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Journal of Materials Processing Technology 153–154 (2004) 589–595

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

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 alloys which are appreciably stiffer, have significantly better wear resistance and may be cast to near net shape to produce 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.

Keywords: Austenitic manganese steel

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, 6[illegible]4, USA traces the 'evolution of the rail-bound manganese frog' [1]. In particular, impact damage is seen in the region of '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 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, 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, 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, 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

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0924-0136/$ – see front matter © 2004 Published by Elsevier B.V.
doi:10.1016/j.jmatprotec.2004.04.136

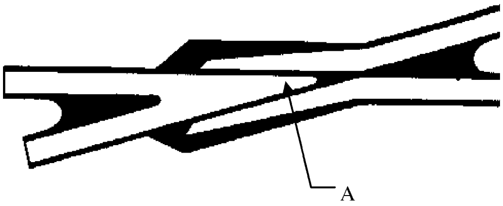

Fig. 1. Illustration of a railway crossing.

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. 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 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, solutionised at 993 °C and water-quenched. The dynamic tests were performed at a reported elongation rate of 16 ft/s, 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, whilst 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 solutionising temperature was lower than that recommended for cast specimens. In addition, it is not clear whether he used any protective atmosphere when solutionising 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, 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 hardness and strength after work-hardening. Since contact fatigue resistance is of primary interest in the degradation of a frog and is determined by strain capacity, i.e. the difference 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 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 solutionising temperature he used (<1000 °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 [illegible] possibility of developing Hadfield steels of modified chemical composition for railway frogs and other heavy impact-wear applications where we have 'traded some [illegible] 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. Usually three "shots" from plastic explosives are used and gives a surface hardness of 350–400 HB [8]. The value falls to 220 HB about 1 in. 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 1 h followed by a water quench. This procedure can normally solutionise 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 ageing in the standard 1.2% C alloy. However, some decarburisation 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 series of elaborate heat-treating cycles [12–17] to optimise precipitate form and distribution but the accompanying decarburisation/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 unmachinable 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 'Toc[illegible] induction furnace. The molten metal was then poured into pre-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 2.

2.2. 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, namely 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 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.

Table 1
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	11.0	–	83.0	–	–	–
Fe–Mo	–	–	–	71.2	–	–
Fe–W	0.01	0.04	–	–	0.03	91.39

Table 2
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	[illegible]	167	386
6R32	0.8	1.0	1.0	2.0	[illegible]	186	417
6R34	0.8	1.0	1.0	1.0	[illegible]	186	399

2.3. Mechanical properties

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

Table 3
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 4
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

