Prominence of Hadfield Steel in Mining and Minerals Industries: A Review

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Abstract – High manganese austenitic steel, popularly called “Hadfield steel” has dominated and played significant role in wear applications, especially in the mines and minerals industries since its invention over a century ago. A review on the researches on this steel revealed that its prominence in these fields is mainly due to its good combination of impact and abrasion wear resistance arising from its high toughness and high hardness respectively. Its strain hardening ability under impact loading is evidenced by increase in hardness as the material work hardens; this lowers the amount of wear in service. The work hardening property of the steel has been linked to governing mechanisms such as dislocation, deformation twinning, and dynamic strain ageing; also, it is enhanced by increase in carbon, ageing temperature and reduction in manganese content. Carbide precipitation along the grain boundaries and within the grains is the major cause of embrittlement of the steel. These carbides together with voids and porosities during casting solidification, improper heat treatment, overheating during welding, use of unsorted scrap metal and wrong wear application have been identified as the causes of premature failure in service. Difficulties encountered during machining of the steel have been overcome through hot machining. Hardfacing method has been proposed as a means of substituting the steel in wear applications, as alternative wear materials such as white cast iron and austempered ductile iron lack the combination of impact and abrasion resistance being offered by the Hadfield steel.

Keywords – Hadfield steel, wear, dominance, mining, minerals, machineries

1. Introduction

Mining and minerals processing activities involve subjection of components of machineries to severe wear. The dominant wear modes in these stone and ore handling facilities being abrasion and impact; while abrasive wear requires components with high surface hardness, impact wear calls for component that are internally tough. Producing wear resistant components that combine these properties has been a major concern of researches in this sector. The Hadfield steel, a high manganese austenitic steel has been the dominant material used in the minerals industries since its invention by Sir Robert Hadfield in 1882 and patented in Britain in 1883 and in the United States in 1884 with patents 303150 and 305151 [1-4].

Unique properties of Hadfield steel include: high hardness, high toughness, and high strain hardening or work hardening capacity with reasonable ductility [5-9]. According to Fadhila *et al.* and other works [5-13], these peculiar properties have paved way for its applications in sectors such as mining, where it is used in grinding mill liners, crusher jaws, impact hammers, cone crusher mantles and concave; transportation, which includes railroad crossings and frogs; military, where it is used in bullet-proof helmets and naval vessels; agricultural and earthmoving equipment, such as crawler treads for tractors, track links in heavy excavators and dredge buckets. Limooei and Hosseini [14] noted that the steel is a non-magnetic alloy, which makes it relevant in applications where magnetic effect is avoided.

Notwithstanding the attestation of good performance in wear applications given to high manganese austenitic steel, it has some shortcomings during its processing, utilization and repairs. More so, its dominance as a wear material for over a century needs to be whittled. The objects of this paper are to unveil the root cause of the prominence of the steel as a wear component in the mining and mineral processing industries, challenges encountered in processing and service, and provide alternative ways of replacing or substituting the material.

2. Composition and Heat Treatment of Austenitic Manganese Steel

The ASTM A28 stipulates the composition of the austenitic manganese steel as 1.0 – 1.4 %C, 10 – 14 %Mn, and the balance Fe [7,15-17]. Achieving manganese to carbon ratio of 10 is of great importance. The ratio of Mn to C being < 10 and phosphorus > 0.05 in the composition of the steel is believed to be catastrophic [2]. Owen and Grujicic [18] stated that the manganese steel with a nominal composition Fe- 12 %Mn, 1.2 %C is a stable single phase austenitic alloy and is usually annealed prior to use within temperature range of 1000 – 1100^{o}C, and quenched to retain all the carbon in supersaturated solid solution. Balogun *et al.* [1] cautioned that high pouring temperature above 1450 ^{o}C should be avoided as segregation of alloying elements occurs above this melting temperature.

