Hadfield Steel and Austempered Ductile Iron: Similar in Metallurgy yet Different in Chemistry, Heat treatment and Application

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***Abstract*—**: Hadfield steel contains high carbon above 1% manganese content above 11% to stabilise austenite at room temperature while ADI has low manganese content of typically less than 0.4% to suppress the precipitation of carbide during austempering. In ADI austenite is stabilised by dissolving carbon that diffuses from graphite nodules and pearlite (in the case of pearlitic ductile iron). The high silicon in the order of 2.6% promotes graphitisation. The heat treatment procedures for the two materials are also different. However, the resulting matrix of microstructure contains austenite, which is meant to transform to martensite by mechanism believed to be both strain-induced and strain-assisted once the material has been strained. The toughness of Hadfield steel and ADI found to be 90J and 8.3J for respectively. These were below the standard values. Similarly, tensile properties of Hadfield steel i.e. yield strength 338 MPa, UTS 568 MPa and elongation of 20% were all below values of the standard values confirming the inferior quality of the local product

***Keywords*—:** Austempered ductile iron, austenite, Hadfield steel, martensite

I. INTRODUCTION

THIS paper discusses the similarities and differences in the chemistry, metallurgy, heat treatment and application of Hadfield steel and austempered ductile iron. These materials have unique properties that combine strength and toughness. Strength arises from the transformation of austenite to martensite upon application of strain to the component while toughness is attributed to matrix austenite and ausferrite. The mode and mechanism of transformation to martensite of dictate the application where there is impact or wear.

II. LITERATURE REVIEW

A. Behaviour and Limitation of Most Ferrous Materials

Most ferrous materials suffer a trade-off between strength and ductility or toughness. A gain in one property invariably comes at the expense of the other. In heat treatment, if a plain carbon steel is austenitised and quenched, the strength increases but ductility and toughness decrease. If hardened steel is tempered, ductility and toughness increase while strength decrease. Hadfield steel and austempered ductile iron have defied this limitation in having a unique combination of both strength and toughness.

B. Differences in Chemistry

TABLE 1

TYPICAL COMPOSITIONS OF HADFIELD STEEL [1] AND AUSTEMPERED DUCTILE IRON [2]

Composition (%)	Hadfield Steel (ASTM128GR B2)	ADI
C	1.05 - 1.2	3 - 4
Mn	11.5 – 14	<0.3
Si	< 1.0	2.4 - 2.8
P	<0.07	

Table 1 shows the chemical specifications of Hadfield steel and ADI. Hadfield steel is basically a high carbon and high manganese steel grade in which the Mn to C ratio should be above 10. Both manganese and carbon contribute to stabilise austenite. ADI is a nodular graphite cast iron with 3 to 4% carbon and low manganese to avoid formation of $(Fe,Mn)_3C$ type carbides

C. Mechanical Properties

Mechanical properties in Table 2 show that what Hadfield steel has in elongation and toughness ADI has in yield strength and hardness. The elongation values show that Hadfield steel can take four times larger strains than ADI. The high impact strength Hadfield steel shows that the material can accommodate impact loads.

TABLE 2

TYPICAL MECHANICAL PROPERTIES OF HADFIELD STEEL [1] AND AUSTEMPERED DUCTILE IRON [3]

Property	Hadfield Steel (ASTM128GR B2)	ADI
Yield (MPa)	350	550 - 1300
Elongation (%)	(5d) 40%	Up to 10%
Charpy (J)	>140J/cm^2	35 – 100J
Hardmess (BHN)	220 - 540	269 - 555

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D. Differences in Heat Treatment

Just as with the chemistry of the two ferrous materials, the heat treatment procedures are also different. However, the microstructural evolution is fairly similar in that both have austenite phase stabilised at room temperature although the mechanism of austenite stabilisation is different.

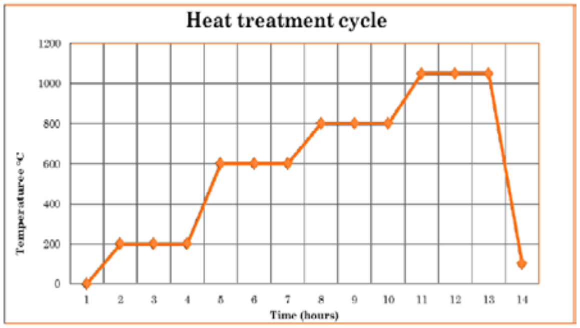

Fig. 1 Heat treatment cycle for Hadfield steel [4]

Fig. 1 shows a staged heat treatment profile for Hadfield steel. The heat treatment shows temperature ramps to 200ºC, 600ºC, 800ºC and ultimately to 1050ºC where soaking for a prescribed period is expected to dissolve carbides. However, gross carbides had formed during solidification may not full dissolve resulting in local brittleness that serve as cracks nucleation sites at grain boundaries. Finally the part is then quenching in water.