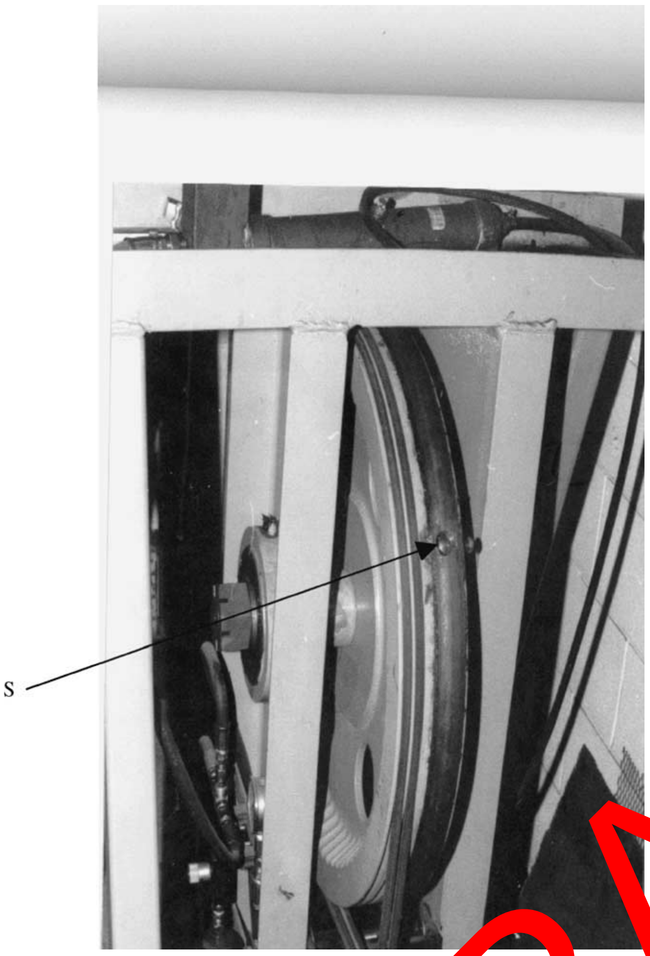

Fig. 2. Rail/locomotive wheel impact simulator; specimen location at ‘S’.

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 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 Fig. 2. This was used to simulate in the specimen, usually a section cut from the undamaged half of a Charpy specimen bar, 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 3[illegible] 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.

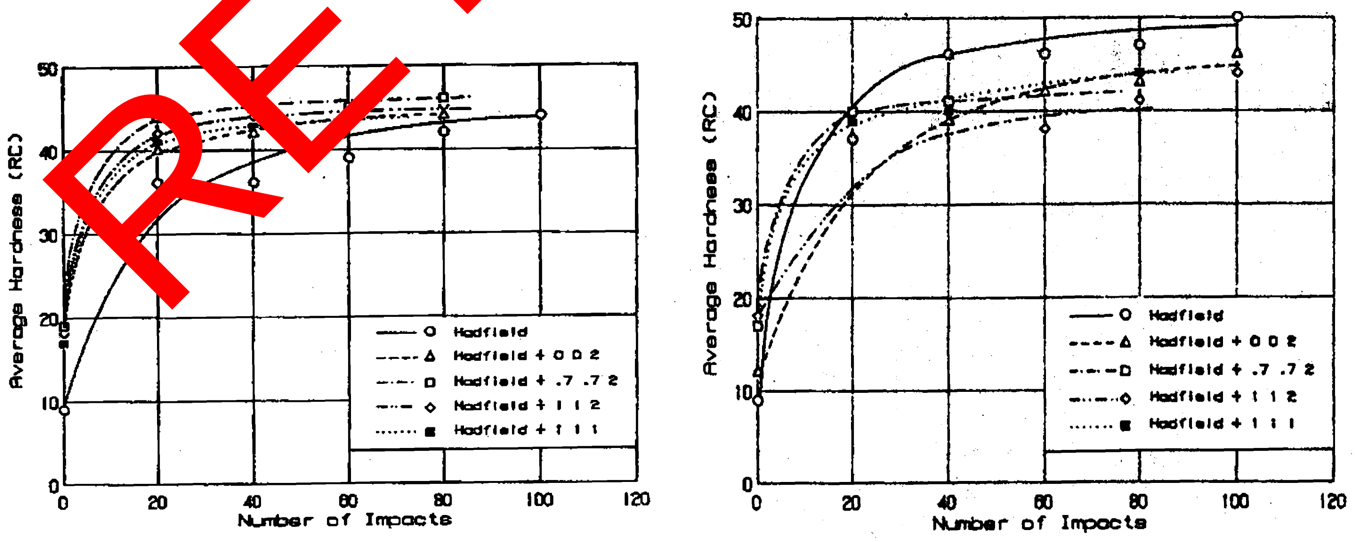

Fig. 3. Work-hardening characteristics of Hadfield steel and Hadfield steel modified with Mo, V and W: (a) 1.2% C; (b) 0.8% C.

