June 16, 1964 P. M. UNTERWEISER 3,137,596

METHOD FOR HARDENING A NITRIDED STEEL

Filed Oct. 3, 1962 7 Sheets-Sheet 1

Fig. 1.

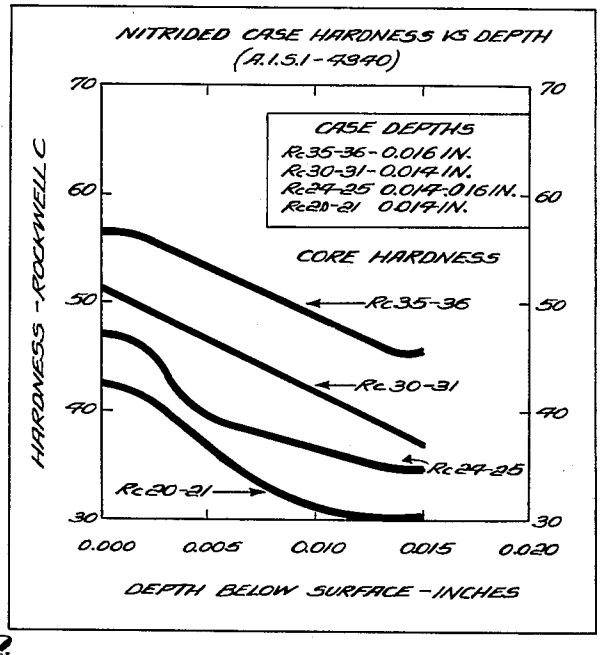
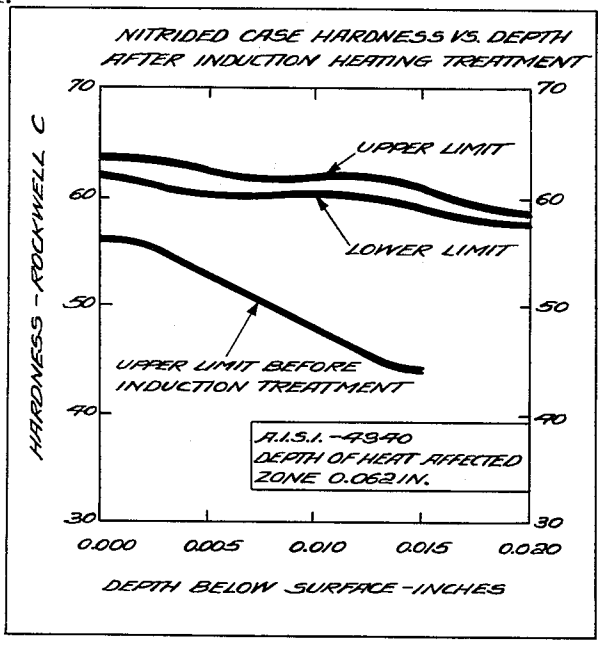


Fig. 2.



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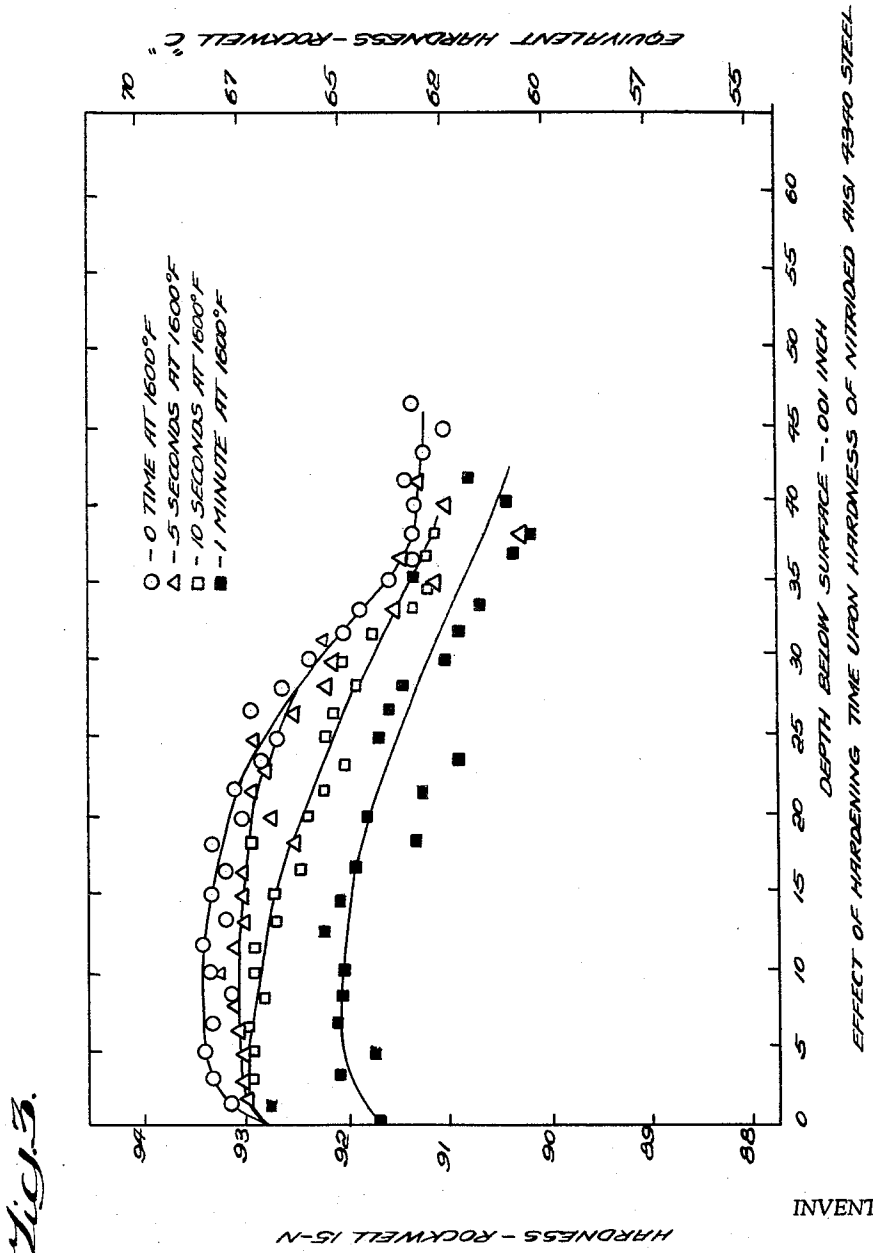


Fig. 3.

