Influence of Vanadium on Mechanical Characteristics of Air-Hardening Steels

Aleksandar Todić
Teaching Assistant
University of Pristina
Faculty of Technical Sciences

Dejan Čikara
Professor
University of Pristina
Faculty of Technical Sciences

Tomislav Todić
Professor
University of Pristina
Faculty of Technical Sciences

Ivica Čamagić
Teaching Assistant
University of Pristina
Faculty of Technical Sciences

The aim of the paper was to investigate the influence of vanadium on the structure, hardness and impact toughness of air-hardening steel type X180CrMo12-1. It is known that vanadium influences the hardening process of these alloys by narrowing the temperature range of the crystallization. Vanadium moves the liquidus and solidus lines to the higher temperatures, forms V_6C_5 carbides, and is distributed between phases present in the steel; carbide $(Cr, Fe)_7C_3$ and austenite. Besides, V_6C_5 carbides which are formed in the structure block further growth of austenite dendrites and help the formation of fine grained metallic base. The existence of vanadium enables the formation of $(Cr, Fe)_{23}C_6$ carbide and its precipitation in the austenite during the cooling process. In the local regions around fine carbide particles, austenite transforms easily to martensite.

So, actually, vanadium decreases the amount of remained austenite and improves steel hardenability. Even in small vanadium concentrations, the impact toughness is noticeably improved, while the hardness is on the satisfactory level.

Keywords: *air-hardening steel, vanadium, impact toughness, microstructure.*

1. INTRODUCTION

Air-hardening steels belong to the group of wear resistant materials with wide application. The basic characteristic of these steels is high toughness for their high carbon content and relatively low impact toughness.

The objective of these investigations made on the above mentioned steels was to maintain this great hardness but also to gain large impact toughness. The investigation was carried out in order to develop these steel characteristics improvement by using the vanadium as an alloying element within the range of 0.5 – 3.0 %. Larger vanadium contents were not used, because previous papers with similar steels, published by other authors, showed that the influence of this alloying element on the structure and mechanical properties is strong only in relatively small portions [1]. The microstructure of this steel in cast state consists of primary austenite dendrites, partially or fully transformed. With increased vanadium content in alloy, hardness is slightly decreased, but the impact toughness is significantly increased, producing the appropriate combination of toughness and hardness, or abrasive and impact-fatigue wearing resistance.

The basic aim of this study is to maintain or slightly reduce the hardness and increase the impact toughness in these steels. This kind of compromise can be searched in heat treatment regime, so the martensite structure with less remained austenite is produced.

Received: January 2011, Accepted: April 2011

Correspondence to: Dr Dejan Cikara
Faculty of Technical Sciences,
Kneza Miloša 7, 38220 Kosovska Mitrovica, Serbia
E-mail: dcikara@sezampro.rs

2. THE INFLUENCE OF CHROMIUM AND MOLYBDENUM ON THE STRUCTURE AND PROPERTIES OF STEEL

Chromium is the basic alloying element in steels with increased hardness and wear resistance. It reacts with carbon and forms hard carbides resistant to the wearing, then prevents the transformation of austenite into pearlite during the cooling process and has an impact on the metallic base structure by closing γ region in the phase diagram. The best toughness and hardness are found in structures with carbides $(Cr, Fe)_7C_3$ formed in the steel containing more than 6 % of chromium. A larger percentage of chromium does not give better results, because it limits carbon concentration, and with increased carbon concentration the eutectic concentration is reduced. Chromium does not increase hardenability but in combination with higher carbon concentration it has an improving effect on the quenched layer depth.

Molybdenum disables pearlite formation and removes the austenite transformation into bainite and martensite region. This is the reason why molybdenum even in small concentrations increases hardenability. It ensures hard and solid martensite basis in which the alloyed carbides are included. Molybdenum forms the interstitial phase Mo_2C whose hardness is approximately 1800 HV, and in increased concentration of Mo, a certain amount of this phase is formed in the steel structure. The phase Mo_2C disperses the metal base [2].

