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Abrasion Wear Behavior of High-chromium Cast Iron

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Abstract

High-chromium cast irons are used as abrasion resistant materials. Their wear resistance depends on quantity of carbides and the matrix supporting these carbides. The paper presents the results of cast irons of chemical composition (in wt. %) 19–22 Cr and 2–4.5 C alloyed by 1.7 Mo + 5 Ni + 2 Mn to improve their toughness, which were tested in working conditions of ferroalloys crushing. Tests showed that these as-cast chromium cast irons with mostly austenitic matrix achieved the hardness of 38-45 HRC, but their relative abrasion resistance Ψ ranged from 1.3 to 4.6, was higher comparing to the tool made from the X210Cr12 steel heat treated on hardness 61 HRC. The transformation of austenite into martensite occurs not only at the worn strained areas (on a surface of scratch) but also in their neighbourhood. Due to the work hardening of relatively large volumes of transformed austenite the cast iron possesses high abrasion resistance also on the surfaces where low pressures are acting. The tough abrasion-resistant cast iron well proved for production of dynamic and wear stressed castings e.g., crusher hammers, cutting tools for ceramic etc.

Keywords: Wear Resistant Alloys, Mechanical Properties, High-Chromium Cast Iron, Abrasion Resistance

1. Introduction

Wear-resistant chromium cast irons are known as materials being characterized by an especially high wear resistance when the previous used types were attributed with a restricted serviceability caused by their brittleness and very low fracture toughness. Long-time experience with a development and manufacturing of the castings intended for abrasive materials processing has shown the substantial improvement in toughness and fracture strength can be achieved by applying the additional deliberate alloying. It enabled the chromium cast irons to become a promising material with many unique and specific utility properties.

The gained results have indicated that to use them more extensively there is desired to deal with several problems such as an effect of microalloying and inoculation of molten metal [1, 2, 3], possibility to modify the utility properties of material using a heat treatment [1, 4], and the method of hardening of the iron‘s matrix under the local plastic strain [1, 5].

Wear resistance and mechanical properties of high-chromium cast irons depend on a type, shape and number of carbides being found in their microstructure, on matrix’s characteristics within which carbides are embedded, and on the strength of the matrix-carbide bonding [1, 3, 4, 6, 7]. Increasing both the carbon and chromium contents increases the amount of carbides. Owing to this the hardness and wear resistance of castings are improved, but the toughness decreases, and fracture resistance worsens.

In practice the hypoeutectic and eutectic cast irons with 15 - 28 wt. % Cr and 2.5 - 3.2 wt. % C have proved successful. Their microstructure contains carbides of M_7C_3 type and a small volume of $M_{23}C_6$. The coarse eutectic carbides cause the known high brittleness of material, and under the abrasion they are pulled out of the matrix. To eliminate this adverse characteristic, a part of chromium can be substituted for an addition of 2 – 4 wt. % of elements like W, V, and Ti. They form special carbides of WC, VC, and TiC, which grow at higher temperatures and independently of carbides M_7C_3 and $M_{23}C_6$ [8]. Therefore, they are finer and irons are not so brittle.

One possibility how to refine a carbide phase, which worsens the fracture resistance, can be an application of micro-alloying by an addition of boron that functions as an inoculant during a primary crystallization [3, 9]. It reduces the carbon solubility in austenite, increases an amount of crystallization nuclei to arise finer carbides, not only in as-cast state but also after heat treatment. Another possibility that has not been enough documented recently is the increasing the molten metal undercooling and solidification rate to affect the cast iron primary crystallization [1, 10].

The presented paper gives the results of tests with the developed high-chromium cast iron with the characteristic chemical composition by wt. %: 19–22 Cr, 2–4.5 C, 1.7 Mo, 5 Ni, 2 Mn, and a trace amount of Ti and V to improve toughness. The iron has very good casting properties, which enable to pour the complex shaped castings with the wall section about 3 mm. The castings do not require being heat treated, and in the range of the wall section from 3 to 40 mm the as-cast material has the remarkable abrasion resistance. The iron has proved successful for the dynamic and wear strained castings e.g., crushing hammers, stonemason tools, etc.

