GEAR FUNDAMENTALS

The Effect of Surface Hardening on the Total Gear Manufacturing System

Maurice A. H. Howes, IIT/IITRI Gear and Bearing Center,
Chicago, IL

Abstract:

Carburized and hardened gears have optimum load-carrying capability. There are many alternative ways to produce a hard case on the gear surface. Also, selective direct hardening has some advantages in its ability to be used in the production line, and it is claimed that performance results equivalent to a carburized gear can be obtained. This article examines the alternative ways of carburizing, nitriding, and selective direct hardening, considering equipment, comparative costs, and other factors. The objective must be to obtain the desired quality at the lowest cost.

Introduction

The major heat treatment used for high quality gears is a case hardening process designed to form a hard surface layer on the gear surface. This layer gives the gear a hard, wear-resistant finish, but also causes a compressive stress system to be present at the surface, which helps to resist fatigue failures. The type of fatigue encountered in a gear is usually pitting fatigue present at the tooth contact points.

The most usual process is carburizing, although nitriding is used for parts particularly susceptible to distortion. Carburizing involves the diffusion of carbon from a gas atmosphere while the part is heated to about 1700°F in an atmosphere furnace. After carburizing, the part is quenched, usually in oil, to produce a hard martensitic layer on the surface. The diffusion times used are from 4 to 20 hours, depending on the temperature of treatment and the case depth required. The case depth is related to the pitch of the gear and is increased as the size of the gear is increased to produce the correct residual stress pattern. Nitriding involves the diffusion of nitrogen from a gas atmosphere in a temperature range of 925° to 1050°F. After nitriding, the parts are hard without quenching, and they have some degree of compressive stresses due to compound formation in the surface layers. Nitriding takes anywhere from one day to one week due to the slow diffusion rates.

As an alternative to carburizing and nitriding, a hard case may be produced by selective direct hardening. Instead of increasing the carbon content of the steel surface by diffusing extra carbon into the case, the steel composition is selected that already contains from 0.4% to 0.6% carbon. This steel could then be through hardened and tempered in a furnace, but a hard case and tough core can be produced by selectively heating the specified surface to the depth required, leaving the core in the original hardened and tempered condition. Both methods produce a case: one by controlling the depth of carbon or nitrogen diffusion, and the other by depth of heating.

Carburizing

Ask a gear maker what his biggest production problem is, and he usually says "heat treatment." This may be because heat treatment frequently causes significant scheduling and quality problems. Heat treatment, such as carburizing and hardening, takes parts away from the production flow for long periods, heats them to high temperatures, exposes them to complicated gas atomospheres, and finally quenches them. The risks of things going wrong during this treatment are high. It is worth considering some of the factors that makes this type of processing subject to variability in results.

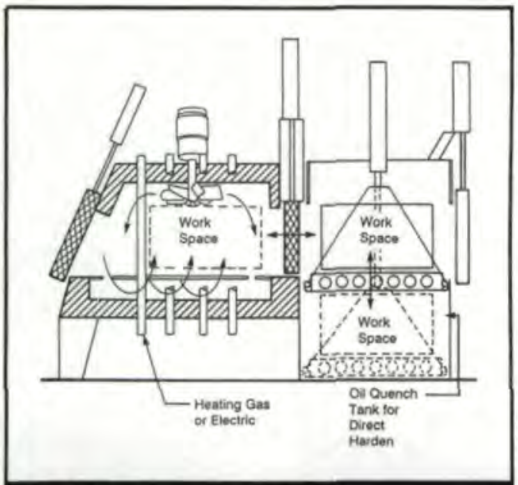


Fig. 1 – Batch-type carburizing furnace.

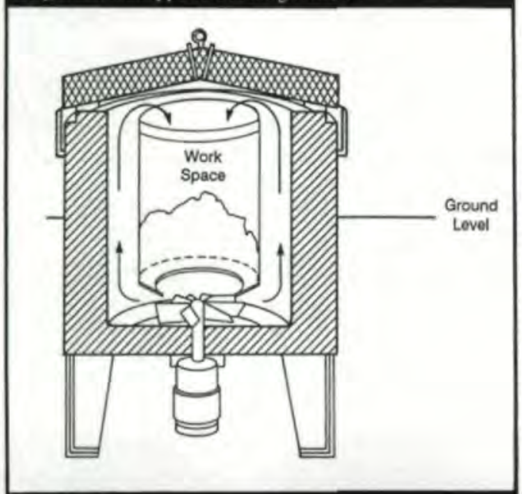


Fig. 2 – Pit-type carburizing furnace.

The furnace itself may be schematically represented by Fig. 1, which shows a typical batch-type furnace supplied with a gas atmosphere from an atmosphere generator. Fig. 2 shows a pit-type furnace which is so called because it is often installed in a pit to make loading the furnace more convenient. The furnace has a circulation system which circulates the atmosphere and helps even out variations in gas composition and in temperature. Government MIL specifications require that furnaces be checked for temperature variation over the load space, but make no requirement for supply of carburizing gas. If areas in the workspace are deficient in temperature or gas circulation, then case carbon and depth of case will suffer.

Carburizing gases are a complex mixture of gasses like N_2, H_2, CO, CO_2, H_2O, CH_4, and O_2, and their carburizing potentials are $(CO)^2/CO_2$ and $CH_4(H_2O)^2$. It is common to measure one component, such as CO_2, CH_4, H_2O, or O_2, and assume that carbon potential is directly related without considering the other component of the ratio, which may be varying due to gas source, air leak, carbon buildup, and other factors. If shim stock is used to assess atmosphere, the measurement gives a good indication of the condition when the shim stock was exposed to the carburizing gas, which may not be the same when the work itself is exposed.

Control of the carbon content is often not very precise,and when consistent results are obtained, it is due to the experience of the heat treatment supervisor rather than scientific control.

