DEVELOPMENT OF ABRASION-RESISTANT, NICKEL-CONTAINING ALLOY WHITE IRONS OF HIGH HARDNESS

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Development of abrasion-resistant, nickel-containing alloy white irons of high hardness

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ABSTRACT
It is suggested that the development and use of the nickel-chromium Ni-Hard irons has been neglected in recent years in favor of high-chromium irons mainly because the latter have been made with a high hardness and better fracture resistance. However, new work is outlined in which it has been shown that Ni-Hard 1 and 4 can be produced with high hardness values of at least 700 Brinell and an associated excellent abrasion resistance, such improvements have been achieved by use of compositional modifications and/or new heat treatments. In particular Ni-Hard 1 with a higher silicon and chromium content than regular Ni-Hard is described with both laboratory and service abrasion results being given. The supposed inferior toughness of the Ni-Hards compared to high-chromium irons is also questioned and discussed as is the general question as to why irons exhibiting only a modest hardness increment can give an exceptional abrasion life. It is further contended that the use of nickel-alloying in the high-chromium irons warrants more attention. Thus nickel markedly increased hardenability compared to other commonly-used elements while previous claims that it will always promote undesirably high levels of retained austenite are disputed. On this basis the development of a 15%Cr, nickel-containing iron, designated IN-3503 is outlined and some new information on its properties, heat treatment and use is provided. In summary, both general classes of these abrasion-resistant white irons have their best respective fields of application, but it is suggested that the benefits obtained from using nickel-bearing irons need now to be reassessed.

INTRODUCTION
Alloy white cast irons are used in the power, mining, cement, construction and other industries for applications where maximum abrasive wear resistance is required with toughness being of lesser importance. Excellent abrasion resistance is obtained from these alloys because their microstructures contain 20–40% of very hard carbides embedded in matrices which consist of martensite, bainite, austenite, and secondary carbides. In National Standards it is usual to specify a minimum of around 550 Brinell (HB) hardness and the alloys are divided into two broad groups; the well-known Ni-Hard or nickel-chromium types and the high-chromium grades. The Ni-Hards may again be divided into two groups viz: those containing 3–4% Ni and 2% Cr and the 9% Cr–6% Ni irons, and it is convenient to here refer to them as Types 1 and 4. The chromium irons contain 12–25% Cr and until recently most of these were distinctive from the Ni-Hards insofar as they are air-hardened rather than just being given sub-critical heat treatments.

For a given iron the abrasion resistance is usually improved as the carbon content is raised owing to the greater volume of eutectic carbides which form on solidification but, at the same time, the toughness or resistance to premature breakage is decreased. Additionally, the matrix structure can affect both wear and spalling resistance so that care is needed in the selection of the best iron for a given application.

Many able reviews detail the metallurgy and use of these alloys with, in particular, Dodd giving a broad perspective of ferrous castings used for abrasive wear applications. In recent years interest has been concentrated on the chromium irons probably because: 1) electric melting has become more prevalent within the foundry industry; 2) it is thought that chromium irons can be made to higher hardness levels than any of the Ni-Hards which in a competitive market is a matter of much topical interest; 3) irrespective of chromium content it has been maintained that they have better toughness because they contain discontinuous M,C (M=Fe, Cr) carbides compared to the M,C carbides in the Type 1 Ni-Hards (but see next section); 4) castings having a more consistent microstructure have been produced. (The more variable structure of Ni-Hard 1 is due to it usually being sold in the as-cast or subcritically treated condition whereas chromium irons are air-hardened). Also, molybdenum is claimed to be specially suitable for the supplementary alloying of chromium irons and there is a belief that nickel is not so suitable because it leads to excessive austenite retention.

While valuable work has been done, it has led to a neglect of the Ni-Hards despite the fact that these are usually less troublesome in the foundry and economical to produce. Admittedly chromium irons have shown better resistance to fracture than Ni-Hard 1 when used in cement and grinding operations, although this aspect is probably less critical in power plant service. More importantly it is suggested that such findings must be qualified by the fact that comparisons among the alloys have not in the past been made at equivalent carbide contents, (again see next section). As far as abrasion resistance is

![Fig. 1. Effect of martensite content on the hardness of Ni-Hard type 1 heat treated at 525F.](image-url)
concerned, comparisons have often been made in the past with Ni-Hards of inferior hardness. Moreover, while in power production the chromium irons have given excellent results, particularly in high-speed, ring-and-ball mills, some utilities are reconsidering the use of Ni-Hard while incomplete test results with other mills indicate that there is no difference in service life between good quality materials. Thus, even standard Ni-Hards have proved satisfactory when well made and harder grades are now possible.

