Archives of Materials Science and Engineering

Volume 74
Issue 2
August 2015
Pages 85-93

International Scientific Journal published monthly by the World Academy of Materials and Manufacturing Engineering

Mathematical modelling of hardness of quenched and tempered steel

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

ABSTRACT

Purpose: In this paper a new mathematical model and expressions for prediction of hardness of quenched and tempered steel was established.

Design/methodology/approach: Novel mathematical expression for prediction of hardness of quenched and tempered steel was established. This expression includes tempering temperature, hardenability properties and degree of hardening. By experimental work it was found out that results of quenching and tempering are related to hardenability properties of steel.

Findings: Based on experimental work it was found out that prediction of hardness of quenched and tempered steel is more precise by novel mathematical expression than by relation according to the German standard DIN 17021, or than by relation established by Just, E.

Research limitations/implications: By taking into account the hardenability properties of steels, influence of diffusivity on kinetic of tempering processes is indirectly taken into account in the mathematical modeling of tempering processes without using the chemical composition of steel.

Practical implications: The established relations were applied in mathematical modeling and computer simulation of quenching and tempering of shaft made of low alloyed steel. It was found out that hardness of quenched and tempered steel workpieces can be successfully calculated by the proposed method.

Originality/value: Hardenability properties of steel are included in the established relation to achieve more precise prediction of quenched and tempered steel hardness. The influence of diffusivity on kinetic of tempering processes is indirectly taken into account in the mathematical modeling of tempering processes without using the chemical composition of steel.

Keywords: Steel; Quenching and tempering; Hardness; Computer simulation

Reference to this paper should be given in the following way:

B. Smoljan, D. Iljkić, N. Tomašić, Mathematical modelling of hardness of quenched and tempered steel, Archives of Materials Science and Engineering 74/2 (2015) 85-93.

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Mathematical modeling of mechanical properties of quenched and tempered steel usually starts by mathematical modeling of as-quenched hardness [1]. Mathematical model of as-quenched hardness of steel can be based on characteristic time of cooling from 800°C to 500°C ($t_{8/5}$) during the quenching [2,3]. The time of cooling at specimen point can be predicted by numerical simulation of cooling using the finite volume method [4]. Hardness at specimen points can be estimated by the conversion of results of characteristic cooling time, $t_{8/5}$, to hardness by using both, the relation between cooling time and distance from the quenched end of Jominy specimen and the Jominy hardenability curve [5].

Many mathematical expressions of relation between as-quenched hardness of steel and hardness of steel after quenching and tempering are established [1,6]. Very useful expressions of hardness of steel after quenching and tempering are relations in accordance with German standard DIN 17021 and relation established by E. Just [7]. Both of these expressions assume one hour of duration of tempering.

Table 1.
Experimental results of as-quenched and quenched and tempered properties of steels [8]

Steel	Maximum hardness, HRC_{max}	Referent minimum hardness, HRC_{min}/HV_{min}	Specific Jominy distance, E_d/mm	As-quenched hardness, HRC_q	Hardness after quenching and tempering, HRC_t		
					873 K (600°C)	773 K (500 C)	673 K (400°C)
AISI 1045	57.15	3.49/131	4.72	51.62	24.18	33.30	-
				27.63	20.37	24.66	25.79
EN 28NiCrMo74	51.00	0.74/109	5.06	49.22	20.91	26.57	-
				19.06	14.21	16.47	17.99
EN 37MnSi5	56.88	3.30/130	7.35	53.41	24.69	35.68	46.71
				33.04	21.43	26.13	31.19
EN 71Si7	65.01	13.07/191	8.53	63.49	35.02	45.47	54.97
				48.35	32.96	39.38	-
AISI 5115	41.52	0.10/104	12.77	39.71	20.00	27.49	35.34
				21.36	12.49	18.05	20.18
AISI 4135	51.53	0.87/110	13.83	42.78	26.03	35.19	39.77
				33.51	23.45	29.76	31.69
EN 42MnV7	57.01	3.39/131	13.93	52.28	32.42	38.87	44.68
				36.52	27.06	30.48	34.27
AISI 4130	46.99	0.15/104	14.04	44.20	24.19	34.49	39.25
				29.62	19.71	25.29	28.00
AISI 5132	51.35	0.82/110	17.70	46.37	28.95	36.07	43.47
				36.28	25.45	29.61	34.75
AISI 5140	56.51	3.05/128	21.13	51.59	27.68	37.63	46.77
				36.56	22.72	28.97	33.62
EN 36Cr6	52.52	1.16/112	23.00	48.41	33.10	39.46	-
				36.19	27.97	31.91	34.62
AISI 3115	41.14	0.10/104	38.61	38.81	22.84	32.15	35.77
				27.01	17.17	22.62	24.70