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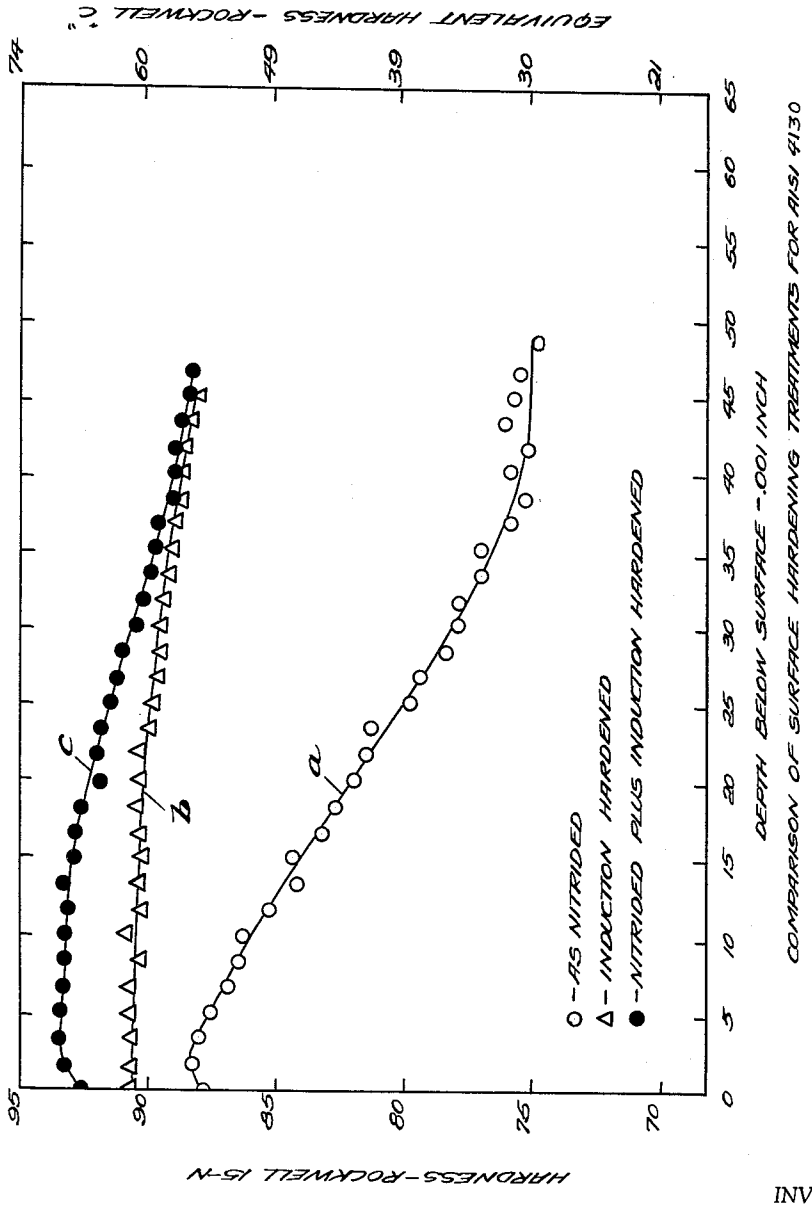


Fig. 4.

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METHOD FOR HARDENING A NITRIDED STEEL

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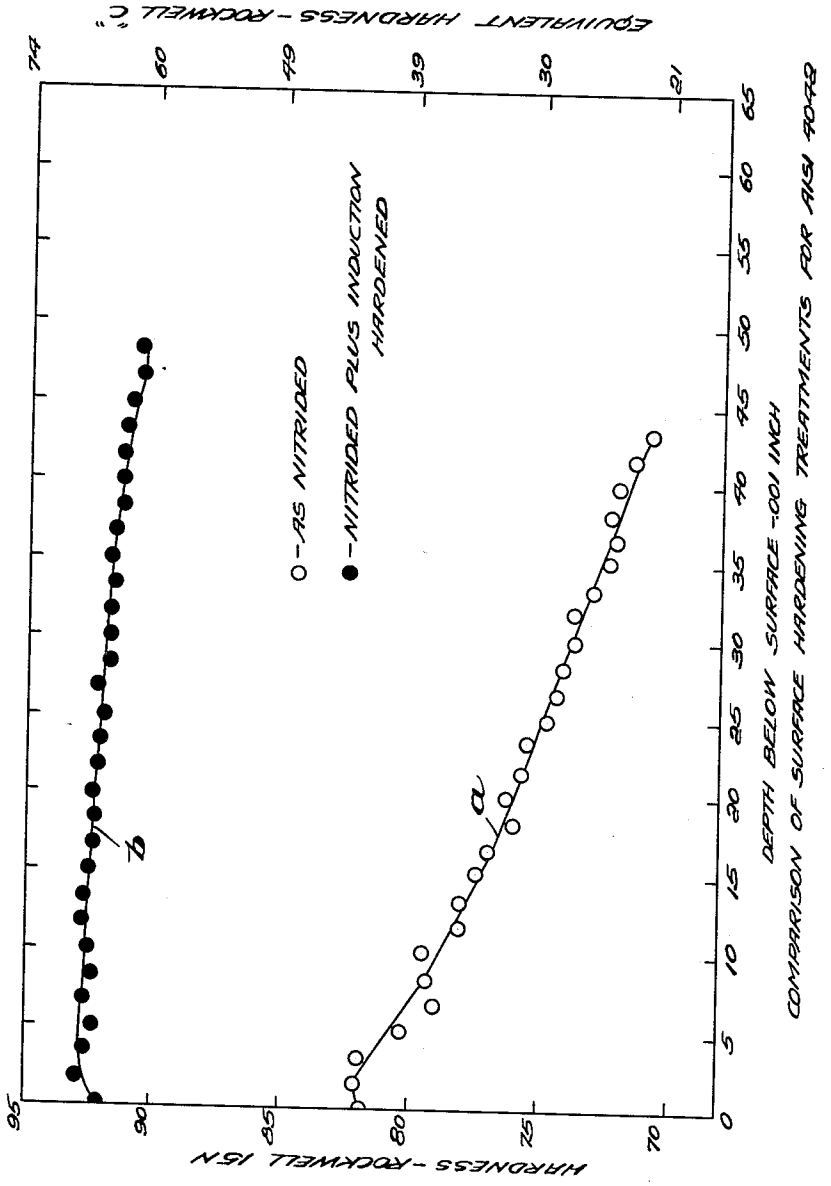


