By Daniel H. Herring and Gerald D. Lindell

Allow “The Heat Treat Doctor” and His Colleague to Take You on a Tour of the Heat-Treating Processes You Need to Understand in Order to Achieve Your Gear Manufacturing Goals.
Whether required to pace the movement of a precision watch or a giant wind turbine, gears play an essential role in the performance of the products that we rely on in our everyday lives. Gears fall into two general categories: motion-carrying and power transmission. Motion-carrying gears are generally non-ferrous or non-metals such as plastic, while load bearing power transmission gears are usually manufactured from ferrous alloys. The focus of this article will be on heat treatment of gears intended for heavy duty service applications.

To understand why heat treating is important we look to the Model of Material Science (Fig. 1) represented as a series of interlocking rings underscoring the interdependence of each element in the model. We see that the end use performance capability of the product is defined by its (mechanical, physical, and metallurgical) properties, which are in turn determined by
the part microstructure that is produced by a specific heat treatment process in a given piece of equipment.

What is clear from this model is that the manufacture of precision gearing depends to a great extent on heat treating as a core competency. Its contribution is vitally important for cost control, durability, and reliability. Heat treating represents a significant portion (≈ 30 percent) of a typical gear manufacturing cost (Fig. 2). If not properly understood and controlled, it can have a significant impact on all aspects of the gear manufacturing process (Fig. 3).
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Figure 4: Load of production gears after atmosphere carburizing furnace followed by oil quenching

Figure 5: Load of production gears in position for loading into a vacuum carburizing furnace followed by high gas pressure or oil quenching

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HEAT TREATMENT PROCESSES: 
PRE-HARDENING

Several heat treatments can be performed before or during the gear manufacturing process to prepare the part for manufacturing. In many cases these steps are essential to the manufacture of a quality gear.

Annealing
Annealing is primarily intended to soften the part and to improve its machinability. There are several annealing processes, all of which involve heating to and holding at a suitable temperature followed by cooling a specific rate usually through a critical range of temperatures. Processes used for gears include: full or supercritical annealing where a gear blank is heated 90-180ºC (160-325°F) above the upper critical temperature (Ac3) of the steel and then slow cooled in the furnace to around 315ºC (600ºF); intercritical annealing where the gear is heated to a temperature between the upper and lower critical temperature (Ac1) and then rapidly cooled; and subcritical annealing, where gears are heated to 10-38ºC (50-100°F) below the lower critical temperature followed by a slow cool in the furnace.

Normalizing
Normalizing plays a significant role in the control of dimensional variation during hardening and case hardening. Normalizing is a process that involves heating the gear above the upper critical temperature and then cooling at a rate equivalent to that of still air to relieve residual stresses in the gear blank and for dimensional stability in subsequent heat treatment processes. In a thermal sense, normalizing is simply austenitizing. In a microstructural sense, normalizing is intended to produce a more homogenous microstructure. A normalized part is very machineable, but harder than an annealed part.

Stress Relief
Stress relief, as its name implies, is intended to relieve internal stresses created in the gear as a consequence of its manufacture. It is recommended for intricate shapes, especially if aggressive machining methods are used or when large amounts of stock are being removed. Stress relief involves heating to a temperature below the lower critical temperature, holding long enough to fully soak the part then cooling slowly enough, usually in air, to minimize the development of new residual stresses.

HARDENING PROCESSES

A variety of heat treatment process choices exist for hardening a gear, each designed to increase gear hardness. These usually involve heating and rapid cooling and are typically classified as through hardening, case hardening (carburizing, carbonitriding, nitriding, nitrocarburizing), and surface hardening by applied energy (flame, laser, induction).

