Investigating the Effect of Manganese Content on the Properties of High Manganese Austenitic Steels

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Abstract: In this study, in order to investigate the effect of increasing the manganese content on microstructure and mechanical properties of high manganese austenitic steels, three alloys with successive increases in weight percentages of manganese (7.55, 13.1, and 16.5) and carbon (0.8 and 1.2) were cast in the presence of a constant amount of chromium (1.5 wt.%) and silica (0.6 wt.%). The samples experienced solution annealing heat treatment comprised of austenitizing at 1100°C for 2 h followed by rapid quenching in stirred water. Hardness, tensile, and wear tests were conducted by dry sand/rubber-wheel abrasion method. Microstructural observations were performed by using optical (OM) and scanning electron microscopies (SEM) and energy dispersive spectroscopy (EDS). The obtained results revealed that after heat treatment a uniform austenite structure has developed in all three samples. With the increase of weight percent of the elements from sample 1 to sample 3, the hardness value reaches from 191 to 218 Vickers. Also, with the increase of manganese weight percent from 7.55 to 16.5, the ultimate tensile strength and wear resistance showed 11% and 29% increase, respectively, to the effect that the most enhanced mechanical properties and maximum wear resistance were observed in sample 3 with 16.5wt % of manganese. This improvement in mechanical properties and wear resistance is related to the formation of the solid solution in the matrix, the increase of hardenability, and the increase of work hardening capacity resulted from the increase of manganese percentage. Examination of the abraded surfaces demonstrated that the involved wear mechanism was scratch wear mechanism.

Key words: Hardness, High manganese austenitic steel, Manganese, Strength, Wear resistance

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1 INTRODUCTION

High manganese austenitic steels which combine good toughness, flexibility, non-magnetism, good work-hardening capacity [1], and high wear resistance [2] are unique materials. However, these steels have some defects such as low yield strength (from 345 to 415 MPa) and inadequate machinability [1]. The proper structure for these steels is a single phase austenitic one [3]. To obtain this structure, the cast parts with carbide structures are exposed to solution annealing heat treatment at the temperature range of 950-1090°C and rapid quenching in stirred water [4]. Regarding the abovementioned properties, high manganese austenitic steels have found many industrial applications such as manganese hammers in cement industries, dredging, drilling, quarrying, dredging and drilling in oil and gas mines [5], and track switches in railway systems [6]. A wide range of researches have been carried out for improving the properties of high manganese austenitic steels. These include the addition of chromium, molybdenum, titanium, vanadium, and niobium for enhancing mechanical and wear properties of these steels [1], [7-10].

Najafabadi et al., observed that titanium addition leads to the formation of more carbides in the austenitic steel matrix and, consequently, hardness and wear resistance improvement [9]. Cao et al., considered the effect of niobium addition on the properties of high manganese austenitic steels and concluded that niobium addition causes the refinement of structure, the increase of strength and total elongation, more stacking fault energy (SFE), more twinning deformation and the improvement of non-magnetism [10]. Hofer and his colleagues investigated the effect of manganese addition on high manganese austenitic steels with 12, 16, and 22% manganese and observed that manganese addition results in the increase of yield strength [11]. In order to improve the wear resistance of high manganese steels under medium and low stress, Haitao et al., studied the effect of simultaneous addition of manganese and silicon on the wear behavior of high manganese austenitic steels and found that the prepared high silicon and high manganese steel exhibited better wear resistance in comparison with the conventional Hadfield steel sample, although it was accompanied by a reduction of mechanical properties, especially 37% decrease of impact resistance [12].

Wear is one of the main parameters involved in destruction of industrial machines, equipment and piece-works. On the other hand, no extensive research has been carried out on the simultaneous addition of carbon and manganese on the wear behavior of high manganese austenitic steels in Iran so far. Apart from that, the elements used in other studies are expensive and leave dual (positive and negative) effects on the properties of such steels, while carbon and manganese are available and consist of low cost elements. For these reasons, in the current work, by increasing the weight percentage of manganese (7.55, 13.1, and 16.5) and carbon (0.8 and 1.2), we aimed to obtain a kind of steel with the most appropriate micro structure and the most enhanced mechanical properties, particularly wear resistance, and consequently reduction of depreciation and part replacement in industry.

