THE EFFECT OF VANADIUM CONTENT ON MICROSTRUCTURE AND IMPACT TOUGHNESS OF FORGED HIGH ALLOY STEEL X96CrMo12-1

Vukoje Vukojević, Srdjan Jović, and Blagoje Nedeljković
Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, Kosovska Mitrovica, Serbia

Aleksandar Sedmak
Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

Ivo Blačić
Military Technical Institute Belgrade, Belgrade, Serbia

https://doi.org/10.1007/s40962-018-0225-4

Abstract

The aim of this research was to examine the influence of vanadium on the structure and impact toughness of the forged high alloy steel X96CrMo12-1. It is known that vanadium affects the process of solidification of this alloy by narrowing the temperature interval of crystallization. Vanadium, as an alloying element, moves liquids and solidus lines toward higher temperatures, approximately for 25–30 °C. In addition, vanadium forms V_6C_5 *carbides, which are partly distributed between the present phases in the steel, carbide* $(Cr,Fe)_7C_3$ *and austenite. The presence of vanadium enables the formation of* $(Cr,Fe)_{23}C_6$ *carbide and its precipitation into austenite during the cooling process. In local areas around fine carbide particles, austenite is transformed into martensite, i.e., vanadium reduces remained austenite and improves quenching process. Studies have shown that as the content of vanadium increases up to 5%, the impact toughness of this steel is significantly increased. The steel X96CrMo12-1 contains remarkably less carbon than high alloyed Cr–Mo ledeburite steels and does not contain a eutectic microconstituent in the structure. So it can be treated by forging process thus provide a more compact and tougher structure. The basic problem in the application of high alloyed Cr–Mo steels is to increase their impact toughness, while sustain a relatively high value of hardness. Studies have shown that vanadium strongly increases toughness while retaining high hardness, which is a requirement for wear-resistant steels.*

Keywords: *vanadium, impact toughness, hardness, microstructure*

Introduction

High alloy steel X96CrMo12-1 belongs to the group of Cold Work steels which makes them useable in a wide range of application. The basic characteristic of this steel is high hardness and high strength but relatively small impact toughness. Research carried out on this steel was aimed to investigate the effect of vanadium on its microstructure and impact toughness. Research has aimed to improve some characteristics of this steel, primarily the impact toughness and wear resistance. The main goal of this study was to obtain appropriate structure of the metallic matrix and carbides that would allow the significant increase in impact toughness and retain a high hardness of the steel.

The Influence of Vanadium

By adding vanadium to the high alloy chromium steels, microstructure becomes finer. Structure refining is explained by the influence of vanadium on the crystallization process. The presence of vanadium, even in small percentage, affects the process of solidification of these alloys by narrowing of the temperature interval of

Table 1. Chemical Composition of the Samples

Series	Chemical composition					
	C (%)	Cr (%)	Mo (%)	P (%)	S (%)	V (%)
1	1.052	12.154	0.980	0.0125	0.0065	0.915
2	1.077	11.539	0.967	0.0126	0.0068	1.967
3	1.071	11.790	0.975	0.0122	0.0087	2.979
4	1.005	12.083	0.992	0.0120	0.0089	3.931
5	0.992	11.925	0.981	0.0119	0.0102	4.994

Table 2. The Influence of Vanadium on the Impact Toughness and Hardness

Series	Impact toughness (J/cm^2)	Impact energy (J)	Hardness (HRC)
1	2.80	2.24	60.20
2	4.21	3.37	58.60
3	8.90	4.40	56.80
4	11.62	5.81	54.20
5	13.91	6.96	51.80

crystallization. Besides that, during growth of primary austenite grain from the melt, V_6C_5 carbides are formed in the steel structure. They block further growth of the austenite dendrites and so help to obtain the fine grain microstructure.[1,2] In addition, austenite in local areas, around these fine carbide particles, transformed into martensite. In other words, vanadium reduces the amount of retained austenite and thus improves the hardenability of steel.[1,2]

