The Through-Hardening Process is generally used for gears that do not require high surface hardness. Typical gear tooth hardness after through hardening ranges from 32 to 48 HRC. Most steels that are used for through-hardened gears have medium carbon (0.3–0.6%) and a relatively low alloy content (up to 3%). The purpose of alloy content is to increase hardenability. The higher the hardenability, the deeper is through hardening of gear teeth. Since strength increases directly with hardness, high hardenability is essential for through-hardening steels. High hardenability, again, has some adverse effect on material ductility and impact resistance. The other drawback of through-hardened gears is lower allowable contact stresses than those of surface-hardened gears. This tends to increase the size of through-hardened gears for the same torque capacity compared with those with surface hardened.

In through hardening, gears are first heated to a required temperature and then cooled either in the furnace or quenched in air, gas, or liquid. The process may be used before or after the gear teeth are cut. If applied before cutting the teeth, the hardness usually is governed and limited by the most feasible machining process. Since these gear teeth are cut after heat treatment, no further finishing operation is needed. On the other hand, gears that are designed for hardness above the machining limit are first cut to semifinish dimensions and then through hardened. In case of some minor heat treat distortion, a finishing operation such as lapping or grinding is very often used to improve the quality of these gears (AGMA class 10 and above); for quality up to class 9, gears are finished cut at least one AGMA class above the requirement prior to heat treatment.

Four different methods of heat treatment are primarily used for through-hardened gears. In ascending order of achievable hardness, these methods are annealing, normalizing and annealing, normalizing and tempering, and quenching and tempering. Sometimes, hardenabilities of through-hardened gears are specified and measured in other scales besides
Rockwell, such as Vickers and Brinell. Table 4.1 shows an approximate relationship among the various commonly used hardness scales.

Table 4.1  Approximate relation between various hardness-test scales

<table>
<thead>
<tr>
<th>Rockwell</th>
<th>Brinell(a)</th>
<th>C</th>
<th>A</th>
<th>30-N</th>
<th>15-N</th>
<th>B</th>
<th>30-T</th>
<th>15-T</th>
<th>Vickers pyramid</th>
<th>Tukon (Knoop)</th>
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(a) Load, 3000 kgf; diam, 10 mm (0.4 in.)

Through-Hardening Processes

Annealing refers to any heating and cooling operation that is usually applied to induce softening. There are two types of annealing—full and process. In full annealing, the steel is heated usually to approximately 38 °C (100 °F) above the upper critical temperature and held for the desired length of time, followed by very slow cooling as in the furnace. The purposes of full annealing are to:

- Soften the steel and improve ductility and machinability
- Relieve internal stresses caused by previous treatment and improve dimensional stability
- Refine the grain structure

In process annealing, the steel is heated to a temperature below or close to the lower critical temperature followed by the desired rate of cooling. The purpose here is to soften the steel partially and to release the internal stresses. In this treatment, grain refinement by phase transformation is not accomplished as it is in full annealing. Process annealing uses temperatures between 550 and 650 °C (1020 and 1200 °F).
Gears with hardness up to 34 HRC are fully annealed by heating to 800 to 900 °C (1475 to 1650 °F) and then furnace cooled to a prescribed temperature, generally below 315 °C (600 °F). Typical hardnesses obtained after full annealing gears of different materials are shown in Table 4.2.

**Normalizing and Annealing.** In general, the term *normalizing* refers to the heating of steel to approximately 38 °C (100 °F) above the upper critical temperature, followed by cooling in still air. The normalizing and annealing process is used, either singularly or in a combination, as a grain structure homogenizing for alloy steel gears. The process also is used to reduce metallurgical nonuniformity such as segregated alloy microstructures from previous mechanical working. A hypoeutectoid steel consisting of a structure of ferrite and coarse pearlite may be made easier to machine if the ferrite and cementite are more finely distributed. A very soft steel has a tendency to tear in machining; therefore, some increase in hardening obtained by normalizing leads to a more brittle chip and thus improves machinability. Some through-hardened gears may just require hardness obtained with normalizing and annealing.

**Normalizing and Tempering.** Normalizing consists of heating gears to 870 to 980 °C (1600 to 1800 °F) and then furnace cooling in still or circulated air. This process results in higher hardness than annealing, with hardness being a function of the grade of steel and gear tooth size. However, normalizing does not increase hardness significantly more than annealing does, regardless of tooth size for plain carbon steels containing up to 0.4% carbon. But it definitely helps to ensure homogeneous microstructure of steels. After normalizing, alloy steel gears are tempered at 540 to 680 °C (1000 to 1250 °F) for uniform hardness and dimensional stability.

