**Tempering of Steel**

By the ASM Committee on Tempering of Steel*

TEMPERING OF STEEL is a process in which previously hardened or normalized steel is heated to a temperature below the transformation range and cooled at a suitable rate, primarily to increase ductility and toughness. Steels are tempered by reheating after hardening to obtain specific values of mechanical properties and to relieve quenching stresses and ensure dimensional stability. Tempering usually follows quenching from above the critical temperature; however, tempering also is used to relieve the stresses and reduce the hardness developed during welding, and to relieve stresses induced by forming and machining.

**Principal Variables**

Variables associated with tempering that affect the microstructure and the mechanical properties of a tempered steel include temperature; time at temperature; cooling rate from the tempering temperature; and composition of the steel, including carbon content, alloy content and residual elements. In a steel quenched to a microstructure consisting essentially of martensite, the iron lattice is strained by the carbon atoms, producing the high hardness of quenched steels. On heating, the carbon atoms diffuse and react in a series of distinct steps that eventually form Fe₃C or an alloy carbide in a ferrite matrix of gradually decreasing stress level. The properties of the tempered steel are determined primarily by the size, shape, composition and distribution of the carbides that form, with a relatively minor contribution from solid-solution hardening of the ferrite. These changes in microstructure usually decrease hardness, tensile strength and yield strength but increase ductility and toughness.

Under certain conditions, hardness may remain unaffected by tempering or may even be increased as a result of it. For example, tempering of a hardened steel at very low tempering temperatures may cause no change in hardness but may achieve a desired increase in yield strength. Also, those alloy steels that contain one or more of the carbide-forming elements (chromium, molybdenum, vanadium and tungsten) are capable of "secondary hardening"—that is, they may become somewhat harder as a result of tempering.

The tempered hardness values for several quenched steels are presented in Table 1. Temperature and time are interdependent variables in the tempering process. Within limits, lowering temperature and increasing time usually can produce the same result as raising temperature and decreasing time. With few exceptions, tempering is done at temperatures between 175 and 700 °C (350 and 1300 °F) and for times from 30 min to 4 h.

**Tempering Temperature.** Several empirical relationships have been made between the tensile strength and hardness of tempered steels such that measurement of hardness is commonly used to evaluate the response of a steel to tempering. Figure 1 shows the effect of tempering temperature on the hardness, tensile and yield strengths, elongation, and reduction in area of a plain carbon steel (AISI 1050) held at temperature for 1 h. Note that both room temperature hardness and strength decrease as the tempering temperature is increased. Ductility at ambient temperatures, as measured by either elongation or reduction in area, increases with tempering temperature.

Whereas elongation and reduction in area increase continuously with tempering temperature, toughness, as measured by a notched-bar impact test, varies with tempering temperature for most steels as shown in Fig. 2. Tempering at temperatures from 260 to 320 °C (500 to 610 °F) decreases impact energy to a value below that obtained at about 150 °C (300 °F). Above 320 °C, impact energy again increases with increasing tempering temperature. Both plain carbon and alloy steels respond to tempering in this manner. The phenomenon of impact-energy minima centered around 300 °C (570 °F) is called "500 °F temper embrittlement" or "blue brittleness". This phenomenon will be discussed more thoroughly in a subse-

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quenched to develop full hardness.

### Table 1 Typical hardnesses of various carbon and alloy steels after tempering

<table>
<thead>
<tr>
<th>Carbon content, %</th>
<th>Heat treatment</th>
<th>Hardness, HRC, after tempering for 2 h at:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>280</td>
</tr>
</tbody>
</table>

