www.czasopisma.pan.pl PAN www.journals.pan.pl

ARCHIVES of FOUNDRY ENGINEERING

ISSN (2299-2944)
Volume 2023
Issue 4/2023

54 – 64

10.24425/afe.2023.146679

7/4

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

The Melting Process and its Impact on the Properties of High-Chromium Cast Iron and the Economic Calculation

J. Mędoń [a, b, *], A. Szczęsny [a], E. Ziółkowski [a], E. Guzik [a], M. Czarny [b], D. Kopyciński [a]

[a] AGH University of Krakow, al. Adama Mickiewicza 30, 30-059 Kraków, Poland

[b] Odlewnia „Świdnica" Sp. z o.o., Świdnica ul. Kliczkowska 53, Poland

* Corresponding author. E-mail address: jasiek.medon@vp.pl

Received 07.06.2023; accepted in revised form 05.09.2023; available online 13.12.2023

Abstract

The subject of this study is to show that the parameters of the melting process of high chromium cast iron affect the cost of casting and the properties of the cast iron. The analysis of the quality of the casting and its price was conducted in terms of the metal charge of high chromium cast iron. As is well known, in order to obtain the correct structure of the casting, and thus good strength properties, it is necessary to use clean batch components free of undesirable impurities. Unfortunately, the quality of the metal charge is proportional to its price. Thus, the use of expensive batch components offers the possibility of obtaining healthy and meeting the strength properties of castings. However, there is a flaw in this approach. And it is from the point of view of economics that production plants are forced to look for savings. Expensive feedstock materials are replaced by cheaper counterparts giving the possibility of obtaining castings with similar properties often, however, at the cost of increased inferior quality. It seems that a way out of this situation is to introduce a modification procedure into the alloyed iron manufacturing technology. The selected modifiers should affect the fragmentation of the structure of the primary austenite. At this point, it can be hypothesized that this will result in the elimination of hot cracking in high chromium cast iron. The industrial research carried out at the "Swidnica" Foundry Ltd. made it possible to show by means of the Althoff-Radtke method that by using the modification of the liquid metal of the so-called "inferior and cheaper" composition of the metal charge, a reduction in the occurrence of hot cracks and shrinkage cavities can be achieved. In addition, iron-niobium modification not only reduced the formation of casting defects in castings, but also slightly improved the impact strength of high-chromium cast iron. The work was written as part of an implementation PhD.

Keywords: Metal batch, High chromium cast iron, Modification, Althoff-Radtke test, Impact strength

1. Introduction

Obtaining alloyed white cast iron with appropriately required mechanical properties requires the ability to control the microstructure of the cast iron as a result of direct influence on the physicochemical state of the liquid metal: chemical composition, type of metal charge, superheating temperature, liquid metal holding temperature and refining processes such as, for example - modification treatment.

In the case of white iron castings, controlling the physicochemical state of the liquid metal boils down to obtaining the right metal matrix in its structure and a given proportion, distribution and type of carbide complex separations. In addition, a second important issue is the ability to control the cooling rate of an alloyed white iron casting through, among other things: chemical composition (thus liquidus temperature), casting modulus, mold material or casting temperature. Also an important issue is the heat treatment of the alloyed white cast iron structure already produced by metallurgical processes.

According to the literature [1-6], the morphology and number of grains of primary austenite should have a great influence on the properties of cast iron. In addition, to ensure sufficiently good mechanical properties, the microstructure of a white cast iron casting should be characterized by the separation of equiaxial grains, which is the result of endogenous crystallization of the casting. It turns out that increasing the carbon content and increasing the pouring temperature of the liquid metal and simultaneous overheating of the metal above the liquidus temperature, leads to endogenous crystallization of the cast iron casting. A similar situation can occur during the modification procedure of white cast iron.

Figure 1 shows the effect of the composition of the metal charge on the type of crystallization that will prevail during the manufacture of a white iron casting. In addition, on the ordinate axis, the numbers indicate the dendritic crystallization type series defined in the work [1,7,8].

The two runs of this relationship show the variation in the composition of the metal charge, which should be taken into account when designing the structure of an iron casting.

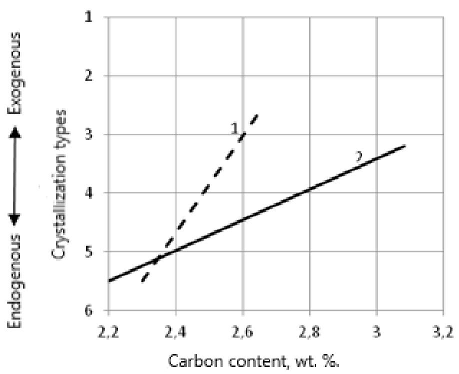

Fig. 1. The effect of carbon in liquid metal on the type of dendritic crystallization during the manufacture of white iron casting [2]; the dashed line (1) refers to a melt in which the metal charge contained: 20% pig iron and 80% steel scrap; while the solid line (2) indicates a metal charge composed of: 25% pig iron and 75% steel scrap

As can be seen from Figure 1, the formation of a type I dendritic microstructure is directly related to the physicochemical state of the liquid metal, that is, in this case, its nucleation state. If the liquid metal shows little nucleation ability then it is certain that a type I structure will be obtained. Industrial practice shows that the type of metallurgical furnace also affects the physicochemical state of the metal. Indeed, it turns out that liquid metal smelted in an electric furnace has a lower nucleation capacity, and in this technology it is necessary to ensure the appropriate composition of white cast iron and to provide for a modification procedure that ensures endogenous crystallization [2,4-6,9-16]. In alloyed cast steel, the situation is similar [17,18]. The metal charge, also affects the type of microstructure of white cast iron, as shown in Fig.1. From this figure, it can be seen that a metal charge composed of a greater proportion of scrap steel (and a lower content of pig iron), can lead to endogenous crystallization and the formation of a greater number of equiaxial grains of primary austenite. The tendency to endogenous crystallization will be enhanced by the already mentioned higher value of superheating temperature and holding time of the liquid metal in the electric furnace and thus increase the nucleation capacity of the liquid metal. This ensures that a greater number of desirable equiaxial grains are obtained in the structure of white cast iron.