2 MATERIALA AND METHODS

The preparation of high manganese steel samples was carried out by melting carbon steel scrap, ferromanganese, ferrochromium, and carbon in a network frequency electric induction furnace with 800 kg capacity (Isfahan Casting Industries Co.). The melting was controlled by a pyrometer at the constant temperature of 1420°C and the successive increase of the weight percentage of the alloy elements was carried out as per ASTEM E8 standard [13]. Chemical composition of the samples was controlled by a Foundry Master 2005 instrument equivalent to ASTM E415-99a standard [14]. Table 1 presents the chemical composition of three samples with successive addition of the elements weight percent. To provide uniform conditions, the prepared samples were solution treated at 1100°C for 2 h and then rapidly cooled down in stirred water.

Table 1 The chemical composition of the as-cast high manganese austenitic samples (weight percent)

Alloy	%C	%Si	%Mn	%P	%S	%Cr
1	0.89	0.61	7.55	0.04	0.03	1.42
2	1.16	0.55	13.1	0.03	0.01	1.61
3	1.2	0.59	16.5	0.04	0.01	1.53

Microstructural investigations before and after heat treatment based on the ASTM E3 standard [15] were carried out by using optical microscopy (Olympus, model PME3). Vickers hardness measurements were done for 3 times on each sample in macro state according to the ASTM E92 standard [16] by a Koopa UV1 instrument with an applied load of 30 kg and in micro state according to the ASTEM E384 standard [17] by a Koopa MH1 instrument with an applied load of 0.5 kg. The tensile test was performed on 2 samples for each chemical composition based on DIN 50125[18] using a Gotech apparatus (model Al-7000LA20) at ambient temperature. To resemble the wear conditions of industrial work-pieces the wear test was performed via dry sand/rubber-wheel abrasion method as per ASTM G65-00 standard [19]. Fig. 1 displays the schematic of the wear test apparatus. In this test, the specimens with 76×25×10 mm dimensions were prepared by using a wire-cut instrument and then placed in front of the rotating abrasive steel wheel composed of Chlorobutyl rubber tire (width=13 mm, thickness =10 mm) with the constant rotational speed of 200 rpm of the rubber wheel.

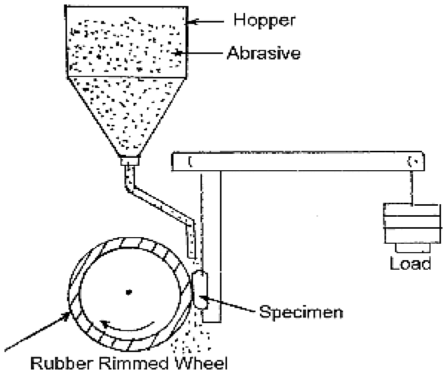


Fig. 1 Schematic of the dry sand/rubber-wheel abrasion apparatus (ASTEM G65-00)

A vertical load of 130 N is applied to the contact point of the sample with the wheel. Silica sand (quartz), grain size = 212-300 μm, humidity= 0.5 %, feed rate= 350 gr. min^{-1} was used as the abrasive media. The abrasive is fed at the contacting face between the sample and the rotating rubber wheel by a sand jet. The wear test was conducted for 30 min in 5 min steps equivalent to 4309 m distance or 6000 rounds and the results were reported based on weight loss (gr) versus time. For a more precise analysis of the abraded surfaces microstructure, scanning electron microscopy (SEM, Philips, model XL30) and energy dispersive spectroscopy (EDS) were utilized. Following that, three samples are named sample 1, 2, and 3 based on the increase of manganese and carbon weight percentages to be investigated in terms of microstructure, hardness, tensile and yield strengths, toughness, and wear resistance.

3 RESULT AND DISCUSSION

3.1. Microstructural studies

Fig. 2 displays the microstructure of the three as-cast samples. In the presence of high percentages of carbon, manganese and iron, there is a high tendency of continuous carbide formation in the grain boundaries. These complex carbides are (Fe, Mn)$_3$C carbides [4], [6], [9], [20]. It is worth mentioning that these carbides belong to the rank of type I carbides with complex crystal networks. Their characteristic property is their easy dissolution by heating at austenitic temperature compared to type II carbides with simple crystal networks [21].

