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INFLUENCE OF VANADIUM CONTENT ON THE TRIBOLOGICAL BEHAVIOUR OF X140CrMo12-1 AIR-HARDENING STEEL

Summary

The paper presents experimental testing of wear resistance of steel samples from the same groups of steel. Test results were recorded and presented in the form of diagrams showing the wear resistance of the tested materials in different sliding conditions. The tested steels have high carbon content; the addition of chromium and molybdenum results in the high hardness and low impact toughness of the steels. The addition of vanadium changes the microstructure when the metal grain becomes smaller and the whole structure is martensitic, with chromium and vanadium carbides in the metal matrix. A change in the microstructure causes a change in mechanical properties. The obtained results showed that the addition of vanadium increases impact toughness. However, it is not known how it affects wear resistance and hardness. This type of steel belongs to a new group of steels resistant to wear. A change in the vanadium content causes a decrease in the hardness and wear resistance of the steel and an increase in its impact toughness.

Key words: *air-hardening steel, vanadium, impact toughness, hardness, wear resistance*

1. Introduction

Air-hardening high alloyed Cr-Mo steels belong to a group of wear resistant steels with increased hardness. This characteristic allows wide application of these steels in industry, mining and metallurgy. Due to their high carbon content, these steels have high hardness and relatively low impact toughness [1, 2]. Their good wear resistance and tribological properties provide high durability of steel parts during exploitation [3]. That material property was defined as wear stability by the authors of the study [4]. They showed that relative wear resistance increases with increasing hardness or decreasing impact toughness, whereas wear stability increases with increasing hardness or impact toughness. Previous studies on a high-alloy Cr-Mo steel samples with a lower vanadium content showed that even a small percentage of vanadium strongly affects the characteristics of the steel [5-11]. Most of the previously mentioned investigations dealt with the influence of vanadium content on the hardness, microstructure, and tribological behaviour of steels. But it should be emphasized that some authors dealt with the effects of vanadium content on the microstructural and mechanical properties of a newly developed hot-work die steel (MPS700V) at room temperature and at elevated temperatures [9]. The results showed that the tensile strength of the tested steel at room temperature and at 700 °C greatly depends on the vanadium content and that an increase in the vanadium content from 0 up to 1.2% at room temperature increases the tensile strength from 1127 MPa to 1442 MPa, and at 700 °C from 400 MPa to 550 MPa. Many researchers have investigated these alloys. The authors of the paper [12] extensively investigated the effects of vanadium addition on the microstructure, hardness, and wear rate of the welded coating layer. The results showed that hardness was significantly increased with higher vanadium content. A similar trend was observed in the case of wear resistance.

The aim of this research is to investigate the effect of vanadium on the impact toughness and wear resistance of X140CrMo12-1 air-hardening steel. The content of vanadium varied from 0.5 to 3.0 wt.%, while the content of other alloying elements and the conditions of casting production remained the same as in [13, 14]. The heat treatment regime was selected in a way to allow the formation of martensitic and bainitic structures of the metal matrix with a very small percentage of residual austenite [15-17].

2. Properties of tested materials

In previous research, the influence of vanadium on high-alloy Cr-Mo steels with carbon content ranging from 1.4 to 2.2% and that of vanadium from 0.5 to 3% was analysed [2, 13, 14]. This paper relates to the testing of air-hardening steel, X140CrMo12-1, with a chemical composition of 1.4% C, 12.5% Cr, 1.2% Mo, and the vanadium content varying in the 0.5-3% range. The samples for these examinations were poured into dry sand moulds; the steel was melted in an ASEA Brown Boveri ITMK-500 type medium-frequency induction furnace. The vanadium content was varied by the gradual addition of vanadium while simultaneously controlling the chemical composition of steel. The control was performed on an optical emission spectrometer, ARL-3460 Metals Analyser. The carbon content was 1.4% and the vanadium content varied from 0.5%, to 1%, 2%, and finally to 3%. The samples were heat treated, quenched, and low-temperature tempered at a temperature of 250ºC for a period of 1 hour. The samples were annealed at 1000°C until complete homogenization of austenite was accomplished and then quenched in a stream of cold air at a cooling rate higher than critical. This type of heat treatment is characteristic of high carbon Cr-Mo steels. The targeted chemical composition of the samples is shown in Table 1. However, under realistic conditions of melting and casting of steel, it is difficult to obtain an absolutely accurate chemical composition. The chemical composition of all four groups of steel is shown in Table 1 and the results of the measured hardness and impact toughness of the samples are shown in Table 2. The samples were produced by sand casting, while the final dimensions and surface roughness were achieved by grinding with intensive cooling. The samples were also heat treated by quenching and tempering.