Dissolution of carbides is achieved by heat treatment. Usually, a fully austenitic structure, carbide free and homogeneous solid solution having C and Mn in the right proportion is desired. Homogeneity can be achieved by ensuring that as-cast structure is free from segregation, inclusions and pre-existing cracks; additionally, slow solidification or quenching should be avoided as it leads to carbide precipitation, alloy segregation, dendritic structure and grain growth, which adversely affect the ductility and strength of the Hadfield steel [4]. Olawale *et al.* [19] posited that embrittling carbides present in as-cast structure are removed by solution treatment and quenching.

Austenite can be obtained at 1050 ^{o}C after holding for 2 hours and water quenching [6]. Likewise, Balogun *et al* [1] recommended an austenitizing temperature of 1050 ^{o}C for 4 hours and soaking time of 5 minutes during quenching in water. Additionally, the usual practice in local foundries where the melt is superheated above 1500 ^{o}C to enhance fluidity of the melt and ease slag removal should be avoided as it is counter-productive, due to excessive slag formation resulting from the reaction of manganese with the refractory lining, which leads to erosion of the furnace lining and subsequently furnace leakage and lifespan reduction. Figures 1 and 2 explain the effect of heat treatment on carbides.

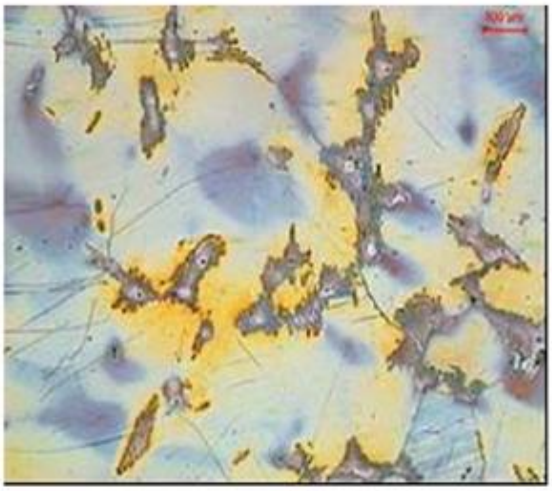

Fig. 1. Microstructure showing carbides in cast high manganese steel before heat treatment [21].

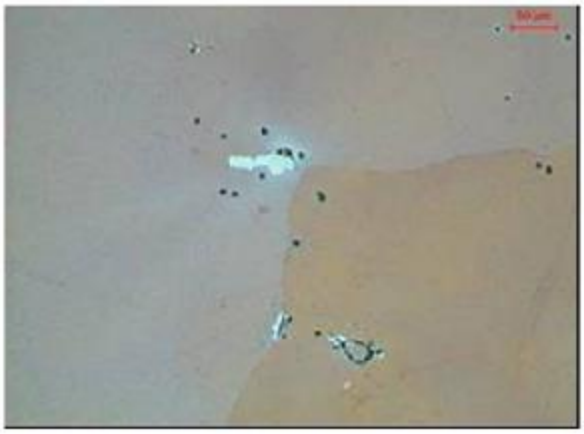

Fig. 2. Carbides in the microstructure of high manganese steel after 5 hours of heat treatment at 1050^{o}C and quenching in water [21].

3. Properties and Alloy Modifications of Hadfield Steel

Hadfield steel exhibits remarkable plastic flow behaviour which is indicated by strain hardening without necking to high levels of strength and strain. This behaviour is valued for severe service applications regardless of its low yield stress [21]. A typical example of this behaviour has been illustrated by Harzallah *et al.* [22] with a rail crossing designated X120Mn12, having composition 1.138 %C, 0.46 %Si, 12.89 %Mn, 0.0033 %P, 0.008 %S and 0.18 %Cr, and mechanical properties as follow: yield strength – 400 MPa, ultimate tensile strength – 1000 MPa, and hardness – 220 HV; with an applied load of 700 N and rolling speed of 275 RPM, the alloy showed the highest surface hardness of 1000 HV after 150,000 cycles, implying four times its initial hardness.

