

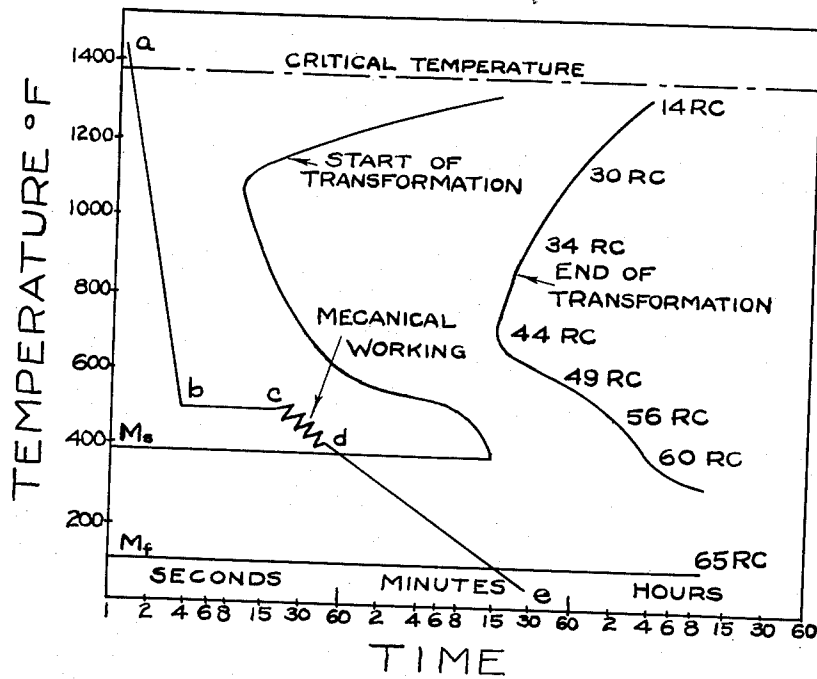
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R. F. HARVEY

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METHOD OF SURFACE HARDENING FERROUS METALS

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INVENTOR.

Richard F. Harvey

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METHOD OF SURFACE HARDENING FERROUS METALS

Richard F. Harvey, Seekonk, Mass.

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This invention relates to a process for mechanically working ferrous metals at elevated temperatures to improve their properties and more particularly to an improved method of imparting residual compressive stress to increase their endurance limit or fatigue resistance.

In order to acquire a better understanding of the background of this invention it should be understood at the outset that conventional methods of cold working used to improve fatigue life have very definite limitations and often weaken rather than strengthen the parts treated.

Cold working may be done in various degrees of intensity by such methods as shot peening, rolling, stretching, twisting, compressing, swaging, pressing, cutting, grinding, or by any other means of mechanical working at about room temperature. In general cold working results in a surface layer which is under stress. In some instances this is in compression and in others in tension. If the surface stress is compressive, balancing tensile stresses are set up in the interior and at any cross section the total sum of the tensile and compressive stresses must be equal to produce equilibrium.

If the stresses at the surface are tensile, this is generally a weakening factor. If compressive, this will generally result in increased fatigue strength. Fatigue failure nearly always starts on the tension side of a member and the longitudinal, residual compression must be exceeded by the applied tensile stress before a net tensile stress results. Since tensile stresses cause fatigue failures introduction of residual compressive stress counteracts part of the applied tensile stress and acts to increase the effective endurance limit or fatigue life of structural parts or machine members.

Shot peening is a common method of cold working with the object of introducing residual compressive stress. The shot peening is done by a driven stream of hard shot. The parts to be peened are subjected to a rain of shot to expose critical areas to the mechanical working. The shot is generally propelled by compressed air or by mechanical means with velocities of the order of magnitude of about 200 feet per second. The shot itself consists of hard, spheroidal particles usually ranging from about $\frac{1}{64}$ inch to about $\frac{3}{32}$ inches in diameter.

Cold shot peening causes plastic flow in the surface of the part, stressing the material beyond its yield strength at its surface resulting in residual compressive stress. In general the magnitude of the compressive stress and the depth to which it extends is dependent upon the properties of the material, the characteristics of the blast, and the amount of shot striking the surfaces being peened. The properties of the blast include the shot velocity and the angle of impact as well as the hardness and size of shot. The amount of shot striking the peened surface depends on the length of exposure to the blast, as well as the quality of shot used.

