PREDICTION OF QUENCHED AND TEMPERED STEEL HARDNESS USING CARBON EQUIVALENT (CE)

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Abstract

Mechanical properties of steel workpiece are often evaluated based on its hardness. For quenched and tempered steels, hardness can be predicted based on quenching and tempering processing parameters. For that reason, prediction of tempered hardness of steel based on its quenched hardness is of big interest. This work establishes a new mathematical relation for prediction of hardness after tempering of quenched steel. This relation is based on relationship given by E. Just. According to E. Just, the hardness after tempering of quenched steel can be predicted by taking into account the temperature of tempering and the degree of hardening, where degree of hardening is quotient of achieved and theoretically possible hardness which is used as measure for hardenability of steel. Improvement of this relationship can be done by considering the chemical composition of steel. Different chemical elements have different diffusivity and different influence on tempering kinetics of steel. Influence of the chemical composition of steel on hardness after tempering is taken into account by the carbon equivalent (CE). Example of application of established relation was given in computer simulation of tempering of quenched steel workpiece, where the hardness of quenched steel workpiece was predicted based on the characteristic cooling time from 800 °C to 500 °C.

Keywords: Mathematical modeling, hardness, quenched and tempered steels

1. INTRODUCTION

Steel hardness is usually the basis for evaluation of other mechanical properties of steels. For quenched and tempered steels, hardness can be predicted by mathematical modeling. Mathematical modeling of the hardness of quenched and tempered steel workpiece usually begins with modeling of the quenched hardness [1-3].

Hardness of quenched steel workpiece can be predicted by mathematical model which is based on the on the cooling time in the temperature interval from 800 to 500 °C ($t_{8/5}$) achieved in different location of quenched steel [4]. The cooling times from 800 to 500 °C at different location of specimen during quenching of steel can be numerically simulated by using the finite volume method [5]. The hardness at different location of specimen can be predicted by converting the cooling times $t_{8/5}$ to hardness. This conversion is provided by the relationship between the cooling times and the distance from the quenched end of the Jominy specimen and the Jominy hardenability curve [6].

Hardness of tempered steel workpiece can be predicted from the quenched hardness [7]. For this purpose, numerous mathematical models have been developed for the relationship between the hardness of quenched steel and the hardness of tempered steel [1,8]. For that purpose, useful expressions are the relations according to the German standard DIN 17021 and the relation established by E. Just [9]. These relations assume a tempering time of one hour. These expressions do not take into account the rate of diffusion processes during tempering.

Other mechanical properties in different location of quenched and tempered steel workpiece can be evaluated from the hardness. All other mechanical properties of the steel workpiece after quenching and tempering directly depends on the degree of quenched steel hardening [4,9].

The aim of this research is to contribute to the methods of prediction of hardness of steel workpiece after the tempering based on hardness after quenching. For this purpose, experimental work has been carried out on most frequent carbon and low-alloy steels. It is supposed that the prediction of hardness of tempered steel could be more accurate if the chemical composition of steel are taken into account. It is because different chemical elements have different diffusivity and different influence on transformation kinetics during the tempering of steel. The chemical composition of steels for quenching and tempering were considered by the carbon equivalent, CE.

2. PREDICTION OF QUENCHED AND TEMPERED HARDNESS

The relationship between the quenched hardness, $\mathrm{HRC_q}$, and the hardness after tempering, $\mathrm{HRC_t}$ can be defined by standard DIN 17021 [8]. In DIN 17021 standard, the hardness $\mathrm{HRC_t}$ of the quenched steel after one-hour tempering is taken as a reference. By DIN 17021 standard, the hardness after tempering can be expressed by equation (1):

$$\mathrm{HRC_t} = \frac{\mathrm{HRC_q} + 17}{\left(\frac{T_\mathrm{t}}{T_\mathrm{ref}} - 2.8\right)}; \quad T_\mathrm{ref} = 167\ \mathrm{K} \tag{1}$$

where:

T_t - tempering temperature (K)

T_ref - referent temperature (K)

