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## NITRIDED ARTICLE OF FERROUS CHARACTER CONTAINING A CASE-TOUGHENING ELEMENT COMBINED WITH A BALANCED CASE-FORMING ELEMENT

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This invention relates to improved nitrided articles of ferrous character containing a case-toughening element combined with a "balanced" case-forming element and to a process of manufacturing such improved nitrided articles, and more particularly to an improved nitrided article constituted of steel or a ferrous alloy and containing a case-toughening element combined with a "balanced" case-forming element and to a process of producing such nitrided article.

It is well known that relatively soft steels may be provided with a hard surface by case hardening them. Heretofore, cases have been produced by carburizing the surfaces of the articles and then hardening them by quenching. Articles hardened in this manner were subject to warpage or distortion which rendered some of such articles unfit for use or necessitated finishing them mechanically after treatment. Moreover, articles which were case hardened with carbon, could only be made with hardness up to about 650 to 750 on the Brinell hardness scale.

For producing greater surface hardnesses in steels, nitriding was proposed. As it is well known, the nitriding (nitride hardening or nitrogen hardening) processes are generally more expensive than the conventional case hardening (carburizing and hardening) processes. Steels of special composition are required (alloy steels) and in addition; the nitrided articles lacked reliability and reproducibility. Moreover, when cases of very high hardness were produced they were relatively brittle and often they cracked in use under comparatively low pressure or shocks in machinery parts. Although the art was struggling to provide improvements in nitrided steels, which would better meet the demands of commercial, industrial and practical use, such improved nitrided steels have not been provided.

In the United States Patents #1,487,554 and #1,649,398 to Fry, a process of nitriding steels and an article produced thereby are set forth which describe that aluminum is an essential element in the steel to be nitrided. The Fry process essentially involves the addition to steel, or ferrous alloys, of aluminum alone or aluminum in combination with chromium or the like. Phillips in a later United States Patent #1,697,083 points out certain limitations and disadvantages of the Fry process and product and states that Fry's product is deficient in toughness and cohesiveness and that molybdenum is necessary in steel for the production of a satisfactory commercial nitrided steel. In addition, the Fry patent contains other defects. For example, Fry states that by the process described in his Patents (#1,487,554 and #1,649,398) marginal layers of an extraordinarily high hardness are acquired in steel alloys which "contain 0.5–2.0% aluminum and either separately or in any desired combination 0.5 to 4.0% silicon, manganese, nickel, chromium, molybdenum, tungster., vanadium, titanium or zirconium and up to 0.6% carbon". It is now known that aluminum is not essential to the production of high hardness in the marginal layers of steel when treated by the ordinary nitriding processes such as heating in ammonia.

Other investigators have published that nickel not only has a retarding action on the nitriding process but also a deleterious or unfavorable effect on the nitrided steel. The aforesaid effects of nickel have been investigated by Guillet as shown in his article in Genie Civil, vol. 91, pp. 38, 60, 86, 472 (1927), by Fry as shown in his articles in Kruppsche Monatschefte, vol. 4, p. 137 (1923) and in Stahl and Eisen 43, 127 (1923) and Sergeson as shown in his article in the Transactions of the American Society for Steel Treating, vol. 16, p. 145 (1929), etc.

It has now been discovered that certain metals, for instance, nickel, molybdenum, chromium, vanadium, heretofore considered as equivalents of each other are not equivalent and interchangeable but have different and sometimes directly opposite characteristics with respect to the nitriding processes for nitriding steels and the products thereof; that some of the metallic elements heretofore considered necessary in steels for nitriding are unnecessary; that a substantial improvement

and increase in toughness of the cases of nitrided steels may be effected; that an increased nitrogen diffusion in the article may be obtained; that the highly important hardness-toughness relations and the depth of the case produced by nitriding may be controlled; and that an improved, stable, reliable and reproducible nitriding steel can be produced by incorporating a case-forming element or several of such elements conjointly with a case-toughening element or several such elements in certain relation to each other in a steel, ferrous alloy or other metal or alloy capable of being case-hardened by nitriding.

By "case-forming" element, is meant such an element that causes the steel to take up nitrogen in its surface or marginal layers in such a manner that the hardness in the marginal layers is increased very appreciably when the steel is nitrided in an accustomed manner, such for example as by heating in an atmosphere of ammonia at suitable temperatures for suitable periods of time.

By "case-toughening" element, is meant such an element that causes an improvement in the toughness of the case. The term "toughness" as used in this specification represents improved ductility combined with improved strength and sometimes also combined with improved shock resistance.

