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ANALYSIS OF THE STRUCTURE AND ABRASIVE WEAR RESISTANCE OF WHITE CAST IRON WITH PRECIPITATES OF CARBIDES

ANALIZA STRUKTURY ORAZ ODPORNOŚĆ NA ZUŻYCIĘ ŚCIERNE ŻELIWA BIAŁEGO Z WYDZIELENAMI WĘGLIKÓW

The resistance of castings to abrasive wear depends on the cast iron abrasive hardness ratio. It has been anticipated that the white cast iron structure will be changed by changing the type of metal matrix and the type of carbides present in this matrix, which will greatly expand the application area of castings under the harsh operating conditions of abrasive wear. Detailed metallographic analysis was carried out to see the structure obtained in selected types of white cast iron, i.e. with additions of chromium and vanadium. The study compares the results of abrasive wear resistance tests performed on the examined types of cast iron.

Keywords: Abrasive wear resistance, white cast iron, intermetallic phase, type of carbides: $(\text{Fe,Cr})_3\text{C}$, $(\text{Fe,Cr})_7\text{C}_3$, VC, TiC

Odporność żeliwa na zużycie ściernie zależy od stosunku twardości metalu i ścierniwa. W pracy założono kształtowanie struktury żeliwa białego w wyniku zmiany rodzaju osnowy metalowej oraz węglików, co znacznie rozszerza obszar zastosowania odlewu w trudnych warunkach zużycia ściernego. Przeprowadzono szczegółową analizę metalograficzną struktury wybranych gatunków żeliwa białego t.j.: chromowego oraz wanadowego. W niektórych przypadkach zaproponowano koncepcję sterowania ilością i rodzajem węglików w osnowie metalowej żeliwa lub wprowadzania dodatkowych węglików do struktury eutektycznej tego rodzaju żeliwa. Ponadto w pracy porównano wyniki badań odporności na zużycie ściernie analizowanych gatunków żeliwa.

1. Introduction

Cast iron structure is formed during crystallisation, cooling and heat treatment of this material. During crystallisation process, the final type, content, distribution and geometry of cast iron phases are decided. On the other hand, the appearance of casting fracture depends on the type of high-carbon phases, i.e. graphite and cementite – in plain cast iron, and alloyed cementite and carbides formed in combination with various elements – in alloyed cast iron. Thus, conventionally, based on the appearance of cast iron fracture, grey and white cast irons, or mottle cast iron are distinguished [1-3], and on this division, the classification of cast iron grades currently produced is based. This paper describes the abrasive wear-resistant white cast iron, in the structure of which there is a high content of carbides. Cast iron of this grade is widely used for parts of devices operating in the mining and construction sectors of the industry, and in milling equipment and machines used by the manufacturing industries, where high resistance to the abrasive effect of minerals and other solid materials is required. Another area of application of this cast iron is for parts of devices operating in the chemical industry, in metallurgy and in the widely understood power industry, i.e. the devices that are expected to offer failure-free operation under the harsh

conditions of high (or low) temperatures, combined with resistance to the harmful effect of corrosive environments and acids. General principles of the crystallisation of white cast iron are illustrated in Figure 1. Figure 1a shows that there is a critical temperature of the crystallisation T_{kr} below which the growth rate of the cementite γ (Fe) + Fe_3C eutectic is higher than the growth rate of the graphite γ (Fe) + C_{grafit} eutectic. As shown in Figure 1b, in accordance with the phase equilibrium diagram for Fe-C alloy system, the critical crystallisation temperature T_{kr} is lower than the crystallisation temperature of the cementite eutectic. The high growth rate of the cementite γ (Fe) + Fe_3C eutectic shown in Figure 1a, as compared to the growth rate of the graphite γ (Fe) + C_{grafit} eutectic in a range below the critical temperature of crystallisation T_{kr} [4].

