The effects of vanadium on microstructure and wear resistance of high manganese steels

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Abstract

The high Mn steels (HMS) are currently used in transportation components, large-scale grinders and crusher, and grinding wheels. This study is dedicated to the effects of vanadium content on the properties and wear behavior of HMS containing 0.3, and 0.6 wt.% vanadium as an alloying element. The samples were cast and then subjected to annealing heat treatment and followed by water quenching. The test samples were then cut via an electrical discharge machine. Characterization methods, including phase analysis via XRD and micro-structural investigations by SEM and OM , were carried out. The samples were also subjected to hardness and wear tests. The obtained results indicated that the addition of V to the HMS leads to the increased hardness and improved wear properties To the extent that in samples with vanadium, the amount of wear becomes practically negligible over time.Such outcomes were attributed to the role of vanadium in altering the precipitation sites of carbides,from grain boundaries to the grains, and its effect distribution of the carbides.

Keywords: High manganese contained steels, Vanadium, Microstructure, Hardness, Wear resistance.

1. Introduction

The austenitic Mn-contained steels, including 1.2 wt.% C and 12 wt.% Mn, were initially introduced by Robbert Hadfield in 1882. The so-called Hadfield steel is currently known as the only austenitic steel which provides an acceptable combination of properties, including ductility, toughness, work hardenability, and wear resistance. While the wear is known as one of the leading causes of failure in industrial components, improving the wear behavior evokes various strategies from materials selection and surface treatment methods.

Wear properties of the materials are commonly measured through the wear tests, most commonly the pin-on-disk method, in which a determined pin sweeps the surface of the test material through circular and cycling movement. The most important test parameters include the vertical force, linear sweep rate, and the swept distance of the pin. While the weight loss of the sample is measured as the primary wear properties, friction coefficient and the surface temperature is also of particular interest. The test can also be carried out in a controlled temperature and environment [1,2)].

In the case of quenched steels, it has been reported that the spherical-shaped carbides of elements such as chromium, molybdenum, vanadium, and titanium present improved properties compared to irregular and/or flaky-shaped intergranular carbide precipitates [2)]. Hence, achieving a similar microstructure in the vanadium-contained Hadfield steels is one of the main goals of the present study, mainly to increase the

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wear resistance, as well as optimizing the mechanical behavior of the mentioned steel. Therefore, different amounts of vanadium have been added to the steel, and the effects of such an alloying element have been studied. In the present study, changes in hardness, wear resistance and functional life of production samples have been studied simultaneously and in parallel, and due to the high consumption of this steel in industry, the results of this study can be used to increase the service life of production parts and Reduced supply costs.

Materials and methods

The samples, Y blocks of the ASTM A 128 grade C Hadfield steel, were prepared through the sand casting via sodium silicate binder and CO_2 hardener. The molten alloy was prepared via an induction furnace, using the steel scraps and the calculated amount of the needed ferroalloys, and aluminum as the degassing agent. Three samples with different amounts of vanadium were prepared and then followed by an annealing-quenching treatment to remove the intergranular precipitated carbides [3]. The chemical compositions of the heat-treated samples are presented in Table 1.

The wear test samples were then prepared according to ASTM G99, including 23×18×19 mm sized blocks cut from the primary Y-shaped components via an electrical discharge machine (EDM). The samples were then weighed and subjected to a pin-on-disk wear test. The test parameters were selected as follows: the distance of 3000 m, the load of 2 kg, SiC disk, room temperature and the moisture content of 30%, the applied tension of 100 KPa, and the linear velocity of 10m/min. The weight losses of the samples were repeatedly measured every 600 m and recorded. While the macro-hardness test was carried out through the Brinnel method according to ASTM E10-10, the vickers method (ASTM E334-69) was applied in micro-hardness measurements.

Results and discussion

The results of XRD analysis of the samples, which are presented in Fig. 1, show a phase arrangement including an austenitic matrix and dispersed Mn_7C_3, Cr_3C_2, and M_3C (M=Mn and Cr) carbides.

Table 1. The chemical composition of the cast samples.

Sample	Composition (wt.%)								
	C	Si	S	P	Mn	Ni	Cr	Mo	V	Fe
1	1.20	0.78	0.01	0.01	12.41	0.05	1.47	0.09	-	
2	1.17	0.81	0.01	0.01	12.38	0.06	1.50	0.07	0.30	blanced
3	1.19	0.82	0.01	0.01	12.33	0.04	1.50	0.09	0.60	