As a result of the analysis of the crystallization of white chromium cast iron, the relationship between the morphology of the dendrite and the tendency to form cracks can be distinguished, as illustrated in Figure 2.

The microstructure of cast iron after exogenous crystallization consists of oriented grains of austenite dendrites and is mostly found in white cast iron, including high chromium cast iron. Such a structure undoubtedly has a high propensity to form casting defects of the fracture type. In addition, this structure naturally produces other casting defects in the interdendritic spaces, namely microporosity and micro shrinkage cavities. The above phenomenon is caused by the presence of a coarse-grained primary austenite structure. As can be expected (Figure 2 a), dendritic grains characterized by large dimensions, inhibit the flow of liquid metal between their branches.

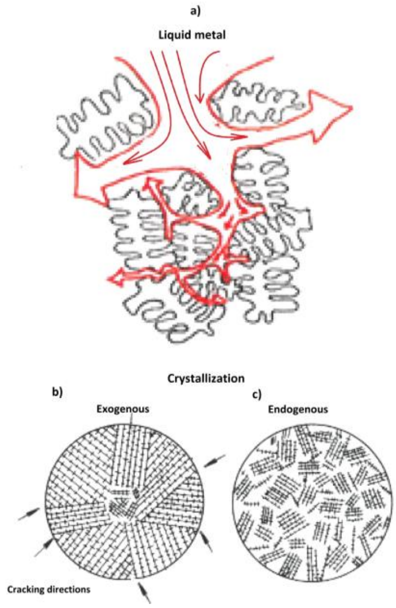

Fig. 2. Coexistence of coarse-grained structure and liquid during crystallization [19] (a) and image of cracks at primary grain boundaries of coarse-grained microstructure formed during exogenous crystallization and determination of crack directions [2,7] (b) and fine-grained microstructure formed during endogenous crystallization [2,7] (c)

On the other hand, primary austenite grains exhibiting small dimensions limit the occurrence of microporosity, shrinkage cavities and cracks in white cast iron castings (this also applies to gray cast iron). The above effect can be explained by comparing Figure 2b with Figure 2c and forcing endogenous crystallization during crystallization. The resistance of a given plastic to cracking, essentially depends on its ability to resist the development and propagation of cracks. Thus, the endogenous nature of crystallization through random orientation and numerous

separations of dendritic grains of primary austenite types V and VI promote a reduction in the propensity of the casting to crack, with an increase in its ability to withstand mechanical loads.
Figure 2 shows a hypothetical casting crack that runs along the lateral surfaces of the grains of primary austenite dendrites in white cast iron. It can be assumed that as a result of the modification of the cast iron, when a fine-grained microstructure of equiaxial grains of primary austenite is obtained in the casting, the length of the boundaries between them increases. Then the length of the fracture path increases, and with it the potential in energy absorption increases, and thus the fracture toughness of the casting increases. It also appears that the morphology of the primary grains also affects the distribution of micro-areas of shrinkage porosity occurrence and related mechanical properties of white cast iron.

2. Mathematical model of fuzzy batch bearing optimization task

Given the chemical composition of the various feedstock materials, defined in terms of the content ranges of each chemical element, a fuzzy mathematical model of feedstock bearing optimization was adopted. This model contains two components: the objective function, which is the mathematical formulation of the optimization criterion, and the so-called system of limiting conditions. In bearing optimization, it is usually assumed that the objective function determines the price of the set charge. In optimization, one will look for such a solution that this function takes on a minimum value, which means that one is looking for such a bearing of the charge that will have the lowest price for the adopted constraints. Such a bearing is also referred to by the term economically optimal bearing.

The system of constraining conditions consists of a series of inequalities and equations derived from the assumed chemical composition of the feedstock materials and the starting alloy. Additional constraints in this system can be related to the assumed lower or upper values of the shares of individual feedstock materials in the calculated bearing.

The mathematical model of the task of fuzzy optimization of the charge bearing consists in determining such values of the share xj of the j-th charge material that the price of this charge in the form:

$$batch\ price = \sum_{j=1}^{N} c_j x_j \rightarrow minimum \quad (1)$$

was the lowest, while meeting the system of limiting conditions:

$$\begin{cases} \sum_{j=1}^{N} A_{ij} x_j \geq A_i^d m_m \\ \sum_{j=1}^{N} A_{ij} x_j \leq A_i^g m_m \\ x_j \geq x_j^d \geq 0 \\ x_j \leq x_j^g \leq m_m \\ i = 1,2,\dots,M \\ j = 1,2,\dots,N \end{cases} \quad (2)$$

Where:
M - the number of chemical elements considered in the calculation,
N - the number of feedstock taken into account in the bearing optimization,
A_{ij} - the range of the content of the i-th chemical element in the j-th feedstock, %,
x_j - the values sought in the optimization task for the share of the j-th feedstock, kg,
A_{dj}, A_{gj} - lower and upper content, respectively, of the i-th chemical element in the juxtaposed starting alloy, %,
mm - mass of liquid starting alloy, kg.

The above model of the optimization task assumes that losses and scaling are not taken into account.

The system of limiting conditions was defined according to relation (2), but due to the size of this system it was omitted in the publication.

3. Batch materials used for smelting carried out under industrial conditions

Batch is called the total of materials intended (necessary) for the melting process in a specific furnace in order to obtain a liquid metal of a given chemical composition.

