GEAR FUNDAMENTALS

Gear Hardness Technology

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Introduction:

In a very general sense, increasing the hardness of a steel gear increases the strength of the gear. However, for each process there is a limit to its effectiveness. This article contains background information on each of the processes covered. In each section what is desired and what is achievable is discussed. Typical processes are presented along with comments on variables which affect the result. By reviewing the capabilities and processes, it is possible to determine the limits to each process.

Throughout this article several hardness scales are mentioned. The abbreviations for these scales are as follows:

BHN - Brinell hardness number
KHN - Knoop hardness number
HRC - Rockwell "C" scale
HV - Vickers hardness number

Preliminary Heat Treatment Processes

There are several heat treatments performed during the manufacturing process which are intended to condition the metal for manufacturing. Since these are essential processes they will be described briefly.

Annealing. Annealing is a process in which a part is heated and then slowly cooled in the furnace to 600°F (316°C). Full annealing involves heating to a temperature above the upper critical (A_3 point). This will result in softening the part and improving the machinability. Intercritical annealing involves heating the part to a temperature above the A_1 point, but below the A_3 point. Finally there is subcritical annealing, which heats the part to just below the first transformation temperature (A_1), as in tempering, and slow-cools it, just as in full annealing. Subcritical annealing is often done to stabilize the structure prior to carburizing.

Normalizing. Normalizing is a process which involves heating the part to above the upper critical as in annealing, but it is cooled outside the furnace in still or agitated air. Normalizing is done to relieve residual stresses in a gear blank and for dimensional stability. A normalized part is very machinable, but will be harder than if it were annealed.

Stress Relieving. Stress relieving is heating to below the lower transformation temperature, as in tempering, and cooling in air. This is done primarily to relieve internal stresses. This process is sometimes called process annealing.

Through Hardening

Through hardening refers to heat treatment methods which do not produce a case. This term does not imply that the hardness is uniform throughout the gear tooth. Since the outside of a gear is cooled faster than the inside, there will be a gradient in the hardness. The achievable hardness is based on the amount of carbon in the steel. The depth of hardness depends on the hardenability of the steel.

For the purposes of this article, we will concentrate on the quench and temper process. This method is used to obtain the final core properties of the material for gears which are either cased or not cased. When this process is used to develop the core properties for nitrided gears, it is done prior to the nitriding cycle. When it is used to harden a carburized gear, it is done after the gear has been carburized. For gears which are not cased, the load carrying capacity of a gear is dependent on the core hardness of the material. (The capacity of case-hardened gears is primarily dependent on case hardness). It is generally accepted to use the hardness value measured at the root diameter in the center of the tooth when making comparisons.

Depending on the loading the gear must handle,

Table 1 - Common Through Hardened Gear Steels

Steel	C	Mn	S max	P max	Si	Cr	Mo	Ni
AISI 1045	0.45	0.75	0.050	0.040	—	—	—	—
AISI 4130	0.30	0.50	0.040	0.035	0.30	0.95	0.20	—
AISI 4140	0.40	0.90	0.040	0.035	0.30	0.95	0.20	—
AISI 4145	0.45	0.90	0.040	0.035	0.30	0.95	0.20	—
AISI 4340	0.40	0.70	0.040	0.035	0.30	0.80	0.25	1.83
AISI 8640	0.40	0.90	0.040	0.035	0.30	0.50	0.20	0.55

Table 2 - Approximate Quenching Behavior of 4140 and 4340 Steel

Quench Effectiveness	Quench time to 500°F, seconds 4140	4340	Structure to be expected
A	25	80	Excellent (over 90% martensite)
B	80	200	Reasonably good (martensite and some other transformation products)
C	200	600	Less good, but may be acceptable (martensite, bainite, pearlite, and perhaps some free ferrite)
D	300	1000	Poor, usually not acceptable for high performance parts (low in martensite, with much bainite, pearlite, and free ferrite)
F	800	7000	Very poor, usually not acceptable (pearlite, free ferrite, some bainite, maybe some martensite)

Notes:

1. A structure not quenched out to full martensite will not be fixed up by tempering.

2. Material in the "F" situation could be tempered to meet about 300 Brinell minimum. (The "as quenched" hardness would be above 300 HB.)

3. Material in the "F" situation would probably fail to meet Charpy V notch and ductility requirements normally expected for a good steel. In addition, the fatigue strength would be poor.

4. Poor quenching results can result from things like an improper prior structure or the wrong austenitizing temperature. (A slow quench is not the only reason for a poor structure.)

it is often necessary to increase the hardness of the steel. According to AGMA standards,[1] a gear with a hardness of 400 BHN, which has a design life of 10^7 cycles, can handle as much as 20% more load than a gear which is hardened to 300 BHN. For hardnesses above 400 BHN the capacity increases with respect to pitting resistance, but the capacity decreases with respect to bending strength, which deteriorates because the tooth becomes brittle.

Though a great deal of attention is given to the hardness of the material, it is important to understand that the microstructure, upon which the hardness depends, is what really matters. Although in-depth discussion of microstructure is beyond the scope of this article, it is worth mentioning that the degree of martensitic structure is one of the prime indicators of a material's quality. AGMA 2004-B89[2] does a good job of identifying other microstructural aspects that must be considered.

Unlike most gear heat treatments, through hardening is a process which can be performed either prior to or after the gear teeth are cut. The hardness is achieved by heating the material to the austenitic range (usually to about 1500-1600°F) and than quenching and tempering. For situations when the teeth are cut after the material has been hardened, machinability becomes a consideration in determining the hardness. For the most part, conventional gear cutting processes (hobbing, shaping, or milling) are capable of cutting materials with hardnesses of up to 400 BHN. Though 400 BHN is machinable, gear teeth are much easier to machine when the hardness is lower. There will be distortion if the hardening is done after the teeth are cut. The teeth may have to be finish-machined to achieve the required accuracy.