Table 1 Chemical composition of samples

Sample number	Chemical composition [%]									
	C	Cr	Mo	S	Si	P	Mn	Al	Ni	V	Sample
1	1.350	11.608	1.056	0.027	0.213	0.020	0.352	0.026	0.000	0.633	1
2	1.380	11.163	1.049	0.024	0.223	0.019	0.337	0.026	0.000	1.216	2
3	1.431	10.896	1.021	0.032	0.865	0.036	0.589	0.145	0.190	1.998	3
4	1.453	10.364	1.006	0.029	0.290	0.021	0.347	0.035	0.000	2.982	4

Table 2 Hardness and impact toughness values

Carbon content [wt.%]	Impact toughness [J/cm^2]				Hardness [HRC]			
	Vanadium content [wt. %]				Vanadium content [wt. %]			
	0.50	1.00	2.00	3.00	0.500	1.00	2.00	3.00
1.40	6.81	6.95	7.10	7.93	56.60	56.00	52.50	51.00

3. Experimental results

The main goal of this research was to determine the wear resistance of samples. The samples had the same chemical composition and the same heat treatment, but different shapes and dimensions. The wear tests were based on the X140CrMo12-1 air-hardening steel. The chemical composition of the steel was: 1.4% C, 11.5% Cr, 1.0% Mo, while the percentage of vanadium varied from 0.5 to 3.0%. A *JEOL type JSM-6610LV* scanning electron microscope (SEM) was used to observe the microstructure. Since this research involves a large number of results, we are able to show here only the representative ones. For illustration, Figure 1 shows two SEM microstructures of the steels with 1% and 2% vanadium.

