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Prediction of quenched and tempered steel and cast steel properties

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Analysis and modelling

ABSTRACT

Purpose: The influence of processing parameters, such as pouring temperature and cooling rate during the casting, as well as application of hot working and pre-heat treatment, on strength and toughness of quenched and tempered steel was investigated.
Design/methodology/approach: Strength and toughness were presented by yield strength and Charpy-V notch toughness, respectively. Experimental procedure of material properties optimization was done using the 25-2 factor experiment.
Findings: It was found out that yield strength is insensitive on differences between applied manufacturing processes, but by application of hot working and with appropriate pouring temperature the Charpy-V notch toughness is increased. Also, Charpy-V notch toughness is increased by interactive effect of the appropriate cooling rate during the casting and application of hot working.
Research limitations/implications: The research was focused mainly on Charpy-V notch toughness of carbon and low alloyed heat treatable steels.
Practical implications: The established algorithms can be used for prediction of tensile strength, yield strength and Charpy-V notch toughness in heat treating practice.
Originality/value: Original relation for prediction of quenched and tempered steel and cast steel Charpy-V notch toughness are developed.
Keywords: Computational material science and mechanics; Quenching and tempering; Steel and cast steel; Charpy-V notch toughness

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1. Introduction

Quenched and tempered steel has relatively good relationship between yield strength and toughness due to fine dispersion of ferrite-cementite mixture. Yield strength and toughness of quenched and tempered steel are higher if the grain size of previous austenite is finer [1]. Moreover, due to refinement of previous austenite grain size the hardenability of steel can be reduced. Except martensite, due to reduced hardenability of steel, the bainite and fine pearlite can be formed after the quenching [2]. Mechanical properties of quenched and tempered steel are worse if as-quenched microstructure is consist of heterogeneous microstructure of martensite, bainite and pearlite [3].

Mechanical properties of quenched and tempered steel casting with typical as-cast microstructure depend on properties of metal matrix, but they are not so good as mechanical properties of quenched and tempered steel with same chemical composition [4].

Basic manufacture processes in steel production are melting and pouring, hot forming, and adequate heat treatment processes.

Differences between microstructure and mechanical properties of quenched and tempered steel and cast steel arise from different processing history.

2. Experimental section

It is known that the mechanical properties of steel and/or cast steel are depend on pouring temperature, cooling rate during the casting, as well as, application of hot working, normalization, and homogenization [5]. In order to determine the influence of such part of manufacturing process on the mechanical properties of investigated steel and cast steel, an investigation based on the factor experiment was done.

Using the factor experiment 2^{5-2} influence of pouring temperature, cooling rate during the casting, as well as, application of hot working, normalization, homogenization on yield strength and Charpy-V notch toughness was done (Table 1).

According to the established factor experiment four castings were casted. Geometry of the die for casting is shown in Figure 1.

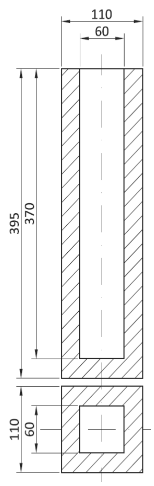

Fig. 1. Geometry of die for casting

Each casting were cut out to four billets (Fig. 2), and by this, it is given 16 billets. From those 16 billets 8 billets are scheduled for hot working and 8 billets are not. Geometry of hot worked billets is shown in Fig. 3. Hot worked billets and as-cast billets are scheduled for heat treatment according to the factor experiment. After all treatments from the factor experiment have been done, all 16 billets are quenched and tempered. From those billets, specimens for tensile test and Charpy-V notch toughness test were cut out. Plan of test specimen cutting is shown in Fig. 4.

All specimens are quenched from 850°C/45 min/oil with H-value equal to 0.2 and tempered at 480°C/60 min/air. Results of factor experiment 2^{5-2} application for yield strength and Charpy-V notch toughness are shown in Tables 2 and 3.

On the base of the factor experiment results it was found out that yield strength is insensitive on differences between applied manufacturing processes, but by application of hot working and with proper pouring temperature the Charpy-V notch toughness is increased. Also, Charpy-V notch toughness is increased by interactive effect of the proper cooling rate during the casting and hot working application.