Fig. 5.

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METHOD FOR HARDENING A NITRIDED STEEL

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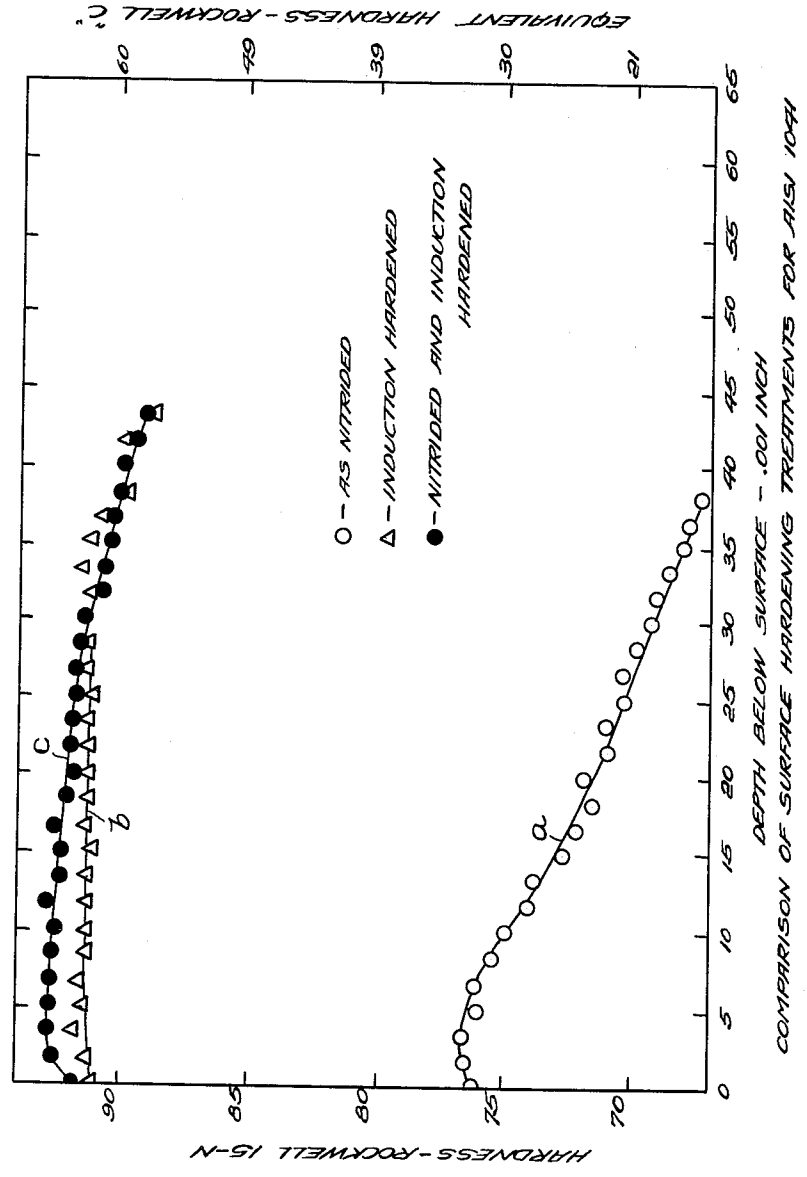


Fig. 6.

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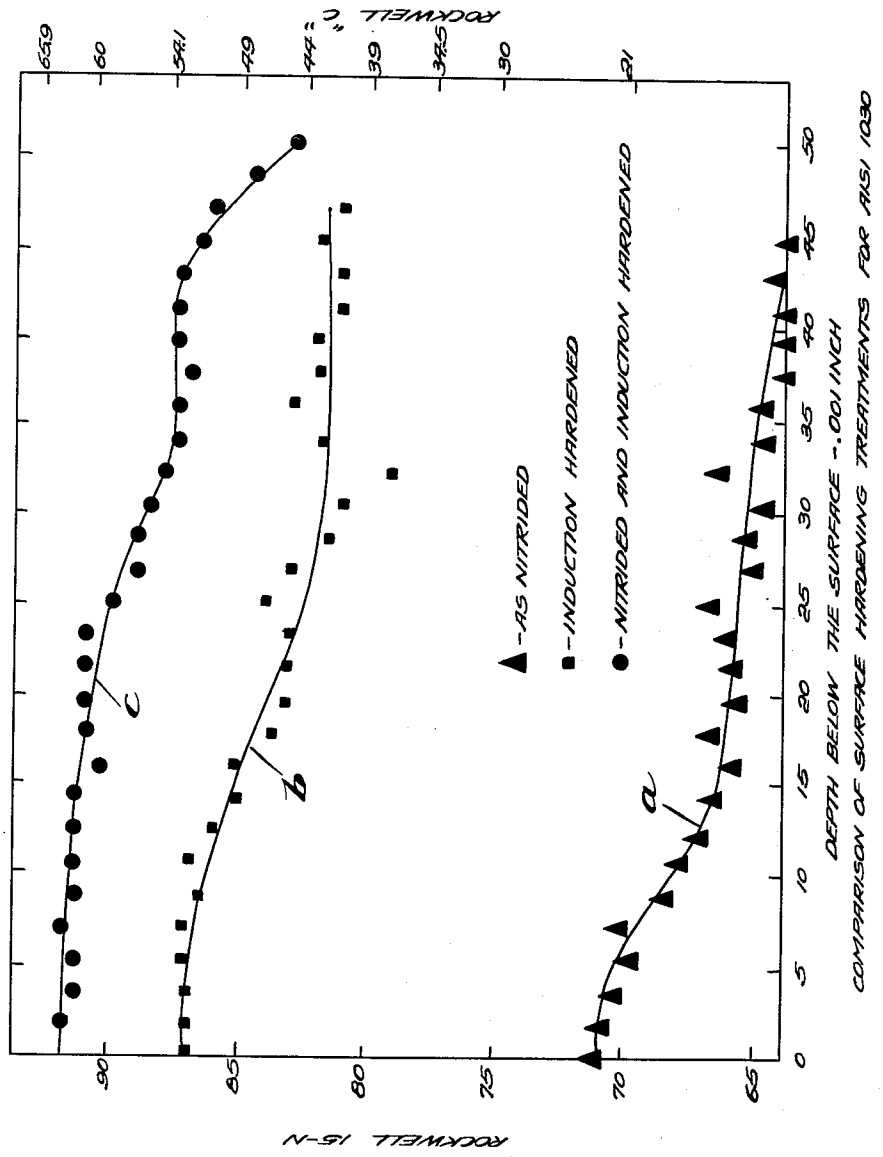
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METHOD FOR HARDENING A NITRIDED STEEL