| Grade | 0.30 | 0.40 | 0.50 | 0.60 | 0.80 | 0.95 | 0.40 | 0.40 | 0.40 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
|-------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|       | 50   | 51   | 52   | 56   | 57   | 58   | 44   | 49   | 55   | 44   | 47   | 55   | 47   | 47   | 47   | 47   |
|       | 45   | 48   | 50   | 55   | 55   | 57   | 42   | 46   | 50   | 42   | 45   | 50   | 45   | 45   | 45   | 45   |
|       | 43   | 46   | 46   | 50   | 50   | 47   | 42   | 43   | 45   | 42   | 42   | 41   | 41   | 41   | 41   | 41   |
|       | 39   | 42   | 44   | 43   | 52   | 47   | 33   | 38   | 38   | 38   | 38   | 38   | 38   | 38   | 38   | 38   |
|       | 31   | 37   | 40   | 37   | 40   | 38   | 30   | 34   | 34   | 34   | 34   | 34   | 34   | 34   | 34   | 34   |
|       | 28   | 30   | 31   | 35   | 39   | 31   | 27   | 28   | 28   | 28   | 28   | 28   | 28   | 28   | 28   | 28   |
|       | 25   | 29   | 30   | 33   | 36   | 33   | 22   | 23   | 24   | 24   | 24   | 24   | 24   | 24   | 24   | 24   |
|       | 22   | 22   | 22   | 26   | 30   | 28   | 21   | 23   | 23   | 23   | 23   | 23   | 23   | 23   | 23   | 23   |
|       | 22   | 22   | 22   | 26   | 30   | 28   | 21   | 23   | 23   | 23   | 23   | 23   | 23   | 23   | 23   | 23   |
|       | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   | 16   |

- Normalized at 900 °C (1650 °F); water quenched from 830-845 °C (1525-1550 °F); average dew point, 16 °C (60 °F)
- Normalized at 885 °C (1625 °F); water quenched from 800-815 °C (1475-1500 °F); average dew point, 7 °C (45 °F)
- Normalized at 900 °C (1650 °F); water quenched from 830-855 °C (1525-1575 °F); average dew point, 13 °C (55 °F)

(a) Hardness, HRB

**Tempering Time.** The diffusion of carbon and alloying elements necessary for the formation of carbides is temperature and time dependent. The effect of tempering time on the hardness of an 0.82% carbon steel tempered at various temperatures is shown in Fig. 3. The changes in hardness are approximately linear over a large portion of the time range when the time is presented on a logarithmic scale. Rapid changes in room-temperature hardness occur at the start of tempering in times less than 10 s. Less rapid, but still large, changes in hardness occur in times from 1 to 10 min, and smaller changes occur in times from 1 to 2 h. For consistency and less dependency on variations in time, components generally are tempered for 1 to 2 h. The levels of hardness produced by very short tempering cycles, such as in induction tempering, would be quite sensitive to both the temperature achieved and the time at temperature.

By use of an empirical tempering parameter developed by Holloman and Jaffe (Ref 2), the approximate hardnesses of quenched and tempered low- and medium-alloy steels can be predicted. The parameter is \( T (c + \log t) \), where \( T \) is temperature in degrees Kelvin, \( t \) is time in seconds and \( c \) is a constant that depends on the carbon content of the steel. Reasonably good correlations are obtained except when significant amounts of carbide-forming elements or large amounts of retained austenite are present.

**Cooling Rate.** Another factor that can affect the properties of a steel is the cooling rate from the tempering temperature. Although tensile properties are not affected by cooling rate, toughness (as measured by notched-bar impact testing) can be decreased if the steel is cooled slowly through the temperature range from 375 to 575 °C (705 to 1065 °F), especially in steels that contain carbide-forming elements. Elongation and reduction in area may be affected also. This phenomenon is
Properties summarized for one heat of 1050 steel that was forged to 38 mm (1.50 in.) in diameter, then water quenched and tempered at various temperatures. Composition of heat: 0.52 C, 0.93 Mn
called "temper embrittlement" and is discussed further in a subsequent section of this article.

Carbon Content
The effect of carbon content on the properties of tempered steel is illustrated in Fig. 4, which presents hardness data for 14 carbon steels that were tempered at temperatures ranging from 205 to 705 °C (400 to 1300 °F) and for times from 10 min to 24 h. The principal effect of carbon content is on as-quenched hardness. Figure 5 illustrates the relationship between carbon content and the maximum hardness that can be obtained upon quenching. The relative difference in hardness as compared with as-quenched hardness is retained after tempering. Figure 6 shows the combined effect of time, temperature and carbon content on the hardness of four carbon-molybdenum steels of different carbon contents. Figure 7 shows the hardness of these steels after tempering for 1 h, as a function of tempering temperature; the effect of carbon content is clearly evident.

