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THE EFFECT OF VANADIUM CONTENT ON THE PROPERTIES OF Fe-C-Cr-V WHITE CAST IRON

VPLIV VSEBNOSTI VANADIJA NA LASTNOSTI BELE LITINE Fe-C-Cr-V

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The effect of the variation in vanadium concentration in a quasi four-component alloy of the Fe-C-Cr-V type on the wear and fracture resistance, and on the hardness and microstructure of as-cast and heat-treated samples was investigated. The wear resistance was examined using a comparative method on a "Taber Abraser" device, model 503. The addition of vanadium in the range from 1 to 11 wt. % significantly changed the solidification morphology of the white cast irons. As a result of microstructural changes, induced by the addition of vanadium and by heat treatment, a proportional increase in the hardness and wear- resistance values was noted. The impact-resistance values were not affected by the vanadium- induced morphological changes of the eutectic carbides to any great extent, although they were increased, to some degree, by heat treatment.

Key words: white cast iron, vanadium, microstructure, wear resistance, impact resistance

Vpliv sprememb vsebnosti vanadija v kvazi štirikomponentni zlitini vrste Fe-C-Cr-V na obrabo, trdnost, trdoto in mikrostrukturo je bil določen pri litih in toplotno obdelanih vzorcih. Obrabna odpornost je bila določena z uporabo primerjalne metode na napravi "Taber abrazer", model 501. Dodatek vanadija v količini od 1 % do 11 % je pomembno spremenil morfologijo strjevalne mikrostrukture. Zaradi dodatka vanadija je bila večja trdota po litju in po toplotni obdelavi, sprememba mikromorfologije evtektičnih karbidov ni vplivala na udarno žilavost, ki se je nekoliko povečala po toplotni obdelavi.

Ključne besede: bela litina, legiranje, vanadij, mikrostruktura, obrabna odpornost, udarna žilavost

1 INTRODUCTION

Castings from alloyed, white cast iron are widely used in the mining and mineral processing industries, where the primary requirements are good abrasion and fracture resistance in the cyclic- and impact-loading environment. Optimization of the chemical composition of alloyed cast irons, with a view to increasing the castings' performance, calls for the consideration of many aspects of their microstructure [1].

It is well known that the mechanical and service properties of this multiphase material depend on the proportions of individual phases or on the amount, distribution and morphology of microstructural constituents in the as-cast and heat-treated conditions. To improve impact toughness and abrasion resistance, alloyed, white cast irons are often heat treated. The parameters, by means of which the acceptability of the microstructure of the as-cast and heat-treated samples of alloyed, white cast iron can be qualitatively and quantitatively estimated, are the hardness, type, volume and form of primary and eutectic carbides as well as the proportions of pearlite, martensite and retained austenite in the matrix [2]. The addition of strong carbide-forming elements, such as vanadium, columbium or tungsten, significantly changes the microstructural and mechanical properties of white cast irons [3-5].

In this work the microstructure, hardness, and the wear and impact resistance of the as-cast and heat-treated white cast-iron samples were studied as a function of vanadium additions.

2 EXPERIMENTAL PROCEDURE

A quasi four-component alloy of the Fe-C-Cr-V type was examined. The alloys were melted in a medium-frequency laboratory, induction furnace. The metal charge consisted of steel scrap, white pig iron, ferrochromium and ferrovanadium. The chemical compositions of the charge materials are shown in **Table 1**.

The chemical compositions of the tested white cast-iron samples were determined by an ARL 8689 X-ray fluorescence spectrometer. A more precise analysis of the carbon and sulphur contents was performed by gaseous diffusion in a CS 444 LECO analyser.

The test samples were poured into moulds made from a mixture of sand and water-glass by means of the CO_2 procedure. The pouring temperature was about 1500 °C. **Figure 1** shows a drawing of the test pieces for impact-resistance testing and their dimensions, along with the corresponding gating and risering systems. The soundness of the cast pieces was checked by radiography. The pieces were subsequently ground into 10×10×55 mm impact-test samples without notching.