In high chromium steels with the content of 12% Cr, 1.0–1.6% C and over 2.5% vanadium, the vanadium carbide, VC type, with a BCC lattice is formed.[3] VC carbides have the globular shape and are very often associated with $(Cr,Fe)_7C_3$ carbides. VC carbides can also appear in the form of rods, which grow radial from the nucleus, to form spherical cells together with the austenite grains. Higher content of vanadium enhances the formation of $(Cr,Fe)_{23}C_6$ carbides and their precipitation in the austenite grains, during the cooling process. Austenite, in local areas, around these fine carbide particles, transformed into martensite. This means that vanadium reduces the amount of retained austenite and thus improves the hardenability of steel.[4–6]

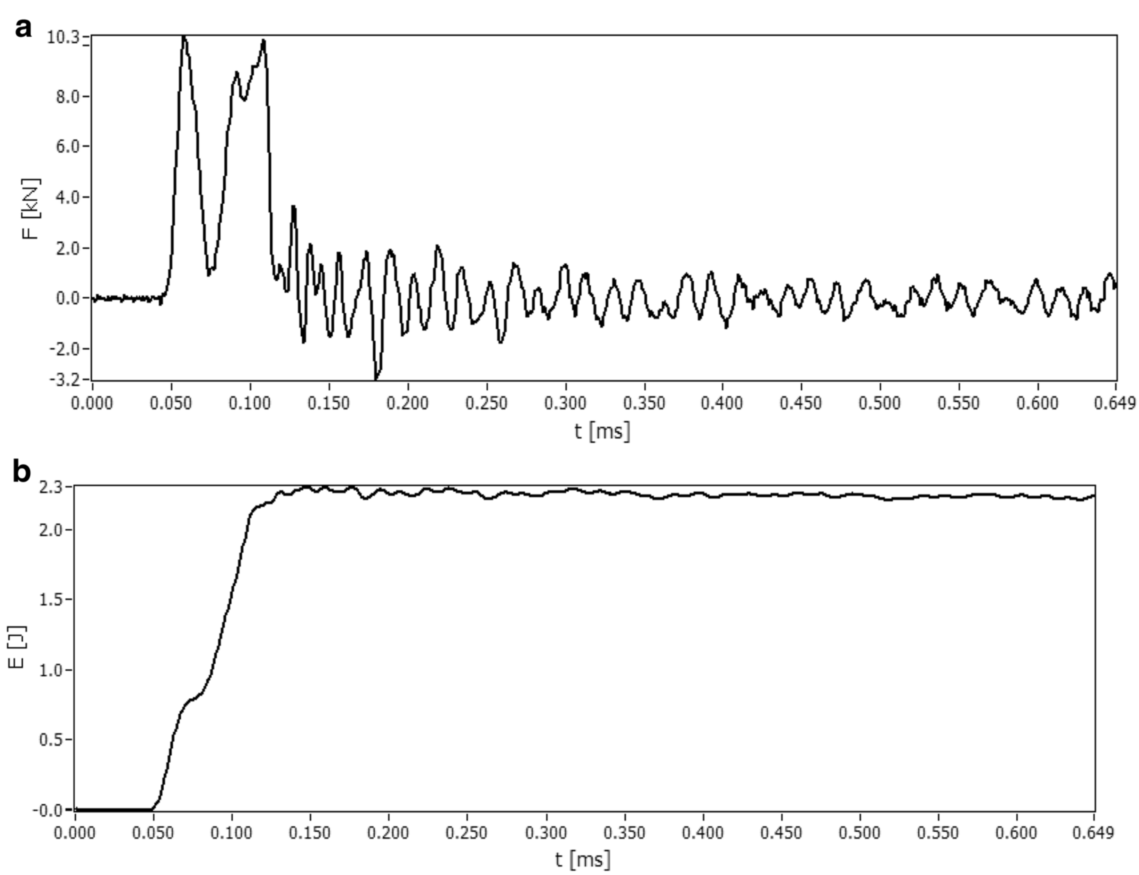

Figure 1. (a) Diagram force–time for sample series 1. (b) Diagram fracture energy–time for sample series 1.

