Wear of Hadfield Austenitic Manganese Steel Casting

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Abstract

The objective of the research work is to optimize the wear resistance of the austenitic manganese steel from Nigerian Foundries used for rock drilling. Emphasis is given to the control of grain size and phases, particularly secondary carbides. To achieve the overall goal, relationships are established between process parameters, mechanical properties, microstructure and alloying elements. Different heat treatments followed by water quenching are studied. Mechanical testing includes tensile, hardness and impact tests. Microscopy investigations include optical and Scanning Electron Microscopy (SEM). The results to date are a substantial grain refinement, dissolution of secondary carbides and overall material homogenization that are expected to improve wear resistance and service life. This can lead to a substantial reduction in costs associated with wear parts maintenance and replacement. Furthermore, this can strengthen Hadfield austenitic manganese steel as a highly cost efficient and preferment material for the mining industry.

Keyword: Carbides, impact, wear and heat treatment

1. Introduction

It was the need for an alloy that combines hardness and toughness that motivated Sheffield Robert Abbott Hadfield to embark on the study of alloys of Iron and other elements in 1878. Four years later, he found that with 10%Mn, under an appropriate heat treatment and water quenching, the material possesses sufficient hardness and toughness. Austenitic manganese steels can offer the best combination of toughness and resistance to high stress and gouging abrasion. Also, Mn steels are simple and cheap to produce and offer excellent potential in replacement of expensive chromium iron alloy, which are known to possess high hardness and wear resistance. However it also shows critical limitations regarding ductility and toughness. As can be seen from the Mn-steel equilibrium diagram any carbon composition greater than 1.2% encourages the formation of acicular carbide which in turn can lead to intergranular embbrittlememt in steel. The high carbon content in Mn steels, if completely retained in solution, provides best resistance to abrasion wear. Mn steels generally exhibit freezing ranges as wide as 200^{o}C (Temperature range between liquidus and solidus lines), making them susceptible to microporosity and the occurrence of deleterious continuous carbide networks, particularly at grain boundaries**.** Therefore, one of the best ways to optimize the wear performance of this alloy is a homogenization heat treatment that allows dissolution of carbides and redistribution of chromium and carbon atoms within the iron-manganese matrix. The final material then possesses a homogenized microstructure and uniform wear properties. Therefore, the presented paper focused on developing relationships between heat treatments, microstructure and mechanical properties. This can help optimize hardness, toughness and wear resistance of austenitic manganese steel for the manufacture of mining jaw plates.

2. Progresses and challenges in the development of hardfield manganese steel:

Specific alloy composition for jaw plates is generally selected depending on application demands and other service requirements. The austenite grain size is mainly governed by furnace de-oxidation practices as well as casting temperature. Non-metallic inclusions, microporosity and austenite grain size are the main factors affecting the wear resistance of manganese steel. The casting temperature of manganese steel greatly affects its solid state grain size, which in turn determines its wear resistance and hardness. Quenching, seeding and micro-alloying can, to a limited extent, refine the grain structure, but this is best done by heat-treatment in the solid state [12]

Because structural phase transformation has been generally agreed as temperature dependent, one of the routes for enhancing the wear characteristics of Hadfield Austenitic Manganese steel is through the interplay of heat treatment and controlled cooling.

In the heat treatment process, the grain size in austenitic manganese steels before quenching is tremendously influenced by diffusive and diffusionless phase transformations, and precipitation. It is primarily a function of the pouring temperature of the casting as well as of the casting thickness. The austenite grain size affects overall mechanical properties such as strength, hardness and ductility. Great scientific progresses have been made in understanding and controlling the austenite grain size during the austenitenization process of the steel over the past half a century [2-9]. Even if the austenite grain size is fine after reverse transformation during heat-up to the single phase austenite region, the grain refinement can be hindered due to the high energy zones created by the heterogeneous nature of the second phase carbides re-precipitation in the microstructure. However, Attempts by researcher to improve the Mn-steel wear resistance were either not successful until now or yielded successes that were negated by substantial disadvantages. For instance, Si addition is known to be essential to aid fluidity during casting and reduce oxidation of alloying elements during melting. However, 2%Si added to a batch of heat in the foundries resulted to outright breakage due to the effect of silicon pyramid in the melt containing returned scrap [13]. Also, the addition of Molybdenum is knows to potentially increase the corrosion resistance and toughness of manganese steel; however, D.D Howat and D.P Enright found that the addition of up to 0.8%Mo does not improve wear properties of Mn steel appreciably, and therefore shows no relevance for jaw plates [14]. Seeding with powder additives during casting [15] with the aim of influencing the composition and conditions for crystal formation was also reported; Laboratory tests [13] have shown that this method can be very effective; however, theoretical conditions must be carefully observed.