3. THE INFLUENCE OF VANADIUM

The addition of vanadium to the high alloyed chromium steels improves fine structures. The graining structure effect is explained by the influence of vanadium on the crystallization process. The temperatures of the beginning of crystallization of austenite primary dendrite and formation of eutecticum in alloy Fe-Cr-C with 15 % Cr and 2.95 % C with no vanadium content were 1250 °C and 1235 °C, respectively and 1275 °C and 1259 °C, in alloy containing 5 % V. Furthermore, vanadium changes morphology of the eutectic $(Cr, Fe)_7C_3$ carbide. With the increased vanadium content the radial carbide distribution becomes more dominant, and the participation of long directed lamellas and plates is not reduced [1].

The presence of vanadium, even in small concentrations has an improving influence on high alloyed Cr-Mo steels, because 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 helping the production of fine grained structures. In high chromium steels (1.4 – 2.0 % C, 12 % Cr), when the vanadium content is over 2.5 %, vanadium carbide type VC is formed in the form of cube crystal grid. The VC carbide is globular and often joined with eutectic $(Cr, Fe)_7C_3$ carbide, crystallizing in the shape of bars, growing radially from the nucleus, forming spherical cells with austenite [3-7].

In lower vanadium concentrations, in the process of primary austenite separation from the solution V_6C_5 carbides are formed, blocking further growth of austenite dendrites and helping the production of fine grained structures. Similar to molybdenum, vanadium, besides forming V_6C_5 carbides is partly distributed between phases present 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 in austenite during the cooling process.

In local areas around fine carbide particles, austenite is transformed into martensite, i.e. vanadium reduces the remained austenite and improves steel hardenability. Even in small vanadium concentrations, the impact toughness is significantly improved.

4. EXPERIMENTAL PROCEDURE

The investigations were based on air-hardening steel X180CrMo12-1.

For the production of the samples the induction medium frequency furnace *ABB* type *ITMK-500* was used. The moulds were made according to the models fitting the standard test tubes shape for impact toughness and hardness testing. The casts were treated by heat treatment of improvement, made by quenching and low temperature relaxing at 250 °C for one hour time interval. This type of heat treatment is characteristic of high alloyed Cr-Mo steels.

The chemical composition of used steel was: C = 1.8 %, Cr = 12 %, Mo = 1.2 % while the vanadium content varied: for the first series 0.5 % V, for the second series 1 % V, for the third series 2 % V and for the fourth series 3 %. There were twenty samples cast. The chemical compositions of the samples of I, II, III and IV series are shown in Table 1.

The sample surface was very rough after casting and heat treatment, so they were cleaned and treated to the standard dimensions. The treatment was done on a grinder machine with permanent cooling with water emulsion to avoid any change of microstructure of the samples. The samples for tensile strength testing were treated by using ceramic tiles for quenched surface treatment type SANDVIK CNGA on universal lathe, also by cooling with emulsion solution. The image of the treated samples is shown in Figures 1 and 2.

Table 1. Chemical composition of the samples

No.	Sample series	Chemical composition				
		C [%]	Cr [%]	Mo [%]	S [%]	V [%]
1	I	1.801	11.754	1.298	0.021	0.523
2	II	1.766	11.556	1.301	0.023	1.005
3	III	1.732	11.466	1.268	0.022	1.998
4	IV	1.762	12.236	1.248	0.02	2.990