According to the present discovery, the case-forming element may be an element such as chromium, aluminum, or some other element which is capable of causing in a steel or ferrous alloy, a relatively high rate of absorption of nitrogen and a relatively low rate of nitrogen diffusion, and the case-toughening element may be nickel, molybdenum or some other element which is capable of imparting to the case on a nitrided steel or ferrous alloy, an increased ductility combined with an increased strength. The case-toughening element or elements are added to steel or ferrous alloy in certain proportions with respect to the case-forming element or elements so as not only to counteract embrittling and weakening effects of the case-forming element or elements in the case on the article but also to improve the structure and other physical properties of the case formed on the article. The additions of case-toughening and case forming elements may be so controlled as to improve, at the same time, the properties of the core of the article. The elements mentioned hereinabove have as a dominant characteristic either case-forming properties or case-toughening properties. In some instances elements may have approximately equal case-forming and case-toughening properties. For instance, vanadium depending upon its conditions of application including percentages present exhibits both case-forming and case-toughening properties. In percentages around 0.5% it shows marked case-forming properties.

Generally speaking, the present invention contemplates increasing the percentage of the case-toughening element or elements as the percentage of the case-forming element or elements is increased in a steel or ferrous alloy so as to counteract certain detrimental tendencies of the case-forming element or elements as well as to effect an improvement in the structure and properties of the case on the article. The percentage of the case-forming element to be added will depend upon the properties desired, such as the strength, hardness, wear-resistance, etc., and upon the individual characteristics of the element and upon the composition of the steel or ferrous alloy to be nitrided. The percentage of the case-toughening element to be added depends upon its individual characteristics, the case-forming element and the percentage thereof added to the metals or alloys under treatment and the composition of the steel or ferrous alloy to be nitrided and upon the properties desired in the final product.

In the practice of the invention, it is preferred to use nickel and molybdenum conjointly as the case-toughening elements because not only tough cases can be provided on the article but also improved core properties not attainable by the use of either of these elements separately can be obtained. It is preferred to have the nickel addition equal or exceed one part of nickel to one part of molybdenum (by weight), but the benefits obtained from the nickel and molybdenum as case-toughening elements are not restricted to these preferred proportions as is shown by the examples hereinafter described.

Generally speaking, it is preferred to use such a percentage of case-toughening element that the ratio of the percentage of case-toughening element to the percentage of the case-forming element is about 0.8:1 when improved case-toughness is desired without an appreciable decrease in maximum hardness. Ratios of not less than about 0.8:1.0 and not more than about 5:1 should be used, the ratio depending upon the characteristics of the case-forming elements added and upon the properties desired in the nitrided steels. The higher ratios of case-toughening element to case-forming element are employed in those instances where the maximum case hardness desired becomes lower. In practice, it has been found that a ratio of 3:1 gives satisfactory and useful results. When the prior art ratios of less than about 0.8:1 are employed, practically no case-toughening is effected and the case on the article is defective and brittle. On the other hand, when the prior art ratios of higher than about 5:1 are employed the case on the article does not possess sufficient hardness and is termed "soft" in relation to ordinary nitrided cases.

For a better understanding of the inven-

crease in case toughness is obtained when the steel is nitrided in a usual manner, viz,—

*Table 3*

| Steel | Steels with small amounts of C, Si, Mn and customary impurities, together with approximately 1% each of the case-forming elements Al and Cr, and— | Maximum case-hardness, monotron-Brinell | Case toughness measured by load in kg on Brinell ball to crack case |
|---|---|---|---|
| E | Case-toughening elements as follows: practically none | 890 | 300 |
| F | 3.53% Ni and ¼% Mo | 795 | 960 |
| G | 5.07% Ni and ¼% Mo | 720 | 1,140 |

The foregoing samples were nitrided for about 48 hrs. at about 975° F. with about 25/30% dissociation of ammonia.

The increase in toughness produced by the relatively large increases of the case-toughening element nickel is accompanied by a decrease in the maximum case hardness (observed at or near the surface of the articles), the amount of the decrease in the hardness and the increase in the case toughness being controllable by the amounts of the nickel added.

The foregoing example clearly demonstrates that the present invention provides the art with a process to control the hardness-toughness relations of the cases of nitrided steels by means of balanced additions of case-forming elements and case-toughening elements as well as with an improved product. The hardness-toughness control feature is of special and practical importance and industrial and commercial value since the adjustment of case hardness and case toughness by tempering subsequent to quenching, which is effective in carbon case hardened steels, is not, as one skilled in the art knows, available in the case on nitrided steels.