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COMPARISON OF SURFACE HARDENING TREATMENTS FOR AISI 1030

Fig. 7.

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METHOD FOR HARDENING A NITRIDED STEEL

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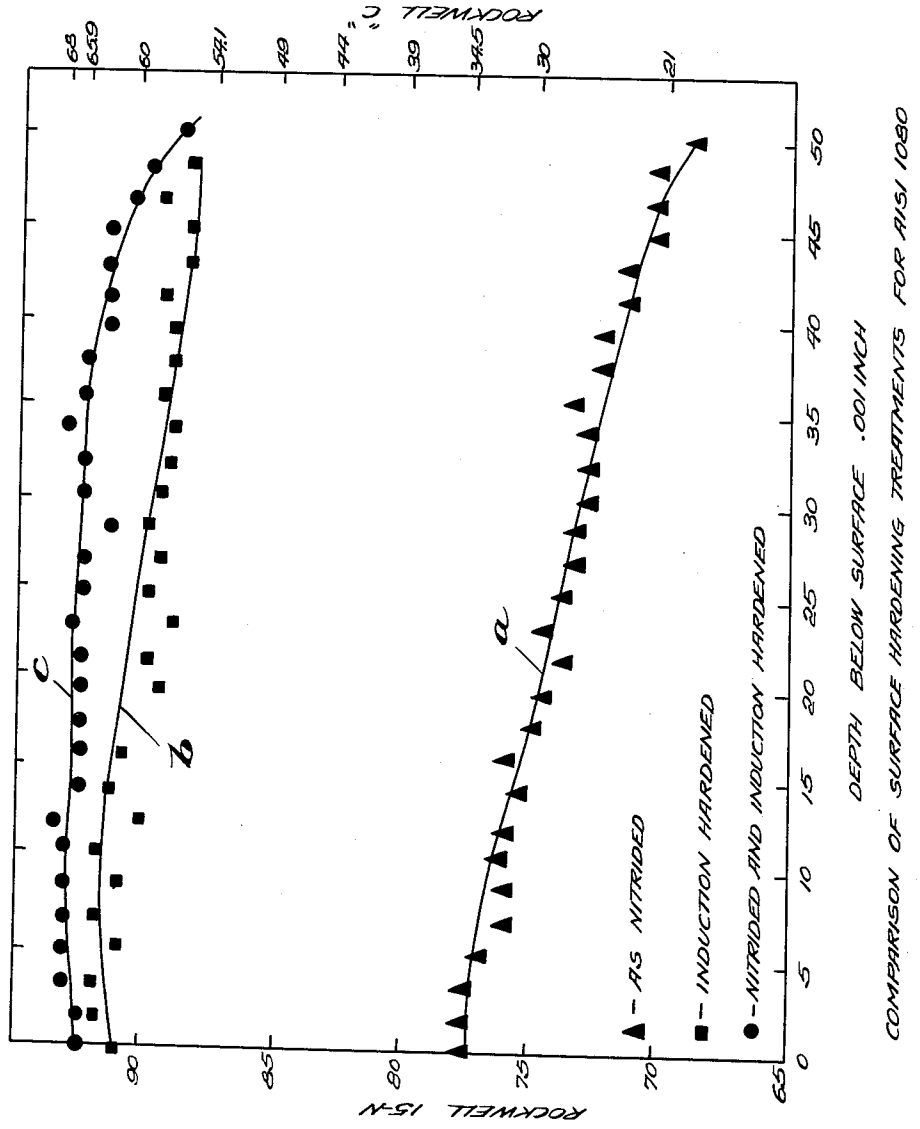


Fig. 8.

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United States Patent Office 3,137,596
Patented June 16, 1964

3,137,596

METHOD FOR HARDENING A NITRIDED STEEL

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Filed Oct. 3, 1962, Ser. No. 229,269
10 Claims. (Cl. 148—152)

The present invention relates to the hardening of steels and more particularly to an improved method for increasing the degree to which plain carbon, and low-alloy high strength steels can be hardened.

When most plain carbon and low-alloy high strength steels are hardened by the well-known nitriding process, even under optimum conditions, a maximum surface hardness of about Rc 35 for the carbon steels and Rc 58 for the alloy steels is about all that can be expected. Even these hardnessess of Rc 35 and Rc 58 respectively are slightly on the high side and cannot always be obtained consistently on a production basis. When finish grinding or lapping is necessary, the final surface hardness can be counted on to be even lower so that in many engineering applications this surface hardness limitation severely curtails the usefulness of the nitriding process on the carbon and low-alloy steels.