Depending on the type of electric furnace (rotary furnace, induction furnace, arc furnace) for melting the same grade of cast iron, batch materials, as a rule, differ in the number of basic components, their proportions and the sizes of pieces that can be loaded. Batch materials include: basic metallic components and auxiliary materials both non-metallic and metallic. Basic metallic components include: pig iron, iron scrap, steel scrap, ferroalloys, technically pure metals. Auxiliary materials include: fluxes, carburizers, deoxidizers, desulfurizing agents, modifiers, spheroidizers, etc. Adequate logistics for the supply of input materials, such as steel scrap, pig iron, other materials, carburizers, modifiers, ferroalloys, metals (Cu, Ni) ensures the foundry continuous and systematic production of castings with the required properties. Also at the foundry, significant amounts of circulating scrap are transported (gating systems, super castings, cull castings). The main input materials are foundry pig iron and special pig iron, steel scrap and circulation scrap (about 40 - 50%).

Table 1 summarizes the parameters of the batch materials considered in the optimization calculations of the batch bearing, for the "Swidnica" foundry.

Table.1
Input material parameters.[22]

Input material and designation		Chemical composition, % C	Si	Mn	P	S	Cr	Ni	Mo
Steel scrap	x_1	0,10÷0,25	0,20÷0,30	max. 0,20	max. 0,04	max. 0,03	-	-	-
Circulating scrap	x_2	1,80÷2,10	0,72÷0,78	1,00÷1,10	0,03÷0,06	0,02÷0,05	19,0÷20,00	1,40÷1,60	2,40÷2,60
FeCr HC	x_3	0,80÷1,00	1,80÷2,00	max. 0,03		max. 0,02	60,0÷64,00	-	-
FeCr LC	x_4	0,08÷0,10	1,40÷1,50	max. 0,03		max. 0,02	60,0÷64,00	-	-
FeMn75A	x_5	6,40÷6,60	3,60÷4,00	min. 75,00	max. 0,45	max. 0,03	-	-	-
FeMo60	x_6	max. 0,05	0,70÷0,80		0,05÷0,10	max. 0,03	-		min. 60,00
Ni	x_7					-	-	min. 98,00	-
FeSi75A	x_8	max. 0,10	72,00÷78,00	max. 0,40	max. 0,05	max. 0,02	max. 0,05	-	-
Carbon	x_9	min. 98,00				-	-	-	-
Pig iron	x_{10}	3,80÷4,00	1,00÷1,20	max. 0,20	max. 0,04	max. 0,03	-	-	-

Table 2 shows the prices of the input materials used. The prices are given according to the price list in force in Poland as of 09.05.2023.

Table 2.
Unit prices of input materials included in the calculation [23].

Price marking of the input material		Price PLN/t
Steel scrap	c_1	2.200
Circulating scrap	c_2	4.160
FeCr HC	c_3	9.700
FeCr LC	c_4	19.400
FeMn75A	c_5	5.900
FeMo60	c_6	167.600
Ni	c_7	109.500
FeSi75A	c_8	8.900
Carbon	c_9	7.798
Pig iron	c_{10}	2.689

3.1. Chemical composition of the starting alloy

Calculation of charge bearing was realized for alloy grade EN-GJN-HV600 (XCr18). The chemical composition of the starting alloy was assumed according to the standard and was as follows: C =1.80 ÷ 2.40, Si = max. 1.00, Mn = 0.50 ÷ 1.50, P = max. 0.08, S = max. 0.08, Cr = 18.00 ÷ 23.00, Ni = max. 2.00 Mo = max. 3,00.

3.2. Results of charge bearing optimization calculations

Batch bearing without additional restrictions

In the first step, the calculation of the cheapest batch bearing was performed, assuming that each batch material has no additional restrictions on its share of the batch being compiled. The calculated batch bearing in such a case will have the lowest price, since introducing additional restrictions on the share of batch materials may result in the determination of a batch bearing with the same or higher price. Table 3 shows the designations of the various batches along with their limitations.

The results of the % of metal charge bearing used in the calculations are presented in Table 4. The results are divided into 3 groups depending on the constraints presented in Table 3. A missing value in the table means that a given charge component was not used in the calculations. Table 4 shows the results of calculations of the cheapest feedstock bearing designated as W1. Table 5 shows the predicted batch chemical composition for the designated charge bearing. The results of the chemical composition of individual batches are presented in

Table 5. The results were divided into 3 groups depending on the limitations presented in Table 4.

As can be seen from the analysis of the data in Figure 3, reducing the share of circulating scrap increases the unit price of the batch bearing from the cheapest (price of 4061.96 PLN/t) to a value as high as 4394.25 PLN/t (about 108% of the minimum price) for the restriction of the share of this scrap max. 300 kg, i.e. max. 30% of the weight of the collated charge. Forcing an increasing weight of pig iron in the charge results in an increase in the bearing price even to the value of 7417.87 PLN/t (183% of the minimum price) for limiting the share of this pig iron min. 350 kg (min. 35%) in the collated charge.

Table 3.
Batch designations along with limitations taken into account in the calculations

Designation batch	Batch limit, %			
W 1	Batch no limit			
W 2	Circulating scrap	≤ 90		
W 3		≤ 80		
W 4		≤ 70		
W 5		≤ 60		
W 6		≤ 50		
W 7		≤ 40		
W 8		≤ 30		
W 9	Pig iron	≥ 5		
W 10		≥ 10		
W 11		≥ 15		
W 12		≥ 20		
W 13		≥ 25		
W 14		≥ 30		
W 15		≥ 35		
W 16	Steel scrap	≥ 10	Pig iron	≥ 20
W 17		≥ 20		≥ 20
W 18		≥ 20		≥ 25
W 19		≥ 20		≥ 30

Forcing an increasing share of steel scrap in the charge significantly increases the unit price. The lower limitation of the share of steel scrap (minimum share) at the level of 100 kg (10% of the weight of the charge) results in a bearing with a unit price of 4304.87 PLN/t, or about 106% of the minimum price.

The obtained results of calculations confirm that in the technological practice of preparation of liquid cast iron production, the assumptions of the share of individual feedstock materials can be made differently, which significantly changes the unit price of the compiled charge but guarantees the achievement of the assumed chemical composition of the liquid metal after smelting.

