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Abrasive Wear Resistance of Cast Iron with Precipitates of Spheroidal VC Carbides

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Abstract

The paper presents the results of abrasive wear resistance tests carried out on high-vanadium cast iron with spheroidal VC carbides. The cast iron of eutectic composition was subjected to spheroidising treatment using magnesium master alloy. The tribological properties were examined for the base cast iron (W), for the cast iron subjected to spheroidising treatment (S) and for the abrasion-resistant steel (SH). Studies have shown that high-vanadium cast iron with both eutectic carbides and spheroidal carbides has the abrasion resistance twice as high as the abrasion-resistant cast steel. The spheroidisation of VC carbides did not change the abrasion resistance compared to the base high-vanadium grade.

Keywords: Abrasive Wear Resistance, High-vanadium Cast Iron, Eutectic Alloy, Spherodisation, Vanadium Carbide

1. Introduction

Owing to its favourable mechanical and technological properties, cast iron not only continues being the most widely used cast alloy, but is also under constant development. This material is used in nearly every branch of the industry, because of a wide spectrum of the available grades with varied mechanical and performance properties. One of the trends in research looking for new cast iron grades is the use of alloying additions, which either change the type of matrix and the morphological features of graphite, or result in carbides crystallisation. The element of very interesting properties as an alloying addition is vanadium. Papers [1, 2] provide information on the microstructure of Fe-12,9% V-2, 94% C alloys, which were observed to have in their composition a fibrous $\gamma + VC_{1-x}$ eutectic with vanadium carbides volume fraction of about 20%, while in [3] the properties of vanadium carbides of the VC type were described.

Fe-CV alloys with high vanadium content are in the group of white cast irons, because all carbon is bound in vanadium carbides. The results of microstructure examinations of such alloys with a carbon content of 1.38-4.16%, and vanadium in the range of 6.7-15.5%, as well as their mechanical and tribological properties are given in [4, 5]. They indicate that both mechanical properties and wear resistance behaviour of the high-vanadium cast iron depend mainly on the type of metallic matrix and change within the following range of values: tensile strength from 433 to 839MPa, yield strength from 185 to 655 MPa, hardness from 174 to 474, and elongation from 0.2 to 7.2%. The abrasive wear resistance of high-vanadium cast iron depends mainly on the type of the crystallised metallic matrix, where the lowest resistance is typical of alloys with a ferritic matrix, medium values are offered by alloys with a pearlitic matrix, and the highest values – by alloys with a complex matrix composed of lamellar and spheroidal pearlite. It is possible to produce Fe-CV alloys with abrasive wear resistance higher than that of Hadfield steel.

A study of the technical literature confirms growing interest in the ordinary high-alloyed white cast irons [6, 7] and in the white cast iron with carbide precipitates in the form of spheroids. In [8-11] information was found on the spheroidising treatment of white alloyed cast iron with a high content of chromium, vanadium and nickel using rare-earth metals to improve the abrasive wear resistance.

To combine the good casting properties of cast iron with the high ductility of cast steel, a spheroidising treatment is carried out, producing the cast iron with spheroidal graphite. The spheroidal form of graphite is the most compact one, with the smallest surface-to-volume ratio, owing to which the casting active section is impaired to a lesser degree, while stress concentrations around the sites where the graphite occurs are much less numerous compared with the graphite in the form of lamellae [12].

These features of the spheroidising treatment were used to produce vanadium carbides VC in the form of spheroids in the studies described in [13]. The spheroidising treatment of VC carbides increased the alloy mechanical properties and improved its ductility.

The aim of this study was to compare the abrasive wear resistance of Fe-CV alloys of a nearly-eutectic microstructure, containing after the spheroidising treatment VC carbides of both fibrous and spheroidal shape.

2. Methods of investigations

To comply with the established research programme, two melts of cast iron of the same nearly-eutectic composition were conducted in a Balzers vacuum furnace in a protective argon atmosphere. Melting was carried out using an Fe-V master alloy containing 81.7% of vanadium, armco iron, and technically pure graphite. The first melt was left in the starting condition (W), while the second one was subjected to a spheroidising treatment (S). The spheroidiser was Elmag 5800 magnesium master alloy. Moulds were made from molochite flour with CO_2 hardened sodium silicate, preheated to a temperature of 550°C, and then poured with liquid cast iron at a temperature of 1700°C. After knocking out of castings, specimens were cut out for the metallographic examinations and testing of tribological properties.