The basis of the present report is to show, in fact, that:

1) Ni-Hards of 700HB can be produced by alloy modifications or heat treatment with the potential to offer the user savings in terms of downtime and maintenance costs.
2) Economic advantages are to be gained from the use of nickel in the high-chromium irons.

The premise that even modest improvements in hardness usually results in a significantly better abrasion life will also be outlined as will the related aspect of toughness and some more general observations on the technology of these materials will be mentioned. First, however, the development of improved Ni-Hards similar to Type 1 Ni-Hard or the Class 1, Grades A, B, C irons in ASTM A532 will be described.

**IMPROVED LOW-NICKEL, NI-HARD IRONS**

**Higher-Silicon, Higher-Chromium Irons**

It has already been implied that the full hardness potential of the Ni-Hards has hitherto not been realized and this is because castings are often made with microstructures that contain excessive amounts of austenite. Apart from new alloys, this problem can be mitigated by more careful production particularly with use of nickel contents that are adapted to the most important section thickness of the casting. Some guidance for correct alloying for example is given in the U.K. National Standard and there is no doubt that harder irons can thereby be produced. With regard to toughness, however measured, it cannot be over-emphasized that high integrity castings are needed because this is sometimes a more important factor than the properties of the iron per se. While obviously this applies to all the white irons it is especially important with the Ni-Hards because the carbon and, hence, the carbide content is usually higher than in the chromium irons.

In other words, it is possible that with a constant matrix structure, toughness is mainly related to the carbide content and, to a lesser extent, to the morphological features of the different types of anomalous eutectic structures rather than carbide type. The fact that it is now known that the M,C, carbides in the higher chromium irons are in fact continuous also supports these ideas (also note results presented elsewhere.). At the same time it might be mentioned that quasibinary phase diagrams produced for commercial alloys confirm that low-chromium Ni-Hards are strongly hypoeutectic. The carbide content remains higher because there is more carbide in the eutectic, but it also means that high carbon contents can be used if so desired, without risk of primary carbide formation.

Having digressed somewhat in an attempt to reassess the effect of carbides on the toughness of the various white irons, it still must be admitted that too much austenite can be present when Ni-Hard is used for the more demanding applications. For the effect of volume fraction of martensite (as opposed to bainite) on hardness see Figure

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Fig. 2. Typical microstructure of Ni-Hard type 1, x500.

Fig. 3. As-cast microstructure of modified, Si-Cr Ni-Hard, x400.
Ni-Hard Type 1 iron containing about 3.2% C, which would give a high hardness either as-cast or after a simple 400°F* draw. Thus, a raised the Ms temperature enough to induce about 80% martensite structure and hardness of 3-inch square keels cast in furane molds. Essentially these tests showed that a slightly higher silicon content obtained from regular Ni-Hard. These tests, which obviously compares favorably to the 600HB obtained from regular Ni-Hard.

The microstructure of the new Si-Cr iron developed as a result of these investigations is compared to that of regular Ni-Hard in Figures 2 and 3. It should be observed that the modified iron exhibited a rather different eutectic carbide morphology as well as containing more martensite. In event it might be supposed that, with about only a 15% improvement in hardness, such a modified composition with associated unknowns would hardly be worthwhile. Nevertheless, there is evidence to show that under some conditions a disproportionate gain in abrasion resistance could be expected. One of the most important factors is the \( H/H_a \) ratio where \( H = \) the metal hardness and \( H_a = \) the abrasive hardness. Discussion of these aspects is outside the scope of this report but, for example, refer to Figures 4 and 5, which show some of the laboratory results given in the cited literature. It will be observed that a considerable benefit accrues as the hardness rises above a critical value, which, in fact, approximates to about 650HB depending on the abrasive hardness (Fig. 4) or a particular \( H/H_a \) ratio (Fig. 5). In any event, certain wear test machines being available, it was next to carry out a limited amount of work on the modified Ni-Hard. Table 1 gives the test machine details and the results obtained are summarized in Table 2 from which it will be seen that, with the exception of the grit blast test, these were all very encouraging.

**Resistance to Fracture**

Obviously any white iron with improved abrasion resistance must not be susceptible to premature fracture and this was considered next.