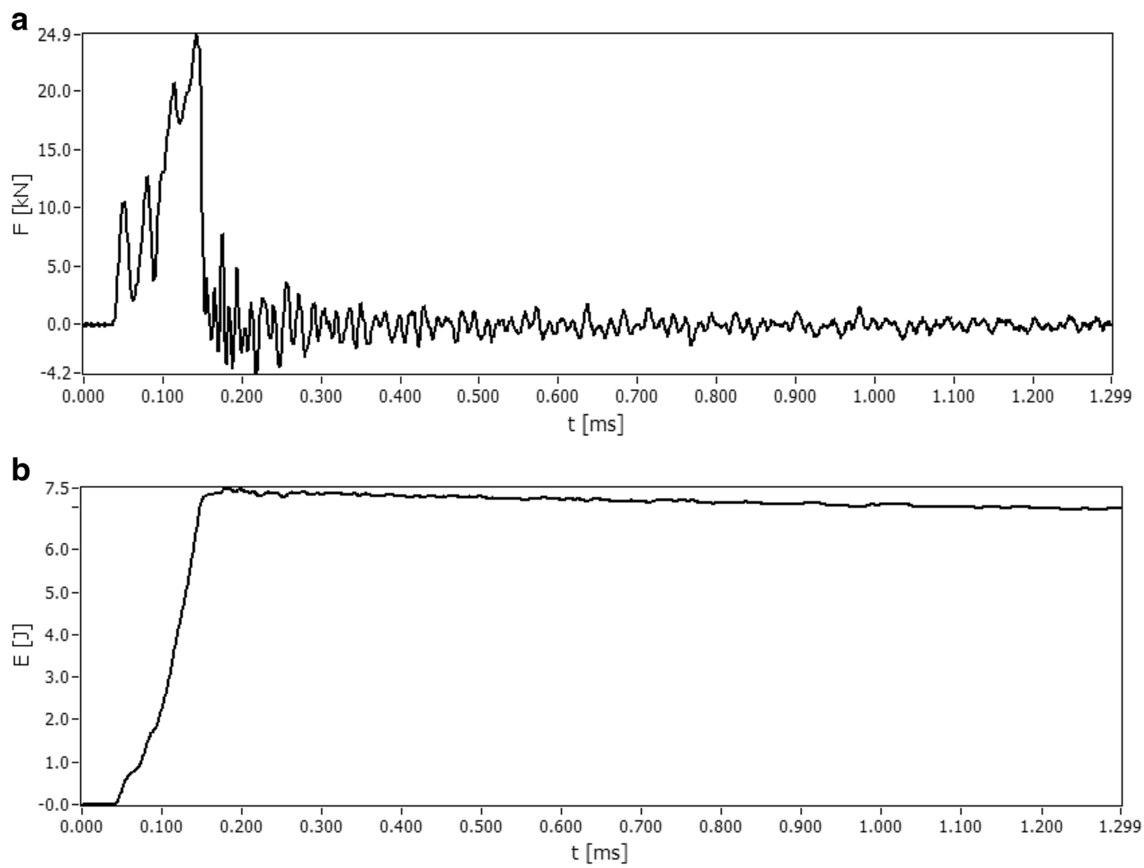

Figure 2. (a) Diagram of force–time for sample series 5. (b) Diagram of fracture energy–time for sample series 5.

Table 3. Hardness and Tensile Strength of the Samples

Content of vanadium (%)	1	2	3	4	5
Hardness (HRC)	61.2	58.6	56.8	55.1	54.2

Experimental Procedure

For the production of the cast samples, the medium frequency induction furnace 250 kg capacity was used. Pouring was done in sand molds. The sand molds were made using the wooden patterns with dimensions Ø30 × 200 mm and 30 × 30 × 200 mm. The pouring temperature was 1600 °C. NDT tests of cast samples were not carried out, but no visible casting defects were observed.

Samples were heat treated by hardening and subsequent tempering. The heating of the cast samples was carried out in an electric furnace, first up to 250 °C with a through heating of 30 min, then up to 450 °C with a through heating of 45 min, and then up to 750 °C. Then, the samples were transferred to an electric induction furnace and heated to a forging temperature of 1050 °C. They are forged with a pneumatic hammer, first light blows and then stronger. The forging was completed at 880 °C. The final dimensions of the samples after forging were 15 × 15 × 250 mm and Ø16 × 250 mm.

