

Chapter 2

Basic Heat Treatment

Topics

- 1.0.0 Heat Treatment Theory
- 2.0.0 Stages of Heat Treatment
- 3.0.0 Recognizing Heat Colors for Steel
- 4.0.0 Types of Heat Treatment
- 5.0.0 Quenching Media

To hear audio, click on the box.



Overview

Welding, cutting, or even grinding on metal produces heat, which in turn has an effect on the structure of the metal. As a Steelworker, you need to understand the effect that heat treatment has on metals so you can attain the desired properties for a particular metal. You also need to know what methods can be used to restore a metal to its original condition.

Heat treatment is the process of heating (but never allowing the metal to reach the molten state) and cooling a metal in a series of specific operations which changes or restores its mechanical properties.

Heat treatment makes a metal more useful by making it stronger and more resistant to impact, or alternatively, making it more malleable and ductile.

However, no heat-treating procedure can produce all of these characteristics in one operation; some properties are improved at the expense of others. For example, hardening a metal may make it brittle, or annealing it may make it too soft.

Objectives

When you have completed this chapter, you will be able to do the following:

1. Describe the heat treatment theory.
2. Identify the stages of heat treatment.
3. Recognize heating colors associated with steel.
4. Describe the different types of heat treatment.
5. Describe the different types of quenching media.

Prerequisites

None

This course map shows all of the chapters in Steelworker Basic. The suggested training order begins at the bottom and proceeds up. Skill levels increase as you advance on the course map.

Introduction to Reinforcing Steel		S T E E L W O R K E R B A S I C
Introduction to Structural Steel		
Pre-Engineered Structures: Buildings, K-Spans, Towers and Antennas		
Rigging		
Wire rope		
Fiber Line		
Layout and Fabrication of Sheet-Metal and Fiberglass Duct		
Welding Quality Control		
Flux Core Arc Welding-FCAW		
Gas-Metal Arc Welding-GMAW		
Gas-Tungsten Arc Welding-GTAW		
Shielded Metal Arc Welding-SMAW		
Plasma Arc Cutting Operations		
Soldering, Brazing, Braze Welding, Wearfacing		
Gas Welding		
Gas Cutting		
Introduction to Welding		
Basic Heat Treatment		
Introduction to Types and Identification of Metal		

Features of this Manual

This manual has several features which make it easy to use online.

- Figure and table numbers in the text are italicized. The figure or table is either next to or below the text that refers to it.
- The first time a glossary term appears in the text, it is bold and italicized. When your cursor crosses over that word or phrase, a popup box displays with the appropriate definition.
- Audio and video clips are included in the text, with an italicized instruction telling you where to click to activate it.
- Review questions that apply to a section are listed under the Test Your Knowledge banner at the end of the section. Select the answer you choose. If the answer is correct, you will be taken to the next section heading. If the answer is incorrect, you will be taken to the area in the chapter where the information is for review. When you have completed your review, select anywhere in that area to return to the review question. Try to answer the question again.
- Review questions are included at the end of this chapter. Select the answer you choose. If the answer is correct, you will be taken to the next question. If the answer is incorrect, you will be taken to the area in the chapter where the information is for review. When you have completed your review, select anywhere in that area to return to the review question. Try to answer the question again.

1.0.0 HEAT TREATMENT THEORY

All heat-treating processes are similar because they all involve the heating and cooling of metals. However, there are differences in the methods used, such as the heating temperatures, cooling rates, and quenching media necessary to achieve the desired properties.

The heat treatment of ferrous metals (metals with iron) usually consists of annealing, normalizing, hardening, and/or tempering.

Most nonferrous metals can be annealed, but never tempered, normalized, or **case hardened**.

To successfully heat treat a metal, you need to have the proper equipment with close control over all factors relevant to the heating and cooling. For example, the furnace must be the proper size and type with the temperatures controlled and kept within the prescribed limits for each operation, and you must have the appropriate quenching media to cool the metal at the correct rate.

The furnace atmosphere itself affects the condition of the metal being heat treated. This atmosphere consists of the gases in the furnace's heating chamber that circulate and surround the metal being heated.

In an electric furnace, the atmosphere is either air or a controlled mixture of gases.

In a fuel-fired furnace, the atmosphere is a mixture of gases and air. Air combines with gases released by the fuel's combustion resulting in various proportions of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H), nitrogen (N), oxygen (O), water vapor (H_2O), and other various hydrocarbons (C_nH_{2n}). When you vary the proportions of air and fuel in a fuel-fired furnace, you can provide three distinct atmospheres: oxidizing, reducing, and neutral.

2.0.0 STAGES of HEAT TREATMENT

You accomplish heat treatment in three major stages:

- Stage 1 — Heat the metal slowly to ensure a uniform temperature.
- Stage 2 — Soak (hold) the metal at a given temperature for a given time.
- Stage 3 — Cool the metal to room temperature.

2.1.0 Heating Stage

In the heating stage, the primary objective is to heat uniformly, and you attain and maintain uniform temperatures by slow heating. If you heat unevenly, one section can expand faster than another, resulting in a distorted or cracked part.

The appropriate heating rate will depend on several factors.

- The metal's heat conductivity. A metal with a high-heat conductivity heats at a faster rate than one with a low conductivity.
- The metal's condition. The heating rate for hardened (stressed) tools and parts should be slower than the heating rate for unstressed or untreated metals.
- A metal part's size and cross section. To prevent warping or cracking, you need to heat large cross-sectioned parts slowly to allow the interior temperature to remain close to the surface temperature. Parts with uneven cross sections will

naturally tend to heat unevenly, but they are less apt to crack or excessively warp when you keep the heating rate slow.

2.2.0 Soaking Stage

In the soaking stage, the objective is to hold the metal to the proper temperature until the desired internal structural changes take place. “Soaking period” is the term you use for the time the metal is held at the proper temperature. The chemical analysis of the metal and the mass of the part will determine the appropriate soaking period. (Note: For steel parts with uneven cross sections, the largest section determines the soaking period.)

Except for the rare variance, you should not bring the temperature of a metal directly from room temperature to soaking temperature in one operation. Instead, heat the metal slowly to a temperature just below the point at which the internal change occurs and hold it at that temperature until you have equalized the heat throughout. Following this process (called “preheating”), quickly heat the metal to its final required temperature.

When a part has an intricate design, you may have to preheat it to more than one temperature stage to prevent cracking and excessive warping. For example, assume an intricate part needs to be heated to 1500°F for hardening.

You may need to heat this part slowly to a 600°F stage and soak it at this temperature for a defined period, then heat it slowly and soak it at a 1200°F stage, and then heat it quickly to the hardening temperature of 1500°F.

NOTE

Nonferrous metals seldom require preheating; in fact, preheating can cause an increase in their grain size.

2.3.0 Cooling Stage

In the cooling stage, the objective is self-explanatory, but there are different processes to return a metal to room temperature, depending on the type of metal.

