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HEAT TREATED STEEL ARTICLE

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This invention relates to the heat treatment of metals and, more particularly to a new method of making a through-hardened steel part which has a fatigue life superior to through-hardened steel parts made by conventional heat treating methods.

The present invention is a continuation-in-part application of my previously filed co-pending patent application Serial No. 674,038, which was filed July 25, 1957, and now abandoned.

It is well known that the fatigue life of a steel part can be substantially increased by imposing a favorable residual stress on the surface of the part. Ordinarily a favorable residual stress is one which is opposite to that imposed on the part during use, a residual compressive stress being most generally used to improve the fatigue life of a part subjected to tensile stresses. Heretofore a residual compressive stress layer could only be formed on the surface of a through-hardened steel part by a special mechanical treatment performed on the part subsequent to the heat treating or hardening operation. Treatments, such as rolling, shot peening, sand blasting and severe grinding, are typical of the methods which have been employed; however, each of these methods entails a separate mechanical process subsequent to heat hardening in order to accomplish the desired results.

In particular, it is an object of the present invention to provide a through-hardened steel part having a substantially thicker surface zone which is in a state of residual compressive stress than that formed with prior mechanical methods.

This object and other objects, features and advantages of the present invention will be more apparent from the following description of preferred examples thereof.

Briefly, the invention encompasses subjecting a through-hardening steel part to a novel heat treatment in which, during quenching, the surface of the part is hardened subsequent to its interior. This, of course, is directly opposite to the effect which obtains during a conventional heat treatment. In the invention an alloying element is preferentially dissolved at a high temperature in a selected area of a through-hardening steel part. The part is then quenched to obtain a sequential hardening of the part in which the selected area hardens after the balance of the part. A residual compressive stress is induced on the surface of a part by preferentially dissolving an alloying element at the surface of the part and quenching the part to successively harden the interior and then the exterior.

The invention is more aptly described in connection with the effects it produces on a through-hardening steel. For this reason reference is herewith made to the nature of a through-hardening steel and the manner in which it is affected by a hardening heat treatment. A heat treatment is generally understood to be a combination of heating and cooling operations, timed and applied to a metal or alloy in the solid state in a way that will produce desired properties.

In general terms, a through-hardening steel is a steel which contains a sufficient amount of carbon in its composition (generally about 0.5% or more) to produce a martensite transformation when the steel is conventionally quenched from an austenitizing temperature. For purposes of this invention, by the term "through-hardening steel" I mean to encompass only those steels which

will undergo a martensite transformation substantially throughout the cross section of a part formed of that steel. Accordingly, if a steel part can be through-hardened, my novel heat treatment can be effectively used.

A through-hardening steel is normally hardened by a heat treatment in which the steel is heated for a sufficient time at a temperature high enough to render the steel soft and ductile. The temperature at which the steel has been heated to make it soft and ductile is called the "austenitizing temperature." Rapidly cooling the hot austenitized steel, such as by quenching it in water, brine, oil, etc., causes a hardening of the steel to occur. Austenitizing, as is well known in the metallurgical art, is the process of forming austenite by heating a ferrous alloy into the transformation range (partial austenitizing) or above the transformation range (complete austenitizing). The transformation range referred to is the range in which alpha iron transforms into gamma iron or, more generally, the range in which ferrite is converted to austenite.

In the austenitizing process, then, iron is transformed from the alpha phase (a body-centered cubic crystalline structure) to the gamma phase (a face-centered cubic crystalline structure). Ferrite is a solid solution in which the alpha iron is the solvent, while austenite is a solid solution in which gamma iron is the solvent. Cementite, on the other hand, is a compound of iron and carbon which may co-exist under some conditions with either the ferrite or austenite. However, the higher the austenitizing temperature, the greater the amount of cementite dissolved in the austenite. The A_1 temperature is that temperature at which austenite begins to form during heating and thus is the lowest temperature at which cementite can be dissolved in autenite. The A_{cm} temperature of a hypereutectoid plain carbon steel is that temperature at which the solution of cementite in austenite is completed during heating.

The sudden cooling of austenite changes the crystalline structure from the soft and ductible gamma form to the hard and brittle tetragonal crystalline form called "martensite."

Austenite, the high-temperature gamma phase in steel, decomposes during cooling into such products as ferrite, cementite, pearlite, bainite or martensite, depending upon the cooling conditions and the composition of the steel. The individual characteristics of these products control the properties of a steel. As the method of cooling governs the formation of these products, the method of cooling also governs the chartacteristics of the resultant steel article formed.

