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AUSTENITIC MANGANESE STEELS – DEVELOPMENTS FOR HEAVY HAUL RAIL TRANSPORTATION

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Abstract — In 1882, Sir Thomas Hadfield patented an alloy with quite remarkable properties. Its composition was Fe-1.3%C-13%Mn and it was the toughest alloy known! The claim has stuck for the century since then and the alloy is now used universally for the "frog" in railway crossings in countries such as Canada where heavy loads are moved by rail using high axle loading. In fact, the alloy is very soft when cast, but hardens rapidly when deformed.

The work described has been concerned with modifying the composition of the alloy in order to trade some of the enormous toughness for improved deformation and abrasion resistance in the as-cast condition. Since these frogs are usually rebuilt by arc welding, this too was examined in the test alloys. Recommendations are made for small metallic additions, improved heat treatment and an improved welding rod composition for use in rebuilding damaged Hadfield's steel frogs.

Résumé — En 1882, Sir Thomas Hadfield a breveté un alliage ayant des propriétés bien remarquables. Sa composition était Fe-1.3%C-13%Mn et c'était l'alliage le plus résilient qui soit! La revendication a tenu tout le siècle qui a suivi et l'alliage est maintenant utilisé universellement pour le coeur d'aiguillage dans les croisements de chemin de fer dans des pays comme le Canada où des charges lourdes sont déplacées par rail en utilisant une charge élevée par essieu. En fait, l'alliage est très mou lorsqu'il est coulé mais il durcit rapidement lorsqu'il est déformé.

Le travail décrit concerne la modification de la composition de l'alliage afin d'échanger un peu de l'énorme résilience contre une amélioration de la déformation et de la résistance à l'abrasion sous la condition de brut de coulée. Puisque ces coeurs d'aiguillage sont habituellement remis en état par le soudage à l'arc, on a également examiné cela dans les alliages évalués. On recommande de petites additions métalliques, un traitement thermique amélioré et une composition améliorée de la baguette de soudure pour utilisation dans la remise en état de coeurs d'aiguillage endommagés en acier de Hadfield.

INTRODUCTION

Hadfield's steel (Fe-1.2%C-13%Mn) is a remarkable engineering alloy which in the fully austenitic solutionized form 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) where heavy axle loads predominate (N. America, Australia, Africa and the U.S.S.R., Figure 1). An interesting paper by E.E. Frank of the Abex Corporation Railroad Products Group, Chicago Ill., 60604, U.S.A. traces the 'evolution of the rail-bound manganese frog' [1].

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 Kutumbarao [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 which often requires complex

Fig. 1. Illustration of a railway crossing.

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 [2,3].

Inasmuch 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 (Mn, C) from the surface of the casting with deleterious effects. However, transfer of material into the metal may also occur (P,C,N,S,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 (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 an 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 (Ti) can be beneficial in reducing the volume fraction of residual eutectic liquid during freezing and so makes the casting less prone to hot tearing [6].

As noted earlier, there has been considerable work conducted to extend the property ranges of Hadfield's steel. One of the most detailed was by Krainer [7] who investigated 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, solutionized at 993 °C and water quenched. The dynamic tests were performed at a reported elongation rate of 16 ft/s which is a value close to the striking velocity of the usual impact machine. He found that forged tensile specimens did not neck locally but deformed with virtually a uniform reduction in area along the gauge length. Thus, because the standard alloy was found to be relatively ductile in the as-quenched state (reduction in area of 35% to fracture), he proposed that the true tensile stress is a more accurate measure of properties. He was able to show that for some additions, while the nominal (engineering) ultimate tensile stress (UTS) changed little with composition, the true UTS changed by almost 60%.

Krainer showed that the true UTS peaked at about 1.1% C (static) and 1.3% C (dynamic) and fell as the Mn content exceeded about 12%. Thus, by good fortune or careful testing, Sir Robert had managed to bracket the more desirable C and Mn ranges in his patent.