Through (Neutral) Hardening
Through hardening refers to heat treatment methods which do not produce a case. The hardness is achieved by heating the material into the austenitic range, typically 815-900ºC (1500-1650ºF), followed by quenching and tempering. It is important to note that hardness uniformity should not be assumed throughout the gear tooth. Since the outside of a gear often cools faster than the inside, there will be a hardness gradient developed. The final hardness is dependent on the amount of carbon in the steel. The depth of hardness depends on the hardenability of the steel as well as the quench severity. Examples of commonly through hardened gear steels are SAE 1045, 4130, 4140, 4145, 4340, and 8640.

Through hardening can be performed either before or after the gear teeth are cut. When gear teeth will be cut after the part has been hardened, surface hardness and machinability become important factors especially in light of the fact that machining will remove some or most of the higher hardness material at the surface.

Case Hardening
Case hardening is used to produce a hard, wear-resistant case, or surface layer, on top of a ductile, shock-resistant interior,
or core. The idea behind case hardening is to keep the core of the gear tooth at a level around 30-40 HRC to avoid tooth breakage while hardening the outer surface to increase pitting resistance. The higher the surface hardness value the greater the pitting resistance. However, bending strength increases for surface hardness up to about 50 HRC, after which the increase is offset by an increase in notch sensitivity.

**Carburizing**

Carburizing is the most common of the case hardening methods. A properly carburized gear will be able to handle between 30-50 percent more load than a through hardened gear. Carburizing steels are typically alloy steels with approximately 0.10 to 0.20 percent carbon. Examples of commonly carburized gear steels include SAE 1018, 4320, 5120, 8620, and 9310, as well as international grades such as 20MnCr5, 16MnCr5, ZF-7B, 20MoCr4, and V2525.

Carburizing can be performed in the temperature range of 800°C (1475°F) to 1090°C (2000°F). Common industry practice today finds the majority of carburizing operations taking place between 870°C (1600°F) and 1010°C (1850°F). Carburizing case depths can vary over a broad range, 0.13-8.25 mm (0.005”-0.325”) being typical. However, it is common to use the carbonitriding process for case depths below 0.4 mm (0.015”). A very good compromise between cost and performance is achieved by atmosphere carburizing (Fig. 4), the present day de facto standard processing method used in the gear industry.

All indications, however, are that the greatest potential for future growth will come from low pressure vacuum carburizing (Fig. 5). This method of carburizing has been shown to offer proven metallurgical and environmental benefits.

**Atmosphere carburizing** is an empirically based, time-proven process in which a carbon-rich atmosphere surrounding a workload is used to chemically react with the surface of the parts to allow an adequate quantity of carbon to be absorbed at the surface and diffused into the material.

In atmosphere carburizing parts are heated to austenitizing temperature in a “neutral” endothermic or nitrogen/methanol containing approximately 40% nitrogen for case hardening.

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percent hydrogen, 40 percent nitrogen, and 20 percent carbon monoxide. Small percentages of carbon dioxide (up to 1 ½ percent), residual hydrocarbons (up to ½ percent) and trace amounts of oxygen and water vapor are also present. Other atmosphere combinations such as nitrogen/natural gas are also possible. This “neutral” or “carrier gas” atmosphere is generally neither carburizing nor decarburizing to the surface of the steel being heated.

In order to perform the carburizing process enriching gas is added to the carrier gas atmosphere. The enriching gas is usually either natural gas which is about 90-95 percent methane (CH\textsubscript{4}) or propane (C\textsubscript{3}H\textsubscript{8}). In atmosphere carburizing it is common practice to begin the flow of enrichment gas just after the furnace has recovered setpoint. This practice contributes to case non-uniformity as various parts of the workload are not uniform in temperature and carburize at different rates.

The water gas reaction (Equation 1) is important in the control of the atmosphere carburizing process. Instruments such as dew point analyzers monitor the H\textsubscript{2}O/H\textsubscript{2} ratio of this equation while infrared (3-gas) analyzers and oxygen probes look at the CO/CO\textsubscript{2} ratio.