In the usual hardening of steel, the desired transformation product is martensite, and the cooling rate must be sufficiently rapid to prevent austenite from decomposing into any of the other possible products, such as ferrite, cementite, pearlite and bainite. Fortunately, time is a major factor in the formation of these other products, and their formation can be suppressed by a sufficiently rapid cooling through the temperature ranges at which they characteristically form. Thus it is possible to supercool the austenite to the particular range where martensite is formed without incurring substantially any decomposition of the austenite into the other crystalline forms. The temperature at which transformation of austenite to martensite starts during cooling is referred to as the "M_s temperature."

Accompanying the transformation of the austenite structure to the martensite structure is approximately a 3%–4% increase in volume. Thus, steel parts which form the martensite crystalline structure upon heat hardening expand approximately 3%–4%. It is this change in volume which is used to produce the unique results attained with the invention. The temperature at which expansion commences (the M_s temperature) can

be regulated. By establishing the desired M_s relationship between the interior and surface regions of a part, the interior can be expanded before the exterior. By thus regulating the relative time and location of expansion, a predetermined stress distribution can be obtained during the hardening.

The M_s temperature is dependent upon the proportion of alloying element which is actually dissolved in the austenite rather than that which is totally present; the greater the proportion of the alloying element dissolved, the lower the M_s temperature. As previously indicated in connection with cementite, the proportion of the alloying element (carbon) dissolved in the austenite can be increased by heating. Hypereutectoid plain carbon steels, those having a carbon content greater than about 0.8% by weight, as well as certain hypereutectoid alloy steels, possess the unique characteristic of having a variable M_s temperature. The M_s temperature of these steels is predominantly dependent upon the temperature at which the steel was austenitized immediately prior to quenching, the M_s temperature being an inverse function of the austenitizing temperature. Some alloy steels are oppositely affected, and an increase in the austenitizing temperature causes an increase in the M_s temperature. Although the concepts of the invention might be used in connection with the latter type steel, it is the former type of steel which readily lends itself to the practice of the invention.

In its most useful application, the invention involves forming a compressive stress on the surface of a through-hardening steel part. This result is attained by establishing a suitable M_s relationship in which the M_s temperature of the interior is higher than the M_s temperature of the exterior, causing a sequential transformation of first the interior and then the exterior into martensite when the part is quenched.

The first modification of the invention is directed to forming the peculiar M_s relationship by means of a two-step austenitizing treatment. The part is initially through-heated at one austenitizing temperature and then heated for only a short time at a second austenitizing temperature. A hypereutectoid plain carbon steel or alloy steel, such as one containing nickel or chromium, is first heated throughout at a comparatively low austenitizing temperature. Then, before substantially any cooling, the steel is heated for only a short period of time at a comparatively high austenitizing temperature, the duration being sufficient to heat only a surface zone of the part to the higher temperature.

A typical example of an alloy steel having this unusual property is SAE 52100. This steel is approximately composed as follows: 0.95%–1.10% carbon; 0.25%–0.45% manganese; 0.025% maximum phosphorus; 0.025% maximum sulphur; 0.20%–0.35% silicon; 1.30%–1.60% chromium; all proportions by weight, and the balance iron.

The following example, employing SAE 52100 alloy steel, will serve to illustrate the variable M_s temperature of chromium alloy steels. When an SAE 52100 alloy steel (typically 1% carbon and 1.5% chromium) is heated at an austenitizing temperature of about 1450° F. for a sufficient duration of time, it becomes soft and ductile. Upon quenching the hot alloy, it is found that the M_s temperature is approximately 500° F. By similarly austenitizing the same steel at about 1900° F., the M_s temperature, upon quenching, is found to be approximately 250° F. This lowering effect on the M_s temperature through austenitization at an increased temperature is more particularly evidenced in steels containing an increased proportion of chromium. The effect is more pronounced in chromium steels containing more than about 1% by weight chromium.

By suitably quenching a part having two M_s temperatures, for example, in oil, so that there are no large temperature gradients formed during quenching, the interior of the part will reach its M_s temperature and start to transform into the hard and brittle martensite before the surface zone reaches its respective M_s temperature. In this sequence of transformation, the surface zone, which is still austenite and hence quite soft and ductile, readily accommodates the expansion of the interior as it transforms into martensite. As the surface yields by plastic deformation to the expanding interior, no residual stress results in the interior, as opposed to the residual compressive stress which normally results therein when expansion occurs against a hardened exterior.

However, when the surface zone transforms into the martensite structure, the accompanying expansion is not so readily accommodated by the already hardened interior. There is no plastic deformation of the interior regions since the interior has already transformed into the hard brittle martensite structure. Thus, the expansion of the surface during the austenite-martensite transformation results in imposing a residual compressive stress on the surface of the hardened steel part.

