The International Journal of Materials and Engineering Technology (TIJMET) (2023) 6(1)
http://dergipark.gov.tr/tijmet
ISSN: 2667-4033

RESEARCH ARTICLE

Investigation of microstructure and wear performance of the high manganese steels

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Article Info

Article history:
Received 29.04.2023
Revised: 23.05.2023
Accepted: 24.05.2023
Published Online: 08.06.2023

Keywords:
Hadfield steel
High manganese steel
Al5Ti1B
Wear
Microstructure

Abstract

High manganese steel is a metallic material that has a very important commercial value especially in heavy industry and stands out with its features such as high wear resistance, and deformation hardening. In order to further improve the properties of these steels, many studies have reported on adding various elements to their structures. However, there is still a lack of understanding of the relationship between the wear mechanism and strain hardening due to changes in the microstructure of high manganese steel during the wear process and the complex carbides it contains. In this study, Al5Ti1B (1% wt.), which is also used as a grain refiner in the metallurgy industry, was added. After melting, casting, and other production processes, test samples were prepared for microstructure analysis, hardness, and wear tests. It was observed that there were carbide phases at the grain boundaries of the test sample, and the hardness value was determined to be 254 HV ± 14. The friction coefficients at 5 and 10 N loads increased by approximately 17.9% and 9.8%, respectively, by increasing the 500 m sliding distance to 1000 m. The effects of strain hardening and brittleness were also observed in the microstructure examinations after the wear test. In addition, a decrease in weight loss was observed, indicating that some deformation hardening occurred in the specimen during wear.

1. Introduction

Steels containing 1-1.4% carbon and 10-14% manganese in industrial applications and whose structure can remain 100% austenitic under suitable cooling conditions are called austenitic manganese steel or high manganese steel. These steels were first produced and patented in England in 1883 by Sir Robert Hadfield. For this reason, austenitic or high manganese steels are also known as Hadfield steel [1, 2]. High manganese steels have an excellent combination of hardness and ductility. This allows them to have high strength, toughness and wear resistance properties. The main reasons for choosing austenitic manganese steels for any particular application are, in order of importance: high toughness and wear resistance. Thanks to these properties, austenitic manganese steels are indispensable metallic materials for industrial areas such as excavation, railways, mining, petroleum and cement. They are used in the production of many other parts, such as crusher jaws, track shoes and rope pulleys, in these industrial areas [3-7].

The initial wear of cast parts subjected to wear under high loads not only shortens the service life of the parts but also significantly increases the production and repair costs of machine platforms. Such special parts should be selected from wear-resistant materials. Because the environmental conditions where abrasive wear is effective and the material properties that can be used in environments where impact wear is dominant are different from each other. However, it is very difficult to produce a uniform material that is resistant to all kinds of wear conditions in foundry conditions. For this reason, martensitic, pearlitic, austenitic and high-chromium steels are generally used in the mining industry, where wear is high, in oil drilling rigs, rolling mills, and excavation machines. Wear is not only a property of the material itself but also a property of the engineering system. For this reason, it is both difficult and uneconomical to produce a material that will show high wear resistance in every working system. The best solution to this problem is the selection of materials suitable for working conditions, the optimization of hardness and microstructure. Important criteria affecting wear resistance of steels have been put forward by scientists as a result of experimental studies. When these studies are examined, it is understood that the hardness and microstructure of the material are the leading criteria that positively affect the wear resistance. The most effective way to control the hardness of steels is to change the carbon ratio and add the appropriate alloying elements [8-10]. In addition, according to the Hall-Petch equation, there is a relationship between grain size and mechanical properties in metallic materials. In the metallurgical industry, Al5Ti1B is recognized for its grain-refining effect [11].

In this study, Al5Ti1B was added to the high manganese steel alloy to improve its wear resistance. Then, the effect of the addition of Al5Ti1B on the hardness, microstructure and wear properties of the high manganese steel alloy systemically was investigated.