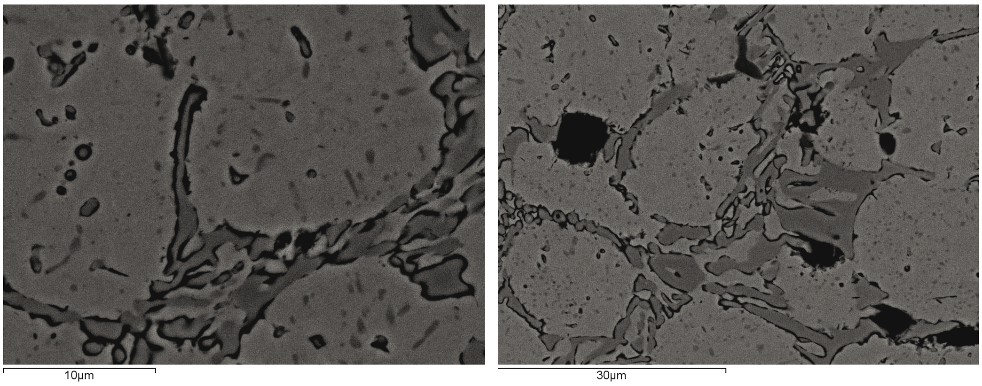


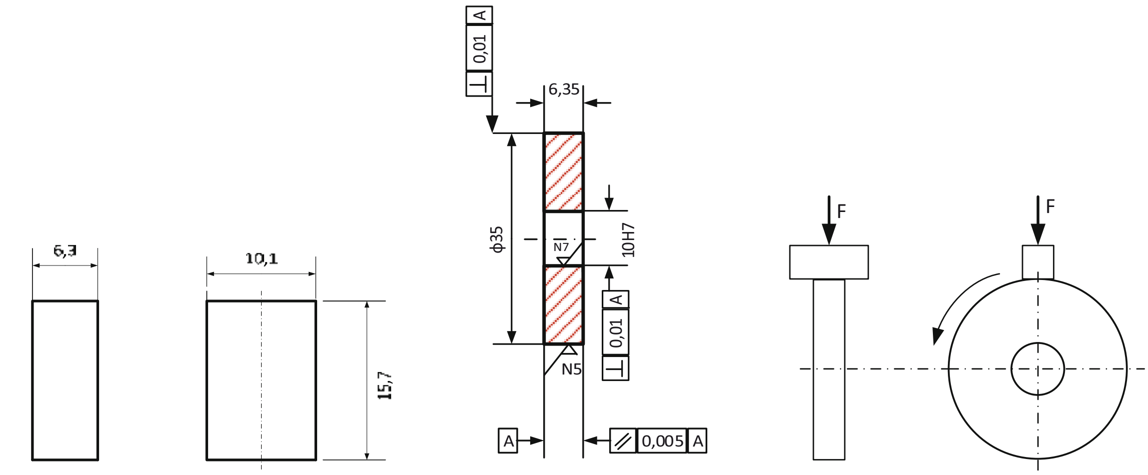
Fig. 1 SEM microstructure of the steel with 1% vanadium (left) and 2% vanadium (right)

When the vanadium content in the steel is 0.5% and 1.0%, the structure consists of a martensitic metal matrix, while at higher contents (2.0% and 3.0%) the structure is bainite with a small amount of residual austenite. Martensite and bainite in the structure were identified by using a SEM. Details about the microstructure are given in [13, 14]. In this paper, the aim was to investigate wear resistance of the tested materials. A small amount of martensite is also present, but mainly along the boundary with eutectic carbide. Clearly expressed carbide networks can be seen around martensite grains, and a small amount of carbide is finely dispersed in the metal matrix. The basic type of carbide is M_7C_3. Hardness was measured by the Rockwell HRC test, while the impact toughness was tested on a SCHENCK-TREBEL 150/300 J pendulum Charpy impact machine, which means that the energy for crack initiation and propagation could be monitored. As for the SEM analysis, samples were prepared by using ultrasonic bath and a vacuum chamber.

Processing of cast and heat-treated samples and reduction to their required dimensions were carried out by cutting and grinding with intensive cooling using appropriate refrigerants so that the processing temperature could not affect the microstructure of the samples. All external surfaces of the samples were processed by fine grinding in order to minimize the resistance in the sample guides. In addition, the hardness of the disc must always be greater than the hardness of the samples. The hardness of friction disc was 59-60 HRC, while the hardness of the samples ranged from 51 to 56 HRC. Technical drawings of a sample and the disc and the testing principle are shown in Fig. 2.

The device works in the following way: the friction disc rotates at a peripheral speed v of 0.5 m/s, and the samples to be tested are placed in the guide, radially positioned on the friction disc. The test piece is subjected to a constant force F of 30 N. The value of friction force depends on the friction coefficient, type of the material, and wear conditions.