In Table 4 are shown the Charpy-V notch toughness results and relevant factors.

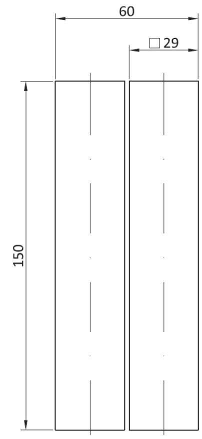

Fig. 2. Cutting scheme of steel castings

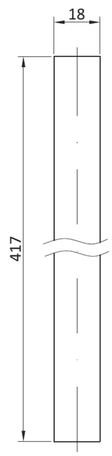

Fig. 3. Geometry of hot worked billets

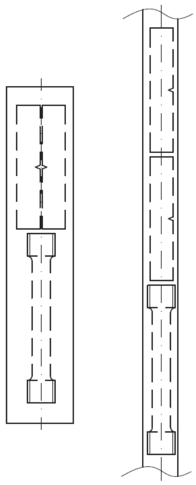

Fig. 4. Plan of test specimen cutting

Table 1.
Factors for the factor experiment 2^{5-2}

Factor	Pouring temperature/°C (X_1)	Die temperature/°C (X_2)	Hot working (X_3)	Normalization (X_4)	Homogenization (X_5)
Min	-1, 1514	-1, 20	-1, No	-1, No	-1, No
Max	+1, 1590	+1, 105	+1, Yes	+1, Yes	+1, Yes

Table 2.
Factor experiment 2^{5-2} for yield strength

Treatment	X_1	X_2	X_3	X_4 X_1X_2	X_5 X_1X_3	X_2X_3	$X_1X_2X_3$	Yield strength, $R_{p0.2}$/MPa		
								I	II	Average
1	-1	-1	-1	1	1	1	-1	1102	1108	1105
2	1	-1	-1	-1	-1	1	1	1110	1128	1119
3	-1	1	-1	-1	1	-1	1	1136	1096	1116
4	1	1	-1	1	-1	-1	-1	1088	1120	1104
5	-1	-1	1	1	-1	-1	1	1070	1060	1065
6	1	-1	1	-1	1	-1	-1	1029	1122	1075.5
7	-1	1	1	-1	-1	1	-1	1086	1126	1106
8	1	1	1	1	1	1	1	1138	1118	1128
E_x	8.63	22.38	-17.38	-3.63	7.63	24.38	9.38	S_p^2=858.31		
Q_x	297.56	2002.56	1207.56	52.56	232.5	2376.56	351.56	F_{tab}(99%)=11.26		
F	0.35	2.33	1.41	0.06	0.27	2.77	0.41			

E_x - average factor effect; F - Fisher's variable; F_{tab} - table value of Fisher's variable; Q_x - sums of squares of average factor or interaction effect; S_p^2 - estimator of variance into treatments.

Table 3.
Factor experiment 2^{5-2} for Charpy-V notch toughness

Treatment	X_1	X_2	X_3	X_4 X_1X_2	X_5 X_1X_3	X_2X_3	$X_1X_2X_3$	Charpy-V notch toughness, KV/J				
								I	II	III	IV	Average
1	-1	-1	-1	1	1	1	-1	20	24	23	24	22.75
2	1	-1	-1	-1	-1	1	1	14	15	14	14	14.25
3	-1	1	-1	-1	1	-1	1	23	24	25	24	24
4	1	1	-1	1	-1	-1	-1	25	26	18	18	21.75
5	-1	-1	1	1	-1	-1	1	48	49	50	47	48.5
6	1	-1	1	-1	1	-1	-1	41	37	44	37	39.75
7	-1	1	1	-1	-1	1	-1	46	44	49	40	44.75
8	1	1	1	1	1	1	1	40	38	37	40	38.75
E_x	-6.38	1.00	22.25	2.25	-1.00	-3.38	-0.88	S_p^2=6.65				
Q_x	325.13	8.00	3960.50	40.50	8.00	91.13	6.13	F_{tab}(99%)=7.82				
F	48.92	1.20	595.94	6.09	1.20	13.71	0.92					

E_x - average factor effect; F - Fisher's variable; F_{tab} - table value of Fisher's variable; Q_x - sums of squares of average factor or interaction effect; S_p^2 - estimator of variance into treatments.