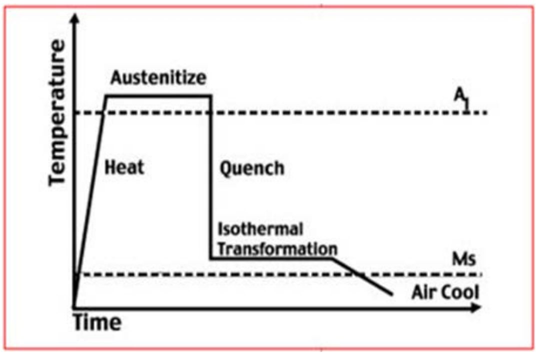

Fig. 2 Heat treatment temperature profile for ADI [5]

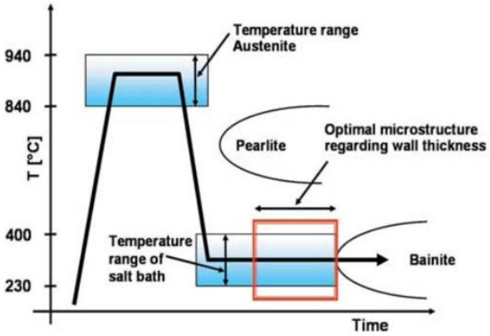

Fig. 3 Austempering cycle showing the ausferrite window and onset of bainitic transformation [2]

The heat treatment of ADI consists of austentising at temperatures between 850 and 950°C followed by austempering in a salt bath at temperatures between 250 and 400°C for controlled times [2].

E. Differences in Microstructure

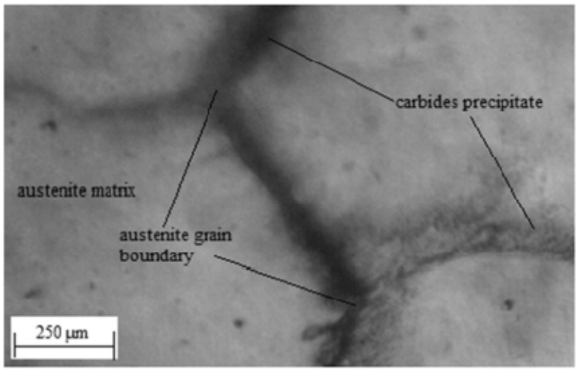

Fig. 4 Austenite grains in Hadfield steel [6]

The microstructure of Hadfield steel in Fig. 4 consists typically of single phase of austenite grains. Carbides that precipitate at grain boundaries have to be dissolved during heat treatment.

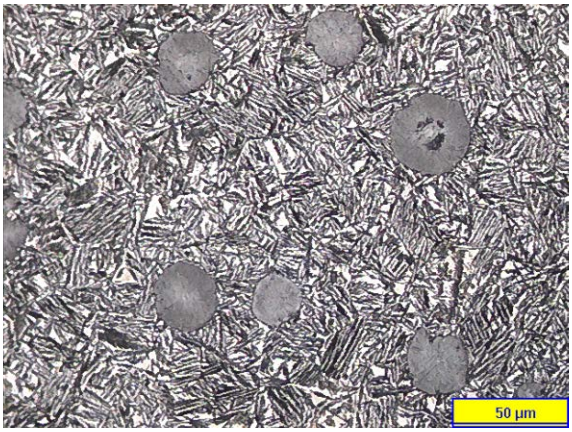

Fig. 5 Ausferrite with nodules of graphite [7]

Fig. 6 is a magnified version showing a graphite nodule in ausferrite. The typical acicular morphology of ferrite in the matrix is evident. Note the integrity of interface between graphie nodule and ausferrite. The graphite nodules act as crack sinks and thus prevent crack propagation resulting in high fracture toughness in ADI.