Various methods to measure the fracture resistance of the alloy white irons have been proposed and in this work the so-called impact-fatigue (I.F.) test originally described by Dixon\(^{22}\) was used. Briefly this involves repeated dropping of several identical ball castings from a height of 21 feet on to an inclined steel anvil, see Figure 6. Two-inch diameter balls of both regular and the higher-silicon Ni-Hard were tested using anvils of varying hardness and the results obtained are shown in Table 3. It should be noted, however, that not all the modified irons were of ideal analysis, some being characterized by a below-normal hardness. This was because the compositional relationships for the alloy were still being developed, but, despite this, the results were taken to indicate that:

1. Irrespective of anvil hardness, the high Si-Cr iron gave better I.F. lives than Ni-Hard.
2. Good I.F. lives were achieved with the new irons despite their higher hardness.
3. A high phosphorus content reduced the I.F. life.
4. The increased anvil hardness did not reduce I.F. life.

A precise explanation for the good I.F. behavior of the modified Ni-Hard is not possible, but it has been shown how high austenite contents can have a detrimental effect in repeated impact tests.\(^{25,23}\) Probably the aforementioned modified carbide structure is also important; thus, Williams\(^{24}\) showed many years ago that white cast irons, which exhibited what appeared to be rather similar carbide morphologies and which he described as plate-like, had better mechanical properties than irons with the normal ledeburitic carbides. In another investigation the fortuitous occurrence of what were described as “blocky” carbides were related to an improved performance of Ni-Hard media used in grinding cement clinker.\(^{25}\) Although undercooling is involved hitherto it has not been known how to consistently produce this structure, but evidently the compositional changes made with the new Ni-Hard were favorable.
<table>
<thead>
<tr>
<th>Test m/c (type)</th>
<th>Principle and other details</th>
<th>Test pieces</th>
<th>Abrasive*</th>
<th>Speed</th>
<th>Load</th>
<th>Test duration</th>
<th>Wear assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsler pad-on-ring</td>
<td>Load</td>
<td>Flat-ended cylinder, 12.7 mm dia., 15 mm long. Ring made from hardened Ni-Cr-Mo steel, 60 mm dia. and 10 mm wide.</td>
<td>Sharp sand in thick oil.</td>
<td>80 rpm.</td>
<td>500 N</td>
<td>Up to 12h</td>
<td>Weight loss and scar depth.</td>
</tr>
<tr>
<td>High stress</td>
<td>Abrasive carrier used to improve feeding of abrasive.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ring-on plate</td>
<td>Medium stress</td>
<td>Flat plate, 12.7 mm thick x 284 mm sq.</td>
<td>1. Sharp sand. 2. Coal.</td>
<td>88 rpm.</td>
<td>284 N</td>
<td>Up to 10h</td>
<td>Weight loss and profilometer trace.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test stopped every 30 minutes to replenish abrasive in contact with plate.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G.T.C. test</td>
<td>Impact abrasion</td>
<td>Block 50 x 25 x 25 mm thick</td>
<td>5% bentonite clay slurry, (Coal produced no measurable wear).</td>
<td></td>
<td></td>
<td>Test piece impacted with a load of 0.5 tonne.</td>
<td>About 200h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plate: 0.7% C steel, 320HV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grit blast</td>
<td>Erosion</td>
<td>Flat plate</td>
<td>95% alumina</td>
<td></td>
<td></td>
<td>Blasted against plate at 6 bar from 12 mm bore nozzle.</td>
<td>30 minutes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Sand 300-400 µm, coal 500 µm, alumina 400-500 µm.
Table 2. Wear or Abrasion Tests on Various Ni-Hard Irons

<table>
<thead>
<tr>
<th>Test</th>
<th>Abrasive</th>
<th>Wear ratio Modified iron Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsler pad-on-ring</td>
<td>Sand</td>
<td>1.61</td>
</tr>
<tr>
<td>Ring-on-plate</td>
<td>1. Sand</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>2. Coal</td>
<td>2.0</td>
</tr>
<tr>
<td>GTC test</td>
<td>Clay</td>
<td>2.0</td>
</tr>
<tr>
<td>Grit blast</td>
<td>Alumina</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Table 3. Impact-Fatigue Properties and Hardness of Regular and Various High Si-Cr Modified Ni-Hards After Heat Treatment for 8-16h at 525°F Unless Otherwise Noted