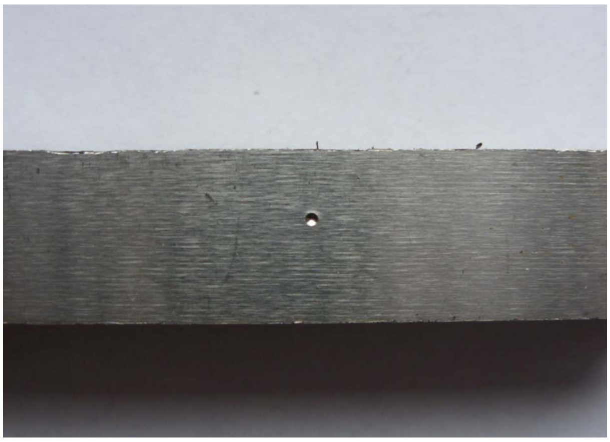

Figure 1. Sample for hardness testing after machinery treatment

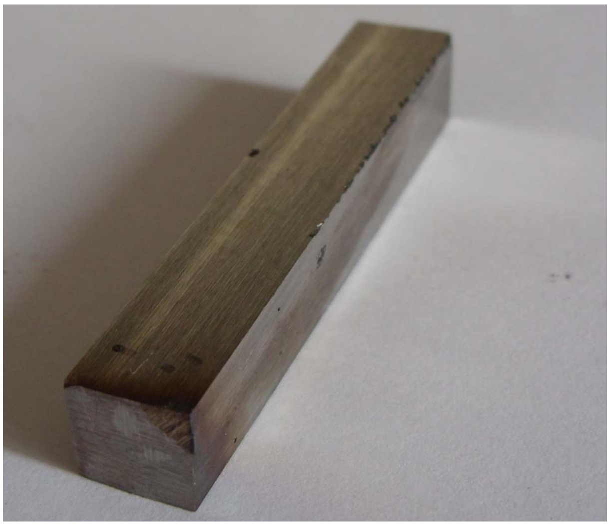

Figure 2. The image of the print on the sample for hardness testing by HRC method

For the purpose of impact toughness testing, according to the standard EN 10045-1, the prepared samples had the following dimensions: 10 × 10 × 55 mm. The testing was done in computerized *Charpy* pendulum *Schenk-Trebell 150/300J*. 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 during the time of testing tube cracking (0.5 – 8 ms) visible. The oscilloscope was connected with the computer for analyzing the received signals.

For the hardness tests, the samples of similar dimensions were made as in impact toughness testing. The testing was conducted by Rockwell-C method on the *OttoWolpert-Werke* instrument.

The analysis of the samples microstructures of the investigated steels was conducted on Light microscope *Olympus GX41*, equipped with digital camera and software for image improvement.

5. THE TESTING RESULTS

The results of the investigation of heat treated samples at 250 °C having different content of vanadium are presented in Sections 5.1, 5.2 and 5.3.

5.1 Influence of vanadium on the hardness

The hardness testing was 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 2.

From the presented data it can be seen that the hardness is decreasing with increased vanadium content in alloy. However, the decreasing is not significant and hardness of the material is still relatively high. This hardness decreasing strictly points to the increase of impact toughness.

5.2 The influence of vanadium on the impact toughness

The impact toughness testing was conducted in six points on the sample, so the average value is taken into consideration. The average values of the comparative results of impact toughness and hardness measurements are presented in Table 2. For the illustration, the characteristic diagram of fracture energy alternation in time is presented in Figure 3.

From the analysis of the obtained data it can be seen that increasing of vanadium content, increases impact toughness, particularly in samples from the IV series, having 3 % of vanadium. The impact toughness improvement in this group is significant (over 100 %) but the hardness values remain satisfactory high.

Hardness and impact toughness values, depending on the vanadium content are presented in Figure 4.