Making white cast iron with appropriate mechanical properties requires skilful and conscious control of the cast iron structure by exerting a direct impact on the physicochemical state of liquid metal, i.e. on the chemical composition, the type of metallic charge, temperature, overheating temperature, holding temperature, and refining processes such as, for example, the process of modification. In the case of products made from this type of cast iron, the control of the physicochemical state of liquid metal consists in producing, in the cast iron structure, proper metal matrix and complex carbide

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precipitates in the required amount, type and distribution. By introducing to cast iron a large amount of alloying elements such as chromium [5-20], vanadium [21-23] and, alloyed white cast iron with interesting functional properties is obtained.

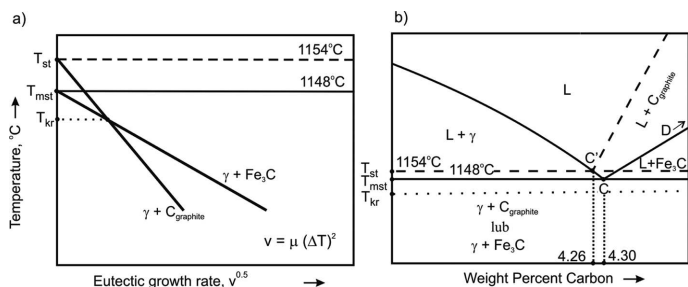


Fig. 1. General scheme of the effect of the growth velocity $v = f(\Delta T)$ of the graphite γ (Fe) + $C_{graphite}$ eutectic and cementite γ (Fe) + Fe_3C eutectic on the critical temperature of crystallisation T_{kr} – (a) and part of the phase equilibrium diagram for Fe - C alloys – (b)

2. High chromium cast iron

Applying the conditions normally encountered in industry, chromium white cast iron was manufactured. The manufactured cast iron had the following chemical composition is show in Table 1. Melting was carried out in an induction furnace of 250 kg capacity, applying the following procedure: in the bottom of the crucible, a charge composed of the pig iron

TABLE 1
The chemical composition cast iron

Melt No.	Chemical compositions										
	Wt. %										
	C	Si	Mn	P	S	Cr	Ni	V	W	Ti	Cu
I/1	3.01	1.07	0.6	0.03	0.05	12.9	0.07	0.005	0.031	0.005	0.039
I/2	2.35	0.65	1.06	0.05	0.07	25.6	1.09	0.009	0.065	0.010	0.962
I/3	1.78	0.70	0.33	0.05	0.06	18.3	0.07	0.005	0.055	0.004	0.047
I/4	3.14	0.96	0.54	0.05	0.06	24.6	0.42	0.047	0.047	0.014	0.079
I/5	3.21	0.71	1.36	0.05	0.06	26.6	0.64	0.032	0.025	0.009	0.047
I/6	4.50	1.06	1.04	0.04	0.06	25.2	1.02	0.007	0.025	0.009	1.020
I/7	3.35	1.51	0.63	0.03	0.05	21.2	0.61	0.036	0.062	0.013	0.193
I/8	3.60	0.93	0.27	0.02	0.01	16.1	0.01	-	-	5.04	0.005

and steel scrap, followed by iron scrap, was placed. After melting down the charge, ferrochromium and ferromolybdenum were added. After dissolving of ferrochromium, ferrosilicon was added. The cast iron was next overheated to a temperature of 1500°C and held at that temperature for 5 minutes. As a next step, the content of manganese was made up with ferromanganese, holding the metal for the next 3 minutes. During holding of cast iron and before tapping, the melt temperature was monitored with a thermocouple. Molten cast iron was transferred to a ladle. The ladle was next handled to a pouring stand and moulds prepared previously were poured with molten metal. As a next step, specimens for mechanical tests

and polished sections for metallographic examinations were prepared.

Figure 2 shows the microstructure of high chromium cast iron obtained from a trial melt. The structure can be defined as hypoeutectic, „slightly” hypoeutectic or eutectic and „slightly” hypereutectic. The spatial arrangement in a structure of this type can be compared to a system of the interpenetrating phases bonded together in eutectic. The microstructure of high-chromium cast iron sample inoculation shows in Figure 2.