Samples were deposited in a warm electric furnace for slow cooling and then they were heat treated by normalization. The heat-treated samples were machined into standard test samples for toughness, hardness, tensile strength and other testings. Square cross-sectional samples were used for the production of a toughness test samples and a round for tensile strength and wear resistance test samples.

The machined samples were heated in a 1050 °C in vacuum furnace, quenched in oil heated to 80 °C and tempered at 250 °C. For all samples, from 1.0 to 5.0 mass% of vanadium, the same 1000 °C austenitization temperature was applied.

The medium chemical composition of used steel was: 1.0% C, C, 12.0% Cr, 1.0% Mo, while the vanadium content varied from 1.0 to 5.0%. A total of five series of samples were released. The accurate chemical compositions of the samples are shown in Table 1.

After forging and heat treatment the sample surface was very rough, so they are cleaned and machined to the standard dimensions. Machining was carried out with permanent cooling, to avoid any change of microstructure.

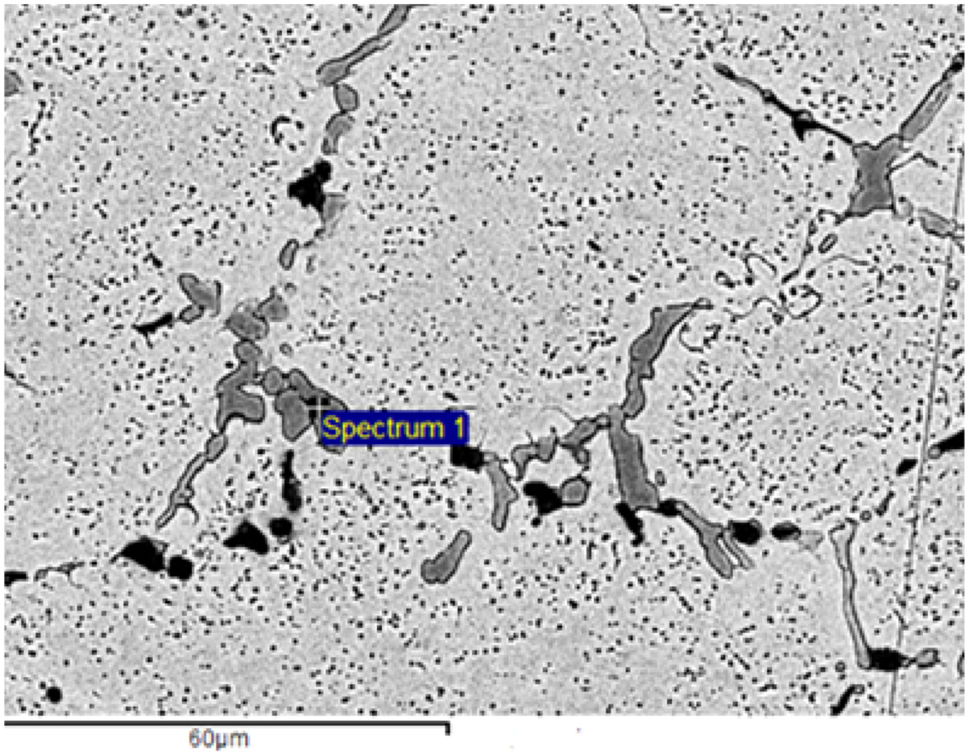

Figure 3. SEM microphotography of the sample with 1% of vanadium.