It should be noted that all the calculations presented in this paper were carried out for feedstock materials that were characterized by ranges of content of individual chemical elements. This means that if these ranges are realistically determined, then for any combination of the actual proportions of the feedstock materials, it is possible to obtain the required chemical composition of the casting alloy. Fuzzy optimization in the calculation of the charge bearing gives this advantage over the classical method of deterministic optimization that, in the case of the latter, it is possible to determine the charge bearing for averaged contents of individual chemical elements. On the other hand, if it turns out in practice that the batch materials used deviate in their chemical composition from the average values, the bearing prepared according to the calculation results in the production of a liquid metal with an incorrect chemical composition. Such a result forces an additional correction procedure. This can cause additional consumption of feedstock materials, electricity, and thus significantly reduce the productivity and economic efficiency of the foundry.

Table 4.
Input material parameters

Batch material and designation		Percentage batch bearing W1-W8 with the limitation of circulating scrap							
		W1	W2	W3	W4	W5	W6	W7	W8
Steel scrap	x_1	5,17	8,34	15,02	21,70	28,38	35,07	41,62	48,18
Circulating scrap	x_2	94,74	90,00	80,00	70,00	60,00	50,00	40,00	30,00
FeCr HC	x_3		1,50	4,67	7,83	11,00	14,17	17,33	20,50
FeCr LC	x_4								
FeMn75A	x_5							0,13	0,27
FeMo60	x_6								
Ni	x_7								
FeSi75A	x_8								
Carbon	x_9		0,16	0,31	0,047	0,62	0,77	0,91	1,05
Pig iron	x_{10}								

		W9-W15 with the limitation of pig iron						
		W9	W10	W11	W12	W13	W14	W15
Steel scrap	x_1	0,26			0,21	3,15	2,44	30,17
Circulating scrap	x_2	94,74	87,80	80,49	72,87	61,24	54,96	5,10
FeCr HC	x_3		2,20	4,51	6,92	10,61	3,01	
FeCr LC	x_4						9,59	28,39
FeMn75A	x_5							0,60
FeMo60	x_6							
Ni	x_7							
FeSi75A	x_8							
Carbon	x_9							0,75
Pig iron	x_{10}	5,00	10,00	15,00	20,00	25,00	30,00	35,00

		W16-W19 with the limitation of pig iron and steel scrap			
		W16	W17	W18	W19
Steel scrap	x_1	10,00	20,00	20,00	20,0
Circulating scrap	x_2	58,54	43,64	36,25	28,79
FeCr HC	x_3	11,46	16,18	14,42	6,17
FeCr LC	x_4			4,10	14,71
FeMn75A	x_5		0,08	0,18	0,28
FeMo60	x_6				
Ni	x_7				
FeSi75A	x_8				
Carbon	x_9		0,1	0,05	0,04
Pig iron	x_{10}	20,00	20,00	25,00	30,00

Economic summary of melts

Fig 3 compares the unit prices of the designated batch bearings from Table 5.

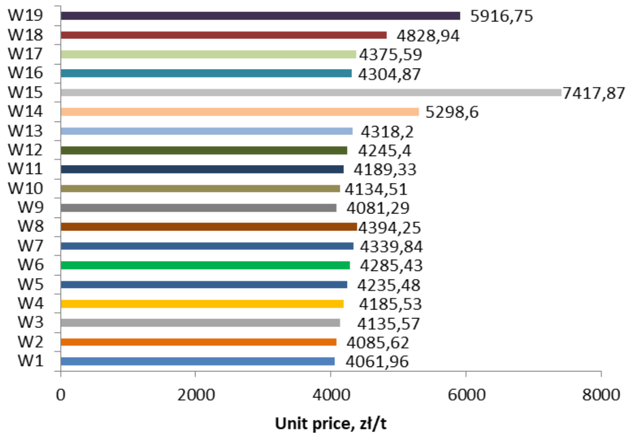

Fig. 3. Summary of unit prices of designated bearings

Table 5.
Results of the chemical composition of metal batches

Chemical element	Batch chemical composition results, content in %mas.							
	W1-W8 with the limitation of circulating scrap							
	W1	W2	W3	W4	W5	W6	W7	W8
C	1.80÷2.09	1.80÷2.09	1.80÷2.08	1.80÷2.07	1.80÷2.06	1.80÷2.05	1.80÷2.04	1.80÷2.03
Si	0.69÷0.75	0.69÷0.76	0.69÷0.76	0.69÷0.77	0.69÷0.77	0.69÷0.78	0.69÷0.79	0.69÷0.80
Mn	0.95÷1.05	0.90÷1.01	0.80÷0.91	0.70÷0.82	0.60÷0.72	0.50÷0.62	0.50÷0.66	0.50÷0.70
P	0.03÷0.06	0.03÷0.06	0.02÷0.05	0.02÷0.05	0.02÷0.05	0.02÷0.04	0.01÷0.04	0.01÷0.04
S	0.02÷0.05	0.02÷0.05	0.02÷0.05	0.01÷0.04	0.01÷0.04	0.01÷0.04	0.01÷0.04	0.01÷0.03
Cr	18.0÷18.95	18.0 ÷18.96	18.00÷18.99	18.00÷19.01	18.00÷19.04	18.00÷19.07	18.00÷19.09	18.00÷19.12
Ni	1.33÷1.52	1.26÷1.44	1.12÷1.28	0.98÷1.12	0.84÷0.96	0.70÷0.80	0.56÷0.64	0.42÷0.48
Mo	2.27÷2.46	2.16÷2.34	1.92÷2.08	1.68÷1.82	1.44÷1.56	1.20÷1.30	0.96÷1.04	0.72÷0.78
	W9-W15 with the limitation of pig iron							
	W9	W10	W11	W12	W13	W14	W15	
C	1.9÷2.19	1.9÷2.27	2.0÷2.34	2.1÷2.40	2.1÷2.40	2.1÷2.40	2.2÷2.40	
Si	0.7÷0.80	0.7÷0.85	0.8÷0.90	0.8÷0.95	0.8÷0.96	0.8÷0.99	0.8÷1.00	
Mn	0.9÷1.05	0.8÷0.99	0.8÷0.92	0.7÷0.85	0.6÷0.78	0.5÷0.69	0.5÷0.79	
P	0.0÷0.06	0.0÷0.06	0.0÷0.05	0.0÷0.05	0.0÷0.05	0.0÷0.05	0.0÷0.03	
S	0.0÷0.05	0.0÷0.05	0.0÷0.05	0.0÷0.04	0.0÷0.04	0.0÷0.04	0.0÷0.03	
Cr	18.00÷19.95	18.00÷19.97	18.00÷19.99	18.00÷19.01	18.00÷19.02	18.00÷19.05	18.00÷19.19	
Ni	1.3÷1.52	1.2÷1.41	1.1÷1.29	1.0÷1.17	0.9÷1.05	0.7÷0.90	0.0÷0.08	
Mo	2.2÷2.46	2.1÷2.28	1.9÷2.09	1.7÷1.90	1.5÷1.71	1.3÷1.47	0.1÷0.13	
	W16-W19 with the limitation of pig iron and steel scrap							
	W16	W17	W18	W19				
C	1.92÷2.17	1.80÷2.04	1.80÷2.02	1.80÷1.99				
Si	0.85÷0.96	0.85÷0.97	0.88÷1.00	0.88÷1.00				
Mn	0.59÷0.71	0.50÷0.65	0.50÷0.68	0.50÷0.71				
P	0.02÷0.05	0.01÷0.04	0.01÷0.04	0.01÷0.04				
S	0.01÷0.04	0.01÷0.04	0.01÷0.04	0.01÷0.03				
Cr	18.00÷19.04	18.00÷19.08	18.00÷19.10	18.00÷19.12				
Ni	0.82÷0.94	0.61÷0.70	0.51÷0.58	0.40÷0.46				
Mo	1.41÷1.52	1.05÷1.13	0.87÷0.94	0.69÷0.75				