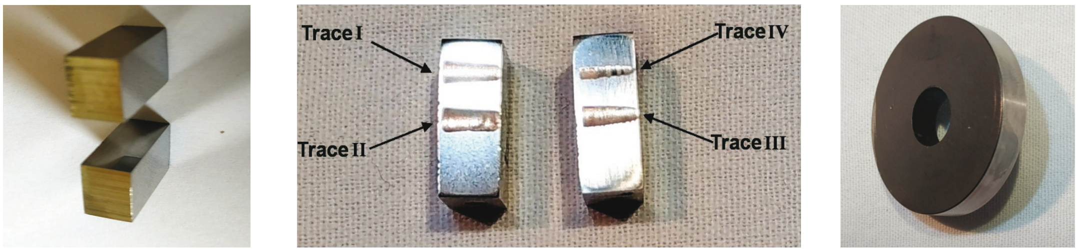
Wear of the samples is done under dry conditions. The friction disc rotates for 1000 s without interruption, which corresponds to a defined distance travelled. The friction disc leaves a characteristic shape on the sample (Fig. 3b) [18, 19]. Using an optical microscope, the amount of wear, i.e. the material loss from the sample, is determined by investigating the contact surface and measuring the depth of the trace. The test was performed on two samples prepared for each quality of steel. Two tests were performed on each sample. The fourth trace on the second sample was made in intermittent testing, in which the test was interrupted after every 100 s and the contact surface and the trace depth were measured; subsequently, the amount of wear was calculated. Such a procedure was applied in order to be able to form a wear curve. For each group of samples, the same preparation was done, and the same test conditions were provided.



a) b) c)

Fig. 2 Technical drawings of a) a sample b) the friction disc; c) position of the sample on the testing device

After each interruption, the friction disc was cleaned of any adhered material, and then the test was continued using the same methodology. In this way, ten interruptions were made, and the same stopping points were obtained on the wear diagram. The friction disc hardness was 59-60 HRC. Figure 3b) shows the samples with wear traces and Figure 4 the friction disc.



a) b) c)

Fig. 3 Appearance of samples: a) before testing, b) after testing, c) Friction disc

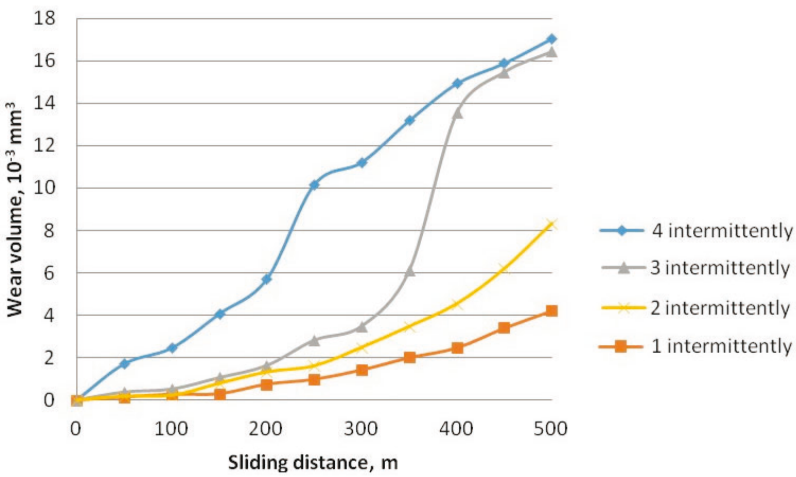


Fig. 4 Diagram of wear volume as a function of sliding distance (friction time)

In addition, the testing device is provided with a sensor that constantly monitors the entire test process, calculates the coefficient of sliding friction and stores data for graphical presentation of the changes in the friction coefficient. Figure 4 shows a characteristic diagram of the change in the wear volume of samples as a function of the sliding distance. Stopping points were made after 100 s, which corresponds to a distance of 50 m.

From the diagram in Fig. 4, one can see that with the increase in the friction time or the sliding distance, the wear volume of material also increases. This change is not linear but parabolic. This type of wear can be interpreted in two ways. The first assumption is that in the initial period, the outer hardened surface of the samples is exposed to wear. The subsequent layers are slightly softer, so the wear is more intense. The second assumption is that the material fatigue may occur in the surface layers during the wear process, which results in more intense wear and reduction in wear resistance. We think that the first assumption is more realistic.