2. Relation between quenched and tempered hardness and as - quenched hardness of steel according to the German standard DIN 17021

In further investigation hardness which steel can achieve after quenching and tempering of one hour duration is accepted as reference value of hardness, HRC_t. And during experimental work, duration of steel tempering is equal to one hour. Hardness at specimen points after quenching and tempering is related to as-quenched hardness. According to the German standard DIN 17021, relation between hardness after quenching, HRC_q and hardness after quenching and tempering, HRC_t is [6]:

$$HRC_q = (\vartheta_t / 167 - 1.2) HRC_t - 17 \qquad (1)$$

where ϑ_t/°C is tempering temperature.

Experimental verification of relation in Eq 1 was made on numerous carbon and low alloyed steels (Table 1). Correlation of hardness values after tempering given by relation according to the German standard DIN 17021 (Eq 1) with experimental results showed that R-square was equal to 0.7541 (Fig. 1).

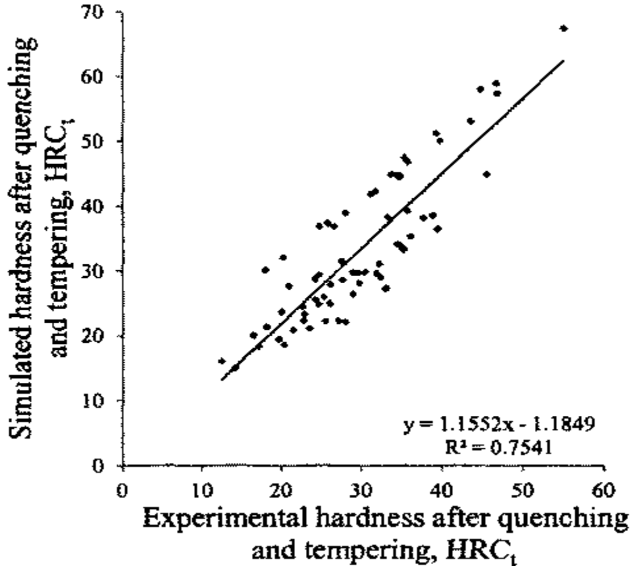

Fig. 1. Comparison of hardness values after tempering given by relation according to the German standard DIN 17021 (Eq 1) with experimental results [8]

Comparison of hardness values after tempering given by algorithm of Just E. (Eq 3) with experimental results was made on numerous carbon and low alloyed steels (Table 1). It was found out that results achieved by Just's relation are more precise than results achieved by relation according to the German standard DIN 17021 (Eq 1). R-square for the algorithm established by Just E. (Eq 3), was equal to 0.9093 (Fig. 2).

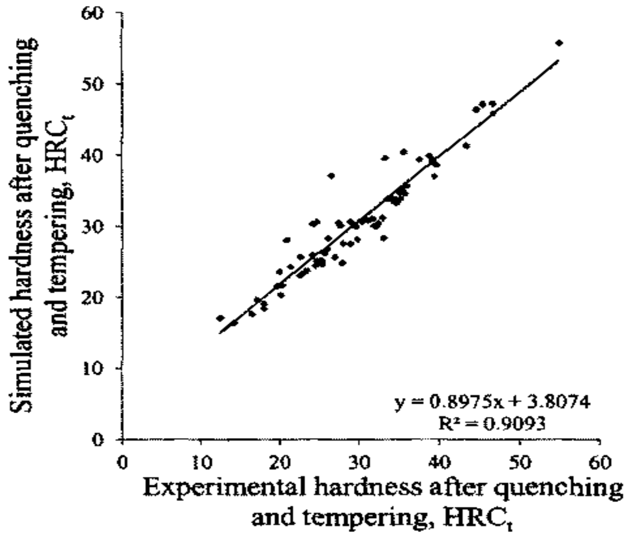

Fig. 2. Comparison of hardness values after tempering given by algorithm established by Just E. (Eq 3) with experimental results [8]