The designer's usual choice for treating the highest performance gears is to specify a carburized alloy steel as the material of manufacture. Carburizing diffuses carbon into the steel to a specified depth, the source of the carbon being usually a hydrocarbon-containing atmosphere. After quenching, the higher carbon surface layer hardens, leaving the core at a lower hardness and in a tougher condition. The process should leave the part with high residual compressive stresses in the surface, thus increasing the resistance to fatigue failure. Since the process produces a hard surface layer, it is often referred to as case carburizing.

The source of carbon can be solid, liquid, or gaseous, but for the last 10 years the preferred method has been to carburize in a gaseous atmosphere. This has been because of the lower costs and the possibility of controlling the carburizing conditions. The rate at which carbon is absorbed and diffuses into steel is temperature-dependent: the higher the carburizing temperature, the more quickly a case depth can be attained. The time required to develop case depths of up to 0.100 in. is shown in Fig. 3.

It is possible to reduce carburizing time by increasing carburizing temperature. Fig. 4 shows the

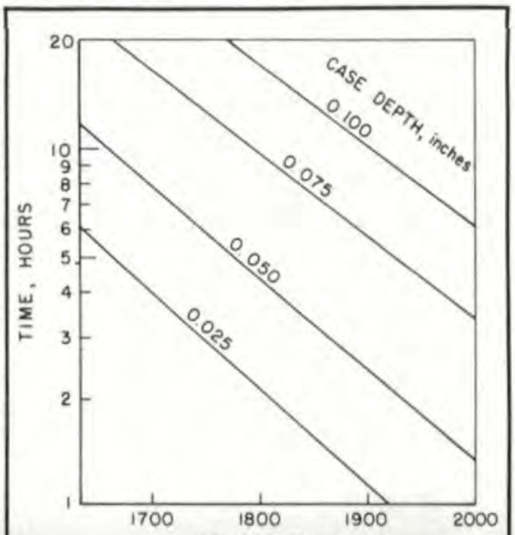


Fig. 3 – Time required to produce a case depth that has a minimum hardness of R_C 55.

Dr. Maurice A. H. Howes

is Director of the IIT/IITRI Gear and Bearing Center and the DLA instrumented factory for gears (INFAC) program. Dr. Howes received his degrees from London University (England) and has worked in manufacturing research and development for over 30 years. He is the author of 60 papers and holds 5 patents.

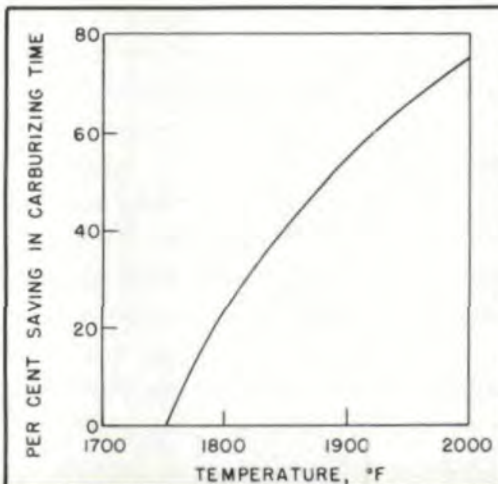


Fig. 4–The effect of processing temperature on carburizing time.

percent savings in carburizing time by increasing the temperature beyond 1750°F.

Control of the Process

Gas carburizing atmospheres can be controlled to be in equilibrium with a wide range of carbon contents. As the surface carbon in a case is gradually increased the hardness of the quenched steel will also rise until it reaches a maximum value. The decrease in hardness from this point is due to retained austenite present in the case. Fig. 5 shows the effect of carburizing a 3310 steel to 0.6% and 1.0% carbon. The carbon increases the hardenability of the steel, but increased carbon depresses the temperatures at which martensite starts to form and at which martensite formation is complete to the 50% and 90% levels. At a case carbon level of 0.6%, martensite formation is complete at above room temperature, but at 1.0% carbon there would be substantial retained austenite, necessitating a subzero treatment to transform it to martensite.

To obtain the desired carbon content in the surface of the case, an atmosphere control system should be installed and well-maintained. Some heat treaters control carbon potential at the desired level through the carburizing cycle; however, others favor a "boost-diffuse" technique, where carbon is introduced to the surface at a much higher level than required in the final case for much of the cycle, and it is reduced to the required level for this last part of the cycle. This is a faster way of introducing the case.

Whichever method is used, atmosphere control is necessary. It is difficult to measure carbon potential directly, but usually some other factor is measurable that is related and can be used for control purposes. The carburizing reactions occurring can be summarized as:

$$2CO \rightleftharpoons C_2 \tfrac{1}{3} CO$$
(in steel)

$$\text{and } CH_4 \rightleftharpoons C \tfrac{1}{3} 2H_2$$
(in steel)

$$\therefore \text{ Carburizing potential } \frac{[CO]^2}{CO_2}$$

$$\text{and } \frac{CH_4}{[H_2]^2}$$

For a particular carrier gas, the concentration of carbon monoxide and hydrogen is roughly con-