According to E. Just, hardness of steel after quenching decreases more during the tempering when the hardness of steel after quenching is higher. Because of that, the hardness prediction of tempered steel would be more precise by taking into account the degree of hardening, *S*. According to E. Just, the relationship between the hardness after quenching, $\mathrm{HRC_q}$ and the hardness after tempering, $\mathrm{HRC_t}$ is equal to as is given by equation (2) [9]:

$$\mathrm{HRC_t} = 8 + (\mathrm{HRC_q} - 8)\exp[-S(T_\mathrm{t}/917)^6\,] \tag{2}$$

where:

T_t - tempering temperature (K)

S - degree of hardening

The degree of hardening – equation (3) - is equal to:

$$S = \frac{\mathrm{HRC_q}}{\mathrm{HRC_{max}}} \tag{3}$$

where:

$\mathrm{HRC_q}$ - quenched hardness

$\mathrm{HRC_{max}}$ - the maximum hardness that can be achieved by quenching

In order to investigate the possibilities of contributing to the methods of prediction of tempered hardness based on the quenched hardness, experimental work has been carried out on numerous carbon and low-alloy steels.

Except of tempering temperature and degree of hardening, hardness after tempering depends on other steel properties. Kinetics of the tempering process also depends on the diffusion of carbon and other elements in the steel [8,10,11]. Steels with lower diffusivity of carbon and other elements have higher hardenability. It can be assumed that the prediction of tempered steel hardness could be more accurate if the chemical composition of steels are considered in the mathematical modeling of the kinetics of tempering processes. The chemical composition of steels for quenching and tempering can be considered by the carbon equivalent, CE. In that way, the influence of diffusivity on tempering kinetics can be taken into account by carbon equivalent, CE.

In order to establish a relation between the quenched hardness and the tempered hardness of steel, an experimental work was performed. This relation includes the hardenability properties for mathematical modeling of the tempered hardness of steel. The chemical composition of the studied steels is given in **Table 1**. The relevant data and experimental results of quenching and tempering of the studied steel are listed in **Table 2**.

Table 1 Chemical composition of the studied steels

Steel	Chemical composition (wt%)											
EN	C	Si	Mn	P	S	Cr	Cu	Mo	Ni	V	Al	Ti
Ck45	0.44	0.22	0.66	0.022	0.029	0.15	-	-	-	0.02	-	
42MnV7	0.43	0.28	1.67	0.021	0.008	0.32	0.06	0.03	0.11	0.10	-	
41Cr4	0.44	0.22	0.80	0.030	0.023	1.04	0.17	0.04	0.26	<0.01	-	
25CrMo4	0.22	0.25	0.64	0.010	0.011	0.97	0.16	0.23	0.33	<0.01	-	
16MnCr5	0.16	0.22	1.12	0.030	0.008	0.99	-	0.02	0.12	0.01	0.015	
71Si7	0.73	1.62	0.73	0.019	0.012	0.10	0.19	-	0.12	0.01		
15CrNi6	0.13	0.31	0.51	0.023	0.009	1.50	-	0.06	1.55	<0.01	0.010	
28NiCrMo74	0.30	0.32	0.51	0.011	0.007	0.07	-	-	3.03	-	0.032	<0.01
34Cr4	0.35	0.23	0.65	0.026	0.013	1.11	0.18	0.05	0.23	<0.01	-	-
34CrMo4	0.30	0.22	0.64	0.011	0.012	1.01	0.19	0.24	0.11	<0.01	-	-
36Cr6	0.36	0.25	0.49	0.021	0.020	1.54	0.16	0.03	0.21	<0.01	-	-
37MnSi5	0.38	1.05	1.14	0.035	0.019	0.23	-	-	-	0.02	-	-

A formula suitable for predicting the hardenability properties of steels for quenching and tempering is the Dearden and O'Neill carbon equivalent formula, CE, adopted by the International Institute of Welding (IIW) in 1967 (equation (4)):

$$\mathrm{CE} = \%\mathrm{C} + \frac{\%\mathrm{Mn}}{6} + \frac{\%\mathrm{Cr} + \%\mathrm{Mo} + \%\mathrm{V}}{5} + \frac{\%\mathrm{Cu} + \%\mathrm{Ni}}{15} \tag{4}$$