The form and dimensions of the rods for the microstructure and hardness testing and the samples for the wear-resistance examination are given in **Figure 2**.

Table 1: Chemical composition of metal charge materials for the induction furnace
Tabela 1: Kemična sestava kovinskega vložka za indukcijsko peč

Charge materials components	Chemical composition, wt. %				
	C	Mn	Si	Cr	V
Steel scrap	0.06-0.1	0.030-0.046	-	-	-
White pig iron	3.7	1.7	0.5	-	-
Fe-Cr	4.0 – 8.0	-	1.5	90-72	-
Fe-V	-	-	-	-	78

For the microstructure examination an optical microscope was used. The specimens for the optical microscopy were prepared by standard metallographic techniques and etched in 5 % nital.

Hardness was measured by the Rockwell C method. The values represent an average of ten measurements.

The impact resistance was examined with the Charpy method at 20 °C on a device with a maximum energy of 30 J. Cast, surface-ground specimens without a notch were used. Although this method of impact-resistance examination may not be the most suitable one for brittle materials such as white cast irons, it could be assumed that the changes in microstructure caused by the different vanadium contents and the heat treatment had a strong effect on the impact-resistance values. The impact-resistance values were taken from an average of five measurements.

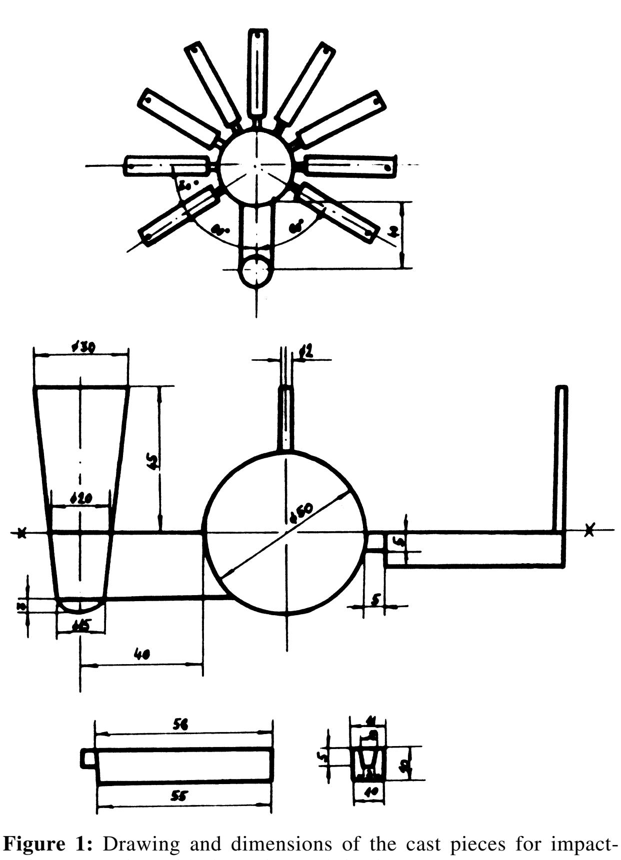

Figure 1: Drawing and dimensions of the cast pieces for impact-resistance testing with the gating and risering systems
Slika 1: Načrt in dimenzija litih vzorcev s sistemom napajalnikov in oddušnikov

The cast pieces were subjected to a heat-treatment procedure. Details of the procedure are not included in this paper. The heat-treatment procedure was performed according to the diagram in **Figure 3**. The heat-treated samples were easily ground.

The as-cast and heat-treated samples prepared for the wear-resistance examination were weighed on an analytical balance, suitable for up to 200 g, with an accuracy of ± $1 \cdot 10^{-4}$ g. The mass of the weighed samples was marked M_1.