Another railway crossing with composition 1.2 %C, 12.4 %Mn, 0.60 %Si, 0.016 %S, 0.022 %P and the balance Fe, which was subjected to about 160 million tonne transportation load with a combination of repeated rolling compression and impact forces from train wheels was solution treated and water quenched with the resulting mechanical properties as follow: percentage elongation – 35.8 %, percentage reduction in area – 22.9 %, ultimate tensile strength – 840 MPa, impact toughness – 320 J/cm^2, and hardness – 225 HV; the average hardness of the deformed steel ranges from 520 to 580 HV [23].

The high toughness of the Hadfield steel results from high strain hardening capacity which enhances stable plastic deformation, thereby avoiding shear localization and loss of load-bearing capacity [24]. Canadinc *et al.* [25] disclosed that the strain hardening response of a manganese steel of composition 13.93 %Mn, 1.3 %C and alloyed with 2.5 %Al was governed by high density dislocation walls that interact with glide dislocations at room temperature. According to Jingpei *et al.* [26], work hardening ability of the austenitic manganese steel increases with carbon and ageing temperature but decreases with increase in manganese; it is enhanced by dispersed secondary particles and dislocation. Reduction in the manganese content results in low austenite stability, which leads to strain-induced martensite transformation and increase in the work hardening ability of the steel.

The work hardening characteristics of the high manganese steel has been attributed to deformation twinning over a wide temperature and strain range, which can combine with any unique ageing effects [27]. Owen and Grujicic [18] apportioned the work hardening behaviour of the steel to dynamic strain ageing, which they described as a direct result of the increase in the number of Mn-C pair produced by the ageing process, and twinning, which adds to the hardening when it occurs.

Additionally, Hai-lun *et al.* [6] observed that the work hardening ability of Hadfield steel castings does not manifest fully when subjected to non-severe impact service conditions. Karaman *et al.* [28] concluded that twinning is the main deformation mechanism in the steel. Also, Mahlami and Pan [17] summarized that work hardening behaviour is responsible for the rapid surface hardening and arises due to dislocation interactions, slips, twins and stacking fault that occur at high impact or compressive loads. Qian *et al.* [23] disclosed that large non-uniformity of hardness distribution in deformed Hadfield steel arises from the underlying non-homogeneous substructure with higher hardness in multiple twin regions and lower hardness in regions where dislocation prevails; hence, hardness value decreases slightly with increasing depth due to larger deformation at locations closer to component surface which generates increasing work hardening compared to inner locations.

A comparative study of the hardness of as-cast Mn13-steel and explosion depth hardened M13EDH-steel showed the hardness of M13EDH was higher than the as-cast steel having recorded a hardness of 315 HV. However, strain hardening was low in Mn13EDH [30]. Zhang *et al.* [30] showed that a Hadfield steel sample with composition 13 %Mn, 1.2 %C, solidified under a pressure of 6 GPa gave rise to refined grain size ~ 7.5 ± 2.5µm as against ~160 ± 45µm recorded under pressure when subjected to metallographic examination, x-ray diffraction revealed that $M_{23}C_6$ carbide was obtained in the steel solidified under 6 GPa, while M_3C was obtained by solidification under normal pressure.

Hadfield steel alloyed with Al and Si and microalloyed with Nb and Ti and subjected to thermomechanical treatment resulted in fine grained structure with the expectation of increase in mechanical properties during subsequent cold plastic deformations [31]. This expectation will be right if the steel obeys Hall-Petch relation which Chinella [21] reported that alloys which obey this relation have increased yield stress and hardness with decrease in their grain size.

