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The investigation of hardenability of low alloy structural cast steel

I. Telejko [a], H. Adrian [b,*], K. Skalny [a], M. Pakiet [a], R. Staśko [a]
[a] Division of Engineering and Materials Technology, Pedagogical University, ul. Podchorążych 2, 30-084 Kraków, Poland
[b] Faculty of Metals Engineering and Industrial Computer Science, AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Kraków, Poland
* Corresponding author: E-mail address: adrian@agh.edu.pl

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Properties

ABSTRACT

Purpose: The aim of the investigation was to verify if published data for calculation of the hardenability of steel can be used for calculation of hardenability of cast steel and the optimal selection of these data for obtaining the best agreement between calculated and experimental data.

Design/methodology/approach: The analysis of the hardenability of low alloy cast steel was carried out using Jominy test and analytical Grossmann method. The optimal data for calculation of ideal critical diameter, D_i and Jominy curve were selected.

Findings: The hardenability curves of cast steel measured on different planes of Jominy test show scatter on the contrary to forged steel

Practical implications: Results of investigations prove that data for calculation of hardenability parameters used for steel can be applied with sufficient accuracy for calculation the hardenability of cast steel. The hardenability of cast steel shows scatter of results.

Originality/value: The analysis of the hardenability of cast steel can be carried out using the same data as for forged steel.

Keywords: Hardenability; Structured cast steel; Jominy test; Grossmann method; Calculation of Jominy curve

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1. Introduction

The problem of material selection in order to secure safety work of designed structural element resolves itself into establishing the necessary minimum of the most important properties and in next step to find the material which meet these demands at the minimum cost. The definition of necessary minimum properties requires the knowledge of work condition of structural element on the base of constructional calculations or experimental investigations. The most frequently the engines or devices are exposed on mechanical loads, the work environment is not chemically aggressive and work temperature is in the range of -40 to 300°C. Such materials are qualified as structural materials. Usually the sufficient characteristic of constructional materials are their mechanical properties. Among cast alloys the most important structural material is cast steel. Most common applied way of investigation of mechanical properties of cast steel is tensile test. The mechanical properties which are obtained using tensile test are: yield point, R_e, tensile strength, R_m, elongation, A and reduction of area, Z. The other important properties are:

hardness, notch toughness, fatigue strength, torsional strength, compressive strength and fracture toughness. Knowledge of these mechanical properties is sufficient for appropriate material selection for specified constructional element.

Above presented set of information regarding cast steel does not include the very important, in some cases the decisive requirement: selection of the cast steel grade should to provide the mechanical properties preventing the effects of tensions with specified value occurring during exploitation in the zone on specified distance from the surface. Cast steel with microstructure of ferrite and highly dispersed uniformly distributed sferoidal cementite shows the best combination of tensile and plastic properties as well as high ratio of R_e/R_m, being a very important index of the quality of the structural materials. Such microstructure can be obtained by tempering of martensite. Quenched and low tempered cast steel shows high hardness whilst quenched and high tempered - the best ductility. With decreasing the martensite content from 100 to 80% the mechanical properties are only slightly changed but with decreasing to 50% the decrease in mechanical properties of heat treated cast steel can be significant. The general rule is that higher content of martensite in the microstructure of quenched cast steel results in better mechanical properties after tempering. The ability of cast steel for formation of martensitic microstructure during quenching is called the hardenability. It defines the thickness of martensite layer after quenching of cast steel. If the cast wall is not fully quenched on martensite and it contains products of diffusional decomposition of austenite the heterogeneity of the mechanical properties on the cross section of wall can occur and the mechanical properties of the external layers of quenched wall will be higher compare to the core.

At room temperature the mechanical properties of different grades of cast steel quenched on martensite and tempered are practically similar independent of chemical composition. Sufficient hardenability (required content of martensite in the microstructure of quenched cast steel) in most cases enables to obtain the basic mechanical properties of quenched and tempered cast steel, sufficient for conventional applications. Heat treatment of cast steel with insufficient hardenability does not provide the maximal mechanical properties in the core. It may decrease of functional quality of product made using cast steel. On the contrary the increase of hardenability is achieved using alloying elements. Excessive hardenability it means waste of alloying elements and the increase of the cost of product.

