Effect of Cr, Mo and Al on Structure and Selected Mechanical Properties of Austenitic Cast Iron

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Abstract

Results of a research on influence of chromium, molybdenum and aluminium on structure and selected mechanical properties of Ni-Mn-Cu cast iron in the as-cast and heat-treated conditions are presented. All raw castings showed austenitic matrix with relatively low hardness, making the material machinable. Additions of chromium and molybdenum resulted in higher inclination to hard spots. However, a small addition of aluminium slightly limited this tendency. Heat treatment consisting in soaking the castings at 500 °C for 4 h resulted in partial transformation of austenite to acicular, carbon-supersaturated ferrite, similar to the bainitic ferrite. A degree of this transformation depended not only on the nickel equivalent value (its lower value resulted in higher transformation degree), but also on concentrations of Cr and Mo (transformation degree increased with increasing total concentration of both elements). The castings with the highest hard spots degree showed the highest hardness, while hardness increase, caused by heat treatment, was the largest in the castings with the highest austenite transformation degree. Addition of Cr and Mo resulted in lower thermodynamic stability of austenite, so it appeared a favourable solution. For this reason, the castings containing the highest total amount of Cr and Mo with an addition of 0.4% Al (to reduce hard spots tendency) showed the highest tensile strength.

Keywords: Austenitic cast iron, Austenite transformation, Heat treatment, Nickel equivalent, Mechanical properties of cast iron

1. Introduction

A characteristic feature of the Ni-Mn-Cu cast iron is the possibility to radically change its structure and properties by small changes of its chemical composition and heat-treatment parameters [1-4].

The basic chemical composition index of this cast iron is the nickel equivalent Equ_{Ni} value that decides thermodynamic stability of austenitic matrix of raw castings [2-4]. If the Equ_{Ni} value, determined according to the relationship given in [2,3], is lower than 16.0%, partial austenite transformation takes place in standard ø 30 mm shaft castings during their cooling-down in the sand mould. As a result, acicular ferrite (mostly martensite) is created. Its quantity increases with decreasing Equ_{Ni} value [2,3]. This leads to lower strength and higher hardness of cast iron, which significantly reduces its machinability.

If the nickel equivalent value is at least 16.0% [2,3], matrix of raw castings is composed of austenite only. Higher equivalent value results in higher thermodynamic stability of austenite. This

is favourable from the viewpoint of obtaining austenitic matrix of castings, stable within a wide temperature range [2]. However, this restricts the possibility to obtain, by heat treatment, hard and abrasive-wear resistant structure, morphologically similar to that of isothermally hardened cast iron.

From this point of view, the most favourable Equ_{Ni} value should be ca. 16.0%. With this value, it would be possible to obtain austenitic castings with low matrix stability and relatively good machinability. After machining, the castings could be subjected to heat treatment (soaking and slow cooling-down) resulting in the matrix structure with higher hardness and strength [2,4]. Proper selection of heat treatment parameters permits, like in the case of ADI cast iron, a controlled, partial transformation of the matrix [5-18].

It seems that mechanical properties and abrasive-wear resistance of Ni-Mn-Cu cast iron can be improved by introducing additions of chromium and molybdenum, the elements commonly used for this purpose in other grades of cast iron. Because of chilling effect of these elements, it seems advisable to add some aluminium to the alloy.

However, the degree to that the additions of Cr, Mo and Al would affect structure and mechanical properties of raw castings should be determined, as well as course and results of the changes occurring during heat treatment.

2. Purpose, scope and methodology of the research

This research was aimed at determining influence of additions of chromium, molybdenum and aluminium on structure and selected mechanical properties of Ni-Mn-Cu cast iron in the as-cast and heat-treated conditions.

Examinations were carried-out on specimens coming from 9 melts of cast iron. At constant concentration of basic alloying elements: 3.4±0.2% C; 1.8±0.2% Si; 4.2±0.2% Mn; 3.2±0.2% Ni;

1.8±0.2% Cu; 0.18±0.02% P and 0.01% S, concentrations of Cr and Mo were changed from 0.4 to 1.8% and from 0.2 to 0.5%, respectively. Moreover, an addition of 0.4% Al was applied in the alloys with higher concentrations of Cr and Mo, in order to compensate their chilling effect.

