Development of high-manganese steels for heavy duty
cast-to-shape applications

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Abstract

In 1882, Robert Hadfield patented the steel that bears his name. It has the nominal composition Fe–1.2% C–13% Mn. This alloy has an enormous capacity for work-hardening upon impact and is still commonly used for railroad components such as frogs and crossings and also for rock-handling equipment. As such, it can hardly be considered to be an “advanced material”. However, studies at Queen’s University have shown that part of this capacity for work-hardening may be “traded” to provide steels which are appreciably stiffer, have significantly better wear resistance and may be cast to near net shape to provide components which still possess remarkable toughness. These materials were produced by the addition of minor amounts of other carbide-forming and solid-solution strengthening elements and by heat-treating the as-cast components. The production and characterisation of these alloys will be described.

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1. Introduction

Hadfield’s steel (Fe–1.2% C–13% Mn) is a remarkable engineering alloy in that in the fully austenitic solutionised form it is soft and ductile. However, when deformed, it rapidly work-hardens and so, even though it may suffer considerable wear in non-impact abrasive conditions, impact or gouging deformation quickly causes it to work-harden. It is the standard material for railway frogs (switches), Fig. 1, where heavy axle loads predominate, e.g. North America, Australia, Africa and the USSR. An interesting paper by E.E. Frank, of the Abex Corporation, Railroad Products Group, Chicago, IL, 60604, USA traces the “evolution of the rail-bound manganese frog” [1]. In particular, impact damage is seen in the region “A”, the “nose” of the frog.

Notwithstanding the great utility of Hadfield’s original formulation, many attempts have been made in more recent times to extend the base alloy’s properties even further by compositional changes and processing variations. Some of these are captured in the review article by Rama Rao and Kattumbarao [2], in particular alloys based on the Fe–Mn–C system and destined for use as austenitic wear resistance steels, and those based on Fe–Mn–Cr for use as austenitic corrosion-resistant steels. In the first group, development has been directed towards increasing the relatively low yield strength in the annealed condition and enhancing abrasion resistance. One of the most attractive metallurgical techniques to achieve this has been precipitation hardening with fine carbides, often requiring complex multi-stage heat treatments. The disadvantage of such an approach is that coarse inter-granular precipitation can take place during various stages of the heat treatment and lead to brittleness in cast-to-shape components [2–4].

In as much as rail transportation application tends to involve primarily cast-to-shape applications, two concerns have excited much interest. The first of these involves the actual foundry practice, in particular, mould materials. It is well known that the physical and chemical processes which occur between the mould material and the steel cast into the mould can cause the loss of some alloying elements (e.g. Mn, C) from the surface of the casting with deleterious effects. However, transfer of material into the metal may also occur (e.g. P, C, N, Si). In particular, the interfacial reactions between high-manganese steels cast into silica or chromite sands have been detailed by Holtzer [5]. At times the loss of Mn in surface layers can be significant, e.g. 10–12%, markedly decreasing abrasion resistance and fatigue life of the cast component.

A second consideration is the influence of minor chemical constituents on the hot tearing propensity of a casting alloy. Usually, hot tearing susceptibility increases with increase in the freezing range of the alloy as occurs when S or P
are present. However, it has been shown theoretically, but
with experimental support from the chemical analysis of
the compounds appearing on the hot tear surfaces, that
the addition of elements which form highly stable solid carbides,

\[ e.g. \text{Ti}, \] can be beneficial in reducing the volume fraction
of residual eutectic liquid during freezing and so make the
casting less prone to hot tearing \[6\].

As noted earlier, there has been considerable work con-
ducted to extend the property ranges of Hadfield’s steel.
One of the most detailed was by Krainer \[7\], who investi-
gated variations of C, Mn, Si, Ni, Cr, Cu, W, Mo, Ta, Ti and
Zr by means of hardness, static and dynamic tensile tests,
toughness and work-hardening characteristics. In all, he
examined 75 experimental heats. These were cast as small
ingots and forged into test-pieces, solutionised at \[993^\circ\text{C}\]
and at as low as a temperature as possible, or in a protective
atmosphere. It should be noted that Krainer \[7\] tested forged samples
for which he used any protective atmosphere when solution-
ising his samples. His use of dynamic testing to get more
information data is open to question since the results are
subject to error and the strain rate is much smaller than, for
example, the impact velocity of a wheel when striking the
“nose” of a railway frog.