Knowledge of the hardenability enables the optimal selection of the chemical composition of cast steel for application on engine components and devices. It enables the grade cast steel selection on specific constructional elements for obtaining required microstructure of tempered martensite in all or part section of heat treated element. The content of alloying elements should not be higher than necessary for providing the hardenability adequate to size of element and way of quenching. If the distribution of stresses on the section is such that stress decreases towards the section centre it is possible to use the cast steel with lower, but sufficient hardenability to secure required mechanical properties, adequate to the loads on the cross section.

One of the measure of hardenability is the ideal critical diameter, D_i, which is the maximal diameter of bar quenched in ideal quenching medium, in which after quenching there is 50% of martensite in the centre of bar. Half martensitic microstructure is particularly important because such microstructure in the centre provides the sufficient mechanical properties for majority of practical applications of cast steel. The other measured parameter of hardenability is critical diameter, D_c, which is the maximal diameter of bar, quenched in given medium, when the 50% of martensite will be obtained in the bar centre.

For quantitative estimation of hardenability for steel and cast steels the Jominy end quench test is used [1]. The other method is Grossmann's analytical method [2] in which for D_i calculation the multiplying hardenability coefficients for alloying elements, presented in the graphical form are applied. The main advantage of calculation method is short time and low cost of obtained results. But the disadvantage of method is, that published data on multiplying hardenability coefficients show scatter and the effect of alloying element on the hardenability may depend on the chemical composition of steel. A comprehensive review of published data on the multiplying hardenability coefficients was presented by Doane [3]. Steel is the iron alloy after plastic deformation and shows difference with cast steel, not deformed. It is interesting if data used for estimation of the steel hardenability provide the accurate hardenability parameters of cast steel.

The aim of the investigation was to verify if published data applied for calculation of the hardenability of constructional steels enable accurate estimation of cast steel hardenability and selection of data for obtaining the best agreement between experimental and calculated hardenability parameters.

2. Materials and experimental procedures

Two grades of constructional cast steels L20HM and L20G were used for investigations. Cast steels were air melted in 7 Mg electric arc furnace with basic liner. Melts were poured at 1630°C into laddle where 1kg/Mg Al was added for deoxidation of cast steel. Next the tentative ingots of shape three leaves according to the norm PN-76/H-04309 were poured. The ingots were normalised at 850°C. The chemical composition of cast steels are given in Table 1.

Table 1.
Chemical composition of cast steels, in mass %

Grade	C	Mn	Si	P	S	Cr	Ni	Mo	Ti	Al	V	Nb
L20HM	0.17	O.60	0.50	0.019	0.011	0.62	0.11	0.39	0.003	0.14	0.003	0.004
L20G	0.25	1.16	0.56	0.014	0.029	0.07	0.08	0.05	0.03	0.05	-	-

From tentative ingots the Jominy test specimens were prepared and Jominy hardenability tests were carried out according to standard procedure [1].

Standard Jominy specimens were austenitised in argon atmosphere for 30 min at temperatures 920 and 1020°C. The austenitising time was measured from when specimen reached the austenitising temperature according to the thermocouple placed near the specimen. One specimen was end quenched for each heat treatment condition. Hardness profiles, using hardness Rockwell tester, scale C, were measured on four flats ground (at angles 90°) to a depth of 0.5 mm and mean hardness profile was then used for estimation of the hardenability.

After hardness testing, a section of 30 mm long from the quenched end of Jominy specimen was removed for metallographic examination. The prior austenite grain size was measured after etching specimens for 15-30 min at room temperature in saturated aqueous picric acid solution containing 10 mL wetting agent. The mean linear chord length l of austenite grain size was measured using computer program SigmaScan Pro [4] on ~500 grain intercepts for each specimen.

