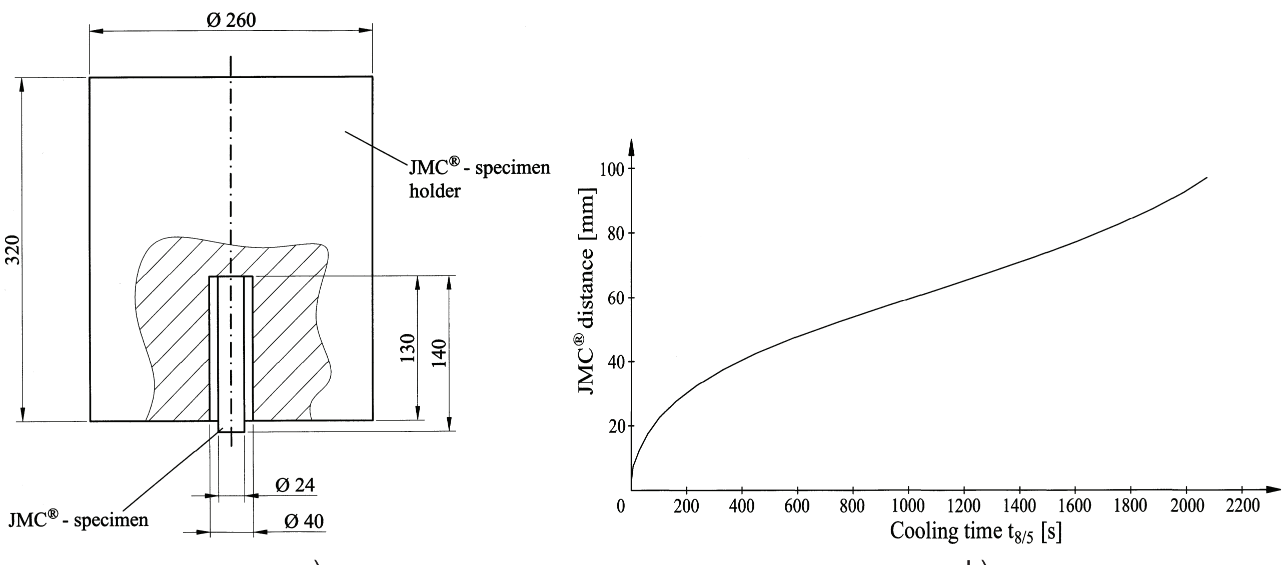
Usually, tool steels are medium to high carbon steels with high-hardenability, which are quenched and tempered to obtain the desired strength, toughness and hardness [5]. Since the critical cooling rate of martensitic transformation of high-hardenability steels is less then minimal cooling rate of original Jominy specimen, numerical modelling of high-hardenability steel quenching can be performed just based on results of modified Jominy test [6].

The transient temperature field in an isotropic rigid body can be described by Fourier's law of heat conduction. Solution of partial Fourier's equation can be found out using the finite volume method [7, 8]. Physical properties included in Fourier's equation can be found out by the inversion method. Relations between thermodynamic properties and hardenability of steel exist [3, 9]. Heat transfer coefficients of quenchants with different Grossmann severity of quenching were estimated simultaneously with estimation of heat conductivity coefficients of characteristic microstructure constituent [6]. Estimation of heat transfer coefficient was provided by varying of heat transfer coefficient values in the established model of cooling of steel bar. Dependences of heat transfer coefficients on temperature for different quenchants with different Grossmann severity of quenching and different bar diameters were defined [6].

2. SIMULATION OF QUENCHED WORKPIECE HARDNESS BASED ON THE COOLING TIME $t_{8/5}$

One of the most important factors for efficient simulation of hardening is the proper selection and use of representative cooling phenomena that is relevant for microstructure transformation.