**Quench and Temper.** The quench and temper process involves heating the gears to form austenite at 800 to 900 °C (1475 to 1650 °F), followed by quenching in a suitable media such as oil. The rapid cooling causes the gears to become harder and stronger by the formation of martensite. Hardened gears then are tempered at a temperature, generally below 690 °C (1275 °F), to achieve the desired mechanical properties. This process is the most commonly used for through-hardened gears.

Tempering lowers both the hardness and strength of quenched steels but improves materials properties such as ductility, toughness, and impact...
resistance. The tempering temperature must be carefully selected based on the specified hardness range, the quenched hardness of the part, and the material. Normally, the optimum tempering temperature is the highest temperature possible while maintaining the specified hardness range. It is to be remembered that hardness after tempering varies inversely with the tempering temperature used. After tempering, parts usually are air cooled at room temperature.

Some steels can become brittle and unsuitable for service if tempered in the temperature range of 430 to 650 °C (800 to 1200 °F). This phenomenon is called temper brittleness and generally is considered to be caused by segregation of alloying elements or precipitation of compounds at ferrite and austenite grain boundaries. If the gear materials under consideration must be tempered in this range, investigation to determine their susceptibility to temper brittleness is needed. Molybdenum content of 0.25 to 0.50% has been shown to eliminate temper brittleness in most steels. (Note: Temper brittleness should not be confused with the temper embrittlement phenomenon that sometimes results from tempering at a lower temperature range, such as 260 to 320 °C, or 500 to 600 °F.)

The major factors of the quench and temper process that influence hardness and material strength are:

- Material chemistry and hardenability
- Quench severity
- Section size
- Time at temper temperature

Of the four commonly used through-hardening processes, the quench and temper method is used widely, particularly when:

- The hardness and mechanical properties required for a given application cannot be achieved by any of the other three processes.
- It is necessary to develop mechanical properties (core properties) in gears that will not be altered by any subsequent heat treatment such as nitriding or induction hardening.

Typical hardness ranges achieved for different materials after through hardening by different processes are illustrated in Table 4.2.

**Some Hints on Through-Hardened Gear Design**

After finalizing a design, a gear designer needs to specify the following information on a through-hardened gear drawing. This information will
help to minimize confusion for all involved with gear manufacturing and material procurement:

- Grade of steel with Aerospace Material Specification (AMS), if applicable
- AMS specification for material cleanliness, if required
- Hardnesses on tooth surface and at the core
- Gear quality level

Each hardness callout should have at least a range of 4 points in HRC scale or 40 points in Brinell hardness (HB). Also, specify a tempering temperature range on the drawing. This allows gear manufacturing engineers to select a particular tempering temperature for a specified hardness.

**Hardness Measurement**

The hardness of through-hardened gears generally is measured either on the gear tooth end face or rim section. This is the hardness that is used for gear rating purposes. Sometimes, achieving specified hardness on tooth end face may not necessarily assure the desired hardness at the roots of teeth because of grade of steel, tooth size, and heat treat practice. If gear tooth root hardness is critical to a design, then it should be specified and measured on a sample (coupon) processed with the gears. However, needless increase of material cost by selecting a higher grade of steel should be avoided.

**Heat Treat Distortion of Through-Hardened Gears**

All steel gears experience distortion during a heat treat process. It is a physical phenomenon and cannot be eliminated from any heat treat operation, although distortion of through-hardened gears is not as severe as in other processes discussed in Chapters 5, 6, and 7. Still, through-hardened gears, particularly quench and tempered class, experience enough distortion that will eventually lower the quality level of gears after heat treatment. This necessitates a finishing operation for higher quality. In general, some materials expand after a through-hardening operation while others contract. This requires a suitable stock allowance to be provided on teeth for finish machining before heat treatment of gears that are likely to distort. The allowance needs to include expansion or contraction of material and also distortion of tooth geometry. For materials with predictable and uniform distortion, gears could be cut to include the distortion so that no finishing operation is required, possibly up to AGMA class 10 gear tooth quality. A great majority of materials
listed in Table 4.2 seem to expand during the through-hardening process, whereas a few materials such as maraging steel are found to contract. The amount of expansion or contraction depends on alloy content, quality of steel, and configuration of gears. In this regard, knowledge of distortion characteristics is helpful in optimizing the manufacturing process of gears. When gears are made from a material without any previous heat treat distortion data, an experimental investigation is beneficial to establish the distortion characteristics of the material. With such data, cost-effective manufacturing methods can be established. An investigation of this nature carried out by an aerospace company to determine the heat treat distortion characteristics of a through-hardened gear rack for an aerospace application is discussed at the end of this chapter. Table 4.3 shows a comparative distortion rating of some preferred through-hardening materials for gears.