3. Just's relation between quenched and tempered hardness and as-quenched hardness of steel

Just, E. has found out that hardness of steel during the tempering will decrease more if as-quenched hardness is higher. The prediction of hardness after quenching and tempering is more precise if the degree of hardening, S is taken into account:

$$S = \frac{\mathrm{HRC_q}}{\mathrm{HRC_{max}}} \tag{2}$$

where $\mathrm{HRC_q}$ is equal to hardness after quenching and $\mathrm{HRC_{max}}$ is maximum hardness which can be achieved by quenching.

According to Just E., relation between the hardness after quenching, $\mathrm{HRC_q}$ and the hardness after quenching and tempering, $\mathrm{HRC_t}$ is equal to [7]:

$$\mathrm{HRC_q} = 8 + (\mathrm{HRC_t} - 8)\exp[S(T_t/917)^6\,] \tag{3}$$

where T_t/K is tempering temperature.

4. New relation between quenched and tempered hardness and as-quenched hardness of steel

Except of tempering temperature and degree of hardening, hardness after tempering could depend on other steel properties. It is known that kinetic of tempering processes depends on diffusivity of carbon and other elements in steel. At the same time, steels with less diffusivity of carbon and other elements have greater hardenability. It can be presumed that prediction of quenched and tempered steel hardness could be more precise if the hardenability properties of steels are taken into account in the mathematical modelling of kinetic of tempering processes. In this way, the influence of diffusivity on kinetic of tempering processes will be indirectly taken into account by implementation of hardenability properties, without using a chemical composition of steel.

Hardenability properties of steel can be represented by both, the Jominy distance, E_d, which corresponds to the distance with 50 % of martensite in the microstructure of quenched steel and maximum hardness, HRC_{max} (Fig. 3). In Fig. 3 hardness HRC_q is achieved hardness at some specimen distance from quenched end of Jominy specimen. It is known that quenched and tempered hardness is depends on the degree of hardening, S (Fig. 3).

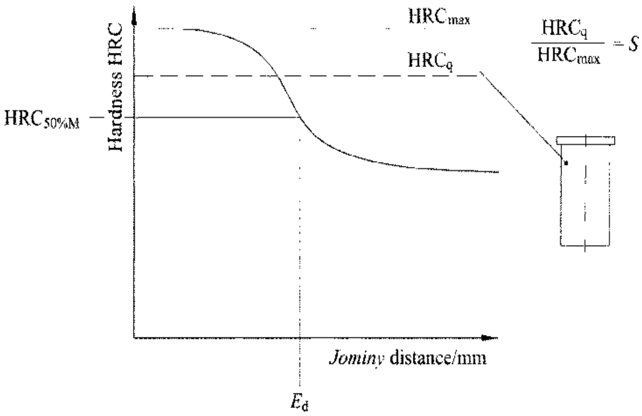

Fig. 3. Characteristic values of Jominy curve

Correlation between hardness of quenched steel with 50% of martensite in the microstructure, $HRC_{50\%M}$, and maximum hardness, HRC_{max} exists [6]:

$$HRC_{50\%M} = 0.73HRC_{max} \tag{4}$$

To establish relation between as-quenched hardness and quenched and tempered hardness of steel an experimental work was done. These relations include hardenability properties for mathematical modelling of tempered hardness of steel.

To improve precision of prediction of hardness of steel after quenching and tempering, hardness HRC_{min} which is material constant which corresponds with hardness of steel after annealing is included in mathematical expressions of hardness [7]. For this reason factor K is included in regression analysis of hardness of quenched and tempered steel:

$$K = \frac{HRC_q - HRC_{min}}{HRC_t - HRC_{min}} \tag{5}$$

Correlations exist between the tempering temperature, degree of hardening, Jominy distance, E_d and factor K. Influences of tempering temperature, degree of hardening, S, and Jominy distance, E_d, on factor K, are shown in Figs. 4-6, respectively.

