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Simulation of mechanical properties of forged and casted steel 42CrMo4 specimen

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Properties

ABSTRACT

Purpose: In this paper, the prediction of working stress of quenched and tempered shaft has been done. Prediction was done for two different manufacture processes. In the first manufacture process the shaft was made of steel and in second one the shaft was made of cast steel. The working stress was characterized by yield strength and impact toughness. The method of computer simulation of working stress was applied in workpiece of complex form.
Design/methodology/approach: Hardness distribution of quenched and tempered workpiece of complex form was predicted by computer simulation of quenching using a finite volume method. Hardness of quenched and tempered steel can be expressed as function of maximal hardness of actual steel, hardness of steel with 50% of martensite in microstructure, according to the time and temperature of tempering. The algorithm of estimation of yield strength and impact energy was based on hardness, HV. Starting point in studying of the mechanical properties of steel castings can be the fact that the mechanical properties of steel castings are derived from the mechanical properties of ordinary steel metal matrix reduced by the influence of the typical as-cast structure, i.e. casting defects on those properties. Hardness and yield strength will be unaffected by most defects. The only effect will be that due to the reduction in area. Coarse as-cast microstructure of cast steel lowers ductility and toughness. Impact energy of quenched and tempered cast steel was predicted based on pouring temperature, temperature of mould during the pouring and fact that steel castings are not subjected to different metallurgical and mechanical processes of microstructure improvement in so far as wrought steels.
Findings: It can be concluded that working stress of quenched and tempered shaft can be successfully predicted by proposed method.
Practical implications: Estimation of hardness distribution can be based on time, relevant for structure transformation, i.e., time of cooling from 800 to 500°C ($t_{8/5}$). The prediction of yield strength and toughness of steel can be based on steel hardness. The prediction of impact toughness of quenched and tempered cast steel can be based on impact toughness of quenched and tempered steel.
Originality/value: Hardness distribution is predicted by involving the results of simple experimental test, i.e., Jominy-test in numerical modelling of steel quenching. Algorithm of estimation of hardness of quenched and tempered steel was improved. New algorithm of prediction of impact energy of quenched and tempered steel cast was found.
Keywords: Steel; Cast steel; Heat treatment; Computer simulation; Mechanical properties

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1. Introduction

Mechanical properties, i.e., hardness, yield strength and toughness are in relation with each other [1]. All mechanical properties of quenched steel directly depend on the degree of quenched steel hardening [2,3]. Hardness distribution in quenched steel specimen could be predicted by computer simulation, and after that yield strength and toughness 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 [4-7].

Two main problems should be solved in simulation of steel quenching: prediction of temperature field change, and prediction of microstructure composition. Mathematical model of microstructure composition in quenched steel can be based on characteristic time of cooling from 800 to 500°C ($t_{8/5}$) during the quenching [8,9]. 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 [10,11].

2. Prediction of quenched and tempered steel hardness

The referent hardness at specimen points in the quenched and tempered state can be estimated from the as-quenched hardness, $\mathrm{HRC}_{\mathrm{quenched}}$, by [2,3,12]:

$$\mathrm{HRC}_{\mathrm{tempered}} = \frac{\mathrm{HRC}_{\mathrm{quenched}} - \mathrm{HRC}_{\min}}{K} + \mathrm{HRC}_{\min} \tag{1}$$

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

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

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, that are established by regression analysis of hardness of quenched and tempered steel. The algorithm for prediction of hardness of tempered and quenched steel given by Equation 1 and Equation 2 was established by regression analysis.

