Abstract—Crushers and hammers used in mineral processing are normally made of Hadfield steel typically containing over 12% manganese. Premature failure of these components is a cause of concern because of the down times and replacement costs. In theory, the Hadfield steel is robust with higher operational life. Thus the loss of integrity has a number of underlying causes. This paper explores the abnormalities associated with the metallurgy and processing of Hadfield steel.

Keywords—Hadfield steel, failure, austenitic, martensite

I. INTRODUCTION

HADFIELD’S manganese steel was invented by Sir Robert Hadfield in 1882 and first patented in Britain in 1883 and in 1884 the patents 303150 and 303151 were granted in the United States [1]. In accordance with ASTM – A128 specification, the basic chemical composition of Hadfield steel is 1 - 1.4% carbon and 11 - 14% manganese. However, the manganese to carbon ratio is optimum at 10:1 to ensure an austenitic microstructure after quenching [2]. The unique properties of high toughness, high ductility and high rate of work hardening resulting in superior wear resistance have made Hadfield’s austenitic manganese steel an engineering material of choice for use in heavy industries such as earth moving, mining, quarrying, oil and gas drilling, among others.

Manganese acts as an austenite stabiliser and delays isothermal transformation to bainite. In Hadfield steel, carbon is dissolved in austenite up to a practical limit of 1.2%. Above 1.2% carbides precipitate and segregate to grain boundaries, resulting in compromised strength and ductility particularly in heavy sections [3].

Although manganese content has little effect on yield strength, it does affect ductility and ultimate tensile strength (UTS). Because the UTS is maximum at 12 to 13% manganese, it is uneconomical to have higher manganese contents [1]. However, Haakonsen [4] worked with Stromhard steels with considerably higher carbon manganese contents of 1.4% and 20% respectively. Chromium was for high hardness before and after work hardening.

When subjected to impact loads Hadfield steel work-hardens considerably while exhibiting superior toughness. However, due to its low yield strength, large deformation may occur and lead to failure before the work hardening sets in [5]. This phenomenon is detrimental when it comes to some applications such as rock-crushing [6]. Work hardening behaviour of Hadfield steel has been attributed to dynamic strain aging [7]. The hardening or strengthening mechanism has its origin in the interactions between dislocations and the high concentration of interstitial atoms also known as the Cottrell-Bilby interaction. Thus, the wear properties of Hadfield steel are related to its microstructure, which in turn is dependent on the heat treatment process and chemical composition of the alloy. According to Haakonsen [4], work hardening is influenced by such parameters as alloy chemistry, temperature and strain rate.

II. EXPERIMENTAL WORK

The production procedures for Hadfield steel hammers and jaw crushers at two South African foundries (names withheld) were reviewed in order to determine the causes of premature failure of components in service. The processes included all stages of the value chain namely; visual examination of failed components, scrap selection for control of chemical composition, tapping/pouring temperature and solidification time, heat treatment procedure and metallographic examination.

III. RESULTS

Visual examination

Fig. 1 Jaw crusher exhibiting a crack that was evident soon after heat treatment.
Fig. 1 shows a crack cutting across a jaw crusher. The crack was observed soon after heat treatment. Micro-crack could have pre-existent in a casting prior to heat treatment as a result of thermal effects and brittle constituents in the microstructure. First, large superheats may have caused hot tearing. Second, phosphorus inclusions and grain boundary carbides can be pathways for pre-existing cracks.

Fig. 2 below illustrates the deleterious continuous carbides at the grain boundaries that have to be controlled by alloy chemistry and strict processing procedures. The seemingly innoxious micro-cracks in castings can grow into gross feature visible to the naked eye as a result of thermal effects of expansion and contraction.

Chemical composition

The chemical composition has a strong bearing on the final microstructure of castings. The chemical compositions of alloys studied are given in Table 1.

<table>
<thead>
<tr>
<th>Component</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer</td>
<td>1.4</td>
<td>14.8</td>
<td>0.5</td>
<td>1.0</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Jaw crusher</td>
<td>1.0</td>
<td>12.8</td>
<td>0.9</td>
<td>0.4</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Specification</td>
<td>1.135</td>
<td>11-14</td>
<td>0.6-1.0</td>
<td>0.5 max</td>
<td>0.05 max</td>
<td>0.07 max</td>
</tr>
</tbody>
</table>

For the hammer, the carbon, manganese and sulphur were too high and out of specification. Carbon and manganese contents have a combined effect in Hadfield steel. Elevated levels of these elements lead to a drastic drop in ductility and toughness, more so with thicker sections. In addition the high carbon tends to form coarse grain boundary carbides. For practical purposes, it is safer to maintain the carbon composition between 1.15% and 1.2% and cap the manganese at 13%. The high sulphur is not a cause for concern because of the high manganese which serves to scavenge the sulphur into a less damaging globular morphology. The jaw crusher met the chemical specification.