All investigated values, tempering temperature, degree of hardening, S, Jominy distance, E_d, have correlation with factor K (Figs. 4-6). It is possible to presume that multiple regression exists between factor K on one side, and tempering temperature, degree of hardening S, and Jominy distance, E_d, on the other side [9]:

$$K = \exp\left[\left(\frac{T_{tr}}{a}\right)^{n_1} S^{n_2} E_d^{n_3}\right] \tag{6}$$

where T_{tr}/K is the reference value of tempering temperature. Reference value of tempering temperature of one hour duration of tempering process, is equal to applied tempering temperature. While a, n_1, n_2 and n_3 are constants that are established by regression analysis. Using established values for a, n_1, n_2 and n_3, factor K can be expressed by:

$$K = \exp\left[\left(\frac{T_{tr}}{808.69}\right)^{6.7484} S^{1.1821} E_d^{-0.3232}\right] \tag{7}$$

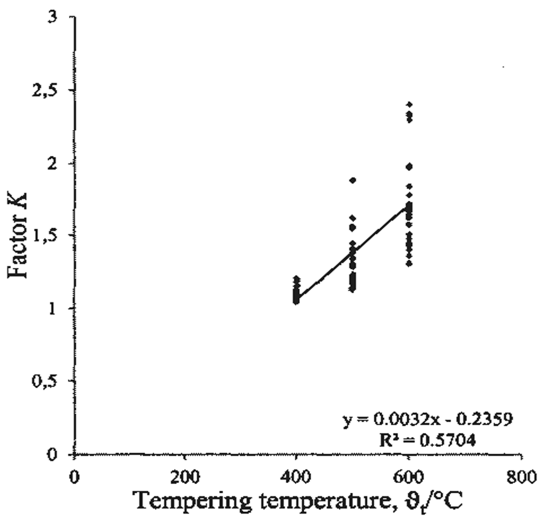

Fig. 4. Influence of the tempering temperature on factor K

Since hardness after quenching and tempering of steel can be expressed based on as-quenched hardness, HRC_q, by [10, 11]:

$$HRC_t = \frac{HRC_q - HRC_{min}}{K} + HRC_{min} \tag{8}$$

Hardness after quenching and tempering of steel can be expressed by [8]:

$$HRC_t = \frac{HRC_q - HRC_{min}}{\exp\left[\left(\frac{T_{tr}}{808.69}\right)^{6.7484} S^{1.1821} E_d^{-0.3232}\right]} + HRC_{min} \tag{9}$$

Comparison of hardness values after quenching and tempering of steel given by established relation (Eq 9), with experimental results was done for numerous carbon and low alloyed steels (Table 1). For established relation (Eq 9) R-square was equal to 0.9567 (Fig. 7).