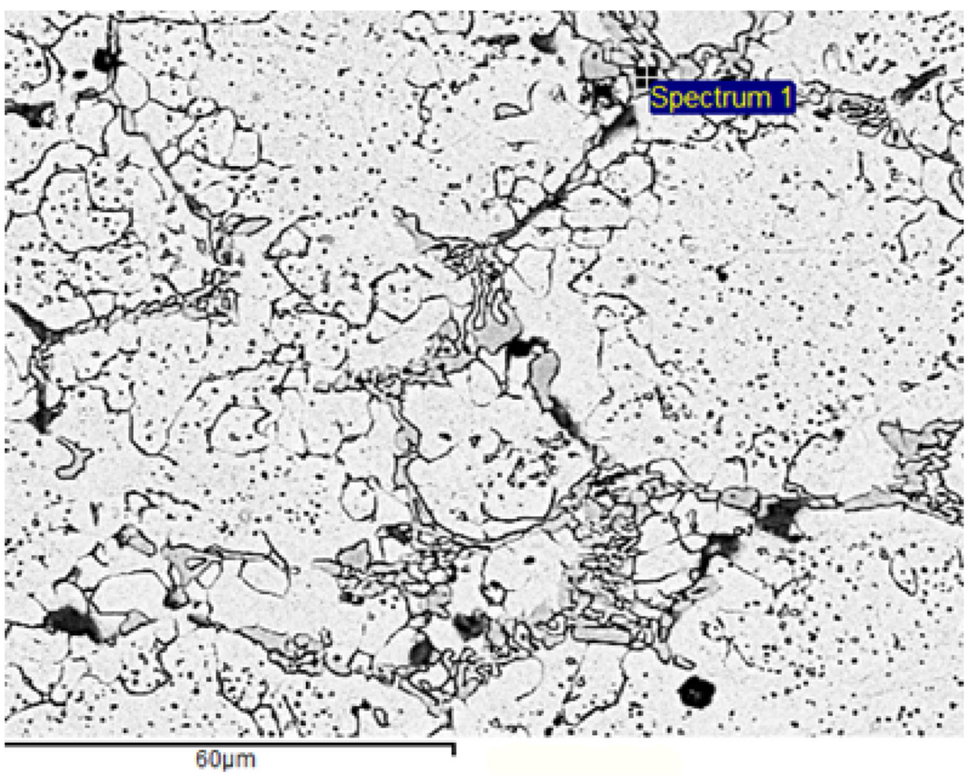

Figure 4. SEM microphotography of the sample with 3% of vanadium.

For the purpose of impact energy testing, according to the standard EN 10045-1, prepared samples have the following dimensions: 10 × 10 × 55 mm. The testing was done in computerized *Charpy* pendulum *Schenk-Trebell 150/300 J*. The force meter, set in the hammer, fracture time detector and deformation measuring device were connected to the oscilloscope, used to make the signals received when the testing tube is visibly cracked. The oscilloscope is connected with computer for analyzing the received signals.

For the hardness tests the samples of similar dimensions are made as in impact energy testing. The testing was done by Rokvel-C method on *OttoWolpert-Werke* instrument.

The analysis of the microstructures of investigated steels was carried out using the light microscope *OLYMPUS GX41*. Microscope was equipped with digital camera and two software modules, *A-MOD-GS-PL* software module for grains planametry and *A-MOD-I-ASTM* software module for the determination of the inclusions or second-phase constituents. Also, for the analysis of microstructures, we used the Scanning Electronic Microscope *JOEL-JSM-6610LV* which was equipped with an energy-dispersive X-ray spectroscopy (EDS) device.

Results and Discussion

The results of the investigation of heat-treated samples of steel X96CrMo12-1 having different content of vanadium are presented in Sects. "The Influence of Vanadium on the Impact Toughness and Impact Energy–Influence of Vanadium on the Microstructure".

The Influence of Vanadium on the Impact Toughness and Impact Energy

The impact energy testing is conducted in six points on the sample, so the average value is taken into consideration. The values of the impact toughness and impact energy of the samples are shown in Table 2 and presented in Figures 1 and 2.

The goal was to achieve the high impact toughness with a hardness value above 54HRC. The optimal content of vanadium is 4% because the toughness is 11.62 J/cm^2 and the hardness is 54.2 HRC.

Influence of Vanadium on the Hardness

The hardness testing is conducted in six points on the sample, so the average value is taken into consideration. The average values of the hardness measurements are presented in Table 3.

From the presented data, it can be seen that the hardness is decreasing with increased vanadium content in alloy, but the decreasing is not significant and hardness of the steels is still relatively high.

