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Effect of Heat Treatment on the Microstructure, Impact Toughness and Hardness of High-Chromium White Cast Iron with Added Niobium and Manganese Minerals

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Abstract

In this work, manganese and niobium were added to high-chromium white cast iron, from which drilling and grinding tools were made. Two melts with different proportions of manganese and niobium (manganese 2.75% and niobium 0.49%, manganese 3.5% and niobium 1.1%) were used. High-chromium white cast iron is considered one of the most important alloys in heavy-duty applications, and its properties are affected by the added alloying elements and heat treatment. Niobium can increase corrosion resistance and hardness, form carbides, enhance thermal conductivity and improve response to heat treatment. As for manganese, it can increase impact toughness, remove oxygen from iron oxide and reduce flexibility. The heat treatment was carried out in accordance with two different programmes: 1- heating to 950 °C with a holding period of 2 h and cooling in atmospheric air; 2- heating to 960 °C with a holding period of 20 min, then cooling in the oven and returning to 425 °C for 3 h. The mechanical properties, such as wear resistance, impact durability and hardness, before and after heat treatments 1 and 2 were compared.

***Keywords**: Wear; impact toughness; hardness; grinding; high-chromium white cast iron; cracking.*

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1. Introduction

High-chromium white cast iron alloys are used in applications that require high hardness, such as in our study on the teeth of excavators and crusher hammers. The American Society for Testing and Materials classified them on the basis of the percentage of chromium and the total percentage of impurities less than 0.15% (ASTM A532-75a).

The density of high-chromium white cast iron is 7.4 gr/cm^3. Below are the most important mechanical properties of the alloy and the influence of niobium and manganese.

Table 1,
Mechanical properties of high-chromium white cast iron

Compressive yield limit stress MPa	1380–1965
Harshness HV	550–775
Impact energy J	120–125
Wear rate	0.0655–0.985

Table 2,
Properties of Nb, Mn and their effect on white cast iron.

Element	Density	Melting temperature °C	Effect on white cast iron
Niobium (recommendation)	8.57 gr/cm^3	2480	It increases wear resistance and hardness, enables the formation of carbides, enhances thermal conductivity and improves response to heat treatment.
Manganese	7.21 gr/cm^3	1244	It increases impact durability, removes oxygen from iron oxide and reduces flexibility.

The importance of the research comes from the significance of this type of cast iron in the mining industry, infrastructure and various industrial and military fields and the necessity of replacing breaking and drilling tools due to the force of impact and high wear during work. Therefore, increasing the actual life of tools in heavy-duty applications by enhancing the mechanical properties of the alloy is necessary.

The goal of this research is to determine the heat treatment that achieves the best properties in terms of hardness values and impact toughness for high-chromium white cast iron with added manganese and niobium, which differs from ASTM A532 classifications. On this basis, crusher hammers and excavator teeth are made by heat treatment in accordance with two different programmes.

In 1999, Guan compared the effects of fermentation, tempering and reflux on high-chromium white cast iron, found that the fermentation samples had lower hardness and fracture toughness values than the tempering and reflux samples and proved that the reflux samples were better [1].

In 2001, Arikan's research tackled the addition of titanium to high-chromium white cast iron, leading to the formation of fine grains, which turned out to be titanium carbides. The wear resistance of the alloy increased by 30% after Ti addition at a rate of 0.38% and quenching. After the review treatment, the properties decreased. Their values during watering were studied. [2]

In 2007, Wu's research resulted in the following: The TiC carbide molecule in high-chromium cast iron acts as crystallisation seeds for primary M7C3 carbides by determining the value of the contrast between the dimensions of their lattice structures. If it is smaller than 6%, then the ability to form crystallisation seeds is high; if it is between 6% and 12%, then the ability is less; if the variation is greater than 12%, then the formation is impossible [3].

In 2008, S. Zic tried to form an alloy of high-manganese steel and high-chromium white cast iron but did not obtain optimal results because of the large difference in the temperature of the Hadfield steel after casting and the font temperature when casting [4].

In 2012, Studnicki's research resulted in a new method for researching the crystallisation process using three tests. This method enabled the characterisation of the sensitivity of cast iron to the cooling kinetics [5].

In 2013, Parente applied a suitable heat treatment to two products of high- and low-carbon white cast iron to obtain a product with great resistance and durability. He found that the compressive behaviour at 500 °C was favourable for these products, which exhibited high compressive strength with ductility, and led to an increase in chromium and carbon [6].

In 2014, Agunsoyer determined that when high-chromium white cast iron was hardened with oil, the fracture toughness was constant between the range of 2.4% and 2.6% carbon. The fracture toughness at a high carbon percentage was controlled by an isolated carbide network that represented weak links in the microstructure. These weak bonds induced dislocations and weakened the material. [7]

In 2017, M.H. Ford classified types of carbides formed in high-chromium white cast iron during crystallisation. They determined that primary carbides formed at a carbon percentage higher than 4% and a temperature higher than the eutectic line, eutectic carbides formed at the eutectic line, and secondary carbides resulted from the transformation of austenite into martensite. The excess carbon was transformed into carbides with a small granular structure [8].