The Process. To harden a part by this process, the part is heated to the austenitic range, a temperature that varies, depending on the carbon and alloy content, within the range of about 1500-1600°F (815-870°C). In this state the steel becomes austenite, which is a term for the solid solution of carbon in fcc iron.[3] Then the part is rapidly quenched in oil (or sometimes water) to transform the austenite into martensite. If the quench is too slow, the structure will not be fully transformed to martensite. The resulting microstructure will then contain what are called transformation products, such as ferrite, bainite, pearlite, and cementite. The properties of hardness, toughness, ductility, and strength are dependent on the transformation products which are present.

The rate of cooling which must be achieved to properly transform the steel to martensite and minimize the percentage of transformation products is dependent on the chemistry of the alloy being used. The amount and type of alloying elements in the steel determine its hardenability.

Hardenability is a measure of the relative depth to which hardness is achieved for a given quench rate and section thickness. In other words, a material with a high hardenability, which is quenched at the same rate as a part of the same size, but with low hardenability, will have hard material deeper.

The alloying elements which have an impact on the hardenability of the steel are manganese, chromium, nickel, and molybdenum. Table 1 is a table showing several alloy steels which are commonly used for through hardened gears. A material such as AISI 4140 is considered to be a low alloy steel and has rather poor hardenability. A material such as AISI 4340 is considered to be rich alloy steel and has much better hardenability.

Once the part has been quenched, it needs to be

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Table 3 - Approximate Carbon Content to Develop Maximum Hardness in Carburized Case of Nickel Alloy Steels

Steel Type	Quenching Cycle	Carburized Case: Carbon Content for Max. Hardness, %	Carburized Case: Maximum Rockwell C Hardness
2315	DQ	0.80	63
2515	DQ	0.80	62
3120	DQ	0.90	65
4320	DQ	0.90	67
4320	RH	0.85	66.5
Krupp[b]	DQ	0.60	61
Krupp[b]	RH	0.60	63
4620	DQ	0.80	65
4620	RH	0.85	65
4626	DQ	0.85	65
4817	DQ	0.70	65
4817 (+0.23% Cr)	DQ	0.70	65
5 Ni-0.25 Mo (SAE EX-1)	DQ	0.70	63
8620	DQ	0.90	65
8620	RH	0.87	65
9310	DQ	0.80	63.5
9310	RH	0.80	65

tempered to reduce the brittleness and toughen the steel, since quenched martensite is hard, but also brittle. Tempering through hardened parts is generally done at 400 to 1000°F (205 to 450°C) for a period of one or more hours, depending on the size of the gear. Higher tempering temperatures increase the toughness, but also lower the hardness.

Limits on the Process. The quench and temper process is limited only by the size of furnaces and quench tanks available. Today, this is as large as several meters. From a practical standpoint, the major limitation comes from the ability to quench gears fast enough to obtain an acceptable microstructure. In some cases, particularly with lean alloy steels, it is just impossible to quench large gears fast enough to obtain an acceptable microstructure.

Table 2 shows the comparison of time required to achieve different levels of metallurgical quality between AISI 4140, a lean alloy steel with poor hardenability, and AISI 4340, a rich alloy steel. In order to compare the hardenability of a material, end quench (Jominy) values are widely used as an indicator of a steel's hardenability.

Since the quench is so critical to the resulting microstructure, it is necessary to verify the results with an appropriate sample. Too often a test coupon is used which is quite small as compared to the gear's sections. The small coupon is rapidly quenched, producing good results, while the cooling rate in the actual part is too slow and produces a poor result. (and this is where it needs to be good).

Carburizing

As mentioned above, the alloying elements in a steel have an effect on the hardenability of the material. In earlier years, it was known that increasing the hardness of the material increased the strength of the gear. This relationship held true up to a hardness of about 40 HRC. At hardnesses above this level, the material become brittle and the gears failed in breakage faster than gears with lower hardnesses. The idea behind case hardening is to keep the core of the tooth at a level which would not be too much beyond 40 HRC, to avoid tooth breakage, but to harden the outer surface, or "case," to increase pitting resistance.

Of the methods for case hardening gears, carburizing is the process which is most often used. The idea behind carburizing is to start with a gear blank which has a low amount of carbon in the base material, and then to add carbon to the outer surface. A properly carburized gear will handle between 30 and 50% more load than a through hardened gear. Case hardening is done primarily to increase the pitting resistance of tooth surface. However, because of the residual compressive stress which is present in the case after carburizing, there is also an increase in bending strength.

The Process. Carburized gears achieve hardness by quenching as do through hardened gears. The difference is that a carburized gear has an increased amount of carbon in the surface, causing this area to become a hard case after quenching, while the lower carbon core reaches a lower hardness.

Carburizing steels are alloy steels with approximately 10 to 20 points of carbon. The process involves heating the gears to a relatively high temperature and then rapidly quenching to obtain the hardness. This heating and quenching will result in distortion of the gear blank. The amount of distortion will depend on the mass and configuration of the gear and can vary from a slight amount to so much that the gear must be scrapped. Since the hard case is relatively thin, grinding to restore tooth accuracy may be so deep on one tooth side that the remaining case is too thin.

Due to the propensity to distort, it is recommended to stress relieve the gear blank before machining and, possibly, again one or more times before carburizing. In really critical jobs, it may be necessary to put the blanks through a "mock" carburizing cycle. A mock carburizing cycle exposes the blank to the temperatures and cycles it will see, and the blank still remains machinable, since no diffusion of carbon takes place.