To cool the metal and attain the desired properties, you may need to place it in direct contact with a **cooling medium** (a gas, liquid, solid, or a combination), and any cooling rate will depend on the metal itself and the chosen medium. Therefore, the choice of a cooling medium has an important influence on the properties desired.

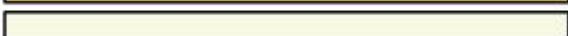
Cooling metal rapidly in air, oil, water, brine, or some other medium is called **quenching**.

Quenching is usually associated with hardening since most metals that are hardened are cooled rapidly during the process. However, neither quenching nor rapid cooling always results in increased hardness. For example, a water quench is usually used to anneal copper, and some other metals are cooled at a relatively slow rate for hardening, such as air-hardened steels.

Some metals crack or warp during quenching, while others suffer no ill effects; so the quenching medium must fit the metal. Use brine or water for metals that require a rapid cooling rate; use oil mixtures for metals that need a slower cooling rate. Generally, you should water-harden carbon steels, oil-harden alloy steels, and quench nonferrous metals in water.

3.0.0 RECOGNIZING HEAT COLORS for STEEL

“Red-hot” is a term you are probably familiar with as it applies to steel, but steel actually takes on several colors and shades from the time it turns a dull red until it reaches a white heat. *Figure 2-1* shows these approximate colors and their corresponding temperatures.

Faint Red visible in dark		750
Faint Red		900
Blood Red		1050
Dark Cherry Red		1075
Medium Cherry Red		1250
Full Cherry Red		1375
Bright Red		1550
Salmon		1650
Orange		1725
Lemon		1825
Light Yellow		1975
White		2200
Dazzling White		2350

Color	Perceived colors depend on lighting.	Temperature	
		F°	C°
Faint Red visible in dark		750	399
Faint Red		900	482
Blood Red		1050	565
Dark Cherry Red		1075	579
Medium Cherry Red		1250	677
Full Cherry Red		1375	746
Bright Red		1550	843
Salmon		1650	899
Orange		1725	940
Lemon		1825	996
Light Yellow		1975	1079
White		2200	1204
Dazzling White		2350	1288

Figure 2-1 — Example of approximate heat colors for steel.

Steel is heated through various temperatures during hardening, normalizing, or annealing, and each temperature produces a color change; so by observing these changes, you should be able to approximate the temperature of the steel.

As an example, assume you must quench-harden a steel part at 1500°F. You should heat the part slowly and evenly while watching it closely for any change in color. Once the steel begins to redden, carefully note each change in shades of red as you continue to apply heat. When the steel is bright red, or approximately 1500°F, quench the part.

Your judgment, ability to distinguish shades of red, and the accuracy with which you identify each color with its corresponding temperature can determine the success of your heat-treating operation. If you are one of the 5–8 percent of males, or less than 1 percent of females who are color blind in some way or another, your inability to distinguish colors will be problematic.

Refer again to *Figure 2-1* and you will see that you need to observe the colors closely. To accurately judge a steel's temperature, you must be able to tell the difference between faint red and blood red, dark cherry and medium cherry, or cherry red and bright red.

Sometimes in various lightings and work environments, this is a difficult task, and to add to the difficulty, your conception of medium cherry may differ from another's conception. For an actual heat-treating operation, use a printed chart showing the authentic colors of steel at various temperatures. Do not rely on the colors displayed on the monitor you are currently viewing, or on printed versions of this course; there are too many variables in monitors and printers to be able to rely on them for accuracy.

4.0.0 TYPES of HEAT TREATMENT

There are four basic types of heat treatment in use today: annealing, normalizing, hardening, and tempering.

The following sections describe the techniques used in each process and show how they relate to Steelworkers.

4.1.0 Annealing

The objective of annealing is the opposite of hardening. You anneal metals to relieve internal stresses, soften them, make them more ductile, and refine their grain structures. The process includes all three stages of heat treatment already covered (heat the metal to a specific temperature, hold it at a temperature for a set length of time, cool it to room temperature), but the cooling method will depend on the metal and the properties desired.

You may need to furnace-cool some metals or bury others in ashes, lime, or other insulating materials to achieve the appropriate characteristics.

Under certain job conditions, or without proper preheating, welding can produce areas of molten metal adjacent to other areas at room temperature. Given specific conditions, welding can actually weaken a metal, for as a weld cools, internal stresses occur along with hard spots and brittleness.

Annealing is just one method for correcting these problems and relieving the stresses.

4.1.1 Ferrous Metal

To anneal ferrous metals and produce the maximum softness(ductility) in steel, you slowly heat the metal to its proper temperature, soak it, and then let it cool very slowly by burying the hot part in an insulating material, or by shutting off the furnace and allowing the furnace and the part to cool slowly together.

Soaking periods depend on both the type and the mass of the metal involved. *Table 2-1* provides approximate soaking periods for annealing steel of various thicknesses.

Extremely low-carbon steels require the highest annealing temperature, but as steel's carbon content increases, its annealing temperatures decrease.

Table 2-1 — Approximate Soaking Periods for Hardening, Annealing, and Normalizing Steel

Thickness of metal in inches	Time of heating to required temperature in hours	Soaking time in hours
Up to 1	$\frac{3}{4}$	$\frac{1}{2}$
1 to 2	1 $\frac{1}{4}$	$\frac{1}{2}$
2 to 3	1 $\frac{3}{4}$	$\frac{3}{4}$
3 to 4	2 $\frac{1}{4}$	1
4 to 5	2 $\frac{3}{4}$	1
5 to 8	3 $\frac{1}{2}$	1 $\frac{1}{2}$

4.1.2 Nonferrous Metal

Annealing nonferrous metals may or may not follow the same process as ferrous metals. For example, copper becomes hard and brittle when mechanically worked, but it can be made soft again by annealing at a temperature between 700°F and 900°F. However, copper may be cooled rapidly (normally associated with hardening) or slowly since the cooling rate has no effect on the heat treatment.

One drawback experienced in annealing copper is the phenomenon called “**hot shortness**.” Copper loses its tensile strength at about 900°F and if not properly supported, it could fracture.

Aluminum also has the characteristic of “hot shortness,” and reacts similarly to copper when heat treating. With the large number of aluminum alloys in use, you must provide special care while heat treating aluminum to produce the best properties for each alloy.

4.2.0 Normalizing

The intent of normalizing is to remove internal stresses that may have been induced by heat treating, welding, casting, forging, forming, or machining. Uncontrolled stress leads to metal failure; therefore, you should normalize steel before hardening it to ensure maximum results.

Normalizing applies to ferrous metals only, and it differs from annealing; the metal is heated to a higher temperature, but then it is removed from the furnace for air cooling.

Low-carbon steels do not usually require normalizing, but if they are normalized, no harmful effects result.

Castings are usually annealed rather than normalized; however, some castings require the normalizing heat treatment.

Refer again to *Table 2-1* and note the approximate soaking periods for normalizing steel, which varies with the thickness.

Normalized steel has a higher strength than annealed steel; it has a relatively high strength and ductility, much tougher than in any other structural condition. Metal parts

that will be subjected to impact and those requiring maximum toughness with resistance to external stress are usually normalized.