$\text{CO + H}_2\text{O} = \text{CO}_2 + \text{H}_2 \quad (1)$

In atmosphere carburizing, intergranular oxidation (IGO) is one of the phenomena taking place as a result of the constant changes occurring in the furnace atmosphere. This can be explained by considering an alternative form of the water gas reaction (Equation 2). Here we see that the transfer of carbon in atmospheres containing CO and H is connected with a transfer of oxygen, giving rise to an oxidation effect in steel with alloying elements such as silicon, chromium, and manganese.

$\text{CO + H}_2 = [\text{C}] + \text{H}_2\text{O} \quad (2)$

Advantages of atmosphere carburizing include:

- The lowest initial capital equipment investment cost.
- Capability of high volume output using a wide variety of equipment styles, types, and workload sizes. Furnace types include box, pit, mechanized box (integral- or sealed-quench furnaces), pusher, conveyor (mesh belt and cast link belt), shaker hearth, rotary hearth, rotary drum (rotary retort), and carbottom styles.
- Adequate process control; that is, all of the process variables are understood and reliable control devices are available to provide a measure of process repeatability.
- Capable of being easily automated with recipe and/or partnumber control of heat treat cycles.
- Well-understood process problems allowing troubleshooting based on an established theoretical and empirical knowledge base.

The last point is very important. Often in the real world, problems cannot be avoided, but it is the ability to quickly and easily address the issues that arise, which dictates the success of a given technology. This certainly is one of biggest advantages of atmosphere carburizing.

Disadvantages of atmosphere carburizing include:

- Knowledge gained through empirically methods is required to achieve repeatable results. This is due to a wide variability in the type of equipment, its operation, maintenance, and constantly changing process conditions.
- The need to “condition” equipment if idled or shut down prior to processing work.
- The need for large material allowances for post-processing operations due to accuracy and finish requirements. Case depths typically are specified in wide ranges (e.g. 0.75 to 1.25 mm (0.030 to 0.050 in.) to compensate for cycle induced variability.
- Case depth quality issues; the best part of the case often is lost due to the amount of stock removal required.
- Processing techniques that produce non-uniformity of case and carbon profiles throughout the gear geometry (tip-pitch line-root). Root case depths are typically 65-80 percent of those at the pitch line.
- The need to constantly be concerned about safety and fire prevention issues (e.g., fire from combustible gases and quench oils, hot contact surfaces, and pinch points).
Many options exist for the heat treatment of quality gears, but the selection of the right combination of processes—along with control of process and equipment variables—remains essential.

- The need to monitor environmental pollution including air quality (for potentially hazardous gases, such as CO and NOx), water quality (for contamination concerns such as oil, minerals, etc.), waste disposal (quench oils), and safety issues.

It is important to note that a great deal of the non-uniformity of case depth can be avoided if adequate soak time at temperature is used or if load preheating techniques are employed.

Vacuum carburizing is a proven method of pure carburizing.
and pure diffusion in which carbon penetrates into the surface of the steel being processed without interference from external influences such as gas chemistry or surface contaminants.

Vacuum carburizing is a modified gas carburizing process in which the carburizing is done at pressures far below atmospheric pressure (760 Torr). The typical pressure range for low pressure vacuum carburizing today is 3-20 Torr.

The advantage of this method is that the steel surface is cleaned during heatup and the vacuum environment makes the transfer carbon to the steel surface faster (higher carbon transfer values) since atmosphere interactions such as those found in the water gas reaction do not take place. In addition, intergranular oxidation cannot occur.

The hydrocarbon currently being used for vacuum carburizing are acetylene (C₂H₂), acetylene/hydrogen (C₂H₂/H₂), acetylene/ethylene/hydrogen C₂H₂/ C₂H₄/H₂, propane (C₃H₈), propane/methane (C₃H₈/ CH₄) and cyclohexane (C₆H₁₂), a liquid. Methane (CH₄) alone is still used in certain applications usually at temperatures above 940°C (1750°F).