In 2019, B Hinckley studied two alloys of high-chromium white cast iron that were heat-treated and concluded that increasing the carbon percentage from 3% to 5% led to the ground changing from a desirable structure containing martensite to an undesirable structure containing pearlite. He indicated that the alloy containing a high percentage of chromium prevented pearlite transformation and facilitated martensitic transformation [9]. S Lung formed high-chromium white cast iron cast at different temperatures. Based on the resulting properties and structures, casting at 1450 °C achieved better wear resistance and impact durability than other processes [10]. Abaad K and Walaa A concluded that heating high-chromium white cast iron to 900 °C for 30 min, then cooling with oil and returning to 550 °C for 4 h improved its hardness, durability and wear resistance [11].

In 2020, Albetar Abaad K concluded that impact toughness and wear resistance were increased with the addition of titanium to high-chromium white cast iron by die casting [12]. M Biere increased the percentage of silicon in high-chromium white cast iron, departing from the ASTM classifications, and reached good hardness values. However, the impact toughness fell below the ASTM values [13]. KH Abdel Aziz showed that, through the heat treatment of high-chromium white cast iron, a secondary quasi-spherical carbide formed within the primary austenitic ground, which later turned into martensite, and the hardness increased [14]. Hua Nan Liu formed a test alloy containing 40% chromium and 9% niobium for wear resistance, compared it with a white cast iron alloy with 25% chromium and concluded that the test alloy had a wear rate of 36% in comparison with the white cast iron alloy [15]. NHK Luan studied the effect of adding vanadium and niobium on the abrasive and impact wear properties of white cast iron with 16% Cr and 3% Mo, then conducted heat treatment of the samples. The researcher concluded that spherical carbides formed in the structure and increased the stability of martensite in the floor. The resistance to abrasive wear was increased, whereas the resistance to impact wear was reduced. In harsh conditions, self-recovery of martensite in the floor occurred owing to the impact energy of the abrasive medium, which increased impact wear [16]. Agustina Guitar found that heat treatment tempering of high-chromium (26%) white cast iron increased the precipitation of M23C6 SC carbides because of the austenitic/martensitic transformation, and the results showed an improvement in the hardness of the floor [17].

In 2022, Luan NH studied the role of the floor structure in resisting impact wear of high-chromium (27%) white cast iron samples by conducting heat treatment. The researcher concluded that increasing the remaining austenite and tempering improved the softness of the structure due to the return of martensite, which limited the wear rate [18].

In 2023, C Le Nué studied the effect of heat treatment on the hardness and ground structure of high-chromium (16.5%) white cast iron. The researcher concluded that the microstructure changed into a homogeneous structure with M23C6 carbides in the ground that completely transformed into martensite upon cooling. He also observed the formation of M7C3 carbides upon cooling, and 1000 °C improved the hardness [19].

In 2024, Ngo HK studied the effect of heat treatment on the wear resistance of high-chromium (24% and 27%) white cast iron. The researcher showed the formation of lamellar pearlite after casting in the microstructure of samples containing 24% Cr after crystallisation and the formation of granular pearlite. After the fermentation treatment and upon tempering, the amount of remaining austenite increased. The researcher concluded that wear resistance was affected by grounding, eutectic carbides and strain hardening [20]. Franco studied the surface wear resistance of high-chromium white cast iron (2.8% C, 14% Cr) through steel ball blasting, and the results showed that the surface wear mechanism was related to the microstructure consisting of austenite and martensite. The researcher heated the white cast iron up to 990 °C, and this process resulted in a high percentage of austenite, martensite and secondary carbides being distributed, which increased the wear resistance. At 1050 °C, the amount of martensite, austenite and carbides decreased, which implied an increase in the wear rate [21]. Chabak investigated the effect of tempering temperature on the wear resistance of aluminium oxide for various samples of cast iron containing boron. The researcher found that the samples heated to 1200 °C for 4.5 h had enhanced wear resistance. With the increase heating temperature, the wear rate was reduced by about 3 times [22]. Xiong studied the effect of retention time during heat treatment on the microstructure and mechanical properties of high-chromium white cast iron and found that the hardness is closely related to the size and cross section of secondary carbides in the ground. The treated sample was heated to 1000 °C for 1 h, resulting in samples with the highest hardness. The hardness decreased in samples with large carbides. The hardness values of samples treated for 14 h were lower than those treated for 10 min. At 1050 °C, the size and density of secondary carbides increased with increasing retention time [23].

The reference studies stressed the importance of studying high-chromium cast iron in heavy-duty applications given its high hardness, but it suffers from low impact toughness. Therefore, we will try to improve the hardness and impact toughness by adding manganese and niobium in different proportions, then carrying out heat treatments.

2. Research Materials and Methods

1. Foundry-Master 01M0026 Optik 01M0026 Spectrograph
2. Wear testing machine for testing samples (ASTM G65-94)
3. Impact tester (Charpy, ASTM E23) and hardness tester (Vickers, Gnehm HarteprUfer) for testing samples
4. Linn Electro Therm heat treatment furnace
5. Optical microscope

2.1 Stages of Work

We obtained samples of high-chromium white cast iron and conducted spectroscopic analysis of them to determine their class in accordance with the American Association. Then, we added manganese and niobium in different proportions and conducted heat treatment on the basis of two different programmes. Afterwards, we performed hardness, wear resistance and impact toughness tests of the samples before and after heat treatment.