Alloy Content
The main purpose of adding alloying elements to steel is to increase the steel's ease of hardenability—that is, its ability to form martensite on quenching from above its critical temperature. The general effect of alloying elements on tempering is a retardation of the rate of softening, especially at the higher tempering temperatures. Thus, to obtain a given hardness in a given period of time, alloy steels require higher tempering temperatures than do carbon steels. Alloying elements can be characterized as carbide-forming or non-carbide-forming. Elements such as nickel, silicon, aluminum and manganese, which have little or no tendency to occur in the carbide phase, remain essentially in solution in
the ferrite and have only a minor effect on tempered hardness. Hardening due to the presence of these elements occurs mainly through solid-solution hardening of the ferrite. The carbide-forming elements, chromium, molybdenum, tungsten, vanadium, tantalum, niobium and titanium, retard the softening process by formation of alloy carbides. The effect of the carbide-forming elements is minimal at low tempering temperatures where Fe₃C forms; however, at higher temperatures, alloy carbides are formed and hardness decreases slowly with tempering temperature. Under certain conditions, such as with highly alloyed steels, hardness may actually increase. This latter effect is known as "secondary hardening".

The effect of molybdenum content on the tempering behavior of a 0.35% carbon steel is shown in Fig. 8. As the alloy content increases, the magnitude of the secondary-hardening effect increases. Synergistic effects of various combinations of alloying elements can occur: chromium tends to produce secondary hardening at a lower temperature than does molybdenum; and the combination of chromium and molybdenum produces a rather flat tempering curve, with the peak hardness occurring at a somewhat lower temperature than when only molybdenum is present. H11 steel is a widely used hot working die steel that contains nominally 0.35% C, 5% Cr, 1.5% Mo and 0.4% V. Figure 9 shows the room-temperature hardness of H11 as a function of tempering temperature. A very flat tempering curve results because of the specific combination of the three carbide-forming elements.

**Tool Steels and Stainless Steels.** Extensive data on tempering of tool steels (including H11) and martensitic stainless steels are given in the articles on heat treating of tool steels and heat treating of stainless steels and heat resisting alloys.

**Other Alloying Effects.** Alloying elements produce a number of other effects besides providing ease of hardening and secondary hardening. The higher tempering temperatures used to temper alloy steels presumably permit greater relaxation of residual stresses and improve properties. Furthermore, the hardenability of alloy steels may permit a less drastic quench to be used so that as-quenched stresses are lower and cracking prior to tempering is minimized. The higher hardenability of alloy steels may also permit the use of a lower carbon content to achieve a given strength level but with improved ductility and toughness.

**Residual Elements.** Residual elements—those not intentionally added to a steel—can cause embrittlement. The elements that are known to cause embrittlement are tin, phosphorus, antimony and arsenic. A discussion of the
Fig. 4 Influence of tempering temperature on room-temperature hardness of quenched carbon steels (Ref 3)
Tempering Procedures

Tempering can be accomplished by soaking entire parts in the furnace for periods of time sufficient to bring the tempering mechanism to the desired point of completion or by selective heating of certain portions of the part to achieve toughness or plasticity in those areas.

**Bulk processing** may be done in convection furnaces or in molten salt, hot oil or molten metal baths. Selection of the type of furnace depends primarily on number and size of parts and on desired temperature. Table 2 gives temperature ranges, most likely reasons for use, and fundamental problems of these four types of equipment.

**Selective tempering techniques** are used to soften specific areas of fully hardened parts or to temper areas that were selectively hardened previously.

Specific effects of these elements can be found in the section on temper embrittlement in this article.
The purpose of this treatment is to improve the machinability, the toughness or the resistance to quench cracking in the selected zone. Induction and flame tempering are the most commonly utilized selective techniques because of their controllable local heating capabilities. Immersion of selected areas in molten salt or molten metal can be accomplished, but with somewhat less control.