The marginal or surface layers of my improved nitrided articles will not only better resist cracking of the case but will withstand higher loads than heretofore and may be deformed further than hitherto without cracking. These features may be shown and demonstrated by the following table showing results of torsion and bend tests obtained upon steels E, F and G of Table 3.

*Table 4.—Torsion test results on steels E and G (specimens ¾ inch diameter—8 inches long)*

| Steel | Torque to crack case, "inch-lb." | Angle at case fracture, deg. per inch. |
|---|---|---|
| E (No added nickel) | 5730 | 2.5 |
| G (5% added nickel) | 9905 | 6.0 |

The foregoing samples were nitrided for about 48 hours at about 975° F. with about 25/30% dissociation of ammonia.

Each of the foregoing results is the average of 2 tests.

*Table 5.—Bend test results on steels E, F and G (specimens ½ inch×½ inch×7 inches—tested on 4 inch span)*

| Steel | Load in lbs. to crack case | Deflection in inches to crack case |
|---|---|---|
| E (No added nickel) | 2835 | .044 |
| F (3.5% added nickel) | 4180 | .060 |
| G (5% added nickel) | 4675 | .067 |

The foregoing samples were nitrided for about 48 hours at about 975° F. with about 25/30% dissociation of ammonia.

Each of the foregoing results is the average of 2 tests.

Many tests in which the nitrided surfaces have been removed to various depths before testing have indicated that these torsion test results and bend test results are typical of the beneficial influences throughout the hard marginal layers (case) of the nitrided articles.

*Example No. 3*

The invention may be illustrated further by adding to low carbon steel containing small amounts of silicon, manganese and the customary impurities, case-forming elements, comprising about 1 per cent of chromium and about 0.5 per cent of vanadium, together with about 1.6 per cent of the case-toughening element nickel. The steel may have the following composition:—

C about 0.14% (by weight).
Mn about 0.62% (by weight).
Si about 0.18% (by weight).
P about 0.02% (by weight).
S about 0.03% (by weight).
Cr about 1.16% (by weight).
V about 0.55% (by weight).
Ni about 1.63% (by weight).
Fe about balance.

Comparison of this steel with the corresponding one in which the case-forming elements have not been balanced against the case-toughening elements shows the marked superiority of the former. The addition of the nickel results in an appreciable increase in the case toughness without appreciable loss in the maximum case hardness.

The torsion test results which follow demonstrate the ability to control the hardness-toughness relations of the marginal layers of nitrided articles through nickel additions

tion, the following specific and illustrative examples are given:

*Example No. 1*

In accordance with the invention a steel, for instance, has incorporated therein about 2% (by weight) of case-forming elements, which may be about 1% (by weight) of aluminum and about 1% (by weight) of chromium, and about 1¾% (by weight) of case-toughening elements, which may be about 1½% (by weight) of nickel and about ¼% (by weight) of molybdenum. The composition of the steel may be as follows:—

C about 0.2% (by weight).
Si about 0.3% (by weight).
Mn about 0.6% (by weight).
P about 0.02% (by weight).
S about 0.08% (by weight).
Cr about 1.05% (by weight) (case-forming element).
Al about 1.07% (by weight) (case-forming element).
Mo about 0.24% (by weight) (case-toughening element).
Ni about 1.54% (by weight) (case-toughening element).
Fe about balance.

The case-forming elements and the case-toughening elements may be incorporated in the steel in any convenient manner. It is preferred, however, to add the aforesaid elements to the steel while the latter is in a molten condition. After the addition to and incorporation in the steel of said elements, the steel may be cast into ingots or the like and articles made therefrom. The articles may then be subjected to nitriding in any approved or suitable manner, as one skilled in the art will readily understand. Preferably, however, the articles are heated in ammonia at 900–1000 deg. F. for a customary period of time. Various temperatures, periods of time, etc., may be used and the following table gives some of the customary temperatures, periods and cycles used in nitriding:

*Table 1*

| Temperature | Period of time |
|---|---|
| Nitride at a temperature between 900° and 1,000° F. | For 1 to 100 hours. |
| Nitride as above, followed by 1,200° F. | For 1 to 100 hours from 1 hour up. |
| Nitride at about 1,200° F. followed by one temperature between 900° to 1,000° F. | From 1 to 48 hours for 1 hour up. |
| Nitride at a temperature between 900° and 1,000° F. Gradually increase temperature to 1,150° F. with increase in heating rate as temperature rises. End at 1,150° | For 1 to 100 hours. |

The improved nitrided articles possess the properties shown in the following table. For comparative purposes, corresponding properties are tabulated of articles made from a similar steel substantially devoid of the combination of the case-forming elements and the case-toughening elements.