2. Development of wear resistant high-chromium cast iron

Development of the chromium cast iron was grounded in the system of 18–22 wt. % Cr and 2–5 wt. % C that was additionally alloyed with elements Ni, Mn, and Mo, which ensure the formation of an austenitic matrix [1, 11]. The austenite portion in a matrix can be supported either alloying by elements expanding the γ-area, or such ones that shift the temperature of the martensite transformations towards low temperatures, and then the metastable non-transformed austenite retains in the matrix [1, 12].

At examining the effect of these additional alloys there has shown that while they were introduced separately into the base Fe-C-Cr material, a predominantly austenitic matrix was produced only by alloying more than 2.5 wt. % of Mo. Separate alloying by nickel and manganese up to content of 5 wt. % did not produce the desirable increase in the austenite portion in a matrix, nor their positive effect on wear resistance was not confirmed.

The final cast iron's chemical composition contains the manganese since, apart from austenite stabilising, it improves significantly a running property at the content above 1 wt. %. Alloying by Cu did not give any positive impacts on wear characteristic. The running results enabled to judge the effect of individual elements of cast iron in general. The abrasion resistance has increased nearly linearly as the contents of C and Cr has risen. Exceeding the limit of 3 wt. % C caused the apparent increase in brittleness, and the increase of the Cr content above 20 wt. % did not have a more major effect on abrasion resistance.

The research on the cast iron with the Cr content of about 20 wt. % has pointed that the outstanding high toughness can be gained by alloying with a combination of 1.7% Mo + 5% Ni + 2% Mn. The high toughness of austenite enables to increase the carbon content up to the hypereutectic region (up to 5 wt. % C). At the upper limit of the C content, the as-cast material has shown very high wear resistance and ductility of about 1.5%. At lower limit of the C content of 2.5 wt. %, the iron had evidently the lower wear resistance and hardness of about 38 HRC, but it was characterized by especially high ductility. This iron was applied to tools used to turn the pressed ceramics, an abrasion effect of which caused the reducing in the cutting wedge height by 5 mm but cutting edge was sharp enough during the whole tool life (about 100 hours), and its radius did not exceed 0.2 mm [13].

3. Experimental procedures

In presenting experiments, the high-chromium cast iron with the C content ranging from 2.5 to 4.3 wt. % was prepared by melting a charge based on two feedstocks in a medium frequency induction furnace of 40 kg. For melting of the cast iron *A*, there was used a low Si pig iron (max 1 wt. % Si) since a certain amount of Si comes into a charge from ferroalloys mainly from the low-carbon FeCr with carbon content less than 1.2 wt. % and the high-carbon FeCr with the C content about 4 wt. %. Then the ferroalloys as FeMo, FeMn, FeTi35, and FeV were charged.

In a charge composition of cast irons *B* and *C*, the pig iron was substituted for steel scrap, and the carbon addition into a liquid metal was made with pelletized petroleum coke. The final carbon content of the molten metal was adjusted by the addition level of two types of FeCr having the carbon contents of 1.2 and 4 wt. % C. After carburizing the alloying metals were added to a molten charge in the same way as a pig iron charge.

The Si content should be as low as possible. For these irons the silicon is a restricted element since it increases carbon activity and promotes a graphite formation and retards the formation of carbides. In addition, the silicon reduces the hardenability and promotes pearlite formation, thus it has an adverse effect on the wear resistance.

To improve the running property, just before the finish of melting the molten metal was treated with 0.1 wt. % of a synthetic slag based on CaF_2 + CaO + Al_2O_3. With regard to the high contents of carbon and alloying metals with a high affinity for oxygen there was not required a separate operation of a deep deoxidation in a finish of melting. The molten iron was poured at temperature of 1450°C into the synthetic resin sand moulds. The chemical compositions of tested cast irons are shown in Table 1.

Table 1.
Chemical composition of tested high chromium cast irons

Cast iron	Chemical composition (wt. %)								
	C	Si	Cr	Mn	Mo	Ni	Cu	Ti	V
A	2.72	1,25	19,39	0,80	1,26	6,00	0,03	0,07	0,11
B	3.83	0.21	21.28	1.05	1.47	5.89	0.10	0.07	0.10
C	4.28	0.20	21.45	1.04	1.46	5.52	0.06	0.03	0.10

4. Results and discussion

Abrasion resistance of the chromium cast irons was examined under the real conditions of crushing the ferroalloys by repetitive strokes using the tools of a cylinder shape of ø 50 mm so called a hammer. Since a crusher could test more materials at the same time, the reference hammers were trialed together with those poured from three types of cast irons listed in Table 1.

