

On the Comparison of Microstructure Characteristics and Mechanical Properties of High Chromium White Iron with the Hadfield Austenitic Manganese Steel

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ABSTRACT

In this study, high chromium white iron (HC-Wi) alloy and the Hadfield steel were studied. The microstructure of this high-chromium iron was studied using Metallurgical optical microscopy (OM) and compared to the Hadfield steel. The hardness and unnotched charpy impact strength of the HC-Wi alloy and Hadfield steel were examined at ambient temperature in the as-cast and heat-treated conditions. A pin-on-disc test at linear speed of 1.18 m/s and a 10 N normal load was employed to evaluate the wear behavior of both steel samples. Microstructural results showed that varying the carbon level in HC-Wi alloys can affect the chromium carbide morphology and its distribution in the austenite matrix which leads to considerable changes of the mechanical properties. Abrasion test showed that HC-Wi alloys have superior wear resistance, about three times of the Hadfield steel.

Keywords: High Chromium White Iron; Hadfield Steel; Microstructure; Wear

1. Introduction

When there was a challenge to develop steel which possesses two extreme properties at the same time, Sir Robert Hadfield invented Hadfield steel in 1882. The idea was to have steel which is tough and at the same time hard. This type of steel with its austenitic matrix has high toughness, high ductility, and high work-hardability. Majority of the cast Hadfield steel are excellent candidates in variety of applications such as: earthmoving, mining, railways, quarrying, dredging and drilling in the oil/gas [1,2].

The global economic recession has continue to place heavy burden on foundries world-wide and Nigeria in particular to look for means of improving their productivity and higher products quality, as well as to strive to achieve the optimum economy in wear industries; in the past decade, the use of carbon steel ball in dry mill grinding has been replaced with in situ ceramic-steel composite synthesis technique to increase the life of the wear parts. In this technique, hard ceramic forming elements are introduced to the molten steel as an alloying element and a more thermodynamically stable reinforcing phase will be formed during solidification by the nucleation and growth mechanism in the parent matrix [3].

One of the most common ceramic reinforcing materials being used in iron base alloys is carbides and among them chromium carbide due to its high hardness of about 1020 - 1835 Hv [4], have proved to be a unique choice to wear resistance of cast high chromium white iron with martensitic microstructure [5,6]. However, less attention has been paid to the research on Hardfield Austenitic Manganese steel.

In general terms, the high chromium iron suitable for wear resisting applications fall within the compositional limits bounded by the austenitic phase field of the ternary liquidus surface of the iron, chromium, carbon diagram. Solidification takes place by a eutectic process The products of the eutectic reaction are austenite and chromium rich carbides of the $(FeCr_7)C_3$. For high chromium white iron with a Cr concentration of some 18 - 20 wt% (hypoeutectic composition), solidification starts with the nucleation of dendritic primary austenite (γ), followed by the formation of $\gamma + M_7C_3$ carbide and its morphology have been well documented by several researchers [7]. The HC-Wi alloy has an austenitic matrix structure at ambient temperature with chromium carbide dispersed within the matrix. The wear resistance of this material is achieved at the surface when the abrasive particle or impact load transforms the unstable Austenite to martensite by strain induced mechanism. This phenomenon of Aus-

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tenite transformation to martensite causes increased surface hardness and less wear rate loss. Carbon content plays a significant role in chromium carbide formation and its morphology as well as hardness, impact toughness and wear resistance. In this study, the effect of carbon content on the microstructure, mechanical properties and wear characteristics of HC-Wi has been studied and compared to the Hadfield steel.

2. Materials

HC-Wi and Hadfield Steel grade of materials were produced in Nigerian Foundries Limited (NFL), Otta, Nigeria using the charge makeup in **Tables 1** and **2** respectively. An Electric Induction Furnace of 500 kg neutral lined was used for the melting operation and the sample representative taken from the molten bath at 1550°C and poured into a CO₂ sand improvised moulds (11 × 11 × 200) mm. The charge makeup used in obtaining the specification is tabulated below.