In order to improve the accuracy of prediction of hardness of steel after tempering, the hardness $\mathrm{HRC}_{\mathrm{min}}$, which is a material constant that corresponds to the hardness of steel after annealing, is included in the mathematical expressions of hardness [9]. For this reason, the factor *K* can be included in the regression analysis of the hardness of quenched and tempered steel – equation (5):

$$K = \frac{\mathrm{HRC}_{\mathrm{q}} - \mathrm{HRC}_{\mathrm{min}}}{\mathrm{HRC}_{\mathrm{t}} - \mathrm{HRC}_{\mathrm{min}}} \tag{5}$$

There is a multiple regression between the factor K on one side and the reference tempering temperature T_{tr} (equation (6)), the degree of hardening S and the carbon equivalent CE on the other side [12]:

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

For one-hour duration of the tempering process, the value of the reference tempering temperature T_{tr} is equal to the applied tempering temperature. Constants a, n_1, n_2 and n_3 are determined by regression analysis.

Table 2 Experimental results of quenched and tempered properties of steels

Steel EN	Maximum hardness, HRC_{max}	Reference minimum hardness HRC_{min}	Carbon equivalent, CE	Quenched hardness, HRC_q	Hardness after quenching and tempering, HRC_t		
					600 °C	500 °C	400 °C
Ck45	57.15	3.49	0.58	51.62	24.18	33.30	37.66
				27.63	20.37	24.66	25.79
42MnV7	57.01	3.39	0.81	52.28	32.42	38.87	44.68
				36.52	27.06	30.48	34.27
41Cr4	56.51	3.05	0.82	51.59	27.68	37.63	46.77
				36.56	22.72	28.97	33.62
25CrMo4	46.99	0.15	0.6	44.20	24.19	34.49	39.25
				29.62	19.71	25.29	28.00
16MnCr5	41.52	0.10	0.56	39.71	20.00	27.49	35.34
				21.36	12.49	18.05	20.18
71Si7	65.01	13.07	0.89	63.49	35.02	45.47	54.97
				48.35	32.96	39.38	47.44
15CrNi6	41.14	0.10	0.63	38.81	22.84	32.15	35.77
				27.01	17.17	22.62	24.70
28NiCrMo74	51.00	0.74	0.6	49.22	20.91	26.57	33.22
				19.06	14.21	16.47	17.99
34Cr4	51.35	0.82	0.72	46.37	28.95	36.07	43.47
				36.28	25.45	29.61	34.75
34CrMo4	51.53	0.87	0.68	42.78	26.03	35.19	39.77
				33.51	23.45	29.76	31.69
36Cr6	52.52	1.16	0.78	48.41	33.10	39.46	47.23
				36.19	27.97	31.91	34.62
37MnSi5	56.88	3.30	0.62	53.41	24.69	35.68	46.71
				33.04	21.43	26.13	31.19

Using the established values for a, n_1, n_2 and n_3, the factor K can be expressed as follows in equation (7):

$$K = \exp\left[\left(\frac{T_{tr}}{956.56}\right)^{6.913} S^{1.1537} \mathrm{CE}^{-0.8513}\right] \tag{7}$$

Since the hardness after tempering of steel can be expressed based on the quenched hardness, HRC_q, by [8,13] – equation (8):

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

the hardness after tempering of steel can be expressed by equation (9):

$$\mathrm{HRC_t} = \frac{\mathrm{HRC_q} - \mathrm{HRC_{min}}}{\exp\left[\left(\frac{T_{\mathrm{tr}}}{956.56}\right)^{6.913} S^{1.1537}\mathrm{CE}^{-0.8513}\right]} + \mathrm{HRC_{min}} \tag{9}$$

The comparison of hardness values after tempering of steel, given by the established relationship (equation (9)), with experimental results was carried out for numerous carbon and low-alloy steels (**Figure 1**). The R-square was equal to 0.9043.