Table 3,
Samples of high-chromium white cast iron classified in accordance with ASTM A532 [12].

			wt%						
			C	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**Cu**
II	A	12% Cr	2.4–2.8	1.5	1.0	11–14	0.5	1.0	1.2
II	B	15% Cr-Mo-LC	2.4–2.8	1.5	1.0	14–18	0.5	3.0	1.2
II	C	15% Cr-Mo-HC	2.8–3.6	1.5	1.0	14–18	0.5	3.0	1.2
II	D	20% Cr-Mo-LC	2.0–2.6	1.5	1.0	18–23	1.5	1.5	1.2
II	E	20% Cr-Mo-HC	2.6–3.2	1.5	1.0	18–23	1.5	2.0	1.2
III	A	25% Cr	2.3–3.0	1.5	1.0	22–25	1.5	1.5	1.2

Samples of high-chromium white cast iron prepared with the addition of manganese and niobium are listed in Table 3.

Table 4 shows the results of spectroscopic analysis using the spectroscopy device.

Table 4,
Spectral analysis of samples manufactured from high-chromium white cast iron, to which 2.75% manganese and 0.49% niobium were added.

	Fe	**C**	**Si**	**Mn**	**P**	**S**	**Cr**
1	64.111	2.800	0.587	2.750	0.001	0.001	24.227
2	64.110	2.799	0.588	2.750	0.001	0.001	24.239
Average	64.110	2.800	0.588	2.750	0.001	0.001	24.288

	Mo	**Ni**	**Al**	**Co**	**Cu**	**Nb**	**Ti**
1	1.478	1.503	0.123	0.052	1.203	0.490	0.0075
2	1.485	1.501	0.117	0.050	1.202	0.492	0.074
Average	1.497	1.502	0.120	0.051	1.202	0.491	0.0074

	V	**W**	**Pb**	**Sn**	**B**	**Ca**	**Zr**
1	0.005	0.001	0.000	0.005	0.002	0.004	0.001
2	0.003	0.001	0.000	0.003	0.002	0.002	0.001
Average	0.004	0.001	0.000	0.004	0.002	0.003	0.001

	As	**Bi**
1	0.000	0.000
2	0.000	0.000
Average	0.000	0.000

Table 5,

Spectral analysis of samples manufactured from high-chromium white cast iron, to which 3.5% manganese and 1.1% niobium were added.

	Fe	**C**	**Si**	**Mn**	**P**	**S**	**Cr**
1	62.078	2.799	0.987	3.501	0.001	0.001	24.795
2	62.079	2.803	0.986	3.501	0.001	0.001	24.793
Average	62.078	2.801	0.986	3.501	0.001	0.001	24.794

	Mo	**Ni**	**Al**	**Co**	**Cu**	**Nb**	**Ti**
1	1.487	1.502	0.148	0.053	1.230	1.195	0.0073
2	1.487	1.503	0.149	0.051	1.226	1.005	0.0074
Average	1.487	1.503	0.149	0.052	1.228	1.100	0.0073

	V	**W**	**Pb**	**Sn**	**B**	**Ca**	**Zr**
1	0.005	0.001	0.000	0.005	0.002	0.004	0.001
2	0.003	0.001	0.000	0.003	0.002	0.002	0.001
Average	0.004	0.001	0.000	0.004	0.002	0.003	0.001

	As	**Bi**
1	0.000	0.000
2	0.000	0.000
Average	0.000	0.000

In the first smelting, the percentage of manganese was 2.75%, and that of niobium was 0.49%. In the second smelting, manganese was 3.5%, and niobium was 1.1%.

2.1.1 Heat Treatment

Eight samples (three samples for impact, three samples for wear and hardness and two samples for microstructure) were taken after casting for heat treatment 1.

Another eight samples (three samples for impact, three samples for wear and hardness and two samples for microstructure) were taken after casting for heat treatment 2.

Fig. 2. Heat treatment furnace.

Table 6,
Heat treatment applied.

Applied heat treatment programmes
1- Heating to 950 °C with a holding period of 2 h and cooling in atmospheric air
2- Heating to 960 °C with a holding period of 20 min, then cooling in the oven and returning to 425 °C for 3 h

2.1.2 Optical Microscope

The microscope consists of two sets of lenses at the ends of a tube that is the body of the microscope. The lens at the beginning of the tube, from which viewing is achieved, is called the ocular lens at the top, whilst the lens at the end of the body that is close to the test sample is called the body lens at the bottom.

Microscopic examination of the samples was performed before and after heat treatment, as described in the following steps:

1. Grinding using silicon carbide grinding paper with different degrees of fineness (120, 320, 500 and 1000 grit/cm^2)
2. Polishing using an alumina solution of 0.3 µm and a special polishing cloth, washing the samples with distilled water and alcohol and drying them after each stage

3. Etching using 2% Nital solution by immersing the sample and then washing the sample with distilled water and alcohol
4. Using an optical microscope (WIDMPS 51) to determine the microscopic structure of the samples

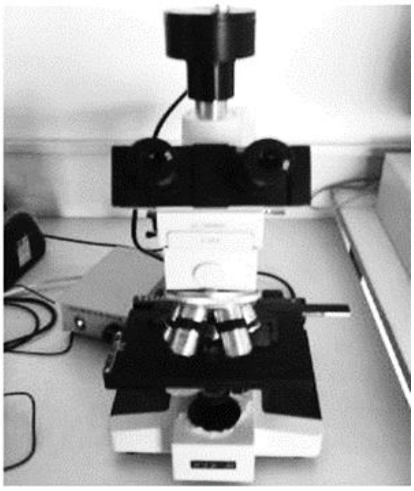


Fig. 3. Hund H600 optical microscope.

