ARCHIVES OF METALLURGY AND MATERIALS
Volume 58 2013 Issue 3
DOI: 10.2478/amm-2013-0068

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OPTIMISATION OF THE DEOXIDATION DEGREE AND MODIFICATION ON THE CAST STEEL PROPERTIES IMPROVEMENT AT LOW TEMPERATURES

OPTYMALIZACJA STOPNIA ODTLENIANIA I MODYFIKACJI STALI NA POPRAWĘ WŁASNOŚCI W NISKICH TEMPERATURACH

Industrial conditions of obtaining thick-walled and shaped castings intended for operations at temperatures: minus 40÷60°C are presented in the paper. The selection of a cast steel grade is based on known studies [1,10,14], however due to castings wall thickness (70-240mm), the way of preparing liquid metal (deep deoxidation and modification, argon stirring in a ladle) and conditions of filling mould cavities (gating system assuring quiet filling, directional solidification and avoiding a formation of inessential heat centres), were developed to assure the required impact strength. Maintaining these parameters as well as the selection of heat treatments for the produced massive castings allowed to achieve the impact strength over 50 J/cm^2 at minus 40°C. This value was obtained for walls of various thickness.

Keywords: stell castings, minus temperature, wall thickness

Przedstawiono przemysłowe warunki otrzymywania grubościennych i kształtowych odlewów, przeznaczonych do pracy w temperaturze minus 40 ÷60°C. Dobór gatunku staliwa oparto o znane prace [1,10,14], jednak ze względu na grubość ścianek odlewów (70-240 mm), opracowano sposób przygotowania ciekłego metalu (głębokie odtlenianie i modyfikacja, argonowanie w kadzi) oraz warunki zapełnienia wnęki formy (układ wlewowy zapewniający spokojne wypełnianie, kierunkowe krzepnięcie i unikanie tworzenia zbędnych węzłów cieplnych), dla zapewnienia wymaganej udarności. Zachowanie tych parametrów jak również dobór obróbki cieplnej dla produkowanych masywnych odlewów, pozwoliły na uzyskanie udarności w minus 40°C wynoszącej powyżej 50 J/cm^2. Wartość tą otrzymano dla ścianek o różnej grubości.

1. Introduction

The selection of the proper cast steel grade depends on the assumed exploitation conditions of the casting, among others on loads which it is supposed to carry, chemical environment and temperatures at which the casting will operate. The material production cost is an equally important selection criterion for the majority of users. There is the whole list of this type of possibilities (Table 1). They allow the cast steel selection according to the assumed conditions (the most often: temperature, stresses, chemical composition).

In case of temperatures minus 20÷40°C an application of low carbon cast steel can be considered [1,2,4], while lower temperatures require the application of low alloyed manganese cast steel [2,5]: Mn-Ni or Cr-Ni [3,5]. However, additional factors should be always taken into account: stresses, corrosion, work time, casting walls thickness (especially in places of wall joints e.g. 40 to 120 mm, Fig. 1, marked: A), and casting structure. Knowledge of an influence of such processes as: the steel deoxidation method and its modification in the ladle [2,14] and the introduced heat treatment [7,8,14], on material properties - is helpful in selecting the proper steel grade. As an example: dual deoxidation of Mn-Ni steel by means of Al and Fe-CaSi allows to shift the impact transition temperature (of steel containing 0.25%C) from plus 15÷20°C – after deoxidation performed only by Al – to minus 40°C, when deoxidation was performed by Al (1kg/t) and by Fe-CaSi (2kg/t), [2]. Another solution constitutes an introduction of the more complex heat treatment: replacing normalization by quenching and tempering leads also to obtaining in cast steel Mn-Ni to KCV^{-40} over 40 J/cm^2 [2]. A successive factor allowing to improve the cast steel impact strength (plasticity) is improvement of its purity, understood as essential decreasing non-metallic inclusions. The papers [7,6], indicating the cast steel quality improvement due to an introduction of secondary metallurgy processes, should be mentioned in this place. Then not only a lowering of gases (mainly oxygen and nitrogen) content is achieved, but also an amount of macro-inclusions decreases and the dangerous, second type, inclusions are eliminated. Even during steel melting without a vacuum application, but with an argon stirring and reducing slag during the refining period, it is possible to obtain a high purity of cast steel [17]. The process of steel modification in the ladle before pouring into moulds is often applied in the foundry practice in