2. Materials and methods

First of all, a Y block wooden model was made to prepare the sand mold for casting. A mixture of fine grained 35-40 AFS (American Foundry Society) silica sand (SiO_2), resin (1.5% of sand) and hardener (25% of resin) was used in the preparation of molding sand. Then, high manganese steel GX120Mn13 alloy obtained from scrap and ores was melted by heating up to 1420 °C in an induction furnace (EGES-EGP1500SE) to obtain 15 kg of Y block samples for experimental studies. For this, after the weight of the molten metal in the furnace reached

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How to cite this article:
Arslan, I., Gok, M.G., Kurt, H.I., Investigation of microstructure and wear performance of the high manganese steels, The International Journal of Materials and Engineering Technology (TIJMET), 2023, 6(1): 16-20

Table 1. The chemical compositions of the materials used in experimental studies

Material	% wt.										
	C	Si	Mn	P	S	Cr	Fe	Ti	B	V	Al
GX120Mn13	1.1-1.3	0.3-0.5	12-14	<0.1	<0.04	<1.5	Balance	-	-	-	-
Al5Ti1B	-	0.099	-	-	-	-	0.066	4.99	1.13	0.013	Balance
Specimen	1.29	0.637	13.5	0.056	0.004	1.68	Balance	0.03	*	-	0.3

** Since the atomic radius of the element boron is smaller than 1 Angstrom, it could not be detected by the current method.*

1200 kg, the desired composition was tried to be achieved by adding the determined ores into the molten metal. In addition, when the temperature of the molten metal reached 1420 °C, perlite was added to the furnace to form slag on the molten metal surface. This slag formed on the liquid metal surface was removed and the melt was cleaned. After these processes, 15 kg of liquid metal were taken into the crucible and 1% by weight of Al5Ti1B was added. The chemical compositions of the materials used as a result of the spectral analysis (Oxford Instruments/Foundry-Master Xpert) are given in Table 1. For heat treatment, GX120Mn13 alloy samples with Al5Ti1B addition were placed in the annealing furnace and heated to 1050 °C for 5.5 hours, and kept at this temperature for 2.5 hours. Then the samples were taken from the annealing furnace and immersed in the water pool.

Afterwards, the samples were cut in the precision cutting device using a water coolant and hot-mounted in the mounting device (Metkon Ecopress52). Then, the hot-mounted samples were wet sanded in a rotating polishing machine (Bulupol Grinding/Polishing Machine) using SiC sandpapers of different grades between 600 mesh and 1200 mesh. In the final step, they were polished on a cloth using a 6-micron diamond solution. A Bursam-NDT brand/model hardness measuring device was used to determine the hardness of the polished samples. In this process, the average of at least 10 different hardness measurements was taken and the standard deviation value was determined. On the other hand, the polished samples were etched in Nital (1-5 ml HNO_3 + 99-95 ml Ethyl Alcohol) solution for 10-20 seconds for microstructure studies. Optical microscopy (Nicon – Eclipse MA100) and scanning electron microscopy (SEM – ZEISS/GeminiSEM300) analyses were performed on the surfaces of GX120Mn13 samples having 1% by weight Al5Ti1B addition in this way. Moreover, the wear loss of the samples at 500 and 1000 m sliding distances under a load of 5-10 N was also investigated. The wear test was performed on the CSM Tribometer pin-on-disc wear device at a speed of 10 cm/sec. In order to determine the weight losses, the samples were weighed on a precision balance (Sartorius BL 210 S) before and after the wear test. Moreover, the scanning electron microscope was also used for the microstructure analysis of the worn surfaces of the samples after the wear test.

3. Results and Discussion

3.1. Microstructure and hardness evaluations

Microstructural images taken from the sample using optical and scanning electron microscopes are given in Figure 1 (a-d). In Figure 1 (a and b), microstructural images taken with an optical microscope at 5X and 50X magnification, respectively, were given. When these microstructures were examined, it was observed that the grains were homogeneously distributed and carbide phases were formed in the grain boundary regions as expected.