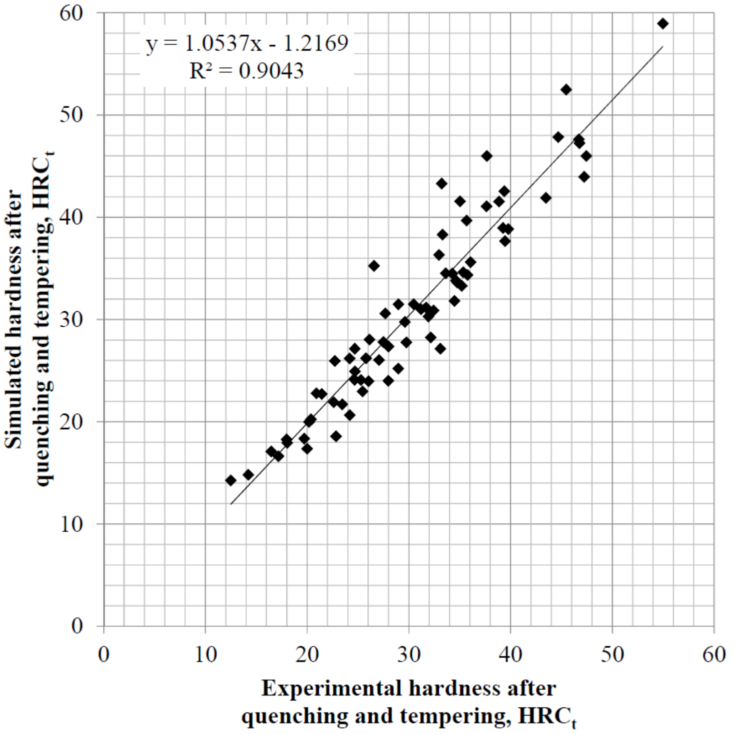


Figure 1 The comparison of hardness values after quenching and tempering, given by the established algorithm (equation (9)), with experimental results

3. APLICATION EXAMPLE

The established relation for prediction of hardness after tempering of quenched steel were applied in the computer simulation of the hardness distribution of a steel workpiece. The computer simulation of the hardness distribution of the quenched workpiece is done by using the computer software BS-QUENCHING [4].

Simulation was done for workpiece made of steel EN 42CrMo4 which was quenched from 850 °C/45 min in oil with an H-value of 0.3 and tempered at 480 °C/60 min followed by air cooling. The chemical composition of workpiece in simulation is: 0.38 %C, 0.23 %Si, 0.64 %Mn, 0.019 %P, 0.013 %S, 0.99 %Cr, 0.17 %Cu, 0.16 %Mo, 0.08 %Ni, < 0.01 %V, with CE = 0.74. The Jominy test results of the investigated steel are shown in **Table 3**. The geometry of the steel workpiece is shown in **Figure 2**.

The hardness distribution of the quenched steel workpiece shown in **Figure 3** was calculated using the computer software BS-QUENCHING [4]. The hardness distribution of the quenched and tempered steel workpiece shown in **Figure 4** is calculated in BS-QUENCHING using the equation (9).

Table 3 The Jominy test results of steel EN 42CrMo4

Distance from quenched end/mm	1.5	3	5	7.5	10	12.5	15	17.5	20	25	30	40	50	80
Hardness HRC	55	54	54	53	52	50	48	45	42	39	37	37	35	34