3. Prediction of quenched and tempered steel microstructure

Microstructure composition of as-quenched steel depends on the chemical composition, severity of cooling, austenitizing temperature and steel history. Actual steel hardness is function of microstructure composition:

$$\mathrm{HV} = \left\{ \begin{matrix} (\%\mathrm{ferrite} + \%\mathrm{pearlite})\mathrm{HV}_{(\mathrm{F+P})} + \\ + (\%\mathrm{bainite})\mathrm{HV}_{(\mathrm{B})} + (\%\mathrm{martensite})\mathrm{HV}_{(\mathrm{M})} \end{matrix} \right\} \Big/ 100 \tag{3}$$

Amount of phase's portions is equal unity:

$$\{(\%\mathrm{ferrite} + \%\mathrm{pearlite}) + \%\mathrm{bainite} + \%\mathrm{martensite}\}/100 = 1 \tag{4}$$

The austenite decomposition results can be estimated based on time, relevant for structure transformation. The characteristic cooling time relevant for structure transformation for most structural steels, is the time $t_{8/5}$. If other heat treatment parameters are constant, the austenite decomposition results in some location of a cooled specimen will depend only on the time $t_{8/5}$. It could be written for *Jominy* specimen that phase hardness depends on chemical composition and cooling rate parameter that corresponds to actual distance d of *Jominy* specimen quenched end. It was adopted that cooling rate parameter is equal to $\log(t_{8/5})$ [13].

$$\mathrm{HV}_{\mathrm{d}}^{\mathrm{M}} = \mathrm{HV}_{\max}^{\mathrm{M}} - K_{\mathrm{M}} \log \frac{t_{8/5d}^{\mathrm{M}}}{t_{8/5\max}^{\mathrm{M}}} \tag{5}$$

$$\mathrm{HV}_{\mathrm{d}}^{\mathrm{B}} = \mathrm{HV}_{\max}^{\mathrm{B}} - K_{\mathrm{B}} \log \frac{t_{8/5d}^{\mathrm{B}}}{t_{8/5\max}^{\mathrm{B}}} \tag{6}$$

$$\mathrm{HV}_{\mathrm{d}}^{\mathrm{P+F}} = \mathrm{HV}_{\mathrm{N}}^{\mathrm{P+F}} + K_{\mathrm{P+F}} \log \frac{t_{8/5N}^{\mathrm{P+F}}}{t_{8/5d}^{\mathrm{P+F}}} \tag{7}$$

where N is normalizing, and $\mathrm{HV}_{\max}^{\mathrm{B}}$ is hardness of lower bainite. Characteristic value of HV, K_M, K_B, K_{P+F} and $t_{8/5}$ in Eq. 5, Eq. 6 and Eq. 7 has to be evaluated for investigated steel combined with *Jominy* test results. Hardness of quenched structures with characteristic percentage of martensite can be predicted by using the diagram of hardness at different percentages of martensite vs. carbon content after Hodge and Orehoski [14] and *Jominy* curve. Similar as for martensite, the regression relations between the time $t_{8/5}$ and characteristic pearlite fractions have to be established [13]. If the total hardness in some location is known and hardness of microstructure constituents separately are known, and if the phase fraction of one of microstructure constituents is known, it is not difficult to predict fractions of other phases by the Eq. 3 and Eq. 4.