*Table 2*

| Steel | Steels with small amounts of C, Si, Mn and customary impurities, and | Maximum case hardness-monotron-Brinell (at or near surface of article) | Case toughness measured by load in kg on Brinell ball to crack case |
|---|---|---|---|
| A | No alloy additions | 250 | No practical case to crack |
| B | Only case-forming elements (1% Al, 1% Cr) | 920 | 275 |
| C | Case-forming elements with insufficient case-toughening elements (1% Al, 1% Cr, ¼% Mo) | 890 | 300 |
| D | Balanced case-forming elements and case-toughening elements (1% Al, 1% Cr, ¼% Mo, 1½% Ni) | 890 | 555 |

The foregoing samples were nitrided for about 48 hours at about 975° F. with about 25/30% dissociation of ammonia.

The addition of the case-toughening elements (1½% of nickel combined with ¼% molybdenum) together with 2% of case-forming elements (1% aluminum and 1% chromium) has resulted in greatly improved case-toughness without an appreciable change in maximum case hardness as compared to a steel containing only case-forming elements (steel B Table 2) or case-forming elements with insufficient quantities of case-toughening elements (steel C Table 2).

The steel D of Table 2 containing nickel has a higher core hardness and strength, as normalized, or when quenched and then tempered at 1200° F. to 1300° F. than a corresponding steel without the nickel treated in a corresponding manner and will give better support to the case when subjected to heavy pressures. In addition, the case of the nickel-containing steel is far superior to that of the corresponding steel without nickel. It has high hardness (compare steels C and D, Table 2) and, at the same time, it is much tougher and when deformed will not break as readily as the case of the corresponding steel without nickel.

The nickel-containing steel is therefore especially well adapted to applications subjected to heavy loads such, for example, as gears in automotive construction, shafts in machinery, etc.

*Example No. 2*

If the case-toughening elements, in amounts appreciably above about 2 per cent are added to steels containing approximately 1% of each of the case-forming elements aluminum and chromium, a substantial in-

adjusted to the case-forming elements present.

*Table 6*

| Steel | C | Cr | V | Ni | Torque in inch-lbs. to crack case after removing the specified depth of case by grinding subsequent to nitriding | | | Angle, deg. per inch to crack case after removing the specified depth of case subsequent to nitriding | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | None | 0.002" | 0.008" | None | 0.002" | 0.008" |
| K | .19 | 1.14 | .49 | None | 6100 | 6090 | 5915 | 1.2 | 2.1 | 2.1 |
| L | .14 | 1.16 | .55 | 1.63 | 6820 | 6990 | 7015 | 2.0 | 5.8 | 5.9 |

The steels listed in Table 6 were nitrided about 48 hours at about 975° F. with about 25/30% dissociation of ammonia. The test specimens were ¾ inch diameter by 8 inches long. All results are from tests in duplicate.

*Example No. 4*

One aspect of the invention may be further illustrated by the following: If, to a steel containing small amounts of carbon and the customary impurities, there is added about 1 per cent of a case-forming element, such as chromium, and insufficient amounts of case-toughening elements, say only about ¼ per cent of molybdenum, the resultant hardness-toughness relations of the marginal layers of nitrided articles made therefrom will not be as good as those which can be secured by balanced additions made according to this invention. In this instance, the addition of about 1¾ per cent nickel combined with the aforesaid alloy additions completes the proper amount of case-toughening elements to give a relatively high degree of toughness without an appreciable decrease in maximum case hardness. This illustrates one feature of the control of the hardness-toughness relations of nitrided articles. The following table illustrates the advantages of this feature of the present invention:

*Table 7*

| Steel | C | Cr | Mo | Ni | Max. case hardness monotron-Brinell | Case toughness load in kg on Brinell ball to crack case |
|---|---|---|---|---|---|---|
| M | .13 | .90 | .31 | None | 680 | 625 |
| N | .18 | 1.15 | .24 | 1.75 | 685 | 760 |

The foregoing samples were nitrided for about 48 hours at about 975° F. with about 25/30% dissociation of ammonia.