In normalizing, since the metal is air cooled, the mass of a metal has a significant influence on the cooling rate and hence on the resulting piece's hardness. With normalizing, thin pieces cool faster in the air and are harder than thick ones, whereas with annealing and its associated furnace cooling, the hardness of the thin and thick pieces is about the same.

4.3.0 Hardening

The purpose of hardening is not only to harden steel as the name implies, but also to increase its strength. However, there is a trade off; while a hardening heat treatment does increase the hardness and strength of the steel, it also makes it less ductile, and brittleness increases as hardness increases. To remove some of the brittleness, you should temper the steel after hardening.

Many nonferrous metals can also be hardened and their strength increased by controlled heating and rapid cooling, but for nonferrous metals, the same process is called heat treatment rather than hardening.

For most steels, hardening consists of employing the typical first two stages of heat treatment (slowly heat to temperature and soak to time and temperature), but the third stage is dissimilar. With hardening, you rapidly cool the metal by plunging it into oil, water, or brine. (Note: Most steels require rapid cooling [quenching] for hardening, but a few can be air cooled with the same results.)

Refer again briefly to *Table 2-1*, and note that the soaking periods for annealing, normalizing and hardening are all the same. The real difference in each heat treatment process occurs in stage three.

The cooling rate required to produce hardness decreases when alloys are added to steel; this is advantageous since a slower cooling rate also lessens the danger of cracking and warping.

The follow provides hardening characteristics for a few irons and low-carbon steel.

- Pure iron, wrought iron, and extremely low-carbon steels — very little hardening properties; difficult to harden by heat treatment
- Cast iron — limited capabilities for hardening
 - o Cooled rapidly, it forms white iron; hard and brittle
 - o Cooled slowly, it forms gray iron; soft but brittle under impact
- Plain carbon steel — maximum hardness depends almost entirely on carbon content
 - o Hardening ability increases as carbon content increases to a maximum of 0.80 % carbon
 - o Increased carbon content beyond 0.80 % increases wear resistance but not hardness
 - o Increased wear resistance is due to the formation of hard **cementite**

Adding an alloy to steel to increase its hardness also increases the carbon's effectiveness to harden and strengthen. Consequently, the carbon content required to produce maximum hardness is lower in alloyed steels than it is for plain carbon steels with the result that alloy steels are usually superior to carbon steels.

When you harden carbon steel, you must cool the steel to below 1000°F in less than one second. When you add alloys to steel and increase the carbon's effectiveness, you also increase the time limit (more than one second to drop below 1000°F). Therefore, you can use a slower quenching medium to produce the desired hardness.

You usually quench carbon steels in brine or water, and alloy steels in oil.

Quenching steel produces extremely high internal stresses. To relieve them, you can temper the steel just before it becomes cold by removing the part from the quenching bath at a temperature of about 200°F and allowing it to air cool. The temperature range from 200°F down to room temperature is called the "cracking range," and you do not want the steel to pass through it in the quenching medium. Further information on tempering follows in another section.

The following presents different commercially used methods of hardening. In the Seabees, a rapid surface hardening compound called *SURFACE-HARDENING (CASE) COMPOUND*, NSN: 9GD 6850-00-139-5936 (10 lb. can) is used, and you can order it through the Navy supply system. More information and three alternative procedures on the use of "Case" are available in the Welding Materials Handbook, P-433.

4.3.1 Case Hardening

The object of case hardening is to produce a hard, wear-resistant surface (case) over a strong, tough core. In case hardening, the surface of the metal is chemically changed by the introduction of a high carbide or nitride content, but the core remains chemically unaffected. When the metal is heat treated, the high-carbon surface responds to hardening and the core toughens.

Case hardening applies only to ferrous metals. It is ideal for parts that must have a wear-resistant surface yet be internally tough enough to withstand heavy loading. Low-carbon and low-alloy series steels are best suited for case hardening. When high-carbon steels are case hardened, the hardness penetrates beyond the surface resulting in brittleness.

There are three principal processes for case hardening: carburizing, cyaniding, and nitriding.

4.3.1.1 Carburizing

Carburizing — a case hardening process by which carbon is added to the surface of low-carbon steel.

When the carburized steel is heat treated, the case becomes hardened and the core remains soft and tough—in other words, it has a high-carbon surface and a low-carbon interior.

There are two methods for carburizing steel:

- Heat the steel in a furnace containing a carbon monoxide atmosphere.
- Place the steel in a container packed with charcoal (or some other carbon-rich material) and heat in a furnace.

The parts can be left in the container and furnace to cool, or they can be removed and air-cooled. In either case, the parts become annealed during the slow cooling. The depth of the carbon penetration depends on the length of the soaking period during heat treatment. Modern methods dictate that carburizing is almost exclusively done by gas atmospheres.

4.3.1.2 Cyaniding

Cyaniding — a case hardening process by which preheated steel is dipped into a heated cyanide bath and allowed to soak.

The part is then removed, quenched, and rinsed to remove any residual cyanide.

This process is fast and efficient. It produces a thin, hard shell, harder than the shell produced by carburizing, and can be completed in 20 to 30 minutes vice several hours. The major drawback is the use of cyanide; cyanide salts are a deadly poison.

4.3.1.3 Nitriding

Nitriding — a case hardening process by which individual parts have been heat treated and tempered *before* being heated in a furnace that has an ammonia gas atmosphere.

This case hardening method produces the hardest surface of any of the hardening processes, and it differs from the other methods in that no quenching is required so there is no worry about warping or other types of distortion.

The nitriding process is used to case harden items such as gears, cylinder sleeves, camshafts, and other engine parts that need to be wear-resistant and operate in high-heat areas.

4.3.2 Flame Hardening

Flame hardening is another process available for hardening the surface of metal parts. In flame hardening, you use an oxyacetylene flame to heat a thin layer of the surface to its critical temperature and then immediately quench it with a water spray. In this case, the cold base metal assists in the quenching since it is not preheated.

Similar to case hardening, this process produces a thin, hardened surface while the internal parts retain their original properties.

The process can be manual or mechanical, but in either case, you must maintain a close watch since an oxyacetylene flame can heat the metal rapidly and temperatures in this method are usually determined visually.

Flame hardening may also be done with automatic equipment.



Whenever possible, automatic equipment is desirable for more uniform results.

Most automatic machines have variable travel speeds to adapt to parts of various sizes and shapes, and the size and shape of the torch will also depend on the part. (Figure 2-2)

Figure 2-2 — Typical flame hardening.

A typical flame hardening torch consists of a mixing head, straight extension tube, 90-degree extension head, adjustable yoke, and a water-cooled tip.