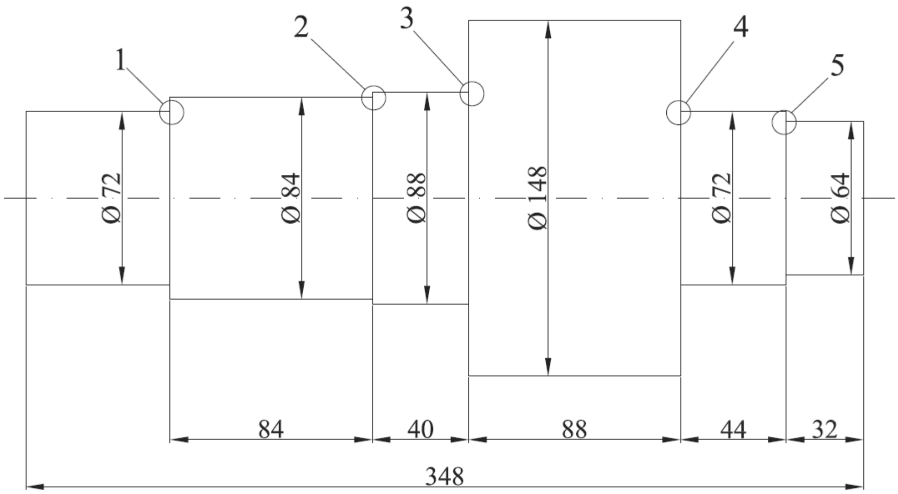

Fig. 1. Geometry of steel shaft

4. Prediction of quenched and tempered steel mechanical properties

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

$$R_{m} = 3.3\mathrm{HV} \quad (8)$$

Relation between hardness, HV, and yield strength, $R_{p0.2}$ [Nmm^{-2}] is equal to [15]:

$$R_{e} = R_{p0,2} = (0.8 + 0.1C)R_{m} + 170C\text{-}200 \quad (9)$$

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].

Impact energy, KU [J], could be estimated from the ultimate tensile stress or hardness [16,17]:

$$\mathrm{KU} = [460 - (0.59 - 0.29C)R_{m}]0.7 \quad (10)$$

Relation between impact energy, KV [J], and impact energy, KU [J] is equal to:

$$\mathrm{KV} = (0.0039\mathrm{KU}^{2} + 0.511\mathrm{KU} - 1.3854) \quad (11)$$

Starting point in studying of the mechanical properties of steel castings can be the fact that the mechanical properties of steel castings are derived from the mechanical properties of ordinary steel metal matrix reduced by the influence of the typical as-cast structure, i.e. casting defects on those properties. Hardness and yield strength will be unaffected by most defects. The only effect on yield strength will be that due to the reduction in area. Since most defects occupy at most only a few per cent of the area of the casting, this effect is usually hardly detectable. Coarse as-cast microstructure of cast steel lowers ductility and toughness. Impact toughness of quenched and tempered cast steel was predicted based on pouring temperature, temperature of mould during the pouring and fact that steel castings are not subjected to different metallurgical and mechanical processes of microstructure improvement in so far as wrought steels.

Relation between impact energy, KV of quenched and tempered cast steel, and impact energy, KV of quenched and tempered steel is equal to:

$$\mathrm{KV}_{SC} = \mathrm{KV}_{S}(a - b\Delta\vartheta_{1} - c\vartheta_{k}) \quad (12)$$

where KV_{SC} [J] is impact energy, KV of cast steel, KV_{S} [J] is impact energy, KV of cast steel, Δq_1 [°C] is diference from optimal temperature of pouring, q_k [°C] is temperature of mould during the pouring, a, b, and c are constants, that are established by regression analysis of impact energy of quenched and tempered cast steel. The expression for prediction of impact energy of quenched and tempered cast steel given by Equation 12 was established by regression analysis.

Fracture toughness, K_{Ic} [Nmm$^{-3/2}$], can be estimated from the mechanical properties obtained by tensile test. The Rolfe-Novak correlation can be successfully used for that purpose [18]:

$$K_{Ic} = \sqrt{6.4R_{e}(100\mathrm{KV} - R_{e})} \quad (13)$$

5. Application

The established method for prediction of yield strength and impact toughness is applied in design of manufacturing process of the shaft made of steel 42CrMo4 (EN). The chemical composition of investigated steel is shown in Table 1. Geometry of steel shaft is shown in Fig. 1.

Jominy test results of the investigated steel, 42CrMo4 (EN) are shown in Table 2.

Table 1.
Chemical composition of steel 42CrMo4 (EN)

Chemical composition [wt.%]						
C	Si	Mn	P	S	Cr	Mo
0.38	0.23	0.64	0.019	0.013	0.99	0.16

Based on the *Jominy* test results the diagram of microstructure composition in dependency of cooling times from 800 to 500°C was done. Calculated microstructure compositions vs. time $t_{8/5}$ of investigated steel is shown in Fig. 2.