In attempting to find additions which will increase the
wear resistance and stiffness of an as-cast Hadfield’s steel,
it is important to note that of interest are the surface hard-
ness and strength after work-hardening. Since contact fa-
tigue resistance is of primary interest in the degradation of
a frog and is determined by strain capacity, i.e. the differ-
ence between the nominal yield point, taken as the 0.2%
yield stress, and the UTS of the work-hardened state, then it
is most desirable that the addition(s) increases both the YS
and UTS of the work-hardened state, without seriously im-
pairing the toughness. Of the elements tested, Krainer found
virtually no increase in true UTS with any element but a
significant increase in nominal UTS for vanadium additions.
He reports that all elements increase the work-hardening
rate to about the 0.3% addition concentration. However, it
should be noted that the low solutionising temperature he
used (\(<1000^\circ\text{C}\)) would not be adequate to solutionise all
of the carbides and so lead to embrittlement and a reduced
UTS with cast-to-shape rather than forged components.

In particular, we have been investigating the possibility of
developing Hadfield steels of modified chemical compon-
ent for railway frogs and other heavy impact-wear applica-
tions where there are “trading off” of the huge toughness of a
steel with the traditional Hadfield formulation for increased
stiffness in the as-cast state by the incorporation of controlled
dispersions of transition-element carbides. In this connec-
tion, it should be noted that, early in the life of a frog, it ex-
periences adhesive wear and deformation. Thus, in Canada,
P.Rail uses explosive depth-hardening to “preharden” the
frog. Usually three “shots” from plastic explosives are used
and the surface hardness of 350–400 HB \[8\]. The value falls to \(200\text{HB}\) about 1 in. from the upset surface. Taylor \[9\]

reports that shot-peeen hardening was examined by C.P.
Rail but was found to produce too superficial a layer to be
useful in-track. Explosive depth hardening does not distort
the frog and can increase life by more than 50%. In addi-
tion, it also provides an excellent quality control check on
the integrity of the casting before incurring the expense of
putting it on-track and suffering a premature failure.

The standard Hadfield’s steel (Fe–1.2% C–13% Mn)
in the as-cast condition contains acicular carbides of
(Fe,Mn)\textsubscript{3}C. A common industrial practice to overcome po-
tential problems is to heat-treat the material at 1010–1090°C
for up to 1 h followed by a water quench. This procedure
can normally solutionise all the \((Fe,Mn)\textsubscript{3}C\) carbides. In this
condition, the steel is very soft (190 HB). As noted earlier,
impact deformation can increase the surface hardness, even
to about 500 HB. The mechanism of such work-hardening
is still disputed; it depends on the local composition but
it normally arises from deformation twinning/dynamic
strain ageing in the standard 1.2% C alloy. However, some
decarburation usually takes place during annealing
and then a low carbon matrix is present which can show
deformation-induced martensite formation \[10,11\]. Thus
any heat-treatment needs to be done as quickly as possible
and at as low as a temperature as possible, or in a protective
atmosphere.

As noted earlier, attempts have been made through the
years to reduce the ease of deformation and abrasive wear
of the as-quenched standard alloy by metallic addition \[12–17\].
Often these modified alloys have been given one of a se-

Fig. 1. Illustration of a railway crossing.
ries of elaborate heat-treating cycles [12–17] to optimise precipitate form and distribution but the accompanying de-carburisation/oxidation has not been reported. In our own work, in trying to find an effective heat-treatment to dissolve the carbides in modified Hadfield’s steels, it was found that exposure at 1250–1300 °C for 5–10 h in even a weakly oxidising atmosphere caused the samples to lose a considerable amount of carbon. Similarly, small specimens held at 1150 °C in air readily decarburised. Thus, the microstructure no longer contained carbides and, in addition, was no longer austenitic, but ferritic. As a result of these findings, a study of the extent of decarburisation in these alloys under the more drastic heat-treating conditions was undertaken [18,19]. From this it is clear that the results obtained by earlier workers who used small specimens and no atmosphere control during heat-treatment are highly suspect [19,20].