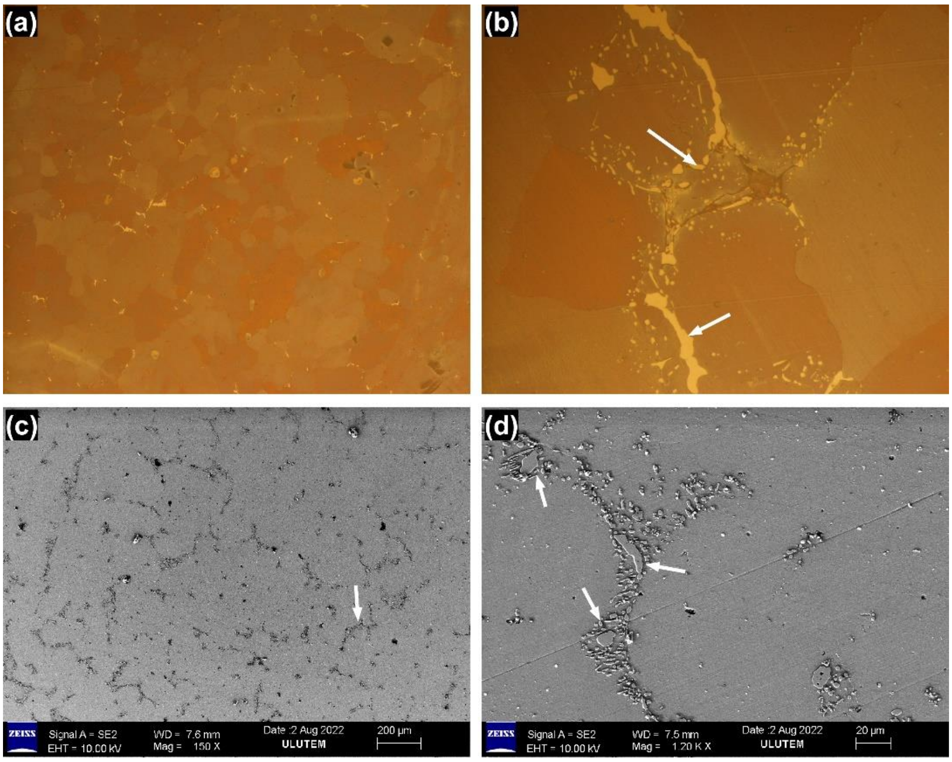

Figure 1. Images taken from the polished and etched sample surfaces by optical microscope ((a) - 5X) and ((b) - 50X) and scanning electron microscope ((c) - 150X) and ((d) - 1200X).

A similar situation was also evident in the microstructure images taken by SEM in Figure 1 (c and d). The carbide phase regions are indicated by arrows on the microstructure images. It is expected that the addition of Al5Ti1B to the chemical composition of high manganese steel decreases the austenite grain size and promotes the formation of carbides by reducing the amount of precipitate. In this case, the formation of carbide phases at the grain boundaries, will cause an increase in the hardness of the manganese steel. It is possible that small amounts of precipitated cementite are present at the grain boundaries of this high manganese steel. Tęcza and Klempka [12] also state that titanium-containing high manganese steel has secondary alloyed cementite at the grain boundaries and its amount is inversely proportional to the titanium content in the alloy.

When the graph of the hardness measurement result given in Figure 2 is examined, it is understood that the hardness of the steel with the Al5Ti1B addition was 254 HV ± 14. In the literature [2], it is seen that the hardness value of high manganese steels is approximately 225 HV. Therefore, as a result of the addition of the Al5Ti1B to the high manganese steel, an increase in the hardness value occurred due to the formation of carbide phases. Especially since the carbides of the elements Ti and B in Al5Ti1B are characterized by their high hardness, the formation of these carbides significantly increased the hardness of the high manganese steel. These carbides were complex and precipitated at the austenite grain boundary regions and had important effects on the mechanical properties of the materials [13-15].

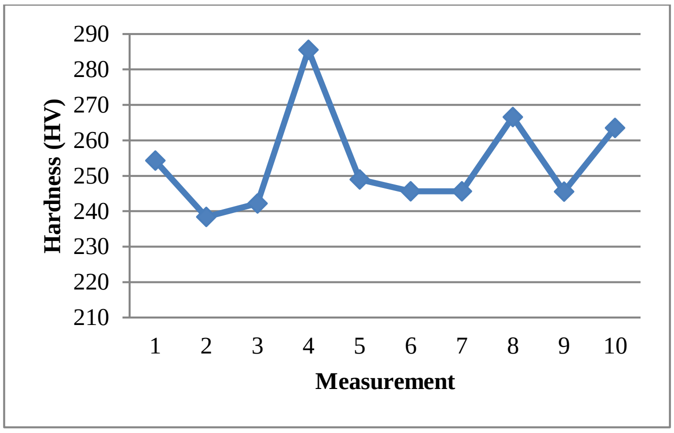

Figure 2. Hardness (HV) measurement results.

3.2. Wear Test Result

The wear coefficient and weight loss graphs obtained after 500 m and 1000 m of sliding distances at different loads (5N and 10N) as a result of the wear test are given in Figure 3 a-c, respectively. When the graphs were examined, it was seen that the friction coefficients increased rapidly from the beginning and reached a constant range after approximately 50 m of sliding distance. This increase was related to an increase in the contact area until full contact was made with the sample surface along the diameter of the pin. It was observed that the friction coefficients of the materials remained in a certain range as expected after a sliding distance of about 50 m. As seen in Figures 3 (a and b), this range was detected to be in a zigzag shape.