The cast iron tools were tested in as-cast condition. The reference hammers *E* were machined from the steel X210Cr12 (by wt. %: 1.8-2.05 C; 0.2-0.45 Mn; 0.2-0.45 Si; 11-12.5 Cr; max 0.5 Ni) quenched and tempered on hardness about 61 HRC.

At abrasion tests, there were pursued the weight losses of particular hammers as well as a loss of a length against an original length of an active portion which was 130 ± 0,2 mm for all tools. As a criterion for evaluating a relative wear resistance Ψ_w was taken:

$$\Psi_w = \Delta w_r / \Delta w_i \ ,$$

where Δw_r is the weight loss of the reference hammer, and Δw_i is the weight loss of the cast hammers.

A relative wear resistance Ψ_l was supplementary criterion:

$$\Psi_l = \Delta l_r / \Delta l_i \ ,$$

where Δl_r is the length loss of the reference hammer and Δl_i is the length loss of the cast ones.

The previous experience proved that value of abrasion resistance Ψ gauged by various devices depended on a type of used abrasive, on speed and pressure of samples against an abrasive carrier, and they did not correspond often with the casting-life tests carried out under the real service conditions. Therefore, the paper presents the results of the working tests to which a great importance was attached. The characteristic of wear of the as-cast cast iron hammers and steel one is documented in Fig. 1.

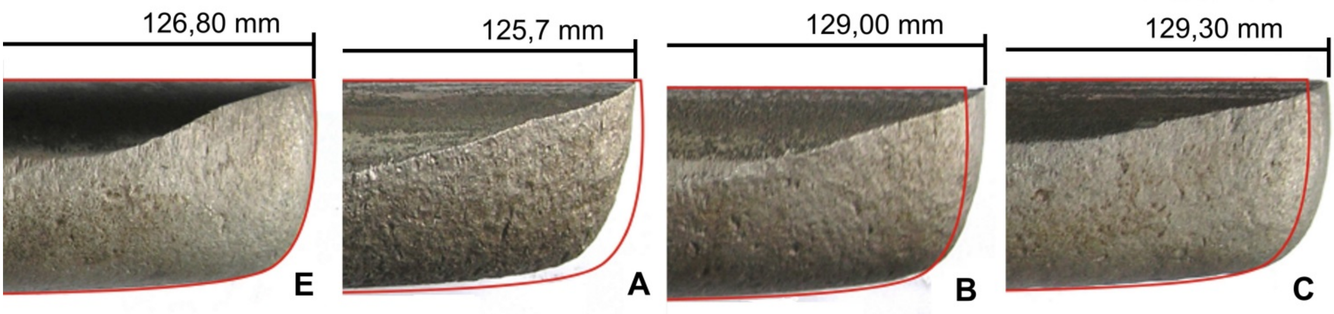

Fig. 1. The change in a length and shape of the worn hammers made from the as-cast high chromium cast irons ***A***, ***B***, ***C***, and the reference hammer made from the X210Cr 12 steel (*E*)

Values of the weight and length losses measured for particular hammers, and calculated values of the relative abrasion resistance Ψ against the reference steel hammer are given in Table 2. There is seen that the abrasion resistance increased as the carbon content is increasing, and there is an apparent anomaly between the losses of weight and length of all cast iron hammers against the reference one. The hammer *C* poured from the hypereutectic cast iron, which diminished from its original length of 130 mm to 129.3 mm, i.e., by 0.7 mm, proved the lowest wear when a flat area about 3 cm^2 remained on its face. The biggest shortening of an active part, by 4 mm, was recorded at the cast iron *A* with the carbon content of 2.72 wt. % that achieved the lowest hardness in as-cast condition. Over the length the tool *B* was worn about 1 mm while the reference one *E* as much as 3.2 mm, nevertheless the weight loss of the hammer *B* was about 66.3 g higher than at more shortened reference one. A discrepancy between the loss of length and weight can be explained by the fact that on hammer's face and at its close vicinity where the tool is exposed to the highest impact stress, in consequence of plastic deformations the austenite transforms into the martensite, and the material becomes significantly more resistant to abrasion wear. The transformation of austenite into martensite occurs not only at the worn strained areas (on a surface of scratch) but also in their neighborhood. Due to the work hardening of relatively large volumes of transformed austenite the cast iron possesses high abrasion resistance also on the surfaces where low pressures are acting [5]. The reference hammer made from the X210Cr12 steel had the hardness about 61 HRC in the whole volume. In its volume nearly no retained austenite occurs, and its resistance to abrasive wear was the same on its face as on its body.