Special processes occasionally are employed to achieve specific properties such as those derived from steam treating or use of protective atmospheres. The tempering mechanism in certain steels is enhanced by cyclic heating and cooling. A particularly important procedure employs cycles between subzero temperatures and the tempering temperature to increase the transformation of retained austenite. The term used for this procedure, “multiple tempering”, also is applied to procedures that employ intermediate thermal cycles to soften parts for straightening prior to the actual tempering operation designed to achieve the desired degree of toughness and plasticity.

**Equipment for Tempering**

Steel usually is tempered in either an air (convection) furnace or a salt bath (Fig. 10). Molten metal baths, oil baths, and flame or induction heating units are used also.

**Convection Furnaces.** The most commonly employed tempering method utilizes the recirculating or forced-air convection furnace, and the equipment most commonly used in conjunction with convection furnaces includes continuous belt conveyor, roller rail or dog beam pusher systems. Batch equipment such as box or pit types are used also.

Forced recirculating air is the most common and efficient method of tempering because it lends itself to a wide selection of furnace designs to accommodate a variety of products and capacities. Moreover, the metallurgical results are very good in terms of price per unit weight of yield.

Convection furnaces generally are designed for tempering temperatures of 150 to 750 °C (300 to 1380 °F). For temperatures up to 550 °C (1020 °F), recirculated hot air is supplied to the product from a chamber separate from the work-holding area, to avoid uneven heating by radiation. For temperatures of 550 to 750 °C, either forced convection or radiant heating is used depending on the metallurgical requirements of the product. To obtain closer control of metallurgical properties, the recirculated forced hot air is employed; but for greater efficiency, radiant heating is used, because transfer of radiant heat is greater as the temperature approaches 750 °C (1380 °F).

The most important phase of convection-furnace design is determination of the proper amount of forced-air supply. The objective of the blower is to furnish...
Table 2 Temperature ranges and general conditions of use for four types of tempering equipment

<table>
<thead>
<tr>
<th>Type of equipment</th>
<th>Temperature range °C</th>
<th>°F</th>
<th>Service conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convection furnace</td>
<td>50 to 750</td>
<td>120 to 1380</td>
<td>For large volumes of nearly common parts; variable loads make control of temperature more difficult</td>
</tr>
<tr>
<td>Salt bath</td>
<td>160 to 750</td>
<td>320 to 1380</td>
<td>Rapid, uniform heating; low to medium volume; should not be used for parts whose configurations make them hard to clean</td>
</tr>
<tr>
<td>Oil bath</td>
<td>Up to 250</td>
<td>Up to 480</td>
<td>Good if long exposure is desired; special ventilation and fire control are required</td>
</tr>
<tr>
<td>Molten metal bath</td>
<td>Above 390</td>
<td>Above 735</td>
<td>Very rapid heating; special fixturing is required (high density)</td>
</tr>
</tbody>
</table>

![Fig. 7 Effect of carbon content and tempering temperature on room-temperature hardness of four molybdenum steels](image)

Tempering time: 1 h at temperature. 4068 is former standard classification. See p 133 in Vol 1 of this Handbook.

![Fig. 8 Influence of molybdenum content on softening of quenched 0.35% C steels with increasing tempering temperature (Ref 1)](image)

![Fig. 9 Variation of room-temperature hardness with tempering temperature for H11 Mod steel](image)

All specimens air cooled from 1010 °C (1850 °F) and double tempered 2 + 2 h at temperature.
by positioning a thermocouple at the hot-air side of the recirculating system close to the product. When this technique is used, there is minimum danger of overheating, and loads of various sizes can be handled. This method also allows the duration of processing (holding time) to be varied by movement of the thermocouple location—but only within the limits of the furnace size (and/or conveyor speed for continuous-type furnaces). Temperatures generally are held within ± 5 °C (± 9 °F).

Efficient use of a continuous furnace cannot be attained when production quantities are small or when parts vary in size, shape and mechanical requirements; the batch furnace is better suited for work of this type. When a continuous furnace is used for such applications, production time is lost in raising or lowering furnace temperature. Sometimes, when the process variables must be changed, a dummy load must be placed in the furnace to accelerate a desired reduction of temperature, or production must be stopped until the temperature is stabilized.