It has been discovered that the surface hardness of carbon and low-alloy steels, such as for example AISI 1020, 1030, 1041, 1080, 4042, 4130 and 4340 can be increased considerably above that heretofore obtainable, by using conventional nitriding practice followed by rapid heating of essentially only the nitrided surface layers of the steels to a temperature where austenite is the stable phase, followed by quenching. A satisfactory way to accomplish this rapid heating has been the application of a short-time induction heating cycle, for example, for about two seconds to raise the surface temperature of the steel into the austenitizing temperature range proper for the alloy composition. It should be noted that the effects of the improved process are not limited to the use of induction heating and that other common methods for rapid heating of the surface such as flame heating, and salt bath heating are applicable as well.

It is known that when the temperature of a carbon or low alloy nitrided steel is increased much above 1000° F. the nitrogen begins to diffuse rather rapidly outward from the case and much of the hardness attributable to the nitriding process itself is lost. By using a short-time (2–3 second) heating cycle it has proven possible to get the surface layers of the nitrided steel up to a higher temperature (1600°–1650° F.) with very little loss in nitrogen due to diffusion. A comparison between photomicrographs taken of AISI 4340 nitrided steel before and after the heating phase indicates quite clearly that after the heating phase of the nitrided steel was complete, the nitride content of the originally nitrided case was considerably increased and that the nitrided case depth has been increased.

The improved method for hardening nitrided steels will become more apparent from the following description of various examples as applied to different steel compositions and the accompanying drawings: In these drawings:

FIGURE 1 shows the influence of core hardness on the surface hardness obtained when AISI 4340 steel is nitrided. It is evident that the surface hardness after nitriding was strongly influenced by the hardness of the steel before the nitriding operation was begun. The higher core hardnesses are reflected in higher surface hardnesses after nitriding. This is believed to be the effect of more alloying elements being available for nitride formation in the steels tempered at lower temperatures after quenching to produce higher hardnesses. That is less alloying element is combined as carbides in this condition so that more alloy is available to form alloy nitrides.

FIGURE 2 shows a comparison of the hardness levels and the range of hardness, reached in both the conventional nitrided condition and after treatment by the improved process of rapid heating of the nitrided surface layers followed by quenching. The improved process produces substantially higher hardnesses to much greater case depths and greatly reduced the effect of core hardness that has heretofore caused a large variation in the surface hardness of nitrided low-alloy steels.

FIGURE 3 shows the effect of holding time at the austenitizing temperature on the hardness measured at various depths within the case after quenching of the austenite. The plot shows that the maximum hardnesses (the optimum) are obtained with short holding times that approach zero, but that there is no substantial decrease in the hardness obtained if holding times shorter than about ten seconds are used. Holding times longer than ten seconds cause unfavorable lower case hardnesses.

FIGURE 4 shows the results obtained with AISI 4130 a chromium containing low-alloy steel when the improved process of rapidly heating the nitrided surface layers into the austenitizing temperature range, followed by quenching was applied. The plot shows Hardness vs. Case Depth and curves showing the hardness variation through a conventional nitrided case on AISI 4130 as well as for the induction surfaced hardened condition are included for comparison. FIGURE 4 shows the superior results obtained with the new process over the separately applied conventional nitriding and surface hardening techniques when used with AISI 4130.

FIGURE 5 shows the results obtained with AISI 4042 a low alloy non-chromium containing steel, when the improved process was used to treat nitrided specimens. The plot shows Hardness vs. Case Depth after the steel was treated by the improved process and for comparison a curve showing the variation in hardness through the case for AISI 4042 steel in the nitrided condition. FIGURE 5 shows the superiority of the improved process of rapidly heating the nitrided surface layers into the austenitizing temperature range followed by quenching when applied to nitrided AISI 4042 steel surface.

FIGURE 6 shows the results obtained with AISI 1041 steel when the improved process was used to treat previously nitrided specimens. The plot shows Hardness vs. Case Depth after the steel was treated by the improved process and for comparison curves showing the variation in hardness through the case for AISI 1041 steel in both the nitrided and surface hardened conditions. FIGURE 6 shows the superiority of the improved process of rapidly heating the nitrided surface layers into the austenitizing temperature range followed by quenching when applied to AISI 1041 over the conventional nitriding and surface hardening processes.

FIGURE 7 shows the results obtained with AISI 1030 a low carbon steel, when the improved process was used to treat previously nitrided specimens. The plot shows Hardness vs. Case Depth after the steel was treated by the improved process and for comparison curves showing the variation in hardness through the case for AISI 1030 steel in both the nitrided and surface hardened conditions. FIGURE 7 shows the superiority of the improved process of rapidly heating the nitrided surface layers into the austenitizing temperature range followed by quenching when applied to AISI 1030 over the conventional nitriding and surface hardening processes.

FIGURE 8 shows the results obtained with AISI 1080, a high carbon steel, when the improved process gas used to treat previously nitrided specimens. The plot shows Hardness vs. Case Depth after the steel was treated by the improved process and for comparison curves showing the variation in hardness through the case for AISI 1080 steel in both the nitrided and surface hardened conditions.

FIGURE 8 shows the superiority of the improved process of rapidly heating the nitrided surface layers into the austenitizing temperature range followed by quenching when applied to AISI 1080 over the conventional nitriding and surface hardening processes.

The improved method was first carried out with AISI 4340 because its nitriding characteristics are well known and its performance in the nitrided condition has been adequately tested, particularly in aircraft.

Test specimens were machined from 1" diameter bar stock. All were copper plated and hardened under protective atmosphere. After hardening, samples were tempered to produce four "core" hardness levels: Rc 20–21, 24–25, 30–31, and 35–36. All specimens were inspected after tempering and found to be free of any surface decarburization.

The core hardness levels were chosen in order to first determine the effect of core hardness on nitrided-case hardness. A maximum hardness of Rc 35–36 was not exceeded because the tempering temperature required to produce this hardness was safely above the nitriding temperature. Consequently, there was no chance of the specimens altering their core hardness during the nitriding cycle.