The ideal critical diameters were calculated using two methods: Grossmann analytical method (D_i) and his multiplying formula and using hardenability curves with help of Har temp computer program (D_{iJ}) [5]. For calculation of the ideal critical diameter, D_i, the data provided by De Retana and Doane [6] were used. The ideal critical diameters D_{iJ} of the steels were estimated using the measured Jominy distances to the 50% martensitic point, l_k. The positions for 50% martensite on the Jominy specimens, l_k were determined using the Hodge and Orehoski relationships between hardness, carbon content and amount of martensite [7]. This hardness is notify as HRC_{50}. The ideal critical diameters D_{iJ} of the investigated steels were determined from the critical distances, l_k, using conversion curve presented by Grossman [8]. Applied computer program enables also to calculate the Jominy curve using data [9-12]. Different modes of calculation of microstructure composition and mechanical properties of heat treated steels are presented in [13-15].

3. Results

3.1. Jominy curves

Results of hardness measurements with distance to end quench of Jominy specimens are presented in Tables 2 and 3. For each point the mean value of hardness, HRC_{sr} was calculated.

Data presented in Tables 2 and 3 shows scatter of hardness values measured at the same distance from quenched end but in different points especially at distances close to end quenched. It may be due to the heterogeneity of chemical composition of cast steels. The relationships between mean values of hardness, HRC_{sr} and distance l are presented in Figs 1 and 2.

It is worthy to notify, that Jominy curves of L20HM are placed above curves for L20G cast steel for both austenitising temperatures.

Table 2.
Results of hardness measurements with distance l from end quenched, for cast steel L20HM, a) 920°C, b) 1020°C

a)

l, mm	HRC_1	HRC_2	HRC_3	HRC_4	$HRC_{śr}$
1.5	45	44.5	54.5	54	44.75
3	44.5	43.5	41	52.5	44.00
5	41.5	39	36	64	40.25
7	37	33.5	44	40.5	35.25
9	32.5	32	30	36.5	32.25
11	29.5	29	29	33.5	29.25
13	27.5	28	25	29	27.75
15	26.5	26	23.5	26	26.25
20	23	24.5	30	25	23.75
25	22.5	22	33	21	22.25
30	20.5	21.5	20	24	21.00
35	20.5	21	29.5	18	20.75
40	20	19.5	40	18.5	19.75
45	19.5	19	17	17	19.25
50	19	18	18	16	18.50

b)

l, mm	HRC_1	HRC_2	HRC_3	HRC_4	$HRC_{śr}$
1.5	46.5	46.5	52.5	42.5	47.00
3	46.5	46.5	41.5	41	43.88
5	43.5	41	39	37.5	40.25
7	40	37.5	34.5	34.5	36.63
9	37	34	32	32	33.75
11	35	32.5	30	30	31.88
13	33	31	27	27.5	29.63
15	32	30.5	28	27	29.38
20	30.5	27	25	25	26.88
25	29.5	27	24	24	26.13
30	29.5	26	22.5	23.5	25.38
35	26	25.5	22	22	23.88
40	26	24.5	21.5	21.5	23.38
45	25	25.5	21	21.5	23.25
50	24.5	24	20.5	22	22.75

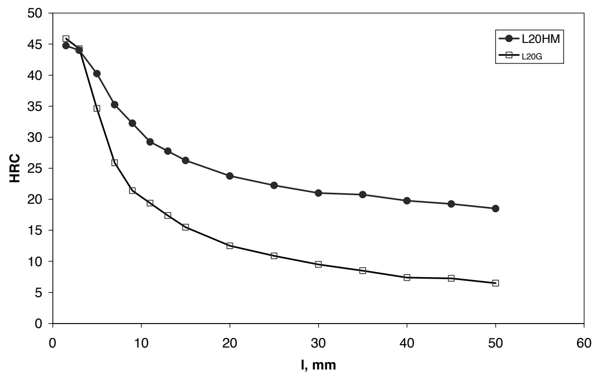


Fig. 1. Jominy hardenability curves for cast steels L20G and L20HM for austenitising temperature 920°C