Table 2
Values of a loss in the weight, the length, relative abrasion resistances Ψ_w and Ψ_l, hardness

Tool	**Material**	**Loss in weight** Δw (g)	**Loss in length** Δl (mm)	Ψ_w	Ψ_l	**Hardness** HRC
E	X210Cr12	332.7	3.2	1	1	61
A*	2.72 % C	524.3	4	0.630	0.80	38.3
B*	3.83 % C	399.0	1	0.830	3.20	41.6
C*	4.28 % C	252.7	0.7	1.316	4.57	44

*as-cast

At the next stage, there was studied the possible contribution of heat treatment to an improvement in service properties of the developed high chromium cast iron. Therefore, an effect of heat treatment on hardness of the high chromium cast irons (*A, B, C*) was studied with samples of 20 x 15 x 7 mm taken from the runners using the water-jet technology and not exposed to the working tests.

The cut off samples were subjected to a heat treatment comprising the austenitizing at temperatures of 900, 1000, and 1100°C for 1 hour, followed by tempering at 400, 450, 500, and 600°C for 6 hours and air cooling. Design of the heat treatment pattern took account of the results obtained with as-cast material and a demand of the advantageous cost to performance ratio. Measuring of HRC hardness did not detect the substantial effect of hardening. In Fig. 2, the best hardening characteristics of the cast irons samples treated under the austenitizing temperature of 900°C is documented.

The microstructure analysis of samples, taken from the original runners, confirmed the results of abrasion wear tests done with the studied high chromium irons. In Fig. 3a, the as-cast microstructure of the hypoeutectic 2.72 wt. % C cast iron (*A*) is formed of the austenite matrix and eutectic cells consisting of eutectic austenite and eutectic carbides M_7C_3 irregularly distributed, but connected one another [1, 8]. After quenching from temperature 900°C and tempering at 450°C there is observed the occurrence of martensite in iron’s microstructure (Fig. 3b, left upper corner). Producing of martensite was confirmed by the hardness increase when the iron *A* reached the highest hardness among the tested irons after this pattern of heat treatment (Fig. 2).

In a microstructure of the hypereutectic cast iron (*C*) with the Cr content of 4.28 wt. %, presented in Fig. 4a, one can pinpoint the large primary carbides of M_7C_3 type, which can achieve hardness up to 2100 HV. Their grain size is far coarser than that of eutectic carbides. The as-cast microstructure (Fig. 4a) corresponds to the highest abrasion resistance proven at crushing of ferroalloys.

Its heat treatment has produced only the minor increase in hardness at a level of 5 – 10 HRC. This is supported by the microstructure documented in Fig. 4b. After the heat treatment, austenitizing at 900°C and tempering at 450°C, there can be observed a larger number of relatively big eutectic carbides besides the primary carbides M_7C_3 embedded in a matrix that have a high retained austenite level, the amount of which could not be determined metallographically.

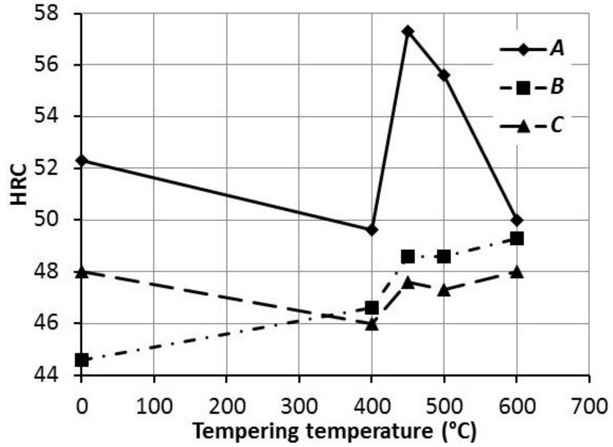

Fig. 2 Hardening characteristics of samples made from the cast irons ***A***, ***B***, and ***C*** being heat treated at the austenitizing temperature of 900°C

5. Conclusions

Today, the high-chromium cast irons are considered a promising category of metal materials. The described high chromium cast irons illustrate what service properties can attain a carbide cast iron with the metastable austenite matrix. The outstanding high toughness of austenite enables substantially to increase the carbon content up to the hypereutectic region where a big volume of carbides ensures the high abrasion resistance, and at the same time the iron has still the sufficient toughness and high fracture resistance.

