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Development of High-Manganese Steel for Heavy Duty Applications in Rail Transportation and Mining

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ABSTRACT ~~In 1882 Robert~~ Hadfield ~~patented the~~ steel ~~which bears his name. It~~ has the nominal composition Fe-13%Mn-1.2% C. This alloy has an enormous capacity for work hardening upon impact and is commonly used today for railway components such as frogs and crossings and also for rock-handling equipment. Work at Queen's over the last five years has been directed toward increasing the yield strength and wear resistance by the addition of minor amounts of other carbide-forming metals and by heat-treating as-cast components. This has necessitated looking at the oxidation/decarburisation occurring during heat-treatment and the effect this has had on the results obtained by other workers. In addition, because the as-cast components are battered out of shape when in use and are often rebuilt by overlay welding, part of the study has been concerned with ensuring that any new formulations/heat treatment procedures are compatible with repair practices. These developments ~~will be~~ reviewed.

1 INTRODUCTION

The structure of standard Hadfield steel (Fe-1/2%C 13%Mn) in the as-cast condition contains acicular carbides of the $(Fe,Mn)_3C$ form. Present practice is to heat-treat the material to 1050°C for up to one hour, followed by a water-quench. This procedure solutionises all the carbides. In this condition, the steel is very soft (190 BHN), and easily deformed (370 Mpa, 0.2% yield) but very tough (270 N.m, Charpy). Under impact loading, the material has a very large capacity for work-hardening. A surface layer is produced which is very hard (500 BHN) and well adapted to resist wear. To take advantage of this property, materials for certain applications e.g. frogs and crossings, are frequently explosively-hardened before being placed in service. Thus, the component will not deform nor wear as quickly as it would in the soft as-quenched condition. Since the material decarburises during austenitising (1), any heat treatment needs to be done as quickly as possible and at as low a temperature as possible or in a protective atmosphere.

Attempts have been made through the years to improve the deformation and wear characteristics of the standard alloy by metallic addition (2,3,4,5,6,7). These modified alloys usually have been given one of a series of elaborate heat-treating cycles (2-8) but the associated decarburisation/oxidation phenomena have not been reported. In our own work in trying to find an effective heat-treatment to dissolve the carbides in modified Hadfield steels, it was found that exposure at 1250°C to 1300°C for 5 to 10 hours in even a weakly oxidising atmosphere caused the samples to lose a considerable amount of carbon. The microstructure no longer contained carbides and, in addition, was no longer austenitic either, 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. The present work is an extention of that done by Sedriks et al, (10) and Stavisyuk (11) to observe the extent of carbon loss from the alloys under different conditions.

2 EXPERIMENTAL TECHNIQUES AND RESULTS

The samples were obtained by melting predetermined amounts of the components given in Table I in a Tocco induction furnace. For these alloys, the melt temperature was determined by the use of a Pt-Pt13Rh thermocouple.

TABLE I
THE CHEMICAL COMPOSITION % OF CHARGED MATERIAL

CHARGED MATERIAL	C	Mn	V	Mo	Si	W
Rail Stock	0.78	0.84	---	---	0.2	---
Armco Iron	0.04	0.06	---	---	---	---
Low C-Fe Mn	0.08	86.4	---	---	---	---
High C-Fe Mn	6.4	75	---	---	---	---
Carbon	11	----	83	---	---	---
Fe-Mo	----	----	---	71.2	---	---
Fe-W	0.01	0.04	---	---	0.03	91.39

The molten metal was poured into previously prepared investment moulds so that only a little grinding had to be performed to obtain the required final dimensions of the specimens required for mechanical testing. Before grinding, the samples were heat-treated in a Lindberg Hevi Duty furnace to which a chamber had been adapted to provide an enclosure in which a flowing argon atmosphere could be introduced.