Shot peening increases the strength and fatigue resistance of a metal, but this also involves a reduction in its ductility and if too intense cold work is done on a metal, its ductility may be completely exhausted and cracks may

result. In other words over-peening results in fractures which actually reduce the strength of parts.

In order to control the effectiveness and intensity of peening it is common practice to employ a flat piece of heat treated steel known as an Almen test strip. When clamped to a solid block and exposed to a blast of shot, the strip on removal from the block will be curved with the peened side being convex. Moreover the peened side will be in residual compression. A dial indicating gage commonly known as an Almen gage is generally used in commercial practice to measure the amount of curvature. The curvature of the peened test strip as indicated by its arc height is taken as a measure of the intensity of residual compressive stress set up on the peened side and hence as a measure of the intensity of peening. Thus 0.016 A denotes an intensity of peening which will result in an arc height of 0.016 inch as measured with an Almen gage on a standard Almen A test specimen 0.051 x $\frac{3}{4}$ x 3 inches. Most cold peening is done at intensities equivalent to about 0.005 A to 0.025 A, the higher intensities being commonly measured with a thicker test strip known as the Almen C specimen.

The intensity of peening for optimum results is difficult to establish and maintain using conventional methods. Underpeening results in insufficient residual surface compressive stress and overpeening actually weakens members due to loss of ductility and formation of cracks.

It is generally accepted that merely elevating the temperature for shot peening does not result in any distinct or worthwhile advantages over conventional cold peening at room temperature.

Everything thus far stated about mechanical working and shot peening is well known and appreciated by those skilled in the field. The presentation of this background has been made as stated in order to provide a better understanding of my invention.

As I shall point out hereinafter, my investigations confirm the experience of the prior workers but show how a given intensity of mechanical work may be employed to impart a greater degree of residual compressive stress and higher fatigue life without adverse weakening effects than has heretofore been possible. I have also found a better surface structure is assured when the mechanical working is conducted in accordance with the teachings of my invention.

I have found that for a given intensity of mechanical working the degree of residual stress imparted can be increased about two-fold and frequently higher without adverse effects by employing the following procedure. Hardenable ferrous metals including steels are first austenitized by heating above their critical temperature, then quenched rapidly in a suitable heat abstracting medium maintained above the temperature range of martensite formation and held for a length of time of sufficient duration to attain the temperature of the quenching medium but not long enough to permit transformation of the subcritical austenite at that temperature level, after which they are mechanically worked while above or less than about 100° F. below the temperature at which martensite starts to form on cooling, and finally the ferrous metals or steels are cooled to room temperature. I have also found that this treatment results in a higher hardness and a more complete transformation of austenite to martensite.

It is therefore one of the outstanding objects of this invention to produce a higher degree of compressive stress without adverse weakening effects for a given intensity of mechanical work than has heretofore been possible with conventional methods of mechanical working.

It is also an object of this invention to employ greater intensities of mechanical working to impart residual stress

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without the adverse weakening effects characteristic of conventional methods of mechanical working.

It is a further object of this invention to increase the strength and more particularly the fatigue life or endurance limit of heat treated parts.

A further object of this invention is to bring about a marked increase in the conversion of austenite to martensite in heat treated parts.

It is furthermore an object of this invention to increase the surface hardness over that obtained by conventional practice.

These and other objects that will be brought out hereinafter may be attained by mechanically working the ferrous metals while in a predominantly austenitic condition above or not more than about 100° F. within the range of martensite formation.

The sequence of steps in the thermal treatment prior to mechanical working of the ferrous metals while at elevated temperatures will be recognized by those skilled in metallurgy as being related to the commercial interrupted quench treatment termed step quenching, martempering, or marquenching. In order to further acquire a better understanding of the background of my present invention which is a combination of interrupted quenching and mechanical working to produce novel and useful results, it should be clearly understood that while the conventional interrupted quench hardening treatment does result in a minimum of residual stress, however as used commercially, it is not particularly effective in setting up residual compressive stress to counteract applied tensile stresses which cause failures especially under repeated applications of loading.

Interrupted quenching as applied to commercial practice comprises: austenitizing the steel by heating above its critical temperature, quenching into a molten or hot bath maintained above or slightly within the range of martensite formation and holding for a time of sufficient duration to enable the steel to attain that temperature but of insufficient duration to permit transformation of the subcritical austenite at that temperature level, and finally air cooling to room temperature.