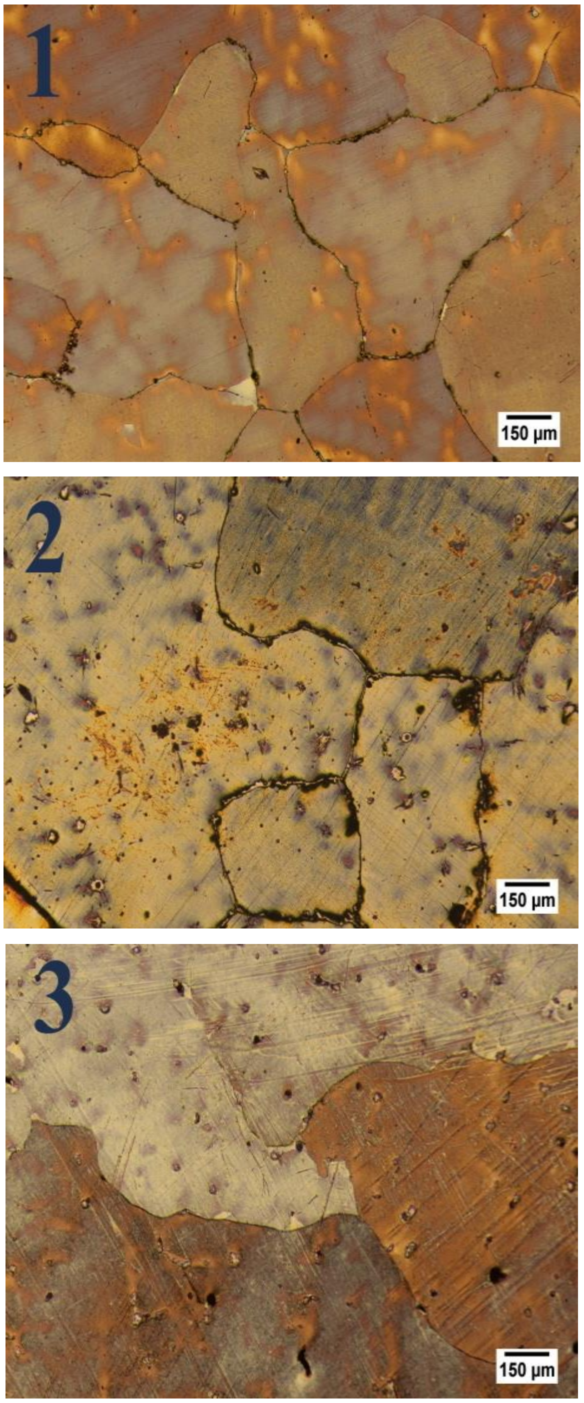
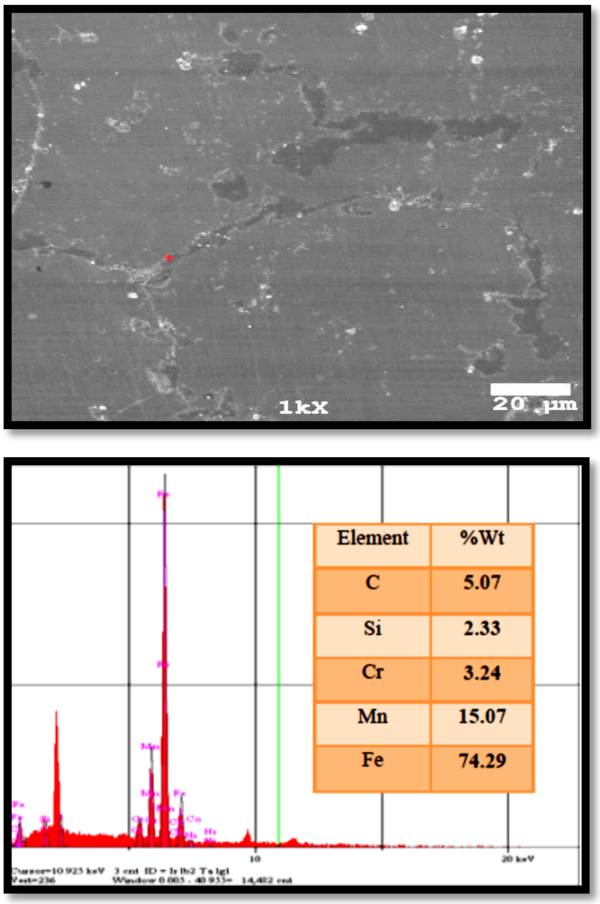