However, before proceeding with the heat-treatment of the various specimens, experiments were conducted to examine the influence of the heat-treatment atmosphere upon the surface condition of the specimen. The details are given elsewhere (12) but for this, three alloys were prepared from investment cast bars (2.6 x 2.6 x 30 cm) namely the standard Hadfield steel (Fe-1.2%C-13%Mn), a modified Hadfield steel with a vanadium addition (Fe-1.2%C-13%Mn-2%V) and a lower carbon-lower vanadium Hadfield Steel (Fe-0.7%C-13%Mn-0.5%V). Samples were heat-treated with or without a protective atmosphere of argon for periods of 1,2,5 and 10 hours at 600° and 1150°C.

It was found that the specimens heat-treated at 1150°C in air decarburised readily. The protective atmosphere of flowing argon reduced the rate but, even so, a 2 mm layer was found to have been affected by decarburisation. Heat-treatment at 600°C did not affect the carbon levels to any extent. Also a sample placed in a nitriding furnace at 520°C for 24 hours was found to be extensively decarburised. 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.

TABLE II
THE CHEMICAL COMPOSITION OF EXPERIMENTAL ALLOYS

	Composition (%) (Balance Fe)									
ALLOY	C	Mn	V	Mo	Ni	Cu	W	Ti	Nb	Cr
R3	1.2	13	---	---	---	---	---	---	---	---
R4	1.2	13	2	---	---	---	---	---	---	---
R5	1.2	13	2	---	3	---	---	---	---	---
R6	0.8	13	---	---	---	---	---	---	---	---
R7	0.8	13	2	---	---	---	---	---	---	---
R8	0.8	13	1	1	---	1	---	---	---	---
R9	0.8	13	1	---	---	---	---	---	---	---
R10	0.8	13	---	1	---	---	---	---	---	---
R11	0.8	13	1	1	---	---	---	---	---	---
R12	0.8	13	1	1	3	---	---	---	---	---
R13	1.2	13	1.5	---	---	---	---	---	---	---
R14	0.8	13	0.7	0.7	---	1	---	---	---	---
R15	0.8	13	1	---	3	---	---	---	---	---
R16	1.2	13	---	---	---	---	2	---	---	---
R17	1.2	13	0.7	---	---	---	---	.7	.7	---
R18	1.2	13	.3	1	---	---	---	.3	.3	2
R19	1.2	13	---	1	---	---	2	---	---	2

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. Charpy notches were cut by spark machining following which the notched impact specimens were boiled in water for two hours to remove any residual hydrogen.

Deformation studies were carried out in two ways. In the first, and to simulate heavy impact, a 73 kg load was dropped three metres onto a specimen clamped on an anvil. The second test was a simulation of actual wheel-rail conditions. In this, the specimen was fixed in the surface of a heavy cast iron flywheel against which a heavily loaded roller-bearing wheel ran. The specimen was mounted so that its surface was initially a controlled distance above the flywheel surface. The subsequent rolling impact deformed the specimen and this deformation was determined as a function of the number of impacts.

Preliminary data is presented as values for impact strength (Charpy and Izod) and Brinell hardness numbers. Efforts were made in an attempt at grain refinement by chill-casting and the introduction of nitrogen gas into the melts. Table II gives the alloy composition. Table III gives the toughness and hardness values. Table IV gives the yield strength for some of these materials.

Accelerated wear experiments were performed on a grinding machine adapted for this purpose. Two types of tests were performed, one with a load (0.05 MPa) for 20 minutes, another with a heavier load (1 MPa) for 5 sec. It was important to dress the wheel before each run. The tests give relative values within these alloy systems. Table V gives the wear results obtained.