Tips are available for hardening flats, rounds, gears, cams, cylinders, and other regular or irregular shapes. Practically any shape or size flame-hardening tip is offered. (Figure 2-3)

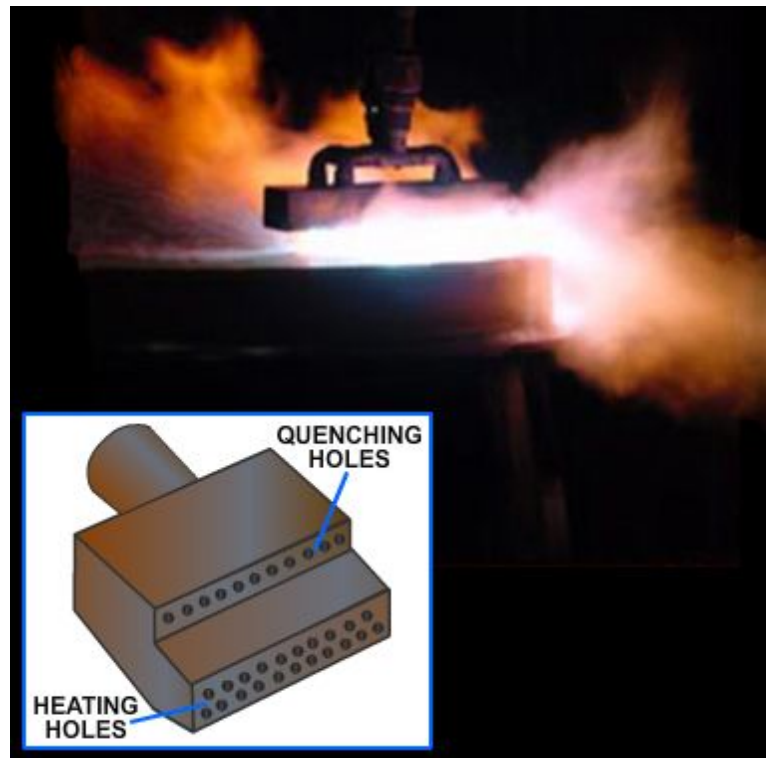
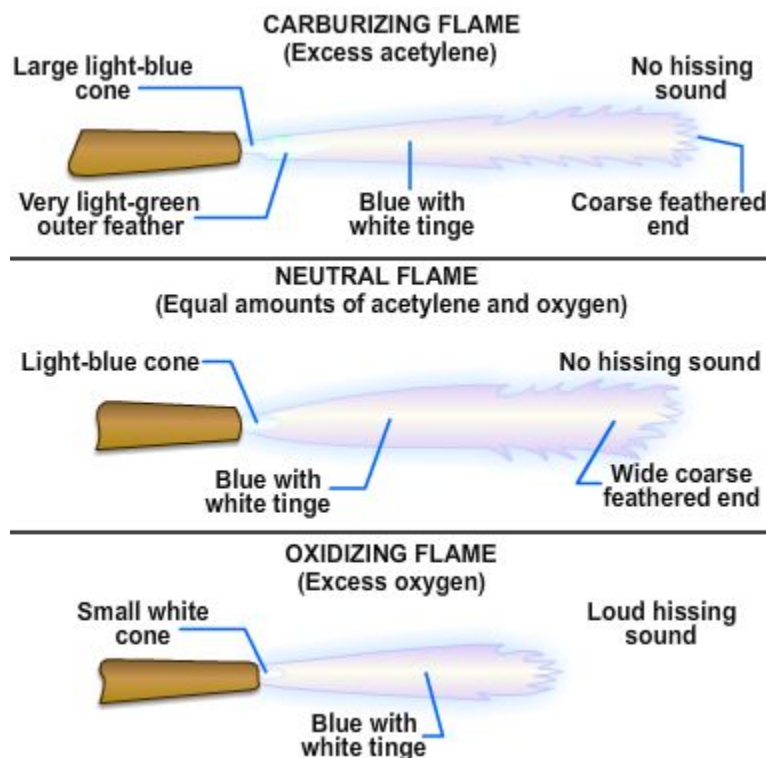


Figure 2-3 — Typical progressive hardening torch tip.



For hardening localized areas, you can flame harden with a standard hand-held welding torch and the torch flame adjusted to neutral for normal heating. (Figure 2-4)

In corners and grooves, however, you should use a slightly oxidizing flame to keep the torch from sputtering, and exercise particular care against overheating.

If dark streaks appear on the metal surface, this is a sign you are overheating, and you need to increase the distance between flame and metal.

Figure 2-4 — Example of carburizing, neutral, and oxidizing flames.

Typically, for the best flame-hardening heating results, you should hold the torch with the tip of the inner cone about an eighth of an inch from the surface and direct the flame at right angles to the metal. Occasionally, you may need to change the angle for better results, but you will rarely use a deviation of more than 30°. The speed of torch travel will depend on the type of metal, the mass, the shape of the part, and the depth of hardness desired.

If you have options in selecting the core material for the part to be flame hardened, select the steel according to the properties desired. When surface hardness is the primary factor, select carbon steel; when the physical properties of the core are also factors, select alloy steel.

For good results in flame hardening, plain carbon steels should contain more than 0.35% carbon, and 0.40% to 0.70% is the effective carbon range for water quenching. A carbon content greater than 0.70% is likely to induce surface cracks unless the heating and quenching rate are carefully controlled.

A section that has a flame-hardened surface is equal to a section that was hardened by furnace heating and quenching for the following reasons:

- The decrease in hardness between the case and the core is gradual.
- The core is not affected by flame hardening so there is little danger of **spalling** or flaking while the part is in use.

Thus, properly done, flame hardening can produce a hard case that is highly resistant to wear, and a core that retains its original properties.

There are five general methods for flame hardening: stationary, circular band progressive, straight-line progressive, spiral band progressive, and circular band spinning.

- Stationary Method — Torch and metal part are both held stationary.
- Circular Band Progressive Method — Object is rotated in front of a stationary torch at a surface speed of from 3 to 12 inches per minute.
 - o Use this method for hardening outside surfaces of round sections.
 - o Heating and quenching are done progressively as the part rotates.
 - o Hardened band encircles part on one completed rotation.
 - o Width of hardened band depends upon the width of the torch tip.
 - o To harden the full length of a long section, torch is moved and process repeated until the part is completely hardened.
 - o Each torch pass should overlap the previous one.

- Straight-Line Progressive Method — Torch travels along the surface, treating a strip that is about the same width as the torch tip. (*Figure 2-5*)
 - o Move the torch and repeat the process to harden a wider area.

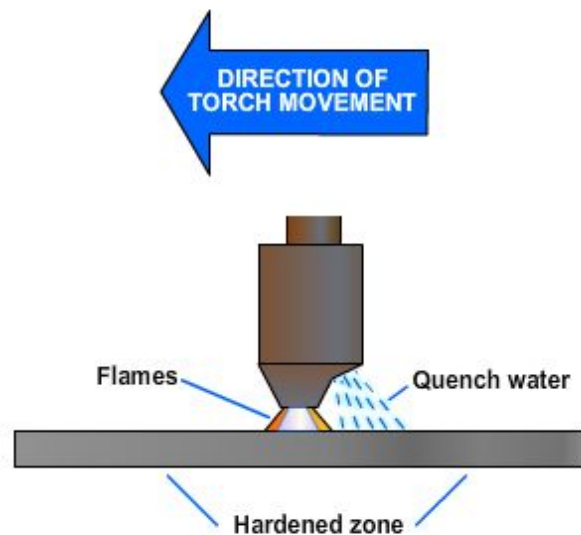


Figure 2-5 — Example of progressive hardening.