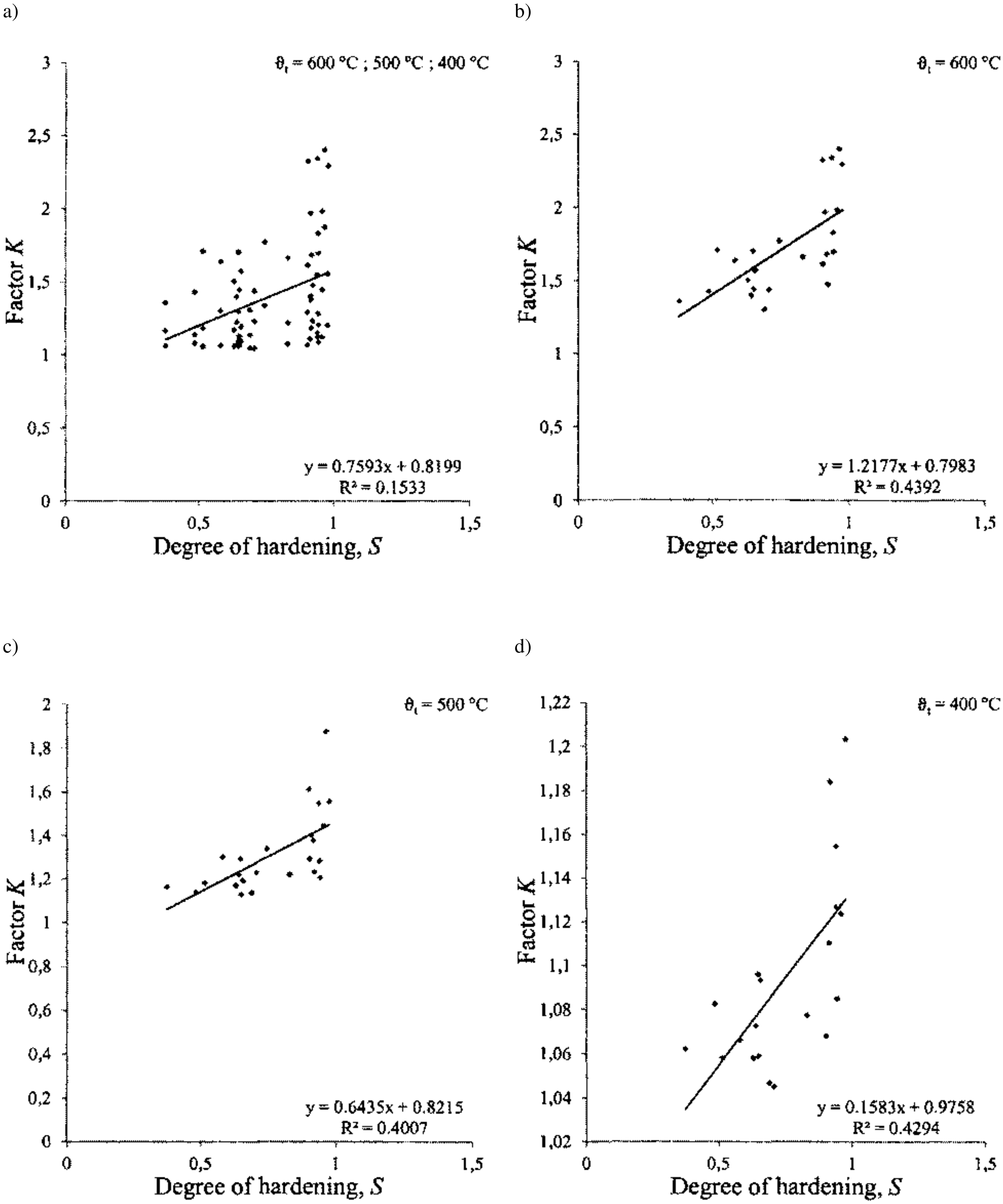

Fig. 5. Influence of the degree of hardening, *S* on factor *K*

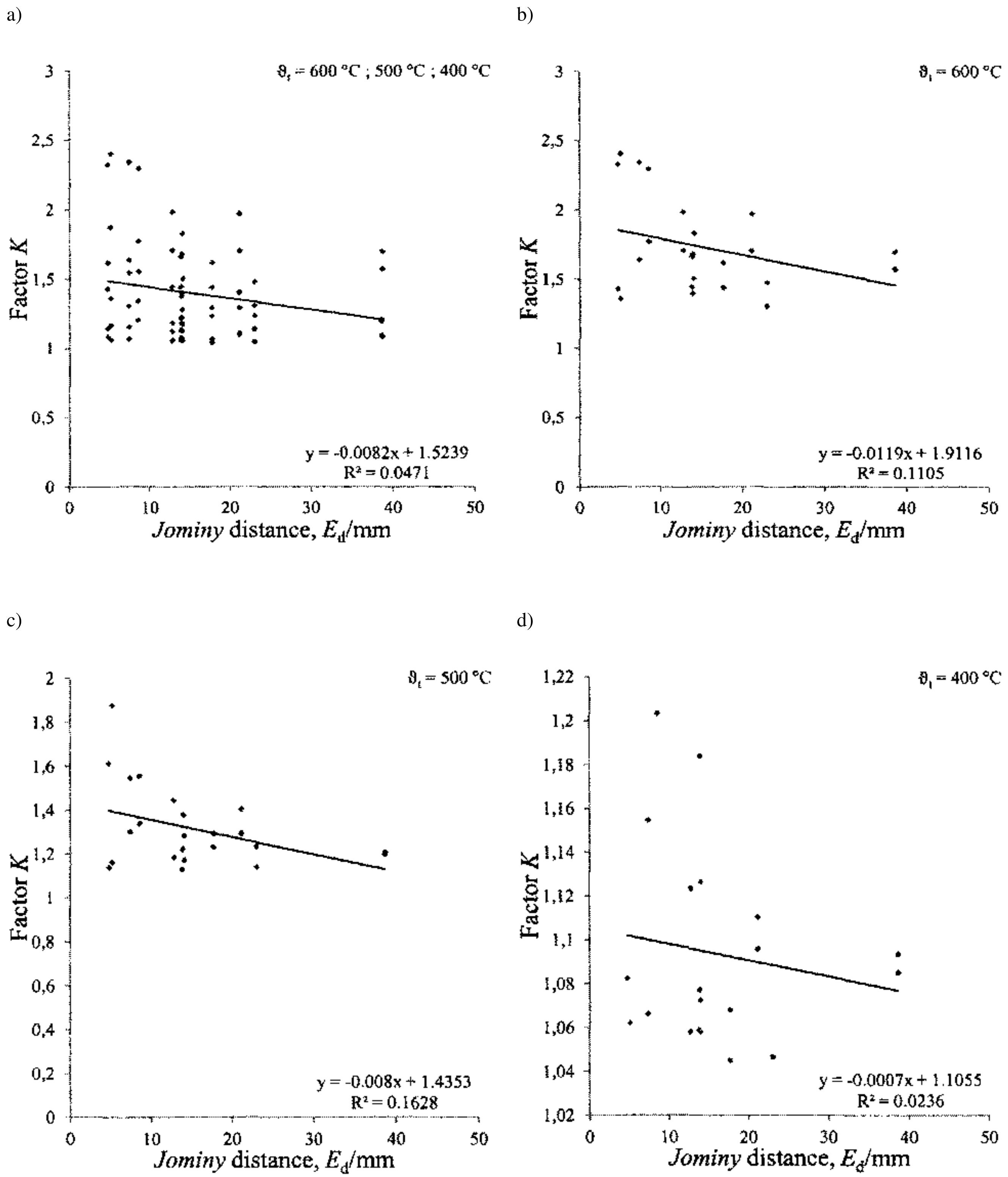

Fig. 6. Influence of the Jominy distance, E_d, which corresponds to the distance with 50 % of martensite in the microstructure on factor *K*

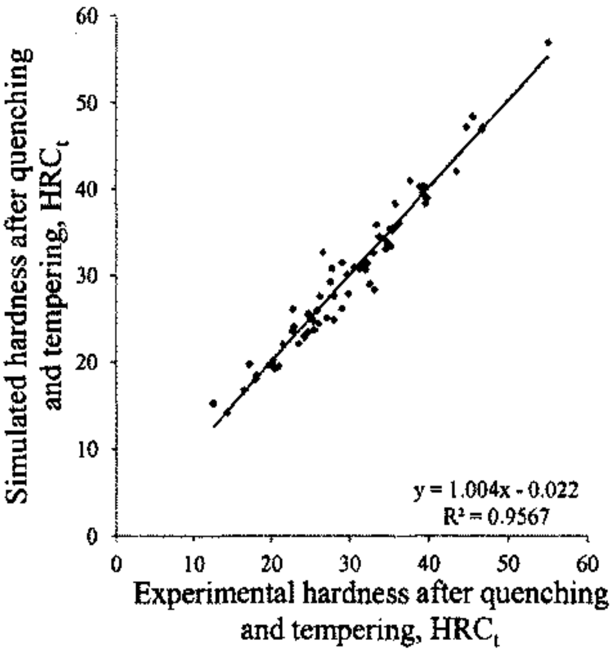

Fig. 7. Comparison of hardness values after tempering given by established algorithm (Eq 9) with experimental results [8]

For algorithm accepted by German standard DIN 17021 (Eq 1), R-square was equal to 0.7541 (Fig. 1), and for algorithm established by Just E. (Eq 3), R-square was equal to 0.9093 (Fig. 2). It is visible that R-square for established relation (Eq 9) is higher than R-square for other two investigated relations.

5. Application

Established mathematical model of hardness of quenching and tempering is applied in the computer simulation of quenching and tempering of the steel shaft. As-quenched hardness of the shaft was predicted by computer program BS-QUENCHING [3].