Salt bath furnaces may be employed for tempering at 160 °C (320 °F) and above. Good heat transfer and natural convection in the bath promote uniformity of workpiece temperature.

All moisture must be removed from parts before they are immersed in the molten salt, because hot salt reacts violently with moisture. If dirty or oily parts are immersed in the bath, the salt will become contaminated and require more frequent rectification.

All parts tempered in salt must be cleaned soon after being removed from the bath, because the salt that clings to them is hygroscopic and may cause severe corrosion. Parts with small or blind holes from which salt is difficult to clean should not be tempered in salt.

Salt bath compositions and operating temperature ranges presented in Table 3 pertain to baths in common use for tempering and are classified according to Military Specification MIL-S-10699A (Ordnance).

Class 1 and class 2 salts are reasonably stable and seldom require rectification. If chlorides are added by carryover from a higher-temperature bath, they will cause an increase in the viscosity of the bath. Chlorides can be removed by filtering through fine screens or by cooling and settling out the insoluble chlorides as a sludge. Occasionally, carbonates become excessive. These can be removed by reaction with dilute nitric acid-base rectifiers. Upper temperature limits must not be exceeded, or salt will become highly oxidizing, even toward alloy steels.

Class 3 salts seldom require rectification. However, their high melting point:

<table>
<thead>
<tr>
<th>Class</th>
<th>Sodium nitrite</th>
<th>Sodium nitrate</th>
<th>Potassium nitrate</th>
<th>Sodium carbonate</th>
<th>Sodium chlorate</th>
<th>Potassium chlorate</th>
<th>Barium chloride</th>
<th>Calcium chloride</th>
<th>Operating temperature °C</th>
<th>Fuming temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>37-50</td>
<td>0-10</td>
<td>50-60</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>165-595</td>
<td>325-1100</td>
</tr>
<tr>
<td>2</td>
<td>...</td>
<td>45-57</td>
<td>45-57</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>290-595</td>
<td>550-1100</td>
</tr>
<tr>
<td>3</td>
<td>...</td>
<td>...</td>
<td>45-55</td>
<td>45-55</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>620-925</td>
<td>1150-1700</td>
</tr>
<tr>
<td>4</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>15-25</td>
<td>20-32</td>
<td>50-60</td>
<td>...</td>
<td>...</td>
<td>595-900</td>
<td>1100-1650</td>
</tr>
<tr>
<td>4A</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>10-15</td>
<td>25-30</td>
<td>40-45</td>
<td>15-20</td>
<td>...</td>
<td>550-760</td>
<td>1025-1400</td>
</tr>
</tbody>
</table>
neutral salts, are quite stable. They sel­

duced to temperatures above 590 °C (1100 °F).

Class 4A salts are close relatives of class 4 salts but contain calcium chlo­

control procedures applicable to the various bath compositions. For further information, see the articles on mar­

SAFETY PRECAUTION: Introduc­

tion of cyanide salts or other reducing agents into nitrite tempering baths will cause violent explosions.
Heat Treating of Steel

Oil bath equipment for tempering may be similar in design to that used for salt baths, or a steel tank over large hotplate-type burners will serve satisfactorily. Submerged electric heating elements may also be employed. Stirring is essential for temperature uniformity and satisfactory oil life. Simple, oven-type temperature controls may be employed, but localized overheating must be avoided to prevent fire and rapid decomposition of the oil. A standard thermometer of the proper range may be used to check the temperature of the oil.

Low-temperature tempering in a hot oil bath is a simple and inexpensive method that is especially useful for holding work at temperature for long periods of time. The practical temperature limit is about 120 °C (250 °F) without special ventilation and fire-protection equipment and about 250 °C (480 °F) with such precautions, which may include extremely efficient ventilators or inert-gas blanketing systems. When a tempering temperature above 205 °C (400 °F) is required, a salt bath is usually preferable to an oil bath.

Oils for tempering must resist oxidation and have a flash point well above the operating temperature. The most commonly used oils are high-flash-point paraffinic oils with antioxidant additives. Oils used for martempering (see the article on martempering of steels) are also satisfactory for tempering.