Further analysis of the diagram shows that the sample number 1, which contains only 0.5 wt.% of vanadium has the lowest wear intensity. Then, in an ascending order, follows the sample number 2 which contains 1.0 wt.% of vanadium, then the sample number 3 with 2.0 wt.% of vanadium, and finally the sample 4 with 3.0 wt.% of vanadium, which has the highest wear intensity, i.e. the lowest wear resistance. We believe that the increased vanadium content reduces the wear resistance of the steel. Figure 4 shows a characteristic wear diagram of the sample intermittent testing. Figure 5 shows a histogram of the wear volume of the materials tested in continuous testing (see traces I, II, and III in Fig. 3b). The histogram shows that the sample Av1 with 0.5wt.% V has the lowest wear volume of the material; it is followed by the sample Av2 with 1.0wt.% V, then by the sample Av3 with 2.0wt.% V, and finally by the sample Av4 with 3.0 wt.% V with the highest wear volume.

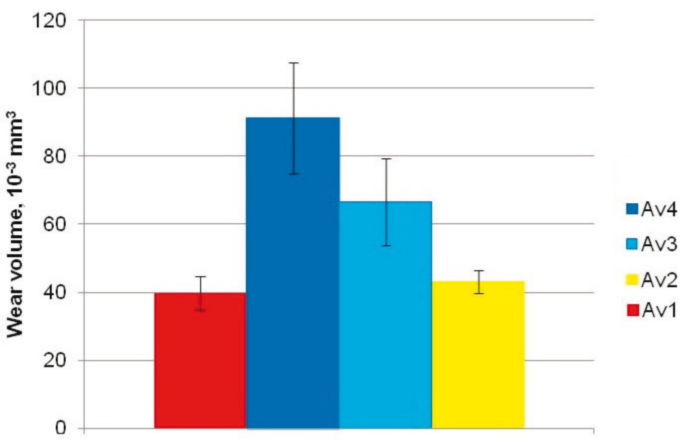
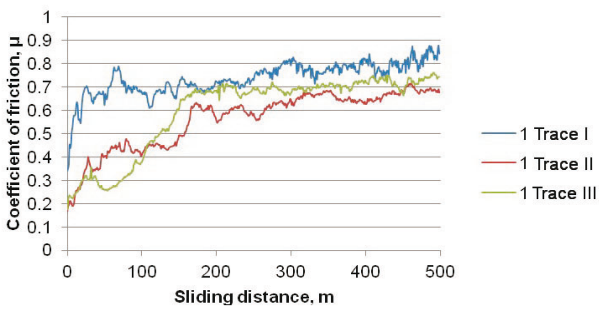


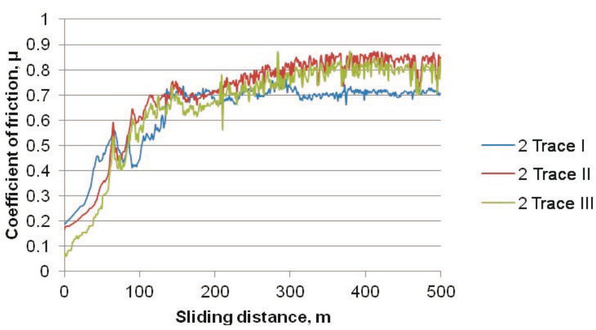
Fig. 5 The wear volume of the tested materials

Characteristic diagrams of the changes in the values of sliding coefficients between the friction disc and the sample for given chemical compositions are shown in Fig. 6. Figure 7 shows the mean values for all the samples for continuous testing.

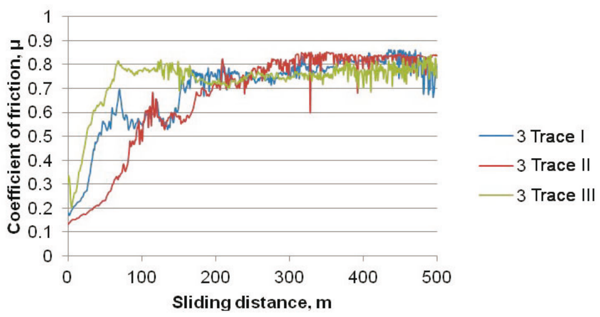
The diagrams of sliding coefficients show similarity because they reflect a comprehensive wear system. In the end, the surface of worn samples was recorded on a MEIJI TECHNO MT8500 light microscope. Figure 8 shows characteristic damages and wear traces of all tested samples.