3. Experimental Procedure

3.1. Materials and methods

Mn steel with a composition in weight percentage of 1.0C-0.6Si-14Mn-1.8Cr-0.05P-0.05S-balance Fe was investigated. To replicate the casting solidification profile in the Laboratory test through the concept of modulus of casting, spherical ball of diameter 104mm as well as rectangular cross-section bars of dimensions 25x25 x150mm were manufactured by the Nigerian foundries limited Lagos, Nigeria. The synthesis of the alloy was carried out in a medium frequency neutral refractory lined, Electric Induction Furnace. A silica sand mould was used. The material was produced to ASTM128C equivalent specification to investigate the effect of different temperatures through solution hardening heat treatment with a view to projecting and predicting the wear characteristic through the material's hardenabilty profile.

The charge calculation for the synthesis of the manganese steel was done by simple stoichiometric method. Steel scrap (0.35C-0.25Si-0.5Mn-0.001P-0.001S-0.02Al-balance Fe) and foundry return (1.25-0.9Si-12.8Mn-2.0Cr-0.002P-0.001S-balance Fe) were melted. Scrap and foundry return compositions are given in weight percentage. The calculated amounts of chromium, petroleum coke (99%C) and both electrolytic silicon and manganese were added into the melt and poured at 1470°C.

Balls and bars were both subjected to inter-critical annealing and homogenization heat treatment at 750°C and 1050°C respectively and held for appropriate time (25.4mm per hour) and water quenched to room temperature. The bars were machined to standard Jominy specimen for hardenability tests. For the determination of the microstructure, samples were cut at different distances (quenched face, middle and far end of jominy samples). Similarly, samples for microstructural investigations were taken at different distances along the ball radius (from ball surface to ball central axis). The samples were ground with Tegrapol-31, polished using a colloidal suspension of 0.04μm silicon dioxide and then etched in 100mL alcohol and 3mL HNO_3 acid after polishing using Allegro with diamond suspension.

4. Results and discussion

The optical micrographs in Fig.1 and 2 show the microstructures of the quenched Jominy samples of manganese steel held at 750°C and 1050°C respectively. The microstructure of the Jominy samples held at 750°C before water quenching one end contain undissolved chromium-carbides, the content of which increases from the quenched face (faster cooling) towards the far sample end (slower cooling). The chromium carbide at this temperature is known to be largely heterogeneous and brittle in nature. However, the Jominy samples show relatively high hardness across it entire length. This can have two possible explanations: (i) either even relatively slow cooling at the farest sample end, which can be assumed close to air cooling, is enough for hardenability purposes. (ii) or the as- cast bars already show sufficient hardness across the samples which remains unchanged during the Jominy test. The latter explanation applies to the present case as proven by the fact that the as-cast Jominy sample shows hardness values nearly identical to those of 750°C heat treated Jominy samples. Therefore, it can be concluded that the chosen bar dimensions provide cooling rates that lead to sufficient hardness across the samples and are not appropriate for hardenability test on the studied Mn steel. Because of the faster cooling rate at the surface, the ball show high hardness values in the outmost layers similar to values measured across the Jonimy samples. As the cooling rate drops towards the ball interior, lower hardness values are measured in the center. This observation is complemented by microstructural variations across the ball from the quenched surface towards the core as observed in Fig 3 (c), (b) and (a). This is in agreement with Papworth and Williams' work [16] who found that there is segregation of alloying elements to austenite grain boundaries in alloy steel as they observed through X-ray mapping in the field emission gun scanning transmission electron microscopy (FEGSTEM).

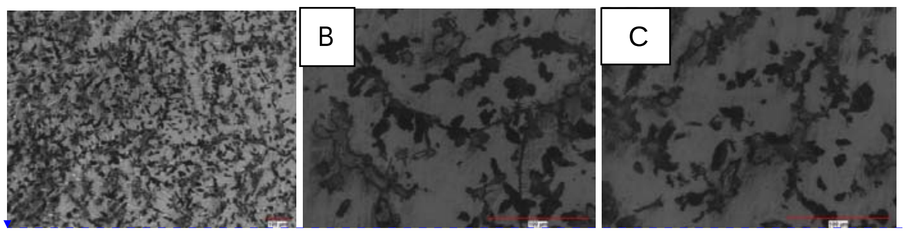

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Fig 1 Micrographs of manganese steel at 750°C: (a) Quenched jominy sample surface; (b) 50 mm from quenched end; (c) 100 mm from quenched end

