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The influence of the vanadium content on the toughness and hardness of high-alloyed Cr-Mo steel

ABSTRACT

Characteristics of air hardening steel are high hardness and low impact toughness. In order to increase the impact toughness while retaining replace with the high hardness value numerous research added. One of the ways to achieve this is the alloying of specified steel with vanadium and application of appropriate heat treatment. Vanadium affects the solidification process of these alloys by narrowing of the temperature interval of crystallization. In addition, vanadium formed V_6C_5 carbides that block the growth of austenitic dendrites and structure makes fine-grained. Vanadium which forms V_6C_5 carbides is partly distributed between present phases in the steel, carbide $(Cr,Fe)_7C_3$ and austenite. Also, the presence of vanadium can enable the formation of $(Cr,Fe)_{23}C_6$ carbide and its precipitation in austenite during the cooling process. In local areas around fine carbide particles, austenite is transformed into martensite. In other words vanadium reduces the amount of remained austenite and so improves hardenability of the steel. In this way, better technical characteristics of these steels are obtained.

Key words: vanadium, impact toughness, hardness, microstructure.

1. INTRODUCTION

Testing of the characteristics of high alloyed Cr-Mo steel was carried out by changing of vanadium content from 0.5 to 3%. According to the chemical composition and carbon content, this alloy belongs to the alloyed cast iron, but according to ENISO10020 added it falls into alloyed steel castings.

The as cast microstructure of this steel consists of primary austenite dendrites, which can be partially or completely transformed. It is expected that with the increasing of the vanadium content, the alloy hardness and wear resistance decreases, and the impact toughness increases.

The basic problem with these steels is low impact toughness. Until very recently, the solution to increase the impact toughness was sought in getting of the complete martensite structure, that can

be achieved by quenching of steel from the temperature of about 1000° C.

In recent years, the research goes in the direction of investigation of the influence of alloying elements such as molybdenum, manganese and particularly vanadium [1- 4].

Vanadium affects the crystallization process, as it moves the liquid and solid lines toward higher temperatures.

In this paper, the research focus is set to study the influence of vanadium on the structure, hardness and toughness of the specified steel.

2. THE INFLUENCE OF CHEMICAL COMPOSITION ON STRUCTURE AND PROPERTIES OF CR-MO STEEL

In order to investigate the influence of chemical composition on the structure and properties of steel added it is necessary to define the influence of certain elements on the properties of steel.

Effect of Chromium

Chromium is the basic alloying element in steels with higher hardness and wear resistance, because its addition establishes several metallurgical functions.

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Chromium reacts with carbon to form hard wear resistant carbides, prevents the transformation of austenite to perlite during cooling of castings and affects the structure of the steel metal matrix by closing of γ area in the phase diagram [5-7].

Carbides Cr_7C_3 type and Cr_{23}C_6 can be alloy with iron to form the interstitial phases $(\text{Cr,Fe})_7\text{C}_3$ and $(\text{Cr,Fe})_{23}\text{C}_6$. Best toughness and hardness have the structures containing carbide $(\text{Cr,Fe})_7\text{C}_3$, which is formed in steel containing more than 6% of chromium. With the increase of chromium content eutectic point is shifted to lower concentrations of carbon. However, chromium does not increase hardenability but combined with higher carbon content increases the depth of the quenched layer.

Effect of Vanadium

The presence of vanadium, even in small concentrations, has a positive effect on high alloyed Cr-Mo steels.

Vanadium affects the solidification process of these alloys by narrowing of the temperature interval of crystallization. Namely, the crystals of V_6C_5 carbides are formed during the separation of primary austenite from the solution, blocking further growth of austenite dendrites and support the production of fine grained structures, [5].

Besides it forms added, V_6C_5 carbides, similar to the molybdenum, vanadium, is partly distributed between present phases in the steel; carbide $(\text{Cr,Fe})_7\text{C}_3$ and austenite. The presence of vanadium enables the formation of $(\text{Cr,Fe})_{23}\text{C}_6$ carbide and its precipitation in austenite during the cooling process. In local areas around fine carbide particles, austenite is transformed into martensite. In other words, vanadium reduces remained austenite and improves steel air-hardening. Vanadium concentration over 2.5% significantly improves the impact toughness. Because of the relatively high ferro-vanadium price, it is added only when a particular quality castings is required.

Effect of microstructure on the steel properties

The microstructure determines the two most important characteristics of the wear-resistant material, hardness and toughness. Customizing content and arrangement of the phases and micro-constituents, present in the structure of steel, is possible to obtain the maximum value of hardness and toughness, or the optimal combination of these characteristics [3]. To clarify the influence of microstructure on the properties of steel, we will consider the basic constituents: carbides and metal matrix.