After the first heat from **Table 1**, a sample representative was taken and casted. For subsequent batches, fine granules of graphite were added in their various compositions of 1.6% C, 2.2% C, 2.7% C and 3.3% C respectively to the molten bath and the temperature maintained at 1520°C - 1543°C for 10 minutes to enable the graphite granules dissolve adequately. This process was repeated

Table 1. Charge makeup for HC-Wi.

Raw Materials Mass (Kg)	Elemental Contribution (%)						
	C	Si	Mn	P	S	Cr	
Returns	156.25	0.94	0.21	0.01	0.01	0.01	7.19
Steel Scraps	223.21	0.09	0.09	0.04	0.02	0.02	0.00
Fe-Cr	98.21	0.10	-	-	-	-	17.68
Fe-Si	2.23	-	0.33	-	-	-	-
Fe-Mn	4.46	0.07	-	0.58	-	-	-
Graphite	3.80	0.51	-	-	-	-	-
Total	500	1.55	0.63	0.63	0.03	0.03	24.87

Table 2. Charge makeup for Hadfield Steel.

Charge makeup for Hadfield Steel Raw Material	Mass (Kg)	Elemental Contribution (%)					
		C	Si	Mn	P	S	Cr
Returns	187.83	0.410	0.190	4.760	0.005	-	0.570
Steel Scraps	234.80	0.095	0.120	0.120	-	-	-
Fe-Cr	7.04	0.001	-	-	-	-	1.280
Fe-Si	2.00	-	0.300	-	-	-	-
Fe-Mn	63.40	0.140	-	9.640	-	-	-
Graphite	4.93	0.66	-	-	-	-	-
Total	500	1.30	0.610	14.52	0.005	0.000	1.850

for all incremental granules addition. To reduce the tendency for oxidation, 1 Kg of Aluminum Briquette was added to the melt. Besides, Hadfield steel melt was prepared according to ASTM 128 C standard as presented in **Table 2**.

The overall chemical composition obtained for the 2 heats and 5 batches is presented in **Table 3**.

A calibrated Hilger Analytical Direct Optical Emission Polyvac Spectrometer E980C with 20 analytical channels was used for the analysis of the chemical composition of the HC-Wi and Hadfield steel. Hadfield steel is difficult to machine due to its work-hardening propensity. Hence, a sample representative was taken from the Hadfield steel molten bath and poured into a (10.20 × 10.2 × 200) mm preheated medium carbon steel mould so as to obtain the required (10 × 10 × 50) mm bar for the impact test. This technique was aimed at avoiding the need to machine the samples. To investigate the effect of the heat treatment of Hadfield steel on the properties of HC-Wi, halves of all the specimens with the size (10 × 10 × 50) mm were solution annealed at 1050°C for 30 minutes and then water quenched.

2.1. Microstructure

For microstructural analysis, all the as-cast and heat-treated samples were cut from the bottom end, ground with tetrapol-31, then polished using a colloidal suspension of 0.04 μm silicon dioxide and then etched in 100 ml alcohol and 3 ml HNO₃ acid after polishing using Allegrol with diamond suspension at the Metallographic Laboratory, Department of Mechanical Engineering of the University of Ottawa, Canada. A metallurgical optical microscopy was used to study the microstructures.

2.2. Mechanical Properties

Vickers micro hardness of tested samples was measured using Duramin-1 microhardness tester struers. The reported hardness values were the average of five measurements. Charpy unnotched impact test was also carried out on (10 × 10 × 50) mm standard Hadfield and HC-Wi specimens at room temperature. In order to compare the wear resistance of the developed HC-Wi alloys with Hadfield steel, abrasive wear tests were conducted on all

Table 3. Chemical composition of the HC-Wi.