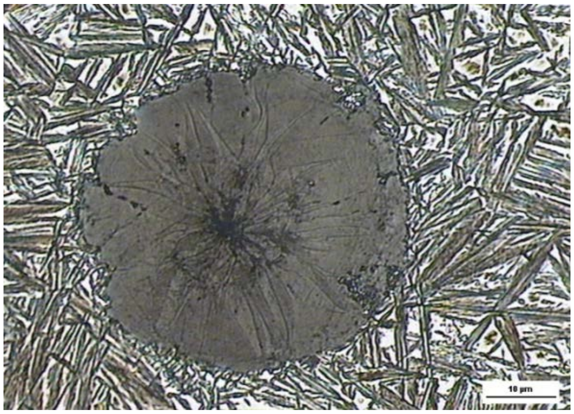

Fig. 6 Magnified graphite nodule in ausferrite [8]

F. Similarities and Differences in Phase Transformation

The transformation of austenite to martensite in both Hadfield steel and ADI is induced by deformation. In Hadfield steel stabilised austenite first exhibits dynamic strain aging than undergoes strain induced transformation to martensite under severe impact loads such as those experienced in crushing hard rock [9]. In both cases the martensite imparts the hardness on the surface.

III. EXPERIMENTAL WORK

A. Materials Used

TABLE 3
CHEMICAL COMPOSITION OF EXPERIMENTAL SAMPLE

Composition %	C	Mn	Si	Cr	Mo
Sample 1	1.25	13.7	0.8	0.5	
Sample 2	1.06	11.7	0.8	0.6	
Sample 3	1.02	13.5	0.7	1.0	0.1
Sample 4	1.12	11.8	0.6	1.5	0.5
Sample 5	1.15	13.5	0.5	0.5	0.3
Sample 6	1.09	12.3	0.8	0.5	0.04

The chemical composition of locally produced Hadfield steel is shown in Table 3 and that of ADI in Table 4 shows the typically high silicon of 2.4% required for graphitisation and the manganese content capped at 0.3%.

TABLE 4
CHEMICAL COMPOSITION OF DUCTILE IRON

C	Si	Mn	S	P	Cr	Cu	Ti	Mg
3.5	2.4	0.3	.002	.02	.04	.04	.02	.07

B. Experimental Procedure

Hadfield steel was cast and heat treated at a local foundry in Johannesburg. Ductile iron was cast at another foundry and delivered to the Department of Metallurgy at the University of Johannesburg for heat treatment. The metallographic examination for the heat treated materials was carried out at the Physical Metallurgy laboratory at the University of Johannesburg.

Hadfield steel samples were soaked at 1050ºC for 3 hours to dissolve carbides in austenite followed by rapid quenching in water. Ductile iron samples were austenitised at 900ºC for 2 hours and quenched in a salt bath at 340ºC and held in salt bath for 2 hours to allow isothermal transformation to ausferrite followed by quenching in water. Samples were cut, sectioned and prepared for metallographic examination.

IV. RESULTS AND DISCUSSION

A. Chemical Composition

Tables 3and 4 show the chemical compositions of Hadfield steel and ADI respectively. Some elements in the alloy have significant effect on the heat treatment and mechanical properties.

Table 3 shows chemical compositions of samples which were significantly high in carbide-forming elements Cr and Mo. These may have been added in bid to improve hardenability and final hardness but have a detrimental effect Carbides form at grain boundaries during solidification because of the carbide formers such as Cr, Mo as well as Mn. In heavy castings carbides of type (Fe,Mn)$_3$C form and with inadequate heat treatment these carbides do not do not dissolve but become nucleation sites for cracks [10]. In addition feeding of Hadfield steel during casting is very difficult because of the large dendrites of austenite that form and make the inter-dendritic flow of liquid steel difficult causing micro-pores and hot spots that eventually form micro-cracks [10].