In terms of structure, this type of steel belongs to the ledeburitic steels. Because of dendritic segregation, crystallization of the ledeburitic steel starts with the separation of primary austenite crystals that containing less carbon, chromium and molybdenum than in the melt. Ledeburite is distributed as a network around the primary austenite crystals. After the solidification of ledeburite, shape, size and distribution of the proeutectic carbide cannot be changed by heat treatment, and solidification process is of essential importance for the steel properties.

At high-alloyed ledeburite, austenitic phase has a higher growth rate, so that the austenite formed a wrapper around carbide fibers and this structure result in higher chromium steel strength and toughness, compared to unalloyed or low alloyed ledeburitic micro-constituent.

Precipitation of secondary carbides, mostly $(\text{Cr, Fe})_{23}\text{C}_6$, from austenite grains takes place during slow cooling or subsequent annealing [6]. At the very beginning, the precipitate is very fine and oriented along the border with eutectic $(\text{Cr, Fe})_7\text{C}_3$ carbide and around the austenite grains boundaries.

The process of precipitation of secondary carbides reduces the chromium and carbon content in the metal matrix so that a higher percentage of austenite will be transformed to martensite. Such a phenomenon of secondary carbides has dual positive effect as follows: hard, fine dispersed phase is formed and the amount of residual austenite is reduced [7].

The main problem in production of high alloy Cr-Mo steel castings is to keep high hardness and, at the same time, achieve good toughness. To achieve this it is necessary that the metal matrix be a cubic martensite or even better bainite, without or with only a very small amount of retained austenite.

3. DESCRIPTION OF THE EXPERIMENT

For melting of the steel, induction furnace added of 250 kg capacity, was used. The samples for the experiments were cast into the sand molds. Molds are made according to the patterns that have the shape and dimensions in accordance to the impact toughness and hardness test standards. Castings were heat treated by hardening in controlled air flow and subsequent tempering. The tempering was done at two temperatures as follows, [8]:

- low temperature tempering at 250°C, which removes micro-stresses, improves toughness and ductility of steel, compared to the hardened state, but keeps high strength and

toughness that is required of wear resistant castings and

- medium temperature tempering at 400°C, which, also removes micro-stresses, but leads to the formation of bainitic structure, and therefore increase the impact toughness of steel.

Predicted chemical composition of the steel for this type of test was: C=2,2%, Cr=12%, Mo=1.2%, while the vanadium changed as follows: for the first series 0,5%V, second 1% V, third 2% V and for the fourth series vanadium was 3%. The chemical composition of samples I, II, III and IV series are in the Table 1.

Table 1. Chemical composition of the samples

Tabela 1. Hemijski sastav uzoraka

Serial Number	Mark	Chemical Composition				
		C (%)	Cr (%)	Mo (%)	S (%)	V (%)
1	I	2,17	11,12	1,1	0,03	0,45
2	II	2,19	11,01	1,12	0,03	0,91
3	III	2,15	11,59	1,09	0,03	1,96
4	IV	2,11	11,52	1,01	0,03	2,80

Surface of the samples, immediately after casting and heat treatment, is very rough so it was necessary to clean up cast samples and machined it to the standard test dimensions. Mechanical processing should be done with permanent cooling in order to avoid any change in the microstructure.

For testing of the impact toughness samples added of 55 mm long and 10x10 mm cross section were prepared. Testing of impact toughness was performed using computerized pendulum *Schenck-Trebel 150/300J*. Pendulum computerization includes connecting of the force meter, detector of the fracture time and deformation gauge through the amplifier with an oscilloscope. As the fracture of the samples caused by impact is a very short phenomenon (since 0.5 to 8 ms), the role of the oscilloscope is to make the signal visible. Oscilloscope is then connected to a computer for processing signals obtained in the measurement.

For the purposes of hardness testing the samples of similar size as the impact toughness tests are made. Because of the relatively high hardness of the material, hardness testing was done by Rockwell C method on the *Vexus SHR-150M* device.

Analysis of the microstructure was performed under a light microscope *Olympus GX41* that was equipped with software for image processing and phase analysis and on SEM microscope *JEOL JSM-6610LV*. Preparation of samples was carried out using standard metallographic procedure.

4. RESULTS AND DISCUSSION

The testing results of steel with different contents of vanadium showed the expected results that are presented in the next tables.

4.1. Effect of vanadium on the hardness

Hardness testing was performed on six points of the sample so that the mean values for the relevant value was taken. Results of hardness testing are shown in Table 2.