Wear resistance of the manganese steel has been raised up to 40 % by addition of titanium and grain refinement [14]. The yield strength, hardening rate and ultimate strength of the steel weld region have been increased by a combination of nitrogen alloying and microstructural refinement [7]. To attain optimal tensile strength, 12 to 13%Mn should be used. Manganese acts as an austenite stabilizer and delays isothermal transformation to bainite. Carbon content below 1 % leads to a decrease in the yield strength. The optimal carbon content has been found to be between 1 and 1.2 %. Above 1.2 %C, yield strength is unaffected; however, > 1.4 %C should not be used as this results in the segregation of carbon to the grain boundaries as carbides, which affects the strength and ductility adversely. Silicon acts as a deoxidizer when present, while chromium increases yield strength and decreases ductility [32].

Also, Balogun *et al.* [1] posited that the presence of chromium in purely austenitic Hadfield steel results in the appearance of cracks arising from elevated internal stresses associated with the liberation of carbides which segregates at grain boundary; however, uniformly dispersed chromium carbides in the base of the austenitic grains provides higher resistance to impact abrasion resistance. Hamada *et al.* [33] stated that strengthening of the steel by addition of manganese offers opportunities for refinement of structure by dynamic recrystallization; similarly, Dobrzański *et al.* [34] reported that dynamic recrystallization occurred in high manganese steel containing 3%Al and 3%Si.

4. Weldability and Failure of the Hadfield Steel

Carbide precipitation is a major challenge encountered during welding of austenitic manganese steel. This is avoided by keeping the temperature of the steel below 300 ºC; arc welding, which involves short period of heating has been suggested as a suitable method for this purpose. Work hardening characteristics and plastic deformation of weld overlay have been exhibited by electrode containing molybdenum than electrodes with nickel-chromium and chromium electrodes [11]. Hence, early failure may be prevented by avoiding overheating of the material. High carbon content in the steel makes it difficult to process due to carbide precipitation which results in poor weldability [35].

According to Olawale *et al.* [19], inadequate quenching operations during manufacturing process of the steel leads to the formation of carbide precipitates which embrittle the steel, reduce its ability to withstand shock and create non-uniform plastic flow as the material strain hardens. Also, Curiel-Reyna *et al.* [36] noted that microhardness differences resulted from carbide precipitation arising from post cooling process. High brittleness at the heat affected zone of a welded Hadfield steel originated from the presence of discontinuities or defects as voids, micro-voids, carbides and micro-cracks at the grain boundaries. Figures 3 and 4 show the microstructure of a sound crusher jaw and a failed defective crusher jaw with carbides along the grain boundary and within the grains, respectively.

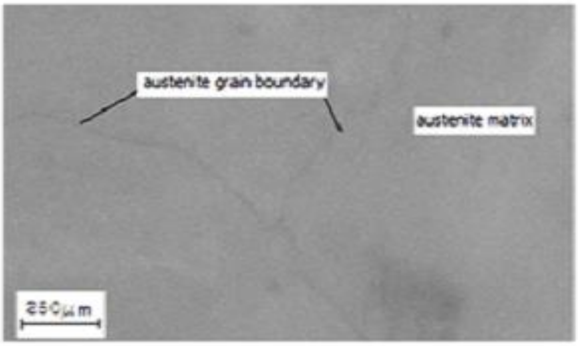

Fig. 3. Optical micrograph of sample of sound crusher jaw showing austenite grain boundaries in austenite matrix [20].

More so, Chojecki and Telejko [20] unveiled the reason for crack formation in service as micro-porosities formed during casting solidification and propagation of the micro-cracks during service conditions involving dynamic stresses. Additionally, castings of wall thickness greater than 60 mm are treated for about 5 hours in foundry practice; this reduces the quantity of carbides to less than 0.8 % and their dimensions to less than 30µm, while secondary carbides are possible nuclei of brittle fracture.

Furthermore, Bhero *et al.* [4] identified major causes of poor field performance of Hadfield steel as: random use of unsorted scrap, improper casting procedures, faulty heat treatment and inappropriate use of product. Slack quenching or warm roll reheating may initiate grain boundary carbide precipitation in high carbon content Hadfield steel, resulting in the introduction of grain boundary void nucleation softening mechanism, leading to plastic instability, low strain and strength [21].