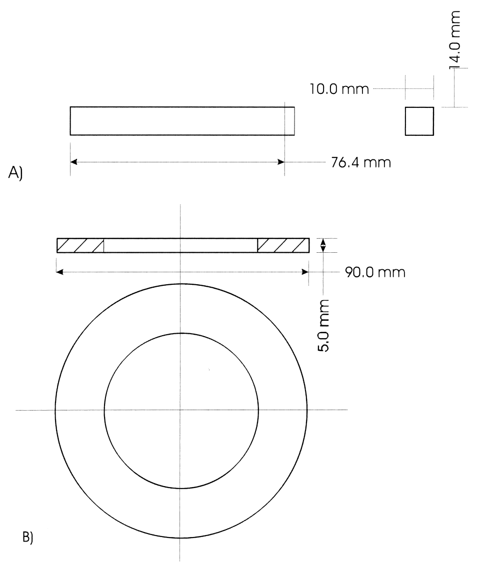

Figure 2: Drawing and dimensions of samples for testing of a) microstructure and hardness, and b) wear resistance
Slika 2: Načrt in dimenzije vzorcev: a) za preiskavo mikrostrukture in trdote, b) za določitev obrabne odpornosti

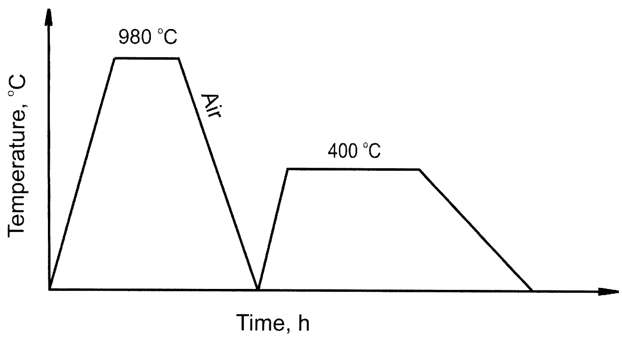

Figure 3: Schematic presentation of the heat-treatment procedure of vanadium-alloyed white cast irons
Slika 3: Shema toplotne obdelave vanadijeve bele litine

The testing of the wear resistance was performed by a comparative method on a "Taber Abraser" model 503. Specified grinding drums, designated H-10, which were 50 mm in diameter and 10mm high, were used. Two abrasion drums were mounted on the device and loaded with a 1 kg mass, while the specimen was fixed to the horizontal plate, which rotated at a velocity of 60 turns per minute. All the specimens were examined under identical conditions with a programmed number of 2000 revolutions. A high-manganese heat-treated austenitic steel sample served as a comparative sample. The amount of wear for this sample, designated as ΔM_0, was 0.540 g.

After the wear examination the sample was weighed again and the mass obtained was designated M_2. From the difference in the sample mass before and after wear, ($M_1 - M_2$), the wear value of the sample was determined, ΔM. The wear-resistance coefficient, ε, was calculated as:

$$\varepsilon = \frac{\Delta M_0}{\Delta M}$$

3 RESULTS AND DISCUSSION

The relationship between the vanadium content in the quasi four-component, white cast iron and the relevant iron properties was determined by an examination of the chemical composition of the iron samples, inspection of their microstructures in the as-cast and heat-treated conditions, and by an assessment of the hardness, wear resistance and impact energy of the heats. **Table 2** shows the chemical compositions of the vanadium-alloyed white cast-iron heats.

Table 2: Chemical composition of vanadium-alloyed, white cast-iron heats and comparative high-manganese steel sample
Tabela 2: Kemična sestava belih litin, legiranih z vanadijem, in primerjalnega visokomanganskega jekla

Heat ID	Chemical composition, wt. %						
	C	Si	Mn	P	S	Cr	V
1	2.84	1.11	1.76	0.028	0.031	1.30	1.20
2	2.80	0.96	1.66	0.035	0.035	1.32	2.86
3	2.84	0.96	1.66	0.046	0.035	1.34	5.96
4	2.94	0.93	1.68	0.030	0.026	1.67	8.72
5	2.73	1.17	1.55	0.038	0.030	1.35	11.35
Comparative sample*	1.30	0.47	13.08	0.074	0.002	1.34	-

*High-manganese steel sample was heat treated – austenitizing at 1100°C followed quickly by water quenching.