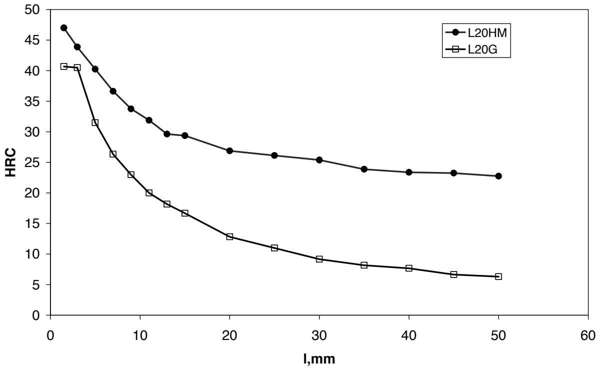


Fig. 2. Jominy hardenability curves for cast steels L20G and L20HM, austenitising temperature 1020°C

Table 3.
Results of hardness measurements with distance l from end quenched, for cast steel L20G, a) 920°C, b) 1020°C

a)

l, mm	HRC_1	HRC_2	HRC_3	HRC_4	$HRC_{śr}$
1.5	49	49	43.5	42	45.88
3	48	47	42	40	44.25
5	36	38.5	33	31	34.63
7	27	28	24	24.5	25.88
9	22	23	20.5	20	21.38
11	20.5	20	19	18	19.38
13	18.5	19	16	16	17.38
15	17	17	14	14	15.50
20	13.5	13.5	11.5	11.5	12.50
25	12.5	11.5	10	9.5	10.88
30	10	10	9	9	9.50
35	9.5	9	8.5	7	8.50
40	9	7.5	7	6	7.38
45	8.5	7.5	7	6	7.25
50	8.5	6	6	5.5	6.5

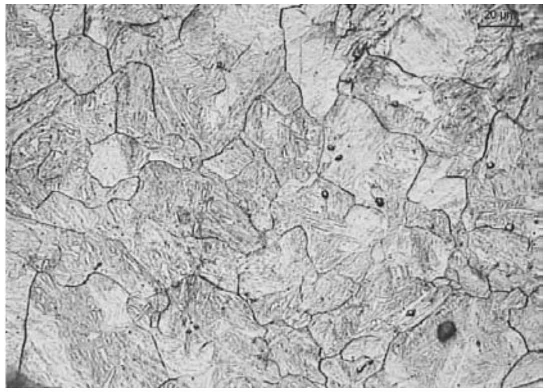
b)

l, mm	HRC_1	HRC_2	HRC_3	HRC_4	$HRC_{śr}$
1.5	37	44	28.5	41	40.67
3	41.5	46	28	34	40.50
5	31.5	38	24	25	31.50
7	26.5	29.5	23	23	26.33
9	23.5	26	21	19.5	23.00
11	21	24	20	15	20.00
13	19.5	21	20	14	18.17
15	18.5	19	17.5	12.5	16.67
20	14	14	12.5	10.5	12.83
25	12	12.5	10	8.5	11.00
30	11	10.5	8.5	6	9.17
35	9	9.5	7.5	6	8.17
40	9	8.5	7	5.5	7.67
45	7.5	7	5.5	5.5	6.67
50	7	6.5	6.5	5.5	6.33

3.2. Austenite grain size analysis

Examples of microstructures with revealed grain boundaries of prior austenite existing at austenitising temperatures are presented in Figs. 3 and 4.

a)



b)

