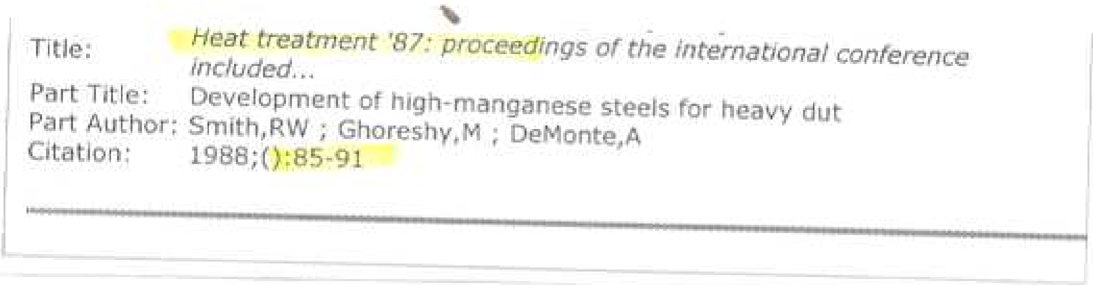

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Development of high-manganese steels for heavy duty cast-to-shape applications in rail transportation and materials handling applications

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SYNOPSIS

In 1882 Robert Hadfield patented the steel which 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 railway 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, work at Queen's over the last six years has shown that part of this capacity for work-hardening may be "traded" to provide alloys which are appreciably stiffer, have significantly improved wear resistance and may be cast to near net shape to produce components which still possess remarkable toughness. These materials have been produced by the addition of minor amounts of other carbide-forming and solid-solution strengthening elements and by heat-treating the ascast components. This has necessitated looking at the oxidation/decarburisation occurring during heat-treatment and the effect this has had on the results obtained earlier by other workers. In addition, because the as-cast components are battered out of shape when used in the solutionised and quenched condition, they are often explosively-hardened prior to installation. However, even then, they still deform in order to provide the necessary toughness. As a result they are often rebuilt by overlay welding. Thus part of the study has been concerned with ensuring that any new formulations/heat-treatment procedures are compatible with repair practices. A rail/locomotive wheel impact simulator was constructed to help in the selection of alloys more suitable for in-track testing. These developments are reviewed and more recent work described.

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) where heavy axle loads predominate e.g. N. America, Australia, Africa and the U.S.S.R., Figure 1.

There has been considerable work conducted to extend the property ranges of Hadfield's steel. One of the most detailed was by Krainer (1), 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/sec., a value close to the striking velocity of the usual impact machine. He found that the forged tensile specimen 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% (dynamic) and fell as the Mn content exceeded about 12%. Thus, by good fortune or careful testing, Sir Robert managed to bracket the more desirable C and Mn ranges in his patent.

It should be noted that Krainer (1) 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 on a railway frog.

In attempting to find additions which will increase the wear resistance and stiffness of a

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 0.2% yield stress (since the true point of yielding is difficult to determine directly) and the UTS of the work-hardened state, then it is most desirable that the addition(s) increase 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 (<1000°C) would not be adequate to solutionise some of the carbides and so lead to embrittlement and a reduced UTS with cast to shape, rather than forged components.

In particular, we are investigating applications for railway frogs and other heavy impact-wear applications. Early in the life of a frog, it experiences adhesive wear and deformation. Thus C.P. Rail uses explosive depth hardening to "preharden" the frog. 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 (2). Taylor (3) 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 castings!

The standard Hadfield's steel (Fe-1.2%C-13% Mn) in the as-cast condition contains acicular carbides of $(Fe,Mn)_3C$. Present industrial practice is to heat-treat the material at 1010-1090°C for up to one hour followed by a water quench. This procedure can normally solutionise all the $(Fe,Mn)_3$ carbides. In this condition, the steel is very soft (190 HB). As noted earlier, impact deformation can increase the surface hardness to about 500 HB. The mechanism of such work-hardening 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 may well show deformation-induced martensite formation (4). 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 (5-10). Often these modified alloys have been given one of a series of elaborate heat-treating cycles (5-10) 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°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. 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 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 (11,12). 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 (12,13).

EXPERIMENTAL DETAILS, RESULTS AND DISCUSSIONS

a) Sample Preparation

The samples were obtained by melting predetermined amounts of the components given in Table 1 in a 'Tocco' induction furnace. For these alloys, the pouring temperature was determined by the use of a Pt-Pt13Rh thermocouple. The molten metal was 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. 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 argon atmosphere could be introduced. The alloys examined in this phase of the project are shown in Table 2.

b) Impact Strength

Since a large impact strength was considered to be an important alloy property, it was decided to examine a number of factors which may adversely influence impact strength, namely grain size, phosphorus and copper content. The latter is a steady increasing component in steel scrap.

It was found that (i) adequate grain size control would be obtained by using suitably heated molds (700°C) (ii) phosphorus levels below 0.05% P were permissible (Table 3) and

(iii) copper in amounts up to 1% were not beneficial (Table 4).

c) 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. Charpy V-notches were cut by spark-machining, following which the notched impact specimens were boiled in water for two hours to remove any residual hydrogen (14).