<table>
<thead>
<tr>
<th>Anvil type and hardness</th>
<th>Regular</th>
<th>Modified iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original, 400 HV</td>
<td>4,498* (653)</td>
<td>6,299 (786)</td>
</tr>
<tr>
<td></td>
<td>5,848 (666)</td>
<td>9,299 (741)</td>
</tr>
<tr>
<td>Higher hardness 580 HV</td>
<td>2,550 (682)</td>
<td>4,466 - 4,979 (780)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5,157 (780)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5,434 (763)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5,736 (754)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6,823+ (725)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9,273+ (743)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15,496+ (710)</td>
</tr>
</tbody>
</table>

* Note that some results are quoted as the maximum life obtained from a 3- or 4-ball test whilst others are reported as a range.

* * 8h/356°F
* + 4h/342°F then 8h/525°F
* · Lower phosphorus, remainder P ≥ 0.4 per cent.

At first it might be thought that the above suggestions conflict with the view expressed earlier: that carbide morphology may have only a minor effect on toughness. However, although the differences in I.F. life between the alloys might appear to be very pronounced this is not so because lower-carbon irons would be expected to give much better results than any of those in Table 3. Thus Rickard** showed that lowering the carbon content of Ni-Hard 4 from 3.48 to 2.6% gave a seven-fold improvement in I.F. resistance. (The absolute values cannot however be compared because a different machine base was used in this earlier work.) Thus, all that is being maintained here is that the modified iron shows a real but nonetheless relatively small improvement in I.F. resistance over regular Ni-Hard.

This section may be concluded with two observations:

1) Although hundreds of p.f. rolls and segments in the high Si-Cr Ni-Hard have been used, to date there has only been one premature failure. While this could not be explained, periodically similar failures occur with regular Ni-Hard and chromium irons.

2) The I.F. life of these Type 1 Ni-Hards will be lower than that of the other alloys to be discussed. In contrast, the fracture toughness is generally similar, but this test measures different characteristics.

Service Tests

Because of the exigencies associated with production usage it is not easy to accumulate reliable service data, but a number of trials in coal grinding applications have been completed: see Table 4, which includes results obtained with different chromium irons. Figure 7 illustrates the Loesche p.f. mill, which has been featured in several tests.

Clearly, performance varied widely and not all users found the modified Ni-Hard to be the most wear-resistant material. However, it will be readily understood that cost effectiveness is also a factor and the new iron is now fully established. Tests other than in power stations are now in progress as are further developments aimed at achieving even better results. Before considering some of the recent work it is, however, necessary to mention that some correlation was found between the results obtained from service test No. 4 (Table 4) and the Amsler pad-on-ring test. It may also be observed that at least some of the tests showed that a disproportionate increase in service life may indeed be obtained as hardness rises above a critical value.

![Diagramatic sketch of the ball testing apparatus.](image)
Fig. 7. Loesche LM 16/1220 D-Nominal output 18 ton/hour.
Other Developments

Cryogenic Treatments

Development work on the modified Ni-Hard is being continued and, as an example, in this section it is proposed to discuss cryogenic treatments together with the effect of magnesium additions on more conventional compositions. Despite stabilization effects, austenite is obviously likely to transform to martensite on exposure to sub-zero temperatures, and exposure to an atmosphere generated by vaporization of liquid nitrogen represents the ultimate that might be done with what has become a very economical method of treatment.

A one-inch keel of the Si-Cr Ni-Hard having a hardness of 730HV (the lowest end of the normal as-cast range) exhibiting about 75% matrix transformation was used. One sample was immersed at -320F and a second also drawn at 400F after sub-zero treatment. The hardness results obtained are compared in Figure 8 to data obtained on other Ni-Hards that had different magnesium contents. Table 5 gives compositional details.

It will be evident that all of the irons increased in hardness after -320F treatment and—although the Si-Cr Ni-Hard, being the hardest material in the as-cast state, showed a lower hardness increment and presumably less further transformation—this gave the best results. The subsequent draw only increased the hardness of three irons with the best of the 3% Cr type Ni-Hards then having the same hardness

![Graph](image)

Fig. 8. Effect of sub-zero treatment, a subsequent draw and magnesium content on the hardness of various Ni-Hards. (Heat analysis in Table 5)

Table 4.
Service Test Results with High Si-Cr Modified Ni-Hard in Coal Grinding Mills
(After a 400F draw unless indicated otherwise)