The interrupted quench treatment known as step quenching, martempering, or marquenching which I first developed is disclosed in detail in my patent application Serial No. 320,998, filed February 27, 1940, now abandoned, the principles of which shall be referred to more particularly hereinafter.

When a carbon or alloy steel is quenched from a temperature above its transformation temperature range, at which temperature the steel is in the form termed austenite, to a temperature below this range, the rate of conversion of the austenite to pearlite, bainite, or martensite varies in marked degree. Thermal hardening time curves known as transformation curves or time-temperature-transformation curves show the progress of the transformation of the austenite to its transformation products. Two curves are generally drawn to show the time for the beginning and completion of the transformation for temperatures below the critical temperature range.

A zone of rapid austenite conversion to lamellar pearlite occurs for many steels at a temperature approximating about 1200° F. to about 900° F. In this range a relatively soft pearlitic structure is obtained.

At a temperature range below about 400° F. hard martensite forms in increasing proportion as the temperature is decreased. Unlike the pearlite formation which is an isothermal transformation, the formation of martensite depends on a lowering in temperature for its continuation.

Between the temperature range of pearlite formation and that of martensite formation the rate of conversion of austenite to fine pearlite or bainite is relatively slow. In general, for many steels and ferrous metals after quenching rapidly through the temperature zone at which

pearlite forms readily, if the quenching is interrupted at a temperature above the range of martensite formation, the steel or ferrous metal may be maintained at this intermediate temperature in an austenitic condition for prolonged intervals of time before the austenite transforms to the crystal structure designated bainite.

By interrupting the quench above the range of martensite formation all sections of the part attain substantially the same temperature and the formation of martensite on air cooling proceeds uniformly resulting in several advantages over continuous quenching from above the critical temperature to room temperature.

However, interrupted quench hardening as commercially used has never produced a substantial degree of prestressing or the deliberate introduction of an effective degree of residual stress to counteract the applied stresses encountered in service. The effectiveness of prior art treatments is relatively slight in this respect as contrasted with the novel results of my present invention.

Everything thus far stated relative to the interrupted quench treatment known as step quenching, martempering, or marquenching is known by those skilled in the field of metallurgy. The presentation of this information has been made to further provide the background for a better understanding of my present invention.

The foregoing explanation of the effects and physical changes which occur on conventional mechanical working and interrupted quench hardening as well as the following explanation of the changes brought about by my modified interrupted quenching-hot working technique are based on careful studies of the metal including measurements of hardness, microstructure, residual compressive stress, endurance life in fatigue, and X-ray examination.

I have found that there is no advantage in merely elevating the temperature of the work to hot peen insofar as residual compressive stress is concerned. However, I have found that when the hot peening is done on ferrous metals or steels while above or up to about 100° F. within the range of martensite formation under conditions which insure that the parent structure at the time of peening is for the most part a face-centered cubic, subcritical austenite, the amount of residual compressive stress increases greatly with entirely satisfactory results.

According to one method of applying the principles of the present invention the thermal treatment and mechanical working with relation to the transformation curves may be conducted in four main steps. These are illustrated diagrammatically in the figure representing the treatment according to the principles of my present invention of a manganese non deforming tool steel commonly classified as A. I. S. I. 0-1 tool steel and having the following typical analysis: Carbon 0.90%, manganese 1.30%, chromium 0.50%, tungsten 0.50%, and the balance substantially iron.

These transformation curves show the times required for the austenite to start and to complete transformation at each temperature as well as the Rockwell C hardness values of the transformation products resulting. They are useful in predicting the approximate structures and hardnesses to be obtained when the steel is cooled or quenched at different rates. This type of curve, in which time is plotted on a logarithmic scale in the figure, is well known and is of fundamental importance to those skilled in metallurgy.

The temperature at which martensite starts to form on cooling, known as the M_s temperature, is less than about 400° F. for the steel represented in the figure. The temperature at which the austenite to martensite transformation is about completed is generally designated as the M_f temperature. It should be understood that the M_f temperature has no exact significance and this symbol merely conveys some idea of the progress of the transformation to martensite on cooling. Many steels retain appreciable percentages of austenite at room temperature, the precise amount being dependent upon several

complex factors. In my own investigation of a manganese oil hardening tool steel represented by the figure, I have found about 10% retained austenite at room temperature with conventional hardening methods.