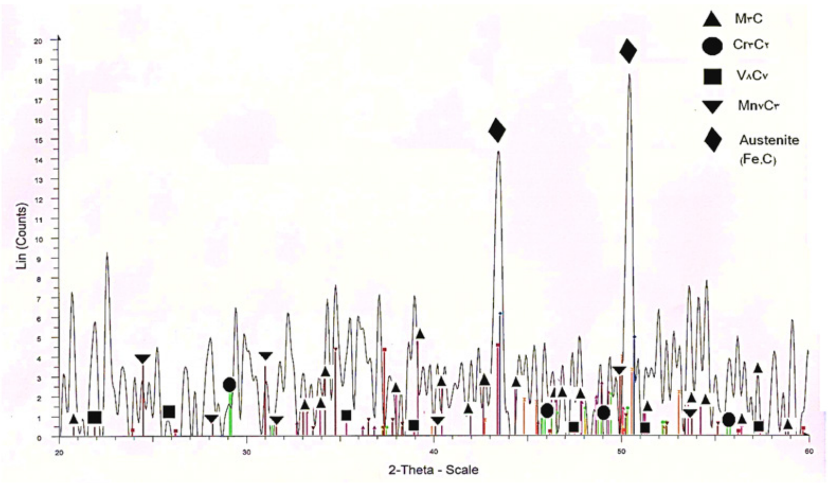


Fig. 1. XRD pattern of as-cast sample 3.

Tables 2 and 3 show the results of macro-and micro-hardness measurements, respectively. As shown in Table 2, increasing the vanadium content of the steel has led to increased hardness, which can be attributed to the precipitation hardening promoted by vanadium [1)].

A similar effect is also seen in micro-hardness results (Table 3), which is mainly derived from the solid solution hardening phenomenon resulted from the dissolution of carbides in the matrix through the annealing treatment.

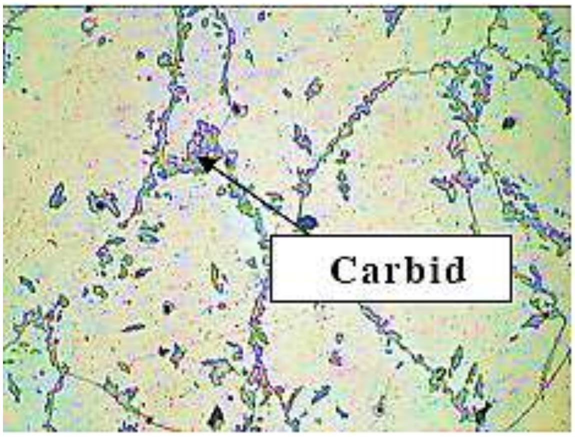
The as-cast and heat-treated microstructures of the witness sample (sample 1) are presented in Figures 2 and 3, respectively, which can be used in comparative studies of the microstructural effects of vanadium on the steel. The related microstructure of 0.3 wt.% V-contained sample is presented in Figures 4 and 6, while Figures 5 and 7 show the as-cast and heat-treated microstructures of 0.6 wt.% V-contained sample, respectively.

Table 2. The macro-hardness results of the samples.

Sample	1	2	3
Average (HBN)	209	215	219

Table 3. The micro-hardness results of the austenite matrix of the samples.

Sample	1	2	3
Average (HV 0.3)	262	283	302



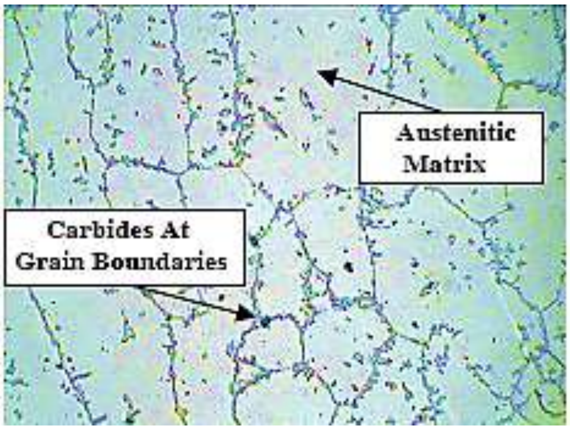


Fig. 2. The as-cast microstructure of sample 1, (a) austenitic matrix and (b) continuous carbides at grain boundaries.

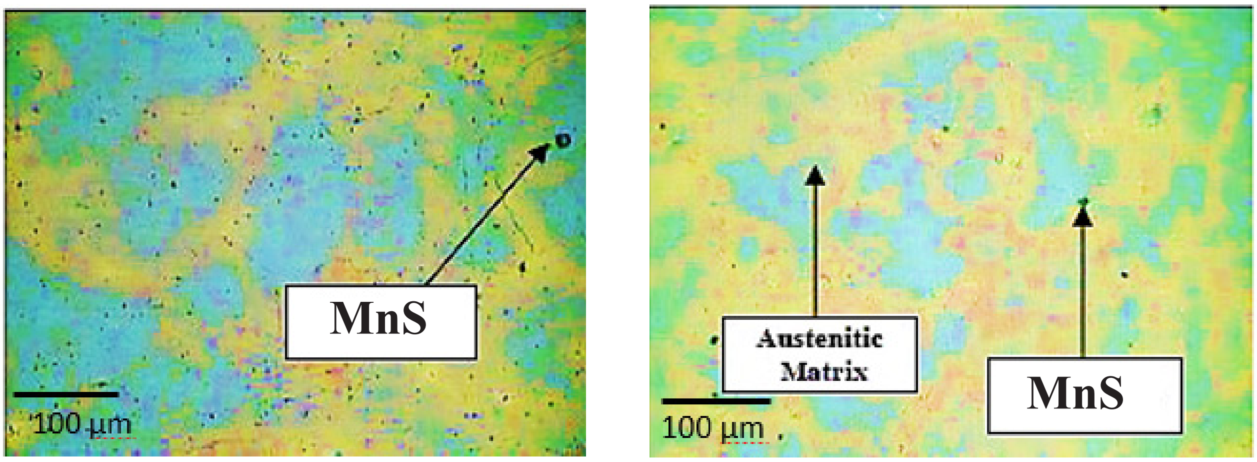


Fig. 3. The heat-treated (annealed) microstructure of sample 1, including the austenitic matrix and MnS particles.