<table>
<thead>
<tr>
<th>N°</th>
<th>Description</th>
<th>Results</th>
<th>Gain %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Initial test of rolls in an LM 45 p. f. mill</td>
<td>Gms lost per hr run: Regular Ni-Hard 30.4 Modified iron 19.4</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>Later extended use in same power station</td>
<td>Typical roll lives: Regular Ni-Hard 6 - 6.500h Modified iron 7 - 7.500h Modified iron, air-hardened* 8.500h</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>Initial test of LM 16 rolls; different station</td>
<td>Roll life: Regular Ni-Hard 3.700h Modified iron 5.400h</td>
<td>46</td>
</tr>
<tr>
<td>4</td>
<td>Rolls in an LM 16/200 mill</td>
<td>Roll life **: Regular Ni-Hard 2.200h Modified iron 3.300h 20Cr-2Mo-1Cu iron 3.300h Modified iron, air-hardened, (Type 2) 4.460h</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>Table segments in an LM 16 mill</td>
<td>Tons of coal ground per set: Regular Ni-Hard 70.000h Modified iron 80.000h IN-3505*** 110.000h</td>
<td>103</td>
</tr>
<tr>
<td>6</td>
<td>Rolls in a CE bowl mill</td>
<td>H/mm wear: Spun Ni-Hard 87 Modified iron 185 IN-3505 221 Stoody 103 overlay 244 Combustalloy overlay 650</td>
<td>113</td>
</tr>
<tr>
<td>7</td>
<td>Cone spout segments in a bowl mill</td>
<td>3 x life of regular Ni-Hard</td>
<td>200</td>
</tr>
</tbody>
</table>

* This test did not get to completion because of other problems and the roll life shown was estimated by the mill engineers.

** Note the hardness of the regular Ni-Hard was about 580HB compared to 700HB for the air-hardened modified iron.

*** IN-3503 is a 15% Cr iron; see Section 4.

+ U.S. Patent N° 4604781. It is not possible to discuss the economics of overlays here but obviously they can give good results.

Table 5.
Average Analysis (%) of Ni-Hards Used in Cryogenic Tests
(Compared to High Si-Cr modified Ni-Hard)

<table>
<thead>
<tr>
<th>N°</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Mg</th>
<th>S</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>233</td>
<td>3.09</td>
<td>.55</td>
<td>.50</td>
<td>4.25</td>
<td>2.40</td>
<td>.054</td>
<td>.007</td>
<td>.020</td>
</tr>
<tr>
<td>234</td>
<td>3.28</td>
<td>.57</td>
<td>.53</td>
<td>4.20</td>
<td>2.40</td>
<td>.120</td>
<td>.006</td>
<td>.021</td>
</tr>
<tr>
<td>235</td>
<td>3.05</td>
<td>.55</td>
<td>.48</td>
<td>3.35</td>
<td>3.40</td>
<td>.036</td>
<td>.011</td>
<td>.018</td>
</tr>
<tr>
<td>236</td>
<td>3.26</td>
<td>.56</td>
<td>.53</td>
<td>3.35</td>
<td>3.35</td>
<td>.100</td>
<td>.006</td>
<td>.024</td>
</tr>
</tbody>
</table>
as the Si-Cr Ni-Hard. Clearly these types of treatment offer the possibility of improving a range of Ni-Hards and, in particular, a beneficial effect of magnesium is evident, a matter which will be mentioned again later. However, it should be pointed out that a simulated 2-inch bar of the same high Si-Cr iron after being air-hardened and drawn showed a hardness of 760HB. It is believed that a contributing factor to the hardness of such structures is carbide precipitation, which would not occur with cryogenic treatments.

Lastly, with recent developments, 750HB has been achieved in as-cast high Si-Cr irons so there is now a need to study the effect of cryogenic treatment and magnesium in these materials.

Effect of High-Temperature Heat Treatment Combined with Magnesium Additions

Although originally intended for use either in the as-cast condition or after a sub-critical draw Ni-Hard castings are now being regularly made that have been subjected to air-hardening heat treatments. More consistent matrix structures are thereby achieved and, while care is required in controlling heating rates and cooling conditions, experience has shown that the Class I type Ni-Hards do not appear to be any more susceptible to cracking problems than the high-chromium irons. It was decided therefore to determine the best hardening temperature of both a regular grade and also a magnesium-containing iron. In other words, despite the development of new compositions it is proposed to show how it is possible to raise the hardness of the standard materials by heat treatment or Ni-Mg ladle additions. A 3.4% Ni-3.3% Cr iron, both magnesium free and containing 0.07% magnesium, was therefore cast in the form of one-inch keel blocks and small samples subjected to various re-austenitising and sub-critical heat treatments. Figure 9 shows the material details, together with the hardness results that were subsequently obtained.