It should be noted that Krainer [7] tested forged samples for which the solutionizing temperature was lower than that recommended for cast specimens. In addition, it is not clear whether he used any protective atmosphere when solutionizing his samples. His use of dynamic testing to get more informative data is open to question since the results are subject to error and the strain rate is much smaller than 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 the surface hardness and strength after work hardening are of interest. Since contact fatigue resistance is of primary interest in the degradation of a frog and is determined by strain capacity (the difference between the nominal yield point taken as the 0.2% yield stress (YS) 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 impairing 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 solutionizing temperature he used (<1000 °C) would not be adequate to solutionize all of the carbides and so leads 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 composition for railway frogs and other heavy impact wear applications where we have 'traded' some of the huge toughness of a steel of the traditional Hadfield formulation for increased stiffness in the as-cast state by the incorporation of controlled dispersions of transition element carbides. In this connection it should be noted that early in the life of a frog, it experiences adhesive wear and deformation. Thus, in Canada, C.P. Rail uses explosive depth hardening to “preharden” the frog [8]. Usually three “shots” from plastic explosives are used and give a surface hardness of 350-400 HB. The value falls to 220 HB about 1” from the upset surface. Taylor [9] also reports that shot peen 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 addition, 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 $(Fe,Mn)_3C$. A common industrial practice to overcome potential problems is to heat treat the material at 1010-1090 °C for up to one hour followed by a water quench. This procedure can normally solutionize all the $(Fe,Mn)_3C$ 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 aging in the standard 1.2% C alloy. However, some decarburization 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 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 series of elaborate heat treating cycles [12-17] to optimize precipitate form and distribution, but the accompanying decarburization/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 to 1300 °C for 5 to 10 hours in even a weak oxidizing atmosphere caused the samples to lose a considerable amount of carbon. Similarly, small specimens held at 1150 °C in air readily decarburized. Thus, the microstructure no longer contained carbides and, in addition, was no longer austenitic, but rather ferritic. As a result of these findings, a study of the extent of decarburization 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].

EXPERIMENTAL DETAILS, RESULTS AND DISCUSSION

Sample Preparation

It is well known that Hadfield’s steel is virtually unmachinable except by very powerful machines. In view of this, samples were obtained by melting predetermined amounts of the components given in Table I 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, the 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 II.

Impact Strength

Since a large impact strength was a desired alloy property, it was decided to examine a number of factors which might adversely influence impact strength, such as grain size, phosphorus and copper content. The latter is a steadily increasing component in the steel scrap used to prepare austenitic manganese castings and can reduce toughness and promote hot tearing susceptibility in some as-cast alloy

Table I – The chemical composition (%) of each charge material

Charge Material	Chemical constituents (balance Fe)					
	% C	% Mn	% V	% Mo	% Si	% W
C.P. rail stock	0.78	0.84	-	-	0.2	-
Armco iron (99.99% Fe)	0.04	0.06	-	-	-	-
Low-C Fe-Mn	0.84	86.4	-	-	0.67	-
High-C Fe-Mn	6.4	75.	-	-	-	-
Carbon	11.	-	83.0	-	-	-
Fe-Mo	-	-	-	71.2	-	-
Fe-W	0.01	0.04	-	-	0.03	91.39

applications. It was found that 1) adequate grain size control could be obtained by using suitably heated moulds (700 °C), 2) phosphorus levels below 0.05% P were permissible (Table III) and 3) copper in amounts up to 1% were not particularly detrimental (Table IV). The values given in Tables II, III and IV are the averages of those obtained from three of the four samples from each mould.

Mechanical Properties

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

Table II – Charpy impact toughness (N-m) Brinell hardness and compressive yield (MPa) for new alloy series

Alloy	% C	% V	% Mo	% W	Toughness	Hardness	Yield
5R3	1.2	-	-	-	261	138	327
5R16	1.2	-	-	2.0	290	152	331
5R29	1.2	0.7	0.7	2.0	91	162	448
5R30	1.2	1.0	1.0	2.0	62	207	452
5R31	1.2	1.0	1.0	1.0	64	192	478
6R6	0.8	-	-	-	258	130	266
6R35	0.8	-	-	2.0	260	137	290
6R33	0.8	0.7	0.7	2.0	108	167	386
6R32	0.8	1.0	1.0	2.0	79	186	417
6R34	0.8	1.0	1.0	1.0	73	186	399

Table III – Charpy impact toughness (N-m) and Brinell hardness of R3 Hadfield steel (1.2% C, 13% Mn) as a function of phosphorus content

Alloy	% P	Toughness	Hardness
4R3a	0.014	>357	170
4R3b	0.020	>357	143
3R3	0.040	351	143
3R26	0.055	342	148
3R27	0.066	266	150
3R28	0.090	296	156

Table IV – Charpy impact toughness (N-m) and Brinell hardness of Hadfield Steel (1.2% C, 13% Mn) with and without additions of vanadium and copper

Alloy	% V	% Cu	Toughness	Hardness
2R3	-	-	190	149
2R25	-	1.0	212	149
2R20	1.0	-	76	187
2R21	1.0	0.5	88	183
2R22	1.0	1.0	85	179
2R4	2.0	-	27	217
2R23	2.0	0.5	28	207
2R24	2.0	1.0	33	207

notched impact specimens were boiled in water for two hours 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 II); and 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 II shows that the yield strength falls markedly as the carbon level is reduced in the standard alloy. Tungsten promotes a somewhat increased yield strength, toughness and hardness. A similar, but less dramatic effect has been seen with single additions of molybdenum [23]. As well, additions of vanadium markedly reduce impact strength but promote a significant increase in work hardening rate [20].