Table 2 The values of hardness

Tabela 3. Vrednosti tvrdoće

Serial Number	Sample Mark	Hardness (HRC)	
		250°C	400°C
1	I	63,00	62,25
2	II	60,30	60,50
3	III	60,10	58,50
4	IV	58,90	57,20

From the table it can be seen that with increasing vanadium content in the alloy, hardness decreases, respectively, and more intensive when the samples were tempered at a temperature of 400°C. When the tempering temperature was 250°C decrease in hardness is less severe, as seen in Figure 1. However, hardness remained at a relatively high level and the decrease of hardness is acceptable.

This reduction in hardness undoubtedly entails increasing of impact toughness.

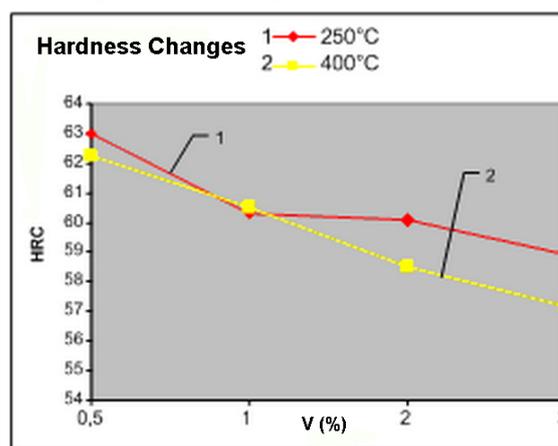


Figure 1. Diagram of hardness changes
Slika 1. Dijagram promene tvrdoće

4.2. Effect of vanadium on the impact toughness

Impact toughness testing was performed on three samples from each series. The mean value of toughness measurements was taken as authoritative. Table 3 presents the results of impact toughness.

Table 3. The values of impact toughness

Tabela 3. Vrednosti za udarnu žilavost

Serial Number	Sample Mark	Toughness (J/cm ²)	
		250°C	400°C
1	I	2,37	5,45
2	II	4,50	5,55
3	III	6,45	6,96
4	IV	7,15	8,71

From the table it can be seen that with increasing of vanadium content increases the impact toughness values, especially at the samples from the fourth series (mark IV) containing 3% V.

Increasing of impact toughness is more noticeable for the samples tempered at temperature of 400°C than for samples tempered at 250°C (Fig. 2). Increasing of impact toughness is significant, while the hardness remained on satisfactory high level.

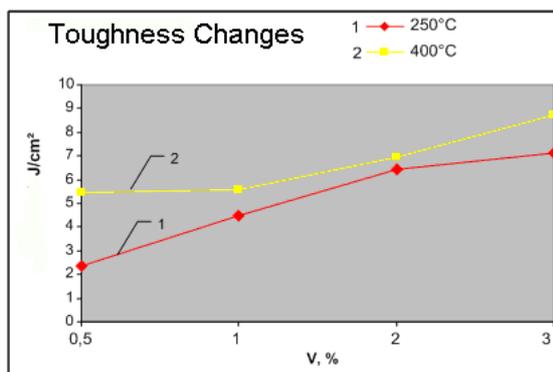


Figure 2 Diagram of toughness changes

Slika 2. Dijagram promene rastegljivosti

4.3. Effect of vanadium on the structure

With increasing of vanadium content, the radial distribution of (Cr,Fe)₇C₃ carbides becomes a dominant but the proportion of long directed lamellas and plates do not change.

Vanadium is soluble in both, eutectic carbide and austenite. In alloys containing 2-3% of vanadium, austenite, is largely transformed to bainite during cooling. In the structure also present added in a small amount of martensite, mainly along the border with eutectic carbide.

Figure 3 shows the structure of the sample made under a light microscope, while Figure 4 shows micrographs of the structures made on SEM. In order to determine the chemical composition of the present phases, the EDS analysis was performed.

From the SEM micrographs it is evident that the metal matrix of the alloy is immersed with fine carbides of alloying elements. A carbide network

has a rounded shape with a small amount of carbide rods. Locations where an EDS analysis was done are marked with the counts 1 to 4. Count 1 is a point on the carbide grains dispersed in metal matrix, while points since 2 to 4 refer to the points in carbide network.