It will be seen that high hardness values of up to 63Rc were obtained while excessive heating had an adverse effect due, of course, to a lowering of the Ms with consequent austenite retention. Also, the benefits of magnesium will again be evident, and although this has not yet been explained it can probably be attributed to a raising of the Ms temperature. The best austenitizing or rather “conditioning” temperature, (so-called because the high-carbon austenite rejects carbon as carbide), also appeared to be higher with the magnesium-containing iron at around 1400F. A word of caution is needed here because the response of all of these materials depends rather critically on cooling rate and alloy content. Thus, in other tests on magnesium-free, regular Type 1 Ni-Hard, a 1500F maximum was found, so the exact conditions must be established for particular circumstances. Figure 9 shows that a significant hardness loss will occur with a subsequent 800F draw if the best hardening temperature is used, but there is little effect on iron hardened from higher temperatures. The latter effect can, of course, be attributed to the transformation of the higher retained austenite content.

Lastly, it has been mentioned that the high Si-Cr iron has also been used with high-temperature treatments and generally it has then been found that better hardness values are reached than with the regular grades used in these tests. A new grade gave 861HV or 66Rc in a 2-inch section and this iron is still under development.

Lower-Carbon Ni-Hard Irons

While high-chromium irons are made with a wide range of carbon contents to suit various applications, as already discussed, the Ni-Hards normally contain a minimum 2.8% carbon so that they are unsuitable for use where high toughness is needed. Recently, therefore, work has been initiated on a Type 3 iron containing around 1.5%C and preliminary results have shown that hardnesses of 64Rc can be developed by a combination of 1600F air hardening and -320F cryogenic treatment. Further investigation of this new family of alloys is continuing, but as can be appreciated, an interesting potential for an excellent combination of high hardness and toughness seems feasible.
**Other New Irons**

Mention has already been made of improved grades of the high Si-Cr Ni-Hard. A titanium-bearing iron has also been developed recently, which has been claimed to give a hardness of 850HB and three times the abrasion life of air-hardened 20%Cr iron in shot blast applications.

**HIGHER-CHROMIUM, HIGHER-NICKEL Ni-HARD IRONS**

Abrasion-resistant irons of this type originally containing 8%Cr-6%Ni and 2%Si were developed in the early 1950s under the names of Eutectic Ni-Hard or Ni-Hard Type 4. The original objective was to produce a Ni-Hard with an improved carbide structure, but recently, it has been claimed to give a hardness of 850HB and an improved spalling resistance.

A titanium-bearing iron has also been developed where, for example, 725HB is obtained in 3-inch keel castings. Iron No. 2 used for the latter would now be regarded as overalloyed with nickel. However, no information is yet available on improved, molybdenum-containing compositions which are being developed. For example, 725HB is obtained in 3-inch keel blocks.

**HIGH-CHROMIUM, NICKEL IRONS**

These well-known alloys are listed in A532, but the present discussion will be concerned only with Class II irons containing 12-20% chromium. A maximum of 1.5%Ni has been specified in the past, which is unfortunate because, as will be shown, very hard economical grades have been developed using up to 3.5% nickel. Thus, nickel is more effective in promoting good hardenability than manganese, molybdenum or copper. The formulae cited by Dodd and Parks clearly showing the quantitative effect of the different elements on hardenability:

\[
\log \text{pearlite time (secs.)} = 2.9 - 0.51 (C\%) + 0.05 (C'\%) + 0.58 (Mn\%) + 0.84 (Ni\%) + 0.40 (Mo\%) + 0.46 (Cu\%).
\]

Rack et al. not only took into account the important effect of silicon, but gave an even larger factor for nickel on isothermal transformation times. (Here, incidentally, it is suggested that a negative factor of 1.0 should be used for the silicon content in contrast to a value of 3.8 advocated in ref. 32).

Next, it should be noted the opinion that nickel alloying will always result in excessive amounts of undesirable retained austenite and, hence, hardness. Additionally, simulated air cooling of a 5-inch diameter bar using a 5.7%Ni iron gave a hardness of 713HB. Thus, as with Ni-Hard 1, use of the optimum nickel content will result in excellent hardness values being obtained over a range of section sizes even with a standard alloy and conventional heat treatments. There have also been reports on irons with a much improved spalling resistance, so that again it will be seen that further research on this alloy is desirable.