Two different manufacture processes of the steel shaft were designed. In the first manufacture process the shaft was made of steel and quenched in oil with the severity of quenching equal to 0.2 and tempered at 560°C. In the second manufacture process the shaft was made of cast steel. In this manufacture process the pouring temperature was 1514°C and the temperature of mould during the pouring was 105°C. After that the shaft made of cast steel was quenched in oil with the severity of quenching equal to 0.2 and tempered at 560°C. Parameters of these two manufacture processes are shown in Table 3.

Distributions of hardness of as-quenched workpiece are shown in Fig. 3. Distributions of hardness of quenched and tempered workpieces are shown in Fig. 4.

Critical location for crack growth are locations 1, 2, 3, 4 and 5 (Fig. 2). Microstructure composition and mechanical properties in critical locations of steel shaft for quenching in oil with the severity of quenching equal to 0.2 and tempering at 560°C are shown in Table 4.

Microstructure composition and mechanical properties in critical locations of cast steel shaft for quenching in oil with the severity of quenching equal to 0.2 and tempering at 560°C are shown in Table 5.

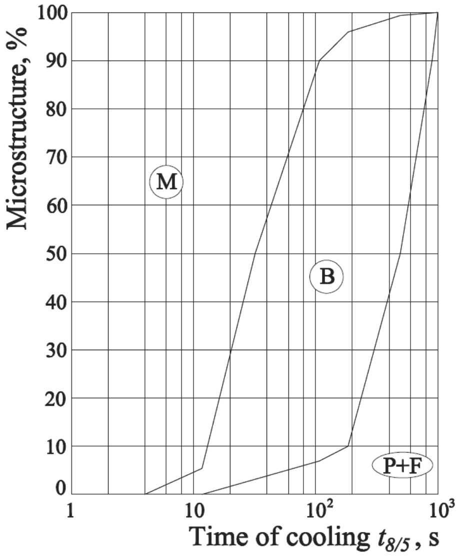

Fig. 2. Microstructure compositions vs. time $t_{8/5}$; (P+F) - Pearlite + Ferrite; B - Bainite; M - Martensite

Table 2.
Jominy test results of steel 42CrMo4 (EN)

Jominy distance [mm]	1.5	3	5	7	9	11	13	15	20	25	30
Hardness, HV	610	605	590	576	555	524	487	446	379	344	324
Jominy distance [mm]	35	40	45	50	55	60	65	70	75	80	-
Hardness, HV	311	303	297	293	292	291	289	288	288	288	-

Table 3.
Parameters of two different manufacture processes of steel shaft

Number	Forging / Casting	Quenching		Tempering	
		Temperature	Quenchant	Temperature	Time
1	Forged	850 °C	poor oil quench - no agitation H = 0.2	480°C	1 hour
2	Casted	850 °C	poor oil quench - no agitation H = 0.2	480°C	1 hour

Table 4.
Microstructure composition and mechanical properties in critical locations of quenched and tempered steel shaft

Properties		Critical location (Fig. 2)				
		1	2	3	4	5
Phase fractions [%]	F+P	5.2	5.6	7.1	7.1	4.7
	B	66.6	69.8	83.2	83.2	61.3
	M	28.2	24.6	9.7	9.7	34.0
Hardness, HV		218	216	206	206	224
Tensile strength R_m [Nmm^{-2}]		720	712	678	678	741
Yield strength R_e [Nmm^{-2}]		541	531	483	483	570
Impact energy KV [J]		124	124	121	121	124
Fracture toughness K_{Ic} [$MPam^{1/2}$]		202	200	189	189	208