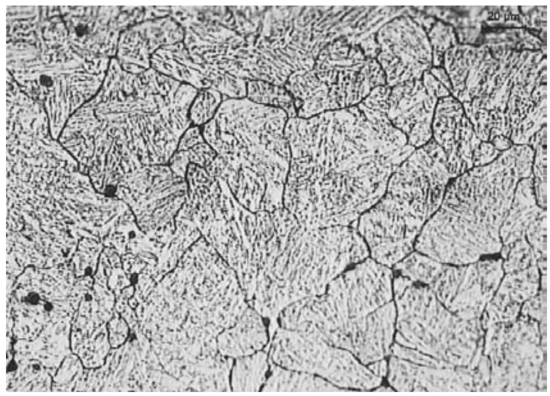


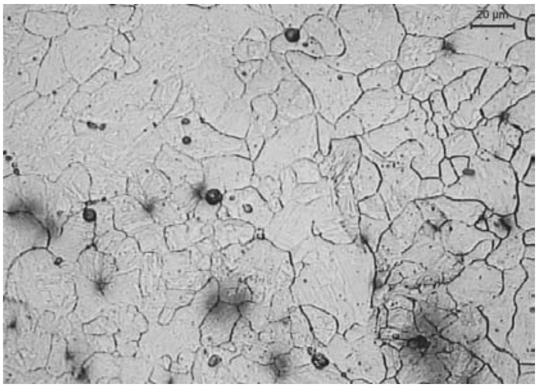
Fig. 3. Examples of microstructures of cast steel L20HM, a) T=920°C, b) T=1020°C

Results of analysed mean chord length, l, and austenite grain size numbers of investigated cast steels are placed in Table 4. For all austenitising temperatures cast steel L20G had lower austenite grain size compare to L20HM.

Table 4.
Austenite grain size of cast steel

Grade	T_h, °C	l, μm	GS
L20HM	920	16.53	8.5
	1020	16.91	8.4
L20G	920	10.13	9.9
	1020	12.96	9.2

a)



b)

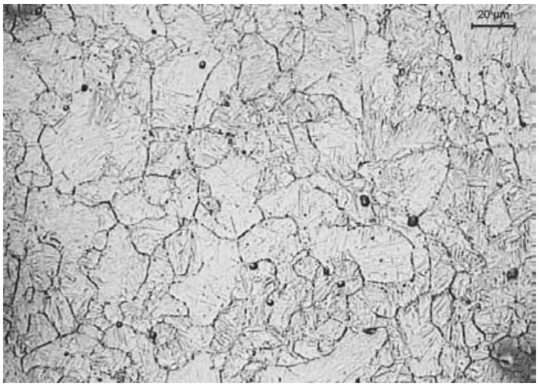


Fig. 4. Examples of microstructures of cast steel L20G, a) T=920°C. b) T=1020°C

3.3. Hardenability parameters

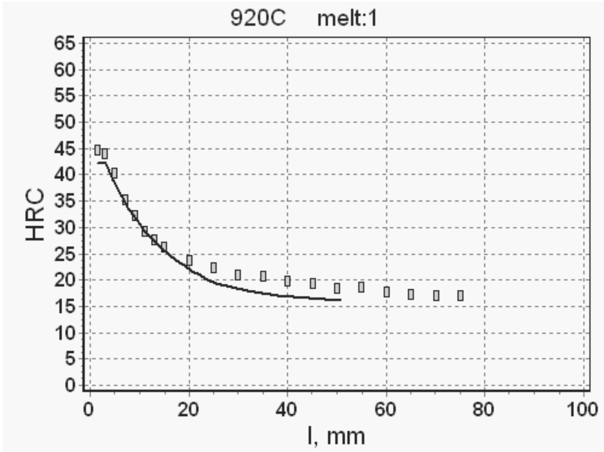
Results of ideal critical diameters. estimated using experimental Jominy curves (D_{iJ}) and calculated by Grossmann analytical method (D_i) are shown in Table 5. At the austenitising temperature 920°C the ideal critical diameters of cast steel L20HM were equal 65 mm and in the range of 32-33 mm for L20G. A very good agreement between D_{iJ} and D_i for both cast steels is observed and the difference between both values did not exceed 1 mm. The higher values of difference between ideal critical diameters estimated using different methods were observed at austenitising temperature of 1020°C. The values of D_{iJ} and D_i were equal 74.1 and 65.3 mm for steel L20HM and for L20G were equal 28.4 and 34.3 mm.

