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Abrasive wear resistance of high-vanadium cast iron

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Abstract

The study presents the results of tribological tests made on Fe-C-V and Fe-C-V-Si alloys undergoing volume solidification and containing carbon in a range of 1,43-2,58%, vanadium in a range of 5,34-14,77%, and silicon in a range of 1,06-3,69%. The, crystallising in Fe-C-V alloys, eutectic is composed of ferrite and vanadium carbides of the VC_{1-x} type, and as such is included in the group of fibrous eutectics. Introducing silicon additions to the Fe-C-V system changes the geometry of the crystallising eutectic from fibrous into complex regular, while the shape of the primary carbides crystallising as non-faceted-non-faceted dendrites changes into a faceted form.

It has been proved that the type of matrix has also a very important effect on the abrasive wear behaviour. The possibility has been indicated to manufacture Fe-C-V alloys with matrix containing lamellar pearlite, characterised by the abrasive wear resistance comparable to that of Hadfield cast steel. It is also possible to make alloys which will have the matrix composed of a mixture of lamellar and granular pearlite, or of a mixture of lamellar pearlite and cementite, and in this case their abrasive wear resistance will be superior to that of Hadfield cast steel. Within the examined range of chemical compositions, the addition of silicon has been reported to reduce the abrasive wear resistance.

Keywords: Mechanical properties; Wear resistance; Eutectic alloy; High-vanadium cast iron

1. Introduction

Owing to its very advantageous technological and mechanical properties, cast iron is not only the alloy most popular and used most frequently, but also the engineering material continuously developed and improved. Cast iron is used in nearly each and every sector of industry. Yet, considering the ever more stringent requirements of the users of this material, new grades of cast iron characterised by better mechanical and useful properties are searched for all the time. One of the trends in these searches is related with the use of alloying elements which, when introduced to cast iron, change the type of its matrix and the morphological features of graphite, or have the power of speeding up the carbides crystallisation. The element offering very interesting, though still in most part unknown, properties is vanadium. The data available on high-vanadium cast iron are very scarce. In [1,2] the authors give information on the structure of Fe-12,9%V-2,94%C alloys, which have been reported to include in their composition a fibrous $\gamma + VC_{1-x}$ eutectic with vanadium carbides present in an amount of about 20 vol.%. The results of microstructural examinations carried out on Fe-C-V alloys with carbon contained in the range of 1,38-4,16% and vanadium in the range of 6,7-15,5% as well as the results of mechanical and tribological tests made on these alloys were described in [3,4]. The research disclosed in [5] has indicated that, added to the Fe-C-V system, silicon changes the geometry of the crystallising eutectic from fibrous into complex regular, and the shape of primary carbides from non-faceted-non-faceted into faceted. In [6] it has been proved that silicon addition raises hardness and mechanical properties, while decreasing the plastic properties of Fe-C-V alloys.

High-vanadium cast iron is included in the group of white cast irons, mainly because the entire carbon present there is chemically bonded in vanadium carbides. Yet, contrary to the common white cast iron in which the volume content of the brittle cementite in eutectic can reach even 50%, in high-vanadium cast iron, the content of the hard carbides is much lower (about 20 vol.%). Due to this, high-vanadium cast iron is capable of offering the plastic properties superior to those of the common white cast iron, which is brittle but resistant to abrasive wear. The abrasive wear resistance of the high-vanadium cast iron remains unknown, and this fact explains the aim of the investigations undertaken and described in the present study.

2. Methods of investigations

To perform the anticipated mechanical tests, a series of melts with varying content of carbon, vanadium and silicon were made, using Balzers vacuum-type furnace and the atmosphere of argon. The Fe-V master alloy with 81,7% vanadium, armco iron, technically pure graphite and commercial 98,5% Si silicon were used. Moulds prepared from molochite flour with CO_2-hardened sodium silicate were preheated to a temperature of 550°C, and poured next with molten iron at a temperature of 1600°C. After knocking out of castings, the specimens were cut out for metallographic examinations and tribological tests.