*Example 5*

The effectiveness and usefulness of nickel as a case-toughening element in nitrided steels and articles made therefrom, which improvement constitutes one aspect of this invention, may be further illustrated by comparison of the results of tests of a steel containing about 2% chromium and a steel containing about 2% chromium and about 2½% of nickel, viz:

*Table 8*

| Steel | C | Cr | Ni | Maximum case hardness monotron Brinell | Case toughness load in kg on Brinell ball to crack case |
|---|---|---|---|---|---|
| O | .20 | 2.08 | None | 780 | 200 |
| P | .25 | 2.53 | 2.61 | 830 | 525 |

The foregoing samples were nitrided for about 48 hours at about 900° F. with about 25/30% dissociation of ammonia.

The balanced composition of the steel P of Table 8 made according to the present invention has very much higher case toughness without appreciable loss in maximum case nardnes as compared to the steel O of Table 8 with unbalanced composition comprising case-forming elements without compensating case-toughening elements.

*Example No. 6*

As has already been set forth, one of the important aspects of this invention is the practicability of the control of the hardness-toughness relations of the marginal layers (cases) of nitrided steels and articles made therefrom by balancing the additions of case forming elements and the additions of case toughening elements. Nickel is especially effective in the group of case toughening elements which may be used for this purpose as is shown by the results of the experiments which follow. The following table shows a steel Q, with no case-toughening element, and steels S and T which embody the principles of the present invention.

*Table 9*

| Steel | Steels with about 1% Al, together with small amounts of C, Si, Mn and customary impurities, and the following nickel additions | Maximum case hardness monotron-Brinell | Case toughness load in kg on Brinell ball to crack case |
|---|---|---|---|
| Q | No added case-toughening element | 805 | 115 |
| S | 3.5% added nickel | 645 | 960 |
| T | 5.1% added nickel | 640 | 1,740 |

The foregoing samples were nitrided for about 48 hours at about 975° F. with about 25/30% dissociation of ammonia.

As is shown in Table 9, by adjusting the relative proportions of the case-forming elements and case-toughening elements in the steel (in this case by varying the amounts of the case-toughening element, nickel), it has been practicable to control the hardness-toughness relations of the marginal layers of the nitrided articles within relatively wide limits. With about 3.5 to 5 per cent added nickel, there was a very marked increase in the case toughness with a corresponding decrease in the maximum case-hardness. The

amount of the increase in the case-toughness and the decrease in the maximum case-hardness was dependent upon the proportions of nickel added, that is to say upon the adjustment of the proportions of case-forming elements and case-toughening elements present.

In addition to the foregoing examples, the following illustrative examples are embodiments of the present invention and are listed in a table for convenience. In Table 10, the percentage of case-forming element or elements and of case-toughening element or elements to be added to an appropriate steel or ferrous alloy are given.

*Table 10*

| Case-forming elements | | | Case-toughening elements | |
|---|---|---|---|---|
| Chromium | Aluminum | Vanadium | Molybdenum | Nickel |
| 1.0% | 1.0% | ---------- | 0.25% | 2.0% |
| 1.0% | 1.0% | ---------- | 0.25% | 5.0% |
| 1.0% | 1.0% | ---------- | 0.50% | 1.5% |
| 1.1% | ---------- | 0.5% | ---------- | 1.6% |
| ---------- | 1.0% | ---------- | ---------- | 2.0% |
| ---------- | 1.0% | ---------- | ---------- | 4.5% |
| ---------- | 1.0% | ---------- | 0.80% | 3.0% |
| 1.1% | ---------- | ---------- | 0.25% | 1.8% |
| 0.5% | 0.5% | 0.5% | 0.50% | 1.5% |

It will be observed that the present invention provides nitrided steels having controlled case-hardness and case-toughness and a process by which such nitrided steels may be produced. In the instances where a steel or ferrous alloy is desired with a nitrided case having relatively high hardness and a relatively good toughness, the ratio of case-toughening element to case-forming element present in the steel or ferrous alloy is about 0.8:1. On the other hand, in the instances where a steel or ferrous alloy is desired with a nitrided case having a relatively good hardness and a relatively high toughness, higher ratios of case-toughening element to case-forming element, of the order of about 3:1 and about 5:1 are used. In no case, however, is a ratio greater than about 5:1 employed. The specific ratio in any given case will also depend partly upon the temperature and time of nitriding, carbon content of the steel or ferrous alloy, characteristics of case-toughening element or elements, of case-forming element or elements, etc. The essential feature is that the case-toughening element must be balanced or controlled with respect to the case-forming element. By means of balancing (or controlling) the case-toughening element to the case-forming element as described herein, the advantages, new and/or improved results set forth in detail hereinabove may be obtained. In addition if cases of equal depth are desired the time of nitriding may be shortened by the use of the present process from about 5% to 25% or more. Moreover, with corresponding nitriding procedures, it is possible to produce by use of the present invention cases deeper than those obtained in the conventional nitrided steels.

