Heat Treat Process and Material Selection for High Performance Gears

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Figure 1—An etched section of a gear that has been case hardened by progressive induction hardening.

Figure 2—A load of large gears are transferred into a furnace for carburizing.

Figure 3—A load of large pinions are transferred into a furnace for carburizing.

Figure 4—Carburized gears are transferred from the heating chamber into the quench section for hardening.

Introduction

The selection of the heat treat process and the congruent material required for high performance gears can become very involved.

A wide variety of options are available, and many issues must be considered. The application requirements must take into consideration the service conditions in which the gears will operate, the speeds and power to be transmitted, and the design life. This data will in turn define the size and shape of the gears and, along with the load carrying capacity required and the volume to be produced, allow material selection in conjunction with the choice of heat treatment to achieve the required mechanical properties.

The improved mechanical properties achieved by case hardening dictate that virtually all high performance gears are processed in this manner. Still, we will include through hardening for core treating in our discussion because it is required to achieve the desired properties when induction hardening and nitriding.

Through Hardening, General Requirements for Core Treating

Core treating prior to induction hardening and nitriding is used to obtain both the desired microstructure for subsequent processing and the required mechanical properties in the finished part. In most cases, core treating is accomplished by hardening and tempering the parts prior to gear cutting. A hardness range of 28–32 HRC (269–302 HBN) is commonly specified in order to obtain good mechanical properties without severely sacrificing machinability.

However, higher core hardnesses are used where increased strength levels are necessary. The material selection and processing sequence must take into consideration the mass of the part and the hardenability of the material, as these influence the depth of hardening in the core treating process. Heavier sectioned parts and coarser pitches require higher hardenability materials or premachining for proper core treating response. Good hardening response is also needed when core treating prior to nitriding because the tempering temperature must be at least 50°F higher than the nitriding temperature, or typically at least 1,050°F, to insure dimensional stability during nitriding.

Case Hardening Processes for High Performance Gears

High performance gears generally require case hardening to produce the required mechanical properties. Contour and tooth-to-tooth progressive induction hardening, carburizing and hardening, and nitriding are therefore preferred while processes such as spin flame hardening and conventional single-shot induction hardening are not capable of producing the required properties.

Each of the above processes is unique and has its own set of pluses and minuses relative to each other. Contour and tooth-to-tooth induction hardening involve heating and hardening only a small portion of the gear, so size change and distortion are relatively small, especially when compared with those produced during hardening of a carburized part. Contour induction hardening is suitable only for small- to medium-sized gears in high volume applications.

In contrast, tooth-to-tooth induction hardening is cost effective only for low volume applications. Also, not all parts

Figure 5—A large carburized pinion is transferred to the oil quench tank for hardening.

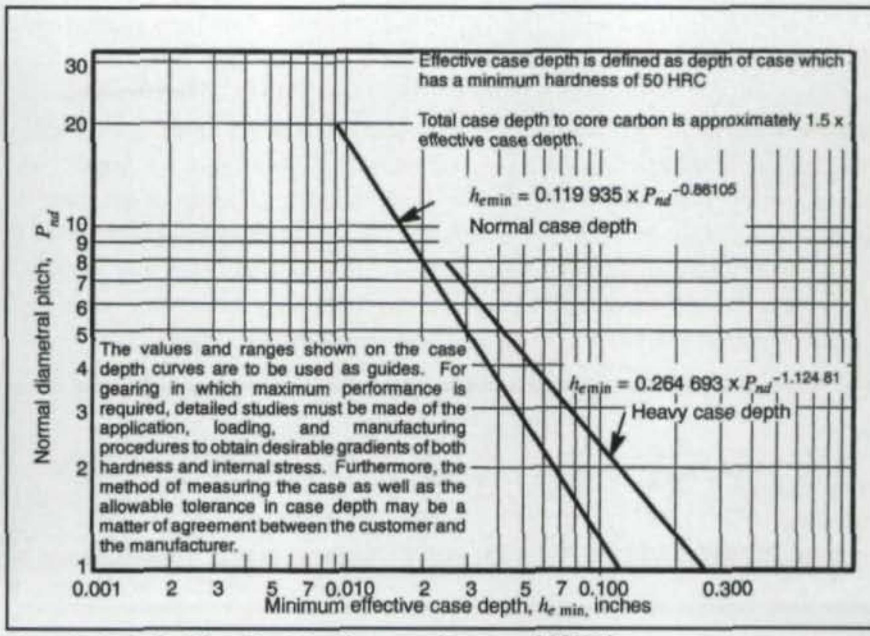

Figure 6—Carburized Case Depth Requirements. (Courtesy of AGMA.)

can be hardened by either type of induction hardening due to their size and shape, and neither type of induction hardened gears has quite as high a load carrying capability as carburized and hardened gears.

For some applications, nitriding is the heat treatment of choice because very good mechanical properties are achieved. Also, it produces distortion and size change so small and predictable that generally hard finishing is not required. Nitriding, however, involves long cycle times and is therefore very costly when trying to obtain deeper case depths required for coarser pitches.