Molten metal baths for tempering have largely been replaced by salt baths. When employed, commercially pure lead, which melts at about 327 °C (620 °F), has proved to be the most generally suitable of all metals and alloys. For special applications, however, lead-base alloys having lower melting points are used.

Lead oxidizes readily. Although lead itself will not adhere to clean steel, adherence of lead oxide to steel surfaces is a problem, especially at higher tempering temperatures. Within the range of temperatures usually employed, a film of molten salt will protect the surface of the lead bath, and the work will be easily cleaned. Above 480 °C (900 °F), granulated carbonaceous material, such as charcoal, may be used as a protective cover.

Because of its high thermal conductivity, lead is useful for rapid local heating and selective tempering. A typical application is the tempering of a ball joint. The part is carburized and quenched to a minimum case hardness of 59 HRC and a core hardness of 30 to 40 HRC. The thread and taper then are tempered in lead to produce a maximum case hardness of 40 HRC.

Because of the high specific gravity of lead, parts tempered in molten lead will float unless held down by fixtures. All parts and fixtures must be dry when immersed in the bath, to prevent formation of steam in, and resultant violent expulsion of, the molten lead. Precautions also must be taken to protect personnel from industrial lead poisoning; hoods and ventilating equipment are required.

Temperature Control. For either gas or electric heat, properly adjusted potentiometers of the on-off type will control the tempering temperature within ± 6 °C (± 10 °F) at the thermocouple location. With proportioning controls, these instruments can maintain temperatures within ± 1 °C (± 2 °F) at the thermocouple location.

Selection of Tempering Equipment

Selection of equipment for tempering is based principally on (a) temperature requirements and (b) quantity and similarity of the work to be treated. Temperature requirements are dictated by prior heat treatment and by the properties to be developed by tempering.

Process Control

Variation in hardness after tempering is most frequently the result of differences in prior microstructure, as discussed previously. When prior microstructure is the same, control of temperature is the most important factor in control of the tempering process.

In general, control of tempering temperature to within ± 3 °C (± 5 °F) is
adequate and is within the practical limits of most furnace and molten-bath equipment. Temperature variations are seldom permitted to exceed ±6 °C (±10 °F) unless mechanical-property requirements are correspondingly broad.

Examples of the range of variation in hardness obtained after tempering for a variety of wrought and cast steel parts are presented in Fig. 11, 12 and 13.

**Tempering of Special Microstructures**

**Carburized Components.** Tempering of carburized parts represents a special instance in that the combination of toughness, strength, hardness, residual stress and retained austenite all must be considered when selecting tempering time and temperature. Core properties cannot always be controlled by tempering when trying to achieve maximum case properties, and a favorable compressive residual stress pattern may be retained only at the expense of over-all toughness.

The effect of tempering on the hardness of carburized cases is shown in Fig. 14, and the influence of tempering on residual stress is illustrated in Fig. 15. The transformation of retained austenite and the resultant change in the relative volume of case and core are primarily responsible for the change in residual stress as a function of temperature. The effect of retained austenite on the performance of components is still a controversial issue. Reduction of retained austenite is apparently desirable for resistance to grinding abuse and to provide dimensional stability, but retained austenite appears to be beneficial for contact-fatigue durability.

**Nonmartensitic Structures.** Tempering of microstructures other than martensite and retained austenite also represents special applications of tempering. Reactions of structures containing substantial amounts of lower bainite are relatively similar to that of martensite in terms of the phenomena associated with carbide growth and coalescence.

Upper bainite and fine pearlite formed by controlled or relatively slow cooling simply respond by carbide growth and eventual ferrite recrystallization. The softening associated with tempering in such instances is shown in Fig. 16.

Impact properties of normalized and tempered and hardened and tempered structures at nearly equal hardness are shown in Fig. 17.

**Induction Tempering**

Extensive production experience has demonstrated the commercial success of induction heating for tempering in several types of applications. This subject is discussed in the article on induction hardening and tempering.