Unetched specimens were examined under an MEF4 M optical microscope supplied by LEICA and under a 5500LV JEOL scanning electron microscope using secondary electrons. This allowed the vanadium carbides to be distinguished from other phases, which is not always possible when only optical microscopy is applied in the studies. For more detailed examinations of the geometry of different phases, the specimens were deep-etched with aqua regia and examined by scanning electron microscopy. The percent content of structural constituents was determined using a LEICA Qwin automatic image analyser.

Studies of abrasive wear resistance were carried out on a Miller machine, whose schematic diagram is shown in Figure 1a. Specimens of a standard size, i.e. 25.4 x12, 7x5 ± 9 mm (Fig. 1b), 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 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. The obtained results of changes in the specimen weight were approximated with an exponential curve described by the following relationship:

$$W(t) = A \cdot t^{B} \qquad (1)$$

where:

W – the weight loss, [g],
t – the time, [hours],
A, *B* – the constants determined by the least square method.

Regardless of the number of trials in a series and the duration of a single test, the mass wear rate V_w determined by the slope of a tangent to the wear curve in the second hour of testing was adopted:

$$V_w = A \cdot B \cdot 2^{(B-1)} \qquad (2)$$

where:
A, *B* – the constants from relationship (1).

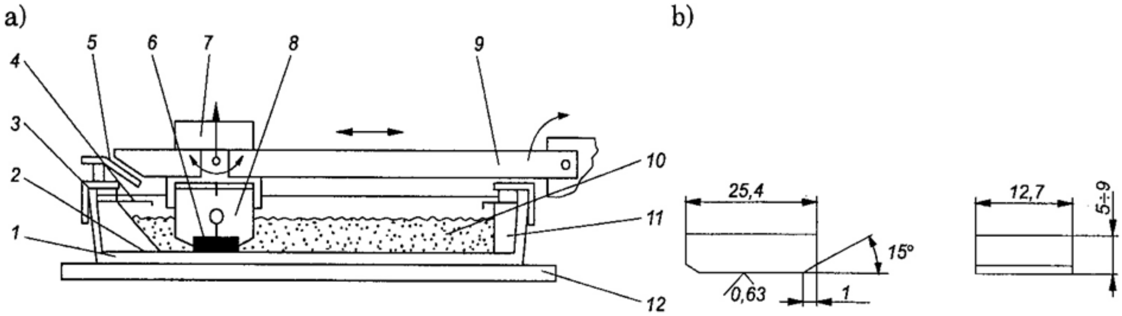
3. Results and discussion

Table 1 specifies the chemical composition of the examined specimens, the C / V ratio, the degree of eutectic saturation, and hardness HV30.

Table 1.
Chemical composition, C/V ratio, degree of eutectic saturation and hardness HV30 obtained in the conducted melts

Melt No.	C wt.%	V wt.%	C/V	S_c	HV30
W	1.40	15.60	0.090	1.00	205
S	1.38	16.25	0.085	1.01	199

The unetched specimens were examined by SEM combined with BEI (Back Scattered Electron Image), which allowed distinguishing vanadium carbides from other phases disturbing the metallographic analysis (Figs. 2a, 2b). Figures 3a and 3b show the microstructure of specimens etched with Vilella's reagent to reveal the matrix and improve the contrast for vanadium carbides. As can be easily noted, except vanadium carbides of different shapes, the matrix is composed of alloyed ferrite. Deep etching with aqua regia followed by SEM examinations enabled more accurate and detailed examination of the geometry of individual phases (Figs. 4a and 4b).



1 – rubber pad, 2 – casing, 3 – clamping strip, 4 – protective plate,
5 – arm lifting mechanism, 6 – specimen, 7 – weight,
8 – specimen holder, 9 – arm, 10 – abrasive material, 11 – cartridge, 12 – base

Fig. 1. Device for testing the abrasive wear resistance (a), dimensions of the specimen (b)

Tests of abrasive wear resistance conducted on a Miller machine enabled comparing the abrasive wear behaviour of the three tested materials, i.e. high-vanadium cast iron with fibrous eutectic (W), high-vanadium cast iron with spheroidal VC eutectic (S), and abrasion-resistant cast steel (SH). The third material containing 13.10% Mn, 1.50% Si, 0.40% Ni, 0.33% Cr was introduced as a reference point.