2.1.3 Hardness Test

The hardness test was carried out with reference to the approach of Vickers, in which the sample was placed on an anvil and gradually raised using a square diamond pyramid until it was in direct contact with the point of the notching tool. A load of 30 kg was gradually applied to the notching tool and then removed.

Fig. 4. Vickers test.

2.1.4 Wear Test

Sand–rubber disk test was performed by placing a sample with dimensions of 25×76 (mm^2) and a thickness of 3.2–12.7 mm in front of a stream of sand so that the sample was pressed with a force of 130 N towards the rubber disk that was rotating at a speed of 2000 rpm. From the difference in weight of the sample before and after the test, the wear rate was determined.

Fig. 5. Wear test.

2.1.5 Impact Test and Results

The impact samples were formed with a V-shaped notch in accordance with the Charpy test. Impact toughness was measured, i.e. the impact toughness at which the sample broke after a shock was directed to it on the opposite side of the face that contained the notch.


A B

Fig. 6. A-Impact test, B-One of the impact specimens.

The following figures show the microscopic structure of the samples before and after heat treatment at 400 magnifications.

Fig. 7. Resulting microstructure of the first case sample, high-chromium white cast iron with 0.491% Nb and 2.75% Mn, without heat treatment.

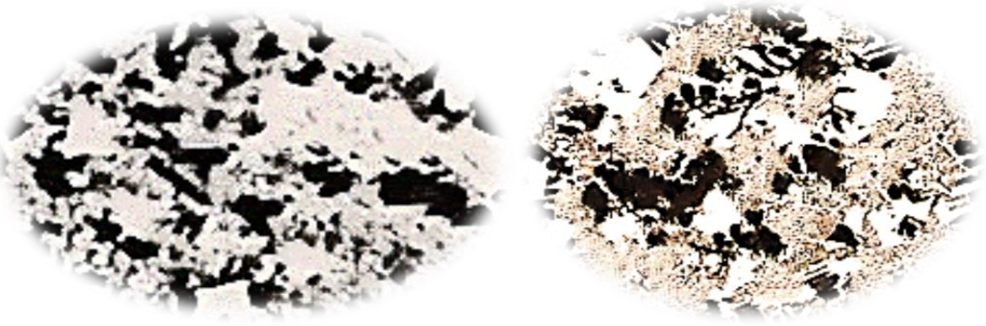


Fig. 8. Resulting microstructure of the first case sample, high-chromium white cast iron with 0.491% Nb and 2.75% Mn, after heat treatment 1.

**Fig. 9. Resulting microstructure of the second case sample... **

NbC

Niobium carbide

The eutectics are rod-shaped and tooth-shaped and are made of M7C3 carbide and austenite

Fig. 10. Resulting microstructure of the second case sample, high-chromium white cast iron with 1.1% Nb and 3.5% Mn, without heat treatment.

Fig. 11. Resulting microstructure of the second case sample, high-chromium white cast iron with 1.1% Nb and 3.5% Mn, after heat treatment 1.

Fig. 12. Resulting microstructure of the second case sample, high-chromium white cast iron with 1.1% Nb and 3.5% Mn, after heat treatment 2.

3. Results and Discussion

Tables 7 and 8 show the results of the hardness test before and after heat treatments.

Table 7,
Hardness test values for samples added with 2.75% manganese and 0.49% niobium.

Arithmetic average	Value	Condition
696 HV	693-694-696 HV	Without treatment
785 HV	786-785-784HV	Treatment 1
910 HV	911-913-906 HV	Treatment 2

Table 8,
Hardness test values for samples added with 3.5% manganese and 1.1% niobium.

Arithmetic average	Value	Condition
710 HV	712-710-714 HV	Without treatment
797 HV	797-798-796 HV	Treatment 1
922 HV	926-922-924 HV	Treatment 2

Table 9,
Wear test results from the case of high-chromium white cast iron with 0.491% niobium and 2.75% manganese.

Without treatment		Treatment 2		Treatment 1		
88.1967	88.4545	89.6748	88.9564	90.2196	89.5479	Mass before test gr
88.1402	88.3975	89.6231	88.9026	90.1659	89.4941	Mass after test gr
0.0564	0.0569	0.0516	0.0537	0.0536	0.0538	Mass loss gr
7.34	7.34	7.34	7.34	7.34	7.34	Density gr/cm^3
7.6969	7.7544	7.0364	7.3236	7.3092	7.3379	Volume loss mm^3 X 1000
0.00536	0.00540	0.0049	0.0051	0.00509	0.00511	Wear rate = volume loss ⁄ 1436
0.00542		0.0050		0.00510		*Average wear rate*

Table 10,
Wear test results from the case of high-chromium white cast iron with 1.1% niobium and 3.5% manganese.