4. Results of charge bearing calculations for chromium iron smelting in a laboratory furnace

The following calculations assume zero metallurgical scale and zero scale of each chemical element.

4.1. Batch materials used for smelting

Table 1 summarizes the parameters of the feedstock materials considered in the charge bearing optimization calculations. Metal chromium, which was used in the laboratory tests, is not included in this list. Table 2 summarizes the unit prices of the feedstock materials here also does not include chromium metal. It turns out that the use of metallic chromium will clearly increase the cost of the resulting high-chromium iron casting. In studies with small masses of metal this is not of great economic importance, but if one converts this to, for example, a ton of feedstock used, then for chromium it is a large value and amounts to 59000 PLN/t.

4.2. Chemical composition of the starting alloy

The calculation of charge bearing was realized for the starting alloy with chemical composition: C = 2.90 ÷ 3.30, Si = 0.50 ÷ 0.70, P = max. 0.04, S = max. 0.04, Cr =19.00 ÷ 25.00.Tables 6-11 show the 6 bearings according to which experimental smelting was carried out.

Table 6.
Composition of bearing 1 and smelting costs

Batch	kg	PLN/kg	PLN/t
Pig iron 17,5%	3,5	8,08	8083,25
Metallic chromium 7,5%	1,5		
Circulating scrap 75%	15,0		

Table 7.
Composition of bearing 2 and smelting costs

Batch	kg	PLN/kg	PLN/t
Pig iron 29,15%	5,7	10,70	10697,64
Metallic chromium 12,78%	2,55		
Circulating scrap 75%	10,0		
Steel scrap 8,5%	1,7		

Table 8.
Composition of bearing 3 and smelting costs

Batch	kg	PLN/kg	PLN/t
Circulating scrap 100%	20,0	4,16	4160,00

Table 9.
Composition of bearing 4 and smelting costs

Batch	kg	PLN/kg	PLN/t
Pig iron 46,5%	9,3	4,93	4927,74
Fe-Cr 33,5%	6,67		
Steel scrap 20%	4,04		

Table 10.
Composition of bearing 5 and smelting costs

Batch	kg	PLN/kg	PLN/t
Pig iron 45,4%	10,0	8,06	8059,17
Metallic chromium 6,7%	1,47		
Fe-Cr 23,8%	5,24		
Steel scrap 24,1%	5,31		

Table 11.
Composition of bearing 6 and smelting costs

Batch	kg	PLN/kg	PLN/t
Pig iron 44,5%	9,27	4,89	4891,85
Fe-Cr 32,1%	6,7		
Circulating scrap 3,3%	0,68		
Steel scrap 20,1%	4,2		

Economic summary of bearings no: 1-6

Figure 4 summarizes the unit prices of designated batch bearings no: 1-6.

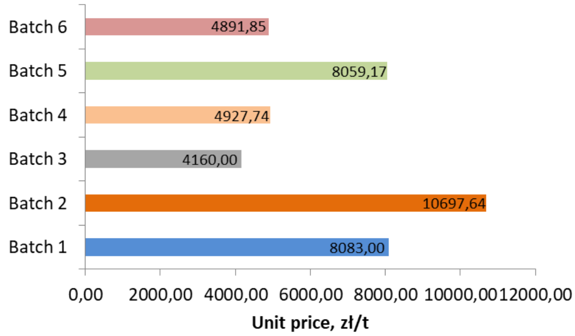

Fig. 4. Summary of unit prices of designated bearings 1-6

As can be seen from the analysis of the breakdown of unit prices in Figure 4, the use of chromium metal as a batch material significantly affects the price of the smelted metal from the cheapest 8059.17PLN/t to values as high as 10697.64PLN/t. Eliminating chromium metal from the batch almost halves the unit cost of one ton of smelted metal (the cheapest 4160PLN/t to a level of 4927.74PLN/t). Removing this ingredient from the charge necessarily entails replacing it with ferro-chromium of lesser purity than metallic chromium or scrap chromium iron, which has chromium in its composition in order to obtain the appropriate percentage of Cr in the final alloy. Unfortunately, the use of inferior batch materials can cause defects in castings.
The only solution to the appearance of defects in castings produced from "inferior quality" and at the same time cheaper metal batch is a modification procedure.