The depth of the residual compressive stress layer at the surface can be readily adjusted by varying the thickness of the surface layer which has been heated to the higher austenitizing temperature.

Since the surface portions ordinarily cool more rapidly than the underlying regions, the quenching rate should be comparatively slow, such as that afforded by an oil quench, so that the smallest possible temperature gradient can be maintained between the inner core and the surface. The small gradient is employed to permit the interior of the part to reach its M_s temperature and to substantially transform into the martensite structure before the surface layer reaches its M_s temperature and is hardened.

A residual compressive stress can be imposed in this manner on the surface of a metal part, such as a bearing ball, which is made of the chromium alloy steel SAE 52100. The bearing ball is heated for a sufficient duration of time to austenitize it completely throughout at a low austenitizing temperature of approximately 1450° F. The bearing ball is then immediately subjected to the increased temperature of approximately 1900° F. for a short period of time in order to austenitize only a surface portion thereof at the increased temperature. The duration of the second heating is determined primarily by the physical dimensions of the part and can vary upwardly from a fraction of a second, such as required for the second heating of small bearing balls.

After the two-step heat treatment the bearing ball is rapidly cooled by quenching in oil. The interior, having an M_s temperature of approximately 500° F. due to the lower austenitizing temperature, transforms into the martensite structure first. The accompanying expansion against the readily deformable outer surface imposes no residual stress on the interior. The subsequent expansive transformation of the outer layer of the ball at approximately 250° F., due to the higher austenitizing temperature, creates a resulting compressive stress thereon.

The oil quench is satisfactory for cooling smaller parts wherein the temperature gradient between the interior and surface portions can be maintained fairly small. For larger articles, an oil quench may prove to be unsatisfactory for maintaining the small gradient, and in such instances it is preferable to use a two-step quench. A two-step quench preferably involves initially immersing the hot part in a molten salt bath for the first step, the temperature thereof being between the two M_s temperatures. Water, oil, brine, etc., can be used for the second step of the quench. In this manner, the interior of relatively large articles can be substantially transformed into martensite structure before the exterior reaches its M_s temperature.

Although the austenitizing temperature is particularly effective in determining the M_s temperature of chromium alloy steels, the method of this invention is not specifically

limited thereto. This method can be effectively employed to impart a compressive stress on the surface of any steel which exhibits a sufficiently rapid lowering of its M_s temperature during the second heating step. The lowering of the M_s temperature must be sufficiently rapid so that the effect of the temperature gradient between the interior and surface portions is not destroyed.

Hypereutectoid plain carbon steels, for example, will exhibit a lower M_s temperature with an increased austenitizing temperature between the A_1 and the A_{cm} temperatures. A hypereutectoid plain carbon steel is preferably initially austenitized completely throughout at a temperature only slightly above the A_1 temperature. The second comparatively short heating would preferably be at about the A_{cm} temperature to obtain the maximum differential between the resultant M_s temperatures. The specific temperatures employed, duration of heating, type of quench, etc., of course, are variable; optimums for each type of steel, part size and configuration will vary.

A second modification of the invention involves preferentially dissolving an alloying element in a surface zone of a part using a single austenitizing temperature rather than the dual-temperature austenitizing treatment previously described. The second modification of the invention produces the particular M_s differential desired to establish a predetermined stress distribution by introducing a selected alloying element into the surface zone of the part from the environment used during austenitizing. In this modification, a part is concurrently austenitized while the alloying element is diffused from the austenitizing environment into the surface of the part. To impart a compressive stress at the surface of a part, a suitable alloying element is diffused into the surface, causing that area to have a lower M_s temperature than the balance of the part.

I have found that by austenitizing a through-hardening steel in the presence of a nitrogen-containing gas, such as ammonia, nitrogen diffuses into the surface of the part while it is concurrently being austenitized. When "nitrogenizing" a through-hardening steel part in this manner, nitrogen diffuses into the surface of the part and is dissolved in the solid solution of austenite, causing a reduction in the M_s temperature of that area containing the dissolved nitrogen. At the austenitizing temperature, the nitrogen dissolves, as opposed to forming the hard iron nitride particles common to conventional nitriding.

Bearing balls having a diameter up to about one-half inch, and races for these balls have been treated in accordance with this modification of the invention. Balls made of SAE 51100 alloy steel and races made of SAE 52100 alloy steel were similarly treated. The bearing element was initially subjected to an austenitizing temperature of approximately 1575° F. for approximately thirty minutes in a slightly reducing atmosphere containing approximately 5% ammonia. The bearing element was then quenched in oil from the austenitizing temperature to room temperature. It was thereafter further quenched to a temperature of approximately −100° F. to reduce the proportion of retained austenite present. Tempering does not destroy the results of the invention, and the elements are preferably tempered for approximately one hour at a temperature of about 300° F. The bearing elements were found to have a surface zone approximately 0.010 inch thick that was in a state of compression.