Fig. 2 Microstructure of the as-cast samples with 100x magnification: 1) The sample with 7.55% manganese, 2) The sample with 13.1% manganese, 3) The sample with 16.5% manganese

The EDS analysis of the grain boundary in the sample containing 13.1% manganese (Fig. 3) indicates (Fe, Mn)$_3$C carbides formation. The presence of these continuous carbides in the grain boundaries leads to the reduction of mechanical properties especially the decrease of impact strength and toughness in these steels. As a consequence, their brittleness prevents their applicability [9], [22]. Fig. 4 shows metallographic images of the samples after the cyclic solution annealing at 1100°C for 2 h and rapid quenching in water.

As can be clearly seen, by choosing a proper temperature and controlling the applied cycle and rapid water quenching, in all three samples, an acceptable austenitic structure (without carbides or with minimum percentage of carbides) is observed. As it was mentioned, continuous carbides lead to the significant reduction of mechanical properties particularly strength and impact resistance, and solution annealing causes the achievement of an appropriate structure and mechanical properties. For better investigation, the images are presented in 400x magnification.



Element	%Wt
C	5.07
Si	2.33
Cr	3.24
Mn	15.07
Fe	74.29

Fig. 3 EDS analysis of the grain boundaries in the sample containing 13.1% manganese

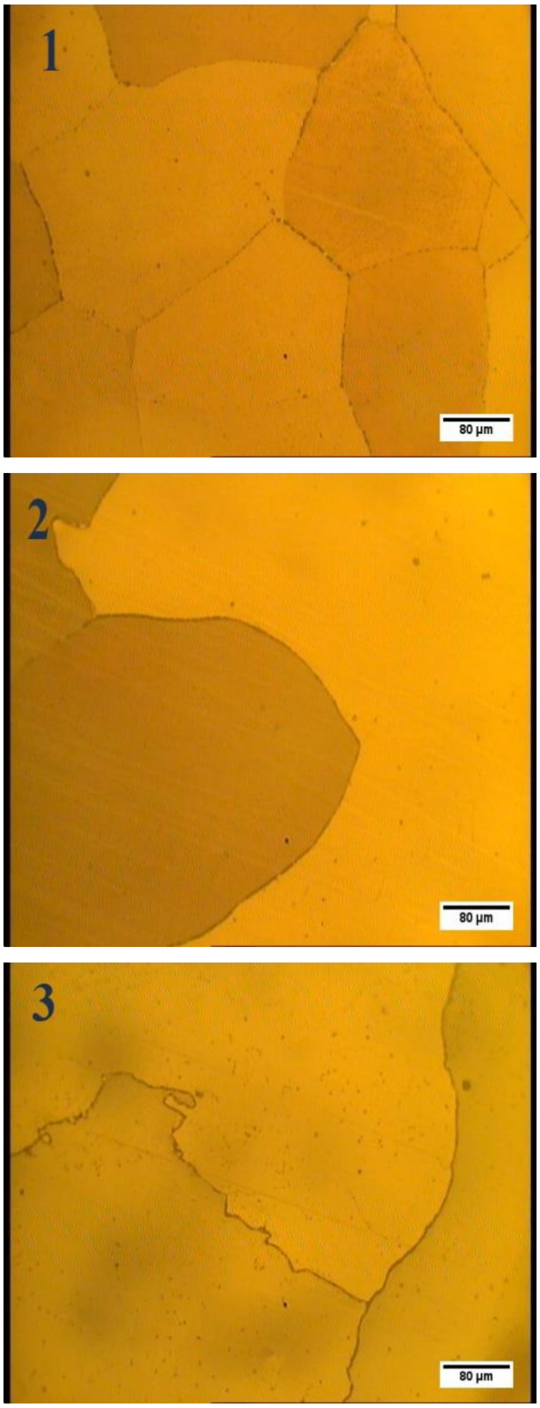


Fig. 4 Metallographic images of the three austenitic high manganese (7.55, 13.1, and 16.5%) samples after heat treatment (400 x magnifications)

3.2. Hardness

For a more detailed study the carbon potential of the as-cast samples was estimated according to equation (1) [12]:

$$C_P=[\,1+0.5(C-0.2)]C+0.15Si+[0.125+0.25(C-0.2)] \quad (1)$$

Mn+[1.25-0.5(C-0.2)]P+0.2Cr+0.1Ni

For each sample, the carbon potential was obtained by placing the elements weight percent in equation (1). As can be seen in Fig. 5, with increase of manganese and carbon weight percentages from sample 1 to sample 3, the carbon potential increased and, as a result, it is expected that hardness and wear resistance increase as well [21].