The shaft was made of steel EN 42CrMo4. The chemical composition of investigated shaft is: 0.38% C, 0.23% Si, 0.64% Mn, 0.019% P, 0.013% S, 0.99% Cr, and 0.16% Mo. Jominy test results of the investigated steel are shown in Table 2. Geometry of the steel shaft is shown in Fig. 8. Shaft was quenched from 1123 K (850°C)/45 min/oil with H-value equal to 0.2. After quenching, shaft was tempered at 753 K (480°C)/60 min/air. Distribution of hardness of the quenched shaft is shown in Fig. 9, and distribution of hardness of the shaft after quenching and tempering is shown in Fig. 10.

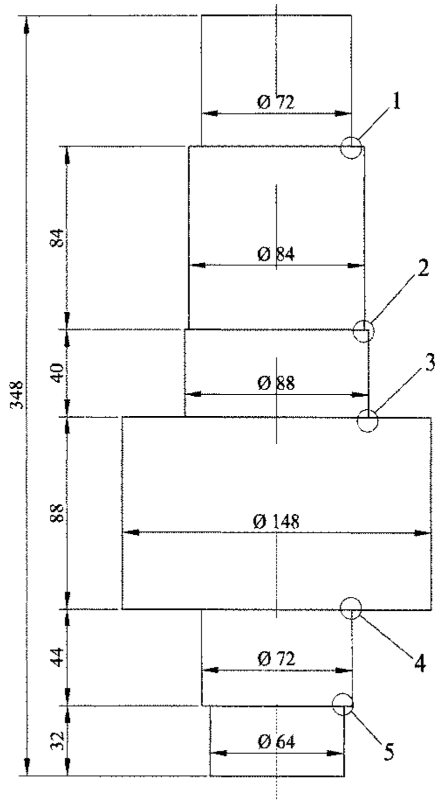

Fig. 8. Geometry of steel shaft

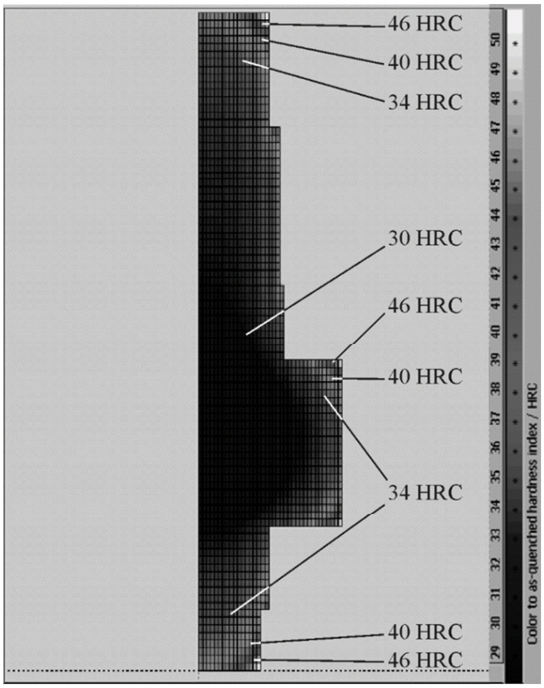

Fig. 9. Distribution of hardness of quenched steel shaft

Table 2.
Jominy test results of steel EN 42CrMo4

Jominy distance/mm	1.5	3	5	7	11	15	20	25	30	40	50
Hardness HRC	55	54	54	53	49	45	39	35	33	31	29

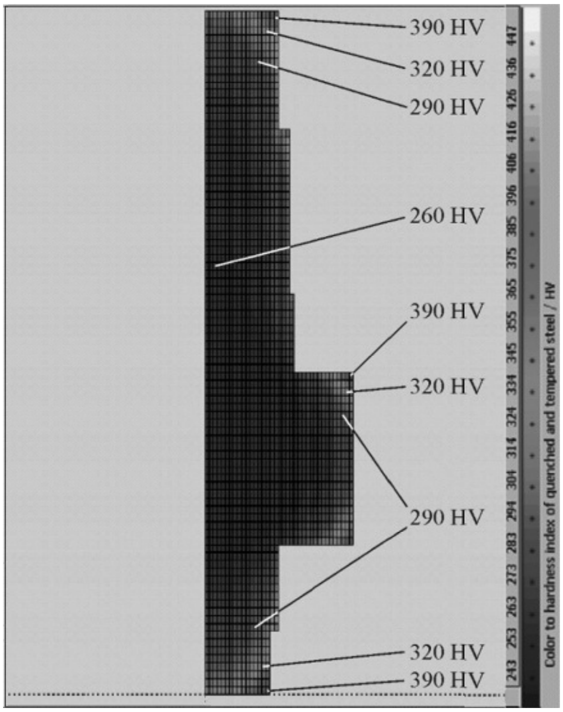

Fig. 10. Distribution of hardness of quenched and tempered steel shaft

6. Conclusions

Some of the most useful mathematical expressions of hardness after quenching and tempering on as-quenched hardness is relation according to the German standard DIN 17021 as well as relations of Just, E. Both of these expressions assume one hour of tempering.