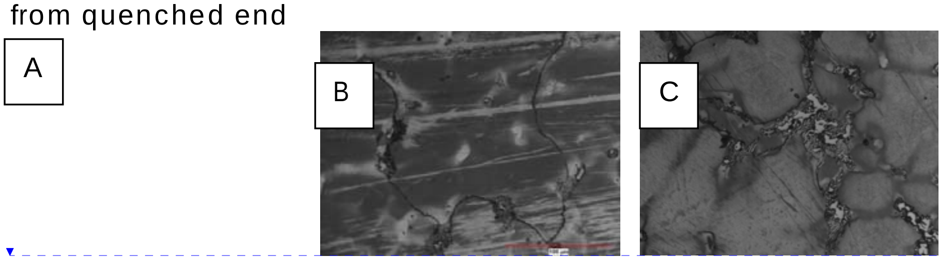

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Fig 2 Micrographs of manganese steel at 1050°C: (a) Quenched jominy sample surface; (b) 50 mm from quenched end; (c) 100 mm

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from quenched end

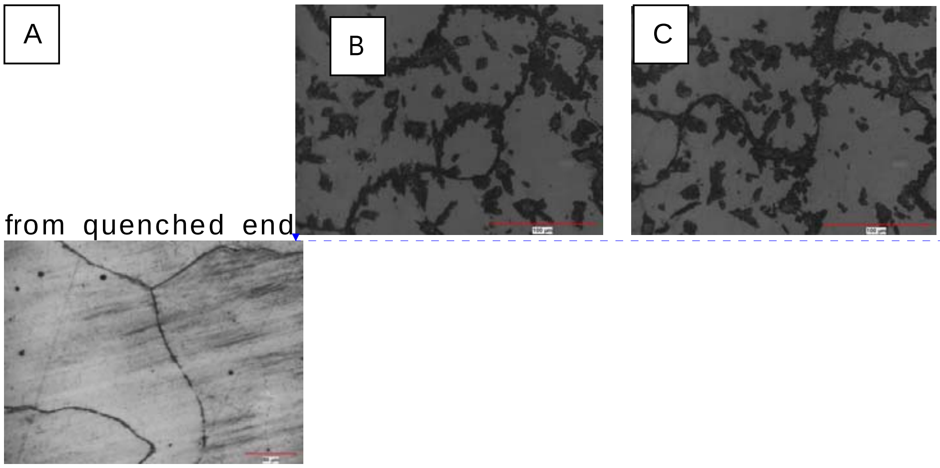

Fig3 Micrographs of manganese steel at 750°C: (a) Ball center; (b) 26 mm from the ball surface; (c) Quenched ball surface