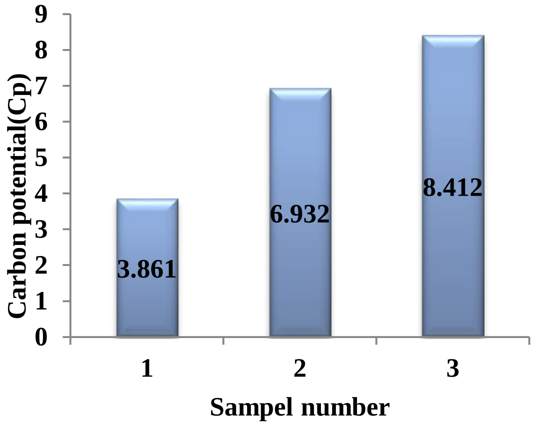


Fig. 5 The carbon potential of the as-cast austenitic high manganese samples

Hardness measurement results after heat treatment are given in Fig. 6. As can be observed, with the increase of weight percentages of manganese and carbon from sample 1 to sample 3, macro hardness has also increased, because these elements increase the samples hardness through the formation of solid solution [23].

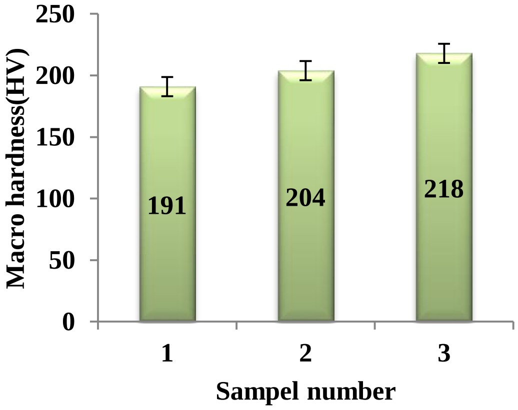


Fig. 6 The comparison of macro hardness in the three austenitic high manganese samples

Agunsoye et al., compared the mechanical properties of white iron with austenitic high manganese steel and observed that the increase of chromium percentage leads to carbide formation in the matrix and increase of hardness as well as improvement of wear resistance [5]. Subhi et al., reported the significant increase of hardness as a result of the formation of cementite (Fe_3C) phase in the matrix due to the increase of silicon percentage in Hadfield steel [24]. Haitao and his colleagues had also reported the increase of hardness with the addition of manganese and silicon to high manganese steel [12]. The hardness values are in good agreement with the carbon potential values of the three as-cast samples.

3.3. Tensile test results

Figs. 7, 8, and 9 demonstrate the tensile test results. As can be seen, the sample containing 16.5 wt.% manganese shows the highest yield strength, tensile strength, and toughness.

3.3.1. Yield strength

Fig. 7 indicates the insignificant increase in the yield strength with increasing manganese percentage [1]. On the other hand, it should be considered that in the presence of a constant weight percentage of chromium, the yield strength has shown a significant increase compared to the results of similar researches [25], [26]. This can be explained by the reinforcement of the austenitic matrix and subsequent increase of the yield strength by chromium [1], [4].

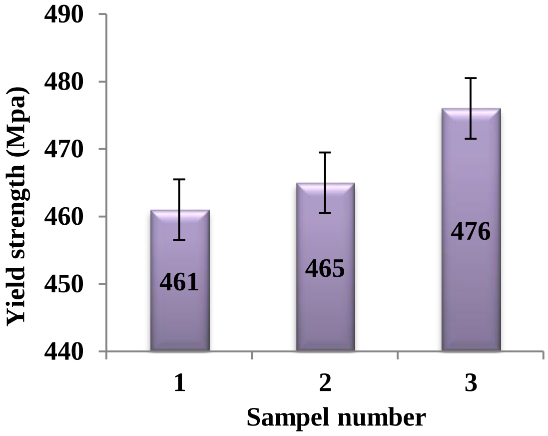


Fig. 7 The comparison of the yield strength in the three austenitic high manganese samples