*Visokomangansko jeklo je bilo austenitizirano pri 1100 °C in gašeno v vodi

The vanadium content varied from 1.2 to 11.35 wt. %. The carbon content was in the range between 2.73 and 2.94 wt. %, that of silicon between 0.93 and 1.17 wt. %, manganese between 1.55 and 1.76 wt. %, and the chromium content was between 1.30 and 1.67 wt. %. It is obvious that there was no significant deviation in the composition of the base cast iron and that the vanadium content was in the range where it could cause distinct variations in the microstructure and hardness as well as in the wear and impact resistance.

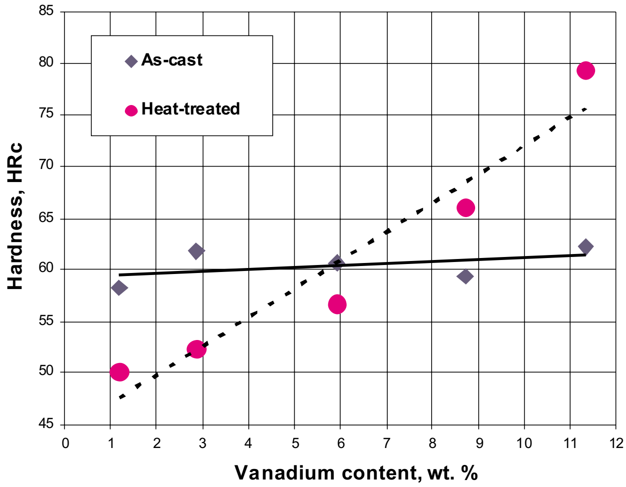

Figure 4: The effect of vanadium content on the hardness properties of white cast-iron samples in the as-cast and heat-treated conditions
Slika 4: Vpliv vsebnosti vanadija na trdoto lite in toplotno obdelane bele litine

The effect of vanadium content on the hardness of the white cast-iron samples in the as-cast and heat-treated conditions is illustrated in **Figure 4**.

Figure 4 demonstrates that the increase in vanadium content did not influence the hardness values in the as-cast samples of white cast iron during the tested interval. This could be attributed to the pearlite microstructure of the matrix in the as-cast condition. A different behaviour was noted for the heat-treated samples, where an increase in the vanadium content was accompanied by a significant rise in the hardness values. Such behavior could be accounted for by the structural changes that had taken place in the matrix.

It was established, by metallographic examination, that the microstructure of the as-cast, white cast-iron sample, alloyed with 1.2 wt. % vanadium, consisted of primary austenitic dendrites and had a ledeburitic eutectic structure. The austenitic dendrites completely transformed to pearlitic dendrites during cooling. **Figure 5** shows a typical, white cast-iron microstructure with massive, continuous mixed $(Cr,Fe)_3C$ or M_3C carbides and a pearlite matrix. The relatively high hardness of this structure is the result of the massive carbide network.

The increase in the vanadium content in the white cast iron to 5.94 wt. % resulted in the precipitation of primary vanadium carbide (VC) during the solidification of the alloy. Thus, a significant amount of carbon was combined in primary carbides and the rest of the carbon precipitated as mixed M_3C carbides. Changes in the morphology of the precipitated carbides and in the matrix structure can be seen in **Figure 6**.

The metallographic analysis of the as-cast micro-structure, heat no. 3, reveals that a vanadium increase

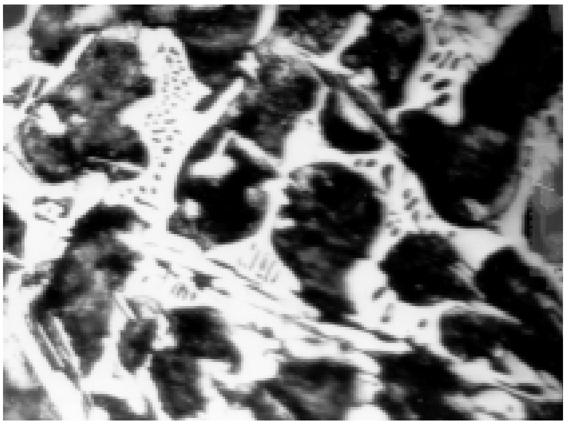

Figure 5: Microstructure of a white cast-iron sample, heat no. 1 with 1.2 wt. % vanadium, in as-cast condition, nital etched, 500×