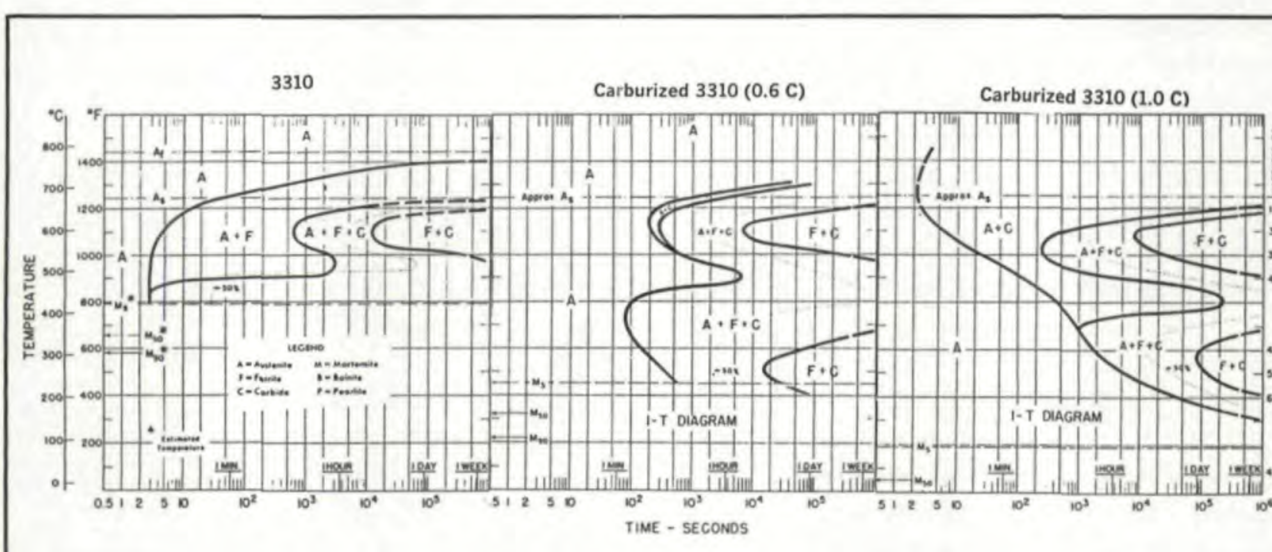


Fig. 5–Effect of case carbon level on isothermal transformation characteristics.

stant for a wide range of carbon potential, therefore increasing the amount of methane or other hydrocarbon. Reducing the carbon dioxide content will increase the carburizing potential. The carbon dioxide will react with hydrogen as follows:

$$CO_2 \ ⅓ \ H_2 = CO \ ⅓ \ H_2O$$

Thus, the carbon dioxide content and water content or dewpoint are interdependent. A high dewpoint will promote the formation of carbon dioxide and, therefore, reduce the carburizing potential.

Methane and other hydrocarbons will react with water as follows:

$$CH_4 \ ⅓ \ H_2O = CO \ ⅓ \ 3H_2$$

Therefore, hydrocarbons may be added to reduce the dewpoint and increase the carburizing potential.

Oxygen potential is related to the carbon potential as follows:

$$C \ ⅓ \ ½ \ O = CO_2$$

Therefore, carburizing potential

$$\frac{CO}{[O_2]^{½}}$$

From this it can be seen that the carburizing potential can be determined by measurement of CO_2, dewpoint, or oxygen level. The relationship between these factors is shown in Fig. 6.

It should be carefully noted, however, that most users of carbon control believe that they are measuring factors relating to carbon potential directly; whereas, actually they are measuring one factor in a ratio and assuming the other factor (usually CO) is constant. If CO, hydrogen, or other components vary, the reactions will shift, making the carbon potential relationship inaccurate. For example, some heat treatment installations generate endothermic gas from natural gas. This is supplied by the local gas company to a calorific value, not to a chemical composition. In time of supply difficulties (mid-winter), the gas company may boost the supply from different fields or even use waste refinery products, causing instability in the gas composition and deviations in case carbon content, even though the control instruments are still showing that everything is under control.

Methods of Carburizing

The majority of gears are carburized in a gas atmosphere usually using natural gas, propane, or nitrogen as the atmosphere source. However, over the last 25 years two other methods have developed, one involving vacuum technology, and the other using plasma.

Gas Carburizing. Gas carburizing using atmospheric pressure treatments in gas-fired or electrically heated furnaces is still the most popular method. Furnace equipment varies widely in construction, but essentially is constructed to be gas-tight and provides means for uniform heating and circulation of the gas atmosphere. For the highest

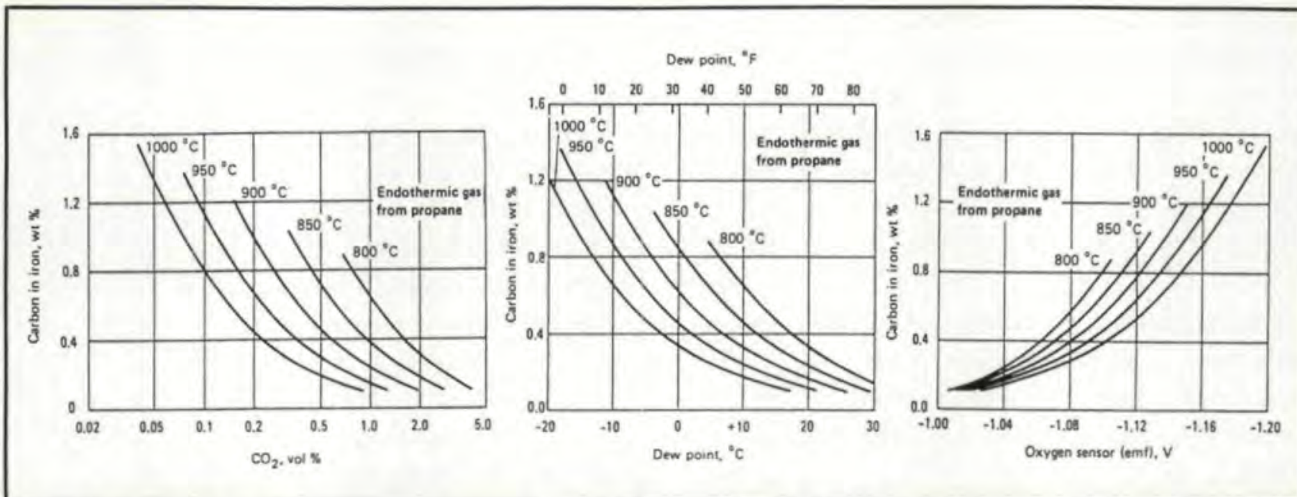


Fig. 6 – Relationship between CO_2, dewpoint and oxygen sensor voltage, and carburizing potential.

quality work, pit furnaces (Fig. 2) are preferred, since temperature uniformity is optimum because of the circular shape, and the fan (generally at the bottom) gives uniform gas and temperature distribution. It is more difficult to automate loading procedure, and direct quenching is not usually possible, since the load is difficult to handle, thus taking a long time to transfer to a quench tank, during which period the parts are not in a protective atmosphere. Many precision gears are treated in pit furnaces, slow-cooled, reheated, and hardened.