The actual carburizing is done by heating the gear blanks to above the critical temperature and exposing the surfaces to carbon. The carbon can be a solid, liquid, or gas. As most carburizing is gas carburizing, the discussion here deals with this method. The carburizing is done in a furnace which contains a carbon atmosphere, such as natural gas. Above the critical temperature, the carbon diffuses into the material on the surface. The amount of carbon in the atmosphere must be controlled. Too much will cause carbide networks to form at the tooth tips and too little will produce shallow case depths, particularly in the root areas. The amount is measured in terms of percent and is referred to as the carbon potential. The optimum carbon potential which leads to the highest surface hardness will vary, depending on the alloy being used. Table 3 shows the carbon potentials which give the optimum results for several alloy steels.

When very deep cases are needed, the carbon potential is held at a slightly higher level (up to 1.1% carbon) in an initial portion of the carburizing cycle to give a boost to the diffusion.

The temperature in the furnace, the time in the furnace, and the carbon potential are variables which have an impact on the case depth. The alloy content does not have an influence on carbon diffusion. Fig. 1 is a chart showing the relation between temperature and time and case depth.

It is possible to directly quench parts from the carburizing temperature. This method minimizes the distortion, but does not result in a microstructure which is capable of long life (10^8 to 10^9 cycles). The case often contains excessive carbides and retained austenite. The core structure is unrefined. This method is used in the automotive field, since automotive gears rarely see more than 10^8 cycles. Also, since the production is high, and the facilities and tooling used for automotive gearing are highly developed, it is possible to obtain acceptable results.

Applications which require a high level of material quality are cooled and then reheated prior to quenching. In some cases it is also necessary to deep freeze the gears so that transformation to martensite is complete.

Limits to the Process. When the specifications are correctly chosen by the engineer and properly achieved by the heat treater, a carburized gear will be able to resist pitting and also have good bending strength. In order to achieve this capability, three things need to be in good order: 1) The surface and core hardness need to be correct; 2) The case depth needs to be deep enough in two areas and not too deep in one other place; and 3) the microstructure needs to be good enough for the level of loading.

1. Hardness. The required surface and core hardness should be selected based on the application. Depending on the alloy used, the hardness can be as high as 760 KHN (62 HRC). Long life power gears which see high loads for something like 10^9 to 10^{10} cycles need to be up to about 730 KHN (60 HRC), and the core hardness should be in the range of 360 to 400 KHN (35 to 40 HRC). Gears which are subjected to shock loading and do not see too many cycles may be better off with a surface hardness which has been tempered back to 55 HRC in order to gain more toughness.

Once the desired hardness has been determined, the drawing or specifications need to be specific as to what is required.[4] For instance, when hardness is checked on a mounted tooth sample, it is typically checked by taking a microhardness traverse. The microhardness is taken either by Knoop, a method using a 500- or 1000-gram load, or sometimes Vickers, using a kg load. Yet nearly all drawings specify surface and core hardness in values of Rockwell "C", a method which uses a 150 kg load. For this reason, a conversion must be made from either the Knoop number or the Vickers number to determine whether the part met the specified Rockwell number. Conversion is not simply a mathematical relationship. Since the structure and cold working properties vary for different materials and hardnesses,

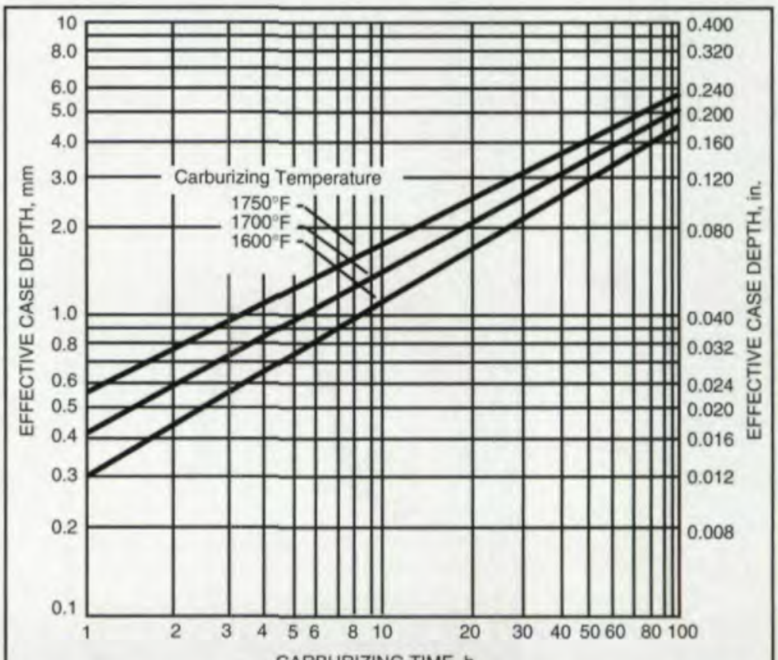


Fig. 1 - Nominal time and temperature requirements for different case depths.

The 150 kg load used for a Rockwell "C" check is inappropriate to check the hardness close to the surface or elsewhere in the case. This is because the size of the indention made by the 150 kg load homogenizes the conditions over a large area. This can mask local deficiencies.

Since it is appropriate to check a part with a microhardness method, the drawing and specifications should state the hardness number terms of a microhardness method. The equivalent Rockwell value could also be noted on the drawing for reference. An example of what is meant is shown below:

Case Hardness: 58-62 HRC
(Poor Practice)

Case Hardness: 690-776 KHN (58-62 HRC, ref)
(Good Practice)

2. Case Depth. Fig. 2 shows the shape of a typical carburized case. Note that the thickness at the tip is thicker than the case at the pitch diameter, while the case at the root fillet is thinner than at the pitch diameter. Though this shape is typical, most drawings only specify one value for case depth. Many drawings also fail to be clear as to how the case depth should be determined.