Slika 5: Mikrostruktura vzorca litine, talina 1 z 1,2 % vanadija, lito, jedkano z nitalom, 500-krat

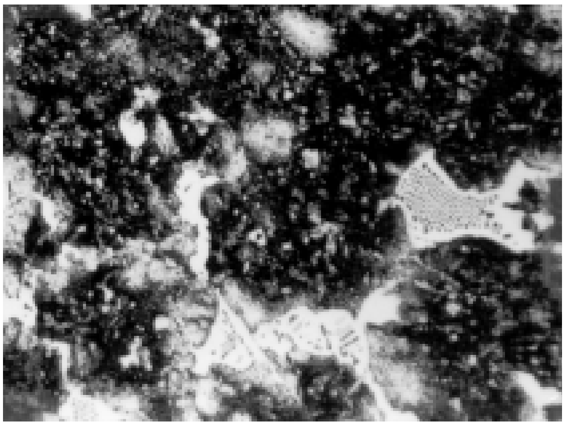

Figure 6: Microstructure of a white cast-iron sample, heat no. 3 with 5.94 wt. % vanadium, in as-cast condition, nital etched, 500×

Slika 6: Mikrostruktura vzorca litine, talina 3 z 5,94 % % vanadija, lito, jedkano z nitalom, 500-krat

causes a breaking of the network of the ledeburitic carbides, which now appear in the structure as isolated, massive carbides with a honeycombed morphology (**Figure 6**). The vanadium carbides come in more compact forms. The matrix structure is still predominantly pearlitic, but is not homogenous. The area around the carbides is carbon-depleted, which may cause this part of the matrix to transform to martensite during slow cooling in the mould.

As shown in **Figure 7**, in vanadium-alloyed, white cast-iron samples with around 9 wt. % vanadium, typical vanadium carbides in the form of a cloverleaf were precipitated.

Figures 7 and 8 show total breaking of the ledeburitic network structure. There are no more honeycombed carbides in the microstructures. The primary vanadium carbides with a dendrite morphology, which in the two-dimensional section of the metallographic picture have a cloverleaf form, can be seen. The eutectic type of vanadium carbides can also be seen. Typically, the eutectic cells are in the form of rosettes, spreading star-like from the nucleation centre. The as-cast structure is fine, with needle-type carbides along the edges of the eutectic cells.

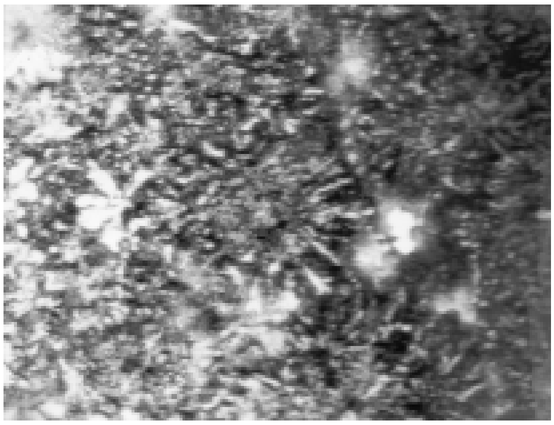

Figure 7: Microstructure of a white cast-iron sample, heat no. 4 with 8.72 wt. % vanadium, in as-cast condition, nital etched, 500×

Slika 7: Mikrostruktura vzorca litine, talina 4 z 8,72 % vanadija, lito, jedkano z nitalom, 500-krat