Cast iron was melted in an induction medium-frequency furnace, in a crucible SiC type A35. The castings in form of dia. 30 mm shafts were cast in shell moulds. Heat treatment of raw castings consisted in soaking at 500 °C for 4 h followed by air cooling.

Chemical analysis was carried-out spectrally with use of a glow discharge analyser GDS 750 QDP Leco and a scanning electron microscope Quanta 250 equipped with a WDS detector. Results are shown in Table 1. The chilling tendency was determined according to ASTM A367-55T, on 3C specimens solidified on a chill. Microscopic examinations were performed using a light microscope MA200 and a scanning electron microscope TM 3000. Brinell hardness was measured acc. to EN ISO 6506-1:2014-12 and Vickers microhardness was measured acc. to EN ISO 6507-1:2018-05. The tensile testing was carried-out using a testing machine Instron 5982 at maximum load of 100 kN, according to EN ISO 6892-1:2016-09.

3. Results and discussion

3.1. Structure and mechanical properties of raw castings

Microscopic observations, including determination of graphite features according to EN ISO 945-1:2009, were carried-out on polished sections unetched and etched with nital. Results of these observations and hardness measurements of raw castings are given in Table 2.

Table 1.
Chemical composition, nickel equivalent Equ_{Ni} and eutectic saturation ratio S_C

Cast iron No.	Concentration of elements [% wt.]										S_C	Equ_{Ni}
	C	Si	Mn	Ni	Cu	Cr	Mo	Al	P	S	[/]	[% wt.]
1	3.5	1.9	4.3	3.3	1.9	-	-	-	0.19	0.01	1.02	16.3
2	3.6	1.8	4.2	3.2	2.0	0.4	-	-	0.19	0.01	1.03	16.1
3	3.4	1.7	4.4	3.0	1.7	0.7	-	-	0.20	0.01	0.95	16.0
4	3.5	1.8	4.2	3.4	1.8	0.9	-	0.4	0.18	0.01	1.02	16.1
5	3.4	2.0	4.1	3.4	2.0	1.8	-	0.4	0.17	0.01	0.99	16.0
6	3.4	2.0	4.3	3.3	1.7	0.7	0.2	-	0.18	0.01	0.97	16.2
7	3.6	1.9	4.3	3.1	1.8	1.0	0.2	-	0.16	0.01	1.01	16.1
8	3.3	1.7	4.2	3.3	1.9	0.7	0.5	0.4	0.20	0.01	0.95	16.0
9	3.5	1.8	4.2	3.2	2.0	1.1	0.5	0.4	0.18	0.01	1.01	16.0

Table 2.
Structure and hardness of raw castings

Cast iron No.	Matrix	Percentage of $Fe_3C - C_{gr}$ * / type of C_{gr} /	HBS 2.5/162.5 [/]	HV0.01N of austenite [/]
1	austenite	0% – 100% / IA4 /	160	168
2	austenite	0% – 100% / IE4 /	170	182
3	austenite	0% – 100% / IE4	185	192
4	austenite	10% – 90% / IE5 /	280	204
5	austenite	95% – 5% / IE6 /	380	230
6	austenite	45% – 55% / ID5 /	205	195
7	austenite	50% – 50% / ID5 /	220	203
8	austenite	55% – 45% / ID5 /	210	214
9	austenite	60% – 40% / ID4 /	250	207

*Fe_3C – cementite; C_{gr} – graphite;
$Fe_3C + C_{gr} = 100\%$

Introducing additional elements to Ni-Mn-Cu cast iron did not affect matrix structure of raw castings. In all cases, the matrix was composed solely of austenite, see Fig. 1. However, features and quantities of graphite varied. This was predominantly affected by chilling action of chromium. Successive increase of Cr concentration in the alloys No. 2 to 5 resulted in decreasing quantity and size of graphite particles and in increasing tendency to their interdendritic arrangement. In spite of the addition of 0.4% Al, partial chilling of the castings occurred starting from 0.9% Cr (cast iron No. 4 and then No. 5). This resulted in increased hardness of the castings from 160 HBS for the alloy No. 1 to 380 HBS for the alloy No. 5. This was also partially contributed by increased hardness of austenite, from 168 HV0.01N in the alloy with no chromium (No. 1) to 230 HV0.01N in the alloy with the largest content of chromium (No. 5).