The effective case depth is usually defined as the depth of hardness to 50 HRC. Since there is room for misunderstanding this statement, a microhardness value similar to the one below would also appear on the drawing of specification:

Effective Case Depth: Determined by 542 KHN cutoff point (50 HRC, ref.)

The case depth at the pitch line (and in the dedendum just below the pitch line) is critical, since this area is most susceptible to pitting. The case depth should be deep enough for the case-to-core interface to be deep enough to avoid cracking due to subsurface shear stresses. The depth of case needs to be determined by the transmitted load and not by any relationship to the diametral pitch. A minimum value of case depth at the pitch line can be determined from the following relationship, which is based on the Hertzian band width:

$$h_{ec} = \frac{s_c d \sin o_t m_g/(m_g+1)}{7.0 \times 10^8 \cos u_b}$$

where,

s_c = maximum contact stress in the region of 106 - 107 cycles

d = pinion pitch diameter, in.

o_t = pressure angle, transverse

u_b = base helix angle

m_G = tooth ratio

For situations where the ratio is high and the lowest point of single tooth is deep in the dedendum, the case depth may also need to be specified at a point in this region.

As mentioned above, carburized gear teeth gain in bending stress because of the residual stress in the case. This gain can only be realized if the case depth in the critical bending area near the root is deep enough. A minimum value for this case depth can be based on the diametral pitch, since the bending stress is related to the tooth size. If the teeth are sized properly for bending stress, then the following relationship should be valid for effective case in the root:

$$h_{et} = 0.6/\text{normal diametral pitch}$$

Such a value should appear on the drawing.

Many gears used today are operating at pressure angles of 22.5 to 25° Also, it is very common for designs to make the pinion "long addendum." Though there are many advantages to these tooth forms, the drawback is that this tends to make the top land quite narrow. To avoid the risk of tooth tips breaking off, the maximum case depth at the tooth tip should be limited to .40 divided by the normal diametral pitch.

Getting the case depth right at all these points becomes unmanageable when the teeth are very small. Twenty-pitch teeth are difficult and 28-pitch is the practical limit. With extreme care, finer pitches can be done. The difficulty in getting the case depth right on small gears is that the portion of time in the carburizing cycle during which the temperature is not stable (coming up to temperature and cooling) is large, compared to the overall cycle. Since the temperature is a variable affecting carbon diffusion, it is hard to

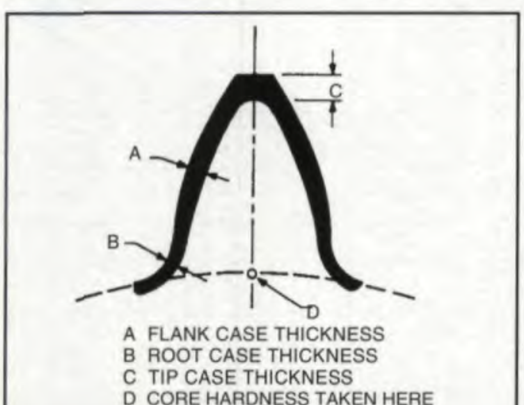
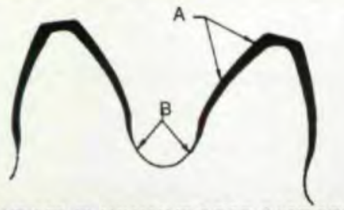


Fig. 2 - Carburized case pattern. Shaded area is all 510 HV (50 HRC) or higher in hardness. Unshaded area is less than 510 HV (50 HRC).



A. TIP AND MID-FLANK HAVE GOOD CASE DEPTH.
B. ROOT FILLET AREA WITH ESSENTIALLY NO CASE.

Fig. 3 - Large carburized gear teeth having inadequate case depth in root fillet area because of heat soak back.

really know the amount of carbon entering the case during the heating and cooling portions of the cycle. Another variable, carbon potential, may not be set just right. On longer cycles, adjustments are made periodically to achieve good results. On short cycles, there is not much time to adjust if things are not just right in the beginning. Because of the number of variables, there is a very high possibility that something could go wrong.

The other problem comes from heat treating large gears. There is the obvious limitation in size due to the physical size of carburizing retorts and quench tanks. There is also a limitation which is more subtle. The transformation of the material to martensite during the quench is dependent on the cooling rate of the steel and its hardenability. When parts are large, it is extremely difficult to quench effectively enough to avoid heat soak back from the gear body. Soak back can prevent critical areas of the root from reaching the necessary hardness. Fig. 3 shows the case of a large tooth which suffered from heat soak back. The case depth at the pitch line was "as needed." A test bar with an appropriate diameter was used in the cycle. The case depth at the pitch line was in good agreement with the test bar; yet only a check on a tooth sample was able to reveal the actual problems.

3. Microstructure. Hardness alone is not enough to determine the strength of a gear. As was hinted above, hardness is only one of the properties that is determined by microstructure. In general, the microstructure is responsible for many of the important mechanical properties of a steel.

Fig. 4 shows some examples of the microstructure in a good carburized gear. Both case and core are relatively free of transformation products, and the structure of the base material is essentially tempered martensite.

Fig. 5, on the other hand, shows some undesirable microstructure variations. Although the case has a background of tempered martensite, there is a large percentage of transformation products in the structure. The core is in much worse condition, with the structure being almost all free ferrite and other undesirable transformation products.

It is important to realize that microstructure can vary from location to location within a gear. Because of this, it is imperative that the microstructure, along with hardness and case depth, be checked at several locations.