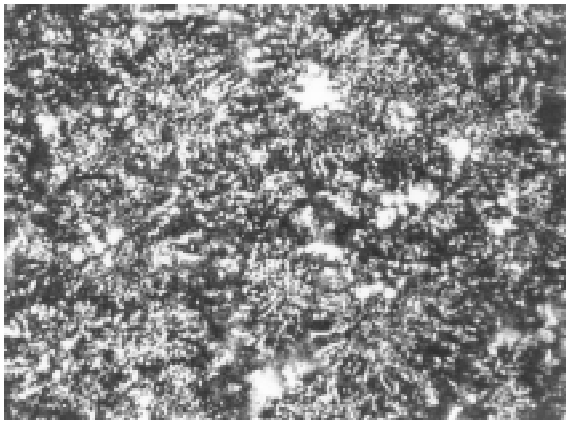

Figure 8: Microstructure of a white cast-iron sample, heat no. 5 with 11.32 wt. % vanadium, in as-cast condition, nital etched, 500×

Slika 8: Mikrostruktura vzorca litine, talina 5 z 11,32 % vanadija, lito, jedkano z nitalom, 500-krat

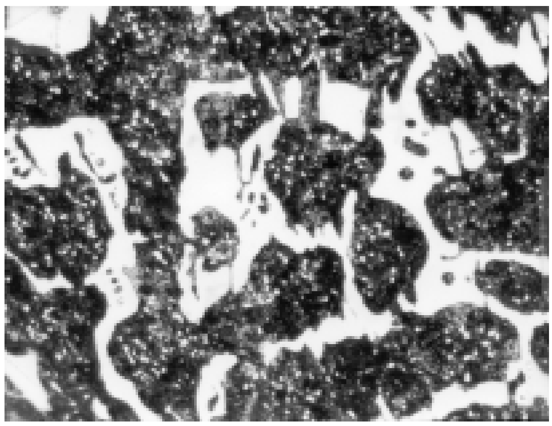

Figure 9: Microstructure of a white cast- iron sample, heat no. 1 with 1.2 wt. % vanadium, in heat-treated condition, nital etched, 500×

Slika 9: Mikrostruktura vzorca litine, talina 1 z 1,2 % vanadija, toplotno obdelano, jedkano z nitalom, 500-krat

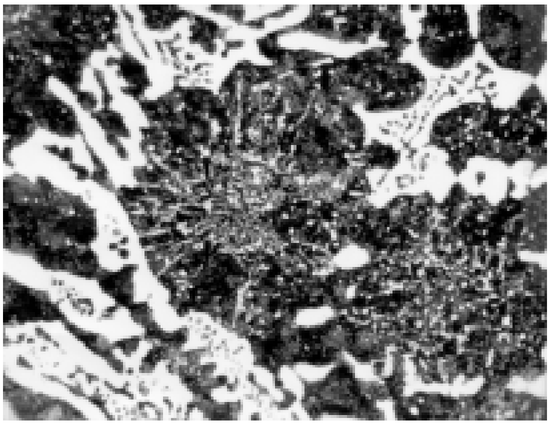

Figure 10: Microstructure of a white cast-iron sample, heat no. 2 with 2.86 wt. % vanadium, in heat-treated condition, nital etched, 500×
Slika 10: Mikrostruktura vzorca litine, talina 2 z 2,86 % vanadija, toplotno obdelano, jedkano z nitalom, 500-krat

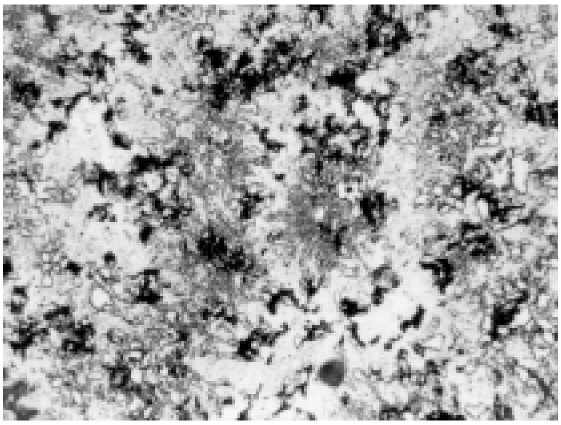

Figure 11: Microstructure of a white cast-iron sample, heat no. 4 with 8.72 wt. % vanadium, in heat-treated condition, nital etched, 500×
Slika 11: Mikrostruktura vzorca litine, talina 4 z 8,72 % vanadija, toplotno obdelano, jedkano z nitalom, 500-krat

The heat treatment of the vanadium-alloyed, white cast irons was performed with a view to obtaining a martensite matrix. Thus, owing to a combination of hard uniformly distributed carbides and a hard, homogenous matrix, a high hardness of the samples was achieved. Apparently, the form and percentage of primary and eutectic carbides after the heat treatment did not change much in relation to those in the as-cast state (**Figure 9**). In the metal matrix, however, fine, uniformly distributed, secondary carbides were observed (**Figures 9 and 10**).