5. Methodology of smelting and strength tests carried out

5.1. Industrial research

The metal was smelted in a medium-frequency induction furnace with a capacity of 2 tons shown in Figure 5. The loading of the batch materials involves placing the correct proportion of the batch components in the furnace. The order of loading is as follows: steel scrap, ferrochrome HC, additives.

Fig. 5. Induction furnace of the "Swidnica" Foundry Ltd.

After loading the furnace and melting the charge, the liquid metal is heated to 1400ºC after which a portion of the metal is taken, which is poured over chemical composition samples. The analysis performed shows the possible need to correct the chemical composition. The next step is to superheat the liquid metal to 1490ºC and hold at this temperature for 5 minutes. The procedure is intended to homogenize the chemical composition throughout the crucible. After this time, the metal is poured into a tilting ladle then transported to the mold pouring station.

5.2. Testing under laboratory conditions

Melting was carried out in a laboratory medium-frequency induction furnace located at the Experimental Foundry of the AGH Department of Foundry Engineering. Liquid metal was superheated to 1490ºC and cast from a temperature of 1420ºC. Shafts of fi 18.3 mm x 250 mm diameter were cast into dried sand molds.

5.3. Strength tests

Strength to bending

Cylindrical specimens with a diameter of Ø18 [mm] are planned to be used to determine the bending strength (Rg) of hard-to-work white cast iron. The contractual bending strength is calculated from the formula, which for a circular section of diameter d0, force Fg and support spacing l0 takes the form [20]:

$$R_g = \frac{8F_g l_0}{\pi d_0^3}, MPa \qquad (3)$$

To determine the bending strength, sets of rollers with a diameter of Ø18 [mm] and a length of 250 [mm] were cast. The test was carried out on a universal testing machine.

Resistance to hot cracking - Althoff-Radtke test

The Althoff-Radtke test is used to evaluate hot cracking of cast steel castings. It has been adapted for white iron castings, in part because of the similar casting shrinkage of cast steel and white iron. It is a buckle shape test that involves pouring liquid metal into a standardized mold [1,6,7].

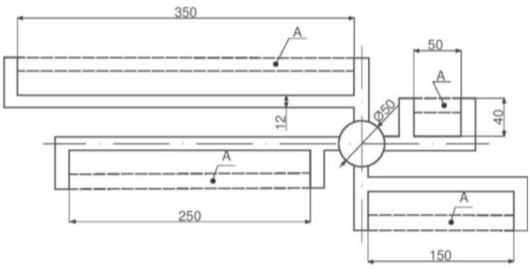

Fig. 6. Standardized mold for the Althoff-Radtke test [21]

Impact strength

The impact test consists of breaking the specimen with a single pendulum hammer blow and measuring its fracture energy. The specimen is supported freely at both ends. The test specimens are standardized, the standard provides for notched and unnotched specimens. Specimens without notch were used in the study. The result of the test according to EN ISO 148-2010, is the ratio of the magnitude of the work corresponding to the energy used to fracture the specimen to its cross-sectional area.

$$K = \frac{L_u}{S_0} \left[\frac{J}{cm^2}\right] \qquad (4)$$

where:
L_u - the value of work corresponding to the energy used to fracture the specimen [J].
S_0 - the initial cross-sectional area at the notch in [cm2].

A Charpy pendulum hammer was used for the test. The test involves breaking a specimen placed at the bottom of the hammer. An arm moving under the influence of gravity strikes the sample and breaks it.

6. Research results

6.1. Laboratory testing

The results of the laboratory tests carried out are presented in Table 13. As it turns out, the smallest values of bending strength Rg were obtained for metal charges composed only of circulating scrap. The reason for such strength properties was a casting defect of the shrinkage cavity type. In most tests, defects of the porosity type appeared, but the bending strength of the cast shafts was satisfactory and reached a value above 600 MPa in most of them. Flexural strength Rg above 700 MPa was achieved when larger amounts of pig iron began to be used in the metal charge. In one case no casting defect was recorded that is for charge bearing number 5,. The bearing of charge number 5 consists of pig iron - 45.4% , chromium metal 6.7%,
ferrochrome 23.8% and steel scrap 24.1%, however, its price is 8059 PLN/t - undeniably a lot. Undoubtedly, it will be possible to reduce the cost of casting production by up to 40% with the optimization of the technology of obtaining high chromium iron of the procedure of modifying the liquid metal. Then the metal charge can have a composition of bearing 6 and, in addition, the modification should be applied.

6.2. Industrial research

The Althoff-Radtke method provides an opportunity to check the alloy's susceptibility to hot cracking. The results of the tests performed are presented in Figure 7 where the reference sample for ferro-titanium-modified samples and Figure 8 the reference sample for ferro-niobium-modified samples are summarized. The metal feedstock of the starting cast iron for modification was composed from batch components that had a low unit price.

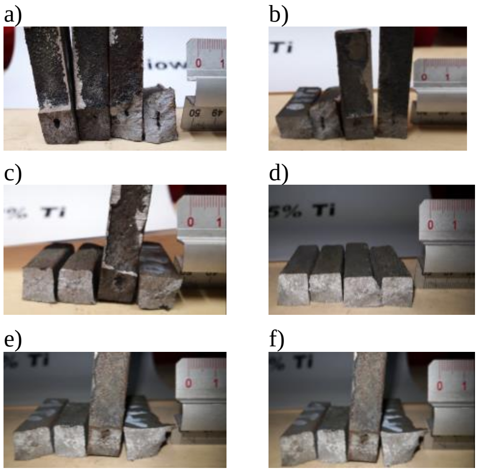

Fig. 7. Results of the Althoff-Radtke method: a) reference sample and modified sample: b) 0,1%FeTi; c) 0,2% FeTi; d) 0,5% FeTi; e) 0,7%FeTi; f) 1%FeTi;