**Special Tempering Procedures**

**Selective Tempering.** Selective or localized tempering is applied to parts in which adjacent areas must have significantly different hardenesses. Chisels, punches, the upset ends of cold formed rivets, and the threaded portions of carburized parts are typical examples. Localized tempering is also employed in preheating and postheating of weld areas when a lowering of the hardness in the heat-affected zone is desired.

Selective tempering entails heating a restricted area to the required tempering temperature without heating the remainder of the part to this temperature.
Fig. 16 Effect of prior microstructure on room-temperature hardness after tempering

(a) 1095 steel tempered at 565 °C (1050°F) for various periods of time. (b) Room-temperature hardness before and after tempering, and amount of martensite present before tempering, in 4320 steel end-quenched hardenability specimens tempered for 2 h

Example 1. An upholsterer's tack hammer, forged from 1086 steel, is hardened on all surfaces to 53 to 60 HRC and then is tempered in salt at 190 °C (375 °F). This treatment provides the desired combination of hardness, toughness and magnetic properties for the horseshoe-magnet end of the hammer. However, the striking head must be selectively tempered in salt at 260 °C (500 °F) to produce the working hardness of 50 to 55 HRC.

Example 2. A chain pipe wrench handle forging, made of 4053 steel, is fully hardened and tempered for 1 h at 355 °C (675 °F) to produce an over-all hardness of 47 to 52 HRC. This is an ideal hardness for the wrench teeth but does not provide sufficient toughness for the I-beam section of the handle. This section is tempered further, selectively, by induction heating for 1 min at 480 °C (900 °F) to produce a hardness of 40 to 48 HRC.

The effect on hardness of the very short tempering times normally associated with selective heating is compared with the effect of furnace tempering in Fig. 18.

Multiple tempering is principally used (a) to relieve the quenching and straightening stresses in irregularly shaped carbon and alloy steel parts and thereby lessen distortion, (b) to eliminate retained austenite and improve dimensional stability in such parts as bearing components and gage blocks, and (c) to improve yield and impact strengths without decreasing hardness. The following examples illustrate these principal applications of the process.

Example 3. A six-throw, seven-bearing, counterweighted diesel-engine crankshaft weighing 80 kg (175 lb) was distorted in rough machining to such a degree that cold straightening was required. The straightening operation introduced additional stresses, which caused severe distortion in final machining. The problem was solved by first tempering the 1046 steel shaft at 455 °C (850 °F) to a hardness of about 321 HB, which allowed hot straightening. The shaft was then retempered at 480 to 540 °C (900 to 1000 °F), depending on the composition of the particular heat, to produce a hardness of 269 to 302 HB and relieve residual stresses.

Example 4. In manufacture of a gage block of W1 tool steel (final hard-
Fig. 17 Effect of microstructure on notch toughness

![Graph showing the effect of microstructure on notch toughness for 4340 steel hardened and tempered to 29 to 30 HRC or normalized and tempered to 31 to 33 HRC.]

Variation in Charpy keyhole-notch impact energy with temperature for 4340 steel hardened and tempered to 29 to 30 HRC or normalized and tempered to 31 to 33 HRC.

Fig. 19 Effect of temper embrittlement on notch toughness

![Graph showing the effect of temper on notch toughness for 5140 steel hardened and tempered at 620 °C (1150 °F); one series of specimens was quenched from the tempering temperature, and the other was furnace cooled. Slow cooling of susceptible steels causes temper embrittlement.]

Variation in Charpy V-notch impact energy with temperature for 5140 steel hardened and tempered at 620 °C (1150 °F); one series of specimens was quenched from the tempering temperature, and the other was furnace cooled. Slow cooling of susceptible steels causes temper embrittlement (Ref 4).

Use of Fixtures

Many high-strength steel components having tensile strength greater than 1720 MPa (250 ksi) are finish machined before final heat treatment. To minimize distortion and satisfy stringent dimensional requirements, some of these components, such as cylinders, pressure vessels and thin parts, are held in fixtures during both hardening and tempering or during tempering only.

External rings, internal mandrels, jacks, screws, weights, wedges, dies and other mechanical devices are used to assist in dimensional correction.