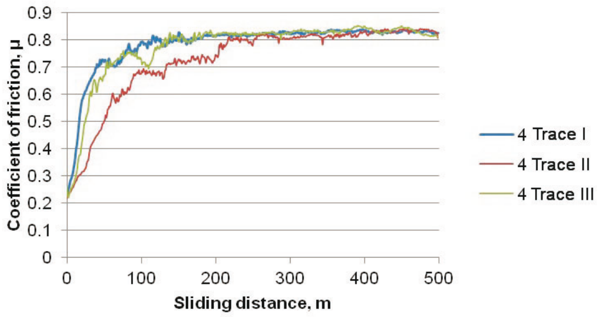
a) Sliding coefficient of the sample 1 (Group I)



b) Sliding coefficient of the sample 2 (Group II)



c) Sliding coefficient of the sample 3 (Group I)



d) Sliding coefficient of the sample 4 (Group II)

Fig. 6 Diagrams of changes in the coefficient of sliding friction between the sliding disc and the samples

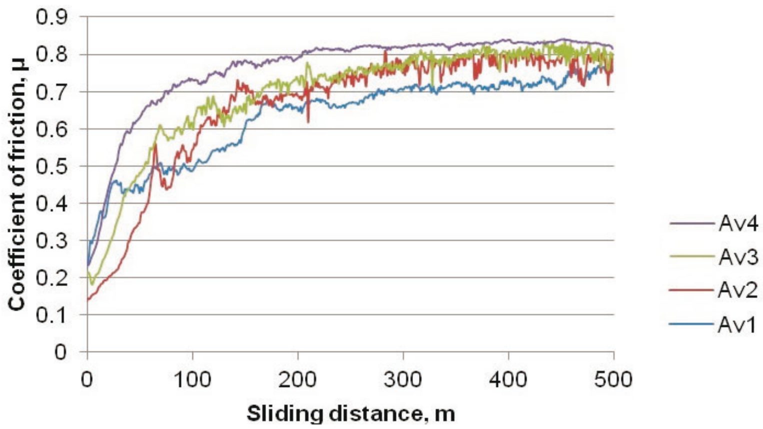
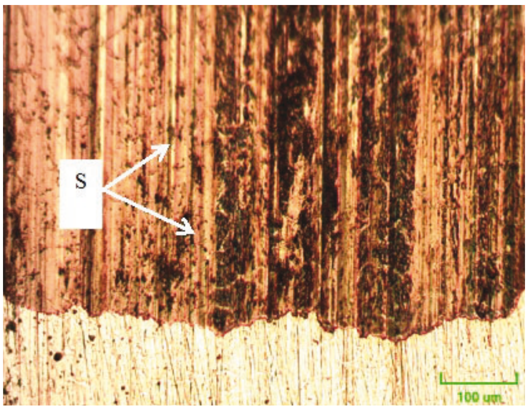
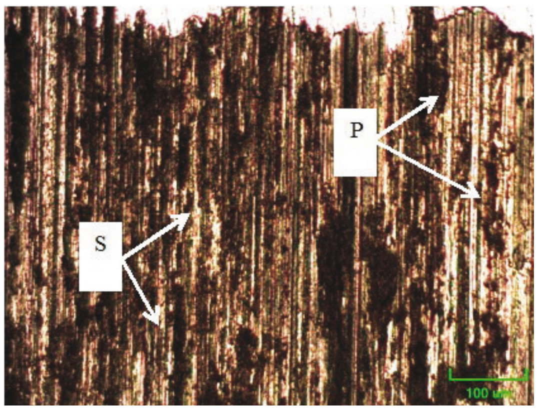