2. Experimental details, results and discussion

2.1. Sample preparation

It is well known that Hadfield’s steel is virtually un-machinable except by very powerful machines. In view of this, samples were obtained by melting predetermined amounts of the components given in Table 1 in a ‘Tocco’ induction furnace. The molten metal was then poured into heated investment moulds (700 °C) so that only a little grinding had to be performed to obtain the required dimensions of the specimens for mechanical testing. Each mould provided four samples for mechanical testing and a ‘button’ for composition determination. Before grinding, all samples were heat-treated in a ‘Lindberg Heavy Duty Furnace’ to which a chamber had been adapted to provide an enclosure in which a flowing dry argon atmosphere could be introduced. The alloys examined in this phase of the project are shown in Table 2.

2.2. Impact strength

Since a high impact strength is a desired alloy property, it was decided to examine a number of factors which might adversely influence impact strength, namely grain size, phosphorus and copper content. The latter is a steadily increasing component in the steel scrap used to prepare austenitic manganese steels, and can reduce toughness and promote hot tearing susceptibility in some as-cast alloy applications. It was found that (i) adequate grain size control could be obtained by using suitably heated moulds (700 °C), (ii) phosphorus levels below 0.05% P were permissible (Table 3) and (iii) copper in amounts up to 1% were not particularly detrimental (Table 4). The values given in Tables 2–4 are the averages of those obtained from three of the four samples from each mould.

2.3. Mechanical properties

The effects of various heat-treatments were followed primarily by metallographic and mechanical testing studies.

Table 1

<table>
<thead>
<tr>
<th>Charge material</th>
<th>Mn (%)</th>
<th>V (%)</th>
<th>Mo (%)</th>
<th>W (%)</th>
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<tbody>
<tr>
<td>C.P. Rail stock</td>
<td>0.78</td>
<td>0.84</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Armco iron</td>
<td>0.04</td>
<td>0.06</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(99.99% Fe)</td>
<td></td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Low-C Fe-Mn</td>
<td>0.84</td>
<td>86.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>High-C Fe-Mn</td>
<td>6.4</td>
<td>75.</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Carbon</td>
<td>11.0</td>
<td>–</td>
<td>83.0</td>
<td>–</td>
</tr>
<tr>
<td>Fe-Mo</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>71.2</td>
</tr>
<tr>
<td>Fe-W</td>
<td>0.03</td>
<td>0.04</td>
<td>–</td>
<td>0.03</td>
</tr>
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</table>