Material	C	Mn	Si	Cr	P	S	Mo	Ni	Al	Fe
HC-Wi-1	1.55	0.63	0.63	24.87	0.03	0.03	0.02	0.01	0.01	Balance
HC-Wi-2	2.22	0.63	0.62	24.60	0.03	0.03	0.01	0.01	0.01	Balance
HC-Wi-3	2.73	0.59	0.60	24.20	0.03	0.03	0.01	0.015	0.02	Balance
HC-Wi-4	3.26	0.56	0.60	23.60	0.03	0.03	0.01	0.01	0.02	Balance
Hadfield Steel	1.30	14.52	0.61	1.85	0.01	0.00	-	-	0.15	Balance

cast sample in the as-cast and heat-treated conditions using a pin-on-disc wear machine as per ASTM G99-95 Standard. The disc used is En-32 steel hardened to 62 HRC, 200 mm track diameter and 12 mm thick with surface roughness of 20 μm Ra. The sample with cross section 10 mm \times 10 mm was taken from the fracture impact test and used for the wear test. Applied normal load on all the samples was 10 N over a sliding distance of 70.8 m on a fresh 120 grit SiC abrasive paper. Before and after each test, the sample was carefully cleaned with acetone and weighed using an analytical balance with an accuracy of 0.001 g. The relative wear resistance was given by the weight loss of HC-Wi alloy samples related to the weight loss of the heat-treated Hadfield steel sample. The reported values are the average of four test runs on each composition material.

3. Results and Discussion

3.1. Microstructural Analysis

Figures 1(a)-(d) show the effect of carbon content on the morphology and distribution of primary chromium carbides in HC-Wi alloys in the as-cast condition. When the high chromium molten alloy starts to solidify; chromium carbide nucleation takes place and grows in the melt and crystallizes as coarse primary chromium carbides between the liquidus and solidus temperatures. It has been observed from the data available from Table 3 and Equation (1),

$$\% \text{Carbide} = 12.33(\% \text{C}) + 0.55(\% \text{Cr}) - 15.2 \quad (1) \quad [8]$$

that as the carbon content of the HC-Wi increases, the amount of chromium carbide increases (Table 4) and primary chromium carbides change from the fairly round, strip into spherical shape and they are distributed more uniformly up to carbon content of 2.73 but further increase in the carbon content decreases the homogeneity of the chromium carbide distribution within the austenitic matrix (Figures 1(b) and 1(c)).

In HC-Wi alloy, due to the presence of >20% Chromium in the composition as one of the strongest carbide forming elements in steel compared to iron or manganese (very high affinity of chromium to absorb carbon), chromium reacts with the dissolved carbon of the molten steel resulting to the formation of chromium carbide instead of iron manganese carbide.

In as-cast Hadfield steels, austenite grain boundary steel are surrounded by a continuous network of segregated and brittle $(\text{FeMn})_3\text{C}$ shown in Figure 3(a). Solution annealing between the temperature range of 1000°C - 1050°C dissolves these carbides in austenite and subsequently quenching in water prevents the formation M_3C in grain boundary as shown in Figure 3(b) [9].

In high chromium austenite steel, due to the presence

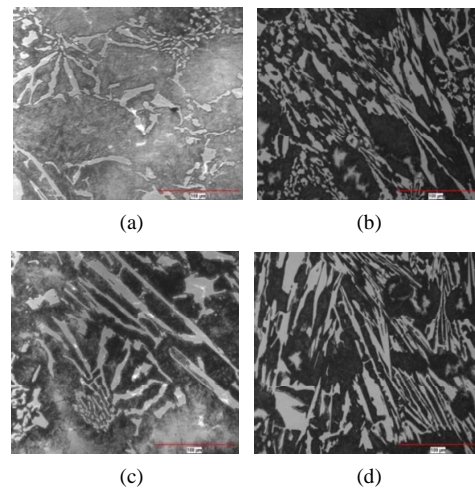


Figure 1. Optical micrograph of HC-Wi in the as-cast condition. (a) HC-Wi-1 (b) HC-Wi-2 (c) HC-Wi-3 (d) HC-Wi-4.

Table 4. The amount of chromium carbide (Cr_3C_7 , %) in the as-cast conditions.