3.3.2. Ultimate strength

The values of tensile strength of the three austenitic high manganese samples are presented in Fig. 8. It can be observed that with the simultaneous addition of manganese and carbon in sample 2 (13.1 wt.% manganese), the ultimate strength has a declining tendency. This is due to the increase of carbon and, consequently, the increase of the stacking fault energy as well as the energy required for twinning, which will lead to the reduction of the ultimate strength. This change of behavior in steels is related to the twinning strain, as the phenomenon of twinning due to plastic strain is dramatically dependent upon the stacking fault energy, so that with the increase of carbon percentage, the twinning energy is weakened [27]. In comparison, by increasing manganese in sample 3 (16.5 wt.% manganese), the stacking fault energy is reduced and hence the shear stress required for sliding is increased, leading to the facilitation of higher twinning strain. As a consequence, a higher tensile strength is achieved [27].

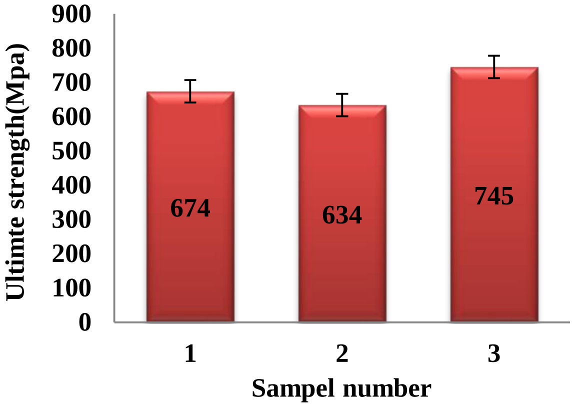


Fig. 8 The comparison of the ultimate strength in the three austenitic high manganese samples

3.3.3. Toughness

The area below the strain/stress curve was estimated. As can be seen in Fig. 9, the increase of manganese percentage from sample 1 to sample 3 leads to the increase of elongation and, as a consequence, the area below the strain/stress curve and the steel toughness have increased as well.

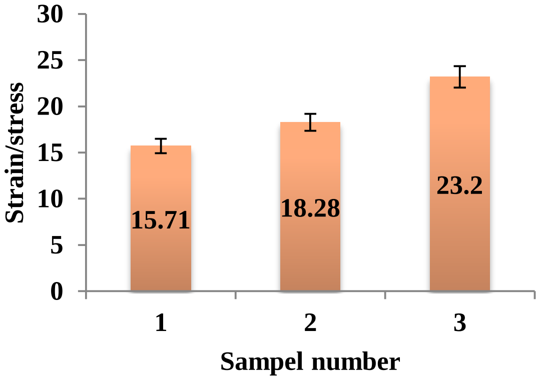


Fig. 9 The area below the strain/stress curve in the three austenitic high manganese samples

Therefore, the energy absorption under loading increase in a slow and uniform manner and a direct relationship between elongation and toughness is observed.

3.4. Wear test results

The wear test was carried out through dry sand/rubber-wheel abrasion test method under the applied load of 130 N for 30 min, the results of which are given in the form of the amount of weight loss versus time in Fig. 10. As can be seen, maximum wear resistance is related to the sample containing 16.5wt.% manganese. This is due to the increase of carbon and manganese percentages and subsequent increase of the samples hardness. It is known that the increase of hardness leads to the increase of wear resistance. Also, it can be observed that with the passage of time the amount of weight loss of the samples has decreased, which is due to the work hardening of the tested samples [1], [4], [28].

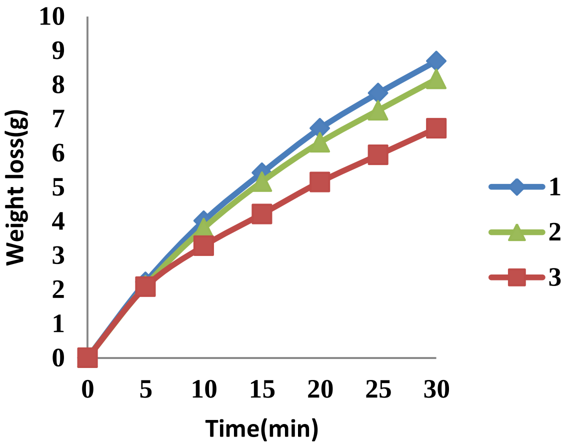


Fig. 10 The samples weight loss versus time

In order to investigate the effect of wear test on work hardening, the samples hardness was measured before and after the wear test. The obtained results are given in Fig. 11. As can be observed, in all samples the hardness increases during the test, which is due to the increase of hardenability resulted from the increase of manganese percentage [21]. It is worth mentioning that the presence of a constant amount of chromium affects the formation of a hard austenitic matrix and the improvement of both hardenability and wear resistance in the austenitic high manganese samples [1, 28].