B. Microstructures

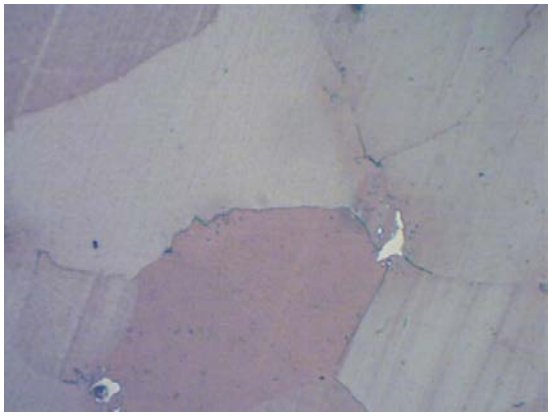

Fig 7: Hadfield steel showing matrix of austenite grains with patches of grain boundary carbides

The microstructure of Hadfield steel after heat treatment shown in Fig 7 consists entirely of a single phase austenite. Austenite is a phase of high toughness, a property necessary for high impact forces experienced in service. Heat treatment should ideally dissolve carbides, which have a tendency of reducing the toughness of Hadfield steel. Some residual grain boundaries carbides are evident in the microstructure. These carbides also serve as nuclei for cracks and hence reduce the fracture toughness of Hadfield steel.

The microstructure of ADI is shown in Fig 8. The matrix is a dual phase of carbon-enriched austenite and acicular ferrite, referred to as ausferrite. Carbide formers were kept at a minimum to suppress the transformation to bainite during austempering. Mo and Mn are good for hardenability. However, in excess of 0.3% carbides of Mo and Mn form during solidification and segregate to grain boundaries.

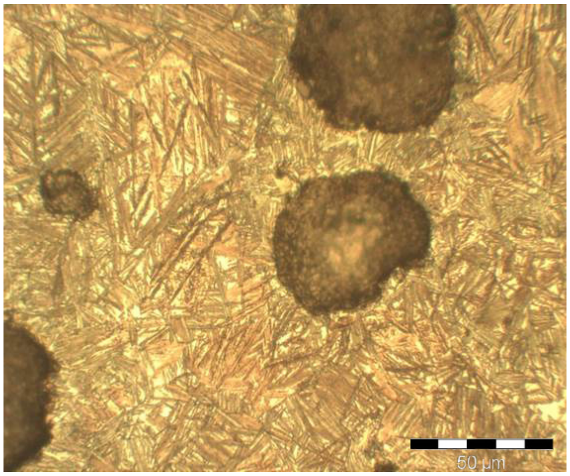

Fig 6: ADI showing a matrix of ausferrite and a distribution of graphite nodules

C. *Mechanical Properties*

The toughness values were found to be 90J and 8.3J for Hadfield steel and ADI respectively. Clearly Hadfield steel is superior to ADI in terms of impact toughness. Wear tests revealed that ADI was superior to Hadfield steel on wear resistance. Relative toughness and wear resistance properties indicate that Hadfield steel transforms to martensite under impact loads while the austenite ADI transforms to martensite by wear. The impact values obtained were far below standard shown in Table 2. Thus, the local products of Hadfield steel and ADI did not meet the specification. Other mechanical properties for Hadfield steel such as yield strength 338MPa, UTS 568 MPa and elongation of 20% were all below values of the standard values confirming the inferior quality of the local product. Cutting and sectioning of ADI was particularly difficult. Disc cutting wear mechanisms. Hence transformation to martensite is more enhanced during sectioning of ADI than Hadfield steel.

While matrices of both materials contain austenite, the volume fraction of austenite in Hadfield steel is much greater than in ADI. It may be possible that when all conditions for martensitic transformation are satisfied, Hadfield steel will produce a larger volume fraction of martensite per unit area than ADI.

V. CONCLUSIONS AND RECOMMENDATIONS

From the analysis made in this paper, the following conclusions are drawn and recommendations made:

1. Carbide formers such as Cr and Mo in Hadfield steel should be kept at a minimum to avoid formation of excessive carbides.
2. Hadfield steel being superior to ADI on toughness would be ideal for applications involving impact loading, while ADI would be suitable in application were wear is the mode of deformation.
3. Basing on the property differences it concluded that Hadfield steel is suitable for hard ore and stone crushing while austempered ductile iron is more applicable for earth-engaging tooling in agriculture and civil works. ADI may be suitable for friable and secondary ore crushing, but there a limit on the heat treatable size of component.
4. After the martensitic transformation, the surface of ADI is likely to be tougher than that of Hadfield steel due to ferrite fraction. On the other hand Hadfield steel surface, consisting of martensite will be hard and brittle.
5. Austempered ductile iron is very difficult to cut. It is recommended that the parts be cast or machine to near net shape prior to austempering so that after heat treatment there would be no need for further machining except for only minor grinding that may be necessary.

ACKNOWLEDGMENT

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