In vacuum carburizing the breakdown of hydrocarbon gases involves non-equilibrium reactions; the acetylene reaction is shown in Equation 3. This means that the surface of the steel is very rapidly raised to the saturation level of carbon in austenite. By repeating the boost and diffuse steps desired carbon profile and case depth can be achieved.

\[ C_2H_2 \rightarrow 2C + H_2 \] (3)

The control of the low pressure vacuum carburizing process is on a time basis. The carbon transfer rates are a function of
temperature, gas pressure, and flow rate. Simulation programs with empirical data input capability have been created to determine the boost and diffuse times of the cycle.

Advantages of vacuum carburizing include:

• Absence of intergranular oxidation.

• Capability of higher temperatures due to the type of equipment and the nature of the process.

• Process and cycle flexibility allows a wider variety of materials to be processed.

• Processing methods produce more uniform case and carbon profiles throughout the gear tooth geometry (tip-pitch line-root). Root case depths are typically 85-90 percent that those at the pitch line.

• Easy integration into manufacturing. The process is clean, safe, simple to operate, and easy to maintain. Also, working conditions are excellent—that is, there are no open flames, heat, and pollution.

• Full automation capability using recipe or part-number control of heat treating cycles.

• Precise process control achieved using computer simulations, which allow adjustments to established cycles.

• On-demand consumption of energy by the equipment and process only when needed due to the nature of the vacuum operation.

• Typically less distortion results provided adequate measures are taken in loading.
Disadvantages of vacuum carburizing include:

- Higher initial capital equipment cost than atmosphere carburizing equipment.
- Part cleanliness is more critical in order to achieve desired results.
- Empirical process control, which requires processing loads to determine optimum settings or to fine tune simulator.
- Formation of soot and possibly tar, which occur due to the type, pressure, and quantity of hydrocarbon gas introduced.

It is important to note that research during the past six years has succeeded in finding combinations of pressure, gas type, and flow parameters to minimize soot and tar formation and eliminate these factors as a concern in the vacuum carburizing process.

Carbonitriding

Carbonitriding is a modification of the carburizing process, not a form of nitriding. This modification consists of introducing ammonia into the carburizing atmosphere in order to add nitrogen to the carburized case as it is being produced. Examples of gear steels that are commonly carbonitrided include SAE 1018, 1117, and 12L14.

Typically, carbonitriding is done at a lower temperature than carburizing, between 700 and 900°C (1300 and 1650°F), and for a shorter time. Combine this with the fact that nitrogen inhibits the diffusion of carbon, and what generally results is a shallower case than is typical for carburized parts. A carbonitrided case is usually between 0.075-0.75 mm (0.003”-0.030”) deep.

Nitriding

Nitriding is another surface treatment process that has as its objective increasing surface hardness. One of the appeals of this process is that rapid quenching is not required; hence dimensional changes are kept to a minimum. It is not suitable for all gear materials; one of its limitations being that the extremely high surface hardness “white (or compound) layer” produced has a more brittle nature than say the surface produced by the carburizing process. Ion (plasma) nitriding techniques have been used to address the compound layer issue. Examples of commonly nitrided gear steels include SAE 4140, 4150, 4340, 7140, 8640, and Nitralloy alloys.

Nitriding is typically done in the 495-565°C (925 to 1050°F) temperature range. Three factors that are extremely critical in producing superior and consistent nitrided cases and predictable dimensional change are steel composition, prior structure, and core hardness. Case depth and case hardness properties vary not only with the duration and type of nitriding being performed, but are also influenced by these factors. Typically case depths are between 0.20-0.65 mm (0.008”-0.025”) and take from 10 to 80 hours to produce.

Nitrocarburizing

Nitrocarburizing is a modification of nitriding, not a form of carburizing. In the process, nitrogen and carbon are simultaneously introduced into the steel while it is in a ferritic condition; that is, at a temperature below that at which austenite begins to form during heating. A very thin white layer is formed during the process, as well as an underlying “diffusion” zone. Like nitriding, rapid quenching is not required. Examples of gear steels that are commonly nitrocarburized include SAE 1018, 1141, 12L14, 4140, 4150, 5160, 8620, and certain tool steels.