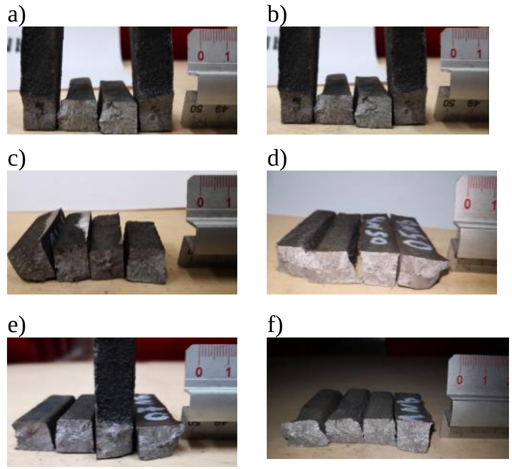

Fig. 8. Results of the Althoff-Radtke method: a reference sample and modified sample: b) 0,1%FeNb; c) 0,2% FeNb; d) 0,5% FeNb; e) 0,7%FeNb; f) 1%FeNb;

From the tests carried out, it can be seen that the most favorable effect on the elimination of hot cracks is the modification with Fe-Nb mortar. In this case, no shrinkage cavities or black areas indicative of defect formation appeared in any arm of the Althoff-Radtke test for modifications above 0.1% FeNb. For each modifier addition, a clear reduction in defects compared to the initial sample can be seen.

Iron-titanium modification also reduced the propensity for hot cracking. The most beneficial effect is the addition of FeTi in the amount of 0.5%. The results of the high-chromium cast iron impact strength tests are summarized in Figure 9. Unfortunately, with the already low impact strength, any action aimed at even lower impact strength is a disadvantageous phenomenon in terms of casting use. Therefore, in further studies of wear resistance under industrial conditions of the "Swidnica" Foundry Ltd. a modifier with niobium will be selected, which does not lower the impact strength As can be seen in Figure 9, it does not lower the impact strength of high chromium cast iron even at its high values already considered as an alloying additive.

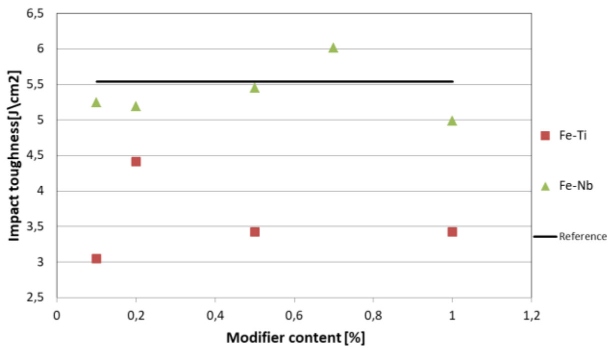

Fig. 9. Impact results of the initial cast iron for the modification treatment (Reference) and with the addition of modifiers (Fe-Ti and Fe-Nb)

7. Summary

When calculating the metal batch, it is very important to compose such a batch to guarantee the required chemical composition of the cast iron after melting the components. Unfortunately, the use of high-purity components is associated with a high price of the melted metal, which from the economic point of view is not a favorable solution. The optimal charge in terms of price and quality seems to be a charge based on pig iron, steel scrap and Fe-Cr. Under industrial conditions, smelting such a composed charge results in the accumulation of circulating scrap. Smelting carried out on the basis of circulating scrap is not favorable in terms of the occurrence of defects in castings, but is necessary to avoid the accumulation of scrap in the batch field. Defects that occur in castings from low-quality batch components can be eliminated by means of modifications, as proven by the conducted research. The modification procedure with this preparation not only eliminated the occurrence of defects in the castings, but also slightly improved the impact strength of the melted alloy through the use of its targeting.

Table 13.
Strength test results of laboratory tests

Batch	Sample No.	F [kN]	F Average [kN]	Rg [Mpa]	Support spacing [mm]	Diameter casting [mm]	Sample quality
1	1	7,0					Porosity
	1	8,8	7,5	558,7	180	18,3	
	1	6,6					
	2	8,2					
	2	7,3	8,2	611,1	180	18,3	
	2	9,0					
2	3	7,4					
	3	10,1	8,6	643,5	180	18,3	
	3	8,3					
	4	7,2					Porosotes on the side
	4	8,0	8,4	628,6	180	18,3	
	4	10,0					
3	5						Shrinking cavity
	5	6,6	6,6	490,1	180	18,3	
	5	6,5					
	6	9,1					
	6	9,0	8,9	668,5	180	18,3	
	6	8,7					
4	7	7,3					Porosity
	7	9,7	8,8	656,0	180	18,3	
	7	9,3					
	8	9,5					
	8	9,9	9,8	730,8	180	18,3	
	8	9,9					
5	9	9,7					
	9	9,8	9,5	710,9	180	18,3	
	9	9,0					
	10	9,1					
	10	8,4	9,3	698,4	180	18,3	
	10	10,5					
6	11	10,3					
	11	9,2	9,6	720,9	180	18,3	
	11	9,4					
	12	7,9					Porosity
	12	9,6	9,3	698,4	180	18,3	
	12	10,5					

8. Conclusions

1. Carrying out batch bearing optimization calculations made it possible to check how the use of different compositions of batch materials affects the price of the obtained EN-GJN-HV600 cast iron. Optimization was carried out not only in terms of price, but also in terms of maintaining an appropriate chemical composition. The most optimal feedstock turned out to be the feedstock where used: 94.74% circulating scrap, 5.17% steel scrap and 0.09% pig iron,
2. Laboratory tests of various batch variants allowed to show that the use of metal batch: 45.4% pig iron; 6.7% Cr metallic; 23.8% Fe-Cr; 24.1% steel scrap make it possible to produce defect-free castings at an unfortunately high cost of batch components.
3. Under industrial conditions of the "Swidnica" Foundry Ltd. using the Althoff-Radtke method, it is shown that the modification of Fe-Ti and Fe-Nb eliminates the formation of casting defects in chromium iron produced from feedstock materials with a low unit price.