TABLE III
TOUGHNESS (N-m) AND HARDNESS VALUES (BHN)

ALLOY	IZOD 1050°C 2 hrs 600°C 6 hrs	IZOD 1150°C 2 hrs	CHARPY 1150°C 2 hrs	CHARPY As cast	HARD-NESS
R3	148	163	285		154
R4	16	15	(26)[1&3] 24 (39)[2&3]	(7)[1&2]	248
R5	28	23	30		229
R6	156	154	217		179
R7	34	27	39		255
R8	68	68	84(122)[3]	(167)[3]	192
R9			81		179
R10			230		149
R11			88		192
R12			92		179
R13			41		192
R14			136(122)[3]	(143)[3]	167
R15			81		179
R16			203		156
R17			42		179
R18			61		197
R19			126		170

1 Samples were cast without N_2 gas bubbled through.
2 Sample was cast with N_2 gas bubbled through.
3 Heat-treated (in vacuum) to 1150°C for 10 hrs and water-quenched.

TABLE IV
COMPRESSIVE YIELD STRENGTH OF EXPERIMENTAL ALLOYS

ALLOY	YIELD STRENGTH MPa
R3	319
R4	346
R5	325
R6	263
R7	350
R8	460
R9	297
R10	289
R11	312
R12	290
R13	329
R14	288
R15	341

TABLE V
WEAR RESISTANCE OF EXPERIMENTAL ALLOYS

ALLOY	Time of Application of Load (20 Min) P = 0.05 MPA		Time of Application of Load (5 Sec) P = 1 MPA	
	W/W%	$W/WW(R_1)$	W/W%	$W/WW(R_1)$
R3	11.5	1	1.57	1
R4	3.18	0.298	0.63	0.48
R5	3.17	0.291	0.81	0.61
R6	4.43	0.390	0.61	0.43
R7	2.85	0.266	0.54	0.42
R8	4.86	0.332	0.50	0.27

$WW(R_1)$ standard Hadfield steel taken as the reference material.

DISCUSSION

The regular heat-treatment of a standard Hadfield's steel (1050°C) readily results in a tough but soft austenitic matrix. As soon as carbide-forming additions are added this procedure for heat-treatment is no longer adequate. The carbides are not fully dissolved, consequently, the material loses some impact strength. Various other treatments have been reported by others, of which a procedure mentioned by Middleham (2) and Norman (7) was claimed to be the most successful. In this the alloys were heated to 1050°C for one hour, water-quenched and then heated to 600°C for eight hours, cooled in air, heated to 980°C for 1 hour 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 even dispersed by this heat-treatment, rather they tended to appreciably coalesce into near-spheres. The carbides were found to be still located along the grain boundaries and 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 2 hours in an inert atmosphere and water-quenched. This process did not dissolve the carbides as the present work and that of Brekel (8) indicated, but, at least, the heavily cored cast structure was partially eliminated and some grain growth occurred.

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 large quantities of carbides. The following of this line of reasoning resulted in alloy R8 (0.8%-1%V-1%Mo-1%Cu) which showed a very high yield strength (in relation to the other alloys) and better than average wear-resistance. This alloy had equiaxed rather than dendritic grains with dispersed carbides.

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. However, if alternative additions are made, then a larger carbon content can be tolerated because of a changed carbide distribution. It was found that an alloy with 1.2%-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 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 waterquenched produced a relatively fine dispersion of carbides in a fine grained matrix.

4 SUMMARY

When the above results are analysed and integrated with detailed compression testing data carried-out by Sant (9), it is clear that the mechanical response of Hadfield's steels may be divided into two components:-

1. The rate of work-hardening of the matrix is dependent primarily on the amount of carbon in solution in the austenite matrix and is mutually independent of the amount, location and dispersion of carbides;

2. The presence, amount and dispersion of carbides significantly influences the wear resistance of the alloy and, if the carbides form interconnected grain boundary films, seriously impairs 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 nitriding atmosphere. The outer 2mm of surface is likely to be decarburised even when applying an inert atmosphere of flowing ultra-high purity argon since this often contains some oxygen or water vapour. Heat-treatment should be at temperatures and for times as low as possible to solutionize the carbides and avoid excessive surface decarburisation. This in turn will affect the the work-hardening characteristics of the materials.

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