Sample	HC-Wi-1	HC-Wi-2	HC-Wi-3	HC-Wi-4
Volume of Cr_3C_7	17.59	25.70	31.77	37.98

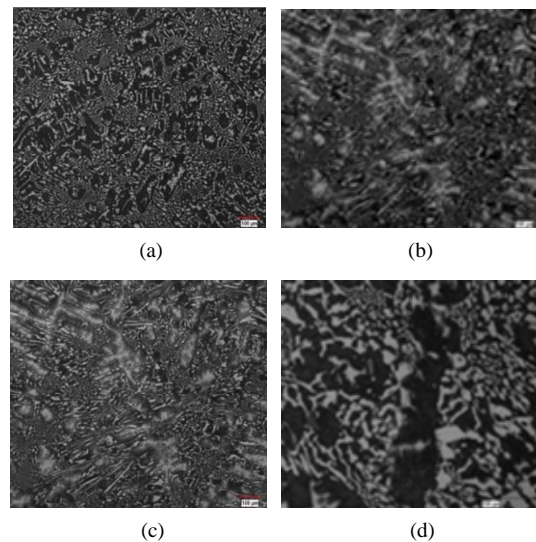


Figure 2. Optical micrograph of HC-Wi in heat-treated condition. (a) HC-Wi-1 (b) HC-Wi-2 (c) HC-Wi-3 (d) HC-Wi-4.

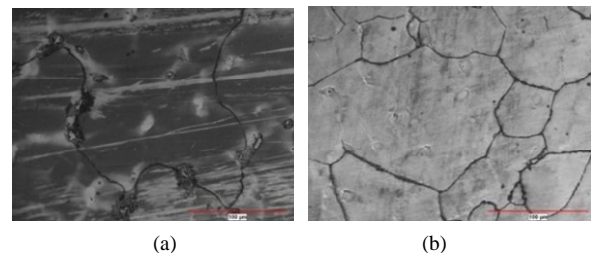


Figure 3. Optical micrograph of the hadfield steel (a) as-cast condition (b) heat-treated condition.

of more than 20% chromium, chromium is one of the strongest carbides forming element in steel compared to iron or manganese (chromium has high affinity for carbon), chromium reacts with the dissolved carbon in the molten steel leading to the formation of a more stable chromium carbides instead of iron manganese carbides. When compared to **Figure 3**, iron manganese carbides in HC-Wi samples virtually non-existence and form a continuous network of brittle phase around the austenite grains.

3.2. Mechanical Properties

Initially measured values of Vickers hardness of all samples in as-cast and heat-treated conditions before the abrasion test are presented in **Figure 4**. It shows that the hardness of HC-Wi alloys is almost 69% higher than Hadfield austenitic manganese steel due to the presence of high percentage of extremely hard chromium carbide Cr_3C_7 in the microstructure. Solution annealing has less influence on the hardness changes of HC-Wi alloy compared to Hadfield austenitic steel. Hadfield steels contain some segregated hard grain boundary carbide of the form Cr_3C_7 within the softer austenite matrix. This is clearly responsible for the increase in overall hardness in the as-cast conditions. **Figure 4** also showed that austenite matrix in HC-Wi alloys is more than twice the hardness of the Hadfield steel (in both as-cast and heat-treated conditions).

This considerable increase in austenite hardness is related to the solution of carbon and chromium elements in iron lattice coupled with the precipitation of secondary chromium carbide (**Figures 1 and 2**) in austenite which strengthens the soft matrix.

Figure 5 shows Charpy unnotched impact toughness of the materials. The main difference in impact energy values before and after the heat treatment was observed in the Hadfield steel and it is due to the dissolution of the

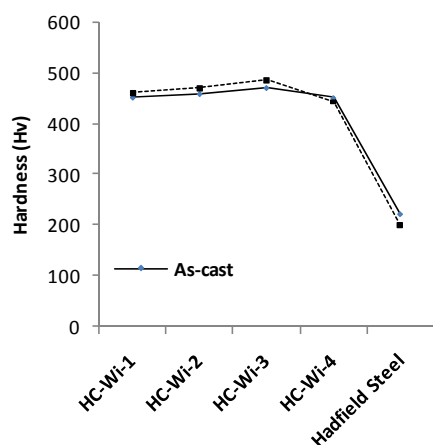


Figure 4. Vickers micro-hardness of as-cast and heat-treated materials.

