Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 40
ISSUE 2
June
2010

Computer simulation of mechanical properties of quenched and tempered steel specimen

B. Smoljan*, D. Iljkić, N. Tomašić
Department of Materials Science and Engineering, Faculty of Engineering, University of Rijeka, Vukovarska 58, HR-51000 Rijeka, Croatia
* Corresponding author: E-mail address: smoljan@riteh.hr

Received 22.03.2010; published in revised form 01.06.2010

Analysis and modelling

ABSTRACT

Purpose: The computer simulation of mechanical properties of quenched and tempered steel was investigated. The established method of computer simulation was applied in prediction of mechanical properties of workpiece with complex form.

Design/methodology/approach: The method of computer simulation of mechanical properties of quenched and tempered steel was established by theoretical analysis of relevant properties which have influence on hardness of quenched and tempered steel, and by regression analysis based on experimental results.

Findings: The new method of prediction of mechanical properties of quenched and tempered steel was established. Proposed method of computer simulation of mechanical properties of quenched and tempered steel is based on predicted steel hardness. Hardness distribution of quenched and tempered workpiece of complex form was predicted by computer simulation of steel quenching using a finite volume method. It was found out that mechanical properties of quenched and tempered steel can be successfully predicted by proposed method.

Research limitations/implications: The investigation was done on carbon and low alloyed steel. The further experimental investigations are needed for final verification of established model.

Practical implications: The established method could be applied in industrial practice.

Originality/value: As-quenched hardness distribution is predicted by involving the results of simple Jominy-test in numerical modelling of steel quenching. Estimation of hardness distribution is based on time, relevant for structure transformation, i.e., time of cooling from 800 to 500°C ($t_{8/5}$). The distribution of mechanical properties in quenched and tempered steel workpiece is estimated based on as-quenched steel hardness, tempering temperature and Jominy-test results.

Keywords: Heat treatment; Computer simulation; Mechanical properties; Yield strength; Toughness; Quenching and tempering

Reference to this paper should be given in the following way:
B. Smoljan, D. Iljkić, N. Tomašić, Computer simulation of mechanical properties of quenched and tempered steel specimen, Journal of Achievements in Materials and Manufacturing Engineering 40/2 (2010) 155-159.

1. Introduction

Mechanical properties, i.e., hardness, yield strength, toughness and fatigue properties are in relation with each other [1]. Hardness distribution in quenched steel specimen could be predicted by computer simulation, and after that other mechanical properties of steel can be predicted based on hardness distribution. The numerical simulation of hardness distribution in quenched steel specimen is one of the highest priorities in simulation of phenomena of steel quenching and in prediction of mechanical properties of quenched steel specimen [2-5]. All mechanical properties of quenched steel directly depend on the degree of quenched steel hardening [6].

Mathematical model of steel quenching can be based on calculated characteristic time of cooling $t_{8/5}$ [7, 8]. The hardness at specimen points can be estimated by the conversion of cooling time results to hardness by using both, the relation between cooling time and distance from the quenched end of Jominy specimen and the Jominy hardenability curve. The time of cooling at specimen point can be predicted by numerical simulation of cooling using the finite volume method [9-11].

Usually two main problems have to be solved in simulation of steel quenching: (1) simulation of temperature field change, and based on it (2) simulation of mechanical properties.

2. Algorithm for prediction of mechanical properties of quenched and tempered steel

High hardness decrease at tempering much more than low hardness, the prediction is more precise if the degree of hardening is accounted. Except of degree of hardening, hardness after tempering depends on steel properties.

The hardness at specimen points in the quenched and tempered state can be estimated from the as-quenched hardness, HRC_{quenched}, by [12]:

$$HRC_{\text{tempered}} = \frac{HRC_{\text{quenched}} - HRC_{\min}}{K} + HRC_{\min} \tag{1}$$

where $HRC_{\min}$ is the materials constant. K is the factor between as-quenched and tempered hardness. Factor K can be expressed by:

$$K = C_1 \cdot t^{n_1} \exp\left[A\left(\frac{a}{T_{\text{temp}}}\right)^{n_2} - B \right] \tag{2}$$

where T_{temp} [K] is the tempering temperature, t [h] is the time of tempering, while A, B, C_1, a, n_1 and n_2 are the material constants.