Without treatment		**Treatment 2**		**Treatment 1**		
89.0912	89.1213	89.6521	90.0012	89.9966	91.0050	Mass before test gr
89.0350	89.0636	89.6025	89.9495	89.9428	90.9516	Mass after test gr
0.0562	0.0567	0.4953	0.5164	0.05375	0.05333	Mass loss gr
7.34	7.34	7.34	7.34	7.34	7.34	Density gr/cm^3
7.682	7.7113	6.7492	0.7036	7.3236	7.2661	Volume loss mm^3 X 1000
0.00535	0.00537	0.0047	0.0049	0.00510	0.00506	Wear rate = volume loss ∕ 1436
0.00536		0.0048		0.00508		Average wear rate

Table 11,
Impact test values for samples added with 2.75% manganese and 0.49% niobium.

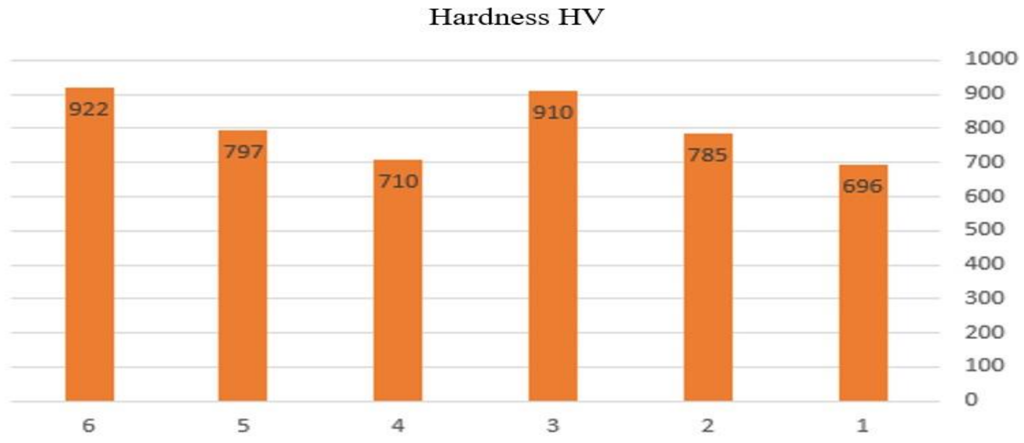
Arithmetic average	**Value**	**Condition**
175 J	175-176-174 J	Treatment 1
181 J	181-180-180 J	Treatment 2
145 J	144-145-146 J	Without treatment

Table 12,
Impact test values for samples with 3.5% manganese and 1.1% niobium added.

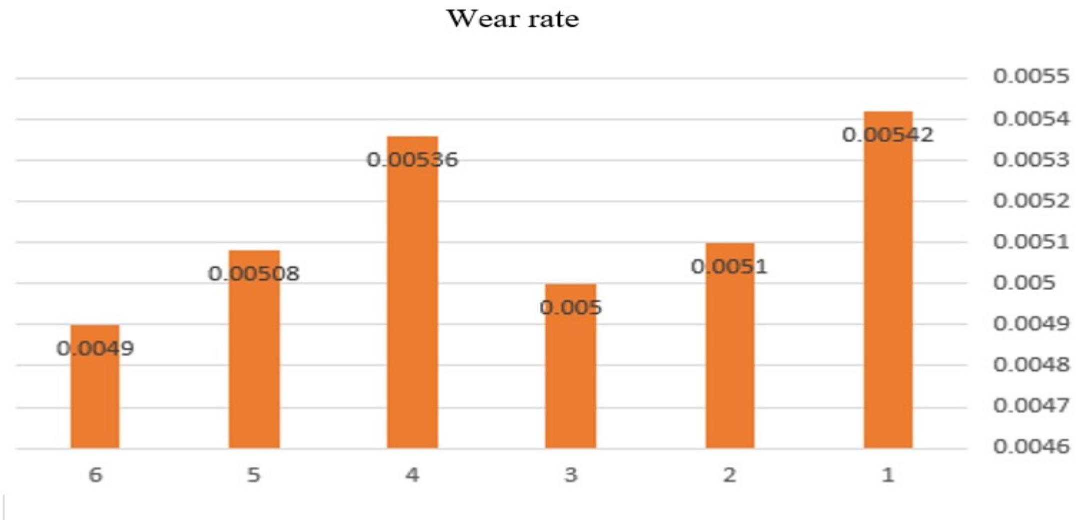
Arithmetic average	**Value**	**Condition**
180 J	178-180-182 J	Treatment 1
190 J	189-190-191 J	Treatment 2
157 J	157-158-156 J	Without treatment

The following figure shows a comparison of the values:

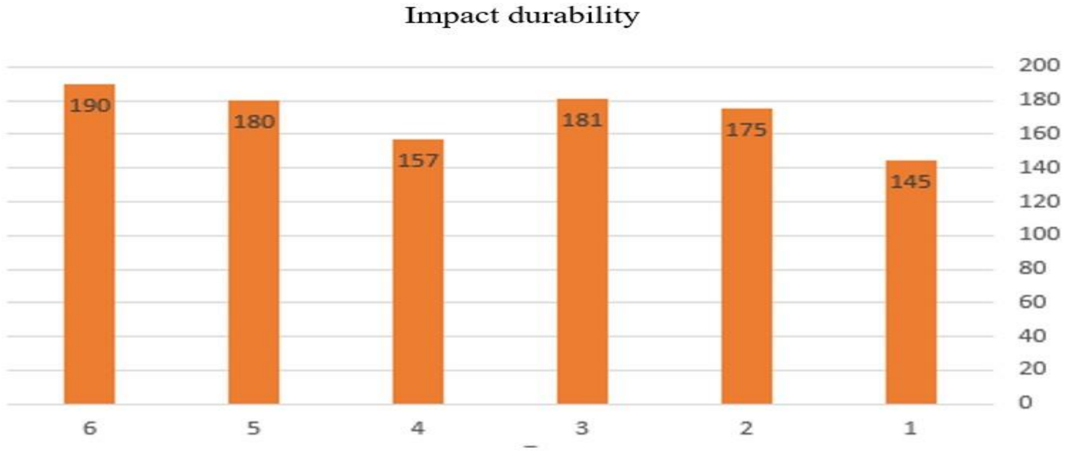
1. Samples with 0.491% Nb and 2.75% Mn without treatment
2. Samples with 0.491% Nb and 2.75% Mn under treatment 1
3. Samples with 0.491% Nb and 2.75% Mn under treatment 2
4. Samples with 1.1% Nb and 3.5% Mn without treatment
5. Samples with 1.1% Nb and 3.5% Mn under treatment 1
6. Samples with 1.1% Nb and 3.5% Mn under treatment 2



(a)



(b)



(c)

Fig. 13. (a) Hardness HV, (b) Wear rate, and (c)Impact durability

With heat treatment, from the values in the tables, the impact resistance and hardness (wear resistance) increased, especially in the second case. By heat treatment 1, the shape of the eutectic cementite and secondary carbide was transformed into a circle. Through hardening and reflux in treatment 2, the pearlite decreased, and the purity of the microstructure increased by adding Nb and Mn. Treatment 2 achieved the best values of hardness, wear resistance and impact toughness in the two melts. The addition of niobium and manganese controlled the formation of carbides M2C and M6C. The application of the gradual heat treatment programme 2 led to a saving in heating time and temperature and thus a saving in economic cost because we did not have to open the oven door and take out the piece.

The results obtained in terms of hardness, wear resistance and impact durability were better than the results in [11], [12].

Based on the microstructures without heat treatment, the resulting structure was not rough and did not contain agglomerates because manganese and niobium reduced the size of primary and eutectic carbides. The hypoeutectic microstructure was evident, which resulted from a small section of supraeutectic dendrite austenite and M7C3 carbides. Carbide was also present in the form of a sharp tooth because of the presence of large pieces of supraeutectic austenite, which became smaller upon cooling (due to the heat released when supraeutectic austenite was formed), forming sharp carbides. Niobium carbide was further formed, which precipitated in the liquid melt and reduced the amount of carbon in the ground, creating M7C3 carbides and activating nuclei that formed austenite branches and dendrites. As a result, the size of the carbide decreased, and the smoothness of the microstructure increased.

When manganese was added to the samples, the ground was made of martensite and austenite because manganese helped stabilise the austenite. The concentration of carbon and alloying elements, especially chromium, in the austenitic floor increased, which prevented the precipitation of pearlite, and the starting point of the martensitic transformation (Ms) decreased.

At the beginning of the melting of the samples (with moderate carbon and manganese content), groups of granular eutectic cementite appeared in the lattice structure, which were regularly distributed in the austenitic floor.

As the content of niobium and manganese increased, large numbers of secondary carbides separated in the ground, their shape being approximately spherical. We observed a small amount of pearlite in the floor.

The structure of all samples contained mainly austenite and a small amount of micrometre-sized martensite near the carbides in the ground. The width of the martensite increased in the ground, and the shape of the eutectic cementite and secondary carbide turned into round after heat treatment of the samples, which led to an increase in hardness and wear resistance.

The carbides in the samples consisted of primary carbide M7C3, carbide M2C and eutectic cementite (Fe, Mn)3C in the ground. The ground structure was a mixture of austenite, pearlite and martensite.

According to many studies, crystallisation takes place first from the molten state to M7C3 and molten and from the molten state to eutectic (austenite + M7C3/M23C6).

A small amount of M2C carbide was formed at a late stage of crystallisation, mainly due to the addition of manganese, which improved hardness and thus wear resistance.

At the crystallisation temperature of about 800 °C, a small amount of M23C6 carbide was formed around M7C3 carbide. Precipitated carbide M2C, rich in Nb and Mn, formed at the end of the crystallisation process.

The chemical composition of the samples changed with the variation in niobium content. When the niobium percentage reached 1%, the ground structure comprised austenite and martensite.

Therefore, the ground of high-chromium white cast iron was mainly composed of austenite, martensite and eutectic cementite secondary carbide M6C.

4. Conclusions

Unlike the reference studies, we used heat treatment and reflux. Guan also compared the effects of fermentation, tempering and reflux on high-chromium white cast iron [1]. We added important alloying elements such as niobium and manganese. Arikan added titanium to high-chromium white cast iron [2], which led to the formation of fine grains, i.e. titanium carbides. We obtained better mechanical properties after adding manganese and niobium.