For case hardened gearing it is good practice to check the case microstructure at several places. It is recommended that this be done at the tooth tip, mid-tooth height, and the root fillet. These are the locations where microhardness traverses are done.

As mentioned above, core structure is generally studied near the root diameter and in the center of a tooth.

Nitriding

Nitriding, like other case hardening techniques, has the objective of increasing surface hardness of a given workpiece. Although nitriding is not suitable for all applications, it has proved to be a viable alternative in many manufacturing situations and deserves discussion.

Despite the fact that there are several nitriding methods available to the gear manufacturer, they all share the following characteristics:

•All nitriding processes require a source of nitrogen and a method of dissociating nitrogen radicals (ions) from the source.

•All nitriding processes rely on the ability of nitrogen to form stable nitrides with the elements of the stock metal.

•Alloying elements, such as aluminum, chromium, vanadium, and molybdenum, in proper amounts, will tend to enhance the success of nitriding processes.

•All steels are nitrided below transformation temperatures, thus quenching is not required. Conventional gas nitriding occurs within the temperature range of 925-1050°F (495-565°C). Ionitriding occurs within the temperate range of 660-1075°F (350-580°C).

•Case hardness achieved during nitriding is dependent upon the core hardness achieved before nitriding. This is especially true for certain alloy steels like AISI 4340, a typical gear steel used for nitrided applications.

•Surface conditions, such as cleanliness, can have marked effects on the nitriding process.

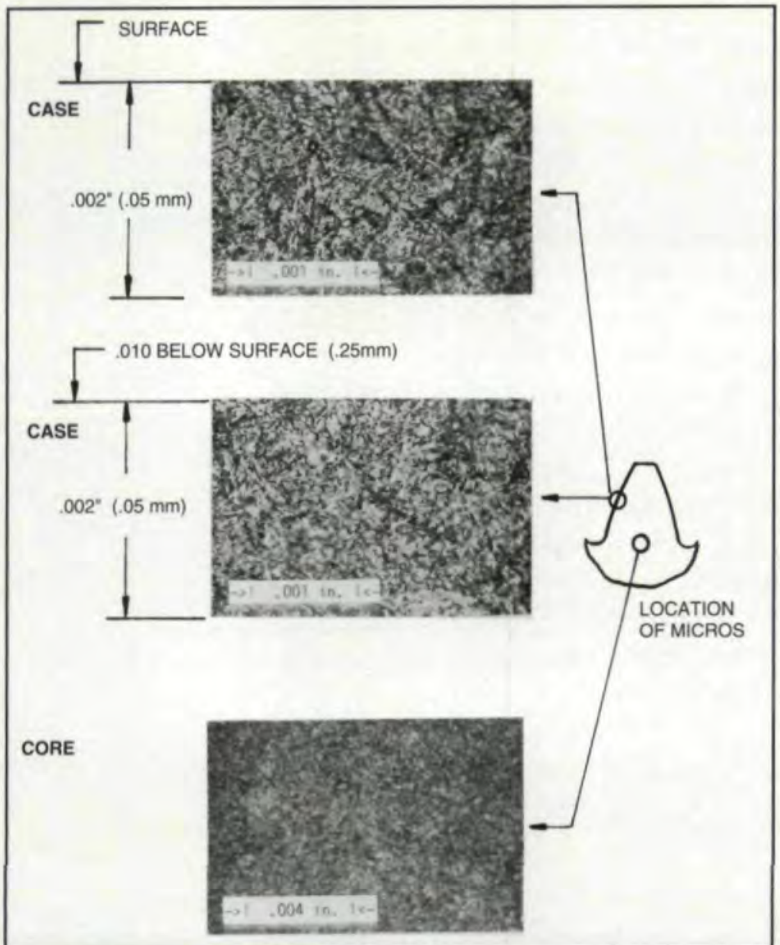


Fig. 4 - Desirable variations in carburized structure (case, core).

As is hinted above, there are many variables that can affect the success of the nitriding operation.

Although many steels can benefit from nitriding, including stainless types, much care should be taken when choosing a gear material. Certain steels are more suitable for nitrided application than others. Nitrides formed with various alloying elements tend to differ in mechanical properties, and the complexity of the situation is such that experience is often the only useful guide. Typical gear steels that are nitrided successfully are shown in Table 4.

After a good material choice has been made, pre-nitride heat treatment is the next step to assure the success of nitriding processes. Hardening and tempering is essential for all hardenable steels, and this relates to the dependence of case hardness on core hardness and microstructure.

The general recommendation is that the steel be treated to the condition of tempered martensite and that the tempering temperature be at least 50°F (30°C) higher than the nitriding temperature.[5] This helps prevent loss of hardness and decarburization, which leads to case embrittlement.

Because nitriding processes typically take place below transformation temperatures, very little distortion occurs in comparison to other common case hardening processes. As a result, gears are usually cut to size before nitriding. Stress relieving of machined parts is usually recommended and surface cleanliness is always required. All scale from prior procedures should be removed before nitriding, and all parts should be degreased. Vapor degreasing is the most common method.

Of the various methods of nitriding, there are three important processes to consider. The first two are gas nitriding processes, and the third process, ion nitriding, is an extension of conventional gas nitriding procedures that utilizes plasma discharge technology. Although several other methods have been developed over the years, many have fallen into obsolescence due to use and/or production of toxic chemicals, such as cyanide.

The Processes

Gas Nitriding - Single & Double Stage Processes. Gas nitriding involves dissociation of a nitrogenous gas, such as anhydrous ammonia, to produce nitrogen ions which can diffuse into the surface of the workpiece. These ions, in turn, form complex nitrides as affected steel surfaces, thereby increasing surface hardness. The process can be accomplished in one or two stages.