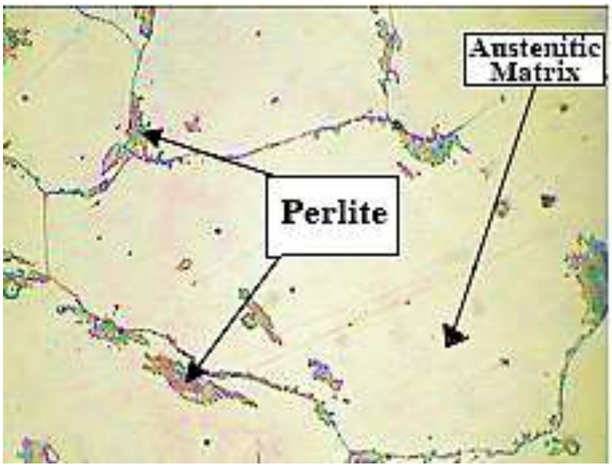


Fig. 4. The as-cast microstructure of sample 2, including the austenitic matrix and perlite.

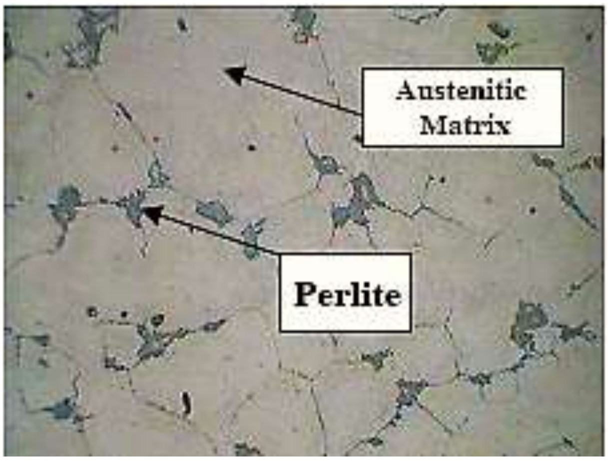


Fig. 5. The as-cast microstructure of sample 3, including the austenitic matrix and dispersed carbide particles at grain boundaries.

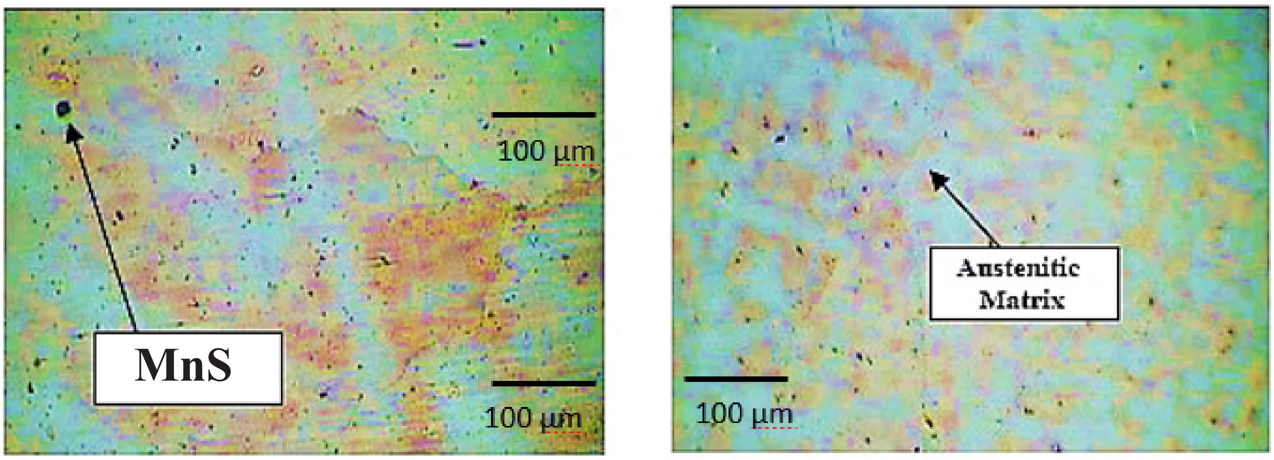


Fig. 6. The heat-treated (annealed) microstructure of sample 2, including the austenitic matrix and MnS particles.