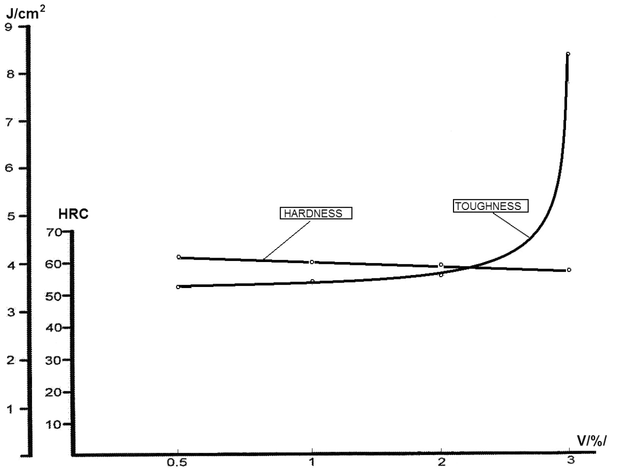

Figure 4. Hardness and impact toughness values vs. vanadium concentration

Table 2. Hardness and impact toughness of the samples

No.	Sample series	Impact toughness [J/cm^2]	Hardness [HRC]	Chemical composition				
				C [%]	Cr [%]	Mo [%]	S [%]	V [%]
1	I	3.48	61.5	1.801	11.754	1.298	0.021	0.523
2	II	3.59	60	1.766	11.556	1.301	0.023	1.005
3	III	3.71	59	1.732	11.466	1.268	0.022	1.998
4	IV	8.35	57.2	1.762	12.236	1.248	0.02	2.990

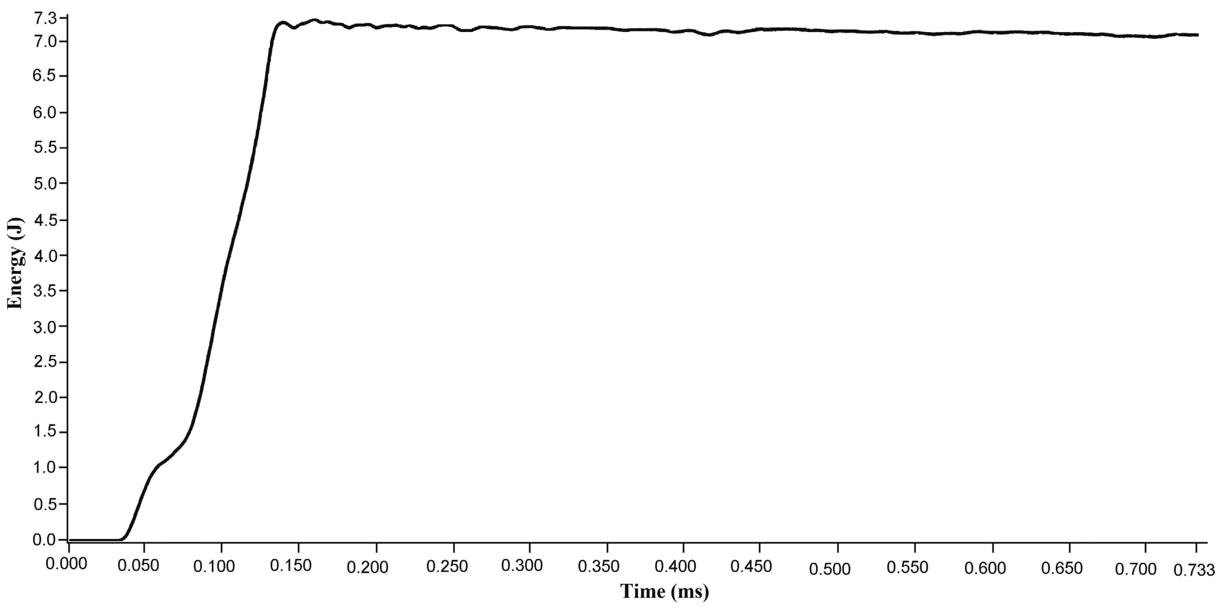

Figure 3. Diagrams of energy vs. time

5.3 The influence of vanadium on the structure

The structures of the samples after heat treatment with quenching and low temperature relaxing are shown in Figures 4, 5, 6 and 7. The samples were homogenized by annealing at 1000 °C to the complete austenization, and after that cooled in the cold air flow at controlled rate over critical rate.