The algorithm for prediction of hardness of tempered and quenched steel given by Eq. 1 and Eq. 2 was established by using regression analysis. Results of prediction of hardness of tempered and quenched steel received by established algorithm was compared with results received by German standard DIN 17021 algorithm:

$$HRC_{\text{quenched}} = \left(T_{\text{temp}}/167 - 1.2\right)HRC_{\text{tempered}} - 17 \tag{3}$$

and by algorithm established by E. Just. [13-14]:

$$HRC_{\text{quenched}} = 8 + (HRC_{\text{tempered}} - 8)\exp[C(T_{\text{temp}}/917)^6\,] \tag{4}$$

where C is degree of hardening.

Regression analysis made on huge number of carbon and low alloyed steels showed that R-square for established algorithm (Eq. 1, Eq. 2) was equal to 0.9567, much higher than for two other algorithms. For German standard DIN 17021 algorithm R-square was equal to 0.7541, and for algorithm established by E. Just R-square was equal to 0.9093.

Tensile test properties of quenched steel or quenched and tempered steel directly depends on degree of quenched steel hardening [1, 14]. Relation between hardness, HV, and ultimate tensile stress, R_{m} [Nmm^{-2}] is equal to:

$$R_{\text{m}} = 3.3HV \tag{5}$$

Yield strength, $R_{\text{p0.2}}$ [Nmm^{-2}], percent elongation, A [%], and percent reduction of area, Z [%], could be estimated from the ultimate tensile stress or hardness [13-14]:

$$R_{\text{e}} = R_{\text{p0.2}} = \left(0.8 + 0.1C\right)R_{\text{m}} + 170C\text{-}200 \tag{6}$$

$$A = 46 - \left(0.04 - 0.012C\right)R_{\text{m}} \tag{7}$$

$$Z = 96 - \left(0.062 - 0.029C\right)R_{\text{m}} \tag{8}$$

Coefficient C which is ratio between the actual hardness and hardness of martensite in Rockwell C hardness, should be taken in account since as-quenched and quenched and tempered steel properties depends on degree of quenched steel hardening [1].

3. Prediction of hardness and yield strength distribution in workpiece of complex form

The established method is applied in prediction of mechanical properties of quenched and tempered steel shaft made of Ck45 steel (EN). The chemical composition of investigated steel is shown in Table 1. Jominy-test results of Ck45 steel (EN) are shown in Table 2. Geometry of steel shaft is shown in Fig. 1. The steel shaft was quenched in oil with the severity of quenching equal to 0.7. The tempering temperature was 500 °C. Parameters of heat treatment of shaft are shown in Table 3.

Table 1.
Chemical composition of Ck45 steel (EN)

Chemical composition [wt.%]						
C	Si	Mn	P	S	Cr	V
0.44	0.22	0.66	0.022	0.029	0.15	0.02

The model of quenching is based on finite volume method. The hardness distribution in the quenched workpiece is estimated based on time of cooling from 800 to 500 °C, $t_{8/5}$, and on results of the Jominy-test. The prediction of distribution of yield strength is based on steel hardness. The as-quenched hardness distribution in the quenched and tempered steel shaft is shown in Fig. 2. Hardness distribution in the quenched and tempered steel shaft is shown in Fig. 3.

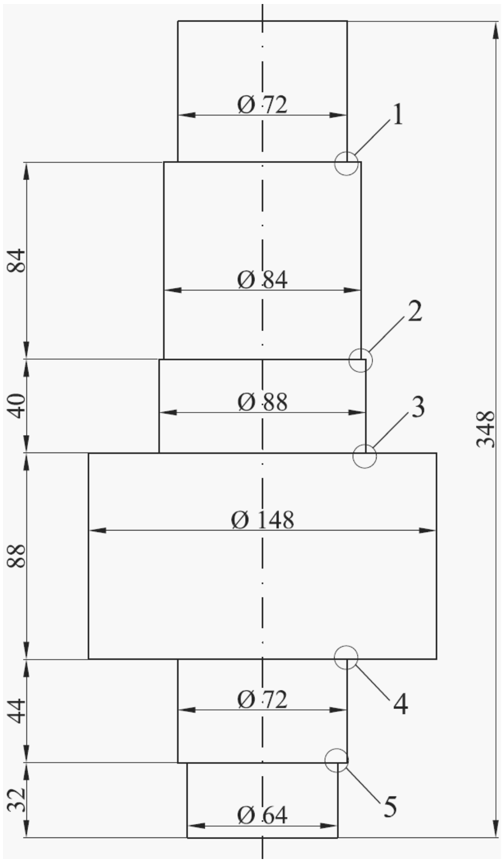

Fig. 1. Geometry of steel shaft

In some critical location experimental verification of established model was done. In Table 4 hardness at critical locations of the quenched and tempered steel shaft made of Ck45 steel (EN) is shown. It is visible that differences between simulated and experimental evaluated hardnesses could be neglected.