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TABLE 1

Selected cast steel grades for operations at negative temperatures [10]

Notation acc. to standard				Chemical composition, wt %									Impact strength
PN	ISO	DIN	ASTM	C	Si	Mn	P	S	Cr	Mo	Ni	Different	[J]
Carbon cast steels for work at temp. -40˚C													
270-480	270-480			0.25	0.60	1.20	0.035	0.035	0.35	0.15	0.40	V_{max}=0.05	KCV=22
270-480W	270-480W			0.25	0.60	1.00	0.035	0.035	0.40	0.15	0.40	V_{max}=0.05	KCV=27
L 400 I				0.10÷0.20	0.20÷0.50	0.40÷0.90	0.025	0.025	0.30	0.20	0.30	-	KCU=25
		GS-Ck 24		0.20÷0.28	0.30÷0.50	0.50÷0.80	0.030	0.030	<0.30	-	-	-	KCV=27 -40
		GS-Ck 16		0.12÷0.19	0.30÷0.50	0.50÷0.80	0.030	0.030	<0.30	-	-	-	KCV=55 -40
Low alloyed cast steels for work at temp. -40˚C													
	C23-41BL			0.20	0.60	1.00÷1.60	0.030	0.030					KCV=27 -40
	C31L			0.29	0.30÷0.60	0.50÷0.80	0.030	0.030	0.90÷1.20	0.15÷0.30	-	-	KCV=27 -40
L25HM				0.22÷0.29	0.20÷0.50	0.50÷0.80	0.035	0.035	0.80÷1.20	0.20÷0.30	-	Cu_{max}=0.30	KCU=31 -45
		GS-26CrMo 4		0.22÷0.29	0.30÷0.50	0.50÷0.80	0.030	0.025	0.80÷1.20	0.20÷0.30	-	-	KCV=27 -40
		GS-17CrMoV 5 11		0.15÷0.20	0.30÷0.50	0.50÷0.80	0.020	0.015	1.20÷1.50	0.90÷1.10	max 0.70	V_{max}=0.30	KCV=27 -50
	C34BL			0.20	0.30÷0.60	0.50÷0.80	0.030	0.030	2.00÷2.50	0.90÷1.20	-	-	KCU=39 -50
L18H2N				0.15÷0.20	0.30÷0.60	0.50÷0.80	0.030	0.030	2.00÷2.50	0.90÷1.10	-	-	KCU=40 -50
		GS-16Mn 5		0.15÷0.20	0.60	1.00÷1.50	0.020	0.015	0.30	0.15	0.40	-	KCV=45 -40
L15G				0.12÷0.20	0.20÷0.40	1.20÷1.50	0.030	0.025	0.30	-	0.30	-	KCV=41 -40
			LCB	0.30	0.60	1.00	0.040	0.045	0.50	0.20	0.50	Cu-0.30, V-0.30	KCV=18 -46
			LCC	0.25	0.60	1.20	0.040	0.045	0.50	0.20	0.50	Cu-0.30, V-0.30	KCV=20 -46
			EH-32	0.18	0.10÷0.50	0.90÷1.60	0.040	0.040	0.25	0.08	0.40	-	-
		GS-20Mn 5		0.17÷0.23	0.60	1.00÷1.50	0.020	0.015	0.30	0.15	0.040	-	KCV=35 -70
L20G				0.15÷0.20	0.20÷0.50	1.20÷1.60	0.030	0.025	0.30	-	-	-	KCV=20
		GS-10Ni 6		0.06÷0.12	0.30÷0.50	0.50÷0.80	0.025	0.025	-	-	1.30÷1.80	-	KCV=47 -90
High alloyed cast steels for work at temp. -70˚C													
		G-X5CrNiV 13 4 1		0.07	1.00	1.50	0.035	0.025	12.0÷13.5	0.70	3.50÷5.00	-	KCV=50 -80
	C39NiL			0.08	1.00	1.50	0.030	0.030	11.5÷13.5	1.00	3.50÷5.00	-	KCV=27 -80
L0H12N4M				0.07	1.00	1.50	0.040	0.035	11.5÷13.5	1.00	3.50÷5.00	-	KCU=55 -80
			LC2	0.25	0.60	0.50÷0.80	0.040	0.045	-	-	2.00÷3.00	-	KCV=20 -73
			LC2-1	0.22	0.50	0.55÷0.75	0.040	0.045	1.35÷1.85	0.30÷0.60	2.50÷3.50	-	KCV=11 -73
	C43L			0.14	0.30÷0.60	0.50÷0.80	0.030	0.030	-	-	3.00÷4.00	-	KCV=27 -70
High alloyed cast steels for work at temp. below -70˚C													
LH18N9				<0.15	2.00	2.00	0.035	0.030	17.0÷19.0	-	8.00÷11.0	-	KCV=40 -296
		G-X6CrNi 18 10		<0.07	<2.00	<2.00	0.045	0.030	17.5÷20.0	<0.70	9.00÷11.0		KCV=48 -195