To insure an optimum nitriding surface, all specimens were cleaned and bonderized prior to nitriding. The specimens were all then nitrided at 975° F. for 25 hours in a single-stage cycle. The rate of ammonia dissociation was maintained between 20 and 30 percent throughout the cycle.

The hardness measurements for the nitrided cases at the four core hardness levels are shown in FIGURE 1. The Rockwell *c* values plotted were converted from actual 15N readings. These values are about average for nitrided 4340 alloy. As might be expected, lower core hardness resulted in lower case hardness.

After nitriding, all four specimens were subjected to the same induction heating cycle. The induction heating unit consisted of a coil of two turns with an internal diameter measurement of about 1⅛ inches within which the 1" diameter specimens were placed, the coil heating a length of about 2" of the specimen. The capacity of the induction unit was 30 kw. and its operating frequency was 1,200 kilocycles. The high frequency was intentionally chosen in order to limit the heat affected zone of the specimens to approximately the nitrided case area. The time of heating was 2½ seconds which was sufficient to bring the surface temperature of the specimens up to between 1,600° and 1,650° F. The time at maximum temperature was not measured but did not exceed a small fraction of a second. After the induction heating phase was completed, the specimens were then quenched in oil.

There is no precedent for a tempering or stress relieving cycle to be used after induction hardening of a nitrided steel. However, it is believed that some stress relief would be advisable. Consequently, all test specimens were held at 400° F. for one hour and air cooled.

Surface hardnesses for all specimens after the induction hardening phase were in the range of 15N 90–92. The highest surface hardness was obtained on those specimens with a core hardness of Rc 35–36.

Even at the lowest core hardness level (Rc 20–21) a minimum surface hardness of 15N 90 was obtained. This is the equivalent of Rc 62 and represents an increase over the nitrided surface hardness of almost 20 points Rockwell. The maximum spread in surface hardness due to core hardness was cut from 14 to 2 points Rockwell.

The range of hardness values obtained as a function of Case Depth are plotted in FIGURE 2. The upper limit of case hardness values were obtained with the Rc 35–36 core hardness. All case hardness values fell within the spread shown, even at the lowest core-hardness level. The depth of heat-affected zone due to induction heating was 0.062 inch.

At the upper limit of case hardness, a hardness of Rc 60 or over is maintained to a depth of almost 0.020 inch. A minimum of Rc 60 is held to a depth of 0.012 inch at the lower limit. In both cases, the results were found to be unusual and were due to a change in case structure.

The holding time at the austenitizing temperatures may be varied somewhat without an adverse effect on the results. Experiments with 4340 have shown that the holding time can be as long as about ten seconds. This is evident from FIGURE 3 which shows plots of Hardness vs. Case Depth for different holding times at the austenitizing temperature before quenching of the heated nitrided surface layers was started. For a minimum holding time such as a fraction of a second or less (approaching zero) one obtains the most favorable Hardness vs. Case Depth relationship. For holding times longer than about ten seconds the results are less uniform and substantially lower hardnesses for a given depth within the case are evident.

In addition to the above described procedures carried out on AISI 4340, similar experiments were conducted on AISI 4130 which is another chromium containing low-alloy steel.

AISI 4130 hot rolled bar stock was purchased and given a preliminary heat treatment by heating to 1550° F. then quenching in water and tempering for four hours at 1020° F. and four hours at 140° F. The bars were then machined to 1" diameter rounds. A portion of the AISI 4130 steel was induction surface hardened, and the remainder was nitrided in a two stage process by a treatment of holding at 985° F. for nine hours in an atmosphere of 25–35% dissociated ammonia, increasing the dissociation to 65–70% during a time period of about five hours holding the steel at temperature for an additional forty-six hours under these conditions and furnace cooling. Some of the nitrided 4130 was examined to measure the Hardness vs. Case Depth relationship in the nitrided condition and the remainder of the nitrided portion was subjected to induction heating to rapidly heat the nitrided surface layer into the austenitizing temperature range for this AISI 4130 alloy (1600° F.) and then quenched with water.

The induction heating was done with a Lepel High Frequency induction generator, using a power input of 28 kw. and a frequency of approximately 300 kilocycles per second. The induction coil was made from 3/16 inch diameter copper tubing flattened to ⅛ inch and had a double winding with four turns in each winding. The coil was of 1 3/16 inches inside diameter and one-inch long. A water spray quenching ring was located directly below the heating coil and was used to quench the specimen from the austenitizing temperature.

The surface temperature was measured with a special radiation pyrometer focused between turns of the coil and connected to a Leeds and Northrup Speedomax Type G controller-recorder. The approximate austenitizing time, i.e., Ae_1 temperature to hardening temperature, was measured from chart records, using a chart speed of one-inch per second.

After hardening the case depth was measured from depth-hardness data and macro-etches samples. The case depth hardness measurements were made using a Rockwell Superficial Hardness Tester. Rockwell 15N hardness measurements were made on a tapered surface which was very carefully ground on the specimens after heat treatment to expose the hardened surface layers. The same technique was used for the three heat treated conditions of as nitrided, as induction hardened, and after hardening of the nitrided surface.

The hardening temperature used for the AISI 4130 alloy was 1600° F. and the austenitizing time was approximately 2.3 seconds; the holding time at the austenitizing temperature of 1600° F. was essentially zero. The results obtained with 4130 steel are shown in FIGURE 4 where Curves (*a*), (*b*) and (*c*) show the results of the Hardness vs. Case Depth measurements for the nitrided,

induction hardened, and nitrided plus heating and quenching conditions. Curve (*c*) in FIGURE 4 shows the superior results obtained with the improved process when compared with the conventional results.