The structure transformations and hardness distribution can be estimated based on time, relevant for structure transformation. Usually, if the cooling time $t_{8/5}$ is equal for two different specimens, i.e. quenched workpiece and Jominy specimen, the hardness of these two specimens could be equal to each other. In the developed computer simulation of hardenability of quenched workpiece, the hardness at different workpiece points is estimated by the conversion of the calculated cooling time $t_{8/5}$ to the hardness by using both, the relation between cooling time, $t_{8/5}$ and Jominy distance and the Jominy hardenability curve [3]. It is known that the cooling time $t_{8/5}$ of austenite decomposition of steels for many high-hardenability steels is ranged from 200 to 100000 s. To determine hardness of high hardenability steels the modified Jominy test (JMC®-test) results can be used (**Fig. 1**) [6].



a) b)

Fig. 1 JMC®-specimen and JMC®-specimen holder, all dimensions in mm

Fig. 1b shows the cooling times $t_{8/5}$ at the depth of 0.8 mm from the surface at different distances from the quenched end of JMC®-specimen.

Maximal cooling time $t_{8/5}$ is ten times longer than the maximal time given by Jominy test. If the hardness of quenched steel workpieces could be estimated using the equivalence of cooling time $t_{8/5}$ in actual location of investigated workpiece and the JMC®-specimen, kinetics and history of microstructure transformation during the cooling have to be similar in the JMC®-specimen and actual steel workpieces for which the hardness have to be determined. So that it is necessary to compare the cooling curves of actual workpieces and the cooling curves of JMC®-specimen [6].

3. PREDICTION OF QUENCHED STEEL MICROSTRUCTURE

Contents of ferrite, pearlite, bainite, martensite and austenite at some temperature can be estimated using the diagram in the **Fig. 2**.

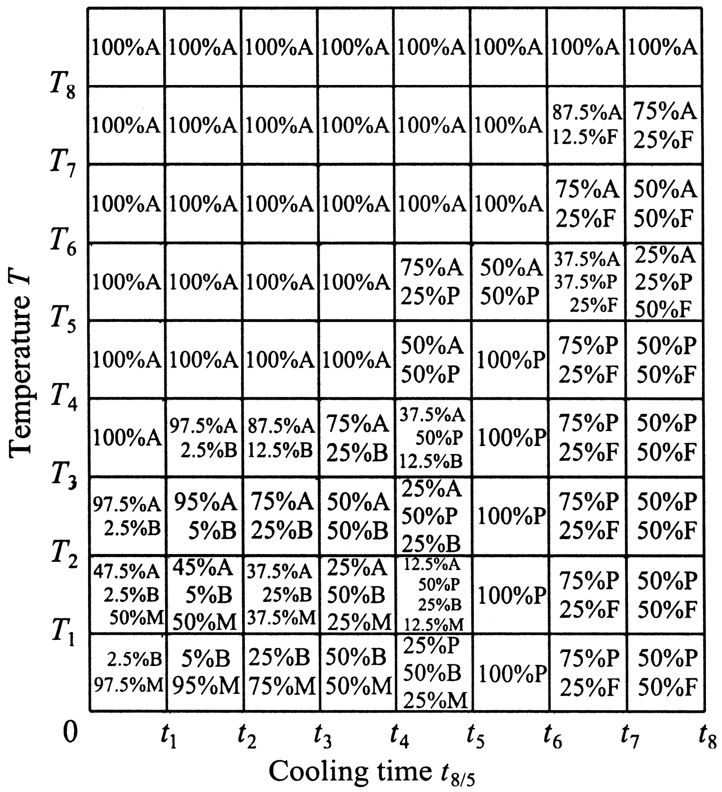


Fig. 2 Contents of ferrite, pearlite, bainite, martensite and austenite at some temperature

Characteristic cooling times, t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8 are equal to cooling time from 800 to 500 °C of characteristic microstructure composition. Characteristic temperatures, T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8 are equal to temperatures of characteristic microstructure [6].

4. APPLICATION

The established relations were applied in computer simulation of quenching of engineering component, quenched by two different quenchants. Computer simulation of quenching includes simulation of hardness and microstructure distribution of the as quenched engineering component. Computer simulation was done using the computer software BS-QUENCHING [3]. Numerical simulation of the cooling time $t_{8/5}$ was based on finite volume method [3].