Based on the results of the weight measurements, the weight losses were calculated as well as a cumulative weight loss after each of the test series (Table 2).

The results showing weight changes in each of the specimens were approximated with an exponential curve described by relationship (1) and, as a next step, the mass wear rate V_w was calculated according to equation (2), as determined by the slope of a tangent to the wear curve in the second hour of testing. The results are shown in Table 2 and Figure 5.

Table 2.
The results of abrasive wear resistance measurements

Melt No.	Weight loss, g				A	B	V_w
	After 4 hours	After 8 hours	After 12 hours	After 16 hours			
W	0.18	0.32	0.44	0.56	0.058	0.816	0.042
S	0.22	0.35	0.42	0.50	0.096	0.595	0.043
SH	0.50	0.91	1.16	1.34	0.192	0.718	0.113

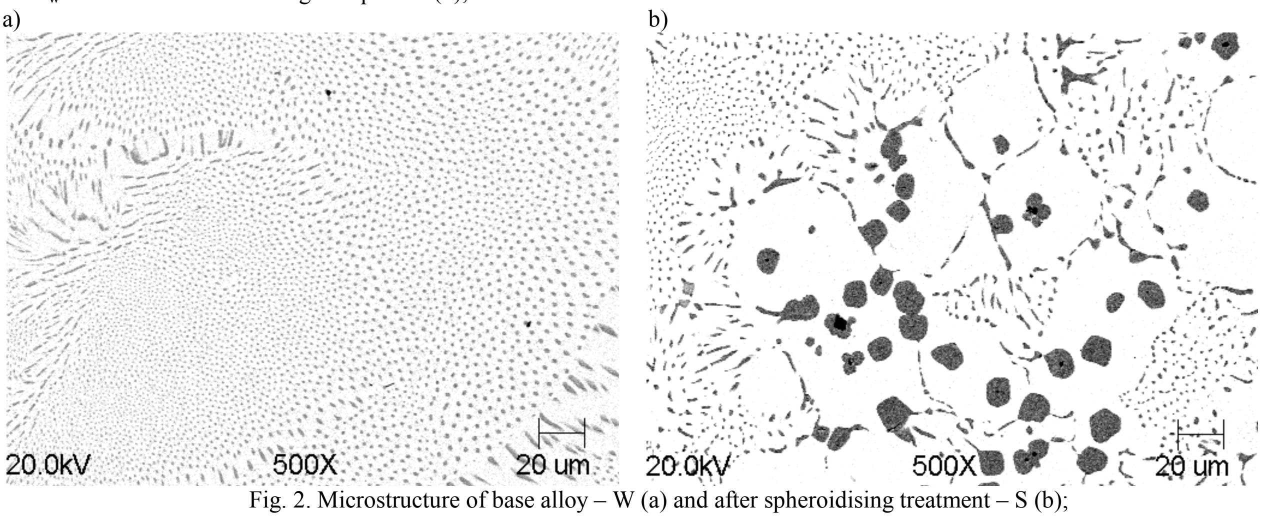


Fig. 2. Microstructure of base alloy – W (a) and after spheroidising treatment – S (b); unetched specimens, BEI