- Spiral Band Progressive Method — Cylindrical part is mounted between lathe centers; a torch with an adjustable holder is mounted on the lathe carriage.
 - o Torch moves parallel to the surface of the part as the part rotates.
 - o Travel is synchronized with the part's rotary motion to produce a continuous band of hardness.
 - o Heating and quenching occur at the same time.
 - o Number of torches required depends on the diameter of the part; seldom more than two.
- Circular Band Spinning Method — Part is mounted between lathe centers and turned at a high rate of speed past a stationary torch.
 - o This method provides the best results for hardening cylindrical parts of small or medium diameters.
 - o Enough torches are placed side by side to heat the entire part.
 - o Part can be quenched by water flowing from the torch tips or in a separate operation. (*Figure 2-6*)

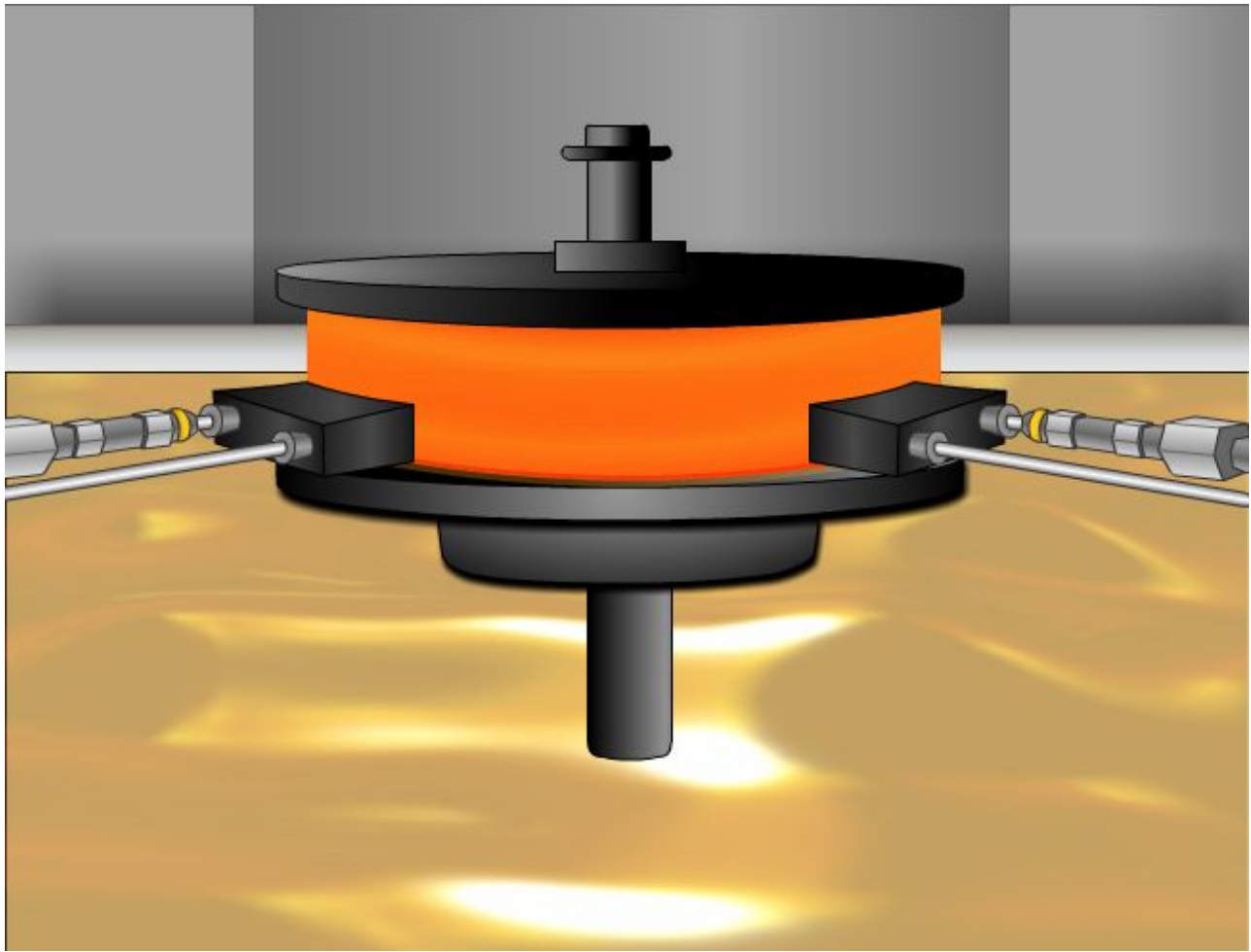


Figure 2-6 — Example of flame hardening with the circular band spinning method.

When heating and quenching are performed as separate operations, the heating tips may be water cooled internally, but no water sprays simultaneously onto the surface of the part.

When you are flame hardening, follow the same safety precautions that apply to welding:

- Guard against holding the flame too close to the surface and overheating the metal.
- When you are judging the temperature of the metal by color, remember the flame makes the metal appear colder than it actually is.

4.4.0 Tempering

After hardening by either case or flame, steel is often harder than needed and too brittle for most practical uses, containing severe internal stresses that were set during the rapid cooling of the process. Following hardening, you need to temper the steel to relieve the internal stresses and reduce brittleness.

Tempering consists of:

- Heating the steel to a specific temperature (below its hardening temperature)
- Holding it at that temperature for the required length of time
- Cooling it, usually in still air.

If this sounds familiar, you are correct; it is the same three-stage process as in heat treatment. The difference is in the temperatures used for tempering, which will affect the resultant strength, hardness, and ductility.

You temper a steel part to reduce the brittleness caused by hardening, and develop specific physical properties; it always follows, never precedes hardening. Tempering reduces brittleness, but it also softens the steel, which you cannot avoid. However, the amount of hardness lost is controllable and dependent on the temperature you subject the steel to during the tempering process. That is true of all steels except **high-speed steel**; tempering increases the hardness of high-speed steel.

The annealing, normalizing, and hardening processes all include steps at temperatures *above the metal's upper critical point*. Tempering is always conducted at temperatures *below the metal's low-critical point*.

When you reheat hardened steel, you begin tempering it at 212°F, and continue as the temperature increases toward the low-critical point. You can predetermine the resulting hardness and strength if you preselect the finite tempering temperature. For planning your tempering time, the minimum should be one hour, or if the part is more than one inch thick, increase the time by one additional hour for each additional inch of thickness.

With most steels, the rate of cooling from the tempering temperature has no effect on the steel. After a steel part is removed from the tempering furnace, it is usually cooled in still air, just like in the normalizing process.