The distribution of yield strength in quenched and tempered steel shaft was predicted based on predicted values of quenched and tempered steel hardness. Yield strength distribution in the quenched and tempered steel shaft Fig. 4.

4. Conclusions

A new mathematical model for prediction of hardness of quenched and tempered steel workpiece is established. In proposed model material properties and parameters of heat treatment should be taken into account.

A developed mathematical model has been applied in computer simulation of a quenched and tempered steel shaft. The computer simulation is based on finite volume method.

The as-quenched hardness distribution in the quenched workpiece is estimated based on time of cooling from 800 to 500°C, $t_{8/5}$, and on results of the Jominy-test.

Hardness of the quenched and tempered workpiece is predicted based on as-quenched hardness and temperature of tempering.

The prediction of distribution of yield strength is based on steel hardness distribution.

Based on experimental verification it could be concluded that mechanical properties of quenched and tempered steel workpieces can be successfully calculated by the proposed method.

Table 2.
Jominy-test results of steel Ck45 (EN)

Jominy distance [mm]	1.5	3	5	7	9	11	13	15	20	25	30
Hardness [HV]	57	55	42	32	30	29	28	27	25	23	21
Jominy distance [mm]	35	40	45	50	55	60	65	70	75	80	-
Hardness [HV]	20	18	17	16	15	15	14	14	14	14	-

Table 3.
Parameters of heat treatment of shaft

Austenitizing			Quenching	Tempering		
Temperature	Time	Media	Media	Temperature	Time	Media
850 °C	1 hour	air	oil, H = 0.70	500 °C	1 hour	air

Table 4.
Hardness at critical locations and hardness distribution of the quenched and tempered steel shaft

Hardness	Location in Fig. 1				
	1	2	3	4	5
Simulation [HRC]	25.0	26.0	23.2	23.2	25.6
Experimental [HRC]	27.0	27.9	25.6	25.6	27.6
Difference [HRC]	2.0	1.9	2.4	2.4	2.0