A typical single stage process goes as follows:

1. Hardening and tempering and machining of gear blank in various orders.
2. Stress relieving of machined gear.
3. Cleaning of machined gear and other surface preparation if necessary. Other surface preparation can include roughing of finish-machined surfaces and mashing of surfaces that are not to be nitrided.
4. Insert gear in nitriding furnace, bring to nitriding temperature and nitride.
5. Cooling cycle.
6. Removal of masking and optional final machining process, depending on white layer requirements.

The gas nitride cycle time will vary depending on cycle parameters, such as flow rate, pressure, temperature, required case depth, and required case hardness.

Typical single stage gas nitriding processes take place at temperatures between 925-975°F (495-525°C). The ammonia will dissociate upon contact with the hot steel surfaces and recommended dissociation rates for the single stage process are between 15 and 30%. This process produces a brittle nitride compound layer at the case surface, and it is termed the "white layer" because it etches out white in a micrograph. Typical thicknesses of the white layer are below .001" (.025mm).

Because the white layer is a brittle structure, it is often required that its thickness be minimized.

Although one can grind the brittle white layer off after the nitriding process, this is a costly operation that is not always practical. There is no guarantee that grinding will be uniform (especially in the root fillet region) and, if it is, that the case will be uniform at different locations on the gear tooth. A tooth that has required hardness and case depth at the O.D. will not always have the required hardness and case depth at the form diameter or other locations. Grinding of a uniform amount of stock can lead to imbalance of the residual stress pattern. For these reasons, control of the white layer is a concern when nitriding gears.

The double stage gas nitriding process has the advantage of producing less white layer than the single stage process. It is also a more efficient process. The double stage process uses two nitriding cycles with the first being similar to the single stage process, except for duration. Normally the gear is first nitrided at a 15 to 30% dissociation rate for 4 to 12 hours. The second stage of nitriding then takes place at a temperature equal to or greater than the first stage, but with a dissociation rate of 80 to 85%. To get this dissociation rate an external dissociator is required. Some typical double stage cycles and achieved case hardnesses and depths are shown in Table 5.

Ionitriding. Ionitriding, as mentioned above, is an extension of conventional gas nitriding which uses the methods of plasma discharge physics to deliver nitrogen ions to the workpiece surface. The general method involves use of high voltage electric energy in a vacuum vessel containing nitrogen gas. The mechanism which cracks the nitrogen gas into monatomic nitrogen ions is similar to that which takes place in a fluorescent lamp. Electrical connections charge the workpiece and the nitriding vessel so that the workpiece becomes a cathode, and the vacuum vessel becomes an anode. Electrons accelerating towards the anode impact with the diatomic nitrogen gas and dissociate the gas into nitrogen ions. These ions, in turn, accelerate towards the cathode and since the cathode is the workpiece, the nitrogen ions actually impinge upon the workpiece.

Limits on the Process. The primary advantage that nitriding has over other case hardening techniques that involve quenching processes is the small comparative distortion of treated parts. Geometry and tolerances of certain gears make nitriding the only viable case hardening alternative. Ring gears and other gearing that have thin-walled sections that would distort too much during a quenching process are often nitrided. In addition, nitriding is used sometimes when the size of a gear makes quench distortion and the subsequent grinding problems unacceptable.

Reproducibility of the nitriding process is another advantage it has over other common case hardening methods. Given parts of identical geometry and similar metallurgical quality and using identical nitriding cycles, case depth, case hardness, and case composition will be comparable. In addition, parts between batches will distort in exactly the same way. This means that machining can be biased before nitriding to compensate for expected distortions.

Ionitriding rates are better in both amount of distortion and reproducibility than conventional gas nitriding. Much of this has to do with the degree to which each of these processes can be controlled. Conventional gas nitriding, though a very controllable process, does not lend itself as well to pro-

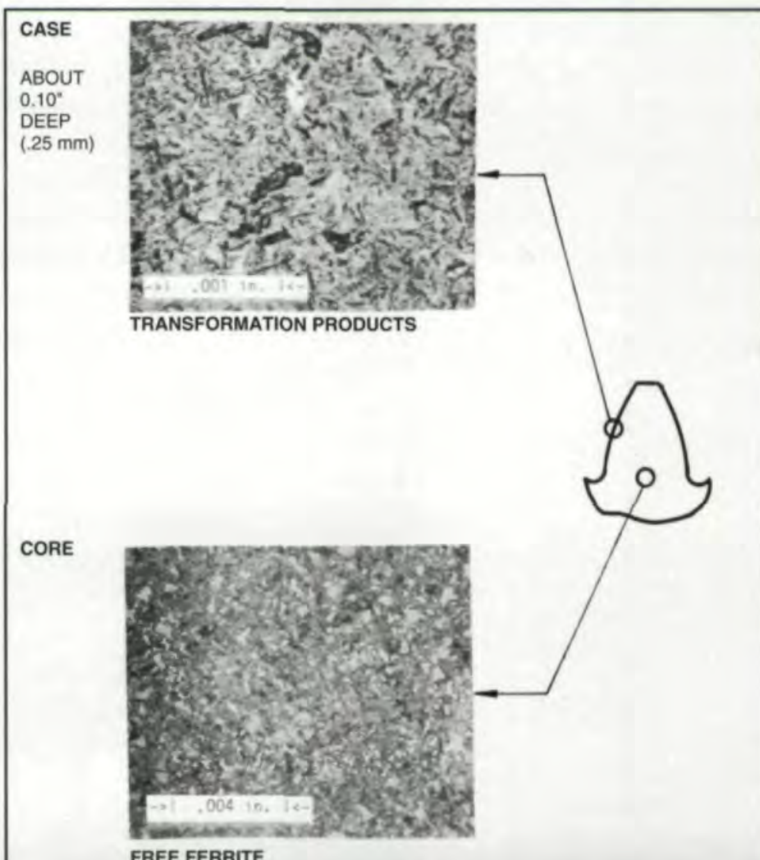


Fig. 5 - Undesirable carburized structure (case, core)