The relation between Charpy-V notch toughness results and pouring temperature, ∇_p, hot working application and temperature of die, ∇_d was established by regression analysis [4]:

$$KV = 35.065 - 0.084x_1 + 8.508x_3 + 0.040x_{23} \tag{1}$$

Hot working is applying in steel production and for steel factor x_3 is equal to one and for production of cast steel is equal to minus one. Including concrete values for other factors difference from optimal pouring temperature, $\Delta\nabla_p$, and interaction of temperature of die, ∇_d and hot working application, Equation 1 can be written as:

$$KV_S = 43.573 - 0.084\Delta\vartheta_p + 0.040\vartheta_d \tag{2}$$

$$KV_{CS} = 26.557 - 0.084\Delta\vartheta_p - 0.040\vartheta_d \tag{3}$$

where KV_S/J is Charpy-V notch toughness of steel, KV_{CS}/J is Charpy-V notch toughness of cast steel, $\Delta\nabla_p$/°C is difference from optimal temperature of pouring, and ∇_d/°C is temperature of die during the pouring.

Using the specimens of quenched and tempered steel EN 42CrMo4, Charpy-V notch toughness estimated by Equations 2 and 3 was verified by experimental results (Figure 5).

Table 4.
Charpy-V notch toughness results and relevant factors

y	x_1	x_3	x_{23}
20.5	0	-1	-105
23.5	0	-1	-105
23.3	0	-1	-105
24.4	0	-1	-105
14.1	76	-1	-105
14.8	76	-1	-105
14.1	76	-1	-105
13.9	76	-1	-105
23.2	0	-1	-20
23.9	0	-1	-20
25.5	0	-1	-20
24.3	0	-1	-20
25.1	76	-1	-20
26.2	76	-1	-20
18.4	76	-1	-20
18.4	76	-1	-20
47.8	0	1	105
48.8	0	1	105
49.7	0	1	105
46.7	0	1	105
40.9	76	1	105
37.0	76	1	105
44.0	76	1	105
37.0	76	1	105
46.3	0	1	20
44.5	0	1	20
48.7	0	1	20
39.9	0	1	20
39.7	76	1	20
37.8	76	1	20
37.0	76	1	20
40.2	76	1	20

y - Charpy-V notch toughness, KV/J; x_1 - difference from optimal pouring temperature, $\Delta\nabla_p$/°C; x_3 - hot working application; x_{23} - interaction of temperature of die, ∇_d/°C and hot working application

Maximal Charpy-V notch toughness of steel and cast steel can be obtained by temperature of die during the pouring equal to 105 °C and by difference from optimal temperature of pouring equal to 0 °C. Charpy-V notch toughness of steel and cast steel can be expressed by:

$$\mathrm{KV_S} = \mathrm{KV_{Smax}}\left[1 - 0.00176\Delta\vartheta_\mathrm{p} - 0.000837(105 - \vartheta_\mathrm{d})\right] \quad (4)$$

$$\mathrm{KV_{CS}} = \mathrm{KV_{Smax}}\left[0.644 - 0.00176\Delta\vartheta_\mathrm{p} - 0.000837(105 + \vartheta_\mathrm{d})\right] \quad (5)$$

where $\mathrm{KV_{Smax}}$/J is maximal Charpy-V notch toughness of steel and cast steel.

Tensile strength, R_m/MPa is related to hardness HV [6]:

$$R_\mathrm{m} = 3.3\mathrm{HV} \quad (6)$$

Since Charpy-U notch toughness, KU is related to tensile strength, R_m [7], and Charpy-V notch toughness, KV is related to Charpy-U notch toughness, KU [8] it can be found out that Charpy-V notch toughness, KV for steel manufactured by casting from optimal temperature of pouring and by optimal temperature of die during the pouring is equal to:

$$\mathrm{KV_{Smax}} = 264.26 - (1.129 - 0.554S)\mathrm{HV} \quad \mathrm{KV} \le 80\ \mathrm{J} \quad (7)$$

$$\mathrm{KV_{Smax}} = 442.84 - (2.201 - 1.082S)\mathrm{HV} \quad \mathrm{KV} > 80\ \mathrm{J} \quad (8)$$