In comparison to chromium, effect of molybdenum on structure of raw castings was much weaker. A weak chilling action of molybdenum demonstrated by slightly higher hardness was visible in the alloy containing 0.7% Cr (Nos. 3, 6 and 8), but this effect was basically negligible in the alloys containing ca. 1.0% Cr.

3.2. Structure and mechanical properties of heat-treated castings

Heat treatment of raw castings, consisting in their soaking at 500 °C for 4 hours followed by air cooling, in all cases resulted in a clear change of matrix structure. Austenite was partially transformed to carbon-supersaturated (0.33±0.02% C) acicular ferrite with hardness from 490 to 550 HV0.1N, similar to bainitic ferrite.
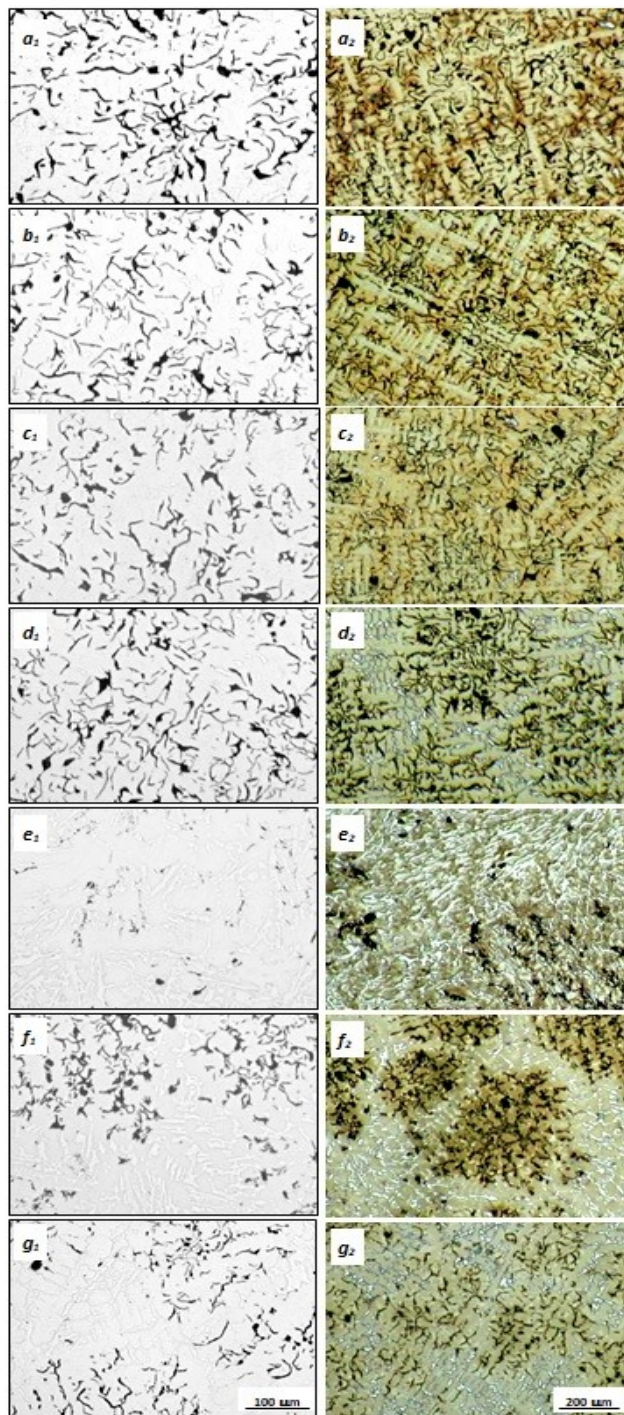