Table 2

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C (%)</th>
<th>V (%)</th>
<th>Mn (%)</th>
<th>W (%)</th>
<th>Toughness (N m)</th>
<th>Hardness (MPa)</th>
<th>Yield (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5R3</td>
<td>1.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>261</td>
<td>138</td>
<td>327</td>
</tr>
<tr>
<td>5R16</td>
<td>1.2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>200</td>
<td>152</td>
<td>331</td>
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<tr>
<td>5R29</td>
<td>1.2</td>
<td>0.7</td>
<td>0.7</td>
<td>2.0</td>
<td>91</td>
<td>162</td>
<td>448</td>
</tr>
<tr>
<td>5R30</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>62</td>
<td>207</td>
<td>452</td>
</tr>
<tr>
<td>5R31</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>64</td>
<td>192</td>
<td>474</td>
</tr>
<tr>
<td>6R6</td>
<td>0.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>258</td>
<td>184</td>
<td>266</td>
</tr>
<tr>
<td>6R35</td>
<td>0.8</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>207</td>
<td>186</td>
<td>290</td>
</tr>
<tr>
<td>6R33</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>2.0</td>
<td>183</td>
<td>186</td>
<td>366</td>
</tr>
<tr>
<td>6R32</td>
<td>0.8</td>
<td>1.0</td>
<td>1.0</td>
<td>2.0</td>
<td>186</td>
<td>186</td>
<td>417</td>
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<tr>
<td>6R34</td>
<td>0.8</td>
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<td>1.0</td>
<td>1.0</td>
<td>186</td>
<td>186</td>
<td>399</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Alloy</th>
<th>P (%)</th>
<th>Toughness (N m)</th>
<th>Hardness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4R3a</td>
<td>0.014</td>
<td>&gt;357</td>
<td>170</td>
</tr>
<tr>
<td>4R3b</td>
<td>0.020</td>
<td>&gt;357</td>
<td>143</td>
</tr>
<tr>
<td>3R3</td>
<td>0.040</td>
<td>351</td>
<td>143</td>
</tr>
<tr>
<td>3R26</td>
<td>0.055</td>
<td>342</td>
<td>148</td>
</tr>
<tr>
<td>3R27</td>
<td>0.066</td>
<td>266</td>
<td>150</td>
</tr>
<tr>
<td>3R28</td>
<td>0.000</td>
<td>296</td>
<td>156</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Alloy</th>
<th>V (%)</th>
<th>Cu (%)</th>
<th>Toughness (N m)</th>
<th>Hardness (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2R3</td>
<td>–</td>
<td>–</td>
<td>190</td>
<td>149</td>
</tr>
<tr>
<td>2R25</td>
<td>–</td>
<td>1.0</td>
<td>212</td>
<td>149</td>
</tr>
<tr>
<td>2R20</td>
<td>1.0</td>
<td>–</td>
<td>76</td>
<td>187</td>
</tr>
<tr>
<td>2R21</td>
<td>1.0</td>
<td>0.5</td>
<td>88</td>
<td>183</td>
</tr>
<tr>
<td>2R22</td>
<td>1.0</td>
<td>1.0</td>
<td>85</td>
<td>170</td>
</tr>
<tr>
<td>2R4</td>
<td>2.0</td>
<td>–</td>
<td>27</td>
<td>217</td>
</tr>
<tr>
<td>2R23</td>
<td>2.0</td>
<td>0.5</td>
<td>28</td>
<td>207</td>
</tr>
<tr>
<td>2R24</td>
<td>2.0</td>
<td>1.0</td>
<td>35</td>
<td>207</td>
</tr>
</tbody>
</table>
After heat-treatment, the alloys were ground to the desired size on an automatic grinder equipped with coolant. Since regular Charpy V-notches were difficult to machine in the samples, they were cut by spark-machining, following which the notched impact specimens were boiled in water for 2 h to remove any residual hydrogen. This technique has now been approved for the preparation of impact specimens from cast austenitic manganese steels by ASTM [21].

Deformation studies on the new alloys were carried out in two ways: (a) regular mechanical testing (Table 2); (b) using a rail/locomotive wheel impact simulator [22].

An inspection of the available phase equilibrium diagrams showed that the solubility of vanadium in the austenite matrix increased with a reduction in carbon content. As a result, alloys with two carbon levels were examined. Table 2 shows that the yield strength falls markedly as the carbon level is reduced in the steel and alloy. Tungsten promotes a somewhat increased yield strength, toughness and hardness. A similar, but less dramatic effect can be seen with single additions of molybdenum [23]. As well, additions of vanadium markedly reduce the impact strength but promote a significant increase in work-hardening rate [20].

The rail/locomotive wheel impact simulator is shown in Fig. 2. This was used to simulate in the specimen, usually a section cut from the undamaged half of a Charpy specimen, but, deformation of a frog under severe conditions. The specimen was placed in the sample holder then mounted in the fly-wheel of the machine. The fly-wheel was rotated at 30 rpm. Spacers were used under the specimen to change the height of the sample after a given number of impacts. The maximum specimen height above the surface of the sample holder was 2 mm for base material and 3 mm for weldment, and the static applied loads were 22,370 and 27,960 N for the base metal and weldment, respectively.

During the test, the specimen was periodically removed from the equipment and the overall length measured. The difference in length was taken as a measure of the amount of plastic flow occurring under the conditions and duration of testing. Fig. 3 shows how the various experimental alloys work-harden as a function of number of impacts.