Nitrocarburizing is normally performed at 550 to 600°C (1025 to 1110°F) and can be used to produce an equivalent 58 HRC minimum hardness, with this value increasing dependent on the base material. White layer depths range from 0.0013-0.056 mm (0.00005”-0.0022”) with diffusion zones from 0.03-0.80 mm (0.0013”-0.032”) being typical.

Applied Energy Hardening

Various methods of hardening by use of applied energy are used in the manufacture of gears; including flame hardening, laser surface hardening, and induction.

Flame

Flame hardening can be used for both small and large gears by either spinning or by a progressive heating technique. In the progressive heating method, the flames gradually heat the gear in front of the flame head, and sometimes this effect must be compensated for by gradually increasing the speed of travel or by precooling. A wide range of gear sizes and materials can be hardened by this technique, including plain carbon steels, carburizing grades, cast irons, and certain stainless grades.

The principle operating variables are rate of travel of the flame head or work; flame velocity and oxygen-fuel ratios; distance from the inner flame cone or gas burner to the work surface; and the type, volume, and angle of quench. The success of many flame
hardening operations for small production runs is dependent on the skill of the operators.

**Laser**

Laser surface hardening is used to enhance the mechanical properties and surface hardness of highly stressed machine parts and as such is of interest to gear manufacturing. The use of lasers for surface treatments is relatively limited due to the high cost of large industrial lasers and the narrow (4-5 mm) band of material that can be hardened without multiple overlapping passes. Adding to the expense is the fact that lasers are not very efficient from an energy standpoint. Gear materials such as SAE 1045, 4340, and cast irons (gray, malleable, ductile) are good candidates for this technology.

**Induction**

Induction hardening is commonly used in the heat treatment of gears. Induction heating is a process which uses alternating current to heat the surface of a gear tooth. The area is then quenched resulting in an increase in hardness in the heated area. It is typically accomplished in a relatively short period of time. The type of steel, its prior microstructure, and the desired gear performance characteristics determine the required hardness profile and resulting gear strength and residual stress distribution. External spur and helical gears, bevel and worm gears, and racks and sprockets are commonly induction hardened. Typical gear steels include SAE 1050, 1060, 4140, 4150, 4350, 5150, and 8650, just to name a few. With alloy material such as 4140, 4150, 4350, and 5150, stress relief or temper as soon as possible from induction hardening to prevent a risk of cracking.

The hardness pattern produced by induction heating is a function of the type and shape of the inductor used as well as the heat mode. One technique for induction hardening of gears is the use of a coil encircling the part. An inductor which is circumferential will harden the teeth from the tips downward. While this pattern is acceptable for splines and some gearing, heavier loaded gears where pitting, spalling, tooth fatigue, and endurance are an issue need a hardness pattern which is more like that found in a carburized case. This type of induction hardening is called contour hardening and is produced via tooth-by-tooth or gap-by-gap techniques by applying either a single-shot
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or scanning mode. Pattern uniformity is very sensitive to coil positioning.

An alternative which has the same effect as contour hardening utilizes dual frequency. A preheat using 3KHz or 10 KHz brings the core temperature up to just below austenitizing temperature. Then the unit changes to medium or high frequency depending on the requirement of the gear. The advantage of this method is shorter cycle times. In a very large gear contour heating will be more cost effective since coils become very expensive as they increase in size.

**POST-HARDENING PROCESSES**

After hardening, gears typically undergo several thermal and mechanical processing steps.

**Sub-Zero Treatment**

The use of cryogenic treatments is becoming more common for high performance gearing. Two types of treatments are used today: deep freezing, or “shallow” cooling, in the temperature range of -85ºC (-120ºF); and cryogenic, or “deep” cooling in the -195ºC (-320ºF) range. In some instances this treatment is combined with subsequent temper operations.