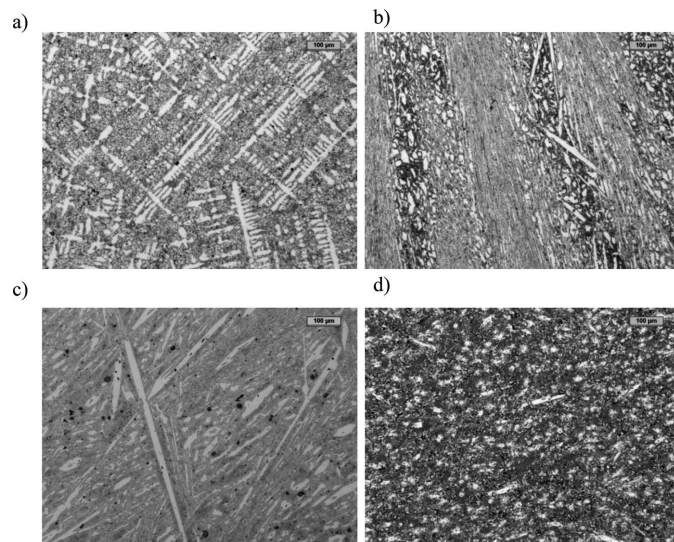


Fig. 2. Example of microstructures of castings made from high chromium cast iron: melt no. I/2 – (a), melt no. I/4 – (b), melt no. I/7 – (c), melt no. I/8 – (d)

The property strength of cast iron are definitely related with the number and structure of the primary and eutectic grains included in the cast iron structure. However, in the high-chromium cast iron after inoculation, retaining the number of the primary grains has proved impossible.

3. High-vanadium cast iron

Vanadium cast iron were conducted in a Balzers vacuum furnace, in a protective atmosphere of argon. The charge for melting had the following composition: ferrovanadium with 81.7% V, Armco iron, and spectrally pure graphite. A series of melt with hypoeutectic, eutectic and hypereutectic microstructure and with precipitates of spheroidal vanadium carbides VC was made. Table 2 describes the chemical composition of the examined specimens and the degree of eutectic saturation S_e . Moulds made of molochite flour with CO_2 – hardened sodium silicate were preheated at 550°C, then poured with liquid cast iron at a temperature of 1700°C. After knocking out of castings, specimens were cut for metallographic examinations and determination of tribological properties. Unetched specimens were examined under a LEICA M MEF4 optical microscope and under a JEOL 5500LV SEM, using secondary electrons. This enabled distinguishing between vanadium carbides and other phases, which is not always possible when optical microscopy is the only tool applied in the studies. High-vanadium cast iron is white cast iron, which has been observed to contain a fibrous $\gamma + VC_{1-x}$ (Fig. 3) eutectic with the volume fraction of vanadium carbides at a level of about 20% [21,22].

TABLE 2

Chemical composition in the examined alloys

Melt No.	Chemical compositions Wt. %			C/V	S _c
	C	V	Si		
II/1	1.44	15.6	0.21	0.09	1.03
II/2	1.55	15.6	0.24	0.10	1.11
II/3	0.85	15.47	0.26	0.05	0.60
II/4	1.38	15.95	0.22	0.09	1,00

Besides eutectic, depending on the C/V ratio (where C, V – content of carbon and vanadium in the cast iron, respectively, %) in high-vanadium cast iron, the presence of the following structural constituents has been detected.

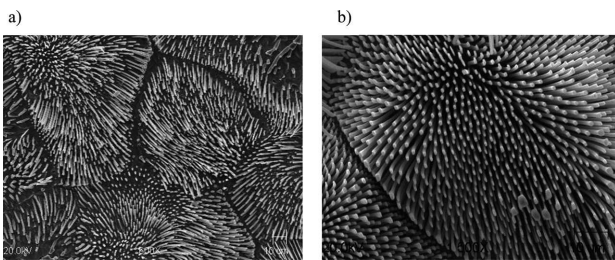


Fig. 3. SEM micrograph showing eutectic cells in near-eutectic Fe-C-V alloys – (a, b)

Adding silicon to Fe-C-V alloys in an amount above 1% changes the crystallising eutectic from fibrous regular (Fig. 3) to complex regular. Silicon addition also changes the shape of primary carbides from non-faceted crystals to the faceted ones [21-23]. Mechanical properties of high-vanadium cast iron depend on the type of the crystallising matrix, where the ferritic matrix causes relatively low mechanical properties and high ductility, the matrix with lamellar pearlite increases the mechanical properties and hardness on the cost of lower ductility, and the matrix with granular pearlite increases, compared to the matrix with lamellar pearlite, plastic properties and reduces hardness [21-24]. Moreover, presence of cementite eutectic in structure favours increase in hardness and decrease in plastic properties of alloys.