Fig. 2. Rail/locomotive wheel impact simulator; specimen location at ‘S’.

Fig. 3. Work-hardening characteristics of Hadfield steel and Hadfield steel modified with Mo, V and W: (a) 1.2% C; (b) 0.8% C.
2.4. Abrasion resistance

Comparative wear tests were made by bringing a standard-sized specimen, under a variety of given loads, into contact with an abrading wheel, mounted on a small workshop grinding machine, for fixed times. Reproducible results could be obtained if the wheel was re-dressed between samples. It was found that a 1% addition of vanadium to the standard alloy reduced the abrasion rate by two thirds, presumably due to the presence of wear-resisting carbides [19].

2.5. Heat-treatment

Significant decarburisation can occur if the standard Hadfield’s solutionising treatment is followed by an oxidising atmosphere [19] (Fig. 4). As noted earlier, this is particularly serious if small castings or experimental alloys are heat-treated prior to testing and metallurgical examination. In practice, with a full-sized frog, some of the decarburised layer would have been ground-off before installation in the track.

The regular heat-treatment followed for the standard Hadfield’s steel (i.e. 1 h at 1010–1090°C is not adequate generally, these carbides, if present also require additions to be made. They are not fully dissolved and consequently the material loses its impact strength. Various ‘beneficial’ treatments have been reported by others, of which a procedure mentioned by Middlham [12] and Norman et al. [17] was claimed to be the most successful. In this treatment, the alloys were heated to 1050°C for 2h, water-quenched and then heated to 650°C for 2h, heated to 900°C for 6h and finally water-quenched. This procedure, it was reported, did not dissolve carbides but dispersed them. In fact, our work indicates that the carbides are not dispersed by this heat-treatment, rather they tended to coalesce into near-spheres. The carbides were found to be still located along the grain boundaries with very few dispersed within the grains. Since the cyclic-type of heat-treatment did not prove effective, a compromise was attempted. The modified material was heated to (1150°C) for 2h in an inert atmosphere and then water-quenched. This process did not dissolve the carbides as the present work and that of Brenchel [18] indicate, but at least, the heavily cored cast structure was partially eliminated and some grain growth occurred to leave earlier grain boundary precipitates within the grains.

3. General discussion

As noted, the addition of vanadium improved the yield strength, hardness and wear-resistance qualities but the resultant loss in toughness had to be overcome. One approach that suggested itself was the possibility of reducing the carbon content thus depressing the formation of a large volume fraction of carbides. This was reasonably effective to maintain good impact strength and produce a wear resistance not much different from the 2% V addition to the standard alloy [23]. However, the results from [19] in which other amounts of vanadium were added to both regular Hadfield’s steel (1.2 wt.% C) and a reduced carbon containing steel (0.7 wt.% C), show that an addition of vanadium in excess of 0.4 wt.% V dramatically reduces toughness. Some multiple additions of transition elements also produced an increase in yield strength.

In addition to improved mechanical properties it is advantageous to go to a reduced carbon content in the alloy for improved weldability since, with a larger carbon content, there is a greater chance for the precipitation of carbides in the heat-affected zone, thus lowering the toughness of the material [24]. However, if alternative additions are made, then a larger carbon content can be tolerated because of the changed carbide distribution and morphology. Small amounts of molybdenum seem to help in this respect while copper additions do not. It was found that an alloy with 1.2% C–13% Mn–2% Cr–1% Mo–2% W, when heat-treated at 1150°C and water-quenched, showed no
dendritic structure but large grains. This material showed significantly greater work-hardening behaviour than the standard Hadfield’s steel. In addition an alloy with 1.2% C–13% Mn–1% Mo–0.3% Nb–0.3% Ti–0.3% V, when heat-treated and water-quenched produced a relatively fine dispersion of carbides in a fine grained matrix [23].