Influence of Vanadium on the Microstructure

The samples are heat treated by quenching from 1000 °C and low-temperature tempering at 250 °C. Quenching was

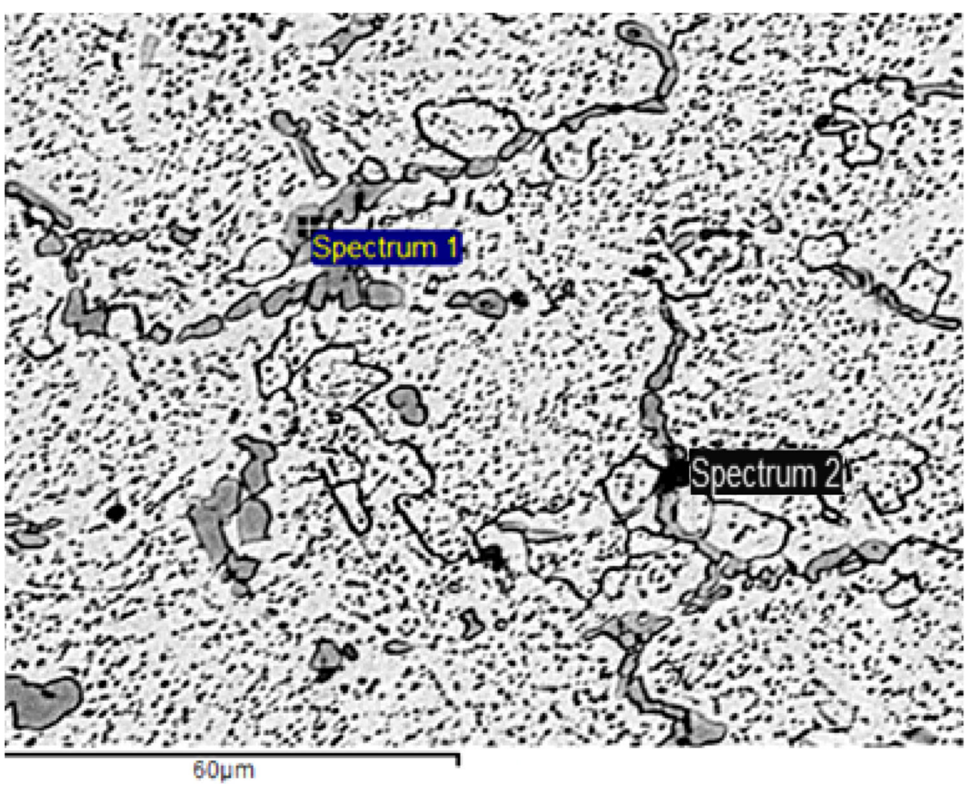

Figure 5. SEM microphotography of the sample with 5% of vanadium.

performed by immersion in an oil heated to 80 °C, and the rate of cooling was greater than critical. Figures 3 and 4 show the microstructure of samples after heat treatment.

In general, the sample structures consisted of martensite metallic base with very little residual austenite and dispersed carbides type $(Cr,Fe)_7C_3$, distributed mainly as a grid by the boundaries of metal grains.

During quenching the transformation of austenite into martensite occured, and in the tempering process, the oversaturated solid solution of martensite was transformed into cubic martensite, and the carbides remained distributed in a form of grid along the basic metallic grain boundaries.

In the alloys containing 5% V, the austenite is transformed during the cooling process into barite, which is not changed either by shape or by size during the low-temperature tempering. After the heat treatment, there are smaller amounts of cubic martensite or remaining austenite present in the structure. The distribution of carbides is changed, the carbide grid is not clear and beside carbide V_6C_5 in the structure, and there is significant part of very hard carbide VC in the structure of the metallic grain, as presented in Figure 5.

In addition, as the content of vanadium increases, the grain size of the metal base decreases, which has an effect on the increase in the impact toughness of the alloy.