### Applications

Of the four different through-hardening processes described, those gears hardened by quenching and tempering have some limited use in power transmission applications. The other three processes are only employed to either improve machinability or to enhance homogeneous grain structure of the gear steel. Use of through-hardened gears is limited because of the low surface hardness that results in low gear pitting life and low power density gearbox compared with the one made with case-hardened gears. Also, for similar torque capacity, through-hardened gears are larger with higher pitch line velocity. This increases dynamic problems substantially in a gearbox. However, in a bending strength limited design, through-hardened gears sometimes are successfully used, particularly for large gears (over 508 mm, or 20 in., OD) that normally exhibit high distortion if a case hardening process is used. An example for such an application is the internal ring gear of an epicyclic gearbox. These gears are usually designed with hardness in the range of 32 to 34 HRC that can be finish cut after hardening, thus eliminating costly finishing operations. Through-hardened gears also are found to be effective in applications susceptible to gear scuffing. It is claimed that profile conformance of through-hardened gears, because of their low surface hardness, reduces sliding friction and thereby helps to increase scuffing resistance.

### Table 4.3 Distortion ratings of through-hardened gears

<table>
<thead>
<tr>
<th>Material</th>
<th>AMS specification</th>
<th>AMS quality</th>
<th>Hardness (HRC)</th>
<th>Distortion rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 4340</td>
<td>6414</td>
<td>2300</td>
<td>48/50</td>
<td>Good(a)</td>
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<tr>
<td>Maraging 250</td>
<td>6520</td>
<td>2300</td>
<td>49/52</td>
<td>Predictable and good(a)</td>
</tr>
<tr>
<td>Maraging 300</td>
<td>6521/6514</td>
<td>2300</td>
<td>52/56</td>
<td>Predictable and good(a)</td>
</tr>
<tr>
<td>AISI 4140</td>
<td>6382</td>
<td>2300</td>
<td>48/50</td>
<td>Good(a)</td>
</tr>
</tbody>
</table>

(a) Within one AGMA class of gear quality.
Overall, through-hardened gears are used in gearboxes that require large gears that cannot be economically case hardened, such as large marine propulsion gears and railway power transmission gears.

Case History: Design and Manufacture of a Rack

As explained in this chapter, all steel gears distort after any type of heat treat process. Carburizing imparts the highest distortion, while through hardening imparts the least distortion. Even then, distorted gears require a finishing operation for higher tooth quality. Sometimes, for through-hardened gears, the knowledge of distortion characteristics may be included in the design of gear cutting tools such that gears after heat treatment meet the desired quality. Such a case history is presented here.

The project was to develop a low-cost, high-bending strength (minimum of 250 ksi, or 1720 MPa, ultimate tensile strength) corrosion-resistant rack. For this application, the quality required was rack teeth of AGMA class 9. To minimize manufacturing cost, it was decided not to consider any post-heat-treat finishing operation. To meet these criteria, selection of a proper material and a process was vital, for which the following investigation was carried out. The dimensions and configuration of the rack are shown in Fig. 4.1.

Material Selection

Table 4.4 shows the chemical compositions of various materials with the positive and negative attributes of each and the associated heat treat process considered before selecting the material for racks.