From the figure it will be noted that after the steel is quenched at a rate equal to or exceeding its critical cooling rate the quenching may be interrupted above the range of martensite formation at, for example, 500° F. where it may be held for about 9 minutes before the austenite starts to transform to bainite. The time for the transformation to be completed at 500° F. is approximately two hours.

The four steps involved in my present invention with relation to the transformation curves in the figure are represented by lines *a-b*, *b-c*, *c-d*, and *d-e*, wherein *a-b* represents quenching the austenitized steel from above its critical temperature range at a rate at least equal to its critical cooling rate to an appropriate temperature level above the range of martensite formation. The line *b-c* represents holding the steel in a subcritical austenitic condition above the range of martensite formation for a sufficient length of time to attain that temperature, but of insufficient duration to form appreciable amounts of the transformation product at that temperature level generally termed bainite. Line *c-d* represents mechanically working the steel while it is substantially above the *M_s* temperature. Line *d-e* represents cooling the steel to room temperature.

Molten salt baths or hot oil may be used as the interrupted quenching medium prior to the mechanical working. Agitated molten salt is generally preferred in view of its more rapid quenching rate. In some instances such as with relatively thin sections which tend to cool rapidly on removal from the interrupted quench it is desirable to permit mechanical working while the ferrous metal or steel is within the range of martensite formation. It is generally not advantageous to continue the mechanical working below temperatures at which the amount of untransformed austenite is reduced by about 40 percent.

In treating case hardening steels by my present invention the *M_s* temperature of the high carbon, carburized case will usually be several hundred degrees Fahrenheit lower than the *M_s* temperature of the low carbon core. For example in carburized A. I. S. I. 8620 steel the *M_s* temperature of the case is about 400° F. and is about 800° F. for the core. I have found that such steels can be mechanically worked above or somewhat within the martensite range of the case although this may be considerably below the *M_s* temperature of the core. It is not practical to interrupt the quench above the *M_s* temperature of the core as the quenching rate is generally too slow to avoid formation of soft pearlite. Also the holding time may be too short to permit equalization of the work in temperature and also avoid bainite formation.

By way of a specific example of an embodiment of my present invention a test specimen 0.140 x 1/2 x 2 1/4 inches made from an oil hardening tool steel of the analysis listed for the example shown on the figure, was austenitized at 1500° F. for eight minutes followed by quenching in hot salt at 500° F. and held for five minutes followed by shot peening while still austenitic and hot with an intensity of peening of 0.016 A. The following data on the hardness and austenite transformation of this specimen will serve to illustrate some of the advantages produced by treating according to the principles of this invention.

	Rockwell A Hardness	Equivalent Rockwell C Hardness	Volume Percent Retained Austenite
Hot Peened Side.....	83.8	64.7	2.4
Unpeened Side.....	82.5	62.4	11.8

The foregoing data show that the surface hardness

has increased by an amount equivalent to at least several points Rockwell C as a result of hot peening. The table also shows that 9.4% of the retained austenite at the surface has been transformed as a result of hot peening.

The volume percent determinations of the amount of austenite were made by an X-ray method employing integrated intensities. The increased transformation of austenite to martensite on peening by the methods of the present invention is consistent with the higher surface hardness resulting. It is known that austenitic structures may be work hardened wherein martensite is formed by deformation. In my present invention the work hardening and thermal treatment are combined in a novel way to result in greater conversion of the austenite to martensite than would result by conventional thermal methods alone. By comparison with the above effects of hot peening, my results with cold peening confirm the experience of prior investigators and show no appreciable increase in hardness or change in the percent of retained austenite on cold peening.

The term "mechanical working" as applied to my invention includes subjecting metal to pressure exerted by rolls, dies, presses, or hammers to change its form or to affect the structure and hence the mechanical and physical properties. The term "deformation" as herein used is defined as the alteration of form or shape of metals as well as the distortion of metals under the action of applied stresses.

It is generally agreed that the amount of retained austenite should be held to a minimum for optimum properties and other investigators have shown that retained austenite reduces the elastic limit, yield strength, fracture stress, energy absorption in tension and also has an adverse effect on the notch properties measured by bend tests.