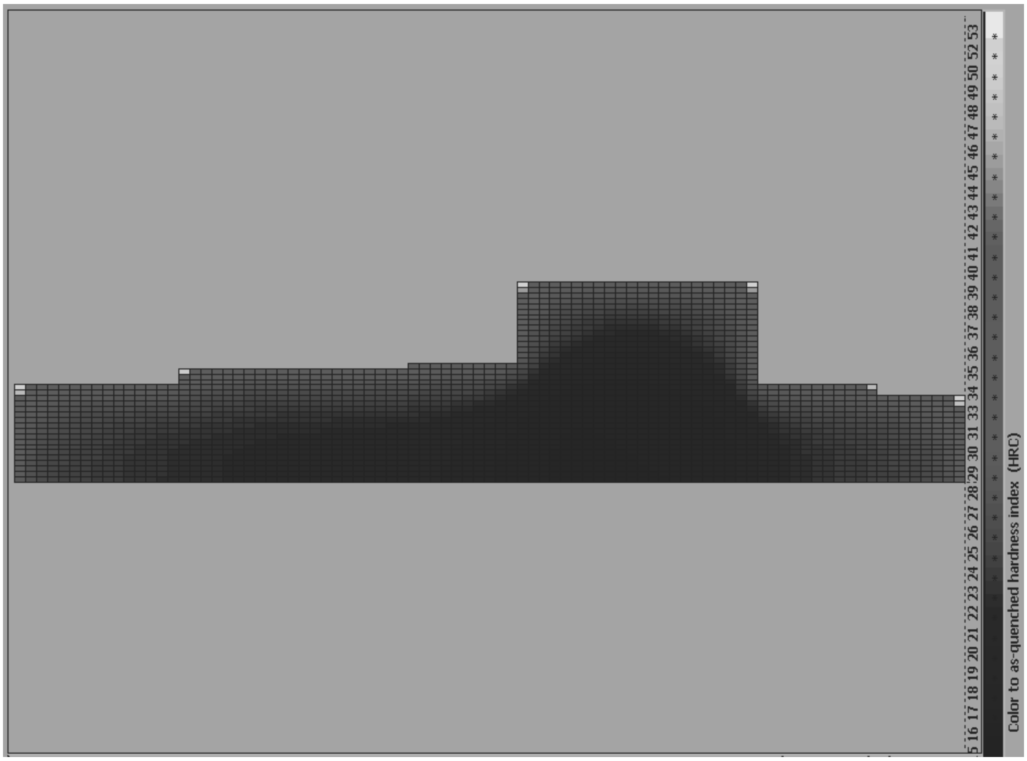

Fig. 2. Distributions of as-quenched hardness

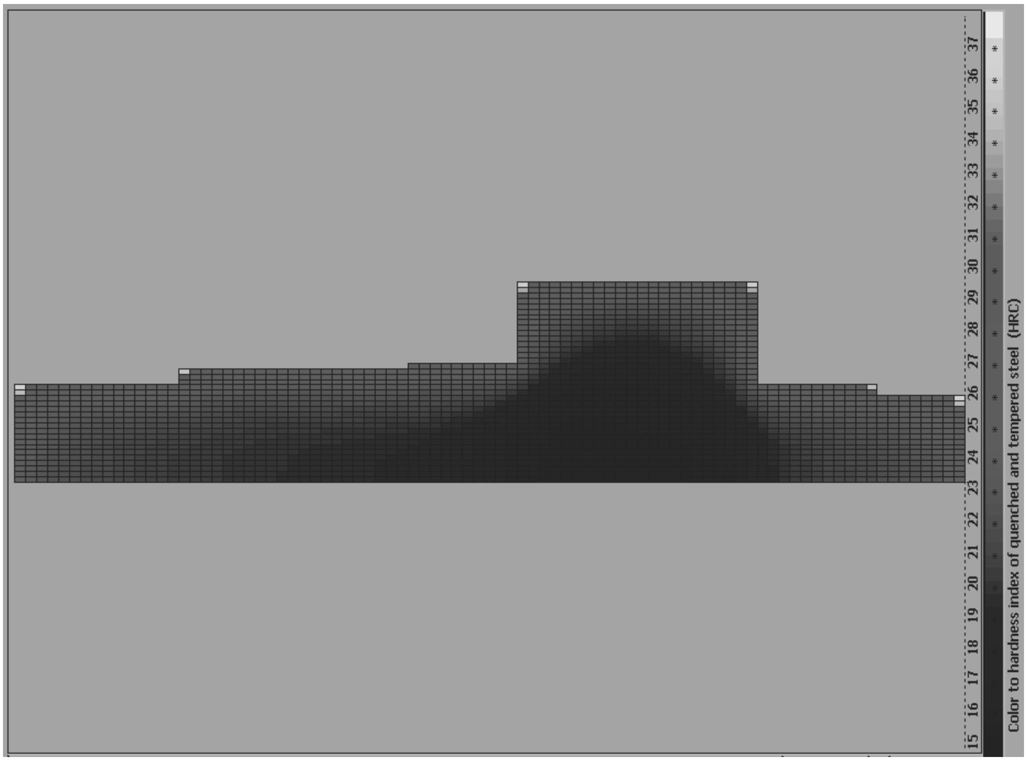

Fig. 3. Hardness distribution in the quenched and tempered steel shaft

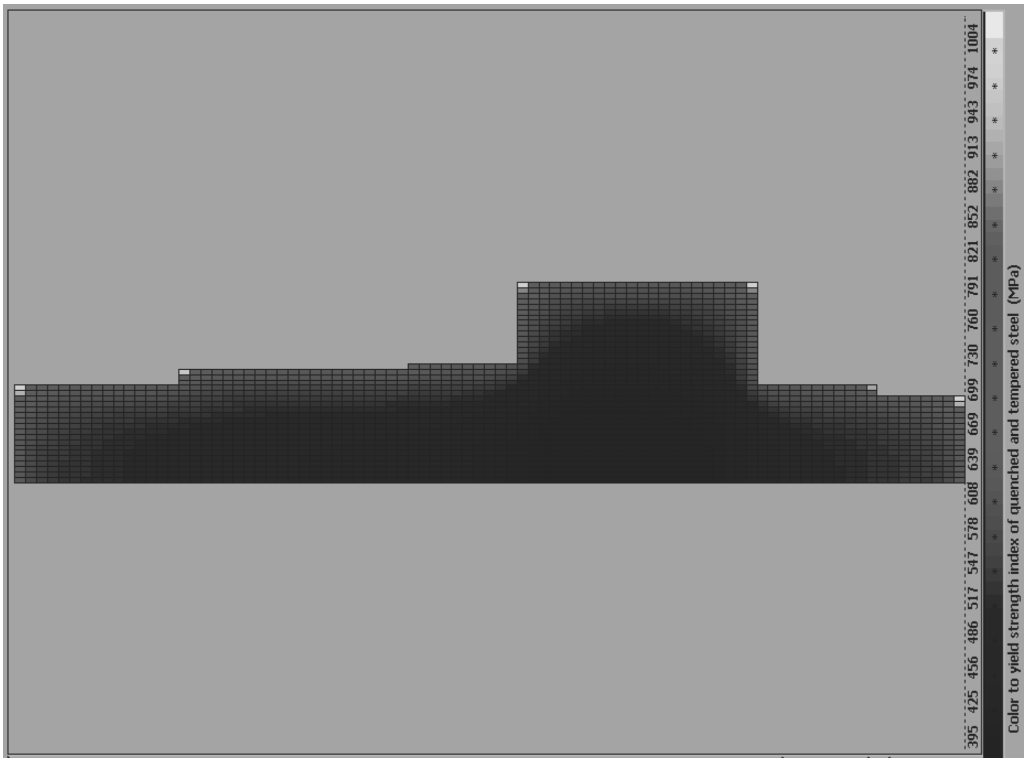

Fig. 4. Yield strength distribution in the quenched and tempered steel shaft

References

[1] B. Smoljan, Prediction of mechanical properties and microstructure distribution of quenched and tempered steel shaft, Journal of Materials Processing Technology 175/1 (2006) 393-397.

[2] L.A. Dobrzański, W. Sitek, The modelling of hardenability using neural networks, Journal of Materials Processing Technology 92-93 (1999) 8-14.

[3] L.A. Dobrzański, J. Trzaska, Application of Neural Networks to Forecasting the CCT diagrams, Journal of Materials Processing Technology 157-158 (2004) 107-113.

[4] P. Bała, J. Pacyna, J. Krawczyk, The kinetics of phase transformations during tempering of Cr-Mo-V medium carbon steel, Journal of Achievements in Materials and Manufacturing Engineering 20 (2007) 79-82.

[5] J. Trzaska, L.A. Dobrzański, A. Jagiełło, Computer programme for prediction steel parameters after heat treatment, Journal of Achievements in Materials and Manufacturing Engineering 24/2 (2007) 171-174.

[6] B. Smoljan, D. Iljkić, F. Traven, Predictions of Mechanical Properties of Quenched and Tempered Steel, Strojniški Vestnik 56 (2010) 115-120.