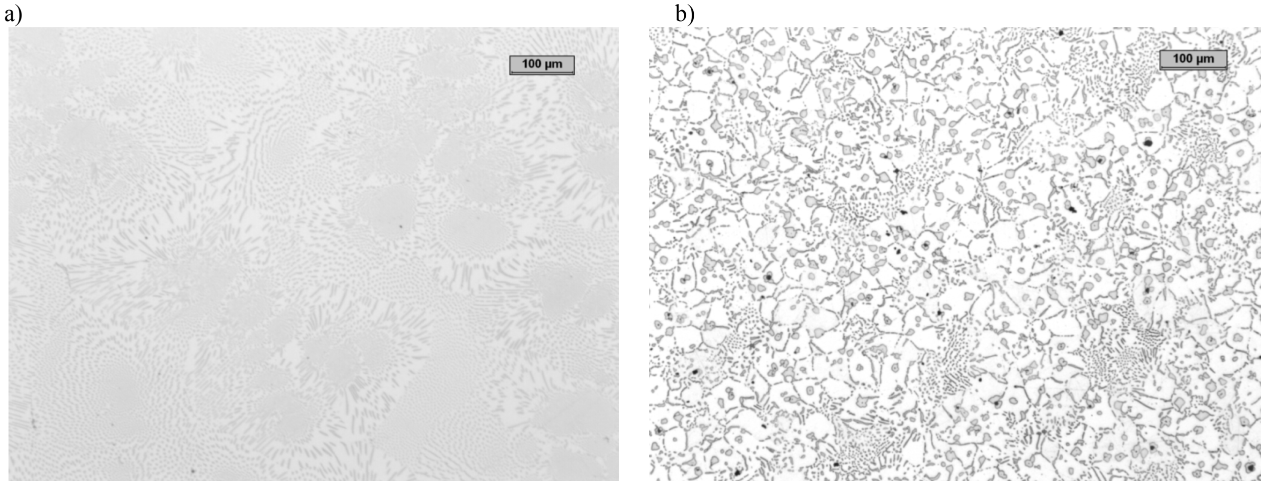


Fig. 3. Microstructure of base alloy – W (a) and after spheroidising treatment – S (b); specimens etched with Vilella's reagent