The rail/locomotive wheel impact simulator is shown in Figure 2. Here the specimen, usually a section cut from the undamaged half of a Charpy specimen bar, is placed in the periphery of a large flywheel. This is then rotated and brought into contact with a pressure loaded roller. The hardness is then measured as a function of the number of impacts by stopping the machine periodically and "shimming" the specimen to maintain a projection approximately 1mm above the rim. Figure 3 shows how the various experimental alloys work harden as a function of the number of impacts. Figure 4 shows how similar impact testing influences the hardness of a Hadfield's steel component which had been overlay welded with welding rods of one of three compositions. The Cr- and N-Cr-bearing welding rods were commercially available and were found by C.P. Rail to be of similar utility for rebuilding frogs. The Mo bearing welding rod was devised by us and is seen to offer some advantage and possibly commercial prospects.

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 periods of time. Reproducible

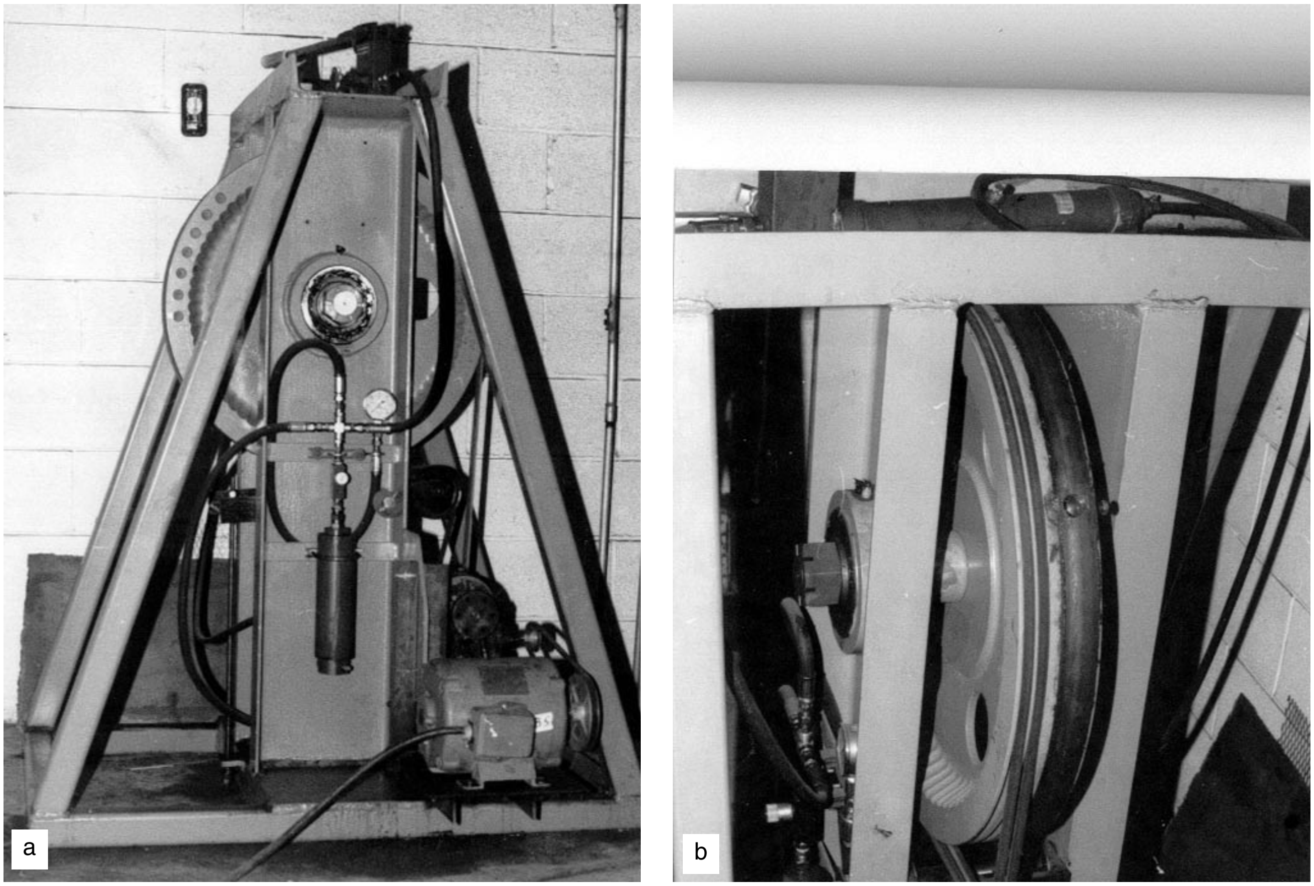

Fig. 2. Rail/locomotive wheel impact simulator; a) general view and b) specimen location.