Figure 11 illustrates the beneficial effect of a draw after hardening on I.F. life and Figure 12 shows TTT diagrams. Except for heavy castings, iron No. 2 used for the latter would now be regarded as overalloyed with nickel. However, no information is yet available on improved, molybdenum-containing compositions which are being developed.
reduced at contents in excess of 2%. With these considerations in mind, some of the work done to develop high-chromium, nickel irons will now be briefly reviewed.

The interrelated effects of nickel and molybdenum on the hardness of a 1742F, air-hardened 3%C-15Cr iron has been investigated. The valuable synergistic effects of the two elements were confirmed with up to 809HB being obtained in 4-inch square x 8-inch long test castings. It was, therefore, possible to develop an iron containing 1-3%Ni and 0.3-0.5%Mo, (depending on section size), which was designated IN-3503. With the normal relative costs of alloys, irons of this type could offer economical advantage over Cr-Mo-Cu alloys because, for example: 1) a 2.2%Ni-0.25%Mo grade of 3503 would give a better hardenability than a 2.45%C-19.82% Mo iron, and 2) the availability of a wide variety of nickel-containing scrap.

Table 6. Service Test Using 90mm dia. Balls in a Mill Grinding Raw Cement Clinker (Cumulative data with 125,150 tons ground and 7,037 hr run with 50 marked balls in each of the samples)

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Alloy type</th>
<th>Dia. loss mm per hr × 10^4</th>
<th>90mm wear rate gm per Kwh</th>
<th>Top up to lot chamber gm per Kwh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundry A</td>
<td>High Cr</td>
<td>2.893</td>
<td>0.975</td>
<td>1.437</td>
</tr>
<tr>
<td>Foundry B</td>
<td></td>
<td>2.903</td>
<td>0.978</td>
<td>1.441</td>
</tr>
<tr>
<td>Foundry C</td>
<td></td>
<td>2.487</td>
<td>0.838</td>
<td>1.235</td>
</tr>
<tr>
<td>Foundry D</td>
<td>IN-3503</td>
<td>1.924</td>
<td>0.648</td>
<td>0.955</td>
</tr>
</tbody>
</table>

Table 7. Analysis (%) of IN-3503 Iron Used in Heat-Treatment Tests

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>S</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.12</td>
<td>0.40</td>
<td>0.99</td>
<td>15.52</td>
<td>2.18</td>
<td>1.22</td>
<td>1.15</td>
<td>0.23</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The U.K. Standard has been amended to allow up to 2%Ni in the 12-20%Cr irons while A532 now specifies a 2.5% maximum. No such restriction applies so far to castings being used by the power industry and, in view of the developments that have been outlined, the irons being supplied depend more on the tradition of individual foundries.

For completeness, note that apart from abrasive life and toughness, the high-chromium, molybdenum irons have been found rather susceptible to spalling failures unless correctly heat treated. This is especially although there has not yet been any laboratory work. However, it could be that generally the Ni-Hards are less prone to this problem.

Service Results
IN-3503 type irons, are now finding extensive usage, for example as mill segments as a result of Test No. 6, Table 4. Further service results obtained from use of the alloy in a cement mill are given in Table 6, which shows that competitive Cr-Mo-Cu-Ni irons were easily outperformed, which was not surprising since the IN-3503 media used were about 800HB in hardness. Careful tests using the irons as table segments in a Loesche LM 16 mill, where service life was based on tons of coal ground, also showed IN-3503 to be superior to a 20%Cr-Mo iron although the difference here was only 10%. As a final example IN-3503 gave a 40% service life increase over 20%Cr iron when used as hammers in a glass crushing mill. Other tests are still being monitored, but enough has been done to show that at the very least, an adequate performance can be expected from these high-chromium, nickel irons.

