

Gear Hardness Technology

by: M. J. Broglie and D. F. Smith, Dudley Technical Group

American Gear Manufacturers Association



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M. J. Broglie and D. F. Smith
Dudley Technical Group

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ABSTRACT:

As progress continually places demands on the gear designer to make gearing that is smaller, lighter and more reliable, the demand for better gear materials and heat treat processes increases. Proper hardness of a gear, both in the tooth and in the body is becoming increasingly critical since load carrying capacity is dependent on hardness.

The scope of this paper is limited to the most common methods of heat treatment of steel gearing, yet within this area there are still many methods of heat treatment in wide use throughout the industry. The fact that there are so many methods in use is testimony to the shortcomings of each process. When a designer selects the material and heat treatment to be used, among the considerations are the size of the gear and the gear tooth, facilities available for heat treatment, the overall cost associated with the material and process, and the reliability which is required by the application of the gear.

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GEAR HARDNESS TECHNOLOGY

Michael J. Broglie and Danny F. Smith
Dudley Technical Group Incorporated
San Diego, California

1.0 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 paper 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 paper 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

2.0 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_2 point. Finally there is subcritical annealing which heats the part to just below the first transformation temperature (A_1), as in tempering, and it is slow cooled, 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.

3.0 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 paper 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, it is often necessary to increase the hardness of the steel. According to AGMA standards (ref. 1), a gear with a hardness of 400 BHN, which has a design life of 10⁷ 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 paper, it is worth mentioning that the degree of martensitic structure is one of the prime indicators of a material's quality. AGMA 2004-B89 (ref. 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 then 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. It may be necessary to finish machine the teeth in order 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 form for the solid solution of carbon in fcc iron (ref. 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 a rich alloy steel and has much better hardenability.

TABLE 1 Common Through Hardened Gear Steels

Steel	C	Mn	S	P	Si	Cr	Mo	Ni
			max	max				
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

Once the part has been quenched it needs to be 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 540 °C) for a period of one or more hours, depending on the size of 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 which are 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 as 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).

TABLE 2 Approximate Quenching Behavior of 4140 and 4340 Steel

Quench effectiveness	Quench time to 500°F, seconds		Structure to be expected
	4140	4340	
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.)

4.0 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 became 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 scraped. 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 car-



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