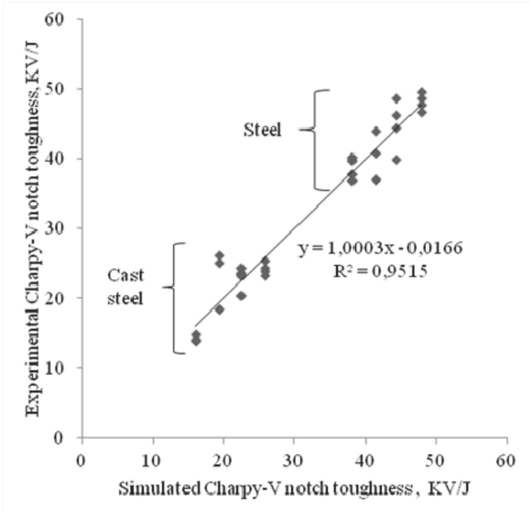

Fig. 5. Charpy-V notch toughness of steel and cast steel estimated by Equation 2 and 3 and by experiment

3. Application

Established mathematical model is applied in computer simulation of manufacture processes of the shaft. Computer simulation of mechanical properties distribution was done using a program, BS Quenching for Windows, based on finite volume method [9-11]. Tensile strength, R_m is calculated by Equation 6. Charpy-V notch toughness, KV is calculated by Equations 4, 5, 7 and 8. Yield strength, $R_{\mathrm{p}0,2}$/MPa can be estimated from the ultimate tensile stress or hardness [7]:

$$R_\mathrm{e} = R_{\mathrm{p}0,2} = (0.8 + 0.1C)R_\mathrm{m} + 170C\text{-}200 \quad (9)$$

Two different manufacturing processes are analyzed. In the first manufacture process the shaft was of steel EN 42CrMo4 and in the second one the shaft was of cast steel EN GS-42CrMo4. Pouring temperature during the casting was 1514°C and the temperature of die was 105°C. In both processes shaft was quenched from 850°C/45 min/oil with H-value equal to 0.2 and tempered at 480°C/60 min/air. 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 5. Geometry of the steel shaft is shown in Figure 6. Distribution of quenched and tempered hardness of the shaft is shown in Figure 7.

Mechanical properties in critical locations 1, 2, 3, 4 and 5 (Figure 6) of quenched and tempered steel shaft and cast steel shaft are shown in Table 6.

Table 5.
Jominy test results of steel EN 42CrMo4, i.e., cast steel EN GS-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

Table 6.
Mechanical properties in critical locations of quenched and tempered steel shaft and cast steel shaft

Properties	Critical location (Figure 6)									
	1		2		3		4		5	
	Steel	Cast steel	Steel	Cast steel	Steel	Cast steel	Steel	Cast steel	Steel	Cast steel
Hardness HV	304	304	291	291	269	269	269	269	315	315
Tensile strength, R_m/MPa	1003	1003	960	960	888	888	888	888	1040	1040
Yield strength, R_e/MPa	803	803	755	755	673	673	673	673	842	842
Charpy-V notch toughness, KV/J	46	22	49	23	55	26	55	26	43	20