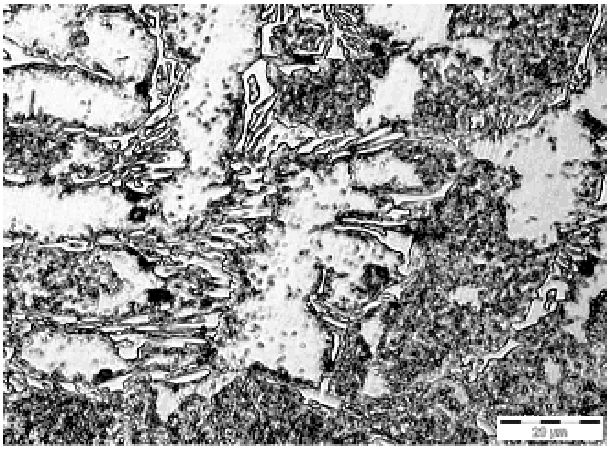

Figure 4. Microstructure of the alloys from group I

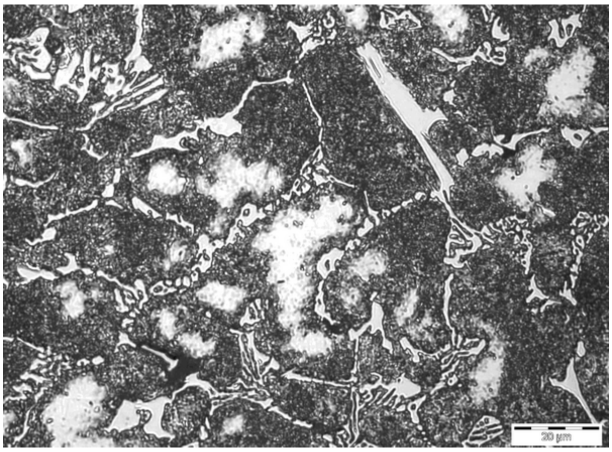

Figure 5. Microstructure of the alloy from group II

Figure 6. Microstructure of the alloys from group III

From the figures it can be seen that with the increase of vanadium content up to 2 %, the carbide distribution remains the same, but its size and stereology form is changed. The vanadium content has an impact on the downsizing of the structures of metallic base and carbide grid. Furthermore, with the increase of vanadium content in the alloy the scattering of carbide particles is decreased and number of fine carbides in the structure is increased, as shown in Figures 4, 5, 6 and 8. Vanadium creates carbides and makes bonds with carbon into carbide V_6C_5, whose composition in the structure is increased with increased part of vanadium in the alloy.

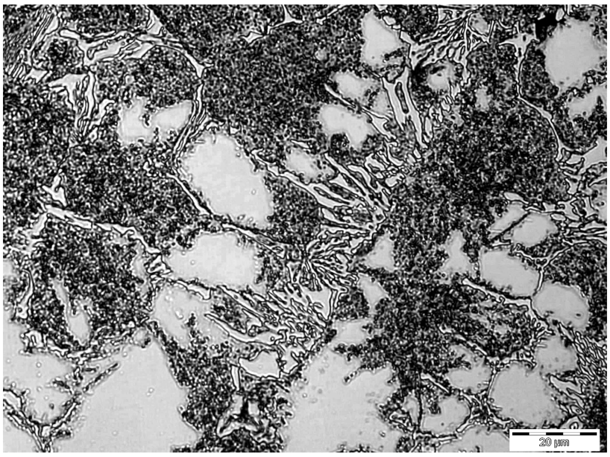

Figure 7. Microstructure of the alloys from group IV

In general, the samples structures consists of martensite metallic base with clearly visible areas of remained austenite and dispersed carbides type $(Cr, Fe)_7C_3$, distributed mainly as a grid by the metal grains boundaries. The carbide phase is formed by eutecticum solidification and has intensive directed growth. The austenite from the eutecticum was transformed into martensite and observed in the form of dark fields between carbide needles.

During the hardening the transformation of austenite into martensite occurred for the primary crystals as well as the austenite from eutecticum. In the relaxing process, the oversaturated solid solution of martensite was transformed into cubic martensite, and the carbides remained distributed in the form of a grid along the basic metallic grain boundaries. The microstructures of the examined alloys are presented in Figures 4, 5, 6 and 7.