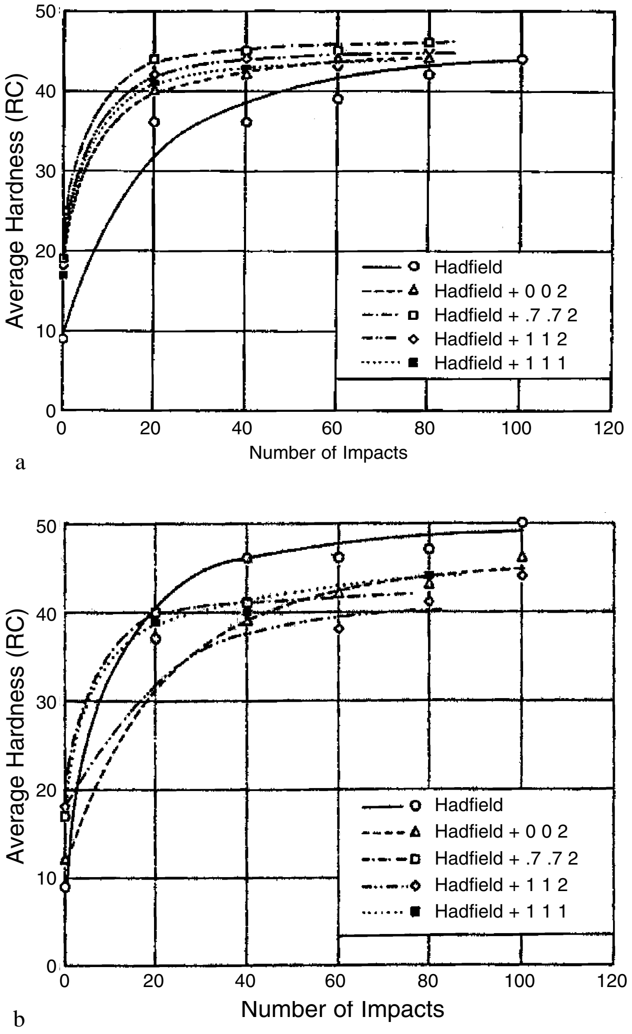

Fig. 3. Work-hardening characteristics of Hadfield steel and Hadfield steel modified with Mo, V and W, a) 1.2%C; b) 0.8%C.

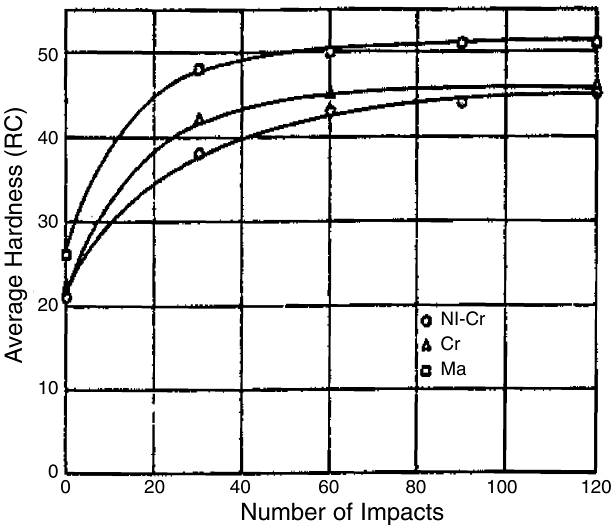

Fig. 4. Work hardening characteristics of weld overlays on Hadfield's steel base.

results could be obtained if the wheel was redressed 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].

Heat Treatment

Significant decarburization can occur if the standard Hadfield's solutionizing treatment is followed in an oxidizing atmosphere [19] (Figure 5). As noted earlier, this is particularly serious if small castings of experimental alloys are heat treated prior to testing and metallurgical examination. In practice, with a full-sized frog, some of the decarburized layer would have been ground off before installation in the track.