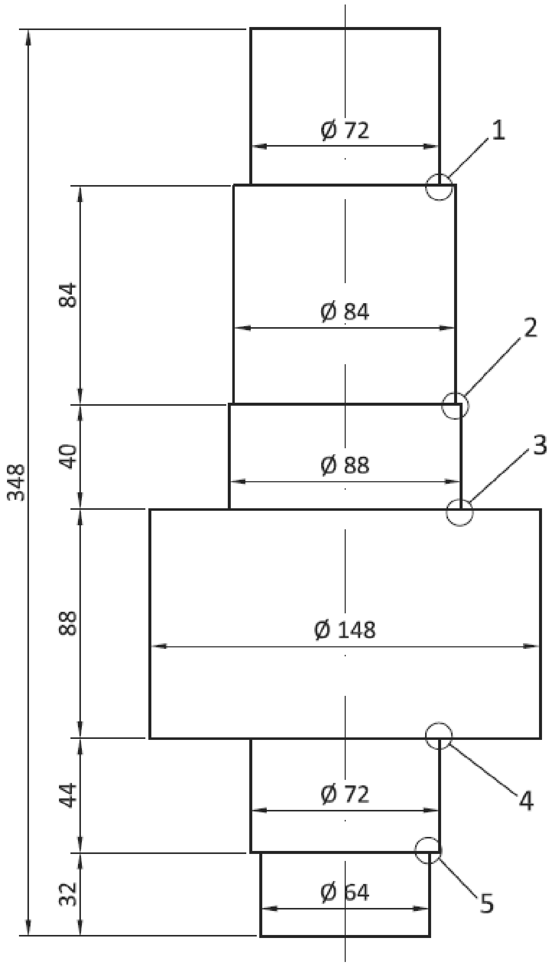

Fig. 6. Geometry of steel shaft

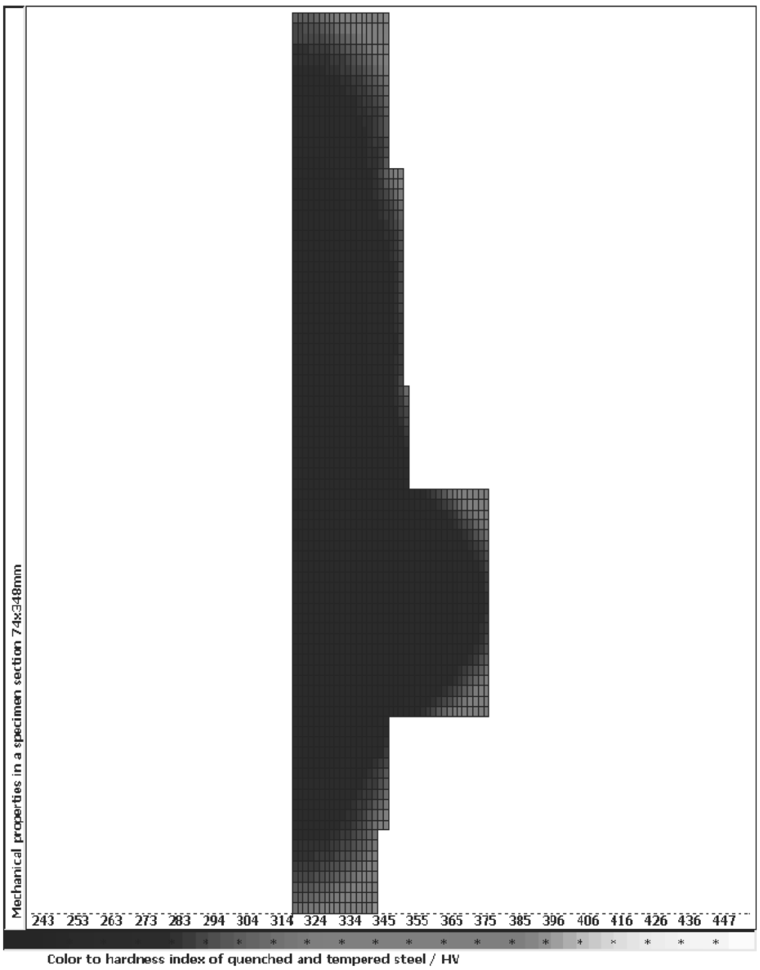

Fig. 7. Distribution of hardness of quenched and tempered steel shaft

4. Conclusions

Since working stress of steel is directly depends on toughness and yield strength, these two mechanical properties of steel and cast steel are investigated.

During the experimental work yield strength and tensile strength were constant and equal to standard values of quenched and tempered steel, independently on investigated parameters of casting, hot-working, homogenization and normalization. On the base of the 2^{5-2} factor experiment results it was found out that by application of hot working and with proper pouring temperature the Charpy-V notch toughness is increased. Also, Charpy-V notch toughness is increased by interactive effect of the proper cooling rate during the casting and hot working.

New relations between the Charpy-V notch toughness, and hardness of quenched and tempered steel and cast steel was established. The established relations were applied in mathematical modelling and computer simulation of manufacturing the shaft. It was found out that Charpy-V notch toughness of quenched and tempered steel and cast steel can be successfully calculated by the proposed method.

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