Fig. 1. Austenitic cast iron: *a)* No. *1*: a_1 – graphite IA4: a_2 – austenite, graphite; *b)* No. *2*: b_1 – graphite IE4; b_2 – austenite, graphite; *c)* No. *3*: c_1 – graphite IE4; c_2 – austenite, graphite; *d)* No. *4*: d_1 – graphite IE5; d_2 – austenite, graphite, cementite; *e)* No. *5*: e_1 – graphite IE6; e_2 – austenite, graphite, cementite; *f)* No. *8*: f_1 – graphite ID5; f_2 – austenite, graphite, cementite; *g)* No. *9*: g_1 – graphite ID4; g_2 – austenite, graphite, cementite. Unetched – x_1; etched with nital – x_2.

The transformation degree was different for individual castings – Fig. 2. Results of quantitative analysis of matrix structure are given in Table 3. The largest changes of matrix were found in the alloy No. *1* (with no Cr and Mo). As a result of heat treatment, ca. 50% of austenite was transformed. Introduction and increase of chromium and molybdenum concentrations successively increased the transformation degree. In the alloys No. *8* and No. *9* with the highest total concentrations of Cr and Mo, 85 to 90% of austenite present in raw castings was transformed. This means that both chromium and molybdenum decrease thermodynamic stability of austenite.

Changes of matrix structure were accompanied by changes of the alloy properties, mainly its hardness. Differences of hardness between individual castings can be considered from two points of view: absolute hardness and hardness increment caused by heat treatment. In the first case, the differences between HB values are affected by different chilling degrees of raw castings and different transformation degrees of matrices, caused by heat treatment. The lowest hardness of 313 HBW was shown by the chromium-less cast iron No. *1* – with no hard spots and with the lowest austenite transformation degree. Higher hardness of the other alloys resulted from increased inclination to chilling and/or increased degree of austenite transformation. Among the alloys with similar initial structure, i.e. the alloys No. *2, 3, 6* and *7*, higher hardness after heat treatment was demonstrated by the castings with higher concentrations of chromium that reduces thermodynamic stability of austenite.

The highest hardness (492 HBW) was obtained for the alloy No. *5* containing 1.8% Cr. However, the main cause of so high hardness of this alloy was very strong chilling of raw castings, meaning also their poor machinability.
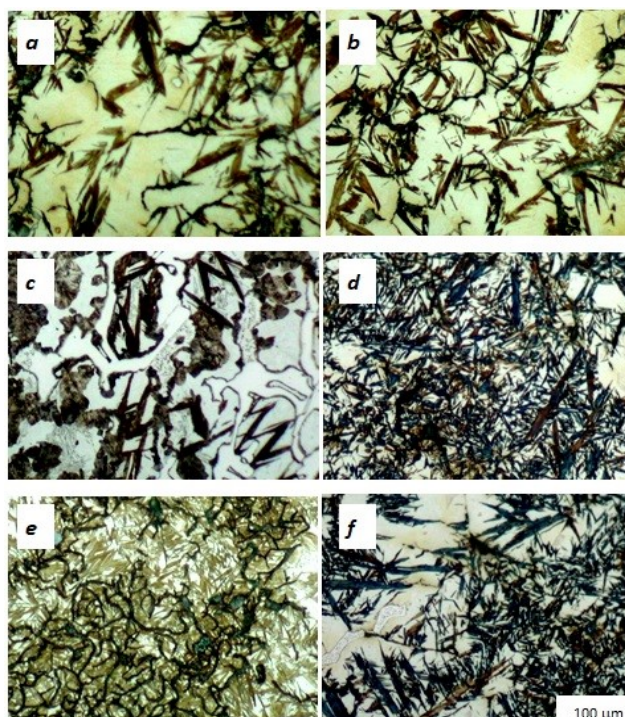