Unetched specimens were examined under a LEICA MEF4 M optical microscope and a JEOL 5500LV scanning microscope, using secondary electrons. This enabled distinguishing vanadium carbides from other phases, which rendered the metallographic analysis particularly difficult. To investigate more precisely the geometry of individual phases, the specimens were deep etched with *aqua regia* and examined under the scanning microscope. The percent content of the structural constituents was determined on a LEICA Qwin automatic image analyser.

The abrasive wear resistance of the examined alloys was tested by two methods. The first test (P1), carried out in a „specimen – abrasive paper” system, consisted in running a $6\times6\times7$ mm specimen of vanadium cast iron against a corundum abrasive paper of granulation 60, where the abrasive path during one cycle was 40 m, and the specimen was loaded by a force of 10 N. For each specimen, four abrasion cycles were performed, determining each time the loss of mass at the accuracy of 0,001 g. Next, mean mass-related wear coefficient J_m, determining the loss of specimen mass expressed in mg along a 1 m long abrasion path was measured. The second abrasive wear test (P2) using a „specimen – counterspecimen” system was running in a to-and-fro motion. A ϕ 3×17 mm mandrel cast from abrasion-resistant Hadfield steel was moving along a track of 6 mm/cycle, rubbing against a specimen of the examined vanadium cast iron of dimensions and under loading as applied in test P1. For each specimen, 30 000 cycles of the abrasive wear test were conducted, followed by determination of the specimen loss of mass and calculation of the wear coefficient.

3. Results and discussion

Tables 1 and 2 give chemical composition of the examined alloys, their microstructure and content of individual structural constituents, as well as the results of the abrasive wear resistance measurements, determined as a loss of mass in Fe-C-V and Fe-C-V-Si alloys. Figure 1 shows examples of microstructures present in the examined alloys, while Figure 2 shows the effect of silicon addition on changes in the microstructure of Fe-C-V alloys. From analysis of these results it follows that silicon addition changes the morphology of the crystallising eutectic from fibrous (Fig. 2a, c) to complex regular (Fig. 2b, d). The shape of the primary carbides changes, too. After introducing an addition of silicon, the non-faceted crystals (Fig. 2e) are transformed into the faceted ones (Fig. 2f).

Table 1.
Chemical composition, content of matrix constituents and results of abrasive wear test made for Fe-C-V alloys

Melt No.	Chemical composition			Matrix constituent content				f_w [%]	f_d [%]	Microstructure	C/V	Wear coefficient, J_m	
	C [%]	V [%]	Si [%]	f_f [%]	$f_{p.z.}$ [%]	$f_{p.p.}$ [%]	f_c [%]					Test P1 [mg/m]	Test P2 [μg/m]
1	1,53	14,77	-	82,11	-	-	-	17,89	-	●	0,10	3,14	31,81
2	1,60	12,60	-	76,00	-	-	-	24,00	-	▲	0,13	3,93	8,75
3	1,55	10,90	-	76,90	5,00	-	-	18,10	23,00	■	0,14	3,54	23,89
4	2,17	9,81	-	-	15,00	61,98	-	23,02	-	●	0,22	0,44	2,50
5	1,80	9,17	-	-	27,30	57,36	-	15,35	23,00	■	0,20	0,62	1,11
6	2,58	7,83	-	-	-	78,19	2,00	20,81	-	●	0,33	2,27	3,33
7	2,23	7,33	-	-	-	86,68	-	13,32	-	▲	0,30	2,05	3,61
8	2,18	7,67	-	-	-	83,65	-	18,58	-	▲	0,28	1,92	3,75
H	Hadfield steel											1,97	-

● - hypereutectic microstructure
▲ – nearly eutectic microstructure
■ - hypoeutectic microstructure

f_f – ferrite content in cast iron
$f_{p.z.}$ – granular pearlite content in cast iron
$f_{p.p.}$ – lamellar pearlite content in cast iron
f_c – cementite eutectic content in cast iron

f_w – vanadium carbide content in cast iron (hypoeutectic and eutectic)
f_d – content of austenite dendrites transformed in ferrite

The results of the abrasive wear test P1 were compared with the abrasive wear of Hadfield cast steel (the specimen of Hadfield cast steel was designated with symbol H). From the results of the test it follows that, like in the case of the mechanical properties, the abrasive wear of the examined alloys depends mainly on the type of the alloy matrix.