Fig. 7 Diagram of the change in the mean value of the sliding coefficient in continuous testing

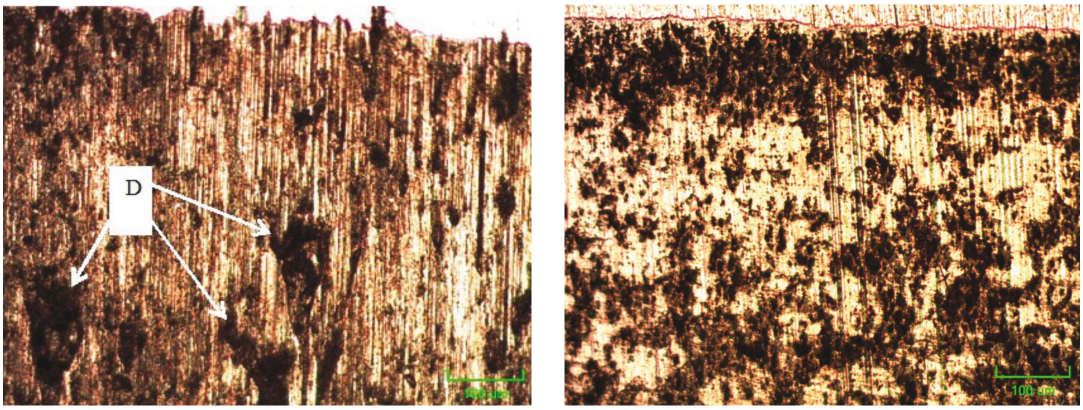
From the images in Figure 8, one can see that abrasive wear was a governing wear mechanism, which is confirmed by clearly visible parallel scratches and abrasive grooves in the sliding direction. As predicted, visual inspection with an optical microscope revealed that there was no visible damage on the disc surface due to its higher hardness. Accordingly, wear of the disc can be assumed as negligible. It should be emphasized that there are wear products (dark areas in Fig. 8) which are smeared and attached to the sliding surface during the process. By comparing the obtained images (wear traces, one can note a distinct difference in wear traces levels of different materials. It can be said that the pulling out of the material occurred in the contact zone, which can later behave as abrasive particles and can further increase surface damages. This surface phenomenon is characteristic of materials with high hardness. Also, characteristic of materials with high hardness tested under dry conditions is the occurrence of oxidation due to high temperatures in contact zones. This assumption could probably be confirmed by SEM analysis.



Sample 1



Sample 2



Sample 3 Sample 4

Fig. 8 Damages on the samples at 20x magnification; D – material detachment, S – scratches, P – pitting.

4. Conclusions

In this paper, the effect of vanadium content on the wear resistance of 1.4 % carbon steel, with chromium and molybdenum, is examined. Previous research has shown that by increasing the vanadium content, the microstructure of these steels becomes finer, which affects their mechanical properties, hardness and impact toughness, in particular. As the vanadium content increases, the hardness decreases slightly, while the impact toughness increases significantly.

By varying the vanadium content from 0.5 to 3 wt.% in the Cr-Mo steel, it can be concluded that the sample with 0.5 wt.% V has the best wear resistance; it is followed by the sample with 1 wt.% V, while the samples with 2 and 3 wt.% V have the worst wear resistance. In addition, the measured hardness is in accordance with the given conclusion.

The performed tests showed that the wear resistance of these steels decreased slightly with higher vanadium content. It can be concluded that the addition of vanadium generally improves mechanical properties, especially impact toughness, while the values of hardness and abrasion resistance remain at an acceptable level.

Based on the above, it can be concluded that the addition of vanadium to high-alloy chromium-molybdenum steels has a positive effect on the mechanical properties and that it allows the field of application of these materials to be expanded.

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