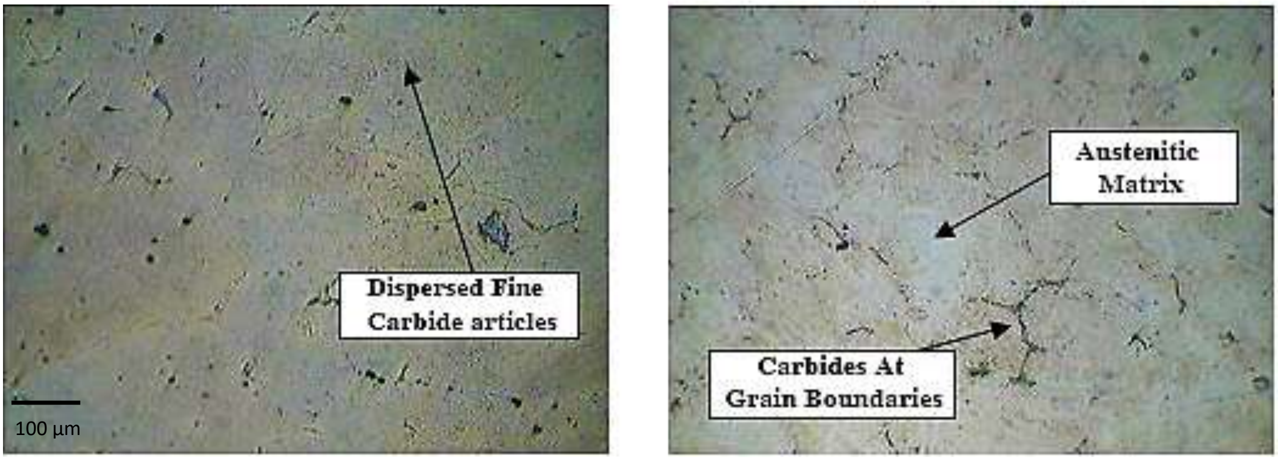


Fig. 7. The heat-treated (annealed) microstructure of sample 3, including the austenitic matrix and dispersed fine carbide particles.

Table 4. The measured weight loss of the samples vs. every step of the wear test (m.gr).

Sample	1st 600 m	2nd 600 m	3th 600 m	4th 600 m	5th 600 m
1	176	52	147	73	73
2	642	375	201	59	35
3	130	56	92	205	22

Table 4 presents the results of the wear test of the samples, which shows the dramatic increase of the wear resistance in sample 3 (0.6 wt.% V-contained), compared to the other heat-treated samples.

It should be noted that although sample 2 initially shows the worse wear behavior compared to the other samples (maximum weight loss through the first and second 600m steps of the wear tests), minimal weight losses are measured for this sample in 3rd, 4th, and the final steps. In other words, the weight loss of sample 2 seems to be even lower than the standard sample at the 4th and fifth wear steps.

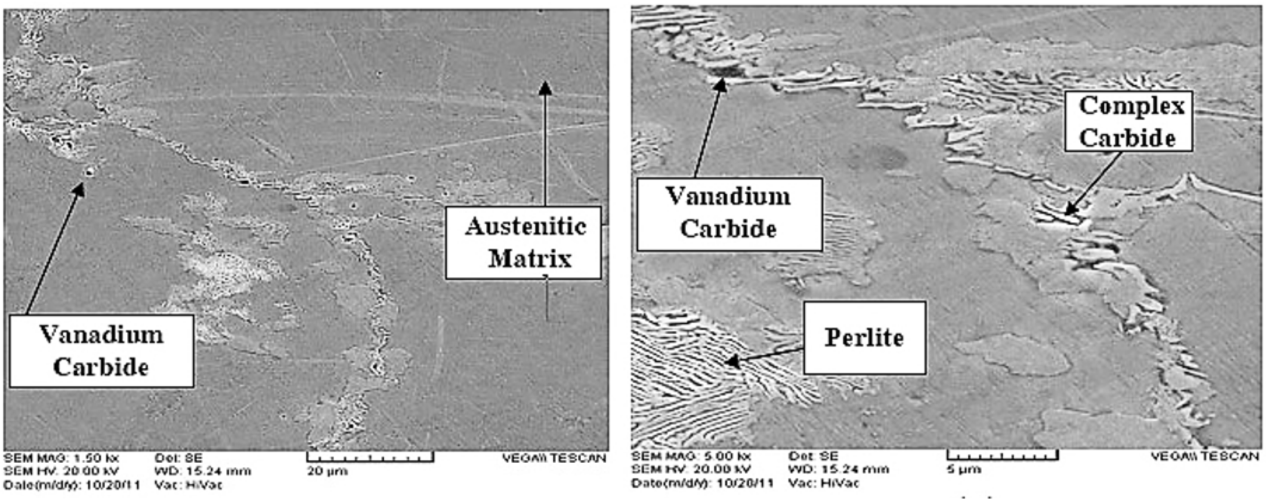
The variation of the weight loss of the samples during the pin-on-disk wear test can be attributed to two competing parameters, including the work-hardening phenomenon and carbide particle detachment [1]. While the former parameter is controlled by the martensitic phase transformation and enhances the wear resistance, the latter parameter is directly affected by the shape of the carbide particles. In other words, the spheroidal carbide particles can be detached and entrap at the interface of the wearing disk and pin, and not only increase the distance between the wearing surfaces but also act as revolving balls and reduce the surface erosion. However, the presence of irregular-shaped carbides may intensify the erosion of the surfaces, either by the detachment of such carbides from the surfaces or scratching the surfaces by the mentioned sharp-edged particles, and consequently, cause enhanced weight loss.