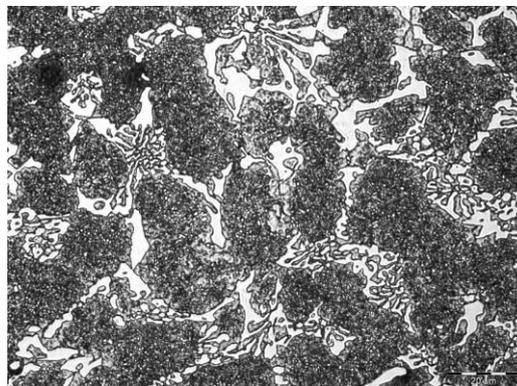


Figure 3. The Structure of the sample made by light microscopy

Slika 3. Mikroskopska struktura uzorka

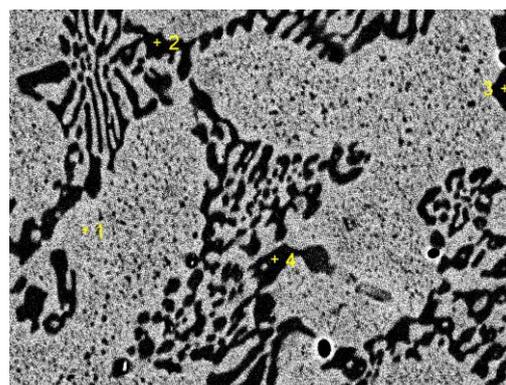


Figure 4. SEM micrograph of the sample

Slika 4. SEM mikrografija uzorka

The analysis in count 1 added which relates to the carbides of metal matrix, shows that the carbides contain 24% of carbon, 10% of chromium, 81% of iron, 0.21% of vanadium and a small amount of manganese that could not be precisely determined. However, carbon content is close to his stoichiometric content in Fe₃C carbide, indicating the possibility that the carbides type M₃C are formed in the metal matrix. EDS analysis shows that in the crystal lattice of this carbide a small number of iron atoms are replaced by atoms of chromium and manganese. Manganese builds Mn₃C carbide that is similar to Fe₃C. It has orthorhombic lattice and is most likely that the carbide (Fe,Mn)₃C is precipitated in a steel metal matrix.

Counts 2, 3 and 4 refer to the eutectic carbide network and EDS analysis shows that these are the M₇C₃ type carbides.

Table 4 presents the chemical composition of the tested phases in weight percentages, while

Table 5 shows the chemical composition of the tested phases in atomic percentages.

On the figure 5 and 6 the chemical spectar done by EDS analysis was shown.

Table 4. Chemical composition of the tested samples in weight percentages

Tabela 4. Hemijski sastav ispitivanih uzoraka u težinskim procentima

Samples	Elements Content (weight %)							Total
	C	Si	V	Cr	Fe	Ni	Mo	
Count 1	7,24	0,63	0,21	9,99	81,04	0,00	0,87	100,00
Count 2	13,07	0,00	2,42	42,50	40,69	0,00	1,33	100,00
Count 3	12,21	0,00	2,23	42,43	41,00	0,00	2,12	100,00
Count 4	13,25	0,00	2,47	42,16	40,07	0,00	2,06	100,00

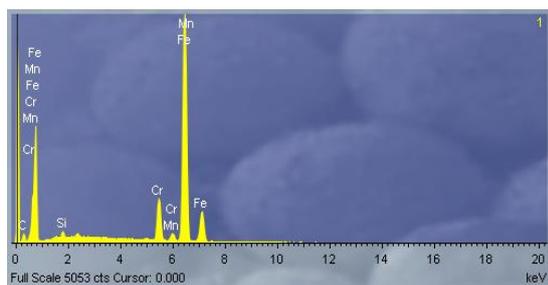


Figure 5. EDS spectrum at point 1

Slika 5. EDS spektar u tački 1

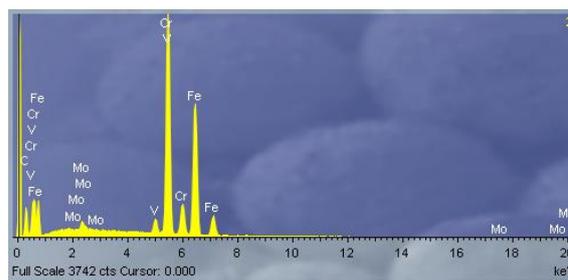


Figure 6. EDS spectrum at point 2

Slika 6. EDS spektar u tački 2

Table 5. Chemical composition of the tested samples in atomic percentages

Tabela 5. Hemijski sastav ispitivanih uzoraka u atomskim procentima

Series of samples	Elements Content (atomic %)						
	C	Si	V	Cr	Fe	Ni	Mo
Count 1	22,72	1,21	0,22	7,94	67,46	0,00	0,44
Count 2	40,94	0,00	1,72	29,90	26,79	0,00	0,66
Count 3	42,77	0,00	1,67	29,38	25,49	0,00	0,69
Count 4	42,40	0,00	1,63	29,77	25,44	0,00	0,77

Based on the SEM micrograph, EDS analysis in figure 5 and 6 and data that are given in Tables 4 and 5, added it can be concluded that the structure consists of bainitic metal matrix with a small amount of martensite and retained austenite and carbide phase, type $(Cr,Fe)_7C_3$.