Fig. 2. Microstructure of cast iron after heat treatment: *a)* No. *6* – retained austenite, acicular ferrite; *b)* No. *7* – retained austenite, acicular ferrite; *c)* No. *5* – retained austenite, acicular ferrite, pearlite; *d)* No. *9* – retained austenite, acicular ferrite; *e)* No. *8* – retained austenite, acicular ferrite; *f)* No. *1* – retained austenite, acicular ferrite. Etched with nital

Table 3.
Composition of matrix, hardness HBW and its increment caused by heat treatment, tensile strength R_m and its increment caused by heat treatment in relation to the alloy No. *1*

Cast iron No.	Composition of matrix A – Fe$_m$ – P * [% - % - %]	HBW 2.5/162.5 after HT** [/]	Increment of HBW 2.5/162.5 [/]	R_m after HT** [MPa]	Increment of R_m in relation to alloy No. *1* [MPa]
1	50 – 50 – 0	313	154	273	-
2	48 – 52 – 0	347	178	281	8
3	47 – 53 – 0	372	189	309	36
4	45 – 55 – 0	411	129	332	59
5	45 – 25 – 30	492	112	315	42
6	45 – 55 – 0	362	157	326	53
7	40 – 60 – 0	383	163	341	68
8	10 – 90 – 0	441	230	383	110
9	15 – 85 – 0	454	205	372	99

*A – austenite; Fe$_m$ – acicular ferrite; P – pearlite;
**HT – heat treatment

From the viewpoint of the possibility to obtain castings with good machinability and high abrasive-wear resistance, it should be an alloy with no hard spots, but with a very high degree of austenite transformation, resulting from heat treatment. An example of such an alloy can be the alloy No. *8*. Hardness of its

raw casting was 210 HBS, and after heat treatment 441 HBW, which means over twice higher hardness.

Effect of chromium and molybdenum on tensile strength of cast iron Ni-Mn-Cu (after heat treatment) is more complex, since, on the one hand these elements increase inclination to chilling and can decrease strength and machinability of castings, but on the other hand, decreasing stability of austenite, they increase the austenite transformation degree, thus contributing to increasing the strength value. It results from the R_m values placed in Table 3 that, in spite of the chilling action of both elements, their introduction to the alloy was favourable, since its strength increased in comparison to the alloy without these additives (the alloy No. *1*). The highest strength (ca. 380 MPa) was obtained for the alloys No. *8* and No. *9* with the largest total concentrations of Cr and Mo and thus with the highest austenite transformation degree. The chilling action of chromium and molybdenum was partially compensated by an addition of 0.4% Al.

4. Conclusions

Matrix structures of all the raw castings were composed exclusively of austenite. This means that the concentration range of Cr, Mo and Al did not cause any phase transformation that can occur in the case of too low thermodynamic stability of austenite. It was only found that hardness of austenite increased with increasing concentrations of Cr and Mo.

However, additions of chromium and molybdenum increased inclination of cast iron to chilling. As concentrations of Cr and Mo (mainly Cr) increased, quantity and size of graphite particles decreased, but inclination to interdendritic arrangement of graphite increased. The chilling degree also increased, which resulted in clearly higher hardness of raw castings. The addition of 0.4% Al slightly limited this tendency.

Heat treatment led to partial austenite transformation in matrices of raw castings. After soaking at 500 °C for 4 hours, carbon-supersaturated, hard acicular ferrite was created during air cooling of the castings. The austenite transformation degree was different in various castings. It depended not only on the Equ_{Ni} value (the lower equivalent value, the higher fraction of acicular ferrite), but also on concentrations of Cr and Mo (austenite transformation degree increased with increasing total concentration of the elements).

If the castings with the highest chilling degree showed the highest hardness, the largest hardness increment caused by heat treatment occurred in the castings with the highest austenite transformation degree. From this point of view, influence of Cr and Mo, reducing thermodynamic austenite stability, appeared favourable.

For the same reason, the highest tensile strength was demonstrated by the castings with the largest total concentration of Cr and Mo, with an addition of 0.4% Al. The addition of aluminium partially compensated the chilling action of Cr and Mo, which decreases tensile strength.

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