Horizontal box furnaces with integral quench (Fig. 1) are used particularly for lower class gears. They are very convenient for load handling, but may suffer from lack of temperature uniformity, particularly near the front loading door. Because of the shape, gas circulation is not uniform, particularly at the extreme corner of the furnace chamber. The circulation system not only supplies the furnace atmosphere, but also is part of the heating system. Deficient circulation leads to lack of atmosphere and lower temperature, both factors adversely affecting case depth.

Continuous furnaces are used for large quantities of gears, often for the automotive industry. Pusher furnaces are developments of the horizontal batch furnaces, and since the parts are moved through different zones during the cycle, more uniform results are possible. Pusher furnaces may be adapted with the last zone at the quench temperature so that gears can be plug- or press-quenched from the furnace.

Vacuum Carburizing. Vacuum carburizing has been used since the early 60s and has developed to a full production process, sometimes with oil quench capabilities. Closed loop carbon control is not currently possible because the gas reactions are out of equilibrium, making it necessary to use a controlled boost-diffuse cycle based on past experience. The furnace is operated under vacuum conditions except under actively carburizing conditions, when a few millimeters pressure of carburizing gas are added, and during the gas cool after carburizing, when the furnace is backfilled with nitrogen. If the furnace is equipped with an oil quench, the load may be reheated under vacuum and quenched without removing it from the furnace.

Vacuum carburizing is often faster because it is carried out at higher temperatures (1800° to 1950°F), rather than the 1700° to 1800°F typically used in gas carburizing. Some gas carburizing furnaces can operate at higher temperatures, and achieve the same carburizing rates as vacuum processing, but a typical gas carburizing furnace takes longer to reach carburizing temperature because of the furnace heat load. Vacuum equipment can be started and shut down in much shorter times than gas carburizers.

The costs of vacuum treating and gas carburizing are likely to be comparable, especially for deeper case depths because of the higher temperature capability. The acquisition costs will also be similar since endothermic generation equipment is not required. Vacuum treatment parts are likely to be cleaner and of more consistent quality.

Plasma Carburizing. This process uses equipment similar to vacuum carburizing, except that the work carrier is electrically insulated from the furnace frame. A DC potential difference is applied across the work, making the work carrier the cathode. A plasma is formed around the work, which is said to enhance the absorption of carbon at the surface of the gear being carburized. Plasma is maintained at a few millimeters of pressure of methane using a DC voltage of 500 to 600 volts. Unlike ion nitriding, additional heating is necessary to achieve carburizing temperatures, and this is accomplished with graphite elements. Carbon level is controlled using a boost-diffuse cycle followed by a controlled cool to about 1550°F, when the parts may be oil quenched.

As with ion nitriding, a high degree of cleanliness is important, and the work carriers must be scrupulously cleaned after use to remove quench oil and other foreign matter. Contamination causes arc-over in the plasma layer, causing the power supply to shut down and restart. Until the parts are clean, a stable plasma will not be established.

The equipment is more costly than a vacuum unit, and the full advantages have yet to be completely documented for gear treatment.

Selective Direct Hardening

Although carburizing is widely used, especially for higher quality gears, it is not a popular process in the manufacturing sequence. Manufacturing engineers do not like it because it is a lengthy batch process done off the main production sequence. Quality engineers dislike it because it is responsible for many quality problems due to variation in case quality and dimensional tolerances. Shop personnel may be disenchanted when their beautifully machined parts are ultimately returned looking burnt, twisted, and unrecognizable.

To overcome some of these disadvantages, selective direct hardening is often applied. In this process the hard case is produced by heating the surface layer only to above the austenitizing temperature and rapidly quenching, leaving the core in the original condition. Carburizing is not necessary because a medium carbon steel is used with the required carbon already in the steel. Since a large proportion of the part remains cool, thus stabilizing the material, distortion is much less than if the entire part were heated. The higher carbon content material compared with a carburized grade may make machining more difficult. Four methods have been used for selective heating for direct hardening of cases. All rely on applying a large amount of energy in a short time.

Flame Hardening. Flame hardening is probably the oldest selective hardening process and, as the name suggests, it employs direct flame contact with the surface being hardened. With coarse pitch gears, individual teeth may be hardened, but with finer pitches, a gear may be spun in a ring of gas burners. Flame hardening, even with oxy-gas fuels, does not provide as rapid an energy transfer as the other methods discussed, and thus has difficulty in producing a hard case of less than about 0.050 to 0.100 in. deep. However, in situations where flame hardening will meet the required specifications and quality levels, it is the lowest cost method. As with induction hardening, self-quenching is usually not possible, and an external quench is necessary.

Induction Hardening. Induction hardening is achieved by using an alternating current in a work coil surrounding the part to be heated. The entire circumference of small gears may be heat treated at the same time, but coils may be designed to treat one tooth at a time if the tooth pitch is such that individual teeth are large. An alternating magnetic field is established that induces a potential in the part, causing a current to flow in the closed circuit. Heating is produced by the resistance to the induced current. The rate of heating depends on the strength of the magnetic field. The depth of the field varies inversely with the frequency of alternation. The higher the frequency, the more shallow the heating effect.

If the circular coil is used to heat a gear, then the tips of the gear are closer or better coupled to the coil, and, thus, they heat more, resulting in a deeper case depth. Techniques are available to reduce this effect, such as pulse or dual frequency hardening.

After the heating is complete, the current is turned off, and the part is quenched by synchronized jets of a quenching fluid, usually water-based.