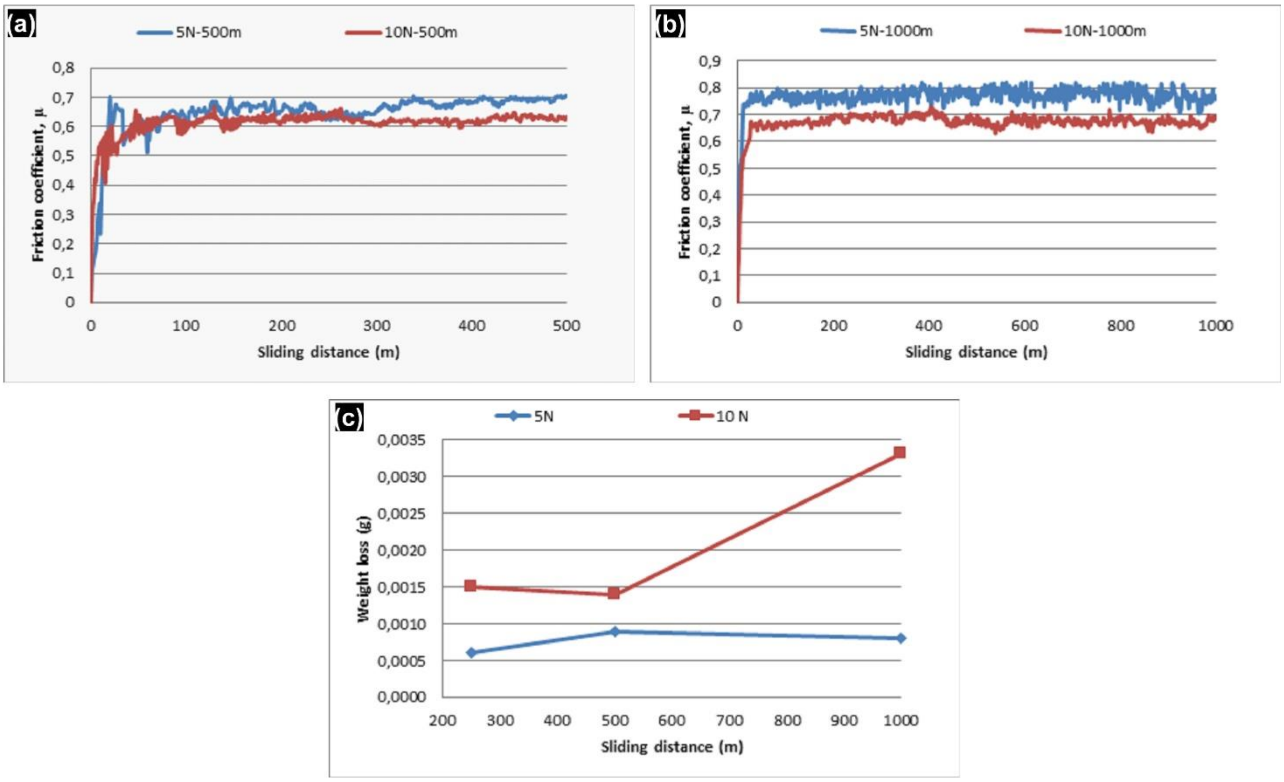

Figure 3. Friction coefficient-slip distance relationship ((a) 500m – 5N and 10N), ((b) 1000m – 5N and 10N) and weight loss-slip distance relationship (c).