The developed high-chromium cast iron is intended for tools exposed to a specific mode of the dynamic and wear strain. A comparison of the results of the as-cast and heat treated cast iron with 4.28 wt. % C has denoted a possibility to achieve the excellent service properties even if omitting their heat treatment.

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a)

b)

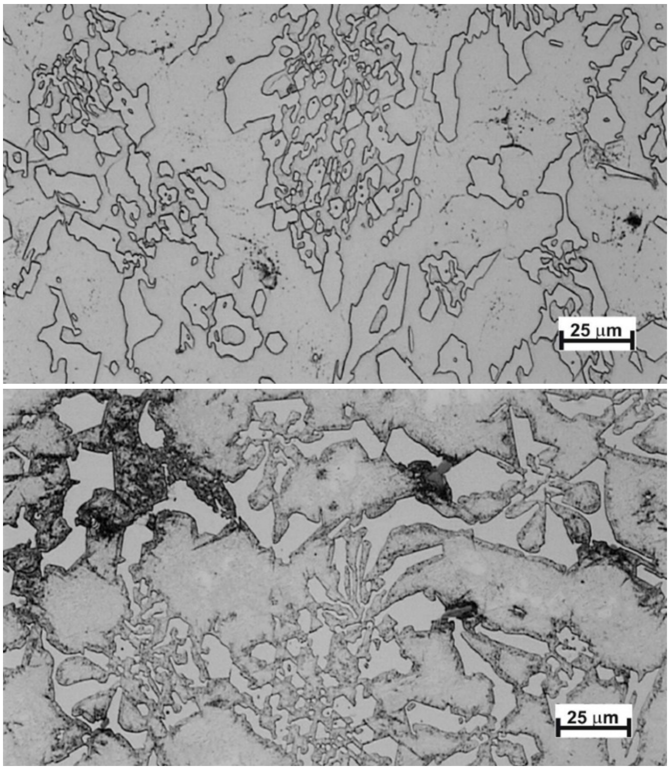

Fig. 3. Microstructure of the high Cr cast iron with 2.72 wt. % C: (*a*) as-cast; (*b)* after heat treatment (austenitizing at 900°C, tempering at 450°C)

a)

b)

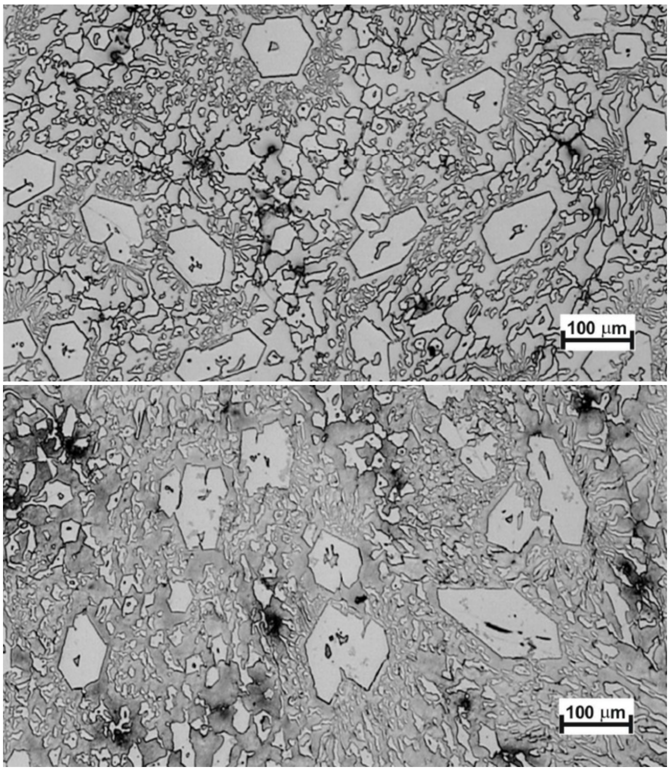

Fig. 4 Microstructure of the high Cr cast iron with 4.28 wt. % C: *a* – as-cast; *b* – after heat treatment (austenitizing at 900°C, tempering at 450°C)

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