In carrying the present invention into practice, various percentages (by weight) and/or combinations of the different case-toughening elements and case-forming elements may be used. In general, steels and ferrous alloys containing the following elements and percentages may be employed to carry the present invention into practice: aluminum 0% to about 5%; chromium 0% to about 25%; nickel 0% to about 16%; molybdenum 0% to about 12%; and vanadium 0% to about 2%. The present invention may be carried into practice with steels or ferrous alloys including cast iron, malleableized cast iron, and substantially carbon-free iron alloys.

When iron, steel or ferrous alloy is referred to in the specification and claims, it is to be understood that the usual amounts of customary elements such as silicon, manganese, sulfur, phosphorus, etc. are present. In the claims the expression "an element of the chromium type" is meant to refer to case-forming elements as described herein, whereas the expression "an element of the nickel type" is meant to refer to case-toughening elements as described herein.

The "crack test" applied to nitrided cases on steels and ferrous alloy articles refers to a test in which the nitrided case is subjected to stress as by the ball of a Brinell hardness testing machine and the case is heard to crack. In practice, the occurrence of a sharp noise or crack denotes that mechanical discontinuity, such as a rupture, has developed in the nitrided case. By carrying the test slightly further, the crack can be confirmed by the use of a microscope, by visual examination or by a bend test or by a torsion test.

It will be noted that the present invention provides an improved article of manufacture comprising a ferrous body having a nitrided case and containing a case-toughening element and a case-forming element in such amounts that the ratio of the former element to the latter element is not less than about 0.8:1 and not greater than about 5:1.

It will be also noted that the present invention provides an improved nitrided steel or the like having relatively high hardness combined with relatively high toughness in which the case has substantial depth without any detrimental tendency to surface scaling and in which the core or body of the steel has sufficient hardness and toughness to support the case even under relatively severe loads or impacts.

When in the claims a nitrided case is referred to as having a relatively high hardness and relatively high toughness or relatively high hardness combined with relatively high toughness, hardnesses and tough-

nesses of the order of those set forth in the foregoing tables are meant.

While specific reference has been made to treatment in ammonia, the described benefits resulting from the employment of the principles of the present invention, processes and products described, are not limited as to the source of the nitrogen which is absorbed in the marginal layers of the steel to form a case.

I claim:—

1. An article of manufacture comprising a ferrous body having a tough nitrided case, as nitrided, and containing a plurality of case-toughening elements of the group comprising nickel and molybdenum balanced with a plurality of case-forming elements of the group comprising chromium, aluminum and vanadium, the ratio of said case-toughening elements to said case-forming elements being not less than about 0.8 : 1 and not greater than about 5 : 1, and the case forming elements being present to an extent of more than about 1.5% and less than about 4% and the case-toughening element being present to an extent less than about 6%.

2. An article of manufacture comprising a ferrous body having a tough nitrided case, as nitrided, and containing about 1.5% to about 3.5% of nickel and about 0.25% to about 0.75% of molybdenum acting as case-toughening elements balanced with about 0.5% chromium, about 0.5% aluminum and about 0.5% vanadium acting as case-forming elements, the ratio of said case-toughening elements to said case-forming elements being not less than about 0.8 : 1 and not greater than about 5 : 1, and the case-forming elements being present to an extent of more than about 1.5% and less than about 4% and the case-toughening elements being present to an extent less than about 6%.

3. An article of manufacture comprising a ferrous body having a tough nitrided case, as nitrided, and containing about 2% to about 5% of nickel, and a material percent to about 0.5% of molybdenum acting as case-toughening elements balanced with about 1% to about 2% chromium and a material percent to about 1% of aluminum acting as case-forming elements, the ratio of said case-toughening elements to said case-forming elements being not less than about 0.8 : 1 and not greater than about 5 : 1, and the case-forming elements being present to an extent of more than about 1.5% and less than about 4% and the case-toughening elements being present to an extent less than about 6%.

In testimony whereof, I have hereunto set my hand.

HERBERT JAMES FRENCH.