However, there are a few anomalies; a few types of steel must be quenched from the tempering temperature to *prevent* brittleness. Known as blue brittle steels, they can become brittle if heated in certain temperature ranges and cooled slowly. Some nickel chromium steels are subject to this temper brittleness.

Providing there is any hardness to temper, you can temper steel that has been normalized, but you cannot temper annealed steel. What would be the purpose? If you will remember, the purpose of both normalizing (air cooled), and annealing (controlled cooling environment) was to relieve stress, the same as tempering.

Tempering relieves internal stresses from quenching, reduces hardness and brittleness, and may actually increase the tensile strength of hardened steel as it is tempered up to a temperature of about 450°F; above 450°F, tensile strength starts to decrease.

Typically, tempering increases softness, ductility, malleability, and impact resistance, but again, high-speed steel is an exception to the rule. High-speed steel *increases* in hardness on tempering, provided you temper it at a high temperature (about 1150°F). Remember, to temper a part properly, you need to remove it from the quenching bath before it is completely cold and proceed with the tempering process. Failure to temper correctly can result in a quick failure of the hardened part.

Permanent steel magnets are made of hardened and tempered special alloys whose most important properties are stability and hardness. They are tempered at the minimum tempering temperature (212°F) by placing them in boiling water for 2 to 4 hours, and because of this low-tempering temperature, are very hard.

Do not temper case-hardened parts at too high a temperature or they will lose some of their hardness. A temperature range of 212°F — 400°F is high enough to relieve quenching stresses for case-hardened parts. The design of the part can help determine the appropriate tempering temperature, and some metals do not require tempering at all.

Tempering by color range is similar in concept to heat treating by color range, but one of the first things you will notice is the extreme differences in temperature gradations. Instead of the large 750° — 2350° range with color changes in 100° — 150° (+ –) segments for heat treating, the entire range for tempering by color is only about 170° with color changes in 10° — 20° (+ –) segments. (*Figure 2-7*)

In addition, instead of being based on the fundamental metal itself and its alloys as in heat treating, tempering by color is based on surface oxides that change colors as you heat the steel. As you slowly heat a piece of polished hardened steel, you will see the surface turn various colors as the surface temperature changes; this indicates you are making structural changes within the metal.

Once the preplanned color appears, rapidly quench the part to prevent further structural change. The part may be heated by torch, furnace, hot plate, or radiation, but in all circumstances, it must be smooth and free of oil for true indication of color.

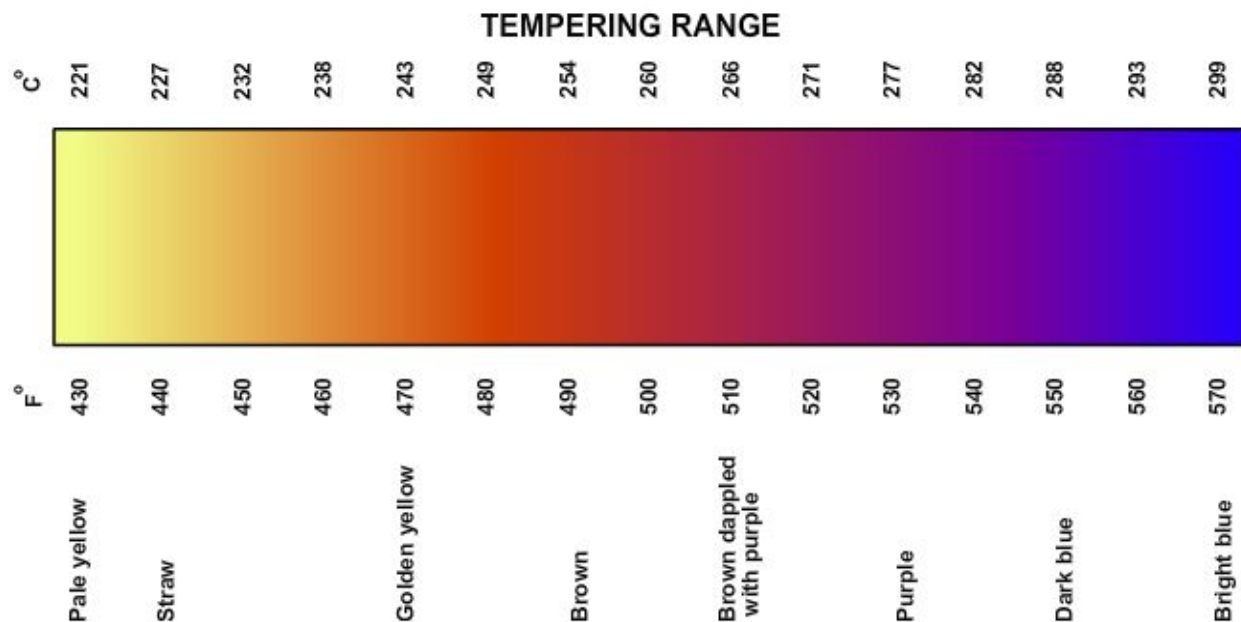


Figure 2-7 — Example of oxide colors for tempering steel.

Cold chisels and similar tools must have hard cutting edges with softer bodies and heads. The heads must be tough but not brittle to prevent shattering when struck, the cutting edge must be twice as hard (or more) as the head, and the zone separating the two must blend the two extremes without a line of demarcation that would encourage breakage.

One method frequently used for tempering chisels and similar tools is one in which the cutting end is heated and tempered by the residual heat of the opposite end of the same tool.

To simultaneously harden and temper a cold chisel by this method:

- Heat the tool to the proper hardening temperature.
- Quench the cutting end only.
- Bob the chisel up and down in the bath, always keeping the cutting edge below the surface.
 - o This method air cools the head (normalizing) while rapidly quenching the cutting edge (hardening).

The result is a tough head, a fully hardened cutting edge, and a properly blended structure.

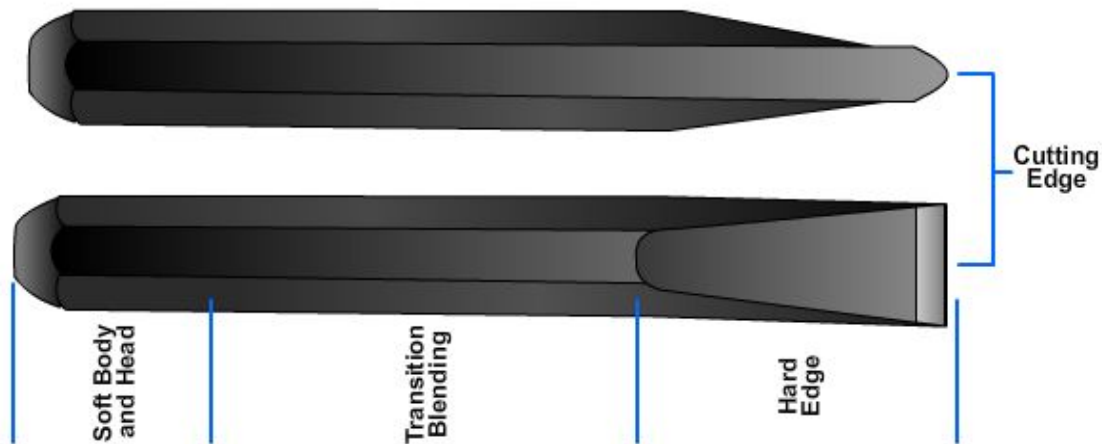


Figure 2-8 — Typical cold chisel tempering areas.