As previously stated peening in accordance with the principles of my present invention results in a greater degree of residual compressive stress than is obtainable by conventional cold peening methods. As illustrative, Almen A specimens 0.051 x 3/4 x 3 inches were cold peened to an arc height of 0.016 inch corresponding to an intensity of peening which is commonly designated as 0.016 A as heretofore described. Identical specimens made from an oil hardening tool steel of the following typical composition: Carbon 1.04%, manganese 0.80%, chromium 1.20%, and molybdenum 0.30% showed an arc height of 0.029 inch when austenitized at 1500° F. for 8 minutes and quenched in molten salt at 500° F. and held for 5 minutes followed by hot peening with the same intensity of peening commonly designated as 0.016 A. This indicates nearly about twice the curvature and residual compressive stress for steel hardened according to my present invention as compared with the lesser effect of prior art practice.

Since the curvature is due to surface compressive stress on the convex side which is also the peened side, grinding away this surface layer should cause the specimens to return to approximately their original flatness. Removal by grinding of the compressive surface layer in both the hot and cold peened test specimens did cause the curved specimens to flatten thus proving that the curvature produced is due in each case to residual surface stress.

The following data on the fatigue properties of standard Moore type fatigue specimens will serve to illustrate the improvement in fatigue life which may be obtained by the teachings of my invention.

Summary of fatigue data (rotating beam) for A. I. S. I. 0-1 oil hardening tool steel hardened by various methods

Typical analysis: Carbon 0.90%, manganese 1.30%, chromium 0.50%, and tungsten 0.50%
Austenitizing treatment: 1500° F.—10 minutes, molten salt
Tempering treatment: 400° F.—1 hour

Quenched	Peened	Stress, p.s.i.	No of Cycles	Remarks
Oil.....	None.....	130,000	69,000	Broke.
Do.....	do.....	128,000	271,000	Do.
Do.....	do.....	128,000	532,000	Do.
500 F-5 min.....	do.....	130,000	184,000	Do.
Do.....	do.....	128,000	271,000	Do.
Do.....	do.....	128,000	565,000	Do.
Do.....	Hot.....	128,000	1,016,000	Do.
Do.....	do.....	128,000	3,024,000	Do.
Do.....	do.....	128,000	1,300,000	Do.
Do.....	do.....	128,000	19,184,000	No failure.
Do.....	do.....	128,000	2,787,000	Broke.

The foregoing test results show that mechanical working in the form of shot peening in accordance with the teachings of my present invention improves the fatigue life over continuous quenching and interrupted quenching.

A further fatigue test was conducted on springs of A. I. S. I. 6150 steel with the following results:

Spring dimensions:

Outside diameter----- $2\frac{9}{32}$ inch.
 Free length----- $1\frac{3}{4}$ inch.
 Solid length----- 1.022 inch.
 Coils per inch----- 4.
 Wire diameter----- 0.128 inch.

Austenitizing treatment, 1600° F. 6 minutes in molten salt.

Tempering treatment, 400° F. 1 hour.

Summary of fatigue data of springs of A. I. S. I. 6150 steel hardened by various methods

Quenched	Peening	Average No. of Cycles to Failure
Oil.....	None.....	138,300
500 F-5 min.....	do.....	150,600
Do.....	Hot 0.016 A Intensity.....	302,700

The tabulated results are the average of six springs for each treatment tested in compression under identical conditions.

The foregoing fatigue test results on test specimens and springs illustrate the improvement in fatigue life which may be realized by applying the principles of my present invention.

In using my present invention no particular skill is required on the part of the operator and conventional heat treating equipment may be used. When shot peening is used as a means of mechanically working the steel while at elevated temperatures in practicing this invention, I have found that centrifugal means for propelling the shot are superior to compressed air. The air blast often cools the work too rapidly for the peening to be effective at the elevated temperatures.

I have also found that intensities of peening of over about 0.035 A can be used with satisfactory results when the peening is conducted by the principles of this invention. Such high intensities of peening cannot generally be used with conventional cold peening practices due to excessive loss of ductility and the formation of cracks.

While a specific embodiment of the principles of my present invention has been described in terms of shot peening it should be understood that other forms of mechanical working may be employed with beneficial results. For example, die cavities may be prestressed in compression to give longer life by hot pressing with the hubs which initially made the impression in the soft dies in the conventional manner.