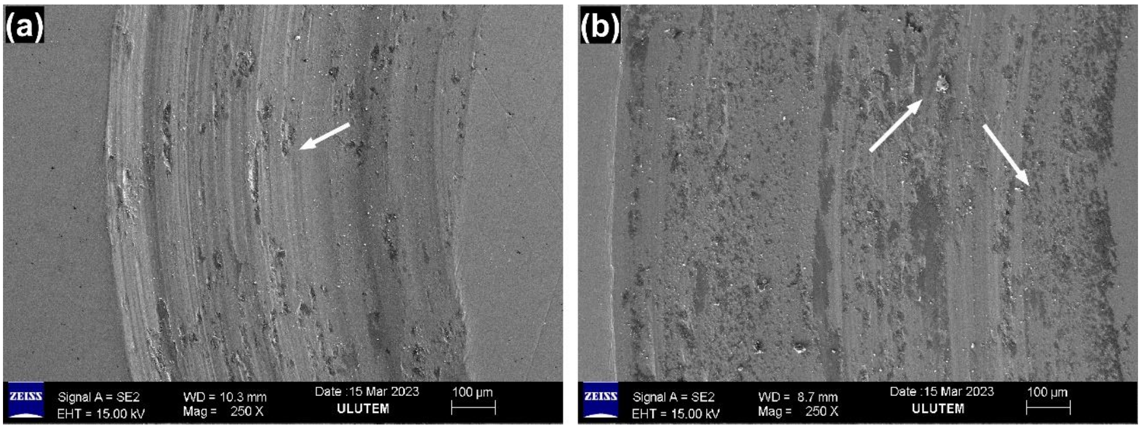

Figure 4. Wear surface images. (a) 5N load - 250m sliding distance and (b) 10N load - 1000m sliding distance.

While the average friction coefficient of the test specimen was 0.65 and 0.6139 μ at 500 m sliding distance and 5 - 10 N loads, respectively, these values increased to 0.7666 and 0.6739 μ with increasing the sliding distance to 1000 m. In addition, when the weight loss graph in Figure 3 (c) depending on the sliding distance at different loads was examined, it was understood that the weight loss increased with the increasing load (5 and 10 N). In the wear test, it was an expected result that with increasing load, the number of contact roughnesses increased and, consequently, the worn surface material increased. On the other hand, the amount of weight loss at 10 N load decreased up to 500 m and then increased. This indicated that strain hardening up to 500 m occurred in the high manganese steel sample, but then embrittlement occurred. In addition, the graph showed that the amount of weight loss in the sample at 5 N load first increased up to 500 m and then decreased. This proved that the 5 N load provided strain hardening of the sample only after 500 m sliding distance. It is well known that the additions of alloying elements and/or process parameters affect the hardness and wear characteristics of the materials and, in the literature, detailed studies were done which are in accord with our study [16-18].

3.3. Wear Surface Microstructure Investigation

In Figure 4 (a and b), SEM images of the wear surface of the samples were given after 5N load – 250 m slip distance and 10N load – 1000 m slip distance, respectively. The microstructures in Figure 4 show typical worn surface properties of high manganese steel. When the figures were compared, it was clearly understood that the amount of deformation on the wear surface increased with increasing load. It was clearly seen that there were tears and ruptures as a result of the wear test on the material surface (white arrows on the Figures). Due to the repeated plastic deformation with increasing load, the depth of surface scratches and surface cavities increases along with the amount. Brittle spalling and severe deformation are noticeable in some parts of the microstructure. Also, as expected, the wear occurred mostly in the matrix due to carbides (dark areas) formed at the grain boundaries. On the other hand, it was understood that the number of hard carbide phase regions on the surface increased with increasing deformation.

4. Conclusions

In this study, a test sample was produced by adding 1% by weight of Al5Ti1B to high manganese Hadfield steel. After the microstructure, hardness and wear tests, the following results were obtained.

1. A homogeneous grain structure was obtained, and carbide phases were observed in the grain boundary regions.
2. The hardness of the produced sample was 254 HV ± 14. The fact that this hardness value is higher than the high manganese steel in the literature was attributed to the formation of complex carbides thanks to the addition of Al5Ti1B.
3. Average friction coefficients of 0.65 and 0.6139 μ were obtained at 500m sliding distance and 5 - 10 N loads, respectively. These values increased to 0.7666 and 0.6739 μ by increasing the slide distance to 1000 m. The effects of strain hardening and embrittlement were also observed.
4. Typical worn surface properties of high manganese steels were observed. Brittle fragmentation and severe deformation were noticeable in some parts of the microstructure. There were even micro-spallations and ruptures. It was understood that the wear occurred mostly in the matrix due to the carbides formed at the grain boundaries.

Acknowledgments

The authors thank to Gaziantep University Scientific Research Projects Unit for financially supporting this study with project number MF.YLT.22.02.

Author contributions

Ibrahim Arslan: Experimental studies; Casting and preparation of samples, Writing - original draft.

Mustafa Guven Gok: Investigation, Visualization, Microstructural Analyses, Writing - review & editing.

Halil Ibrahim Kurt: Project administration, Methodology, Wear test, Writing - review & editing.

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