Table 4 - Common Nitriding Gear Steels

Steel	C	Mn	Si	Cr	Al	Mo	Ni
Nitralloy 135M	0.41	0.55	0.30	1.60	1.00	0.35	—
Nitralloy N	0.23	0.55	0.30	1.15	1.00	0.25	3.00
AISI 4340	0.40	0.70	0.30	0.80	—	0.25	1.83
AISI 4140	0.40	0.90	0.30	0.95	—	0.20	—
31 CrMoV 9	0.30	0.55	0.30	2.50	—	0.20	—

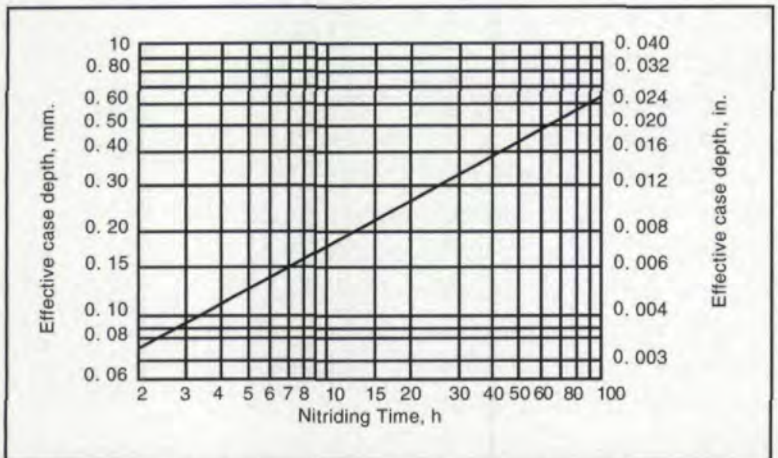


Fig. 6 - Nominal time required for different nitride case depths. Note: Under the most favorable conditions, about 40% more case depth is possible.

cess control. One example of this is the fact that the thickness and composition of the compound (white) layer can be successfully and repeatedly controlled when ionitriding. One even has the option of requiring no white layer. As controversy exists over whether the brittle compound layer is an initiation site for cracking, this is an attractive option.

Of the disadvantages of the nitriding process, the main one is that it takes much longer than other common case hardening techniques. The diffusion rate being exponentially dependent on temperature, nitriding takes place much slower than typical case carburizing or induction hardening procedures. The unpleasant side effect of this time dependence is that practical nitrided case depths are shallower than other case depths. Fig. 6 is a chart showing typical nominal gas nitriding times for different case depths.

Other disadvantages include the dependence on and sensitivity of the achievable case hardness to the metallurgy of the base material, and the tendency of nitrided cases to be less ductile than other cases. Lower case hardnesses and less ductility, in general, result in lower allowable stresses for nitrided gears.

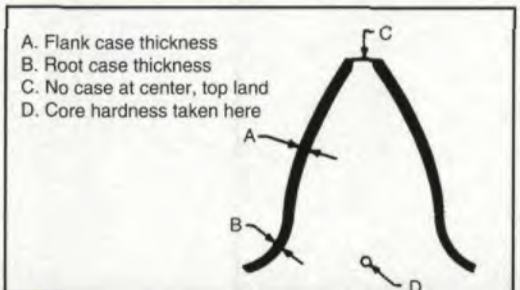


Fig. 7 - Induction hardened case pattern by the *scanning method of tooth heating.*

Carbonitriding (Gaseous). Carbonitriding as a process is related to both carburizing and nitriding. Typically carried out within the temperature range of 1550 to 1650°F (845-900°C), carbonitriding utilizes temperatures above transformation temperatures. Diffusion of carbon from a carbonaceous atmosphere is part of the process as well. However, like nitriding, diffusion of nitrogen is also involved. This is usually accomplished by addition of anhydrous ammonia to the carbon atmosphere.

The advantages of this process are related to the fact that it is essentially a compromise between the two parent processes. Taking place at lower temperatures than straight carburizing, the process has reduced distortion. Having a more favorable diffusion rate, the process produces a case faster than straight nitriding.

Carbonitriding is used for small gears with finer pitches than could be controllably carburized.

Induction Hardening. Induction hardening is a heat treating process which uses alternating current to heat the surfaces of a gear tooth. The area is then quenched resulting in an increase in hardness of the heated area. The hardness pattern which is achieved varies, depending on the type and shape of the inductor. An inductor which is circumferential will harden the teeth from the tips downward. While this pattern may be acceptable for splines and some gearing, heavily loaded gears need a hardness pattern which is more like a carburized case. This type of induction hardening is known as contour hardening. A typical case for a contour induction hardened tooth is shown in Fig. 7. Also shown in this figure are the three critical places to check the case on an induction hardened part. The discussion in this section deals with gears which are hardened by this method.

Since the area below the surface remains cool, it acts as a fixture minimizing distortion. In order to achieve high surface hardness, an induction hardening material usually has from 40 to 50 points of carbon. The resulting surface hardness is generally 53 to 58 HRC. The core hardness is developed by quenching and tempering the blank prior to the induction hardening.