The chemical composition of investigated engineering component is (in wt. %): 0.55 C, 0.94 Si, 0.34 Mn, 0.015 P, 0.012 S, 1.27 Cr, 0.05 Mo, 0.12 Ni, 0.18 V, 2.10 W. JMC® test results of the investigated steel are shown in **Table 1**. The geometry of the engineering component is shown in **Fig. 3**.

Table 1 JMC® test results of steel EN 60WCrV7

JMC® distance/mm	2	4	6	8	10	15	20	25	30	35	40
Hardness HRC	63	63	63	63	62	62	61	60	58	56	55
JMC® distance/mm	45	50	55	60	65	70	75	80	85	90	-
Hardness HRC	53	52	51	51	50	50	50	49	49	49	-

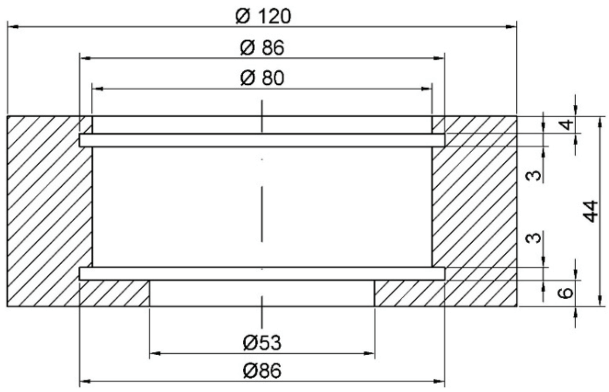
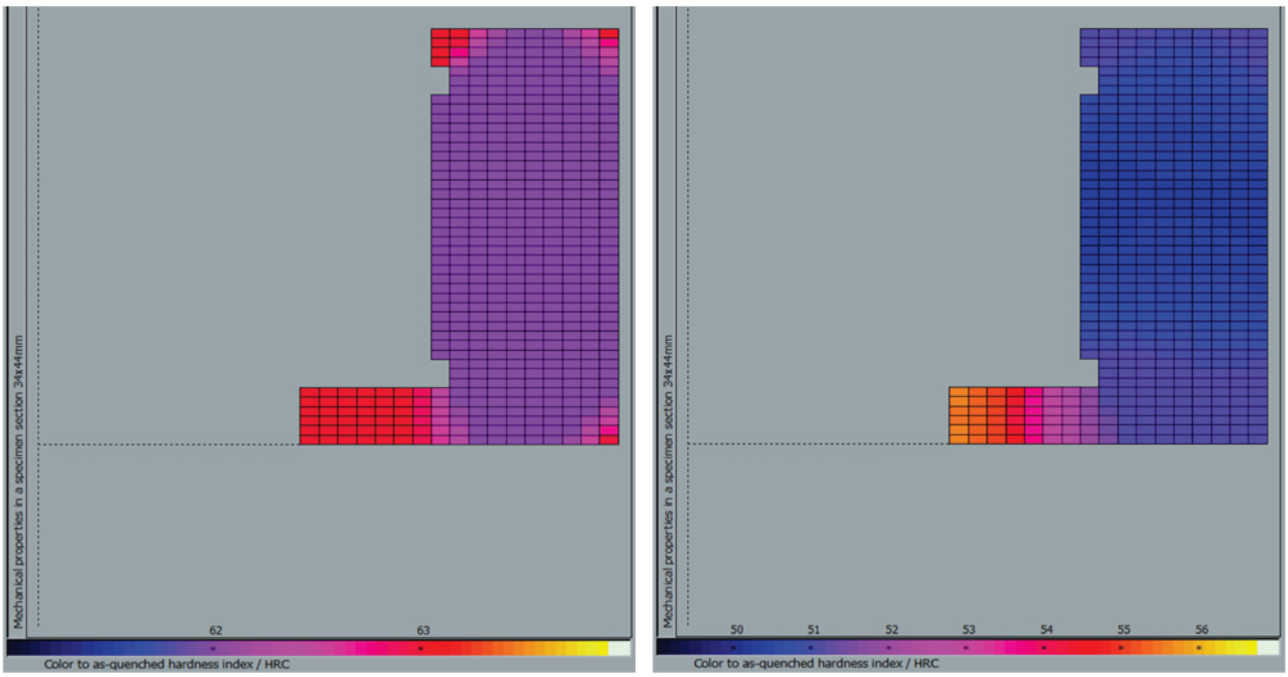