Fig. 4.1 Rack dimensions (in.) for preliminary tests. DP, diametral pitch; PA, pressure angle
Option 1: Use of Quench-Hardening Steels. The following steels were considered:

- AISI 4340
- 300M
- HP 9-4-30
- H-11

An excellent survey was made from published literature to determine the various properties of each, with the following results and conclusion:

**Results.** High heat treat distortion:

- Grinding of rack is necessary after heat treatment to attain the required accuracy of teeth.
- High cost of material
- Poor corrosion resistance; additional process needed to make racks corrosion resistant

**Conclusion.** None of these materials was found suitable for the application.

Option 2: Use a Precipitation Hardening Steel. Steels considered:

- 17-4 PH
- 13-8 Mo

**Results** were as follows:

- Attainable mechanical properties were not at specified strength level.
- Heat treat distortion was not predictable.
- Sensitive to grind burns
- Problems with alloy segregation for any post-heat treat finishing, in section size needed

**Conclusion.** Materials were not suitable.

Table 4.4 Chemical composition of steels considered for racks

<table>
<thead>
<tr>
<th>Material</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
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(a) Courtesy Republic Steel Corporation, Cleveland, Ohio
Option 3: Use an Age-Hardening Steel (Maraging C-250). This maraging steel has high nickel (18% or more), very low carbon (under 0.03%), and is capable of developing very high tensile and yield strengths by means of an aging process. It is sold in the martensitic state, which, because of the low carbon, is soft enough to be readily machinable. Heating to approximately $480 \, ^\circ C$ ($900 \, ^\circ F$) for aging, and cooling in the furnace, causes a change in material microstructure that increases the hardness up to 52 HRC. This meets the required tensile strength.

Results were as follows:

- Published literature indicated distortion of maraging C-250 steel is predictable.
- The material is available as forged, as well as in bar form, to AMS 6412. Sheet or plate stock available to AMS 6420 was not acceptable due to nonuniform distribution of mechanical properties.

Conclusion. Maraging C-250 forgings met the design requirements and were selected for this application.

Process Selection

Heat Treat Distortion of Racks Made of C-250. Although published literature indicated distortion of maraging C-250 material is predictable, it was still necessary to find out how much the distortion would be for a rack tooth used in this application. To determine these characteristics, a preliminary investigation was undertaken with racks made from readily available C-250 of shorter lengths (305 mm, or 12 in., long); longer lengths were not commercially available at the time of this investigation. To expedite the program further, a standard shaper cutter was used to cut the teeth. The racks were then heat treated.

Heat Treatment of Racks. Some preliminary experiments were conducted to select a suitable heat treat furnace. The following furnaces were considered:

- Partial vacuum furnace
- Full vacuum furnace
- Air furnace

Heat treatment in the air furnace was not acceptable due to:

- Oxidation of racks
- Scale removal resulted in size change.

Both full and partial vacuum furnaces produced oxidation-free racks.

Conclusion. Full vacuum furnace that ensures oxidation-free parts was selected to determine heat distortion.
Twelve racks were selected for heat treatment. All critical dimensions of the racks were inspected and recorded before heat treatment. 

**The heat treat procedure** consisted of the following steps:

- Vapor degrease racks
- Wipe racks with a cleaning chemical such as acetone
- Select any two racks
- Hold the racks together back to back with nickel-plated bolts—processed horizontally on a flat base in the furnace
- Heat treat racks along with one tensile test bar in each production lot, at $480 \pm 6 \degree C$ ($900 \pm 10 \degree F$) for 4.5 h at this temperature
- Furnace cool racks

**Inspection** consisted of:

- Critical rack dimensions after heat treatment
- Mechanical properties of material such as hardness and tensile strength

**Results.** From the experimental results and inspection, the following conclusions were made:

- Contraction rate of maraging steel was between 0.0005 and 0.0007 mm/mm (in./in.) and found to be linear and consistent in each lot.
- Parts remained flat after the hardening process.
- Pitch and accumulative pitch errors were within acceptable limit.
- Teeth perpendicularity (lead errors) were between 0.013 and 0.025 mm (0.0005 and 0.001 in.).
- Pitch dimensions measured over a pin were held to 0.038 to 0.076 mm (0.0015 to 0.003 in.).

**Recommendations** included:

- Design of rack to include 0.076 mm (0.003 in.) tolerance for pitch dimension over the pin
- Tooth perpendicularity (lead) error to 0.025 mm (0.001 in.)
- A shaper cutter to be developed to include 0.0006 mm/mm (in./in.) contraction rate of rack tooth geometry with the expectation that this might eliminate finish processing of racks after heat treatment.

**New Shaper Cutter.** With the proposed contraction rate, a shaper cutter was designed and manufactured by a cutter manufacturing company. Figure 4.2 shows the dimensions of this special cutter. An investigation was then carried out with full-length racks.