But where the best performance is required, carburizing and hardening is usually relied upon because it produces excellent mechanical properties and is suitable for low and high volume applications. Size change and distortion can be serious problems, but they can be dealt with.

Tooth-to-Tooth Progressive Induction Hardening

Tooth-to-tooth induction hardening is often used for low to medium volume requirements when the size or design of the part allows this process to be used. In tooth-to-tooth induction hardening, an inductor with a profile matching the shape of the tooth space is traversed through each tooth space. Controlling the power input and scanning speed progressively hardens the active profile and root area of each adjacent tooth face to the desired depth. Since the size of the air gap between the inductor and the tooth surface is critical, a custom inductor is often required for each gear design. For fine- to medium-pitch gears, this process is generally performed with the part submerged in a quenchant.

As each tooth space must be individually scanned, the floor-to-floor time for hardening a gear in this manner is relatively long when compared to contour hardening where all the teeth are hardened at one time. Offsetting this is the versatility and size range capability of the tooth-to-tooth process. Gears from 10–1 DP are routinely hardened in this manner. To determine the case depth and pattern produced, it is necessary to cross-section several teeth from a hardened gear in contrast to being able to check a test piece when carburizing or nitriding (see Fig. 1).

A core treated, medium-carbon alloy steel, such as 4142, 4150 or 4340, is generally specified for most applications with the choice dictated by the diametral pitch and size of the gear. The larger the part and coarser the pitch, the higher the hardenability required for good hardening response. In higher volume applications, lower cost grades, such as 15B41, are utilized where the material's hardenability is matched to the specific parts requirements and large enough quantities are used so that availability is not an issue.

Contour Induction Hardening

For higher volume applications of small- to medium-sized gears in the 8–4 DP range, contour induction hardening is a viable option and can compete with carburized gearing. Contour induction hardening is similar in appearance to the classic single shot, spin induction process where the gear is rotated in an induction coil to heat the teeth and then quenched in place. In most cases, however, this through hardens rather than case hardens the teeth. The contour induction hardening process has been developed to produce a heat pattern that

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follows the profile of the teeth and produces a true case hardened tooth. This is generally accomplished through the use of high intensity, multistage heating where the teeth are first preheated using a low frequency, and then the tooth surfaces are rapidly heated with a burst of high power, high frequency energy.

The nature of contour induction hardening requires that the tooling, process parameters and equipment be tailored to each application. Multiple, high-powered power supplies with very sophisticated control systems are necessary. This makes the process capital-intensive and seldom practical for lower volume applications, but justifiable for higher volumes. Another advantage it has over all other gear hardening processes is that it lends itself to integration into manufacturing cells, especially when combined with induction tempering.

Carburizing and Hardening

Of the case hardening processes, carburizing and hardening is the most widely used process today for heat treating high performance gears. It is adaptable to both high and low volume requirements as well as to both large and small parts (see Figs. 2 and 3). And, with the proper choice of materials and processing techniques, it will produce the highest allowable contact and bending stress ratings obtainable.

To achieve the desired results, it is important that the material selection be in accord with the nature and size of the gear as well as its service requirements. All carburizing grades are low carbon alloy steels, but coarser pitch, heavier sections and more severe service necessitate using higher hardenability, higher alloy, and more expensive materials. Common grades in increasing hardenability are: 4118, 8620, 8822, 4320, 4820, 9310 and 17CrNiMo6. These materials are also produced in different quality levels to comply with the different AGMA grade requirements, depending on service requirements.

It is recommended that, prior to machining, the lower alloy grades be normalized and the higher alloy grades be normalized and tempered or normalized, quenched and tempered to obtain improved machinability as well as more reproducible size change and distortion results during subsequent carburizing and hardening.

From a manufacturing standpoint, the

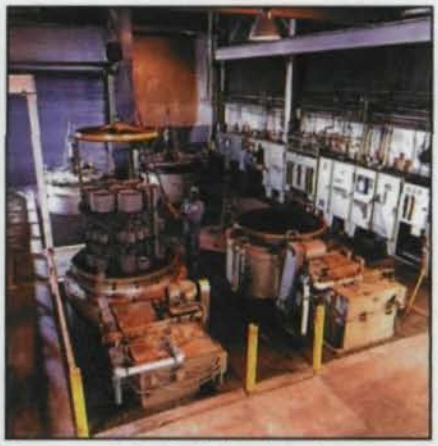

Figure 7—A load of diesel engine gears is removed from the furnace after nitriding.