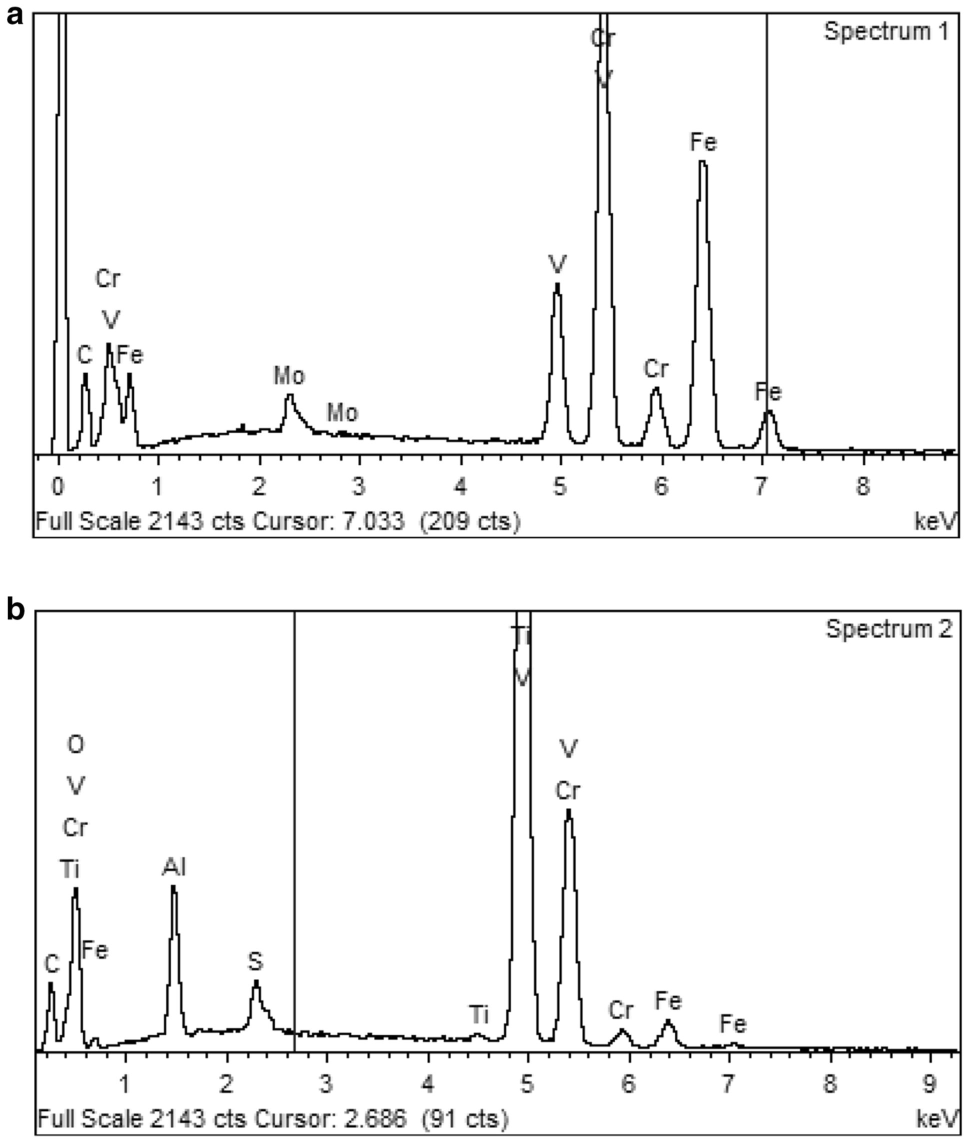

Figure 6. (a) EDS spectrum of the sample with 5% of vanadium at point spectrum 1. (b) EDS spectrum of the sample with 5% of vanadium at point spectrum 2.

Table 4. Chemical Composition of the Examined Phases of the Sample with 5% of Vanadium

Examined points	Content of elements (mass%)								
	C	O	Si	V	Cr	Fe	Ti	Mo	Total
Spectrum 1	16.63	–	–	10.46	34.44	35.31	0.00	1.13	100.00
Spectrum 2	9.79	28.85	0.84	45.64	8.56	2.31	0.29	–	100.00

In Figure 5, markers Spectrum 1 and Spectrum 2 indicate points in the carbide network in which the EDS analysis was performed.