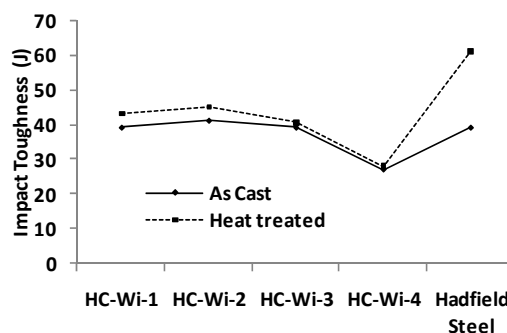


Figure 5. Impact toughness of HC-Wi alloys and Hadfield steel.

brittle carbide, segregated along the austenite grain boundaries in the as-cast condition (**Figure 3(a)**). These brittle phases with lamellar/acicular morphology along the boundaries cause stress to be built-up in the matrix, leading to dislocation pile up, crack initiation, propagation and crack growth and subsequently low impact toughness of the Hadfield steel in as-cast condition. For HC-Wi alloys, chromium carbide morphology and its distribution both influence significantly the impact energy. HC-Wi-1 composition with uniform distribution of chromium carbide has the highest impact toughness, while the HC-Wi-4 has the lowest impact toughness. As the carbon content increases, the morphologies of the chromium carbides in the matrix also change. The distribution of the chromium carbide influences the mechanical properties of the material.

3.3. Wear Resistance

The wear loss of HC-Wi alloys compared to the heat-treated Hadfield steel in the as-cast and heat-treated conditions are presented in **Figure 6**. The predominant wear mechanism in the pin-on-disc abrasion test is micro cutting and surface hardness of the materials plays a significant in determining the wear resistance. Hence, HC-Wi alloys shows remarkable higher wear resistance (3 times) than Hadfield steel due to higher surface hardness caused by the existence of hard carbide phase dispersed within the austenite matrix. Despite the low surface hardness of HC-Wi-3 compared to HC-Wi-4, the wear resistance of HC-Wi-3 is superior and higher than HC-Wi-4 (**Figure 6**). This is because the carbide distribution in HC-Wi-4 is heterogeneous (**Figure 2(d)**). Hence, that the distributions of the hard second phase carbide also affect the wear resistance.

4. Conclusions

1) High chromium white iron alloy have superior wear resistance compared to hadfield austenitic manganese steel due to the presence of hard chromium carbide distributed within the matrix of the microstructure.

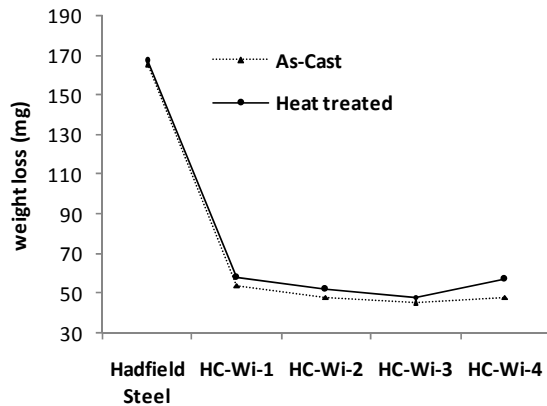


Figure 6. Weight loss of HC-Wi alloys and Hadfield steel.

2) The presence of chromium carbide lowers the impact toughness of HC-Wi alloys compared to Hadfield austenitic manganese steel.

3) The mechanical properties of HC-Wi alloys are affected by the distribution of the hard second phase particles in the austenite.

4) For practical application where replacements of worn-out mechanical components result to frequent plant shutdown with associated high maintenance cost, the more expensive HC-Wi alloys are recommended over the cheaper Hadfield manganese steel.

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