Figure 4 shows the microstructure of the examined specimens etched with Vilella's reagent to reveal the matrix and vanadium carbides. As can be easily noted, except vanadium carbides of different shapes, the matrix is composed of alloyed ferrite.

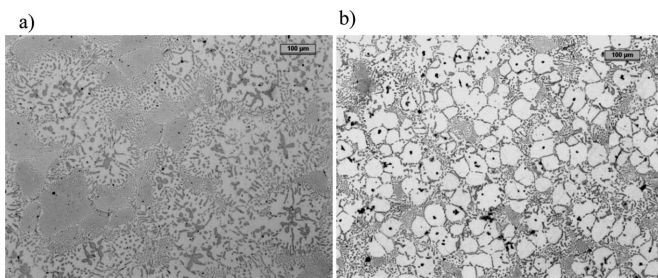


Fig. 4. Microstructures of castings made from cast iron: melt no. II/2 – (a), melt no. II/3 – (b)

4. Abrasive wear resistance of white cast iron

Studies of abrasive wear resistance were carried out on a Miller machine [25]. Specimens of a standard size, i.e. $25.4 \times 12.7 \times 5 \pm 9$ mm, were charged with the weights and subjected to an abrasive wear test, rubbing in a reciprocating motion against the bottom of a gutter filled with the aqueous mixture of an abrasive medium (SiC + distilled water). The study involved three tests performed in 16-hour series consisting of four-hour shifts each. Then, the respective wear resistance curves were plotted. After each run the specimens were washed, dried and weighed to the nearest 0.1 mg. Based on the results of the measurements, the weight losses and the cumulative weight losses were determined after each test in a given series, enabling the results to be plotted on a time – weight graph. The cumulative (summarised) weight losses (regarded as a total mass loss which has occurred since the beginning of the constant load effect) were recorded after 4, 8, 12 and 16 hours of the test cycle. Tests of abrasive wear resistance conducted on a Miller machine enabled comparing the abrasive wear resistance of the materials tested. In addition, as a reference, the chromium cast steel was tested, which is generally considered a material of high abrasion resistance. The obtained results are displayed in the form of a collective graph in Figure 5.

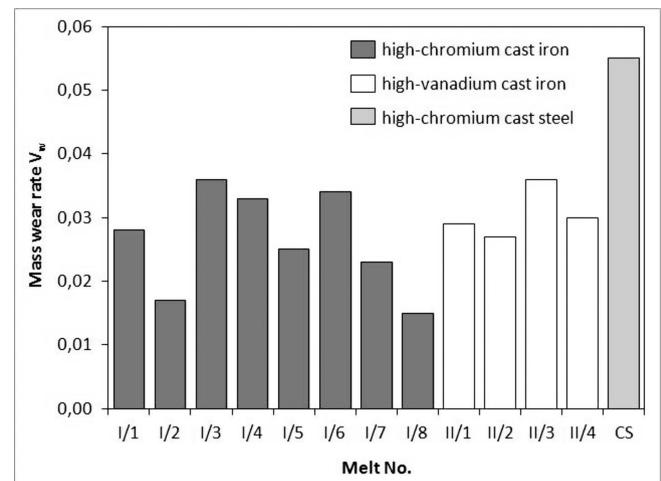


Fig. 5. Comparison of the mass wear rate observed during a 16 hour test cycle in the examined grades of abrasive wear resistant alloyed white cast iron and in the cast steel grade from melt no. CS used as a reference material