The purpose of cryogenic treatment is to transform retained austenite and raise the hardness of the as-quenched structure. In addition, better dimensional stability is often achieved. Sub-zero treatments have as their ultimate goal an increase in wear resistance, improved bending fatigue life, and minimizing residual stress.

**Tempering**

Any temperature under the lower critical temperature can be used for tempering, but it is the balance of hardness, for strength, and toughness required in service that determines the final tempering temperature. Tempering in the range of 150-200ºC (300-400ºF) is common for gearing producing a slight increase in toughness that is adequate for most applications requiring high strength and fatigue resistance where loading is primarily compressive. Double tempering is sometimes performed on gears for the purpose of ensuring completion of the tempering reaction and to promote stability of the resulting microstructure.

**Shot Peening**

Shot peening is a cold working process in which the surface of the gear is bombarded with small spherical media called shot. Shot peening is a controlled process in which the size, shape, and velocity of the media are carefully monitored and controlled. A common requirement for shot peening of gears is to peen the tooth roots with overspray allowed on the flanks. Shot peening should not be confused with shot blasting, a cleaning process.

The purpose of shot peening is to induce a residual compressive stress on the gear surface that is used to enhance tooth bending fatigue properties. The residual compressive stress offsets the applied tensile stress that may cause bending fatigue fail.

**GEAR MATERIAL SELECTION**

Power transmission gears (Fig. 6) are manufactured from a wide variety of steels and cast irons. In all gears, the choice of material must be made only after careful consideration of the performance demanded by the application end-use and total manufactured cost, taking into consideration such issues as machining economics. Key design considerations require an analysis of the type of applied load, whether gradual or instantaneous and the desired mechanical properties, such as bending fatigue strength or wear resistance, all of which will define core strength and heat treating requirements.

Each area in the gear tooth profile sees different service demands. Consideration must be given to the forces that will act on the gear teeth with tooth bending and contact stress, resistance to scoring and wear, and fatigue issues being paramount. For example, in the root area good surface hardness and high residual compressive stress are desired to improve endurance or bending fatigue life. At the pitch diameter, a combination of high hardness and adequate subsurface strength are necessary to handle contract stress and wear and to prevent spalling. Some of the factors that influence fatigue strength are: hardness distribution (e.g. case hardness and depth, core hardness); microstructure (e.g. percentage of retained austenite, grain size, carbides (size, type, distribution), the presence of non-martensitic phases); and extraneous factors (e.g. geometry, surface finish, inclusion (e.g. type, distribution) residual compressive stress pattern, intergranular toughness).

Although material represents only a small percentage (≈ 10 percent) of the cost to manufacture a typical gear, material selection (Table 1) is a combination of raw material cost and performance capability. Knowledge of the function of each of the alloying elements present in the material and their effect on the physical properties of the alloy is critical in material selection. Properties to be balanced by material selection include tensile, yield and impact strength, as well as elongation.
Hardness in the part section of interest needs to be considered when making the selection of a material. If the core hardness is too low it will not support the case under high load and if the core hardness is too high “chipping” of the gear teeth at the case/core interface can occur.

CONCLUSIONS

Many options exist for the heat treatment of quality gears, but the selection of the right combination of heat treatment processes—along with control of process and equipment variables—remains essential.

REFERENCES:


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<th>From 1” Diameter, 64 D.P.</th>
<th>Max. Face</th>
<th>Max. Size</th>
<th>Max. Pitch</th>
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<tr>
<td>Internal Gears &amp; Splines</td>
<td>8”</td>
<td>100” P.D.</td>
<td>1 1/4 D.P.</td>
</tr>
<tr>
<td>Ground Gears, Crowned or Straight</td>
<td>20.5”</td>
<td>72” P.D.</td>
<td>1 D.P.</td>
</tr>
<tr>
<td>Herringbone Gears, Center Grove</td>
<td>14”</td>
<td>36” P.D.</td>
<td>2 D.P.</td>
</tr>
</tbody>
</table>

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