Relation according to the German standard DIN 17021 is taking in account only influence of tempering temperature, while relation of Just, E. except tempering temperature, is taking in account the degree of hardening. It was found out that results achieved by Just's relation are better than results achieved by relation according to the German standard DIN 17021.

Novel mathematical expression for prediction of hardness of quenched and tempered steel was established. Except tempering temperature and degree of hardening this expression includes hardenability properties. By experimental work it was found out that results of quenching and tempering are related to hardenability properties of steel.

Since the steel hardenability is proportional to diffusivity of carbon and alloying elements in steel, it was reasonable to establish expressions between hardness of steel after quenching and tempering on one side and degree of hardening S, and Jominy distance, E_d, and tempering temperature on the other side. The influence of diffusivity on kinetic of tempering processes is indirectly taken into account in the mathematical modelling of tempering processes without using the chemical composition of steel.

Based on experimental work it was found out that prediction of hardness of quenched and tempered steel is more precise by novel mathematical expression than by relation according to the German standard DIN 17021, or than by relation established by Just, E.

The established relation were applied in mathematical modelling and computer simulation of quenching and tempering of shaft made of low alloyed steel. It was found out that hardness of quenched and tempered steel workpieces can be successfully calculated by the proposed method.

Acknowledgements

This work has been fully supported by Croatian Science Foundation under the project 5371.

Additional information

Selected issues related to this paper are planned to be presented at the 22nd Winter International Scientific Conference on Achievements in Mechanical and Materials Engineering Winter-AMME'2015 in the framework of the Bidisciplinary Occasional Scientific Session BOSS'2015 celebrating the 10th anniversary of the foundation of the Association of Computational Materials Science and Surface Engineering and the World Academy of Materials and Manufacturing Engineering and of the foundation of the Worldwide Journal of Achievements in Materials and Manufacturing Engineering.

References

[1] D.U. Furrer, S.L. Semiatin, Process and Quality Control Considerations, ASM Handbook, Volume 5: Heat Treatment, ASM International, Material Park, OH, 2006.

[2] B. Smoljan, The calibration of the heat conductivity coefficient in mathematical model of steel quenching, Proceedings of MicroCAD`99, Hungary, 1999.

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

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

[5] A. Rose, F. Wever, Atlas zur Wärmebehandlung der Stähle I, 2, VDI, Düsseldorf, 1954.

[6] B. Liščić, Steel Heat Treatment, Steel Heat Treatment Handbook, G.E. Totten (Ed.), p 277, Taylor & Francis Group, Boca Raton: CRC Press, 2007.

[7] E. Just, Vergüten - Werkstoffbeeinflussung durch Harten und Anlassen, VDI-Ber. 256 (1976) 125-140 (in German).

[8] B. Smoljan, D. Iljkić, G.E. Totten, Mathematical Modeling and Simulation of Hardness of Quenched and Tempered Steel, Metallurgical and Materials Transactions B, 2015.

[9] D. Iljkić, A contribution to the development of the mechanical properties prediction of quenched and tempered steel and cast steel, Doctoral Thesis, Department of Materials Science and Engineering, Faculty of Engineering, University of Rijeka, 2010. (in Croatian).

[10] B. Smoljan, D. Iljkić, S. Smokvina Hanza, Journal of Achievements in Materials and Manufacturing Engineering 34/2 (2009) 152-158.

[11] T. Reti, I. Felde, M. Guerrero, S. Sarmiento, Using Generalized Time-Temperature Parameters for Predicting the Hardness Change Occurring during Tempering, International Conference on New Challenges in Heat Treatment and Surface Engineering (Conference in honour of Prof. B. Smoljan, B. Matijević, Eds., June 9-12, Dubrovnik-Cavtat, Croatia, 2009, 333-342.