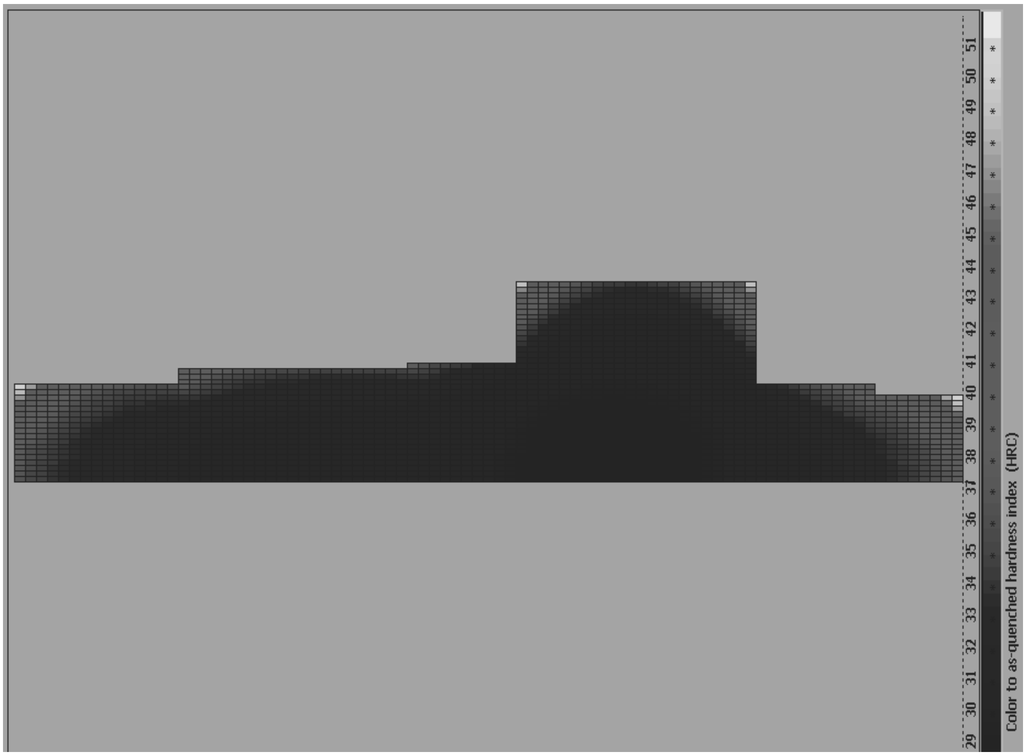

Fig. 3. Distributions of hardness of as-quenched workpiece

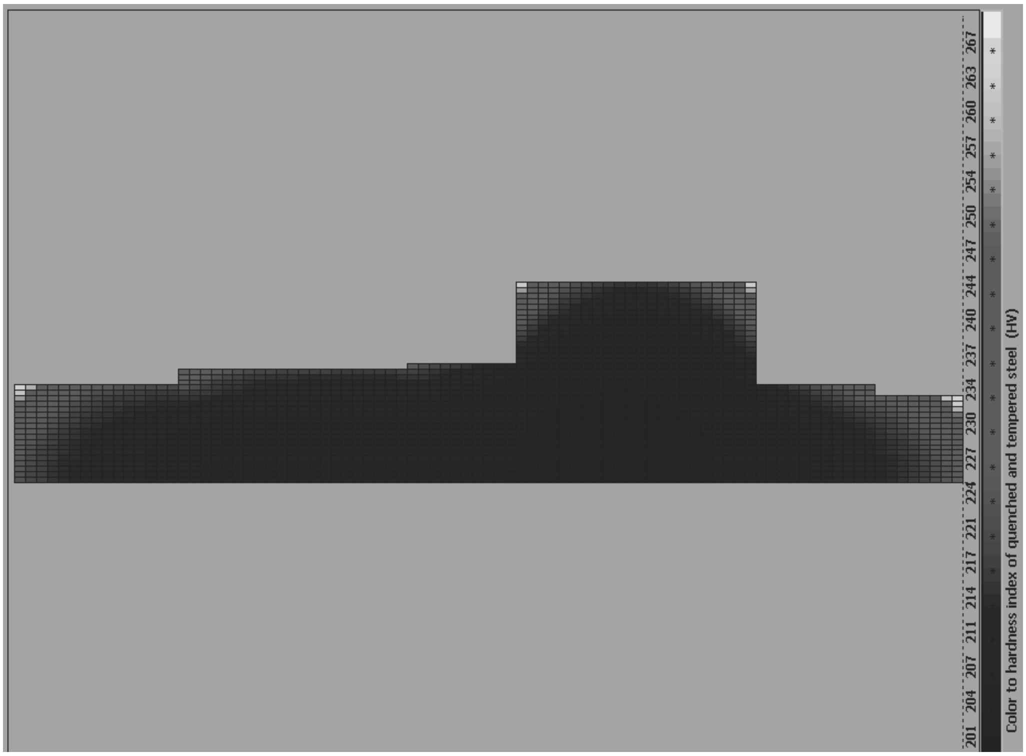

Fig. 4. Distributions of hardness of quenched and tempered workpiece

Table 5.
Microstructure composition and mechanical properties in critical locations of quenched and tempered cast steel shaft

Properties		Critical location (Fig. 2)				
		1	2	3	4	5
Phase fractions [%]	F+P	5.2	5.6	7.1	7.1	4.7
	B	66.6	69.8	83.2	83.2	61.3
	M	28.2	24.6	9.7	9.7	34.0
Hardness, HV		218	216	206	206	224
Tensile strength R_m [Nmm^{-2}]		720	712	678	678	741
Yield strength R_e [Nmm^{-2}]		541	531	483	483	570
Impact energy KV [J]		58	58	57	57	58
Fracture toughness K_{Ic} [$MPam^{1/2}$]		135	133	126	126	138

6. Conclusions

A mathematical model for prediction of mechanical properties of quenched and tempered steel was developed. The model is based on finite volume method. The mathematical model has been applied in optimization of the manufacturing of a quenched and tempered shaft. 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. Hardness of quenched and tempered steel can be expressed as function of maximal hardness of actual steel, hardness of steel with 50% of martensite in microstructure, according to the time and temperature of tempering. The prediction of distribution of yield strength and impact energy is based on steel hardness.

It can be concluded that mechanical properties of quenched and tempered shaft can be successfully calculated by the proposed method. Proposed method was successfully applied in optimization of the manufacturing of quenched and tempered engineering steel components.

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] B. Smoljan, S. Smokvina Hanza, D. Iljkić, Computer simulation of quenched steel working stress, Journal of ASTM International 5/10 (2008)

[3] 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.