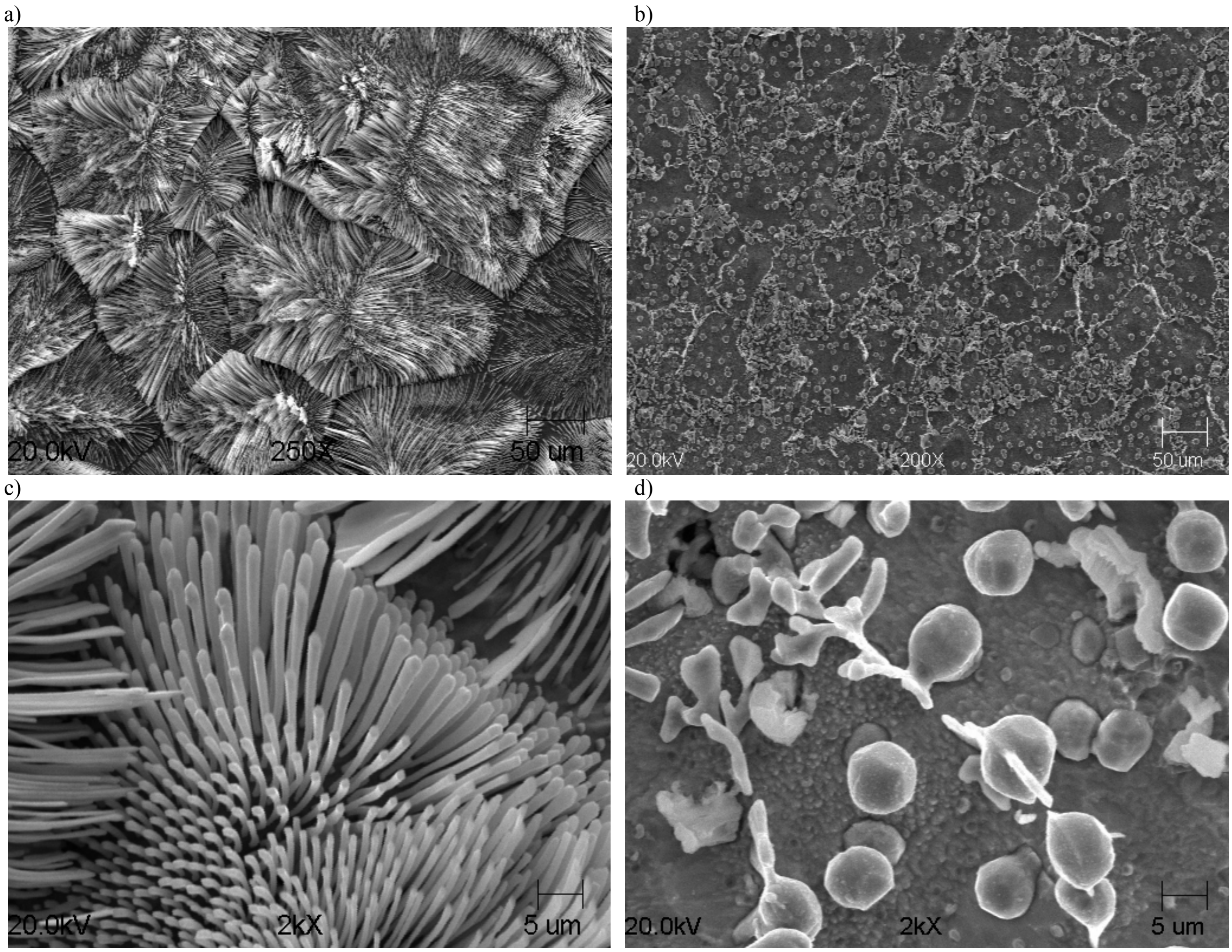


Fig. 4. Microstructure of base alloy – W (a,c) and after spheroidising treatment – S (b,d); specimens deep etched with aqua regia, SEM

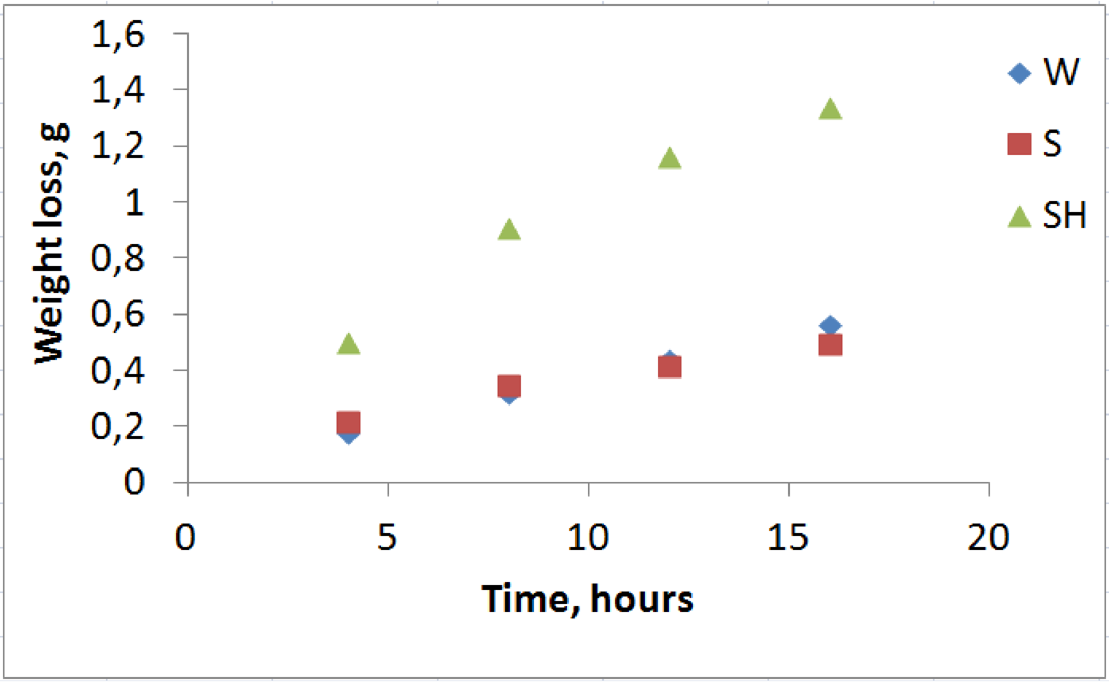


Fig. 5. Abrasive wear behaviour compared for high-vanadium cast iron and abrasion-resistant cast steel during 16-hour test cycle

4. Conclusions

The test results enabled the following conclusions to be drawn:

1. In high-vanadium cast iron of eutectic composition, the microstructure is composed of fibrous VC carbides and alloyed ferrite. The introduction of magnesium master alloy to this material has resulted in crystallisation of vanadium carbides in the spheroidal form.
2. The high-vanadium cast iron in both starting condition and after spheroidisation has very good resistance to abrasion. The mass wear rates are in both cases very similar and almost three times lower than the values obtained for the abrasion resistant cast steel.
3. Both tested high-vanadium cast iron grades showed high hardness related with the presence of hard VC carbides. The spheroidising treatment of VC carbides did not cause any significant changes in hardness.

Acknowledgements

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