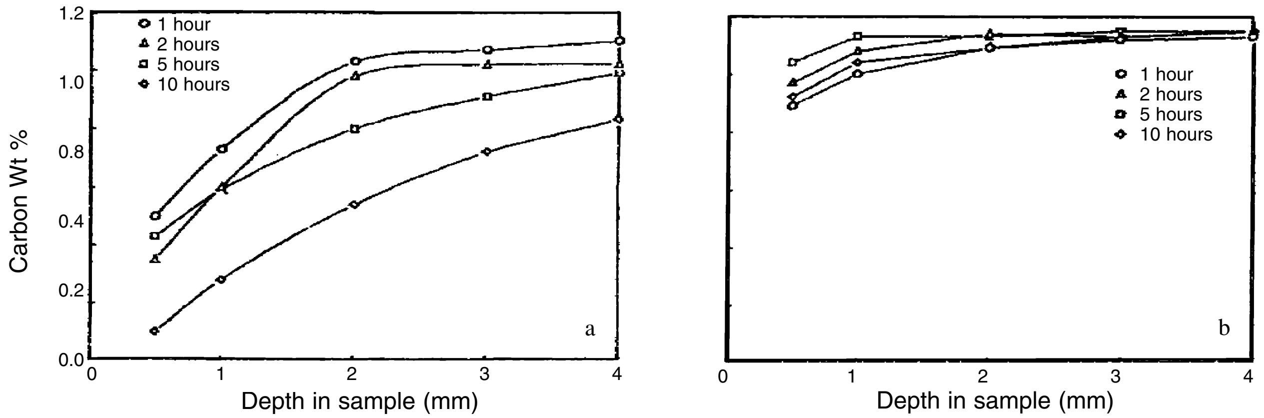

Fig. 5. Decarburisation of Hadfield's steel during heat treatment. Carbon concentration as a function of depth from surface in Fe-1.2%C-13%Mn, heat-treated at 1150 °C for 1, 2, 5 and 10 hours; a) in air and b) in argon.

The regular heat treatment followed for the standard Hadfield's steel (one hour at 1010-1090 °C) is not generally adequate whenever carbide forming additions are made. The carbides are not fully dissolved and consequently the material loses some impact strength. Various 'beneficial' treatments have been reported by others. The procedure mentioned by Middleham [12] and Norman [17] was considered to be the most successful. In this treatment, the alloys were heated to 1050 °C for two hours, water quenched and then heated to 650 °C for two hours, heated to 900 °C for six hours and finally water quenched. This procedure did not dissolve carbides but rather dispersed them. In fact, our work indicates that the carbides were not dispersed by this heat treatment, but 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 materials were heated to 1150 °C for two hours in an inert atmosphere and then water quenched. This process did not dissolve the carbides as the present work and that of Brekel [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.

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 molybedenum 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 rather 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 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 span of 30 years, but required significant replacement/rebuilding after less than 10 years of use. However, of particular interest to the foundry man is the extent to which the purchaser of 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 130 million gross tonnes. The most expensive alloying additions used in our program to date would increase the charge costs by 200-300%. However, many of the elements are now relatively abundant (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 which includes purchased casting, straightening, grinding off the decarburized 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 while the research activities reported here were primarily designed to examine the effects of small changes in chemical composition on the bulk properties of austenitic manganese steel in order to reduce the shape changes suffered by frogs due to battering, it is acknowledged that most rail components suffer from cracking and eventual spalling from mechanical contact fatigue. As noted earlier, this is determined by the material's strain capacity which is the difference between the 0.2% YS and the UTS being available, although most additions increase the YS. However, a complicating factor in determining the mechanical properties of cast austenitic manganese steel components is the presence of casting defects (porosity and voids) and of embrittling grain boundary films. Explosive depth hardening practised by many rail component suppliers/users tends to provide a convenient quality assurance (QA) 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 so 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 a result of this work, particular alloy additions have been recommended to C.P. Rail, one of the sponsors of the program. 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 these is the production of a 1mm thick layer on a 0.2 wt% C steel by laser cladding [25]. While such materials are unlikely ever to form track components in heavy haul rail transportation networks, they could provide inexpensive "wear plates" as needed in ore milling processes.

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 steels may be divided into two regimes:

1. The rate of work hardening of the matrix is dependent primarily on 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 decarburization/oxidation analysis shows quite clearly that austenitic manganese steels should not be heat treated in open air or a weak oxidizing atmosphere unless the decarburized layer is removed before testing or use. Heat treatment should be at temperatures as low as possible and for minimum times to solutionize the carbides and avoid excessive surface decarburization. This in turn will affect the work hardening characteristics of the materials.

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