In the alloys containing 3 % V the austenite is transformed during the cooling process into bainite, which is not changed neither in shape, nor in size during the low temperature relaxing. After the heat treatment there are smaller amounts of cubic martensite or remained austenite present in the structure. Martensite is distributed mainly along the border line to the eutectic carbide. The distribution of carbides is changed, the carbide grid is not clear and besides carbide V_6C_5 in the structure, there is a significant part of very hard carbide VC in the structure, as presented in Figure 8. The alterations of volume parts, sizes and morphology of the present phases in the microstructure of Fe-C-Cr-V alloys point to the fact that with increased vanadium concentration the alloy composition is closer to eutectic in the quaternary Fe-C-Cr-V system having influence on the decreasing of the temperature interval of solidification.

6. APPLICATION POSSIBILITIES

The addition of 3 % of vanadium to the steels marked by X180CrMo12-1 the alloy is formed with very good

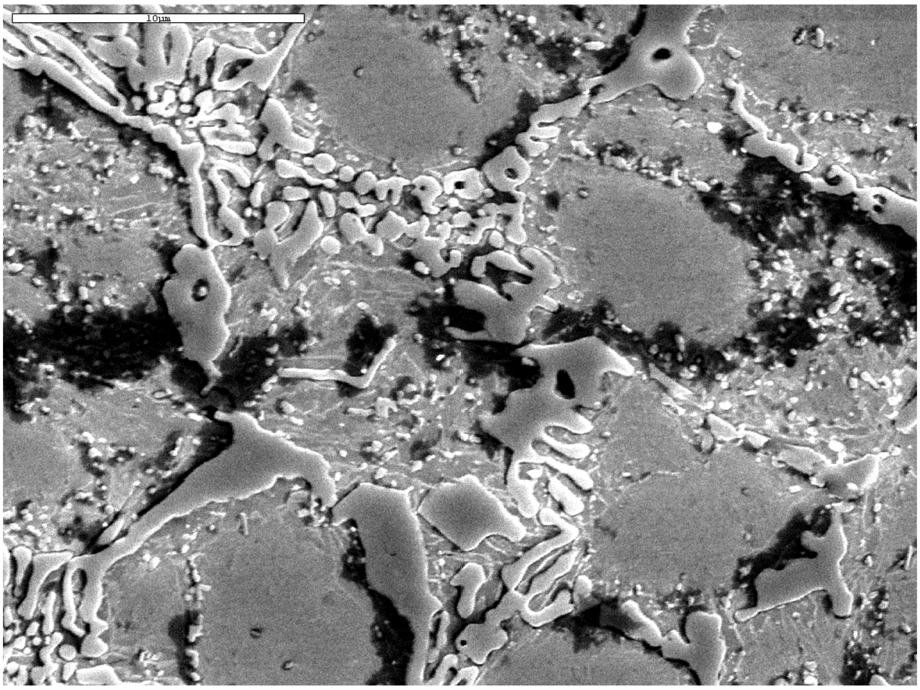

Figure 8. SEM microphotography of the sample of group I

combination of hardness and toughness having a wide field of application.

This steel with the addition of 3.0 % of V can be successfully used for the parts and systems exposed to abrasive, corrosion-abrasion, impact-fatigue or combined type of wearing. The assortment of these parts are: civil engineering and mining machines (digger's teeth and covering plates), parts for crushers and mills for stone, ore, coal and minerals (balls, hammers, impact plates, mills plates and separation grids), wearing parts in process plants (bunker's shuts for abrasive materials, sanding machines shallows, oil pumps bodies, coal briquettes and steel shreds moulds, tanks and transporters tracks etc.).

7. CONCLUSION

In this paper we studied the influence of vanadium on the hardness, impact toughness and microstructure of the steel with 1.8 % of carbon, 12 % of chromium and 1.3 % of molybdenum. With the increased content of vanadium the structure becomes fine, having the influence on the steel's mechanical properties, i.e. on the hardness and impact toughness. In the examined alloy the vanadium content was gradually increased; in the first series 0.5 % of V was added, in the second 1 % of V, in the third 2 % of V and 3 % of V in the fourth. Larger amount of vanadium has no influence on the quality of alloy, so the investigations with larger content of vanadium were not included in this paper.