[7] B. Smoljan, The Calibration of the Heat Conductivity Coefficient in Mathematical Model of Steel Quenching, Proceedings of the Conference MicroCAD`99, Miskolc, Hungary, 1999.

[8] B. Smoljan, The Calibration of the Mathematical Model of Steel Quenching, Proceedings of the 5th World Seminar "Heat Treatment and Surface Engineering" Isfahan, 1995, 709-715.

[9] B. Smoljan, D. Iljkić, S. Smokvina Hanza, Computer simulation of working stress of heat treated steel specimen, Journal of Achievements in Materials and Manufacturing Engineering 34/2 (2009) 152-158.

[10] S. Patankar, Numerical Heat Transfer and Fluid Flow, McGraw Hill Book Company, New York, 1980, 60.

[11] B. Smoljan, Numerical simulation of as-quenched hardness in a steel specimen of complex form, Communications in Numerical Methods in Engineering 14/1 (1998) 277-285.

[12] B. Smoljan, S. Smokvina Hanza, D. Iljkić, G. E. Totten, I. Felde, Computer simulation of mechanical properties of steel dies, Proceedings of the 2nd International Conference "Heat Treatment and Surface Engineering of Tools and Dies", Ljubljana, Slovenia, 2008, 154-155.

[13] B. Liščić, T. Filetin, Computer-aided Determination of the Process Parameters for Hardening and Tempering Structural Steels, Heat Treatment of Metals 3 (1987) 62-66.

[14] T. Filetin, B. Liščić, J. Galinec, New Computer-aided Method for Steel Selection based on Hardenability, Heat Treatment of Metals 3 (1996) 63-66.