order to increase the steel impact strength at negative temperatures. Additions of vanadium, titanium and niobium (in amounts below 0.1%) are used. E.g. an addition of vanadium in amounts up to 0.08% increases the impact strength of carbon cast steel and Mn-Ni KCV^{-40} to a value over 40 J/cm^2. Especially favourable influence has a combined introduction of vanadium and niobium [9,]. However, there are also data of unfavourable influence of vanadium [5,10,11]. These discrepancies are explained by its (and also Ti, Zr) affinity to nitrogen and carbon. Due to that, controlling of the nitrogen content in liquid steel, before its modification, is necessary. Influencing of V, Ti, Nb, Zr should be related to the cast steel matrix refinement, since these elements are applied as micro additions in high strength low alloyed (HSLA) cast steels. An increase of R_m and R_e in these steels (cast steels) is explained by a precipitation of fine-dispersive particles of carbonitrides [12÷15] and hampering by them dislocation movements. However, in dependence on the dissolution temperature of these precipitates during castings austenitisation, and also in dependence on the chemical composition, deoxidation and desulphurising degree, the morphology of carbonitrides is diversified and it decides on the final strength parameters [12,13,15,16].

2. Investigation methods

Steel for massive castings: 10000kg, 6800kg, 3600kg (Fig. 1, 2 and 3) was melted in the basic electric arc furnace of a capacity 8-9 tones. Each melt was done in a full refining process (ore + oxygen). As a standard the falling deoxidation was applied by means of Al in the arc furnace and in the ladle and it was also introduced during Fe-CaSi tapping. Each time metal bath was argon stirred, for minimum 4 minutes. Argon was introduced through the porouse plug, shaped element installed in the bottom lade.