5. Conclusions

The obtained results show us that titanium added to conventional grades of white cast iron increases quite remarkably both hardness and wear resistance. This study also shows that titanium introduced to chromium cast iron as an additional alloying element exerts a significant effect on the structure of this material. Titanium is a carbide-forming element but, unlike other elements of this type, it does not form complex carbides in the chromium cast iron, but TiC carbide only. This carbide is formed at high temperature in the liquid metal. Introduced to cast iron, titanium has a modifying effect, as revealed by the structure refinement (Fig. 2d) and increased

performance characteristics. It turns out that the greatest abrasive properties has a chromium cast iron around the eutectic structure (Fig. 2a,b,c).

Other grades of the abrasive wear resistant cast iron include vanadium cast iron which, in spite of having a low hardness value, can match the chromium cast iron as regards the abrasive wear resistance.

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REFERENCES

- [1] Cz. P o d r z u c k i, Cast Iron. ZG STOP Publication, Krakow 1991.
- [2] E. G u z i k, Archives of Foundry Engineering 1M, (2001).
- [3] J.R. D a v i d, Cast Irons. ASM Specialty Handbook, ASM Inter. Mater. Park, OH, 1996.
- [4] E. F r a ś, Crystallization of metals. Scientific and Technical Publishing, Warsaw 2003.
- [5] A. S t u d n i c k i, J. S u c h o ń, Archives of Foundry Engineering 11, 282-288 (2003).
- [6] A. S t u d n i c k i, Archives of Foundry Engineering 10, 209-216 (2010).
- [7] J. Z h o u, China Foundry 8/3, 337-349 (2011).
- [8] H. C h e n, Z. C h a n g, J. L u, H. L i n, Wear 166, 197-201 (1993).
- [9] M. R a d u l o v i c, M. F i s e t, K. P e e v, J. of Materials Science 29, 5085-5094 (1994).
- [10] P. C h r i s t o d o u l o u, N. C a l o s, Materials Science and Engineering 301, 103-117 (2001).
- [11] C. G u o, P.M. K e l l y, Materials Science and Engineering 352, 40-45 (2003).
- [12] A. B e d o l l a J a c u i n d e, R. C o r r e a, J.G. Q u e z a d a, Mat. Scie. and Engin. 398, 297-308 (2005).
- [13] G. S i l m a n, E. P a m f i l o v, S. G r y a d u n o v, Metal Scie. and Heat Treat. 49, 405-410 (2007).
- [14] X. Z h i, J. X i n g, H. F u, B. X i a o, Materials Letters 62, 857-860 (2008).
- [15] Y. Q u, J. X i n g, X. Z h i, J. P e n g, H. F u, Materials Letters 62, 3024-3027 (2008).
- [16] Z. L i u, Y. L i, X. C h e n, K. H u, Mat. Scie. and Engin. 486, 112-116 (2008).
- [17] D. K o p y c i ń s k i, Archives of Foundry Engineering 9, 191-194 (2009).
- [18] D. K o p y c i ń s k i, S. P i a s n y, Archives of Foundry Engineering 12, 57-60 (2012).
- [19] D. K o p y c i ń s k i, E. G u z i k, S. P i a s n y, Arch. of Foundry Engineering 11, 61-66 (2011).
- [20] E. G u z i k, Paper of Commission Metallurgy and Foundry. Metallurgy 34, 73-89 (1986).
- [21] E. F r a ś, E. G u z i k, Archives of Metallurgy 25(4), 757-772 (1980).
- [22] M. K a w a l e c, E. F r a ś, ISIJ International 48(4), 518-524 (2008).
- [23] E. F r a ś, M. K a w a l e c, H.F. L o p e z, Mat. Scien. and Engi. A. 524, 193-203 (2009).
- [24] W. W o ł c z y ń s k i, E. G u z i k, W. W a j d a, D. J ę d r z e j c z y k, Archives of Metallurgy and Materials 57, 105-117 (2012).
- [25] B. K a l a n d y k, J. G ł o w n i a, Arch. of Foundry Engineering 2(4), 376-383 (2001).

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