When the cutting end has cooled:

- Remove the chisel from the bath.
- Quickly polish the cutting end with a buff stick (emery).
- Watch the polished surface for heat from the opposite end feeding back into the quenched end.
 - Oxide colors will appear on the hardened end as the temperature increases, progressing from pale yellow, to a straw color, and finally to blue colors.

As soon as the correct shade of blue appears:

- Quench the entire chisel to prevent further softening of the cutting edge.
 - Temper the hardened end as soon as the proper oxide color appears; quenching merely prevents further tempering by halting the process.
 - This final quench has no effect on the body and the head of the chisel. Their temperatures will have dropped below the critical point by the time the proper oxide color appears on the cutting edge.

By completing this described process, you will have hardened and tempered the chisel, and it only needs grinding.

The oxide color at which you quench the steel during tempering will vary with the properties you want to attain in the part. Refer again to *Figure 2-7*. To see the colors clearly, turn the part from side to side under good lighting conditions. While hand tempering can produce the same result as furnace tempering, there is a greater possibility for error, so the slower you perform the operations the more accurate your results will be.

Test your Knowledge (Select the Correct Response)

1. **(True or False)** To make a metal more useful, heat treating can make it stronger, more resistant to impact, malleable, and ductile with one process.
- A. True
B. False

5.0.0 QUENCHING MEDIA

The rate at which you can cool an object will depend on several factors:

- Size of the part
 - o The mass of the part will affect quenching; the greater the mass, the greater the time required for complete cooling.
- Configuration of the part
 - o Parts may be of the same size, but those containing holes or recesses cool more rapidly than solid objects.
- Composition of the part
 - o The composition of a metal will determine the maximum cooling rate possible without the danger of cracking or warping.
- Initial temperature of the part
 - o Different steels and steel alloys require a wide range of temperatures for heat treatment.
- Final properties desired
 - o The medium must cool the metal at the rate you need (rapidly or slowly) to produce the results you want.

Each is a factor in deciding which quenching medium you should use.

The value of any quenching medium's cooling rate upon a quenched part will vary with the medium's temperature; therefore, to get uniform results, you must keep the medium's temperature within prescribed limits.

The quenching medium's absorption of heat will also depend on the circulation of the medium or the movement of the part; agitating the liquid or the part breaks up gas that forms an insulating blanket between the part and the liquid, hence increasing the time element to cool to a given temperature.

Normally, when you quench a metal, hardening occurs and the metal's composition will determine the type of quench to use to achieve the desired hardness.

For example, shallow-hardened, low-alloy, and carbon steels require more severe quenching than deep-hardened alloy steels with large quantities of nickel, manganese, or other elements. Therefore, the shallow-hardening steels are usually quenched in water or brine while the deep-hardening steels are usually quenched in oil.

Sometimes it is necessary to use a combination quench (starting with brine or water and finishing with oil), for in addition to producing the desired hardness, the quench must minimize cracking, warping, and soft spots.



The quenching liquid's volume needs to be large enough to absorb all the heat during a normal quenching operation.

As you quench more metals, the medium's temperature will rise as the liquid absorbs the heat.

This temperature rise will cause a decrease in the cooling rate, which in turn will negatively affect your efforts to harden the metal.

Some tanks use mechanical means to keep temperatures at prescribed levels during continuous operations, such as the heat exchanger shown in *Figure 2-9*.

Figure 2-9 — Example of a controlled temperature quench tank.

5.1.0 Liquid Quenching

There are two methods for liquid quenching:

- Still-bath
 - o Metal is cooled in a tank of liquid; only movement of the liquid is caused by movement of the hot metal.
- Flush quenching
 - o Liquid is sprayed onto the surface and into every cavity at the same time to ensure uniform cooling; used for parts with recesses or cavities not quenchable by ordinary methods; assures a thorough and uniform quench; reduces the possibilities of distortion.

As already mentioned, for satisfactory heat treating results, quenching liquids must be maintained at uniform temperatures; this is particularly true for oil. Many commercial operations that use oil-quenching tanks maintain the oil bath at their proper temperature by circulating the oil medium through coils that themselves are water cooled. Self-contained coolers are an integral part of large quench tanks.

Quenching tanks have a wide range of capabilities, from the large commercial polymer-quenching tank shown in *Figure 2-10 View A*, to the small portable water- and oil-quenching tank that may be available to the Seabees, shown in *Figure 2-10 View B*.



A. Commerical polymer quench tank.

Figure 2-10 — Examples of the wide range of quenching tanks.

The typical portable quenching tank shown in *Figure 2-10 View B* can be moved to various parts of the Steelworker shop for heat treating as needed. These portable tanks may have just one compartment, but typically, they have compartments for containing water in one segment and oil in another, with a liquid-tight partition to prevent mixing.

Each compartment has a drain plug, a screen in the bottom to catch scale and other foreign matter, and a mesh basket to hold the parts. In addition, shops can attach a portable electric pump or a mechanical agitation mixer to the rim of the tank for liquid circulation to aid in uniform cooling.

5.1.1 Water

You can use water to quench some forms of steel, but water is not recommended for **tool steel** or other alloy steels. Water absorbs large quantities of atmospheric gases, which have a tendency to form bubbles on the metal's surface when you quench a hot piece. The bubbles tend to collect in holes or recesses causing soft spots that can lead to cracking or warping.

For any given part to be treated, the quench tank must meet the following criteria:

- Large enough to hold the part being treated
- Adequate circulation and temperature control
- Water temperature not exceeding 65°F

- Water volume large enough to prevent a temperature rise of more than 20°F during a single operation
 - o Temperature rise may exceed 20°F for heavy-sectioned parts but should be kept as low as possible,
 - o For wrought products, temperature should be about 65°F and never exceed 100°F before the piece enters the liquid,
- Water changed daily; more often if required

When you quench aluminum alloys and other nonferrous metals, always quench them in clean water.

5.1.2 Brine

You prepare brine by dissolving common rock salt in water. The brine solution should contain from 7% to 10% salt by weight or three-fourths pound of salt for each gallon of water. Brine reduces the water's absorption of atmospheric gases, thus reducing the amount of bubbles and allowing greater surface contact to cool the part more rapidly than water. The correct temperature range for a brine solution is 65°F to 100°F.

You can quench low-alloy and carbon steels in brine solutions, but brine is not recommended for high-carbon or low-alloy steels with uneven cross sections; the rapid cooling rate of brine can cause cracking or stress in the latter.

In addition to rapid and uniform cooling, a brine medium removes a large percentage of any scale that may be present, but do not quench nonferrous metals in brine due to the corrosive action brine has on these metals.