In sample 2, it seems that the amount of vanadium (0.3 wt.%) is not sufficient to promote the early martensitic transformation. In other words, the postponed martensitic transformation consequently causes delayed work hardening (till the 3rd 600 m steps). However, the occurrence of martensitic transformation in the next steps (4th and fifth) would be accelerated compared to vanadium-free sample, which manifests as improved wear resistance. The higher weight loss at the first three steps of the wear test in sample 2 can also be attributed to the detachment of the irregular-shaped (sharp-edged) carbides (Fig. 9). However, further erosion of these carbides would eliminate their sharp edges, and then, scratching the surface by the carbides would be stopped according to the previously mentioned mechanism of interfacial entrapped spheroidal particles (increased wear resistance).

The increased vanadium content in sample 3 (0.6 wt.%), however, causes accelerated work hardening and martensitic transformation, and results in improved wear behavior at the early steps of the wear test. Additionally, the presence of 0.6 wt.% vanadium has resulted in the formation of spheroidal carbides in the as-cast microstructure (as shown in Fig. 11) and, consequently improved wear resistance through the previously discussed mechanism.

According to Table 3, it should be noted that the presence of vanadium in samples 2 and 3 has resulted in higher hardness of the steels compared to the standard high Mn steel (sample 1), which logically promotes the detachment and erosion of the spheroidal carbides (higher wear resistance).

According to Figures 6 and 9 it seems that most of the precipitated carbides at the grain boundaries have been dissolved in the matrix through the annealing heat treatment, and then, except for some fine and dispersed carbides, no grain boundary phases are formed in the vanadium-contained samples. Also, a skinny thin layer of the boundary carbides can be identified in Figures 7 and 11, which are fine agglomerated carbide particles (see Fig. 11). Therefore, it can be concluded that most of the grain boundary carbides have been successfully removed through the heat treatment, and most of the remained carbides are dispersed as fine particles in the matrix. According to Figures 9 and 11, it can be concluded that the presence of 0.6 wt.% vanadium has led to more spheroidal and fine carbide particles inside the grains, which confirms the improved wear behavior of sample 3. The as-cast microstructure of samples 2 and 3 are presented in Figures 8 and 10, respectively.



Element	Weight%	Atomic%	Element	Weight%	Atomic%
V	67.96	43.96	V	0.39	0.25
Cr	6.19	3.93	Cr	3.50	2.17
Mn	1.81	1.09	Mn	16.43	9.63