Laser Heat Treatment. Laser heat treatment is a surface-hardening process in which laser energy is used to heat the surface to above the austenitizing temperature. When the source of energy is removed, the part self-quenches, owing to the diffusion of heat into the mass of the part. This is made possible by the extremely rapid heating rate that the laser can achieve. As the rate of heat input increases, the depth of hardening is reduced, since the temperature gradient becomes

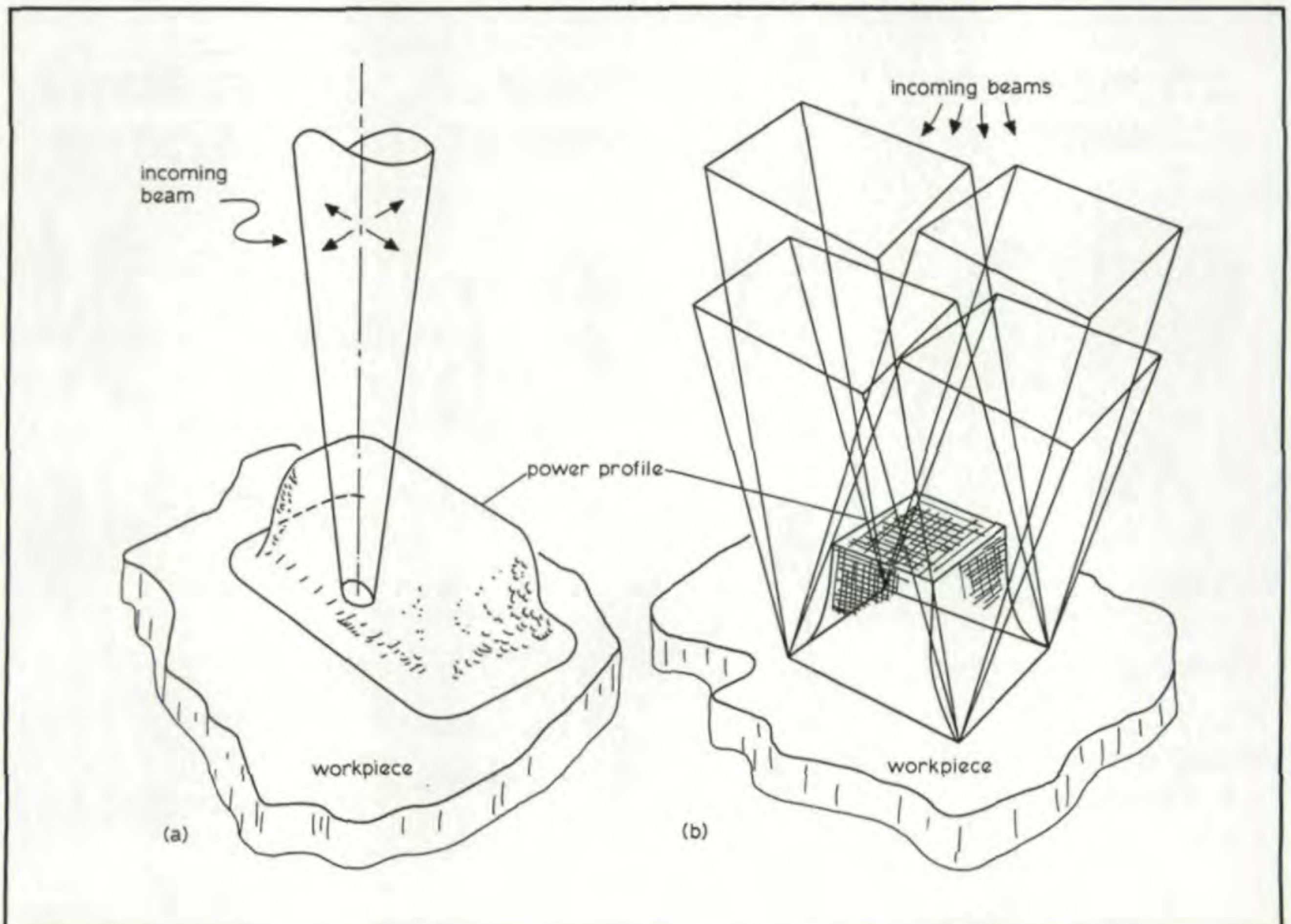
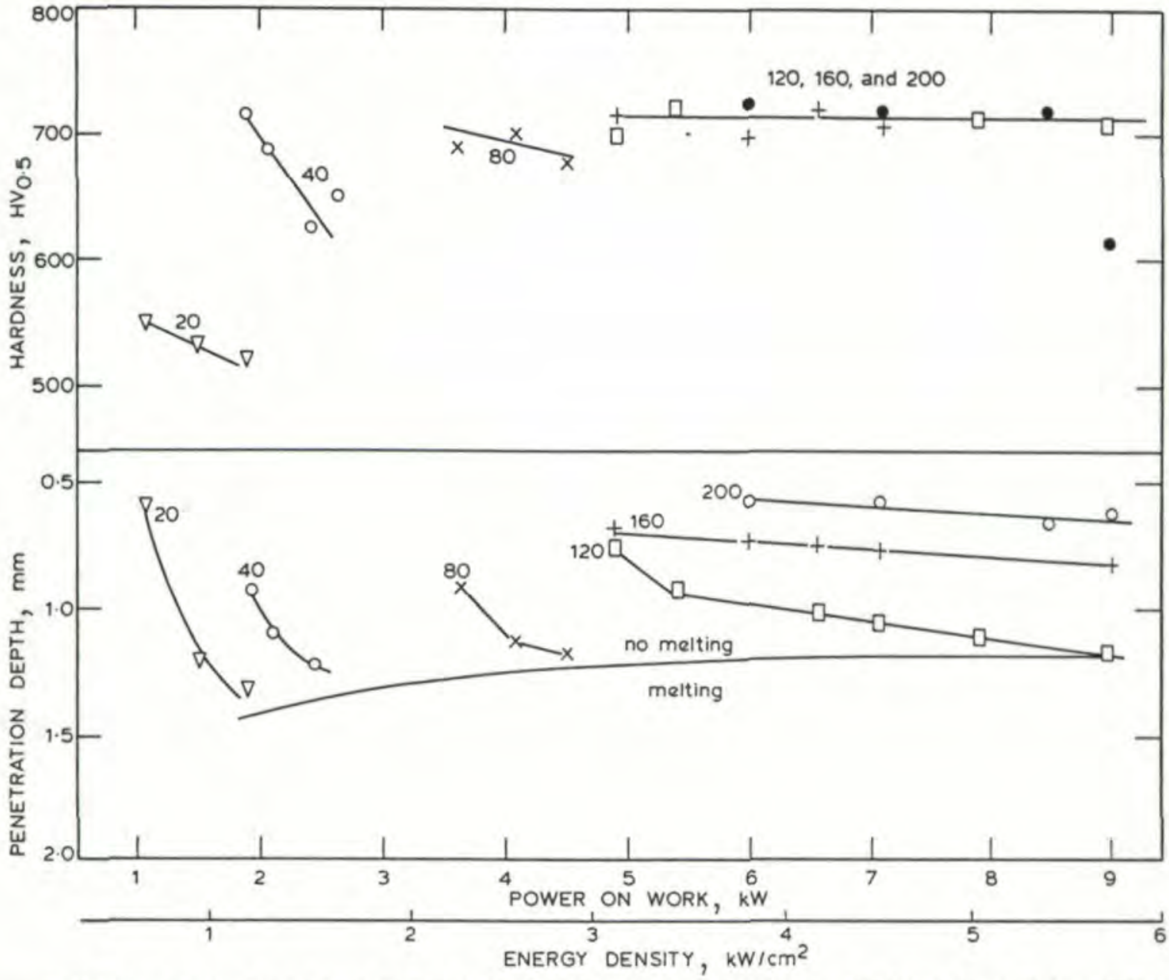