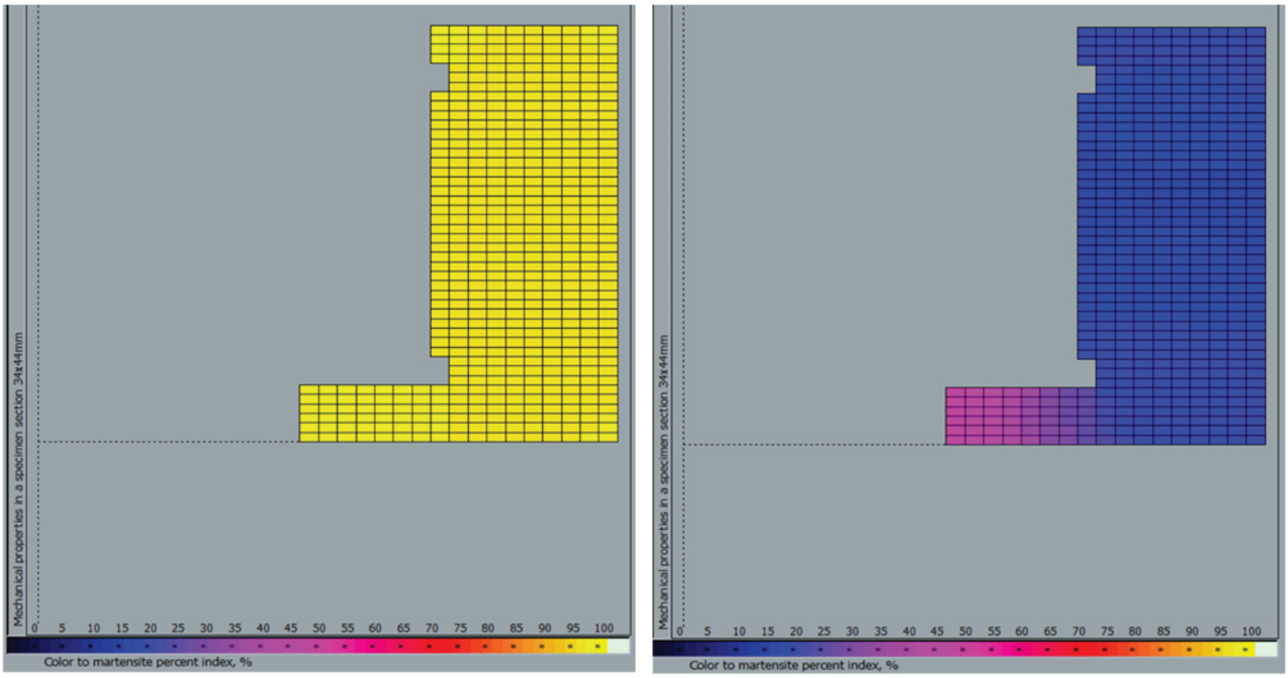
Fig. 3 Geometry of the engineering component

In simulation the engineering component austeniziting temperature was equal to 850 °C/45 min. One simulation was done for quenching in oil with *H* value equal to 0.3, and another was done for cooling in ordinary air with *H* value equal to 0.025. The distribution of hardness of the as quenched engineering component is shown in **Fig. 4**. The distribution of martensite and bainite of the as quenched engineering component are shown in **Figs. 5-6**.