In our study, the carbide molecule TiC acted as crystallisation seeds for primary M7C3 carbides by determining the value of the contrast between the dimensions of their lattice structures, similar to what Wu obtained in the study [3].

By adding manganese and niobium, we obtained much better results than the study of S. Zic [4], who tried to form a metal alloy from high-manganese steel and high-chromium white cast iron. He did not obtain optimal results owing to the high difference in the temperature of the Hadfield steel after casting and the font temperature when pouring.

In our research, we did not address new methods of crystallisation, as Studnicki did [5]. In comparison with the study in [6], we performed heat treatment, but with the addition of effective alloying elements, and observed the resulting microstructures.

Agunsoyer [7] showed that when high-chromium white cast iron was hardened with oil, the fracture toughness was between the range of 2.4% and 2.6% carbon. In our research, we quenched it in atmospheric air and the oven without resorting to water or oil cooling medium. M.H. Ford [8] examined the types of carbides formed in high-chromium white cast iron during crystallisation and classified them. Likewise. we discussed the types and nature of carbides in the microstructures.

In terms of heat treatment and the resulting structures, the explanation of the resulting structures of eutectic, niobium carbides and hypoeutectic austenite was similar to that in [9]. In [10], S Lung formed high-chromium white cast iron cast at different temperatures and studied the resulting properties and structures. In our research, we cast at a specific temperature on the basis of the state of the melt and the alloy additives we used. We also carried out heat treatment with atmospheric air without using oil, compared with Abaad K and Walaa A [11] who heated high-chromium white cast iron to 900 °C for 30 min. Then, cooling with oil and returning at 550 °C for 4 h improved hardness, durability and wear resistance. Albetar Abaad K concluded that impact durability and wear resistance were increased with the addition of titanium to high-chromium white cast iron by casting in metal moulds [12]. This approach differed from our research approach of casting in sand moulds and adding niobium and manganese, not titanium, and we obtained better results in terms of mechanical properties. In [13], M Biere increased the percentage of silicon in high-chromium white cast iron, deviating from ASTM classifications, and reached good values for hardness, but the impact strength decreased from the values in ASTM. As for our research, it dealt with the addition of niobium and manganese. In the study of KH Abdel Aziz [14], through the heat treatment of high-chromium white cast iron, secondary semispherical carbides were formed within the primary austenitic ground, which later transformed into martensite. In [15], Hua Nan Liu formed a test alloy containing 40% chromium and 9% niobium for resistance to normal wear, compared it with the white cast iron alloy including 25% chromium and concluded that the test alloy had a wear rate of 36% relative to the white cast iron alloy. We followed an experimental approach of adding niobium and manganese in different proportions and performing heat treatment in accordance with two different programmes to improve the properties of shock and harshness.

In [16], Ngo studied the effect of heat treatment on the wear resistance of high-chromium cast iron. He showed the effect of this treatment on surface hardening and wear behaviour through a floor rich in eutectic carbides. The wear rate was determined to be dependent on the degree of strain hardening during work. Our research did not cover surface hardening but relied on the results of tests.

Le Nué studied the evolution of the structure upon heat treatment, which led to the formation of an almost homogeneous structure that turned into martensite upon cooling. Various carbides were formed by carbon and heating to temperatures above 1000 °C [17]. In [18], Luan presented research on the role of the ground structure in resisting impact wear for cast iron that contained 27% chromium. Heating treatment to 1223 K increased the size of the initial martensite, and the wear rate reached its maximum at 60 degrees. When heated to 1423 K, the ground, which was mostly austenite, showed the maximum wear rate at 45 degrees due to the transformation from unstable austenitic to martensite by stress and impact. The hardening resulting from martensite induced by stress interfered with the softening caused by initial martensite recovery, which contributed to reducing the corrosion rate. On the contrary, in our research, we conducted two heat treatments and added the elements manganese and niobium. In [19], Luan NH showed the effect of vanadium and niobium on the impact and abrasion wear properties of white cast iron containing 16% chromium and 3% molybdenum. Spherical carbides (MC) were formed through the incorporation of Nb and V, in addition to martensite, in the more stable ground, which improved wear resistance. As mentioned, our research focused on the addition of magnesium and niobium and then heat treatments. Guitar [20] studied the effect of thermal processes and chemical composition on carbide precipitation. After heat treatment, an increase in the hardness of the floor was observed owing to the precipitation of M23C6 during the transformation and the austenitic martensitic transformation during tempering. The secondary carbide M7C3 precipitated during heating up to 850 °C. At 980 °C, the transformation to M23C6 was complete. We also carried out heat treatment, but with completely different parameters. Franco studied the abrasive and wear resistance of an alloy with 2.8% C and 14% Cr [21]. The results revealed the presence of a high percentage of martensite/austenite at 930 °C–990 °C and secondary carbides, which provided high abrasion and wear resistance and indicated the absence of eutectic carbides. Because the floor was hard and able to bear loads and reduce plastic deformation during impact with balls, heating to 1050 °C increased wear because the ground had low martensite/austenite content and secondary carbides. In the completed research, we used a wear device in accordance with a specification and a different programme in heat treatment. Chabak demonstrated the role of tempering temperature in developing wear resistance in cast iron (5 wt.% W, 5 wt.% Mo, 5 wt.% V, 10 wt.% Cr, 2.5 wt.% Ti, 0.3–1.1 wt. %C and 1.5–2.5 wt.% B) [22[]. Heat treatment was carried out by heating hardening to 900 °C–1200 °C for 2 h, then cooling with oil and returning at 200 °C. The resulting microstructures showed the deposition of ferrite, martensite and pearlite/bainite in the floor with secondary carbide, which greatly reduced the corrosion rate. In [23], Xiong studied the effect of instability time on the microstructure and properties of high-hypoeutectic cast iron. The hardness of carbides was determined to be related to proportion and size, and the hardness continued to increase with the increase in the size of dual carbides, reaching the maximum hardness at 950 °C–1000 °C. When kept at this temperature, the carbides melted in the ground, which reduced the hardness. Therefore, the retention time should not be prolonged. Our research tackled the effects of two different heat treatments on the microstructure, impact toughness and hardness of high-chromium white cast iron with different proportions of niobium and manganese.