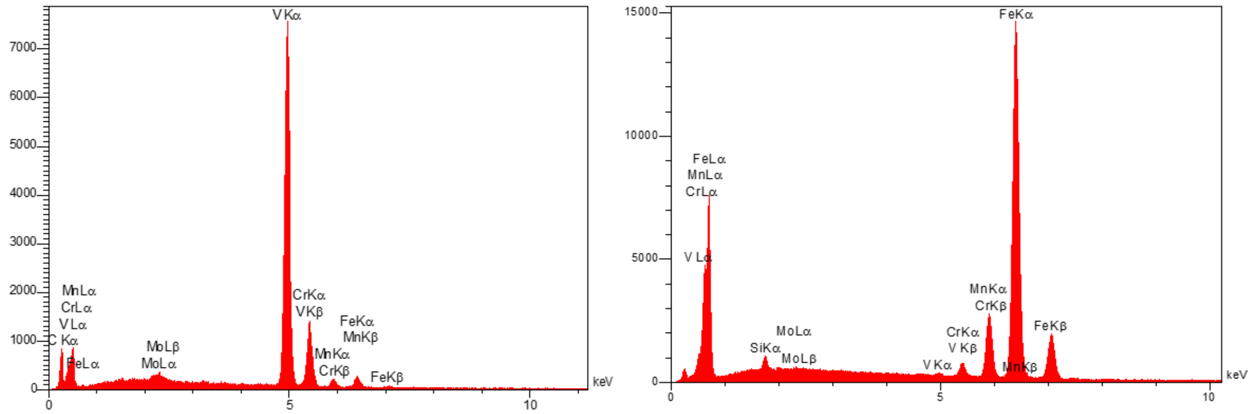
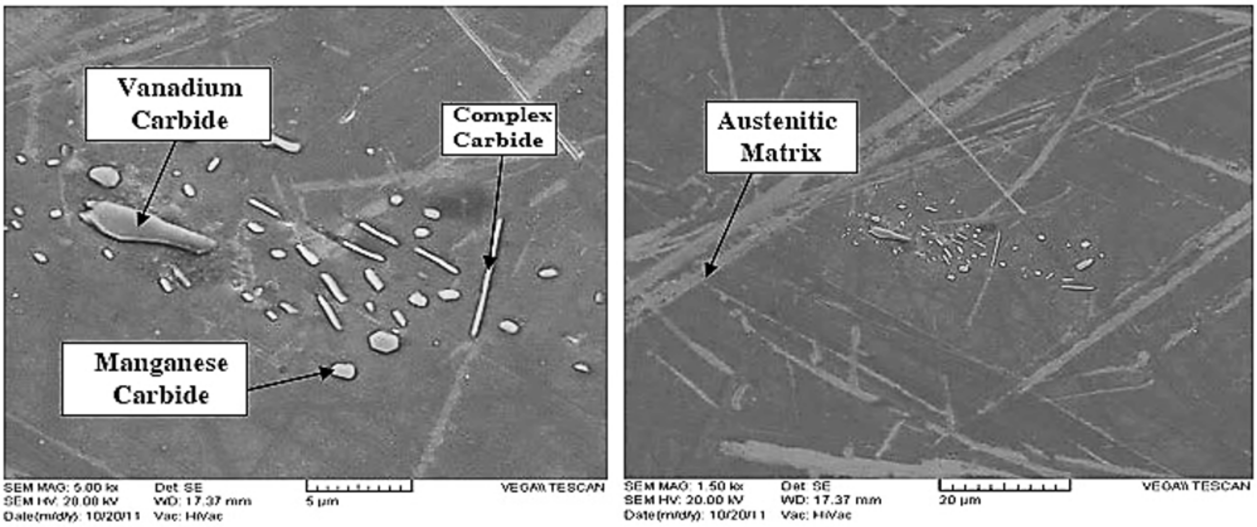
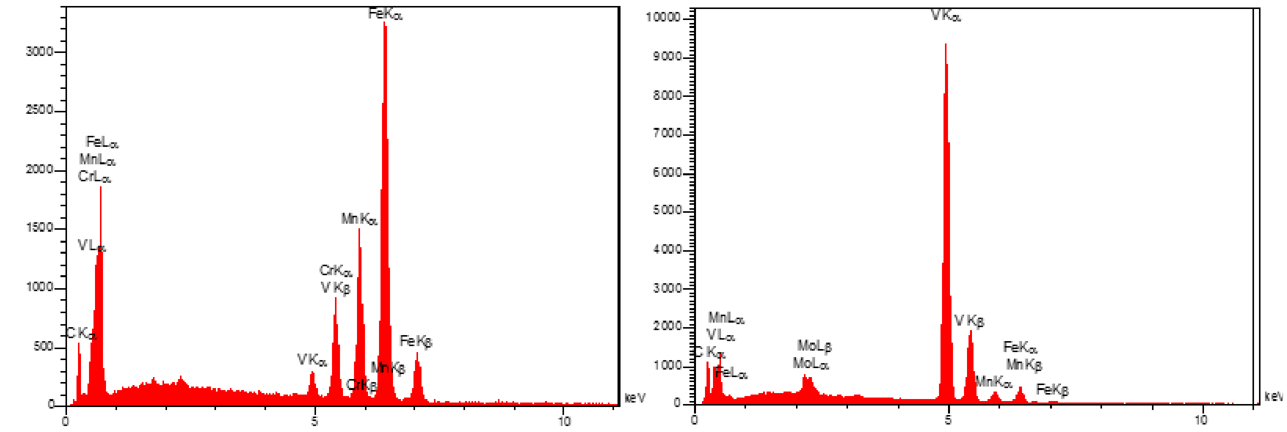


Fig. 8. The FESEM micrographs of the as-cast microstructure of sample 2 and related EDS results, (a) 1500X and (b) 5000X magnifications.



Element	Weight%	Atomic%	Element	Weight%	Atomic%	Element	Weight%	Atomic%
V	57.3	29.7	V	0.76	0.47	V	1.71	0.9
Cr	-	-	Cr	1.54	0.71	Cr	7.1	3.62
Mn	3.12	1.47	Mn	12.13	5.53	Mn	15.76	7.72