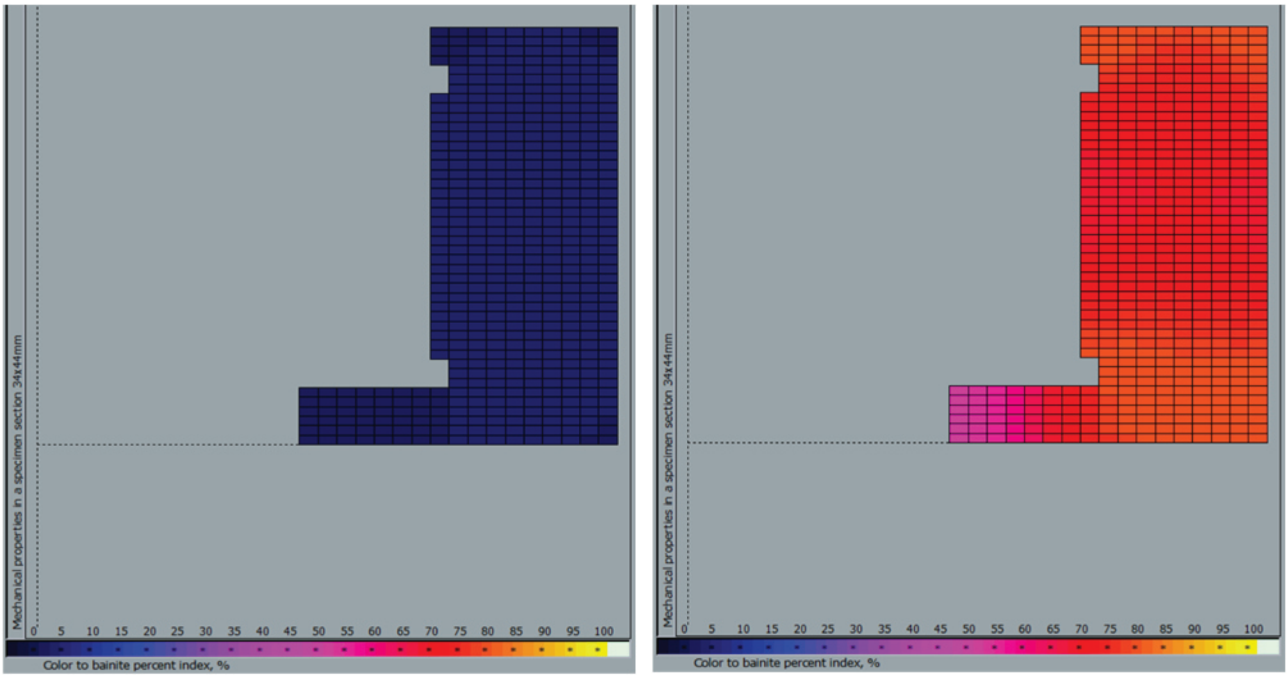
a) b)

Fig. 4 Distribution of hardness of as quenched engineering component, a) oil quenched, b) air cooled



a) b)

Fig. 5 Distribution of martensite of as quenched engineering component, a) oil quenched, b) air cooled



a) b)

Fig. 6 Distribution of bainite of as quenched engineering component, a) oil quenched, b) air cooled

5. CONCLUSION

The mathematical model of steel quenching was developed to predict the hardness and microstructure distribution in a specimen with complex geometry made of high hardenability steel. The developed mathematical model has been successfully applied in computer simulation of heat treating process of engineering component. The computer simulation is based on finite volume method.

The numerical simulation of quenching is consisted of numerical simulation of transient temperature field of cooling process and of numerical simulation of hardening. Hardness and microstructure composition in specimen points was calculated by the conversion of calculated time of cooling from 800 to 500 °C to hardness and microstructure composition. For high hardenability steel a modified Jominy specimen, i.e., JMC®-specimen is applied to predict hardenability of high hardenability steel.

The proposed mathematical model is applied in simulation of the hardness and microstructure distribution in a quenched specimen with complex geometry made of high hardenability steel. Simulation was made for air, and oil, as quenchants. It can be concluded, that the proposed method can be successfully applied in analysis of quenching of high hardenability steel.

ACKNOWLEDGEMENTS

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