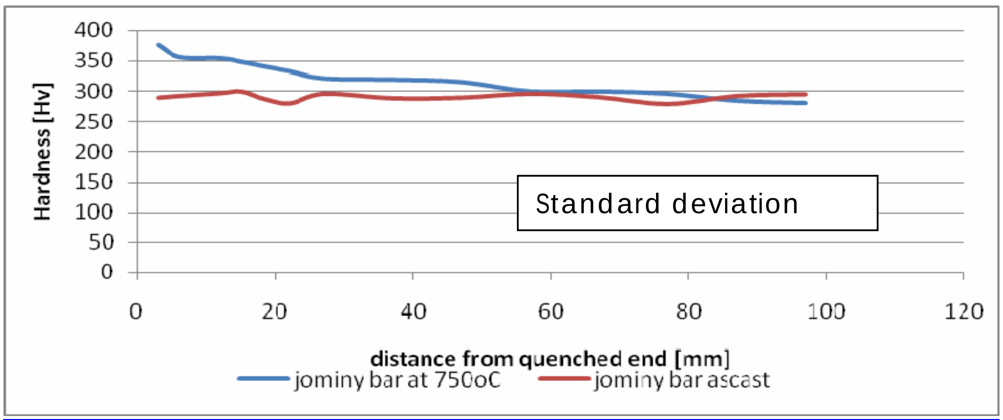

Fig 4 Hardness profile of jominy bar at 750^{o}C

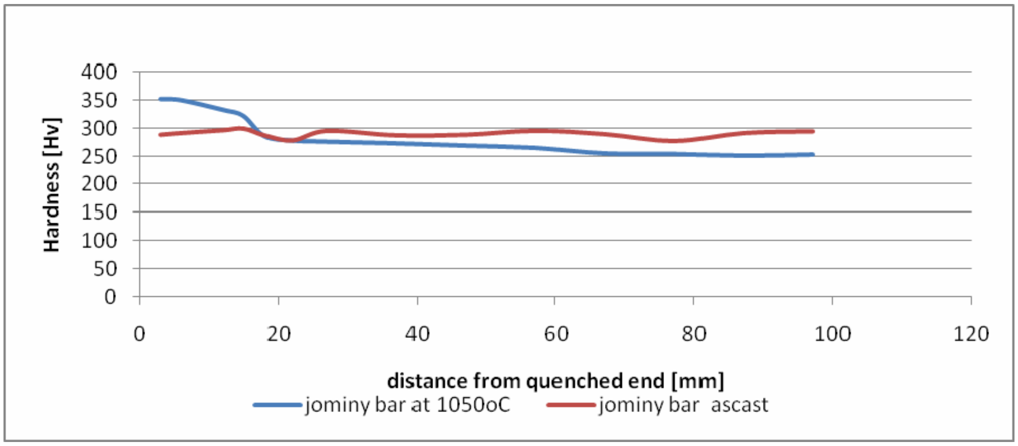

Fig 5 Hardness profile of jominy bar at 1050^{o}C

Table1 Chemical compositions of the experimental steel (wt %)

C	Si	S	P	Mn	Cr	Fe
1.27	0.55	0.017	0.03	13.9	2.01	bal

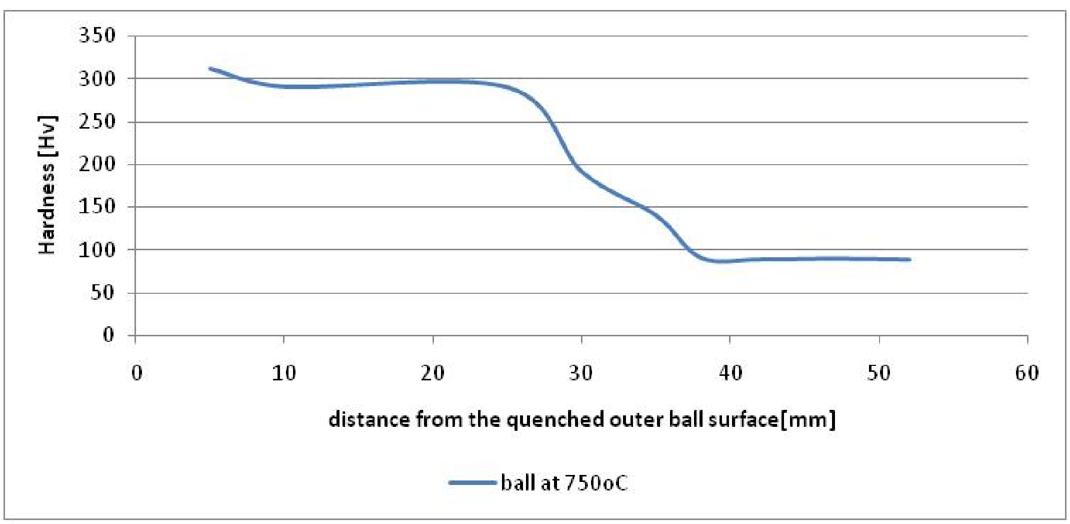

Fig 7 Hardness for 104mm diameter ball water quenched from 750°C

The relative high hardness observed with Mn-steel at 750°C can be indicative of the fact that the carbide present have a structure that is not detrimental for hardness. However, their impact on the toughness could not be estimated which will be the subject of future research. The results also show that 750°C is not a suitable temperature for homogenizing Mn-steel. On the contrary, about 95% of the carbide are dissolved at 1050°C; only very few precipitates can be fond across the noticeable at 1050°C.
This present study has shows that the Jominy test bars can only be used to predict the hardness and microstructure of manganese steel only within the first 27 mm below the surface of the balls as can be seen in Fig. 7. This is due to the very poor thermal conductivity that leads to cooling rates much lower than for air cooling below this depth even when the balls are quenched in water.

5. Conclusion and outlook:

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This paper shows that detrimental Cr_3C carbides build in the investigated Mn steel during casting from 1550°C. Therefore, a homogenization heat treatment is necessary to dissolve those carbides and homogeneously redistribute chromium and carbon within the Mn-Fe matrix and provide the steel with necessary solid solution hardening together with improved ductility. The Jominy samples seems to be thin enough not to cause any substantial precipitation of carbides and therefore show relatively high hardness independent of heat treatment and distance from the quenched end of the Jominy samples. However, samples annealed at 750°C still show carbides while those annealed at 1050°C show a completely homogenized microstructure. In contrast, the balls with 104 mm diameter show a strong drop in hardness across their diameter from surface to center, when annealed at 750°C. It can be concluded that the ball would necessitate a homogenization at much higher temperature, e.g. 1050°C, in order to assure complete dissolution of the carbides, high hardness and potentially high ductility and wear resistance of Mn steel for mining jaw plates.

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