**Example 5.** A welded pressure vessel made of 4135 steel, 380 mm (15 in.) in outside diameter by 1.8 m (6 ft) long by 3.2 mm (0.125 in.) thick, was found to be 1.3 to 3.8 mm (0.050 to 0.150 in.) out-of-round over its entire length when measured in the as-quenched condition. A tempering fixture consisting of a series of steel rings 125 mm (5 in.) wide reduced maximum out-of-roundness to 1.3 mm (0.050 in.) after tempering at 455 °C (850 °F) for 2 1/2 h.

Steels that are susceptible to cracking at room temperature after hardening are given a low-temperature tempering treatment (a "snap draw") immediately after hardening and prior to final tempering in fixtures.

Cracking in Processing

Because of their carbon or alloy contents, some steels are likely to crack if they are permitted to cool all the way to room temperature during or immediately following the quenching operation. This likelihood is caused by gener-
ation of high tensile residual stresses during quenching, due to thermal gradients, abrupt changes in section thickness, decarburization or other hardenability gradients. Accordingly, for carbon steels containing more than 0.4% C and alloy steels containing more than 0.35% C, it is recommended that the parts be transferred to tempering furnaces before they cool below 100 to 150 °C (212 to 300 °F). Alternately, many heat treating operations use quenching oil for the tempering operation (martempering) or to avoid cooling below 125 °C (255 °F). Steels that are known to be sensitive to this type of cracking include 1060, 1090, 1340, 4063, 4150, 4340, 52100, 6150, 8650 and 9850.

Other carbon and alloy steels are generally less sensitive to this type of delayed quench cracking but may crack as a result of part configuration or surface defects. These steels include 1040, 1050, 1137, 1144, 4047, 4132, 4640, 8632, 8740 and 9840. Some steels, such as 1020, 1038, 1132, 4130, 5130 and 8630, are not sensitive.

Before being tempered, parts should be quenched to room temperature to ensure transformation of most of the austenite to martensite and to achieve maximum as-quenched hardness. Austenite retained in low-alloy steels will, upon heating for tempering, transform to an intermediate structure, reducing over-all hardness. However, in medium- to high-alloy steels containing austenite-stabilizing elements (nickel, for example), retained austenite may transform to martensite upon cooling from tempering, and thus such steels may require additional tempering (double tempering) for relief of transformation stresses.

**Temper Embrittlement**

When carbon or low alloy steels are slow cooled from tempering above 575 °C (1065 °F), or are tempered for extended times between 375 and 575 °C (705 and 1065 °F), a loss in toughness occurs that manifests itself in reduced notched-bar impact strength compared to that resulting from normal tempering cycles and relatively fast cooling rates (see Fig. 19). The cause of temper embrittlement is believed to be precipitation of compounds containing trace elements such as tin, arsenic, antimony and phosphorus along with chromium and/or manganese. The intergranular nature of the fracture suggests that the embrittlement occurs at the prior austenite grain boundaries. Although manganese and chromium cannot be restricted, reduction of the other elements and quenching from above 575 °C are the most effective remedies for this type of embrittlement. It also has been found that small amounts of molybdenum retard embrittlement.

A second form of embrittlement, called "blue brittleness", occurs when steels are tempered at about 300 °C (570 °F) after being hardened. This is illustrated in Fig. 19. Generally, for steels containing potent carbide formers such as chromium, tempering between 200 and 370 °C (390 and 700 °F) should be avoided.

**Hydrogen Embrittlement**

Selection of tempering temperature, and the resultant hardness or plasticity, must include consideration of the potential problem of hydrogen embrittlement should the part be exposed to hydrogen through electroplating, phosphating or other means, or if environmental conditions cause cathodic absorption of hydrogen during service.

Generally, the restricted notch ductility of steels with hardness above 40 HRC presents ideal conditions for development of stress concentrations in parts containing notches or defects that would, in the presence of relatively low hydrogen concentrations, lead to failure of parts at stresses far below the nominal tensile strength of the material. Thus, tempering should be carried out to achieve hardness below 40 HRC if the part will be subjected to relatively high stresses and probable exposure to hydrogen.

**REFERENCES**