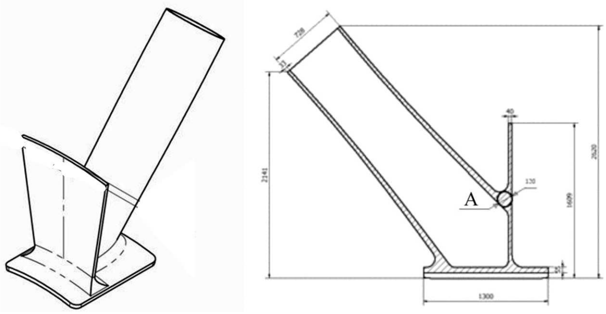

Fig. 1. Low alloyed cast steel, Gs20Mn5, mass 3800kg

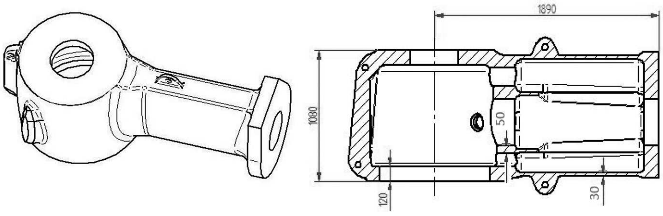

Fig. 2. Low alloyed cast steel, Gs20Mn5, mass 6800kg

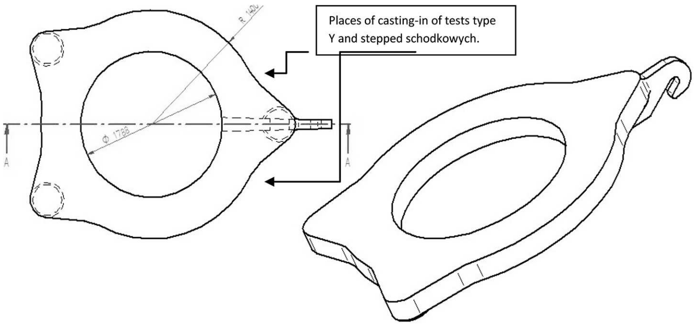

Fig. 3. Low alloyed cast steel, Gs20Mn5, mass 10000kg

Wedge tests, type Y, and stepped tests were cast-in to castings (Fig. 4). The casting together with tests was at first normalized and then quenched and tempered. Tests were cut out after the casting heat treatment. In order to show the favourable modification effects, melts were made with and without micro-additions of vanadium (Table 2). The heat treatment – normalisation (950°C) was performed for castings and tests Y type as well as quenching and tempering were carried out for stepped tests (950°C, water cooling, tempering at 550°C).

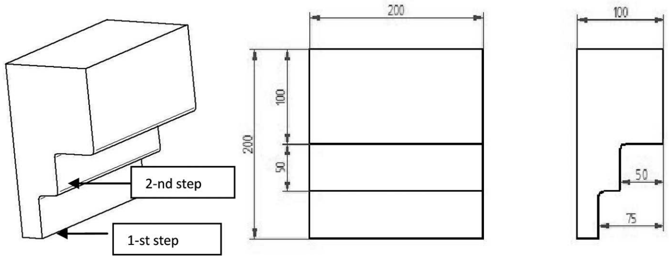

Fig. 4. Stepped test (riser head was placed on the upper surface)

3. The obtained results and their discussion

On the bases of wedge tests, performed acc. to PN-90/H-04309, investigations of mechanical properties acc. to PN-EN ISO 6892-1:2010 and PN-EN ISO 148-1 were carried out, together with the determination of the impact strength at a temperature of -20°C (Table 3). Next, the impact strength was determined at -20, -40 and -60°C, performing tests on the bases of stepped tests from the bottom part (1-st step) and the middle part (2-nd step). Due to a rather small thickness of the bottom part (1-st step), only 3 tests were performed for each temperature. The middle part (2-nd step) was divided into three levels: lower (L), middle (M) and upper (U), and for each level 9 tests were made (3 for each temperature) – Table 4.

TABLE 2

Chemical composition of cast steel Gs-20Mn5 in the melts

	Melt 145928	Melt 245832	Melt 145726	Melt 145763
C [%]	0.21	0.19	0.21	0.21
Mn [%]	1.41	1.33	1.36	1.40
Si [%]	0.41	0.37	0.54	0.51
P [%]	0.004	0.017	0.006	0.013
S [%]	0.010	0.012	0.009	0.015
Al. [%]	0.031	0.065	0.049	0.036
V [%]	0.050	0.057	-	-

TABLE 3

Mechanical properties from test bars of Y type (after normalisation)

	Melt 145928	Melt 245832	Melt 145726	Melt 145763
Re [MPa]	420	439	487	404
Rm[MPa]	621	595	625	595
KV[J/cm^2]	105	122	84.7	49,3
KV$_{-20}$[J/cm^2]	52.6	31.3	51.25	32.25
A [%]	28.4	30.1	27.2	25.4

At estimating the obtained analysis results the influence of metallographic factors should be taken into account: deoxidation and modification (Fig. 5). When carbon, silicon and manganese contents are similar (Table 2), the way of performing melts is essential. In dependence on the bath oxidation degree the final aluminium content, after deoxidation of the bath either before tapping or in the ladle, leads to a nearly two times decrease of the impact strength at minus 20°C (Fig. 5) (if aluminium concentration is over 0.06%).