The invention has also been found to be applicable to other low-alloy steels which do not contain chromium as an alloying element such as, for example AISI 4042. In this case preparation of the sample, nitriding, and hardening were carried out in the same manner as for 4130 and the results are shown in FIGURE 5 which illustrates the favorable results obtained when the improved process is applied to AISI 4042. The curves in FIGURE 5 show the Hardness vs. Case Depth relationship for 4042 steel hardened by (*a*) nitriding and (*b*) the improved process of rapidly heating the nitrided surface layers into the austenitizing temperature range followed by quenching. The superior hardness results obtained by the use of the improved process are shown in Curve (*b*).

In addition to the low-alloy steels, experiments have confirmed the fact that similar favorable results are obtainable when the improved process, namely rapid heating of a nitrided surface into the austenitizing temperature range followed by quenching is applied to low, medium and high plain carbon steels that have been nitrided.

As an example of a medium carbon steel, a sample of AISI 1041 was processed as follows: Hot rolled bar stock was purchased and given a preliminary heat treatment by heating to 1570° F., then quenching in warm oil and tempering at 1100° F. for four hours. In this case the nitriding was carried out as described for the AISI 4130 steel above. The heating and quenching equipment used was the same as for the 4130. The approximate austenitizing time (heating above the Ae_1) was three seconds; the maximum austenitizing temperature was about 1625° F. The samples were water quenched after the induction heating cycle. The favorable results obtained with the improved process when applied to nitrided AISI 1041 are shown in FIGURE 6. The curves in FIGURE 6 show the Hardness vs. Case Depth relationship for AISI 1041, steel hardened by nitriding (Curve *a*), induction hardening (Curve *b*) and the improved process of rapidly heating the nitrided surface layers into the austenitizing temperature range followed by quenching. The superior hardness results obtained by the use of the improved process are shown in Curve (*c*) of FIGURE 6.

As an example of a low carbon steel, a sample of AISI 1030 was processed as follows: one inch diameter hot rolled bars were purchased and given a preliminary heat treatment by heating to 1600° F., quenching in water and tempering at 1100° F. for four hours. The hardness after this treatment was 64 R15N. Some of the heat treated 1030 steel was machined to a diameter of ⅞ inch and nitrided by heating to 985° F. and holding for 15 hours 20% dissociated ammonia, increasing the dissociation to 80% in an eight hour period, holding for an additional forty-two hours and then furnace cooling. The surface hardness after nitriding was 71 R15N. The variation in hardness through the nitrided surface layers was measured and the results are shown in Curve (*a*) of FIGURE 7.

Another sample of AISI 1030 which had been the preliminary heat treatment described above and machined to ⅞ inch diameter but not nitrided, was induction hardened. The induction hardening was done using a Lepel High Frequency induction generator at a power input of 15 kw. and a frequency of approximately 300 kilocycles per second. The induction coil and quenching method used were the same as for the AISI 4130 steel. The surface temperature was measured with a Chromel-Alumel thermocouple percussion welded to the specimen surface. The temperatures and times were recorded on a Leeds and Northrup Speedomax G controller-recorder as in the AISI 4130 experiments. A hardening temperature of 1700° F. was used and the heating time was 2.5 seconds. The hardness variation through the case was measured and the results are shown in Curve (*b*) FIGURE 7. The maximum surface hardness measured was 87 R15N.

A portion of the nitrided AISI 1030 was treated by the improved process using the same temperature and time as for induction hardening. In addition to the water quenching the sample was immersed in liquid nitrogen for twenty minutes. The results of hardness measurements through the case produced by the improved process are shown in Curve (*c*), FIGURE 7. The superior results obtained are evident in FIGURE 7 and the maximum surface hardness measured was 92 R15N. The increased case hardness over the induction hardened test specimen is maintained to at least a depth of 0.050 inch which is in excess of the original nitride case depth of 0.044 inch.

As an example of a higher carbon nitrided steel, a sample of AISI 1080 was processed in essentially the same manner as for AISI 1030. The preliminary heat treatment was to heat to 1550° F., quench in warm oil and temper at 1100° F. for four hours. The hardness after this treatment was 70 R15N. The nitriding process was the same as used for AISI 1030. The austenitizing temperature used for induction hardening of the non-nitrided and nitrided specimens was 1650° F. and the heating time was 2.5 seconds. The samples were then quenched in the same manner as the AISI 1030 specimen.

The results obtained with AISI 1080 when processed by the improved method are shown in FIGURE 8. Curve (*a*) shows the Hardness vs. Case Depth for 1080 steel in the nitrided condition, (*b*) the Hardness vs. Case Depth for induction hardened 1080 steel and (*c*) the superior Hardness vs. Case Depth for 1080 steel processed by the improved process of rapid heating of a nitrided surface into the austenitizing temperature range following quenching. The maximum surface hardness of 77.5 R15N in the nitrided condition has been raised (by treatment with the improved process) to 92.5 R15N which is superior to the 91 R15N obtained by induction hardening alone. The increased hardness of the case produced with the improved process over the induction hardened case depth beyond is maintained to the depth of the original nitrided case.

Similar favorable results as regards increased hardness and depth of case were obtained in experiments carried out on nitrided samples of AISI 1020, AISI 1030, and AISI 1080, that were treated by the improved process but not immersed in liquid nitrogen after quenching to room temperature.

The extra hardening effect produced by the rapid heating into the austenitizing temperature range and quenching of the nitrided surface layers is believed to be a combined effect of two hardening mechanisms:

(*a*) In the conventional nitrided case, the ability of the alloying elements to form carbides is known to influence case hardness. As the tempering temperature is increased, more and more of a carbide-forming element is precipitated as a carbide, leaving less in solution in the iron for nitride formations. Nitralloy steels containing aluminum are not so markedly affected in this way since virtually all of the element remains in solution and is available for nitride formation.

Depending upon the amount of precipitated carbide, for example, in tempered 4340, nitride case hardness can vary within a fairly broad range when the steel is nitrided in the conventional manner. It apparently cannot exceed a maximum hardness of about Rc 58 because too much of the carbide-forming elements have already been precipitated prior to nitriding. The short heating cycle raises the surface temperature of the steel to 1600°–1650° F. momentarily. This treatment is sufficient to place carbides back into solution thus releasing carbide-forming elements for further chemical combination.