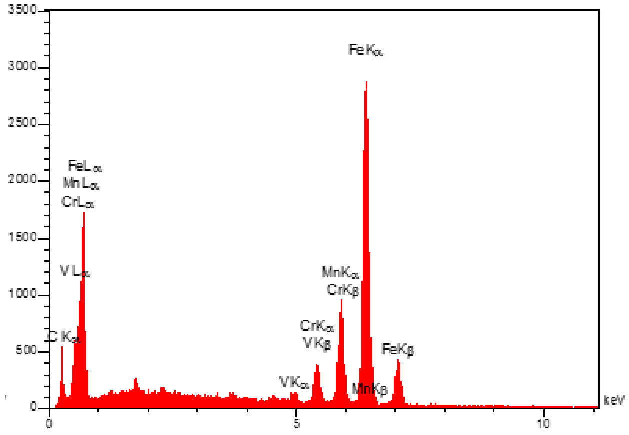
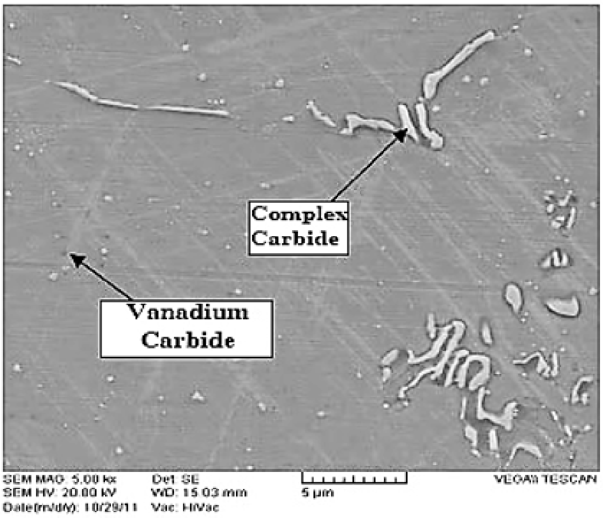
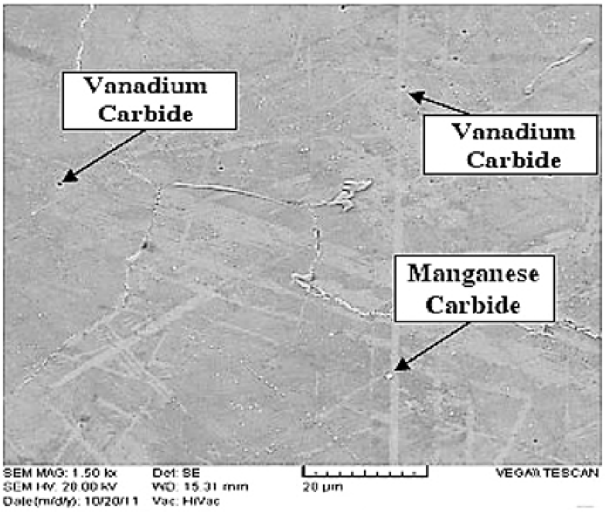


Fig. 9. The FESEM micrographs of the heat-treated (annealed) microstructure of sample 2 and related EDS results, (a) 1500X and (b) 5000X magnifications.





Element	Weight%	Atomic%	Element	Weight%	Atomic%
V	40.00	22.22	V	0.3	0.2
Cr	-	-	Cr	2.67	1.71
Mn	5.43	2.80	Mn	12.8	7.79

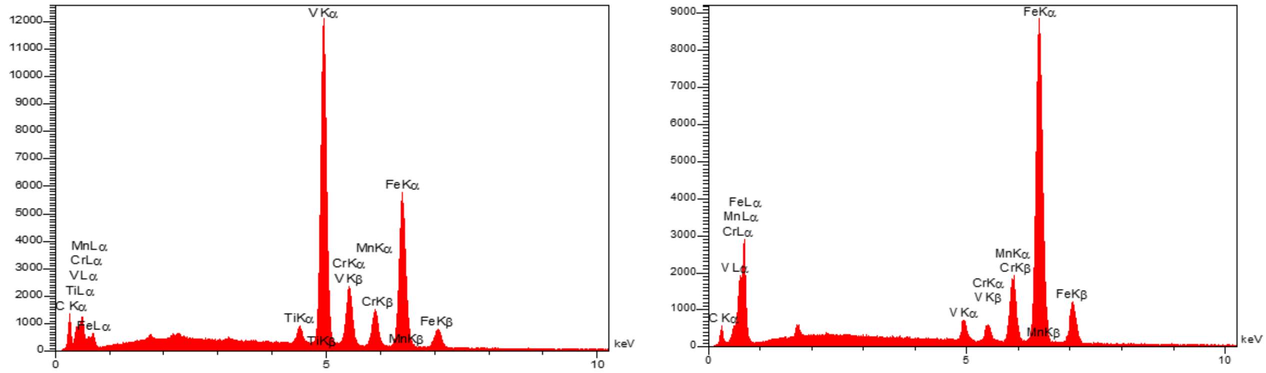
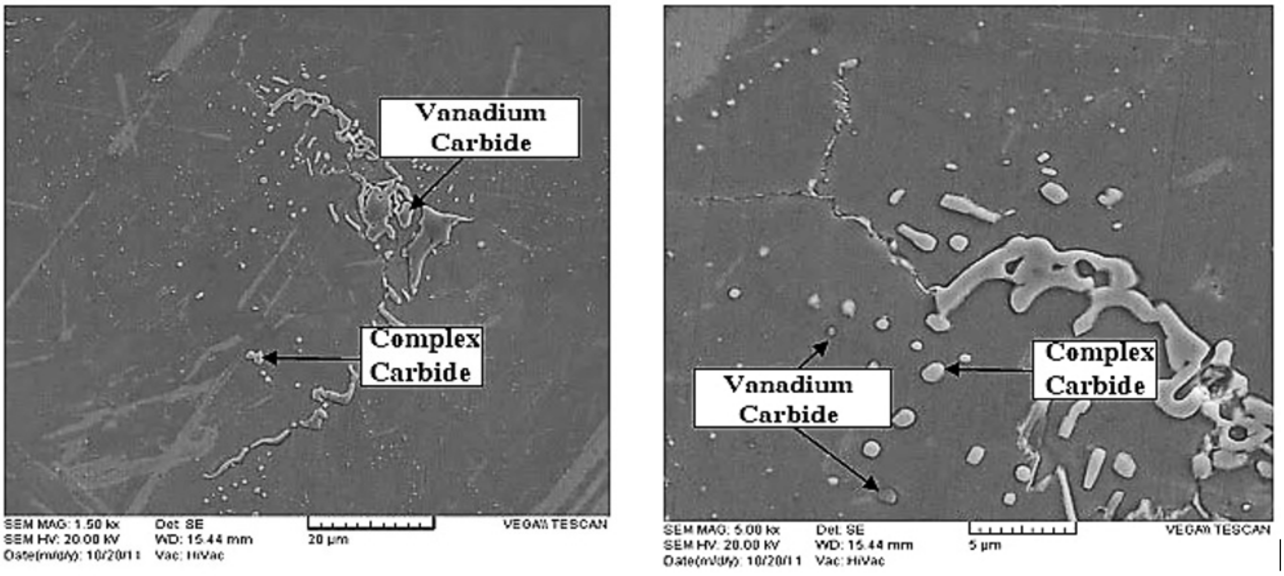