In this work, the structure of all samples contained mainly austenite and a small amount of micrometre-sized martensite near the carbides in the ground. The width of the martensite increased in the ground, and the shape of the eutectic cementite and secondary carbide turned into round after heat treatment of the samples, which led to an increase in hardness and wear resistance. The carbides in the samples consisted of primary carbide M7C3, carbide M2C and eutectic cementite (Fe, Mn)3C in the ground. The ground structure was a mixture of austenite, pearlite and martensite. According to many studies, crystallisation takes place first from the molten state to M7C3 and molten and from the molten state to eutectic (austenite + M7C3/M23C6). A minimal amount of M2C carbide formed at a late stage of crystallisation, mainly due to the addition of manganese, which improved hardness and thus wear resistance. The addition of niobium and manganese controlled the formation of M2C and M6C carbides. At the crystallisation temperature of about 800 °C, a small amount of M23C6 carbide formed around the M7C3 carbide. Precipitated carbide M2C, rich in Nb and Mn, also formed at the end of the crystallisation process.

The chemical composition of the samples changed with the variation in niobium content. When the niobium percentage reached 1%, the ground structure was austenite and martensite. Therefore, the ground of the high-chromium white cast iron was mainly composed of austenite, martensite and eutectic cementite secondary carbide M6C.

Through heat treatment, the impact toughness and wear resistance were increased, especially in the second case. By heat treatment 1, the shape of the eutectic cementite and secondary carbide was transformed into a circle. Owing to hardening and reflux in treatment 2, the pearlite decreased, and the purity of the microstructure increased with the Nb and Mn addition.

In sum, the addition of niobium and manganese controlled the formation of M2C and M6C carbides. Implementing the gradual heat treatment programme 2 led to savings in economic costs and thus savings in heating time and temperature in heat treatment.

5. Recommendations

1. Heat treatments should be performed after adding Nb and Mn to improve mechanical properties such as impact durability and wear resistance.
2. Heat treatment parameters and variables should be altered with comparison of the results.
3. Other minerals should be added, if possible, and the resulting mechanical properties and microstructures should be assessed.
4. The shape of the breaking hammer or drill bit should be modified to enhance properties and lifespan, in addition to using simulation programmes to determine where the stresses are concentrated.

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تأثير المعالجة الحرارية على البنية المجهرية ومتانة الصدم وقساوة الحديد الصب الأبيض عالي الكروم المضاف إليه معدني النيوبيوم والمنغنيز

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المستخلص

تم العمل على إضافة المنغنيز والنيوبيوم إلى الحديد الصب الأبيض عالي الكروم الذي تصنع منه أدوات الحفر والطحن، وذلك وفق صهرتين بنسب مختلفة من المغننيز والنيوبيوم (المنغنيز 2.75% والنيوبيوم 0.49%، المنغنيز 3.5% والنيوبيوم 1.1%)، حيث يعتبر الحديد الصب الأبيض عالي الكروم من أهم السبائك المستخدمة في التطبيقات الشاقة، وتتأثر خواصه بالعناصر السبائكية المضافة والمعالجة الحرارية. حيث يعمل النيوبيوم على زيادة مقاومة الاهتراء والقساوة، وله قدرة عالية جدًا على تشكيل الكربيدات، ويزيد من التوصيل الحراري مما يحسن الاستجابة للمعالجة الحرارية. أما المنغنيز فيزيد من متانة الصدم، ويخلص الحديد من الأكسجين، ويقلل من مرونته. تم إجراء المعالجة الحرارية وفقًا لبرنامجين مختلفين (1)، (2) (1- التسخين إلى 950 درجة مئوية مع فترة ابقاء لمدة ساعتين والتبريد في الهواء الجوي، 2- التسخين إلى 960 درجة مئوية مع فترة ابقاء لمدة 20 دقيقة، ثم التبريد في الفرن والعودة إلى 425 درجة مئوية لمدة 3 ساعات.) وتمت مقارنة الخصائص الميكانيكية، مثل مقاومة الاهتراء ومتانة الصدم والقساوة قبل وبعد المعالجة الحرارية 1، 2.