Points Spectrum 1 and 2 in Figure 5 refers to points in the carbide network. EDS analysis of points Spectrum 1 and Spectrum 2 is shown in Figure 6a, b. Chemical composition of the examined phases of the sample with 5% of vanadium is shown in Table 4.

In the mass spectrum of the carbide network (Points Spectrum 1 and Spectrum 2), it is observed that the content of vanadium is increased, especially on the Spectrum 2 sample. This indicates the presence of carbide type M_7C_3 and complex Cr–Fe–V–Mo carbides (Spectrum 1) or V_6C_5 carbide, which is stable below 1000 °C (Spectrum 2).

It is known that vanadium carbides and complex Cr–V carbides form at the grain boundaries during initial solidification and still remain after heat treatment. However, the presence of vanadium over 2% enhances the formation of complex Cr–V carbides and $(Cr,Fe)_{23}C_6$ carbides and their precipitation in the austenite grains, during the cooling process. Austenite, in local areas, around these fine carbide particles, transformed into martensite. This means that vanadium reduces the amount of retained austenite and thus improves the hardenability of steel.

Possibility of Application

Adding 4–5% of vanadium in steels, quality X96CrMo12-1, forms the alloy that have very good combination of impact toughness and hardness and thereby may have wide area of application. Therefore, this steel with addition of 5% V can be successfully used for making parts and components that are exposed to abrasion, corrosion–abrasion, and impact-fatigue wear or combined type of wear. Assortment of these parts are: construction and mining machinery parts (excavators teeth and teeth covers), parts of grinders and mills for stone, ore, coal and minerals (balls, hammers, impact plates, mill linings and separation grids, etc.).

Conclusion

This work considered the effect of vanadium on microstructure, impact toughness and hardness of steel X96CrMo12-1. In the tested samples, content of vanadium was increased; in first series 1.0% V was added, in second 2% V, in third 3% V, in fourth 4% and in fifth 5% V.

Research showed that with increasing of vanadium content, from 1.0 to 5.0%, the structure becomes finer, and this has an influence on the mechanical properties. Impact toughness increases from 2.80 to 13.91 J/cm^2, impact energy increases from 2.24 to 6.96 J and hardness decreases from 61.2 to 54.2 HRC. This phenomenon can be very important for further practical application of this steel.

The increased content of hard carbides type M_7C_3, $(Cr,Fe)_7C_3$, V_6C_5 and VC, their appropriate distribution and morphology provides good abrasive wear resistance, even in cases when they are in contact with extremely abrasive materials such as silica, feldspar and others.

REFERENCES

1. A. Todić, D. Čikara, T. Todić, B. Pejović, M. Mišić, I. Čamagić, The effect of vanadium content on mechanical properties and structure of self-hardening steel X160CrMo12-1. J. Mech. Eng. Autom. **3**, 168–172 (2013)
2. N. Yamanaka, K. Kusaka, Influence of vanadium and molybdenum on the properties of air-hardening die steel containing 1.5% Carbon and 12% Chromium. Iron Steel Inst. Jpn. **41**(6), 613–620 (1955)
3. D. Čikara, M. Rakin, D. Čikara-Anič, Quality optimization of steel milling balls, in *Proceedings of 18th International Conference on Material Handling, Constructions and Logistics*, Belgrade, pp. 131–138 (2006)
4. A. Todić, D. Čikara, T. Todić, B. Pejović, I. Čamagić, V. Vukojević, The influnce of the vanadium content on the toughness and hardness of wear resistant high-alloyed Cr-Mo steel. FME Trans. **45**(1), 130–134 (2017)
5. M. Filipović, Ž. Kamberović, M. Korać, Uticaj termičke obrade na žilavost i otpornost na habanje Fe-C-Cr-Nb legura. J. Metall. **14**(4), 243–252 (2008)
6. M. Filipović, Uticaj sadržaja vanadijuma i brzine hlađenja na stereološke parametre faza u strukturi Fe-C-Cr-V legura. J. Metall. **10**(2), 127–138 (2004)