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

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

[6] 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.

[7] 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.

[8] B. Smoljan, The Calibration of the heat conductivity coefficient in mathematical model of steel quenching, Proceedings of the MicroCAD`99, Miskolc, 1999, 143-148.

[9] B. Smoljan, The Calibration of the Mathematical Model of Steel Quenching, Proceedings of the 5th World Seminar on Heat Treatment and Surface Engineering, Isfahan, Eds. M. Salehi, ISSST and IFHT 1 (1995) 709-715.

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

[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] T. Reti, I. Felde, M. Guerrero, S. Sarmiento, Using generalized time-temperature parameters for predicting the hardness change occurring during tempering, Proceedings of the International Conference on New Challenges in Heat Treatment and Surface Engineering (Conference in honour of Prof. Božidar Liščić), Dubrovnik-Cavtat, Croatia, 2009.

[13] B. Smoljan, Computer simulation of microstructure transformation during the quenching, Proceedings of the 1st International Surface Engineering Congress and 13th IFHTSE Congress (ASM International), Columbus, Ohio, 2002.

[14] B. Smoljan, M. Butković, Simulation of mechanical properties of hardened steel, Proceedings of the MicroCAD'98, Miskolc, 1998, 3-9.

[15] B. Smoljan, Numerical simulation of steel quenching, Journal of Materials Engineering and Performance 11/1 (2002) 75-80.

[16] E. Just, Verguten-Werkstoffbeeinflussung durch Harten und Anlassen, VDI-Berichte 256 (1976) 125-140.

[17] 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.

[18] Impact Toughness Testing. In section: Impact Toughness Testing and Fracture Mechanics. ASM Handbook - Volume 8: Mechanical Testing and Evaluation, Material Park, ASM International, Ohio, 2000.