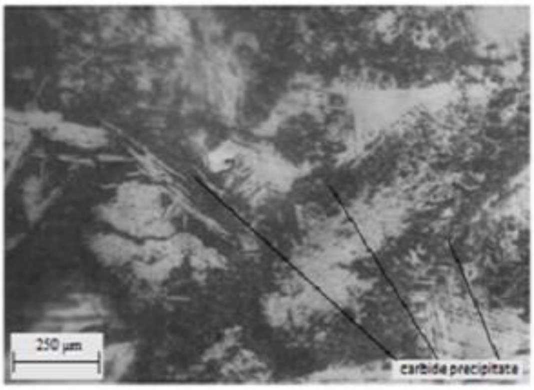

Fig. 4. Optical micrograph of sample of failed crusher jaw showing microstructure of large carbides at the grain boundaries and in the grains of austenite matrix [20].

5. Machinability of Hadfield Steel

Machinability of austenitic manganese steel has been reported to be very low; this has been attributed to its high hardness, strain hardening behaviour, strength, toughness, wear resistance and low thermal conductivity [37,38]. Hadfield steel containing dispersed Ti(CN) has higher wear resistance but severely reduced machinability [37]; consequently, the high manganese steels are referred to as difficult-to-cut materials [39]. Armstrong *et al.* [40] posited that the steel has metastable austenite at room temperature, which transforms to stable martensite during machining. Cebron *et al.* [41] noted that the steel hardens substantially during machining and causes wear of the cutting tool; the degradation of the tool can be linked to the strain hardening while being worked on and the structure of the material after heat treatment.

Strong abrasion and notch wear have been observed when turning Hadfield steel [37]; more so, increase in micro-hardness was recorded from cutting and machining the material [22]. Rapid tool wear occurs as well as built-up edge on cutting tool tip [42]. Increasing the feed rate or cutting speed leads to an increment in the level of hardening [41]; these machining difficulties led to the search for a better way of machining the material. Armstrong *et al.* [40] noted that it was impracticable to machine Hadfield steel at room temperature; however, the material was easily machined at higher temperature and martensite transformation did not occur; hence, they concluded that hot machining improved the machining property of the material.

According to Çakir [43], hot machining has been established as the solution to the machining challenges of Hadfield steel. This process offers high tool life, better surface finish and higher material removal rates. Potter [44] recommended that the material should be heated to a temperature between 300° C and 420° C, while being machined. Pal and Basu [45] recorded tool lives of 1 min at room temperature, 5 – 6 mins at 400° C, 7 – 8 mins at 500° C and 10 mins at 650° C. The work piece is heated before or during machining around the area being machined. Heating methods that have been used include: plasma arc, electric current, flame, induction, laser and arc heating. Also, hot machining leads to reduced cutting forces and lowers machining costs [46]. Kopac [38] reported that increase in the temperature of the material results in reduction in hardness and the material will likely lose its hardness and related properties after 500° C. Figure 5 shows a diagram of Hadfield steel workpiece undergoing hot machining.

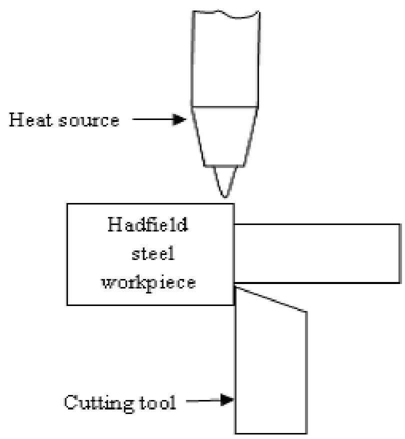

Fig. 5. Hot machining of Hadfield steel.