One question posed to C.P. Rail and still to be answered by that industry is what impact strength is adequate for a heavy haul railway frog; axle loads appear to gradually creep-up and so ‘as high as possible’ seems always to be the answer. An example of this is the fact that a rail line from an iron ore production facility in northern Australia was built with an anticipated life of 30 years but required significant replacement/rebuilding after less than 10 years of use. However, of particular interest to the foundryman is the extent to which the purchaser (of say) frogs is likely to pay an appropriate premium for superior frogs. Most certainly C.P. Rail would like to be able to install a frog with a 50% increase in the service life from the present figure of, for example, 130 million gross tonnes. The most expensive alloying additions used in our programme to date would increase the charge costs by 200–300%. However, many of the elements are now relatively abundant, e.g. tungsten, and so the price would fall dramatically with increased consumption. A detailed cost benefit analysis of using a 200 million gross tonnes frog, as compared with the present one, is required. It is clear that the initial casting price is a small part of the total cost of a frog, i.e. purchased casting, straightening, grinding off the decarburised layer, explosive hardening, fitting, installation, rebuilding and finally replacement. We await the results of such an analysis with much interest.

It should be noted that whilst the research activities reported here were primarily directed to examine the effects of small changes in chemical composition on the bulk properties of austenitic manganese steels, in order to reduce the shape changes suffered by frogs due to battering, it is acknowledged that rail components suffer from cracking and eventual failure due to mechanical contact fatigue. As noted earlier, the YS is determined by the material’s strain capacity, which is very close between the 0.2% YS and the UTS of rails, although such increases increase the YS. However, a complicating factor in determining the mechanical properties of rail is that the manganese steel components is the presence of casting defects (porosity, voids, etc.) and of embrittling oxide boundary films. Explosive depth hardening practiced by that rail component suppliers/users tends to provide a convenient QA (quality assurance) to detect potential failure sites before the component is installed in the line.

It is further noted that embrittling networks can form due to the excessive use of carbide forming metallic additions and to reduce the UTS of an alloy. In the work described here, great care was exercised in controlling the level of the addition and subsequent heat-treatments to ensure that such networks did not arise. As the result of this work, particular alloy additions have been recommended to C.P. Rail, one of the sponsors of the programme. The plan is to have modified-composition Hadfield’s steel frogs cast and put into service in rail sorting yards to provide practical evidence of the beneficial (or otherwise) effects of carbide-forming metallic additions to the basic Hadfield’s steel. The work is on-going and the results of these C.P. Rail tests are not yet available.

In closing, it is interesting to note that new materials processing routes arise in order to obtain the advantages of a Hadfield’s steel surface layer, bonded to a much cheaper, low carbon steel. Typical of this is the production of a 1 mm thick layer on a 0.2% C steel by laser cladding [25]. Whilst such materials are unlikely even for track components in heavy rail transport networks, they could provide in expensive “wear plates”, as needed, in ore milling processes and in foundry runners.

4. Summary

When the above results are analysed and integrated with the detailed compression testing data carried-out by Sant [20], it is clear that the mechanical response of Hadfield’s steel may be divided into two regimes: (1) the rate of work-hardening, i.e. the amount of carbon in solution in the austenite matrix and the presence of a fine dispersion of carbides; (2) the presence, amount and dispersion of carbides significantly influence the wear resistance of the alloy and, if the carbides form interconnected grain boundary films, seriously impair its impact strength.

In addition, the decarburisation/oxidation analysis shows quite clearly that austenitic manganese steels should not be heat-treated in open-air or a weakly oxidising atmosphere unless the decarburised layer is to be removed before testing or use. Heat-treatment should be at temperatures as low as possible and for minimum times to solutionise the carbides and avoid excessive surface decarburisation. This in turn will affect the work-hardening characteristics of the materials.

Acknowledgements

This work forms part of a continuing programme of foundry science and alloy development at Queen’s University and has involved many individuals amongst which the contributions of Mr. Harry Holland and Dr. Mansor Ghovesky stand-out. It has been supported from a variety of sources including Queen’s Advisory Research Council, Natural Sciences and Engineering Research Council of Canada, BILD (Province of Ontario), the Canadian Transportation Development Centre, C.P. Rail, ESCO and the American Foundrymens’ Society. This financial and other support is gratefully acknowledged.
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