TABLE 4

Impact strength of cast steel Gs-20Mn5 from stepped tests, average from 3 measurements

	Melt 145928			**Melt 245832**			**Melt 145726**			**Melt 145763**		
Heat treatment	Improvement			Improvement			Improvement			Improvement		
1-st step												
KV$_{-20}$[J/cm^2]	72			38.6			66.5			49.8		
KV$_{-40}$[J/cm^2]	50			23.6			44.2			34.2		
KV$_{-60}$[J/cm^2]	34			17.4			35.2			32.5		
2-nd step	L	M	U	L	M	U	L	M	U	L	M	U
KV$_{-20}$[J/cm^2]	56	57	61	43	36	39	47	46	46	63	50	60
KV$_{-40}$[J/cm^2]	39	31	40	31	34	36	36	36	37	38	33	29
KV$_{-60}$[J/cm^2]	22	43	35	31	33	34	32	28	22	20	24	24

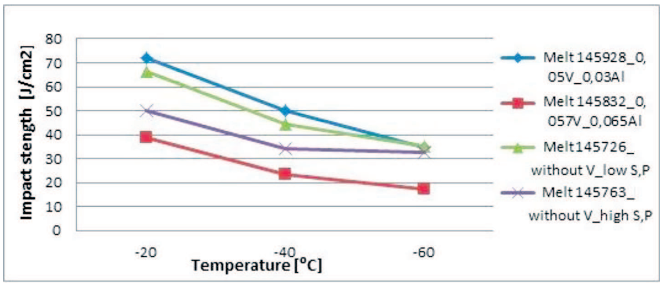

Fig. 5. Impact strength in dependence of a temperature for samples taken from the '1-st step'

The similar dependence can be seen when comparing the impact strength of samples from the melt without addition of V but of a very low P and S content (Fig. 5 and 6). The reason of decreased impact strength of samples with a higher S content is known [2,6,7]. It is related to the probability of inclusions of sulphides or oxysulphides along the primary grain boundaries of cast steel [4,16,17]. An influence of argon stirring of steel in the ladle on the amount of macro-inclusions is also important [17].

An influence of the way of refining (on dephosphorisation degree), and the steel-refining course in the arc furnace (desulphurising and deoxidation degree), are visible, especially when the combined influences of S, P and Al on the impact strength are compared (Fig. 5). At higher phosphorus and sulphur contents (melts 145832 and 145763), the impact strength is two times lower. When castings are operating at low temperatures, this factor is of an essential meaning.

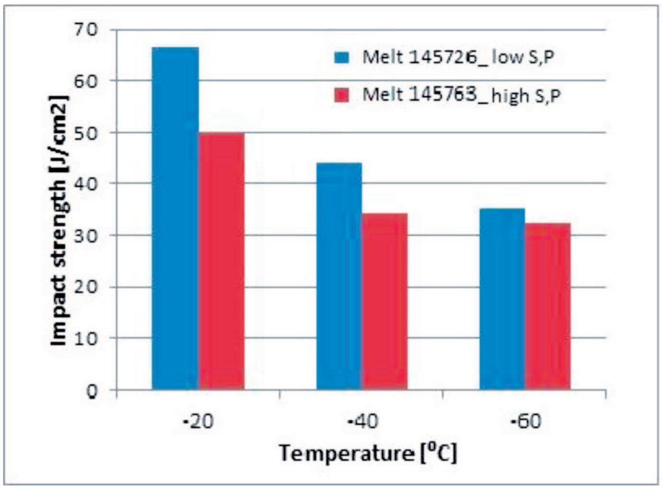

Fig. 6. Comparison of the impact strength of samples taken from the '1-st step' at negative temperatures for melts of various S and P contents

An influence of vanadium on the steel impact strength at low temperatures is presented in Fig. 8. At a comparable vanadium content (and C, Mn, Si – Table 2), within the whole range, it was found that the impact strengths are decisively higher for the melt of a lower content of final Al (melt 145928). Since increased Al content unfavourably influences the impact strength (especial at negative temperatures [7,18]) shifting the impact transition temperature in the direction of positive temperatures. The final Al. content in the melt should be controlled by determining the oxygen activity before deoxidation. This would allow introducing into a liquid bath only such amount of Al., which is necessary for the proper steel deoxidation. Excessive amounts of aluminium in liquid steel react with nitrogen dissolved in this bath, forming complex carbonitrides (Fig. 8). Their presence is the most often the reason of cast steel brittleness, and when their amount is smaller – they cause the impact strength decrease.