A comparison of experimental and calculated Jominy curves for both cast steels austenitised at 920°C is presented in Fig 5. It is worthy to emphasize a very good agreement between experimental and calculated Jominy curves at distances below 20 mm from end quenched.

Table 5.
Hardenability parameters of cast steels

Grade	T_h. °C	HRC_{50}	l_k. mm	D_{iJ}. mm	D_i. mm
L20HM	920	30.37	10.25	65.08	64.97
	1020	30.37	12.33	74.07	65.33
L20G	920	34.94	4.93	33.05	32.13
	1020	34.94	4.23	28.36	34.34

a)



b)

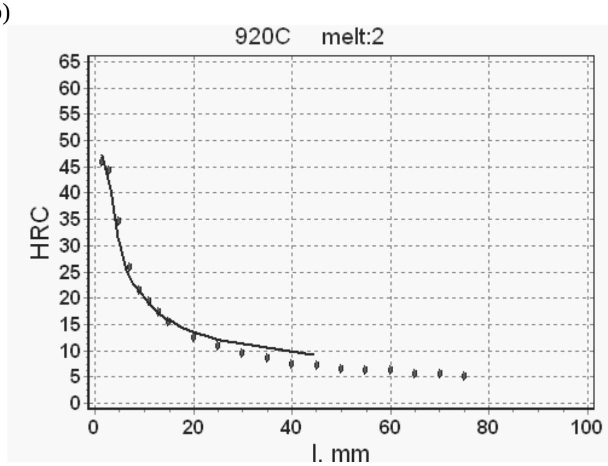


Fig. 5. Experimental (points) and calculated (line) Jominy curves for a) L20HM, b) L20G

4. Discussion of the results

The comparative investigations of the hardenability of two low alloyed structural cast steels. grades L20HM and L20G. were carried out with application of the Jominy test as well as analytical Grossmann method. The investigated steels showed significant differences in hardenability resulting from difference in chemical composition. Higher hardenability showed cast steel L20HM. containing 0.6 %Mn. 0.62 %Cr and 0.39 %Mo in comparison with L20G. containing 1.16% Mn. Additional reason for this difference was lower austenite grain size in cast steel L20G which contained 0.03% Ti and 0.05% Al. Both elements promote of low austenite grain size because of austenite grain boundary pinning effect caused by precipitation of carbonitride Ti(C.N) and nitride AlN. Low austenite grain size decreases the hardenability of steel because during cooling from austenitising temperature the diffusional products of austenite decomposition on austenite grain boundaries can nucleate.

At austenitising temperature 920°C a very good agreement of hardenability parameters estimated using two different methods was obtained for both cast steels. It testify to the fact that the methods applied for analysis of hardenability of steels are fully useful for estimation of hardenability of cast steels. This is expected if cast steel has similar chemical composition to steel and if there is no segregation of alloying elements or porosity in cast. In investigated cast steels there was no found porosity by metallographic examination but segregation of alloying elements was present and it was the main reason for the differences in hardness measured in different places but at the same distance from end quenched on Jominy tests. In spite of this the estimated hardenability parameters. D_i and D_{iJ} were approximated each other. It is worthy to emphasize the agreement between calculated and experimental Jominy curves for austenitising temperature 920°C. At austenitising temperature 1020°C the difference between D_i and D_{iJ} were higher.

5. Conclusions

a) The investigated cast steels L20HM and L20G showed differences in austenite grain size at austenitising temperatures of 920 and 1020°C. The cast steel L20G which contained 0.05% Al and 0.03% Ti showed lower austenite grain size.
b) Higher hardenability showed cast steel L20HM in comparison to L20G. because of higher content of alloying elements.
c) The differences in the cast steels Jominy curves measured at different sides of Jominy specimens were possibly caused by alloying elements segregations.
d) In both cast steels a very good agreement between ideal critical diameters estimated using experimental and analytical method was observed for austenitising temperature of 920°C.
e) A satisfied agreement between experimental and calculated Jominy curves was observed for 920°C.

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