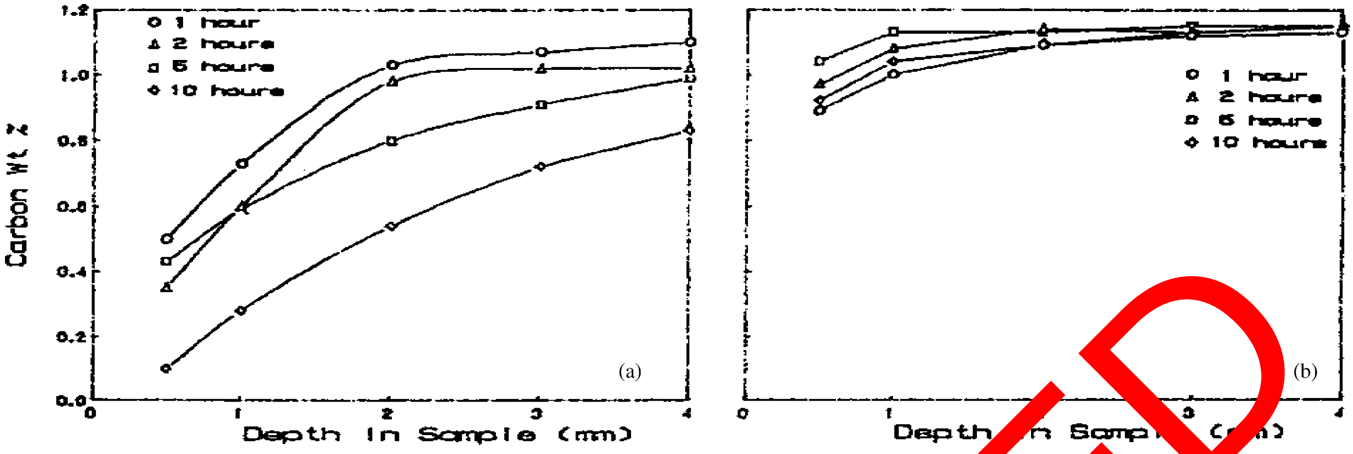

Fig. 4. Decarburisation of Hadfield's steel during heat-treatment. Carbon concentration as a function of depth from surface in Fe–1.2% C–13% Mn, heat-treated at 1150 °C for 1, 2, 5 and 10 h: (a) in air; (b) in argon.

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 in an oxidising atmosphere [19] (Fig. 4). 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 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 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, of which a procedure mentioned by Middleham [12] and Norman et al. [17] was claimed to be the most successful. In this treatment, the alloys were heated to 1050 °C for 2 h, water-quenched and then heated to 650 °C for 2 h, heated to 900 °C for 6 h 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 [illegible] attempted. The modified materials were heated to (1150 °C) for 2 h 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 lead to 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 designed 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 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, i.e. the difference between the 0.2% YS and the UTS is available although most 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, voids, etc.) and of embrittling grain boundary films. Explosive depth hardening practiced by many 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 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 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 these is the production of a 1 mm thick layer on a 0.2 wt.% C steel by laser cladding [25]. Whilst 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.

4. Summary

When the above results are analysed and integrated with the detailed compression testing data carried-out by Sant [[illegible]0], 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 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.

References

[1] E.E. Frank, Evolution of the rail-bound manganese frog, Transport. Res. Rec. 1071 (1986) 43–44.

[2] P. Rama Rao, V.V. Kutumbarao, Developments in austenitic steels containing manganese, Int. Metall. Rev. 34 (2) (1989) 69.

[3] D.M. Rodionov, M.G. Lyubinov, Y.E. Mishutin, A. Stepanova, L.V. Smirnov, Segregation of impurities on the free surface of Hadfield Steel during heating, Phys. Met. Metall. 68 (5) (1989) 73–78.

[4] N.N. Stepanova, D.P. Rodionov, M.G. Lyubimov, S.V. Nesgovorov, V.K. Farafonov, L.B. Smirnov, Grain boundary embrittlement of Hadfield steel, Phys. Met. Metall. 68 (4) (1989) 179–183.