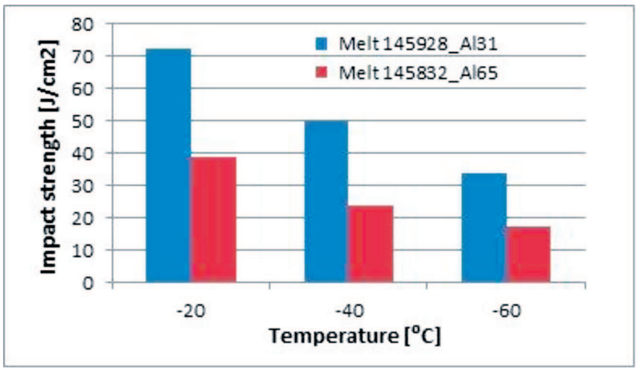

Fig. 7. Comparison of the impact strength of samples taken from the '1-st step' of the stepped test at negative temperatures

Underrated values of impact strength can be improved, in the foundry practice, thus saving massive castings from rejection. A significant improvement of the impact strength is obtained after quenching and tempering (Fig. 8), (more than 20% increase).

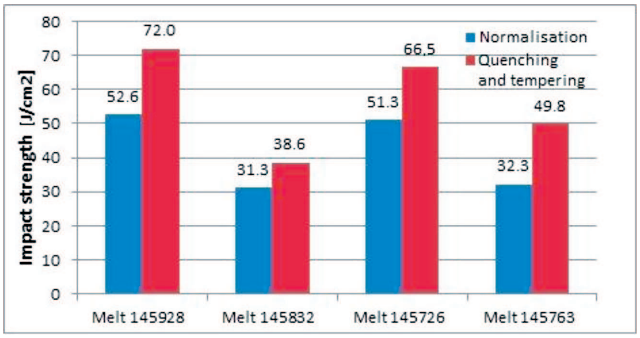

Fig. 8. Impact strength of samples in the normalised state and after quenching and tempering at a temperature of -20°C

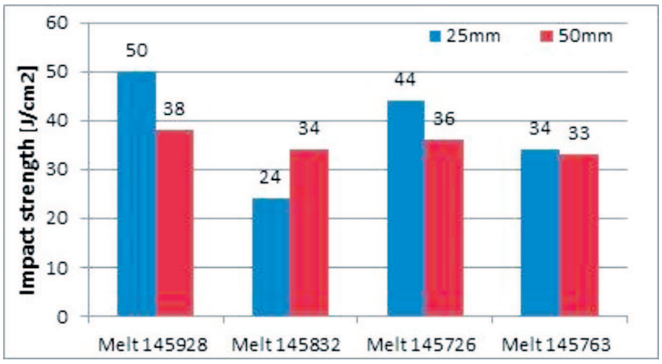

Fig. 9. Influence of a wall thickness – stepped test after quenching and tempering. Temperature: -40°C

In case of good quality melts (low S and P content and favourable final aluminium content) a significant margin of the impact strength is achieved (melts 145928 and 145726) and in melts of an increased aluminium content values of the minimum impact strength are exceeded. For the producer it is a significant economic effect.

The influence of a casting wall thickness on the impact strength is quite complex. Although in thinner walls the impact strength is higher (Fig. 9), in individual melts it is diversified. Not only an influence of the final aluminium content (melts 145928 and 145832) is here exposed, but also the quality of the obtained material. In melts without a vanadium addition, decreased sulphur and phosphorus contents allow to obtain the impact strength comparable with the one of the cast steel modified by vanadium (especially in walls 50 mm thick).

4. Conclusions

1. Vanadium improves the impact strength at low temperatures (-20 to - 60°C).
2. Its influence is the more favourable the smaller sulphur and phosphorus content in cast steel.
3. When aluminium contents are increased the impact strength at low temperatures significantly decreases. Introducing quenching and tempering instead of normalisation does not compensate these losses.
4. When the cast steel modification is done by vanadium the final nitrogen content in liquid steel before its tapping into the ladle should be taken into account.

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Received: 15 February 2013.