From **Figures 9 and 10** it can be seen that in heat-treated, low-vanadium-alloyed, white cast iron the presence of the ledeburitic carbides network in the microstructures is still high. Inside the network of carbides a eutectic rosette-like-shaped colony is visible, consisting of needle-like vanadium carbides and of products of austenite decomposition (**Figure 10**).

In addition to affecting the proportion and morphology of the carbides in the microstructure, the increased vanadium content also produced an effect on

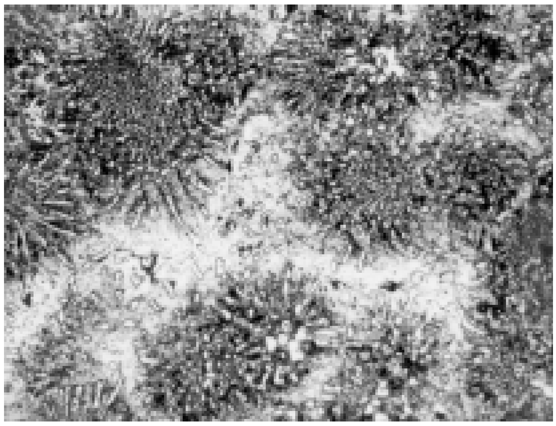

Figure 12: Microstructure of a white cast-iron sample, heat no. 5 with 11.32 wt. % vanadium, in heat-treated condition, nital etched, 500×
Slika 12: Mikrostruktura vzorca litine, talina 5 z 11,32 % vanadija, toplotno obdelano, jedkano z nitalom, 500-krat

the hardenability of the alloy. After heat treatment of samples, heats 4 and 5, it is obvious that the vanadium increase was accompanied by a diminished pearlite share in the matrix (**Figures 11 and 12**).

Figures 11 and 12 show characteristic eutectic colonies. Along the edges of these colonies there is a small portion of pearlite (dark areas) in an otherwise martensitic matrix. The increase in the vanadium content in the heat-treated, white cast-iron samples changed the morphology of the eutectic carbides and decreased the pearlite content in the matrix, having as a consequence a proportional increase in the hardness. It can be supposed that this change in microstructure and the elevated hardness will have a bearing on the wear and impact resistance of the examined alloys. The effect of vanadium content on the impact resistance of the as-cast and heat-treated white cast-iron samples is presented in **Figure 13**.

Wear was examined by a comparative method; a sample of quenched, high-manganese-alloyed austenitic steel was used for the calibration. All samples were tested under identical conditions. The results of the wear testing are shown in **Table 3**.

Table 3: Results of abrasion wear testing of vanadium-alloyed, white cast-iron samples
Tabela 3: Rezultati preizkusa obrabne odpornosti z vanadijem legiranih belih litin

Heat ID no.	Vanadium content in alloy, %	Mass of sample, M1, g	Mass of sample after wear, M2, g	Mass sample difference, ΔM, g	Wear resistance coefficient*, ε
1	1.20	162.9040	162.3670	0.5370	0.1005
2	2.86	153.1226	152.4817	0.6409	0.0842
3	5.94	124.4424	124.2820	0.1604	0.3366
4	8.72	128.0050	127.9150	0.0900	0.6000
5	11.35	123.2418	123.1618	0.0737	0.7327

*ΔM_0 = 0.54 g.