Deformation studies on the new alloys were carried-out in two ways: a) regular mechanical testing (Table 2); and b) using a rail/locomotive wheel impact simulator (15).

An inspection of the available phase equilibrium diagrams showed that the solubility of vanadium in the austenite matrix increased with reduced 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 (16). As well, additions of vanadium markedly reduce impact strength but promote a significant increase in work hardening rate (13).

The rail/locomotive wheel impact simulator is shown in Figure 2. Here the specimen, usually an undamaged section 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 number of impacts by stopping the machine periodically and "shimming" the specimen to maintain approximately a 1mm project above the rim. Figure 3 shows how the various experimental alloys work-harden as a function of number of impacts. Figure 4 shows similar tests done on a vertical section specimen through a Hadfield's steel component which had been overlay welded. The Cr- and N-Cr-bearing welding rods were commercially available and found by C.P. Rail to be of similar utility for rebuilding frogs. The Mo-bearing rod was devised by us and is seen to offer commercial prospects.

Comparative wear tests were made by bringing a standard-size specimen, under a variety of given loads, into contact with an abrading wheel 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 would reduce the abrasion rate by two thirds, presumably due to the presence of wear-resisting carbides.

d) Heat-Treatment

Significant decarburisation can occur if the standard Hadfield's solutionising treatment is followed (12) (Figure 5). As noted earlier, this is particularly serious if small castings of experimental alloys are heat-treated. In practice, with a full-sized frog, some of the decarburised layer is ground-off before fitting.

The regular heat-treatment followed for the standard Hadfield's steel i.e. one hour 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 (5) and Norman (10) was claimed 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, 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 appreciably 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 (11) indicated, 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 (16). Some multiple additions 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 (17). 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 finedispersion of carbides in a fine grained matrix (16).

One question still to be answered is what impact strength is adequate for a heavy haul railway frog. Hopefully, this will be answered shortly when we receive the results from C.P. Rail of the in-track testing of a number of modified Hadfield's steel frogs.

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 procure 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 being prepared. 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, fitting, installation, rebuilding and, finally, replacement. We await the results with much interest.

SUMMARY

When the above results are analysed and integrated with detailed compression testing data carried-out by Sant (13), it is clear that the mechanical response of Hadfield's steels may be divided into two considerations: 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 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 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.

ACKNOWLEDGEMENT

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Table 1. The chemical composition (%) of each charge material.

Charge Material	Chemical constituents (balance Fe)					
	%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

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	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 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

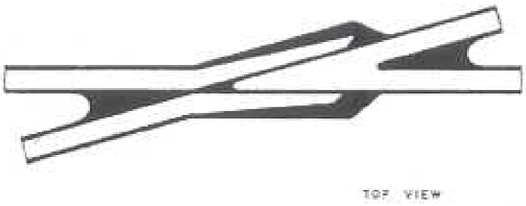
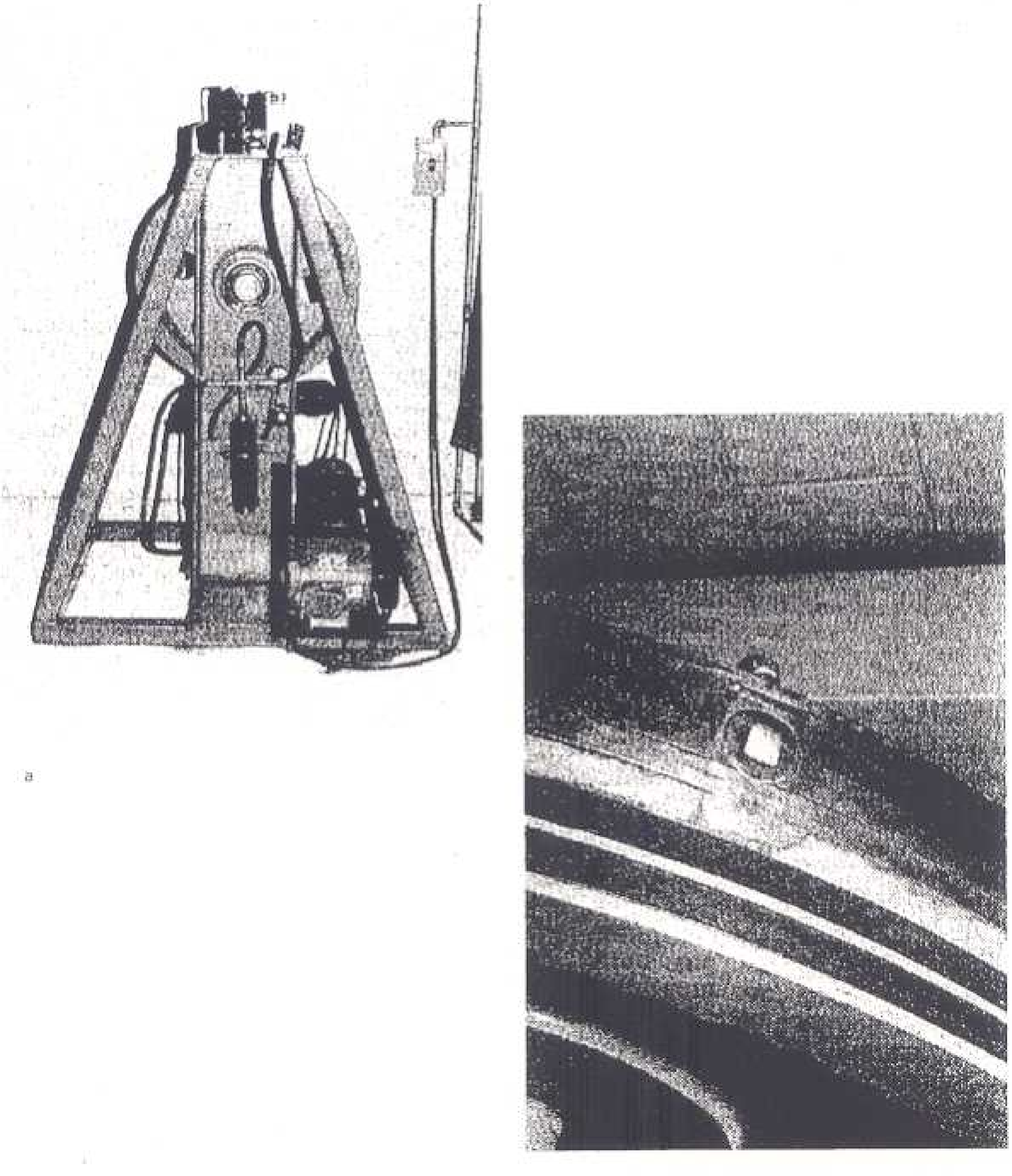