A deeper surface layer was imposed by using the following treatment. SAE 51100 and 52100 alloy steel bearing elements were austenitized for an hour at about 1575° F. in the above-described ammonia-containing atmosphere and oil-quenched to room temperature. These parts were then re-austenitized at about 1575° F. in the same ammonia-containing atmosphere for approximately thirty minutes, oil quenched to room temperature, quenched to about −100° F., and finally tempered for about an hour at about 300° F. The re-austenitizing produces a finer grain size and may therefore be a preferred process in certain instances. The bearing elements resulting had a compressively stressed surface layer of about 0.015 inch in depth.

This modification of the invention is especially useful in that it provides a highly consistent means of forming a specific predetermined stress distribution under commercial production conditions. It is to be understood that any alloying element which will adequately reduce the M_s temperature and which can be analogously diffused to a sufficient depth can be used. Austenitizing in an atmosphere containing chromic chloride, nickel, carbonyl, etc., may provide satisfactory results in certain instances. However, this modification of the invention can be most effectively commercially practiced employing nitrogen. Nitrogen radically affects the M_s temperature of a through-hardening steel and will diffuse quite deeply into the surface of such a steel part.

The invention contemplates still a third means of establishing the peculiar M_s relationship which is characteristic of the invention. The third modification of the invention encompasses initially applying an alloying element to a selected area of the part before it is heat treated. The part is then austenitized, at which time the previously applied alloying element is dissolved in the austenite of a selected area of the part. The dissolving of the alloying element in the selected area, as hereinbefore mentioned, produces a lowering the M_s temperature of that area.

More specifically, this modification of the invention concerns initially treating a through-hardening steel part to apply the alloying element to the surface of the part. The alloying element may be applied as a coating on the surface, or the surface may be impregnated with the alloying element. An alloying element, such as chromium or nickel, could be electro-deposited onto the surface of the part and subsequently diffused into the surface during the austenitizing heat treatment. In this manner, only a single austenitizing temperature need be used since only a surface zone of the part would be affected by the previously applied alloying element. The duration of the austenitizing treatment would determine, in part, the depth to which the alloying element would diffuse and, consequently, the deph of the surface zone which would be affected; hence, the zone put under compression when the part is subequently quenched.

The surface of a through-hardening steel part is impregnated with an M_s affecting alloying elment when it is conventionally nitrided, such as immersion in a fused salt bath or the like. In my method, the discreet particles of iron nitride formed in the conventional nitriding would be dissolved during the subsequent austenitizing treatment and produce effects analogous to those obtained in accordance with the second modification of the invention. A through-hardening steel could also be boronized by electrolysis in fused borax prior to heat treatment thereof in my manner. The effects produced are analogous to those obtained by conventionally nitriding such a steel prior to heat treatment thereof in my manner.

A rolling contact bearing element formed of SAE 51100 or SAE 52100 can be treated in the following manner. The element is treated for five hours at about 975° F. in approximately a 15%–25% dissociated ammonia atmosphere, and immediately thereafter at about 1050° F. for an additional five hours in approximately a 83%–86% dissociated ammonia atmosphere. With or without an intermediate cooling, the elements are subsequently austenitized at about 1550° F. for about twenty minutes, quenched to room temperature, then quenched to about −110° F. in a Dry Ice-acetone mixture. It is then tempered for about thirty minutes at 300° F. The resulting element made in this manner exhibits a compressively stressed zone extending to a depth of about 0.045 inch.

The above-mentioned second and third modifications of the invention provide the most suitable commercial

production means of attaining the benefits of the invention. The compressively stressed surface layer can be formed so deeply with the invention that even the usual surface grinding used in finishing rolling contact bearing elements only removes a small portion of the compressively stressed surface region. Bearing balls up to about one-half inch can be made having compressively stressed surface regions greater than about 0.01 inch and race elements greater than about 0.005 inch.

It is to be understood that although the invention has been described in connection with certain specific examples therefor, it is not intended that the invention be limited thereby, except as defined in the appended claims.

I claim:

1. A finished rolling contact bearing rolling element having a diameter up to about one-half inch, said element being formed of a through-hardening steel, said element being hardened to generally the same hardness substantially throughout its cross section, and a compressively stressed surface zone on said element extending to a depth greater than about 0.010 inch.

2. A finished rolling contact bearing race element formed of a through-hardening steel, said element being hardened to generally the same hardness substantially throughout its cross section, and a compressively stressed surface zone on said element extending to a depth greater than about 0.005 inch.

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