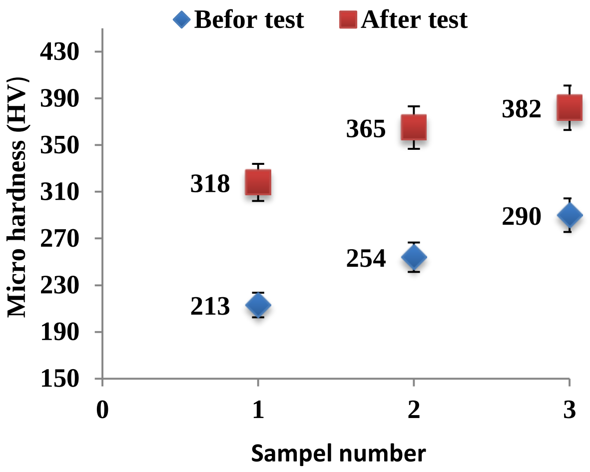
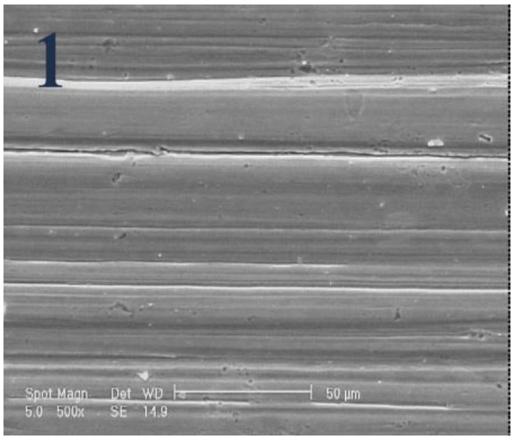
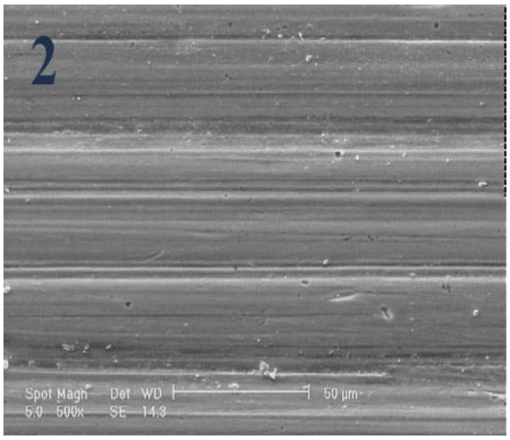


Fig. 11 The Micro hardness results before and after the wear test

3.4.1. Investigating wear surfaces and mechanisms

In order to study the wear mechanism, the samples abraded surfaces were examined by scanning electron microscopy (SEM). As can be seen in Fig. 12, due to the formation of parallel grooves on the surface, the dominant wear mechanism in all samples is scratch mechanism [29].