Table 2.
Chemical composition, content of matrix constituents and results of abrasive wear test made for Fe-C-V-Si alloys

Melt No.	Chemical composition			Matrix constituent content				f_w [%]	f_d [%]	Microstructure	C/V	Wear coefficient, J_m	
	C [%]	V [%]	Si [%]	f_f [%]	$f_{p.z.}$ [%]	$f_{p.p.}$ [%]	f_c [%]					Test P1 [mg/m]	Test P2 [µg/m]
Si-1	1,43	11,86	2,12	63,23	20,00	-	-	16,27	-	●	0,12	3,15	29,44
Si-2	1,77	9,97	3,69	-	84,81	-	-	15,19	-	●	0,18	3,27	26,67
Si-3	1,43	9,74	2,17	39,30	40,00	-	-	20,27	-	▲	0,15	3,29	9,72
Si-4	1,48	9,64	1,06	-	79,69	-	-	20,31	-	■	0,15	3,11	19,17
Si-5	1,73	7,49	2,65	-	84,33	-	7,00	15,67	-	●	0,23	2,31	0,28
Si-6	1,68	5,34	2,42	-	10,00	76,13	3,00	13,87	16,62	■	0,31	2,54	0,83
H	Hadfield steel											1,97	-

● - hypereutectic microstructure
▲ – nearly eutectic microstructure
■ - hypoeutectic microstructure

f_f – ferrite content in cast iron
$f_{p.z.}$ – granular pearlite content in cast iron
$f_{p.p.}$ – lamellar pearlite content in cast iron
f_c – cementite eutectic content in cast iron

f_w – vanadium carbide content in cast iron (hypoeutectic and eutectic)
f_d – content of austenite dendrites transformed in ferrite