In the presence of nitrogen contained in the nitrided case, this permits the formation of additional nitrides and results in an appreciable increase in case hardness.

(*b*) A second effect of heating the nitrided surface layers into the austenitizing temperature range is to effect the solution of some of the nitrides (as well as carbides) so that nitrogen would be dissolved in the austenite as an alloying element. On quenching of the nitrogen enriched austenite the dissolved nitrogen would remain in solution and on transformation of the austenite produce nitrogen rich products of decomposition of increased hardness. The dissolved nitrogen would behave in a manner similar to carbon as an interstitial element to promote a hardening effect. This is particularly evident in the carbon steels where little nitride forming elements are present, so that an increased hardness because of solution of carbide forming elements other than iron to cause an increased dispersion of nitrides would not be expected, and further the increased hardness effect caused by the nitrogen on heating and quenching has been shown to be dependent on the hardenability (i.e., the carbon content) of the steels. The maximum gain in hardness achieved over the induction hardened samples was seen in the 1020 steel, and the incremental hardness decreased, although the maximum hardness reached increased, as the carbon content was increased from 0.20 through 0.30 to 0.80%.

The properties of the quenched structure produced by heating and quenching of a nitrided surface further suggests that the nitrogen has entered into the hardening reaction as other than an increased dispersion of nitrides. This was shown by an increased resistance to softening, i.e., tempering, of the quench hardened nitrided case on reheating. This shows that the product of this hardening reaction is of a different nature to the normal carbon martensites. The difference is believed to be because of the dissolved nitrogen which enhances the hardenability of the austenite.

Both of the above mechanisms (*a*) and (*b*) cause the increased hardness measured in the specimens treated by this new hardening process; the proportional increase caused by each is dependent on the alloy content and primary hardenability of the steel treated. The effect of increased dispersion of the alloy nitrides was seen to be minimized in the carbon steels, where the alloying effect of the nitrogen on the hardness of the transformed austenite was the greatest.

This application is a continuation-in-part of my copending application Serial No. 819,627, filed June 11, 1959.

I claim:

1. The method of treating a steel which has been nitrided which comprises the steps of rapidly heating substantially only the nitrided portion of the steel to a temperature within the austenitizing range for the steel, holding the steel at the austenitizing temperature for a relatively short time ranging from about ten seconds down to and approaching zero, and then initiating and continuing quenching until a temperature is reached such that substantially all of the austenite in the nitrided portion is transformed into nitrogen bearing martensite.

2. The method as defined in claim 1 of treating a steel which has been nitrided wherein the total time for heating the steel and for holding it at the austenitizing temperature does not exceed about thirteen seconds.

3. The method as defined in claim 1 of treating a steel which has been nitrided wherein the heating time is not in excess of about three seconds.

4. The method of treating a steel which has been nitrided, said nitrided steel being selected from the group consisting of plain carbon steels and low alloy steels which comprises the steps of rapidly heating substantially only the nitrided portion of the steel to a temperature within the austenitizing range for the steel, holding the steel at the austenitizing temperature for a relatively short time ranging from about ten seconds down to and approaching zero, and then initiating and continuing quenching until a temperature is reached such that substantially all of the austenite in the nitrided portion is transformed into nitrogen bearing martensite.

5. The method of treating a steel which has been nitrided, said nitrided steel being a chromium containing low alloy steel, which comprises the steps of rapidly heating substantially only the nitrided portion of the steel to a temperature within the austenitizing range for the steel, holding the steel at the austenitizing temperature for a relatively short time ranging from about ten seconds down to and approaching zero, and ten initiating and continuing quenching until a temperature is reached such that substantially all of the austenite in the nitrided portion is transformed into nitrogen bearing martensite.

6. The method of treating a steel which has been nitrided, said nitrided steel being a non-chromium containing low alloy steel, which comprises the steps of rapidly heating substantially only the nitrided portion of the steel to a temperature within the austenitizing range for the steel, holding the steel at the austenitizing temperature for a relatively short time ranging from about ten seconds down to and approaching zero, and then initiating and continuing quenching until a temperature is reached such that substantially all of the austenite in the nitrided portion is transformed into nitrogen bearing martensite.

7. The method of treating a steel which has been nitrided, said nitrided steel being selected from the group consisting of low carbon steels including AISI 1020 and AISI 1030 which comprises the steps of rapidly heating substantially only the nitrided portion of the steel to a temperature within the austenitizing range for the steel, holding the steel at the austenitizing temperature for a relatively short time ranging from about ten seconds down to and approaching zero, and then initiating and continuing quenching until a temperature is reached such that substantially all of the austenite in the nitrided portion is transformed into nitrogen bearing martensite.

8. The method of treating a steel which has been nitrided, said nitrided steel being a medium carbon steel including AISI 1041, which comprises the steps of rapidly heating substantially only the nitrided portion of the steel to a temperature within the austenitizing range for the steel, holding the steel at the austenitizing temperature for a relaitvely short time ranging from about ten seconds down to and approaching zero, and then initiating and continuing quenching until a temperature is reached such that substantially all of the austenite in the nitrided portion is transformed into nitrogen bearing martensite.

9. The method of treating a steel which has been nitrided, said nitrided steel being a high carbon steel including AISI 1080, which comprises the steps of rapidly heating substantially only the nitrided portion of the steel to a temperature within the austenitizing range for the steel, holding the steel at the austenitizing temperature for a relatively short time ranging from about ten seconds down to and approaching zero, and then initiating and continuing quenching until a temperature is reached such that substantially all of the austenite in the nitrided portion is transformed into nitrogen bearing martensite.

10. The method of treating a chromium-containing, low alloy steel which has been nitrided which comprises the steps of raising the temperature of substantially only the nitrided portion of the steel to a temperature within the austenitizing range of from about 1600 to 1650° F. within a short time not exceeding 2–3 seconds, initiating quenching within a fraction of a second after attaining said austenitizing temperature, and continuing the quenching to a temperature below that at which martensite is formed so as to convert substantially all the austenite into martensite containing nitrogen as an alloying constituent.

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