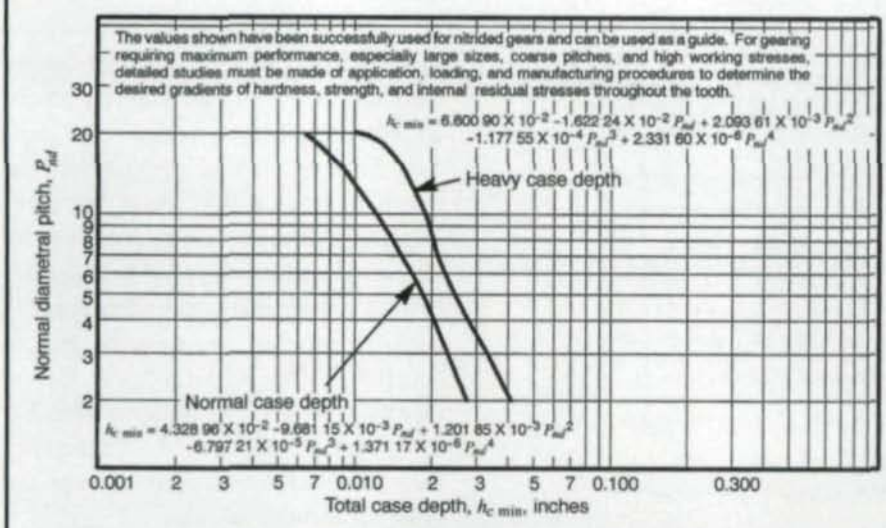

Figure 8—Nitrided Case Depth Requirements. (Courtesy of AGMA.)

most serious problem with carburized gearing is the size change and distortion that occurs during hardening. This is very design-dependent. Gears that have nonsymmetrical cross sections or are heavily relieved for mass reduction will present more problems than relatively solid symmetrical parts.

While proper fixturing must be employed during carburizing to minimize creep-induced distortion, part orientation during hardening is most critical in order to obtain a uniform quench. Quenching in hot (250–350°F) oil, marquenching and high-pressure gas quenching can often be employed to reduce the size change and distortion but, since they are slower quenches, it is often necessary to use a higher hardenability grade than necessary with conventional oil quenching (see Figs. 4 and 5).

When the design of the gear is such that excessive distortion is produced during free quenching, techniques such as plug and/or press quenching should be used. For size and shape control of thin-walled gears and internal splines, plug quenching is recommended. However, where the movement of the whole gear must be controlled, press quenching is necessary. This requires the availability of a suitably sized quench press and generally custom tooling for holding the part during the quenching process. Since both of these processes require handling each part individually, they often significantly increase processing costs.

The depth of the carburized case must be in accord with the diametral pitch and service requirements of the gear. Coarser pitches and more severe applications require deeper cases. Figure 6 shows the AGMA chart for determining the effective case depth to be used for a given diametral pitch. The effective case depth is typically defined as the depth at which the hardness has decreased to 50 HRC and is measured on a representative test sample or a sectioned part.

Nitriding

Nitriding is another case hardening process that has been gaining popularity for use on high performance gearing due to advances that have been made in both gas and ion nitriding. Nitriding produces a hard surface with excellent wear properties, improved corrosion resistance and very good high-cycle fatigue properties. This is a rather unique process in that it is performed at a relatively low temperature, in the 950–1,050°F range, and quenching is not involved. Since the base material does not go through any structural change, size change and distortion are very low, and rarely is any finishing necessary after nitriding (see Fig. 7). The processing time required, however, is relatively long, especially for coarser diametral pitches where deeper case depths are

Table 1—Allowable Design Stress for Steel Gears.[1] *								
Heat Treatment	Material	Minimum Surface Hardness	Contact Stress (KSI)			Bending Stress[5] (KSI)		
			GR1	GR2	GR3	GR1	GR2	GR3
Through Hardened	4140/4340	32 HRC	127	140		36	48	
		43 HRC	160	175		43	58	
Induction Hardened[2]	1045/4340	54 HRC	175	195		45	55	
Carburized and Hardened	8620/9310	58 HRC[3]	180	225	275	55	65	75
Nitrided[5]	4140/4340	84.5 HR15N	155	168	180	37	50	
	Nitralloy 135M	90 HR15N	170	183	195	38	50	
	31CrMoV9[4]	90 HR15N	176	196	216	41	52	60[5]

[1] Table compiles data from various tables and graphs in ANSI/AGMA 2001-C95.
[2] Tooth-to-tooth and contour induction hardening, with ANSI/AGMA type A pattern.
[3] Minimum surface hardness of 55 HRC is acceptable for GR1; all other grades require a *minimum of 58 HRC.*
[4] Basically the same as 2.5%Cr without Al.
[5] The seven bending stress values for nitrided materials are based on a core hardness of 300 HB.

needed.

Three different types of medium-carbon alloy steels are used for nitrided gears, depending on the service requirements. In all cases, core treating is employed to produce both the desired strength and the structure needed for good nitriding response. When the service requirements are not too severe, 4140 or 4340 is typically specified. For more demanding applications, it is necessary to use a grade, such as Nitralloy 135M or 31CrMoV9, that is especially designed for nitriding. Figure 8 shows the AGMA chart for determining the total nitrided case depth required for different diametral pitches.

Summary

The purpose of this paper was to give a general overview of the different heat treat processes and materials used in high performance gearing and thus help guide the designer and process engineer in making the best selection for a given job. Table 1 outlines values of contact and bending allowable stresses for each of the aforementioned hardening processes. For full data and details, see ANSI/AGMA 2001-C95. ○

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