Tapping and pouring temperatures

The tapping and pouring temperatures at the foundry producing jaw crushers was found to be variable and rather out of control. The tapping temperature ranged between 1450°C and 1500°C while the pouring temperature ranged between 1420°C and 1441°C. The control of pouring temperature is crucial for the optimum performance of austenitic manganese steel. The freezing range of Hadfield steel is 1371°C to 1250°C. High pouring temperatures may create large superheats, which according to Balogan [8] should not exceed 120°C.

With high temperature regimes, castings cool slowly because metal stays hot for longer. This however depends on the size of casting. The slow solidifications causes a number of undesirable effects such as carbide precipitation, alloy segregation, dendritic structure and grain growth are detrimental to the strength and ductility of manganese steel. Segregation leads to local variation of carbon and manganese and can also occur during heat treatment, causing unstable austenitic regions that are prone to stress induced transformation to martensite.

Thicker sections are often linked to the problem of large superheats. First, in trying to avoid freezing of metal before mould filling, operators prefer higher pouring temperatures. Second, because of the bulkiness of the casting, heat conductivity at the core is relatively poor, thus cooling is very slow. Thermal or hot tearing may occur particularly in steels containing high carbon and high phosphorus.

Heat Treatment

The role of heat treatment is to dissolve all the carbides. A fully austenitic structure, carbide free and completely homogenous with respect to both carbon and manganese is desirable. To achieve this, the initial as-cast structure should be free from segregation, gross inclusions and pre-existing cracks. In thick sections the centre is only partially transformed due to ineffective quenching.

Fig 2 shows the continuous carbides along austenite grain boundaries and discontinuous carbides within austenite grains. These carbides need to be dissolved in the matrix of austenite by soaking at temperatures, 10°C to 37°C above the Acm for sufficiently lengthy times. However, grain growth may occur under such conditions. Fine grained specimens have shown superior with elongations of 30% [1]. Thus, grain size and carbide morphology should be controlled in order to avoid prolonged soaking during heat treatment.

![Fig. 2. As-cast Hadfield steel showing grain boundary carbides](image-url)
governing the use of Hadfield austenite. These are underlying metallurgical fundamentals transformed phases consisting predominantly of soft which would cause rapid wear of untransformed or partially transformed phases. Friable ores have an abrasive effect and result in poor transformation and if the part remains austenitic and tough. Friable ores have an abrasive effect and result in poor transformation and if Hadfield steel is used static loads, sand and fine ore particles would cause rapid wear of untransformed or partially transformed phases consisting predominantly of soft austenite. These are underlying metallurgical fundamentals governing the use of Hadfield.

IV. MECHANISM OF AUSTENITE TO MARTENSITE TRANSFORMATION

Stabilised austenite in Hadfield steel undergoes dynamic strain aging followed by strain-induced transformation to martensite. Heavy impact or shock loads such as those experienced in crushing hard rock and stone are required to cause deformation that results in the formation of imperfect twins or “pseudo-twins” [9]. The surface hardens and becomes wear resistant due to a martensitic case. The bulk of the part remains austenitic and tough. Friable ores have an abrasive effect and result in poor transformation and if Hadfield steel is used static loads, sand and fine ore particles would cause rapid wear of untransformed or partially transformed phases consisting predominantly of soft austenite. These are underlying metallurgical fundamentals governing the use of Hadfield.

V. RECOMMENDATIONS

The following recommendations relate the production and appropriate use of Hadfield steel.
1. Controlling of alloy chemistry at 1.25%C, 13%Mn, 0.05% P and minimal Cr will reduce volume fraction of carbides. Scrap sorting may help to control unwanted tramp elements. A pouring temperature of approximately 1420°C on small-batch casting would eliminate the need for large superheats and thus shorten solidification time.
2. Slow heating to soaking is recommended to prevent nucleation of internal cracks. Sufficient soaking time should be allowed for complete dissolution of carbides.
3. More severe quenching media such as brine solution should be considered for fully austenitic structure after quench for section thickness above 152 mm (6 inches).
4. Hadfield steel is satisfactory in applications involving heavy impact loads rather than abrasive action. Thus for friable ores austempered ductile iron may be considered.

VI. CONCLUSION

The major causes for poor field performance of Hadfield steel can be traced back to deficiencies along the product supply chain. Random use of unsorted scrap introduces unwanted tramp elements into the chemical composition. Because of improper casting procedures, faulty heat treatment and inappropriate use of product, there are misconceptions about Hadfield steel. Before alternative materials can be sought, it would be prudent to correct the errors inherent in the processing route and make sure that the Hadfield steel produced meets the expected mechanical properties and performance levels. The inferior grades being produced in some foundries are a result of deviation from recommended procedures rather than the materials itself.

VII. ACKNOWLEDGMENT

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