Fig. 7 – Representation of power distribution with (a) oscillator optics and (b) integrator optics.



speed of work travel, cm/min, indicated for each curve; transverse oscillation 450 Hz; axial oscillation 120 Hz; pattern 1·27 × 1·27

Fig. 8 – Hardness and depth of penetration obtained with oscillating optics (F105) on AISI 1045 steel using a manganese phosphate coating.

steeper, and the surface temperature is limited by the need to avoid melting.

The method of applying the energy becomes a critical part of the heat treatment process. If a sharply focused laser beam is used, then the hardened zone becomes quite narrow, although it is more usual to use a defocused beam to increase the area over which the laser energy is spread. This, however, represents the most unsophisticated way of controlling the heat treated area and, in a modern work station, other types of optics would be preferable.

Two of these methods are illustrated in Fig. 7. Fig 7a shows the use of oscillating optics, in which a defocused beam is oscillated in two directions to produce a rectangular patch of energy. Oscillation frequency is typically 100 to 500 Hz in both directions. This method also allows control of the shape of the energy patch. Fig. 7b shows the use of integration optics using a faceted mirror. The beam is broken into segments and recombined with or without magnification at a plane in space that coincides with the location of the work surface. This method is lower in cost than oscillation equipment, but will only produce a fixed shape energy patch.

Laser Power. The influence of power on penetration is direct, but not linear. Useful tradeoffs can be made if low-speed processes can be tolerated. For example, in Fig. 8 power levels as low as 1 kW produced slight hardening with the ½ x ½ mm rectangular spot in these tests. At 2 kW significant surface hardness occurred if the speed was increased from 20 cm/min to 40 cm/min, and a reduction of 0.5 m (30%) could be tolerated in depth of hardening. The suggestion here is that speed or exposure time is a more important process element than power, per se.

In fact, increasing power at a given speed was clearly detrimental to hardening until relatively high speeds were reached in Fig. 8.

The power at which surface melting occurs is directly related to speed in Fig. 8, and the boundary formed by this relationship forms the major process limits.

Speed of beam. It is possible to interchange speed and power to achieve a given depth of hardening for a specific beam impingement area (a ½ x ½ in. rectangle in this case). For example, in Fig. 8, a hardened depth of 1 mm can be obtained at 7 kW, and 160 cm/min or at 2 kW at 40 cm/min. If the lower speed satisfies production requirements, the potential for a reduction in capital expenditures is clear. However, the 40 cm/min process is sensitive to power variations in terms of both penetration and hardness. For example, a 0.4 kW increase in power reduced hardness from 725 HV to 685 HV. At the same time, penetration increases by 0.3 cm. Such sensitivity places a premium on accuracy of beam generation (and delivery). Rejection rates may be increased in the lower speed procedures outlined in Fig. 8.

Electron Beam Heat Treating. This method is similar in principle to laser heat treating, except that heating is achieved by an accelerated stream of electrons instead of a light or infrared beam. When the electron beam is turned off, the part self-quenches. Many of the same considerations apply that are true for laser processing, but there are basic differences in the equipment used. The beam and workpiece are manufactured in a vacuum environment, which is not necessary with a laser, and this requirement introduces some complications into the fixturing. Another difference is in beam manipulation, since laser energy may be directed and focused by mirrors, and an electron beam is manipulated by magnetic coils.