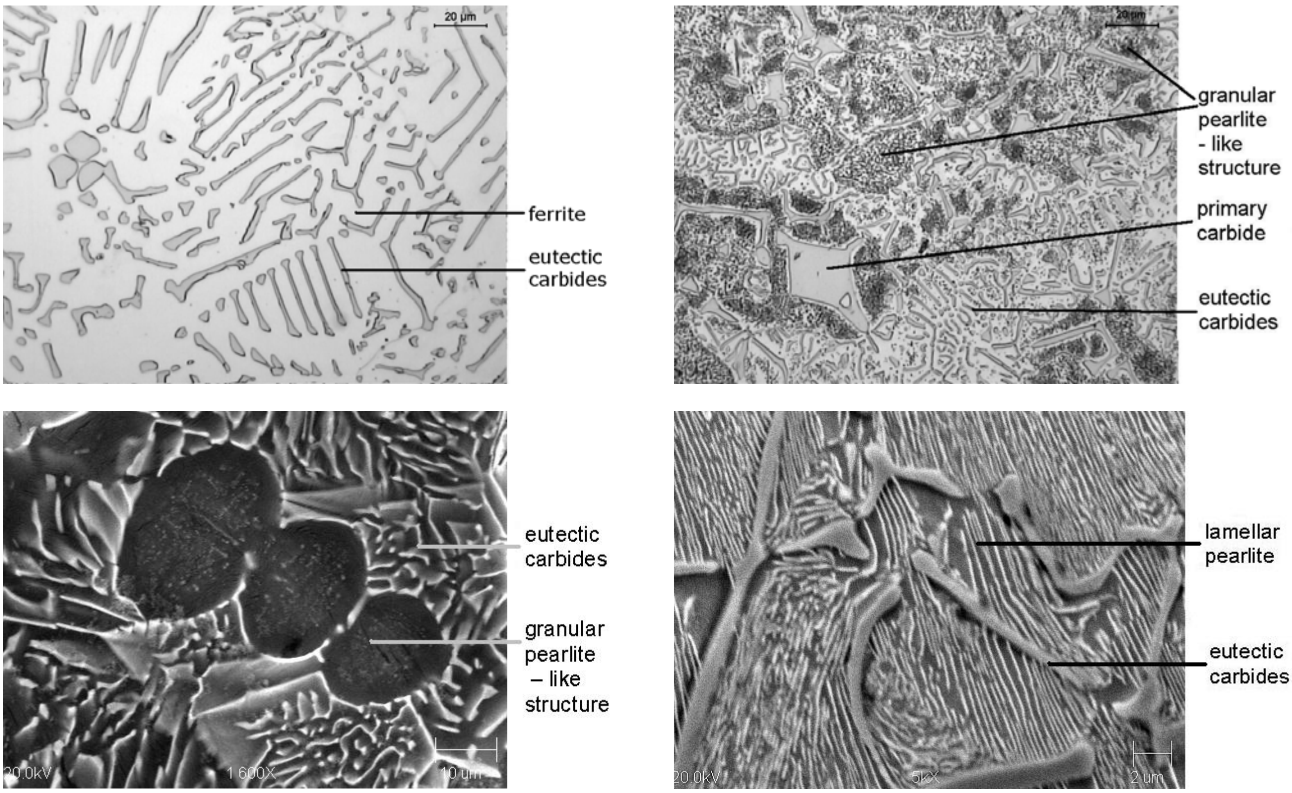


Fig. 1. Microstructure of high-vanadium cast iron