[5] M. Holtzer, Interfacial reaction between high-manganese cast steel and silica sand or chromite sand, The Foundryman 1 (1990) 133–141.

[6] A. Chojecki, I. Telejko, Effect of the chemical composition of Fe–Mn–C–P alloys on the brittle–ductile transition temperature in the solidification range, Steel Res. 63 (10) (1992) 447–452.

[7] H. Krainer, Archiv Eisehuttenwesen 11 (1937) 279–282.

[8] E.H. Taylor, Internal Report Explosive Depth Hardening, C.P. Rail, 27 January 1987.

[9] E.H. Taylor, Memorandum TRCHWORK (9-2-26(35-201-CIGGT) 0M00496), 9, 1986.

[10] S.B. Sant, R.W. Smith, The mechanism of work hardening in austenitic Fe–Mn–C and Fe–Mn–C–V alloys, in: Proceedings of the Conference on Strength of Metals and Alloys, vol. 1, Pergamon Press, Montreal, Canada, 1985, pp. 219–224.

[11] S.B. Sant, R.W. Smith, A study of work-hardening behaviour of austenitic manganese steels, J. Mater. Sci. 22 (1987) 1808–1814.

[12] T.H. Middleham, Some alloy additions to manganese steel, Alloys Met. Rev. 12 (112) (1964) 11.

[13] V.I. Grigorkin, G.V. Korotushenko, Effect of carbon, manganese, plastic deformation and heat treatment on the structure and properties of austenitic manganese steel, Met. Sci. Heat Treatment Met. 2 (1968) 130–132.

[14] V.I. Grigorkin, I.V. Frantsenyuk, I.P. Galkin, A.A. Osetrov, A.T. Chemeris, M.F. Chernenilov, Increase in the wear resist of hammer mill hammers, Met. Sci. Heat Treatment Met. 16 (4) (1974) 52–354.

[15] G.I. Sil'man, N.I. Pristuplyuk, M.S. Frol'tsov, Effect of vanadium on the structure and properties of high-manganese steel, Met. Sci. Heat Treatment Met. 22 (2) (1980) 124–127.

[16] D.C. Richardson, W.B.F. Mackay, R.W. Smith, An improved Hadfield Steel for use in railway castings, in: Solidification Technology, The Metals Society, Warwick, England, 1981, pp. 409–413.

[17] T.E. Norman, D.V. Doane, A. Soloman, Austenitic manganese steels—some metallurgical factors influence, AFS Trans. [illegible]8 (1960) 287–300.

[18] N.C. Brekel, Hadfields Steels, B.Sc. Thesis, Queen's University, Kingston, Canada, 1981.

[19] A.I. DeMonte, Effects of vanadium on Hadfields Steel, Ph.D. Thesis, Queen's University, Kingston, Canada, 1984.

[20] S.B. Sant, Mechanism of work hardening in Hadfields Steel and the effect of minor amounts of carbide formers, M.Sc. Thesis, Queen's University, Kingston, Canada, [illegible]4.

[21] M. Ghoreshy, [illegible]B.F. Mackay, R.[illegible] Smith, Preparation of impact specimens from [illegible] austenitic manganese steels, J. Test. Evaluat. (ASTM) 13 (2) (198[illegible]) 176–177.

[22] J.I. M[illegible]ez, Weldability of Hadfields Steel, M.Sc. Thesis, Queen's University, Kingston, Canada, 1984.

[23] R.W. Smith, unpublished work.

[24] H.S. Avery, H.J. Chapin, Austenitic manganese steel welding electrodes, Weld. J. [illegible] (5) (1954) 459–479.

[25] [illegible]M. Pelletier, [illegible] Oucherif, P. Sallamand, A.B. Vannes, Hadfield Steel coatings on low carbon steel by laser cladding, Mater. Sci. Eng. A202 (1995) 142–147.