4. Studies show that Fe-Nb also slightly improves the impact strength of cast iron melted with low-cost metal feedstock - and peno does not lower it.
5. In industrial conditions, it is necessary to use additives of circulating scrap in the metal charge because it does not seem economical to sell scrap circulating cast iron and melt on expensive batch components.

Acknowledgments

Part of the research was able to be carried out thanks to the Polish Ministry of Science and Higher Education's "Implementation Doctorate" Programme.

References

[1] Podrzucki, C. (1991). *Cast iron. Structure Features Application Volumes 1 and 2*. Wydawnictwo ZG STOP. (in Polish).

[2] Zhou, J. (2009). Colour metallography of cast iron. *China Foundry*. 6(2), 152-163.

[3] Guoxiong, S., Xiaoming, Z. & Zhidong, L. (1989). Microstructure and properties of grey cast iron. *Spherical Graphite Cast Iron*. 50-62.

[4] Miyake, H. & Okada, A. (1998). Nucleation and growth of primary austenite in hypoeutectic cast iron. *AFS Transactions*. 106, 581-587.

[5] Siekaniec, D., Kopyciński, D., Guzik, E. & Szczęsny, A. (2022). Effect of inoculation treatment on number of primary austenite grains in hypoeutectic chromium cast iron: EBSD imaging and mathematical structure prediction. *Materials*. 15(18), 6318, 1-14. https://doi.org/10.3390/ma15186318.

[6] Guzik, E., Kopyciński, D., Burbelko, A. & Szczęsny, A (2023). Evaluation of the number of primary grains in hypoeutectic chromium cast iron with different wall thickness using the ProCAST program. *Materials*. 16(8), 3217, 1-15. https://doi.org/10.3390/ma16083217.

[7] Döpp, R. (1975). *Solidification and graphite formation in white cast iron.* In proceedings of the Second International Symposium on the Metallurgy of Cast Iron, Geneva, Switzerland, May 29-31, 1974. Switzerland: Georgi Publishing Company.

[8] Tabrett, C.P., Sare, I.R. & Ghomashchi, M.R. (1996). Microstructure-property relationships in high chromium white iron alloys. *International Materials Reviews*. 41(2), 59-82. https://doi.org/10.1179/imr.1996.41.2.59.

[9] Filipovic, M., Kamberovic, Z., Korac, M., Gavrilovski, M. (2013). Microstructure and mechanical properties of Fe–Cr–C–Nb white cast irons. *Materials & Design*. 47, 41-48. https://doi.org/10.1016/j.matdes.2012.12.034.

[10] Stefanescu, D.M. (1998). *Solidification of eutectic alloys: Cast iron*. In: ASM Handbook, Vol. 15 Casting, ASM International, Metals Park, OH.

[11] da Silva, A.E. Rabelo de Melo I.N., Pinheiro I.P., da Silva L. R. (2020). Characterisation and machinability of high chromium hardened white cast iron with and without the addition of niobium. *Wear*. 460-461, 15, 203-463. https://doi.org/10.1016/j.wear.2020.203463.

[12] Kopyciński, D., Kawalec, M., Szczęsny, A., Gilewski, R. & Piasny, S. (2013). Analysis of the structure and abrasive wear resistance of white cast iron with precipitates of carbides *Archives of Metallurgy and Materials*. 58(3), 973-976. DOI: 10.2478/emm-2013-0113.

[13] Penagos, J.J., Pereira, J.I., Machado, P.C., Albertin, E. & Sinatora, A. (April 2017). Synergetic effect of niobium and molybdenum on abrasion resistance of high chromium cast irons. *Wear*. 376-377, B, 983-992. https://doi.org/10.1016/j.wear.2017.01.103.

[14] Dojka, M., Dojka, R., Studnicki, A., Stawarz, M. (2018). Influence of Ti and Re on primary crystallization and wear resistance of chromium cast iron. In 73rd World Foundry Congress “Creative Foundry”: WFC 2018 – Proceedings, pp. 61-62.

[15] Dojka, M., Dojka, R., Stawarz, M., Studnicki, A. (2019). Influence of Ti and REE on primary crystallization and wear resistance of chromium cast iron. *Journal of Materials Engineering and Performance*. 28(7), 4002-4011. https://doi.org/10.1007/s11665-019-04088-x.

[16] Studnicki, A., Dojka, R., Gromczyk, M., Kondracki, M. (2016). Influence of titanium on crystallization and wear resistance of high chromium cast iron. *Archives of Foundry Engineering*. 16(1), 117-123. DOI: 10.1515/afe-2016-0014.

[17] Tęcza, G. (2023). Changes in abrasion resistance of cast Cr-Ni steel as a result of the formation of niobium carbides in alloy matrix. *Materials*. 16(4), 1726, 1-14. https://doi.org/10.3390/ma16041726.

[18] Tęcza, G. (2022). Changes in microstructure and abrasion resistance during miller test of hadfield high-manganese cast steel after the formation of vanadium carbides in alloy matrix. *Materials*. 15(3), 1021, 1-14. https://doi.org/10.3390/ma16041726.

[19] Dorula, J. (2013). Macro- and microstructure formation of modified cast iron with low sulfur content. PhD thesis. Kraków. Akademia Górniczo-Hutnicza. (in Polish).

[20] Podrzucki, C., Kalata, C. (1976). *Metallurgy and cast iron foundry*. Katowice: Wyd. Śląsk. (in Polish).

[21] Jura, S., Cybo, J. & Jura, Z. (2001). Hot cracking of steel castings is still an unresolved problem. *Archives of Foundry*. 1(2/2), 512-519. (in Polish).

[22] Collective work. (2013). Foundryman's Guide. Contemporary foundry. Tom 1. Kraków: Wydawnictwo STOP. (in Polish).

[23] Data provided by Sylwia Rosińska Head of Purchasing Department of "Świdnica" Foundry Ltd.