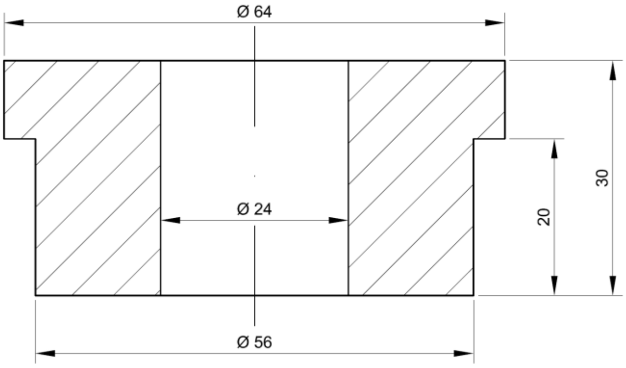
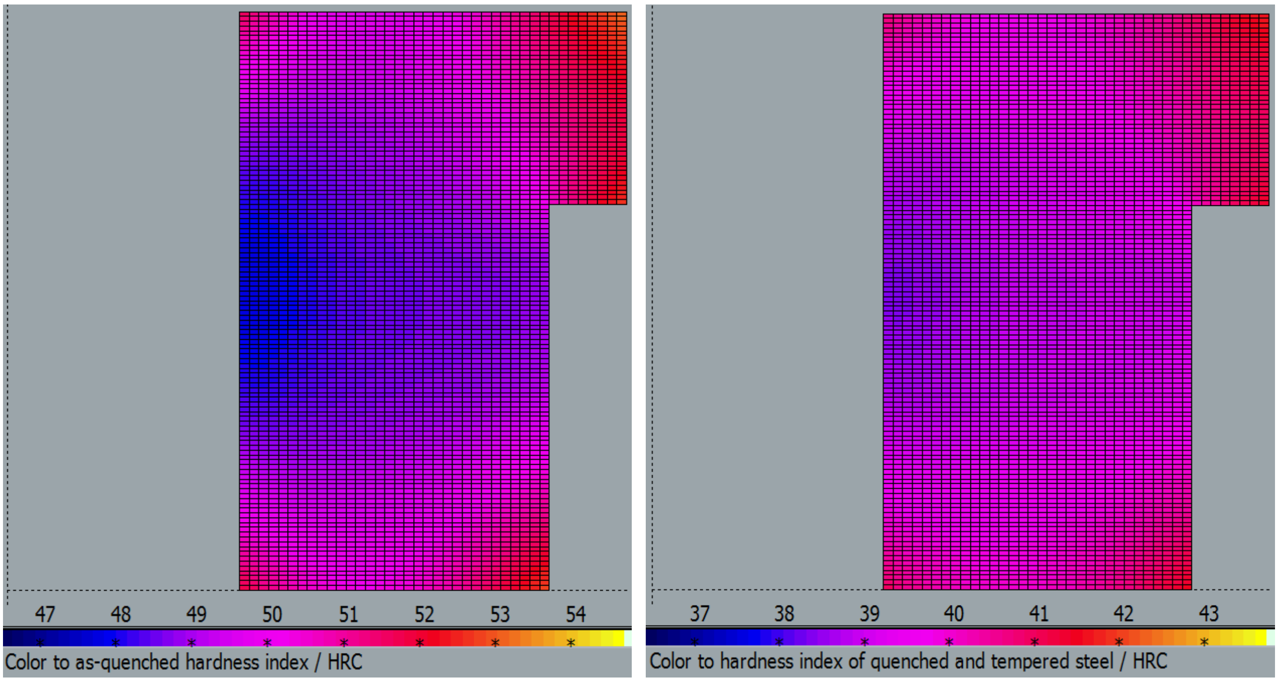


Figure 2 The geometry of the steel workpiece



a) b)

Figure 3 The hardness distribution in steel workpiece: a) quenched state, b) quenched and tempered state

4. CONCLUSION

The most used relation for prediction of hardness after tempering of quenched steel is the relation defined by the German standard DIN 17021 and the relation established by E. Just.

In this work presents a new mathematical relation for prediction of hardness of steel after tempering of quenched steel. That relation, except the tempering temperature and the degree of hardening includes chemical composition of steel.

Since the kinetics of tempering process depends on the diffusivity of the carbon and alloying elements in the steel, it was useful to establish relationship between the hardness of the steel after tempering on one side and the degree of hardening, the tempering temperature and the chemical composition of steel on the other side. The influence of diffusivity of chemical elements on the tempering kinetics is taken into account by using the carbon equivalent CE.

Comparison of the hardness after tempering predicted by established mathematical relation with experimental results leads to the conclusion that the proposed mathematical relation could successfully predict the hardness of the considered steels.

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