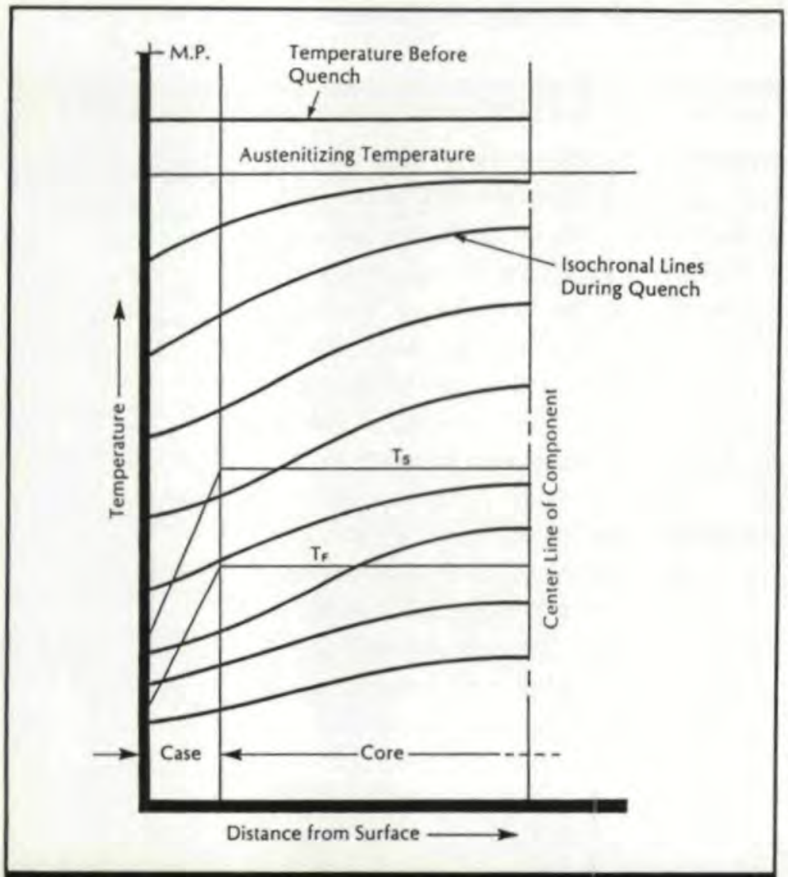


Fig. 9 – Temperture distribution in steel parts during quench after carburizing.

However, electron beams have some important advantages. First, the cost of electron beam power is lower than laser energy, since the conversion efficiency is higher. Secondly, higher electron beam power is available, and while a 40 kW electron beam gun is commonplace, a 15-20 kW laser is very large. The third advantage, which is not generally exploited, is the availability of programmable raster patterns. While laser beams may be patterned by oscillating optics and integrator optics, the pattern produced is not capable of the flexibility made possible by scanning an electron beam. This could be of particular importance in hardening complex geometric shapes, such as gear teeth, where different amounts of energy are required on different parts of the surface as the geometry changes. Electron beam equipment may be more compatible with CNC controls, particularly in a flexible manufacturing situation.

Residual Stress Patterns

One advantage of case carburized parts is that when the treatment is properly carried out, it leaves a compressive stress system at the surface. Compressive stresses help counteract tensile stresses produced during bending fatigue and contact fatigue and, thus, increase the expected life. Fig. 9 represents conditions during the quenching of a carburized part. This part has been carburized and heated to a temperature above the austenitizing temperature and then quenched. The isochronal lines show how the surface cools faster than the center of the section because heat is abstracted from the surface by the quenching media. This trend continues right through the quenching process. Fig. 9 also shows lines representing the start of martensitic transformation (T_S) and the finish of transformation (T_F). It will be seen that these temperatures are depressed as the case carbon increases. The net result is that transformation of austenite to martensite starts at the case/core interface with an expansion as martensite is formed. The case is the last material to transform, and the expansion to martensite causes compressive stresses because the core is already transformed and restrains the case.

The situation is different in selective hardening (Fig. 10), but the results are similar. Energy is transmitted quickly into the surface, resulting in a surface layer heated above the austenitizing temperature. This layer will later become the hardened case. When the energy is turned off, rapid cooling progresses, and again the case is the last to transform, and the restraint induces residual compressive stresses as the surface expands during transformation from austenite to martensite.

Nitriding

Nitriding is an alternative case hardening process often specified for gears when distortion would be difficult to control if the gear were case carburized and quenched. In nitriding, nitrogen is introduced into the surface of the steel at relatively low temperature (925° to 1050°F) from a nitrogen-containing atmosphere, such as ammonia. A hard case is produced by the formation of hard compounds in the surface, making quenching unnecessary.

Special steels are needed for nitride containing elements, such as aluminum or chromium, that will form hard nitrides during treatment. The steel is nitrided in the hardened and tempered condition. The process is controlled by adjusting the dissociation of the ammonia. More often the Floe process is used, which is a double stage process analogous to the boost diffuse cycle in carburizing. In the first stage, the dissociation level is controlled at 15 to 30% by using a temperature range of 925° to 975°F, producing a white nitride layer which is diffused in the second stage by increasing the dissociation to 80 to 85%. The high dissociation can be achieved by increasing the temperature range to 1025° to 1050°F and using an external dissociation. Even with the two-stage process, nitriding is slow, taking about a day (24 h) to produce a 0.020 in. case. The process produces very hard cases with minimum distortion. Volume increases during nitriding cause favorable compressive stresses to build up in the case.

Ion Nitriding. Ion nitriding or plasma nitriding is similar to plasma carburizing in that a plasma is formed around the work during treatment. It is claimed that the process gives more reproducible results and a shorter process time.

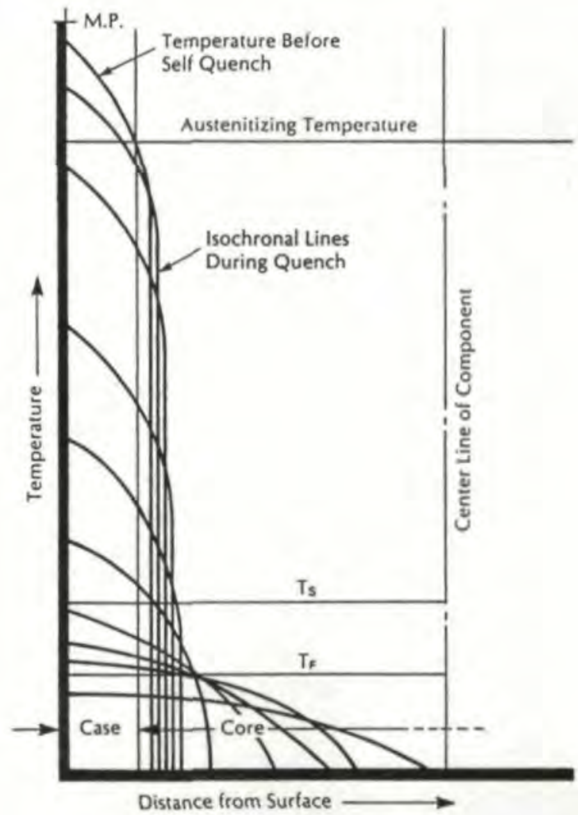


Fig. 10 – Temperature distribution in a steel part after laser heat treatment.