Fig. 10. The FESEM micrographs of the as-cast microstructure of sample 3 and related EDS results, (a) 1500X and (b) 5000X magnifications.



Element	Weight%	Atomic%	Element	Weight%	Atomic%
V	59.64	30.47	V	1.15	0.67
Cr	4.5	2.25	Cr	4.67	2.68
Mn	1.26	0.6	Mn	13.51	7.33

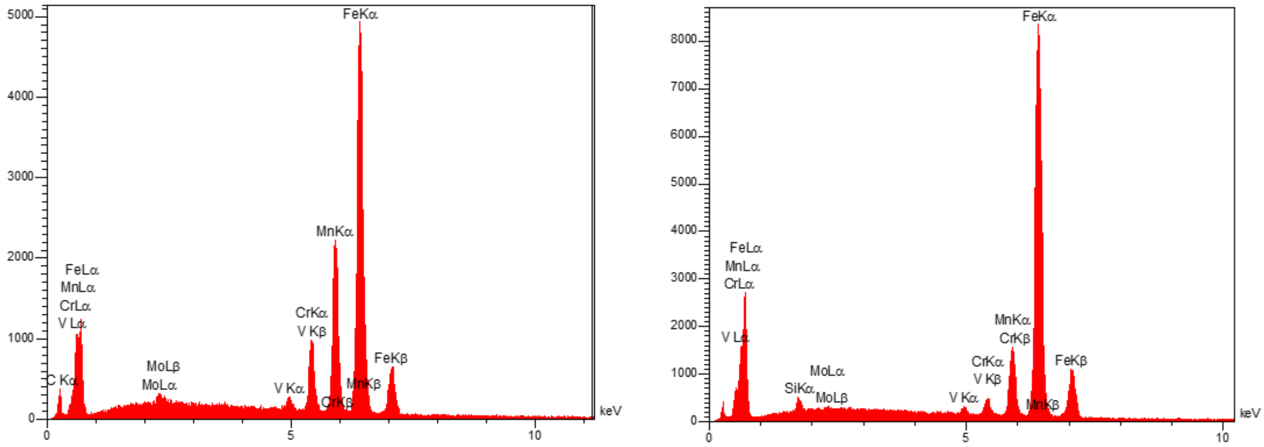


Fig. 11. The FESEM micrographs of the heat-treated (annealed) microstructure of sample 3 and related EDS results, (a) 1500X and (b) 5000X magnifications.

According to the stability of vanadium carbide particles, such carbides can act as the nucleation sites for the other carbides in the system. Hence, increased vanadium content can lead to increased nucleation sites, which result in more dispersed and finer carbides in the matrix. The EDS spectra of the mentioned carbides also show vanadium in all the investigated carbide particles, which confirms the role of vanadium carbide as the nucleation sites. Consequently, increased vanadium content also can lead to more stabilized carbide particles in the system.

4. Conclusion

- Addition of about 0.6 wt.% vanadium into the HMS results in the formation of V_8C_7, Mn_7C_3, Cr_3C_2, and complex M3C (M=Mn and Cr) carbide phases in the microstructure.
- The addition of vanadium improves the wear resistance of HMS.
- The sample contained 0.6 wt.% vanadium presents the best wear behavior.

- The detachment of the spheroidal carbide particles through the wear test and the entrapment of them between the two wearing surfaces results in the revolution of the ball-type carbides and decrease the rate of weight loss
- The irregular-shaped and sharp-edged carbide particles inversely affect the wear behavior of the studied steels, promote the local scratch and erosion of the wearing surfaces, and increase weight loss (poor wear behavior).
- The presence of vanadium in the steels may act as the nucleation sites for the other carbide phases

  The addition of 0.3 wt.% vanadium to the HMS initially results in decreased wear resistance and then, followed by improved wear behavior.
- Increasing the vanadium content of the steel to 0.6 wt.% results in improved wear behavior through all the steps of the wear test.
- A combination of work hardening and particle detachment can be introduced as the dominant wear mechanism in the vanadium-contained HMS.

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