Table 5 - Typical Double Stage Gas Nitriding Cycles					
Steel	Cycle	Effective Case Depth (Rc 50)	Maximum White Layer	Minimum Surface Hardness	Core Hardness
Nitralloy 135M	10 hr @ 975°F 28% diss. 50 hr @ 1026°F 84% diss.	.018"	.0007"	Rc 62-65	Rc 32-36
Nitralloy N	10 hr @ 975°F 28% diss. 50 hr @ 975°F 84% diss.	.014"	.0007"	Rc 62-65	Rc 38-44
AISI 4140	10 hr @ 975°F 28% diss. 50 hr @ 975°F 84% diss.	.025" etched	.0007"	Rc 49-54	Rc 27-35
AISI 4340	10 hr @ 975°F 28% diss. 50 hr @ 975°F 84% diss.	.025" etched	.0007"	Rc 48-53	Rc 27-35

By heating the outside layers the material tries to expand while being restrained by the inner material. As this layer cools, there is an increase in volume due to the increased hardness. The result, if properly done, is an outer case with residual compressive stress at the surface. The case-core interface is a critical area on induction hardened gears. If not properly done, this area is susceptible to cracking. In this region, there are high residual stresses due to drastic differences of the case and core structures and the fact that the transition occurs in a very short distance. (See Fig. 8.)

Induction hardening is done primarily to increase the pitting resistance of a gear. Though the load carrying capacity of induction hardened gearing is not as high as the best carburized gears, it is still quite high. And, in addition, this process does have some advantages over carburizing, such as less distortion on particularly thin-rimmed internal gears.

The Process. Through hardening materials are used for induction hardened gears. The same comments on hardness and hardenability as were made in the through hardening section apply here. Simply put, the amount of carbon in the material determines the achievable hardness and the alloy content determines the hardenability. This leads to the same conclusion reached in the through hardening section; that is, if high surface hardness and a deep case are required, a rich alloy steel with an adequate carbon content is needed.

As with through hardening, the teeth can be cut either prior to or after the quench and temper cycle which develops the core properties.

When a gear is carburized, it is said to go through one complete heat treat cycle, while a gear which is induction hardened is said to go through a number of heat treat cycles equal to three times the number of teeth. The inductor scans one tooth slot at a time and, because the heat treating conditions are different at the tooth ends than in the middle, it can be said that three heat treatments occur per tooth. One heat treatment occurs as the inductor enters the tooth slot, one occurs across the middle of the slot, and a third as the inductor passes off the tooth. Therefore, the more teeth there are, the greater the complexity of the job.

The case depth is a function of the power and speed of the inductor travel. It is difficult to verify the case depth on an induction hardened part without sectioning an actual part. Checking on the end is not practical because the case depth on the tooth end is usually not as deep as in the center area to prevent heat damage on the ends.

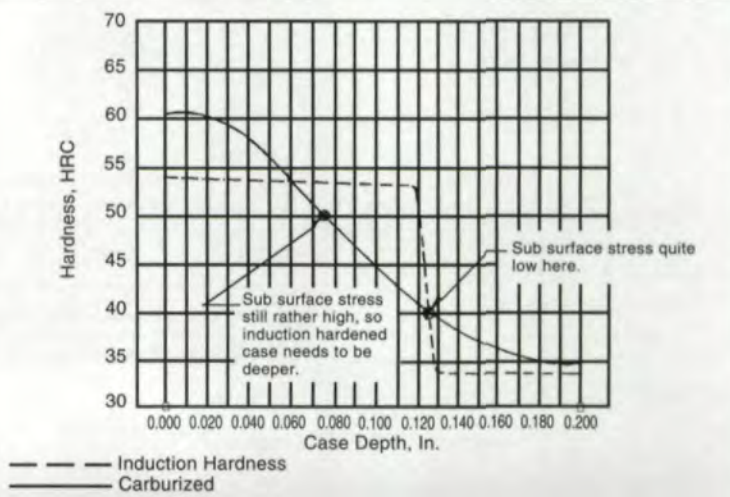


Fig. 8 - Comparison of case hardness gradients for induction hardened vs. carburized gear teeth.

It is usually necessary to grind induction hardened gears after hardening to restore the required accuracy.

Limits to the Process. Induction hardening becomes attractive as a process when the gears start to get large enough that carburizing becomes difficult; that is, when either the mass of the gear makes an effective quench impossible, or the shape of the part is such that the overall distortion is untenable. The teeth also need to be about 10-pitch or larger in order for an inductor to fit in the tooth slot.

Induction hardened teeth generally need more case than do carburized gears which are subject to identical loads. In order for a gear to resist pitting, the strength of the material in the case needs to exceed the stress which it sees. The shape of a curve of subsurface shear stress as plotted against depth is similar to the hardness-versus-depth plot of a carburized case. This means if the carburizing is done properly, the level of subsurface shear drops off faster than the material hardness. The drastic drop off of material strength on an induction hardened tooth may result in a drop off in hardness ahead of a drop off of stress. As mentioned, this area is subject to cracking. The results would be drastic. To avoid these problems, a deeper case is then specified. (See Fig. 8.)

Summary and Conclusions

Heat treating is a subject of great complexity and depth, and an in-depth discussion of all processes in current use is beyond the scope of this article. The general points covered are as follows:

- There is a wide variety of heat treatment processes available because there is a correspondingly large number of specialized needs.
- Often choosing the proper heat treatment requires assessing all the trade-offs.
- Sometimes, only one process will satisfy a particular application.
- The gear designer and manufacturer need to be cognizant of when a heat treatment is appropriate and when it is not. Understanding the capabilities and shortcomings of the common processes is necessary for such judgments.

Often the higher cost of a better material, better process, and a little bit of research can be substantially offset by savings in rejected parts and extra manufacturing steps. ■

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