To cite another example, the bores of gun barrels may be hydraulically pressed hot to impart a greater degree of compressive stress in the bore walls than may be imparted by conventional methods of cold pressing generally known as autofrettage. In each case the mechanical working should be done while the steel is austenitic and above or somewhat within the range of martensite forma-

tion in accordance with the principles of my present invention. Also other suitable methods of mechanical working such as squeezing, rolling, stretching, swaging, hammering, compressing, twisting, etc. may be used to advantage to increase the strength, fatigue life, and other properties of steels and ferrous metals according to the principles of this invention.

While several specific analyses of steels were cited in the foregoing examples of my invention it should be understood that the principles of this invention are applicable to any ferrous metal or steel hardenable by heat treatment. The unalloyed ferrous metals and steels, however, are limited to relatively small sections. An effective amount of transformation retarding alloying element or elements is required in the relatively thicker sections to avoid transformation to soft pearlite on quenching from the austenitizing temperatures as heretofore described.

I claim:

1. A method of surface hardening a quench-hardenable cast or wrought ferrous metal comprising the steps of heating the said ferrous metal above its critical temperature to render it austenitic, quenching the said ferrous metal at a rate at least equal to its critical cooling rate to a temperature range between about 300° F. and 700° F. for a length of time insufficient to form appreciable amounts of bainite at said temperatures, uniformly working the surface of the said ferrous metal in said temperature range in the absence of bending deflection to impart residual, compressive stresses thereto, and finally cooling the said ferrous metal to room temperature.

2. A method of surface hardening a quench-hardenable cast or wrought steel comprising the steps of heating the said steel above its critical temperature to render it austenitic, quenching the said steel at a rate at least equal to its critical cooling rate to a temperature below the range of pearlite formation and above the range of martensite formation for a length of time insufficient to form appreciable amounts of bainite, subjecting a surface of said steel to a substantially uniform mechanical working without permanent bending deflection within the latter temperature range to impart residual compressive stresses thereto, and finally cooling the said steel to room temperature.

3. The process of surface hardening in accordance with claim 2, wherein there is effected during said working a substantial reduction in the retained austenite on subsequent cooling to room temperature.

4. The process of surface hardening in accordance with claim 2, wherein there is effected during said working at least an 8% conversion of the austenite.

5. The process of surface hardening in accordance with claim 2, wherein there is effected during said working an increase in hardness on the order of approximately 2 points Rockwell C.

6. The process of surface hardening steels substantially in accordance with claim 2, wherein the working is done at temperatures not less than 100° F. below the temperature of martensite formation.

7. A method of surface hardening a quench-hardenable cast or wrought steel comprising the steps of heating the said steel above its critical temperature to render it austenitic, quenching the said steel at a rate at least equal to its critical cooling rate to a temperature range between about 300° F. and 700° F. for a length of time insufficient to form appreciable amounts of bainite, shot-peening the steel in the latter temperature range using intensities of peening equivalent to about 0.005 A to about 0.040 A, and finally cooling the said steel to room temperature.

8. A method of surface hardening a quench-hardenable cast or wrought steel comprising the steps of heating the said steel above its critical temperature to render it austenitic, quenching the said steel at a rate at least equal to its critical cooling rate to a temperature between

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about 300° F. and 700° F. for a length of time insufficient to form appreciable amounts of bainite, uniformly working a surface of said steel in said temperature range to impart residual, compressive stresses thereto in the absence of appreciable residual surface tensile stresses, and finally cooling the said steel to room temperature.

9. A method of surface hardening quench-hardenable cast or wrought steel characterized by high load-carrying capacity and endurance which comprises heating the said steel above its critical temperature, quenching rapidly into a molten bath maintained in the temperature range below about 700° F. and substantially above the temperature of martensite formation, holding the steel in the molten bath for a length of time sufficient to enable the steel to uniformly attain the temperature of the said bath but for a length of time insufficient to permit substantial transformation of the austenite to bainite, uni-

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formly working the said steel at its surface in the absence of permanent deflection to effect a substantial conversion of the austenite to martensite at the surface of the said steel in the stated temperature range and to impart residual compressive stresses to the surface thereof, and finally cooling the said steel through the range of martensite formation to room temperature.

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