Dimensional Problems Caused by Heat Treatment

It is believed that heat treatment causes more quality problems than any other manufacturing step. This is because heat treatment causes dimensional changes due to volume changes, resulting from phase transformation. Distortion is caused by a combination of geometric factors and stress relief. These two factors acting together often cause unpredictable results. Variables that contribute to the dimensional changes include:

- Variations in material composition
- Residual stress differences
- Size of part (within tolerance range) before heat treatment
- Surface condition
- Carburizing heating cycle
- Carburizing atmosphere control
- Depth of case
- Quenching parameters
- Quenching die dimensions
- Post heat treatment.

Gear manufacturers hope to bring the component size under control in the finish grinding or hard turning stage. This leads to a dilemma: if excess material is left on the part prior to heat treatment, there will be enough stock to enable the size to be brought under control: however, if too much is taken off, the most effective parts of the carburizing (or nitrided) case are removed. Fig. 11 shows excessive material being removed from a tooth after heat treatment. In the example shown in Fig. 12, the tooth has distorted to the right, and to correct the profile, excess stock has to be ground from the right side of the tooth. This has several serious consequences.

First, there is lack of uniformity in case depth leading to uneven residual stress distribution. Second and worse is that the gear appears satisfactory in a nondestructive inspection, even though the performance of the gear will be less than optimum. Third, a considerable thickness of material has to be removed during grinding, increasing the probability of grinding burns. There is little doubt that some problems that are blamed on grinding can in reality be traced back to heat treatment. Thus the effects of the heat treatment process have to be considered before and after the process in both the soft machining and hard finishing stages. The attraction of selective direct hardening processes that minimize distortion and can be done on the manufacturing floor, reducing the work in

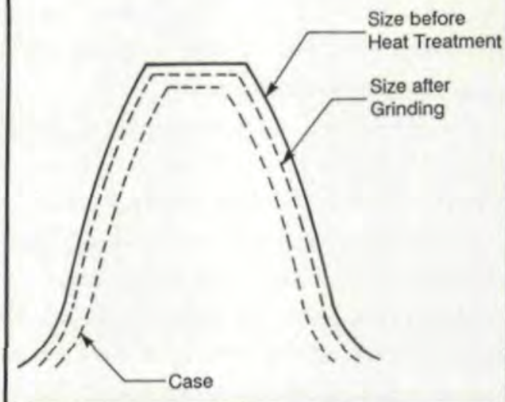


Fig. 11 – Schematic of material ground from gear tooth.

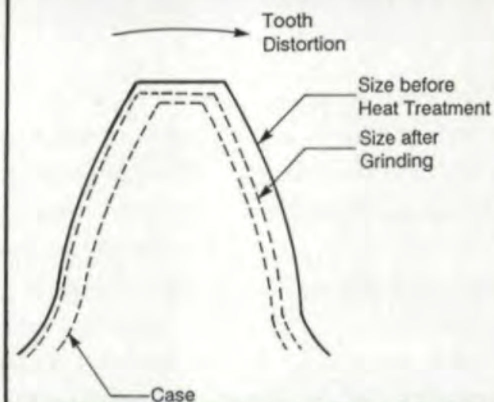


Fig. 12 – Schematic of material ground from a distorted gear tooth.

Table 1. Comparison of Case Hardening Processes

Process	Cost of Equipment	Cost of Operating	Quality of Product	Environmental Effects	Time Taken to Complete Process	On-Line Process
Case Hardening						
Gas carburizing	M	M	M	H	M	N
Vacuum carburizing	M-H	M	M	L	M	N
Plasma carburizing	H	M-H	H	L	M	N
Nitriding	M	H	H	M	H	N
Ion nitriding	H	H	H	L	H	N
Selective Direct Hardening						
Flame hardening	L	L	L-M	M	L	Y
Induction	M	L	M-H*	L	L	Y
Laser	H	L	H*	L	L	Y
Electron beam	H	L	H*	L	L	Y

Legend: H = high; M = medium; L = low; Y = yes; N = no.

*Design engineering may be reluctant to change from carburizing to direct hardening since a material change is necessary, and an extensive acceptance testing program may be required.

Note: Lot size should be considered when selecting a case hardening process, since small lots sizes often mean the use of smaller, less automated equipment. It may be difficult to justify the tooling usually required in a direct hardening process if only a few parts are contemplated.

progress, become apparent, and there will be serious attempts to use these processes wherever possible.

Conclusions

Cost comparisons between plants and companies are difficult to make because of variables, such as energy costs, labor costs, part geometry, lot size, and accounting practice, but Table 1 attempts to compare generally perceived costs together with product quality and the environmental effect of the process.

In diffusion type processes, gas carburizing is the most generally used process using endothermic gas atmospheres. Vacuum and plasma carburizing are slowly being introduced as cleaner, more consistent processes. If distortion is difficult to control, then nitriding or the newer ion nitriding is used. All of the above processes are done in a special heat treatment area off the production area.

The size of batch-type heat treatment equipment is often determined by the lot size and quantity of parts to be treated. Large volume producers may use continuous carburizing furnaces, while small job shops may use much smaller base furnaces. Small work lots may be accumulated to make a full furnace load if the parts are of comparable size and require the same case depth.

Production engineers would like to heat treat gears as part of the manufacturing sequence on machines situated in the production line. This is achievable by selective direct hardening, which can be done by one of several methods in times comparable with the manufacturing process. However, a medium carbon steel has to be used, which can be more difficult to machine and causes designers concern that a direct-hardened gear may not be equivalent to a carburized gear for power transmission purposes. The selection of a direct hardening process and equipment may be influenced by lot size, since it may not be feasible to provide the necessary tooling for treating a few parts.

Process selection is often determined by the available equipment, but it is worth knowing all the options that are available to the gear maker, particularly when difficulties are encountered or new equipment is purchased.

Acknowledgement: *Reprinted with permission of the American Gear Manufacturers Association. The opinions, statements and conclusions presented in this paper are those of the Author and in no way represent the position or opinion of the AMERICAN GEAR MANUFACTURERS ASSOCIATION.*