The relationship between the wear resistance coefficient, ε, and the vanadium content in the heat-

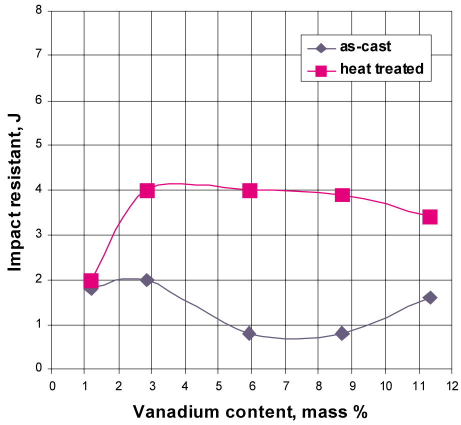

Figure 13: The effect of vanadium content on the impact resistance of as-cast and heat-treated white cast-iron samples, tested without notch
Slika 13: Vpliv vsebnosti vanadija na žilavost litih in toplotno obdelanih litin; preizkušanci brez zareze

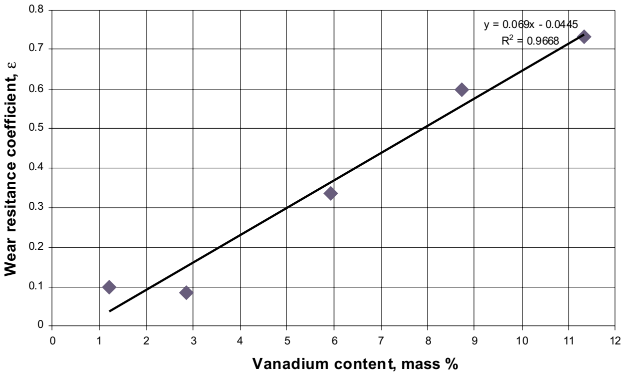

Figure 14: The effect of vanadium content in vanadium-alloyed, white cast-iron samples on the abrasion wear-resistance coefficient
Slika 14: Vpliv vsebnosti vanadija na koeficient obrabne odpornosti litin

treated, white cast-iron samples is presented in a graph (**Figure 14**).

From the relationship between the abrasion wear resistance and the vanadium content in vanadium-alloyed, white cast-iron samples it is obvious that the wear resistance increased linearly with the increase in the vanadium concentration in the alloy. This increase in wear resistance was conditioned by the effect of vanadium on the microstructure of heat-treated samples, and thereby on the hardness of examined alloys.

4 CONCLUSION

An examination of the effect of increased vanadium content on the microstructure, hardness, and on the wear and impact resistance of white cast irons, showed the following:

- Vanadium additions to a multicomponent alloy, Fe-C-Cr-V, in the range from 1 to 11 wt. % vanadium caused significant changes in the microstructures of the as-cast and heat-treated samples.
- The morphology of primary and eutectic carbides changed with vanadium addition from a continuous network of honeycombed ledeburitic eutectics to rosette-shaped eutectic colonies with rod- and needle-like carbides on the edges and characteristic primary carbides in the form of a cloverleaf.
- In the as-cast condition the carbides were submerged into a relatively soft pearlitic matrix. That is why the hardness values of the tested white cast-iron samples did not differ too much.
- The implemented heat treatment did not change the form or distribution of the primary and eutectic carbides to any great extent. However, it produced an effect on the matrix by increasing the amount of fine, randomly distributed, secondary precipitated carbides and thereby caused a change in the concentration of the carbon and the alloying element in the matrix as well as in the kinetics of the austenite decomposition. Consequently, a decrease in the pearlite content and an increase in the martensite content of the matrix microstructure occurred.
- The mentioned changes in the microstructural features, induced by an increased vanadium content in the alloys and by the heat treatment, led to a proportional increase in the hardness of the examined white cast-iron samples.
- An increase in the vanadium concentration in the white cast-iron samples brought about changes in the morphology of the eutectic solidification but did not affect the impact resistance values very much. The impact resistance increased to some extent owing to the heat-treatment process.
- The wear resistance of the heat-treated alloyed white cast-iron samples was proportional to the increase in vanadium concentration in the alloys, in accordance with the effect of this element on the microstructure and hardness.

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