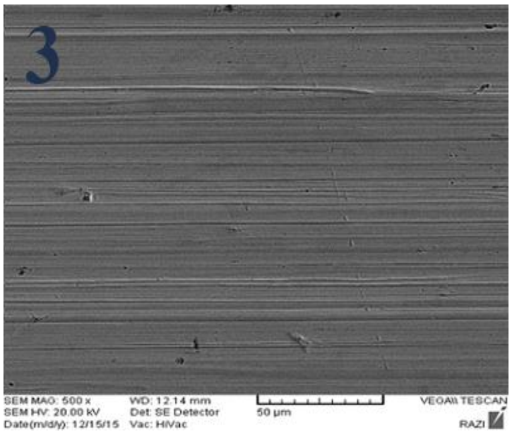
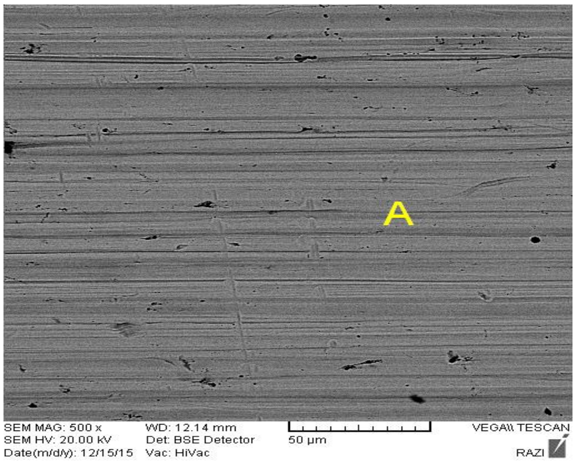
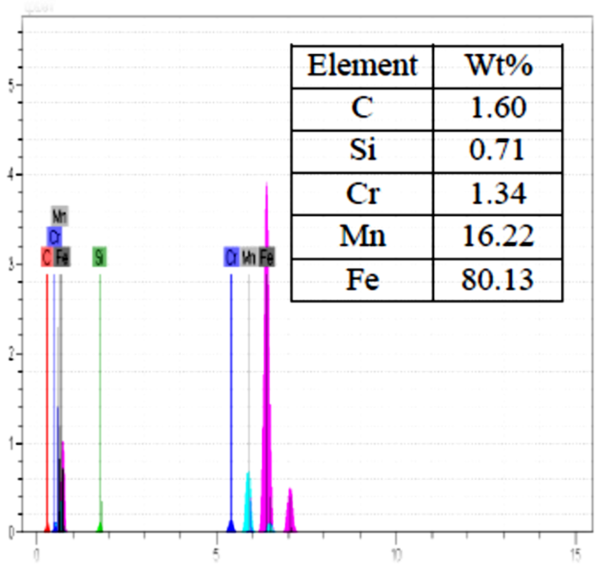


Fig. 12 The SEM images of the wear surfaces in samples 1) 7.55 wt.%, 2) 13.1 wt.%, and 3) 16.5wt.% of manganese

This is due to the increase of hardness resulted from the solid solution and also the effect of manganese on the increase of hardenability [21]. For investigating the occurrence of tribochemical wear, the EDS analysis was carried out on the surface of sample 3 (maximum wear resistance). The EDS analysis results in Fig. 13 indicate the absence of oxygen in the worn surface. Hence, it can be claimed that no tribochemical wear has occurred in these samples [30-32]. Improvement of wear resistance by the addition of various elements has been reported by other researchers, too. For instance, one can refer to the effect of 36% increase in titanium nitride as a composite to the austenitic high manganese steel matrix and the resulting improvement of wear resistance [33].





Element	Wt%
C	1.60
Si	0.71
Cr	1.34
Mn	16.22
Fe	80.13

Fig. 13 The SEM image and EDS analysis of point A of the wear surface in sample 3 (16.5wt% manganese)

4 CONCLUSION

1) The presence of continuous carbide in the grain boundaries of the three as-cast austenitic high manganese samples leads to brittleness and reduction of mechanical properties and, as a result, the performance of heat treatment is necessary. It was revealed that solution annealing heat treatment at 1100°C for 2 h resulted in the elimination of these continuous grain boundary carbides.

2) The hardness of the sample containing 16.5 wt.% of manganese showed 145 and 7% increase in comparison with the sample containing 7.55wt.% and 13.1wt.% of manganese, respectively. The reason could be found in the formation of solid solution due to the dissolution of carbides (iron, manganese and chromium) in the as-cast conditions and reinforcement of the austenitic matrix.

3) Maximum yield and tensile strengths obtained in the sample with 16.5wt.% manganese were 476MPa and 745MPa, respectively. Thus, the problem of low yield strength in Hadfield steel was overcome by increasing the manganese percentage.

4) The wear test indicated that in the sample with 16.5wt.% of manganese, wear resistance shows 29% and 6.5% increase in comparison with the 7.55wt.% and 13.1wt.% samples, respectively. This is due to the increase of hardness in the sample with 16.5wt.% of manganese with its high manganese content which reinforces the austenitic matrix through the formation of solid solution and increase of work hardening capacity.

5) Examination of the wear surfaces revealed that the dominant wear mechanism in the samples was scratch wear mechanism. The sample containing 16.5wt.% of manganese shows the lowest degree of scratch wear effects. The EDS analysis indicates that no tribochemical wear has occurred in the samples.

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