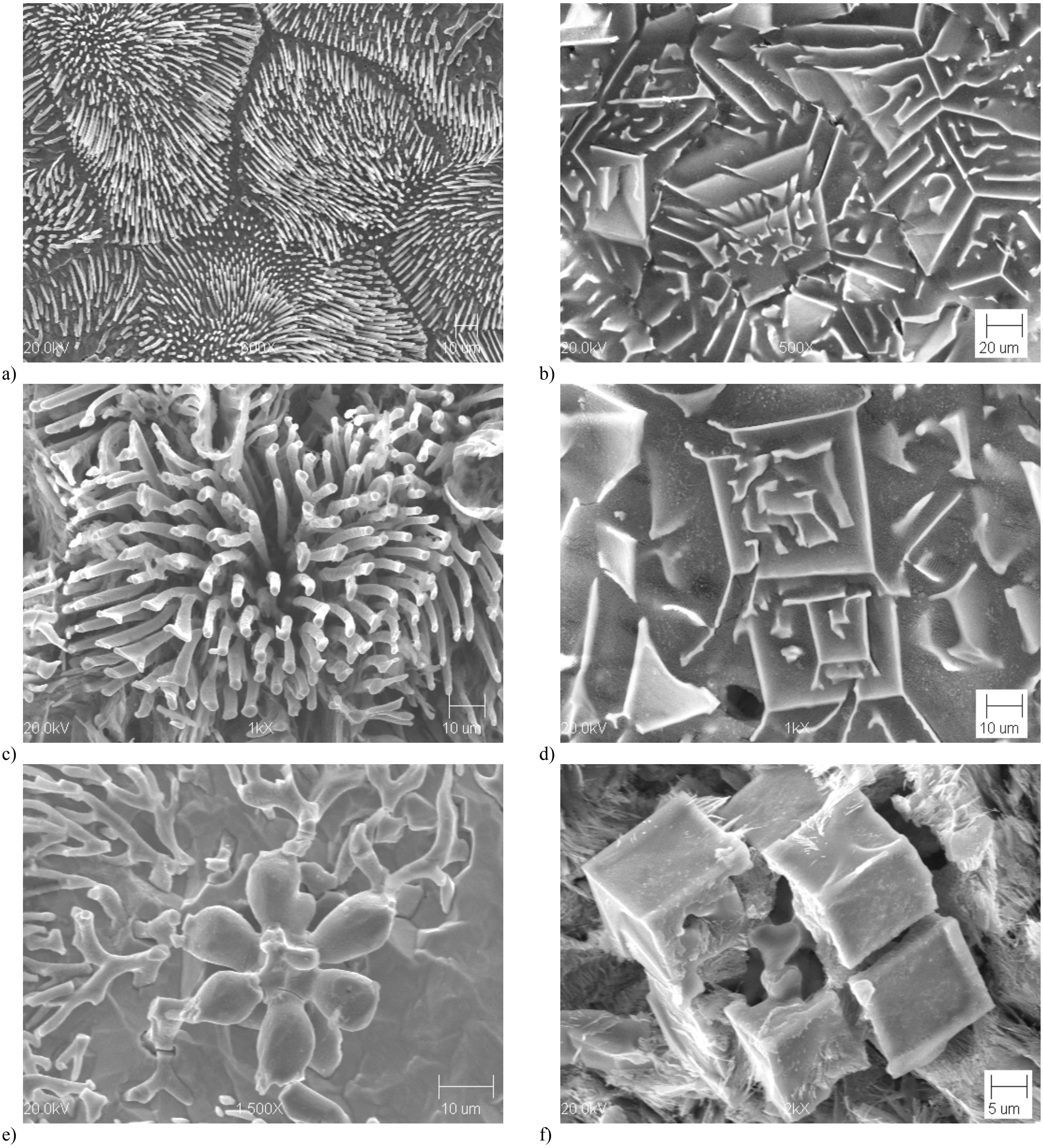
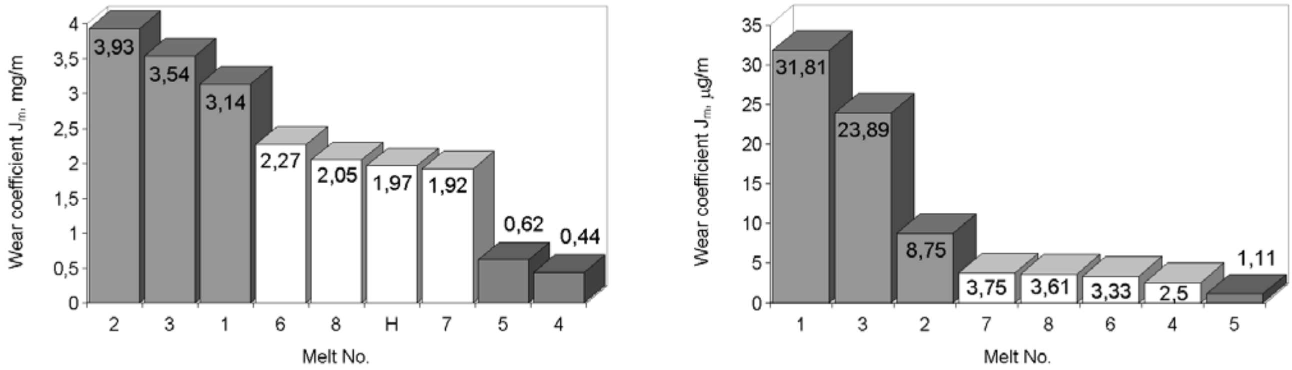
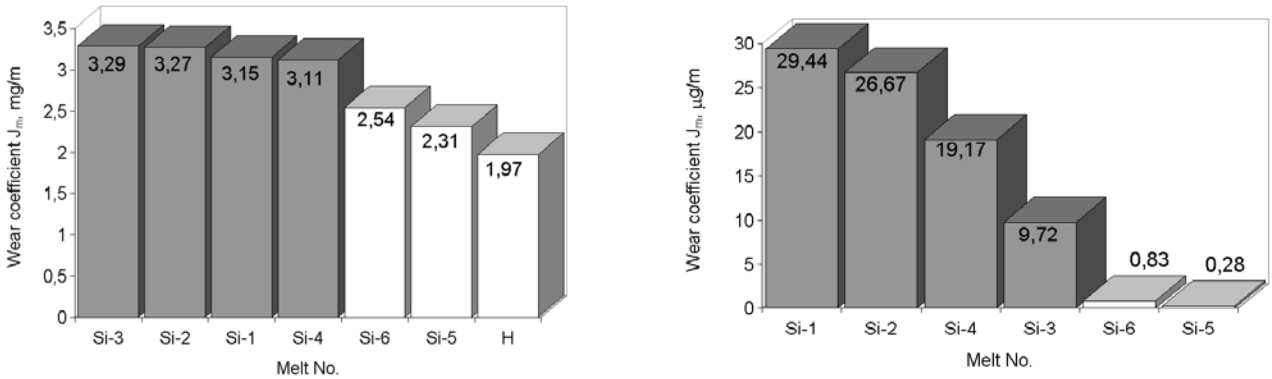