The discussion of the results given in the Sections 5.1, 5.2 and 5.3 points to the fact that increased concentration of vanadium has positive influence on the toughness and microstructure. The investigation of the samples from group I, with 0.5 % of vanadium, has shown high value for hardness, while the impact toughness was extremely low. With increased vanadium concentration up to 2.0 %, in the samples from groups II and III, the hardness was slightly decreased, and impact toughness was increased moderately. With further increasing of vanadium concentration to 3.0 %, in the group of IV samples, the hardness was continually, but slightly decreased, and impact toughness had rapid growth and reached the value of 8.35 J. This phenomenon can be very important for further application in practice.

The presence of hard carbides type $(Cr, Fe)_7C_3$ V_6C_5 and VC, their content, distribution and morphology enable good wear resistance even in cases of contact with extremely abrasive materials such as quartz, feldspate and others.

REFERENCES

[1] Radulović, M.: *The Influence of Vanadium on the Microstructure and Mechanical Properties of a High Chromium White Iron*, PhD thesis, Faculty of Technology and Metallurgy, University of Belgrade, Belgrade, 1991, (in Serbian).

[2] Čikara, D.D., Marković, S. and Čikara, M.D.: Wear resistance, structure and possible applications of high chromium iron alloys, Metalurgija-Journal of Metallurgy, Vol. 7, No. 1, pp. 45-59, 2001, (in Serbian).

[3] Filipović, M., Kamberović, Ž. and Korać M.: The effect of heat treatment on toughness and wear resistance of Fe-Cr-C-Nb alloys, Metalurgija-Journal of Metallurgy, Vol. 14, No. 4, pp. 243-252, 2008, (in Serbian).

[4] Filipović, M., Marković, S., Kamberović, Ž. and Korać, M.: The influence of titanium and cerium on microstructure and properties of Fe-C-Cr-Nb alloys, Metalurgija-Journal of Metallurgy, Vol 11, No. 4, pp. 345-351, 2005, (in Serbian).

[5] Filipović, M.: Influence of vanadium content and colling rate on the stereological parameters of phases in the structure of Fe-C-Cr-V alloys, Metalurgija-Journal of Metallurgy, Vol. 10, No. 2, pp. 127-139, 2004, (in Serbian).

[6] Čikara, D., Rakin, M. and Čikara-Anić, D.: Quality optimization of steel milling balls, in: *Proceedings of the 18th International Conference on Material Handling, Constructions and Logistics*, 19-20.10.2006, Belgrade, Serbia, pp. 131-138.

[7] Yamanaka, N. and Kusaka, K.: Influence of vanadium and molybdenum on the properties of air-hardening die steel containing 1.5% carbon and 12% chromium, The Iron and Steel Institute of Japan (ISIJ), Vol. 41, No. 6, pp. 613-620, 1955.

УТИЦАЈ ВАНАДИЈУМА НА МЕХАНИЧКА СВОЈСТВА САМОКАЉИВИХ ЧЕЛИКА

Александар Тодић, Дејан Чикара, Томислав Тодић, Ивица Чамагић

Сврха истраживања била је да се испита утицај ванадијума на структуру, тврдоћу и жилавост самокаљивог челика квалитета X180CrMo12-1. Познато је да ванадијум утиче на процес очвршћавања ових легура тако што сужава температурни интервал кристализације. Ванадијум помера ликвидус и солидус линије ка вишим температурама, образује V_6C_5 карбиде, а једним делом се распоређује између фаза присутних у челику: карбида $(Cr, Fe)_7C_3$ и аустенита. Поред тога, створени V_6C_5 карбиди блокирају даљи раст аустенитних дендрита и на тај начин помажу добијање ситнозрне структуре металне основе. Присуство ванадијума омогућава формирање $(Cr, Fe)_{23}C_6$ карбида и његово таложење у аустениту у току процеса хлађења. У локалним подручјима око финих карбидних честица аустенит се лако трансформише у мартензит. Другим речима ванадијум смањује количину заосталог аустенита и на тај начин побољшава прокаљивост челика. Већ при малим садржајима ванадијума видно се побољшава ударна жилавост, док тврдоћа остаје на задовољавајућем нивоу.