Recent Work
Apart from alloy costs, a marginal advantage, which might be expected to accrue from using nickel as opposed to molybdenum as the primary alloying element in the high-chromium irons, is the fact that a lower hardening temperature should be possible. Although it has been argued that this would lead to a lower carbon content in the austenite and, therefore, a martensite of reduced hardness, several things must be recalled. First, nickel also moves the carbon solubility in austenite to higher carbon contents thereby counteracting the first effect. It may be speculated that this is why there is less effect of nickel in lowering the Ms temperature with higher nickel contents as noted earlier. Second, it is doubtful whether any minor differences that might still arise would have any practical significance. Thus, as mentioned, Cr-Ni-Mo irons can exhibit very high hardness values: nonetheless a 1742F austenitizing temperature was used with only a few tests to establish this temperature being done. Moreover, although Dawson and Craig investigated these various aspects of nickel-bearing irons their results are to some extent vitiated by the fact that only small specimens were used. It was decided, therefore, to check their important finding that 1% nickel lowers the optimum austenitizing temperature by 95F.

Bars 2 ½-inch dia. x 6-inch long of an IN-3503 type iron, having the analysis shown in Table 7, were heated for 2 hours at temperatures ranging from 1517-1787F and cooled in still air. After hardness tests these were drawn 2½ hours at 482F and then further hardness tests were made.

Figure 13 shows the results with the maximum hardness being achieved after austenitizing at 1562F. In contrast Fairhurst and Röhrig stated that 15%Cr-Mo irons should be hardened from 1724F while it has been indicated that an iron of unspecified composition required treatment at 1832F. The latter recommendation rather exaggerates the effect of nickel but the principle will be clear enough. Similarly, it may be mentioned here that Cias in investigating the effect of various alloying elements including nickel, on transformation characteristics used a fixed austenitising temperature of 1751F and thereby would have obtained misleading results. Lastly, it is also evident that a similar diagram produced in the earlier report is misleading in suggesting that a 1742F austenitizing is needed for IN-3503 type irons.

The actual peak hardness of 730HV is not particularly high and again contrasts with the cited earlier work despite the fact that the V/A ratio of the test castings used were similar in these two series of experiments. This is no doubt due to the fact that the combined nickel,
molybdenum, copper, and manganese contents were really too high for the section size involved*. Thus, rather more austenite would be retained because, as it will be appreciated, the Ms temperature is a complex function of composition, austenitizing temperature, and cooling rate.

The fall in hardness on treating at 1517°F is due to the fact that this temperature was evidently just below the Acl. As far as the draw is concerned, Figure 13 shows that a 25HV hardness loss occurred with iron hardened from 1670°F. Less hardness loss occurs after higher temperature austenitizing because these irons could contain excessive retained austenite, which would partly transform on re-heating, thus partly counteracting the loss arising from softening of the original martensite.

Hence, the high-chromium nickel irons can, indeed, be hardened from relatively low temperatures. It is also again evident that the best results from any of these materials will only be obtained if careful attention is given to alloying that will match the cooling conditions.

*Because the composition was designed for some larger castings poured from the same heat.

SUMMARY

It has been proposed in this review that the idea that Ni-Hard or other nickel-containing irons are inferior as abrasion-resistant alloys is not, by any means, a settled question. On the contrary, the work considered shows that the various Ni-Hard irons have much to offer in providing very hard, cost-effective, abrasion-resistant castings.

Hardness values of 700HB and above can be achieved in modified Type 1 irons even without high-temperature heat treatment while regular Type 1 Ni-Hard can be improved by either air-hardening, cryogenic treatments and/or magnesium additions. Type 4 irons of improved hardness are also in use and subject to further research as are now low-carbon grades. Lastly, it has been suggested that high-chromium irons primarily alloyed with some 2.5% Ni show economic advantages and castings that will give an abrasion-resistance equal to or better than more established alloys can be made.

ACKNOWLEDGMENTS

The author is indebted to Sheepbridge Equipment Ltd. for permission to use the information on the modified Type 1 Ni-Hard which is the subject of various patents. Acknowledgment is also made to Inco Limited for their permission to use other data included in this paper.

APPENDIX

Hardness conversions

Brinell vs. Rockwell C.

\[ HB = 0.363 \times (HRC)^2 - 22.515 \times (HRC) + 717.8 \]

Vickers vs. Rockwell C.

\[ HV = 0.343 \times (HRC)^2 - 18.132 \times (HRC) + 595.3 \]

Vickers vs. Brinell

\[ HV = 1.136 \times (HB) - 26.0 \]

From J. L. Parks, AFS Transactions, 87, 195 (1979).

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Fig. 13. The effect of hardening temperature and a 482°F draw on the hardness of a 15% Cr-2Ni-1Mo-1Cu iron. (2 ½-inch dia. x 5-inch long bars)
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