5. POTENTIAL OF APPLICATION

This type of steel, because of its high hardness and satisfactory impact toughness, and therefore high wear resistance, can have a wide application area.

Parts and components that are exposed to abrasive, impact-fatigue or combined wear are used in mining, metallurgy, engineering constructions, paper industry, mechanical engineering, etc. Assortment of these parts are: parts of mining machinery (excavator teeth and tooth covers, crusher plates for stone coal and ore minerals, mills hammers, plates and linings, separation grates, etc.). In addition, this material can be used for

making bunkers lining for abrasive materials, sand blasting shovels, mud pumps housing, molds for briquetting of coal and steel turnings, tanks and transporters caterpillars, and many other parts. Mills hammers and jaw crushers plates are exposed to abrasive wear combined with the high compressive stress and impulse impact loads. Therefore, the materials used to manufacture these parts should, in addition to hardness, have a good impact toughness.

6. CONCLUSION

In this paper, the influence of vanadium to the microstructure, hardness and toughness of the steel with 2.2% of carbon, 12% of chromium and 2.0% of molybdenum was discussed. Generally, with increasing vanadium content, the structure becomes finer affecting the mechanical properties of the steel i.e. the hardness and impact toughness. Vanadium content in the steel added was varied: as first series added is 0,5%V, for the second series is 1%V, for the third series is 2%V

and for the fourth series is 3%. A total of 20 samples were casted. The chemical compositions the samples of I, II, III and IV are showed in Table 1.

Vanadium content higher than 3% have a negative influence on the properties of steel (significant decrease in hardness) and therefore the research with a higher percentage of vanadium were not included.

It can be seen that an increase of vanadium has a positive effect on the structure and the properties of materials. Testing samples of Series I showed high hardness while the impact toughness is extremely small. Samples of the Series II showed a slight reduction in hardness while the impact toughness is greater than the toughness of Series I. Hardness of the samples of Series III follows this trend and is slightly lower than the Series I and II, while the impact toughness slightly increased compared to Series I, and for Series II. Series IV showed the best properties. Hardness is reduced compared to Series III but is still satisfactory, while the increasing added the impact strength is significant.

It is well known that these materials have extremely high hardness but their impact toughness is very small, so their use is limited. From this research added can be concluded that the composition of the steel with 3% of vanadium have impact strength which is, for this type of material added is extremely high, while the hardness decreased slightly but remained at an acceptable level. These mechanical properties enable new applications of steel with chemical composition corresponding to Series IV.

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IZVOD

UTICAJ SADRŽAJA VANADIJUMA NA ŽILAVOST I TVRDOĆU VISOKO LEGIRANIH Cr-Mo ČELIKA

Karakteristike kaljenih čelika na vazduhu su visoka tvrdoća i mala udarna žilavost. U pokušaju da se poveća udarna žilavost uz zadržavanje visoke tvrdoće brojna istraživanja su izvršena. Jedan od načina da se postigne ovaj cilj je legiranje specifičnih čelika sa vanadijumom i primena odgovarajuće toplotne obrade. Vanadijum utiče na proces očvršćavanja ovih legiranih čelika u uskom temperaturnom intervalu kristalizacije. Dodavanjem vanadijuma nastaju V_6C_5 karbidi koji sprečavaju rast austenitnih dendrita i strukturu čine sitnozrnastom. Vanadijum koji formira V_6C_5 karbide je delimično raspodeljen između prisutnih faza u čeliku, karbidne $(Cr,Fe)_7C_3$ i austenitne. Takođe, prisustvo vanadijuma može omogućiti formiranje $(Cr,Fe)_{23}C_6$ karbida i njegovo taloženje u austenite tokom procesa hlađenja. U području oko čestica finih karbida, austenite se transformišu u martenzit. Drugačije rečeno vanadijum redukuje količinu zaostalog austenite i na taj način unapređuje sposobnost čelika za kaljenje. Ovim postupkom dobijaju se povoljnije karakteristike ovih čelika.

Ključne reči: vanadijum, udarna žilavost, tvrdoća, mikrostruktura

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