Fig. 2. Microstructure of specimens etched in *aqua regia* (SEI): eutectic grains in Fe-C-V alloy (a, c), grains of complex regular eutectic in Fe-C-V-Si system (b, d), primary vanadium carbides of dendritic form in Fe-C-V alloy (e), primary carbides crystallising in the form of faceted dendrites in Fe-C-V-Si system (f).



a) b)

Fig. 3. Comparison of abrasive wear resistance of Fe-C-V alloys: specimen – abrasive paper (a), specimen - counterspecimen (b)



a) b)

Fig. 4. Comparison of abrasive wear resistance of Fe-C-V-Si alloys: specimen – abrasive paper (a), specimen - counterspecimen (b)

The results obtained on Fe-C-V alloys in test P1 can be divided into three groups (Fig. 3a). The first group includes alloys with ferritic matrix or ferritic matrix with small content of granular pearlite; these alloys are characterised by the highest values of the wear coefficient (J_m = 3,14 – 3,93 mg/m) with carbon content from 1,53 to 1,60 % and vanadium from 10,9 to 14,7 %. The second group contains from 2,18 to 2,58 % carbon and from 7,3 to 7,8 % vanadium, and is characterised by the matrix composed of lamellar pearlite and the wear coefficient J_m comparable to Hadfield cast steel (J_m ≈ 2 mg/m). The third group includes cast iron characterised by the highest wear coefficient (J_m ≈ 0,44 – 0,62 mg/m); it contains from 1,80 to 2,17 % carbon and from 9,1 to 9,8 % vanadium and has the matrix composed of a mixture of lamellar and granular pearlite or of lamellar pearlite and cementite. Comparing the results of the abrasive wear resistance test (Table 1 and Fig. 3) it can be concluded that the resistance in test P2 is higher than in test P1. The reason is, first of all, the different nature of abrasion used in both tests. Like in test P1, also in test P2 the cast iron of ferritic matrix is characterised by the highest abrasive wear (J_m = 8,75 – 31,81 µg/m). The highest resistance to abrasive wear (J_m = 1,11 µg/m) is offered by the specimens from melt no. 5; the remaining specimens have a moderate resistance.

The results of the tests carried out for Fe-C-V-Si alloys in test P1 can be divided into two groups: the first reperesents low values of the abrasive wear resistance (J_m above 3 mg/m), while the second has the abrasive wear resistance comparable to that of Hadfield cast steel (J_m ≈ 2 mg/m). The first group includes alloys of ferritic-pearlitic matrix (with granular pearlite); while alloys in the second group have the matrix with lamellar pearlite and precipitates of alloyed cementite. In the case of Fe-C-V-Si alloys, abrasion test P2 gave the results similar to test P1. The best abrasive wear resistance (J_m below 1 µg/m) offered the alloys of pearlitic matrix with precipitates of alloyed cementite. Alloys of ferrtic-pearlitic matrix or with granular pearlite were characterised by very low abrasive wear resistance (J_m above 10 µg/m). In respect of the abrasive wear resistance, alloys with an addition of silicon were not superior to Hadfield cast steel.

4. Conclusions

1. The abrasive wear resistance of high-vanadium cast iron mainly depends on the type of the metallic matrix, where the lowest resistance is revealed by alloys with ferritic matrix, moderate – by those with pearlitic matrix, and the highest by the alloys of complex matrix composed of lamellar and granular pearlite.
2. It is possible to produce Fe-C-V alloys of the abrasive wear resistance superior to that of Hadfield cast steel.

3. Within the examined range of chemical compositions, an addition of silicon reduces the abrasive wear resistance of high-vanadium cast iron.

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