Uncoated Al_2O_3/TiC mixed with ceramics which composed of 70% of Al_2O_3 and 30% of TiC has been used a cutting tool for the material [47]. Coated TiAlN tools produced by physical vapour deposition method showed lowest surface roughness and cutting forces when compared with TiCN/Al_2O_3/TiN and TiAlN/AlCrO coated by chemical vapour deposition and physical vapour deposition, respectively [39]. While carbide cutting tools have been found to provide better tool life and surface finish than high speed steel tools, cubic boron nitrate tools were more useful as they offer the highest cutting speed of about 200 m/min. Moderate feed rate has been recommended, as lower feed rates would cause higher strain hardening due to longer contact between the cutting tool and workpiece. Additionally, the depth of cut must be higher than the work-hardened thickness, to prevent higher tool wear [43].

6. Alternative Wear Materials to Hadfield Steel

Low alloy wear resistant steels and high chromium white cast iron are alternative wear materials to Hadfield steel. However, their applications are by either complex manufacturing process or too low toughness [10]. Austempered ductile iron (ADI) has been suggested by Skoczylas *et al.* [48] as a substitute to Hadfield steel due to its excellent combination of strength, ductility and toughness in addition to low weight loss when subjected to abrasive wear test. The authors did not take into cognizance the increase in hardness of the Hadfield steel as it workhardens under impact loading. Modern trend in wear applications is that parts are being hardfaced based on the wear mechanisms and service conditions, which determine the selection of the hardfacing alloy, substrate material and welding method.

7. Conclusions

Findings of different researchers on Hadfield steel regarding its composition requirements, unique combination of mechanical properties, special care and shortcomings are summarized as follow:

The optimal manganese to carbon ratio in the austenitic manganese steel is 10, with carbon ranging from 1 to 1.2 % and manganese content between 12 and 13 %, in order to attain optimal tensile strength. Carbon content greater than 1.4 % leads to segregation of carbides, which results in the embrittlement of the steel.

Wear resistance of the steel can be increased by addition of alloying elements such as titanium or chromium. Explosive depth hardening has been used to increase its hardness prior to use, while appreciable grain refinement has been achieved through solidification under pressure. Dynamic recrystallization in the steel has been associated with the presence of manganese, aluminium and silicon.

High strain hardening ability of the steel favours toughness, while dispersed carbides in the microstructure favours hardness. Work hardening is enhanced by increase in carbon, ageing temperature, dispersed secondary particles and dislocation. It has been associated with mechanisms such as deformation twinning and dynamic strain ageing. The rate of work hardening in as-cast structure is greater than that of a previously hardened bulk material. However, the latter has the advantage of high hardness before use which translates to less wear damage of the latter than the wear in the former. This explains why the steel performs best when subjected to impact and abrasive loading conditions.

Precipitation of carbides at the grain boundaries arises from improper heat treatment procedures such as holding at inadequate austenitizing temperature for a short period and slack quenching. Usually, the carbide precipitates in the microstructure are dissolved by solution treatment at an austenitizing temperature of 1050 ºC, at holding time from about 3 hours and above, depending on the amount of carbide present, while quenching in water is carried out at very fast rates to ensure austenitic microstructure. These carbide precipitates embrittle the steel and results in poor weldability.

Difficulties experienced during machining of Hadfield steel arise due its high hardness, strain hardening behaviour, toughness, wear rate and low thermal conductivity. The challenges encountered during machining include: rapid tool wear, hardening of workpiece, built-up edge on cutting tool tip, strong abrasion and notch wear These have been overcome through the use of hot machining technique, which lowers the cutting forces and machining costs, increases the tool life, offers better surface finish and material removal. Coated carbide tools are more effective in machining the material than high speed steel; however, moderate feed rate should be used, while the depth of cut should be higher than the work-hardened thickness to prevent strain hardening and higher tool wear, respectively.

Alternative wear materials such as white cast iron and austempered ductile iron lack good combination of hardness and toughness to replace Hadfield steel in wear applications; hence, its prominence in the mining and minerals processing industries. Development of economical hardfaced wear components with good combination of hardness and toughness is being proposed as a means of substituting the Hadfield steel in ores and stones processing involving impact and abrasive wears.

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