Fig. 1: Illustration of a railway crossing



a

b

Fig. 2: Rail/locomotive wheel impact simulator
(a) General view
(b) Specimen location

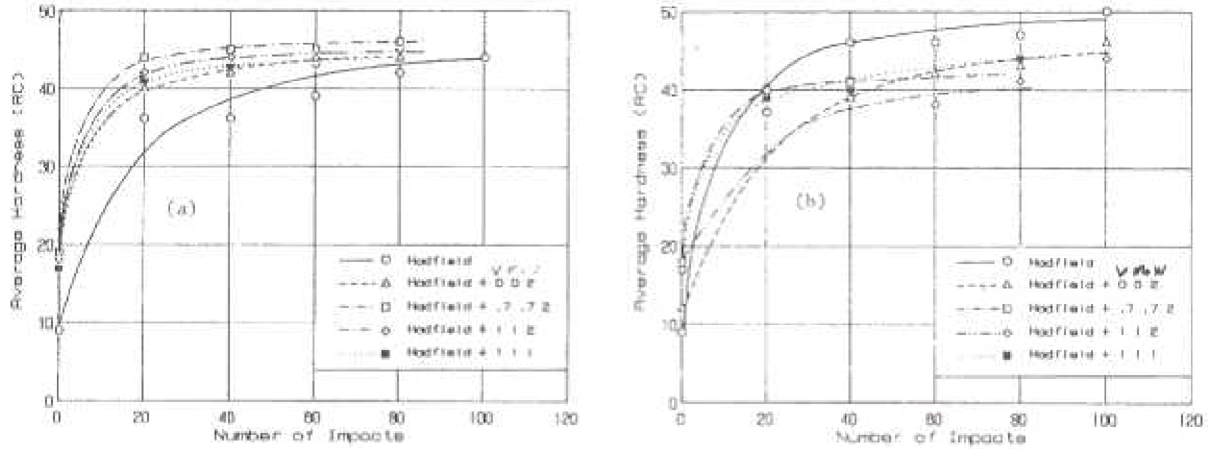


Fig. 3: Work-hardening characteristics of Hadfield steel and Hadfield steel modified with Mo, V and W

Δ

(a) 1.2%C

(b) 0.8%C

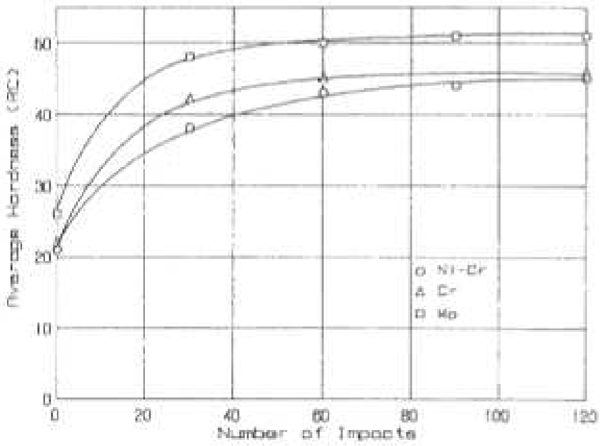


Fig. 4: Work-hardening characteristics of weld overlays on Hadfield's steel base

◁

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