5.1.3 Oil

Use oil to quench high-speed and oil-hardened steels and preferably all other steels if you can obtain the required hardness. Practically any type of obtainable oil is acceptable as quenching oil, including the various animal oils, fish oils, vegetable oils, and mineral oils.

Oil is classed as an intermediate quench; its cooling rate is slower than brine or water but faster than air. Keep the quenching oil's temperature within a range of 80°F to 150°F.

In small amounts, the water that usually collects in the bottom of a quenching oil tank is not harmful, but in large quantity it can interfere with the quenching operations. For example, if the end of a long piece extends through the oil into the water at the bottom of the tank, the more rapid cooling action of the water can cause the piece to crack.

Nonferrous metals are not routinely oil quenched unless called for in the specifications.

Table 2-2 provides the properties and average cooling rates of various quenching oils relative to water.

Table 2-2 — Properties and Average Cooling Abilities of Quenching Media

Quenching Media	Cooling Rate Compared to Water	Flash Point (°F)	Fire Point (°F)
Caustic Soda (Sodium Hydroxide) (10%)	2.06		
Brine (10%) at 65°	1.96		
Water at 65°	1.00		
Prepared Oil	0.44	365	405
Fuel Oil	0.36	205	219
Cottonseed Oil	0.36	610	680
Neatsfoot Oil	0.33	500	621
Sperm Oil	0.33	500	581
Fish Oil	0.31	401	446
Castor Oil	0.29	565	640
Machine Oil	0.22	405	464
Lard Oil	0.19	565	685
Circulated Air	0.032		
Still Air	0.0152		

5.1.4 Caustic Soda

Only use **caustic soda** for specific types of steel that require extremely rapid cooling. Refer to *Table 2-2*. Like brine, a solution of water and caustic soda (10% caustic soda by weight) has a higher cooling rate than water. However, caustic soda (note the name “caustic”) requires special attention.



CAUTION

Never quench nonferrous metals in caustic soda

Caustic Soda requires special handling because of its harmful effects on skin and clothing

5.2.0 Dry Quenching

As the term implies, when you dry quench, you are using materials other than liquids and in most cases only to slow the cooling rate to prevent warping or cracking.

5.2.1 Air

You use air quenching for cooling some highly alloyed steels. If you use still air, place each tool or part on a suitable rack so air can reach all sections of the piece.

If you use circulated air, place them in the same manner in a suitable rack, but ensure that the circulated air from the source reaches the parts equally for uniform cooling.

You can use compressed air to concentrate cooling on specific areas of a part, but to prevent cracking the metal you must first ensure that the air lines are dry and free of the moisture that typically builds in compression tanks and lines.

To quench nonferrous metals, you should use water, but when necessary, you can use forced-air drafts to cool pieces too large to fit into the quench tank. However, you should only use an air quench for nonferrous metal when the part will *not* be subjected to severe corrosion conditions, and the required strength and other physical properties can be developed by a mild air quench.

5.2.2 Solids

The solids you can use for cooling steel parts include cast iron chips, lime, sand, and ashes. Generally, you would use them to slow the rate of cooling; for example, you might place a cast iron part in a lime box after welding to prevent cracking and warping. Regardless of which solid you select, it must be free of moisture to prevent uneven cooling.

Summary

This chapter has covered just a few elements of the heat treating theory and explained how you can change the properties of a metal. The heat treatment you apply as a Steelworker can, if done properly, extend the service life of appropriate TOA parts and equipment. Conversely, if done improperly, you could shorten the service life.

To recognize the appropriate treatment for achieving the desired properties for a selected metal is your challenge. However, you should now be able to recognize a reference chart for color temperature, and be able to select a suitable general method of heat treatment with the correct quenching medium to achieve the targeted properties. You may not achieve the ultimate properties on the first try, but repeated practice and experimentation will improve your ability in this set of skills.

Review Questions (Select the Correct Response)

1. What process consists of tempering, normalizing, hardening, and annealing?
 - A. Cold forming of metals
 - B. Heat treatment of nonferrous metals
 - C. Heat treatment of ferrous metal
 - D. Quenching of austenitic materials

2. **(True or False)** Most nonferrous metals can be normalized and case hardened but not annealed.
 - A. True
 - B. False

3. Which of the following conditions is required for the successful heat treatment of metals?
 - A. Proper size of furnace
 - B. Proper furnace atmosphere
 - C. Suitable quenching medium
 - D. All of the above

4. What type of furnace produces an atmosphere consisting of a gas/air combustion product?
 - A. Oil-fired only
 - B. Both gas-fired and electric
 - C. Both oil-fired and gas-fired
 - D. Both oil-fired and electric

5. Which of these gas mixtures are constituents of a fuel-fired furnace atmosphere?
 - A. Carbon dioxide, hydrogen, oxygen, and nitrogen
 - B. Carbon monoxide, nitrogen, argon, and radon
 - C. Hydrogen, bromine, oxygen, and chlorine
 - D. Hydrogen, oxygen, argon, and radon

6. What allows you to provide an oxidizing, reducing, or neutral atmosphere in a fuel fired furnace?
 - A. Varying the type of fuel
 - B. Construction of the furnace
 - C. Varying the proportion of air to fuel
 - D. All of the above

7. What type of furnace(s) allows the atmosphere to consist of air only?
- A. Oil-fired
 - B. Electric
 - C. Both oil-fired and gas-fired
 - D. Both oil-fired and electric
8. What is the primary cause of distortion and cracking of the heat-treated part?
- A. Heating the part too slowly
 - B. Increasing the soaking temperature too slowly
 - C. Uneven expansion due to carbon deposits in the part
 - D. Heating one section of the part more rapidly than other parts
9. How do you determine the soaking period when parts are uneven in cross section?
- A. By the total weight
 - B. By the largest section
 - C. By the lightest section
 - D. By the number of parts
10. What type of medium is normally used to quench nonferrous metals?
- A. Oil
 - B. Brine
 - C. Air
 - D. Water
11. What effect is produced when steel is cooled very slowly in a medium that does NOT conduct heat easily?
- A. Maximum softness
 - B. Maximum hardness
 - C. Maximum ductility
 - D. Minimum ductility
12. Copper becomes hard and brittle when mechanically worked, but it can be made soft again by annealing. Within what temperature range must you heat it to anneal it?
- A. 500°F to 600°F
 - B. 600°F to 700°F
 - C. 700°F to 900°F
 - D. 900°F to 1100°F
13. **(True or False)** Normalizing is a form of heat treatment applicable to nonferrous metals only.
- A. True
 - B. False

14. Which of these metals are difficult to harden by heat treatment?
- A. Wrought irons
 - B. Pure irons
 - C. Extremely low-carbon steels
 - D. All of the above
15. What factor almost completely determines the maximum obtainable hardness in plain carbon steel?
- A. The carbon content of the steel
 - B. The thickness of the steel
 - C. The heating time
 - D. The temperature to which it was heated
16. What case-hardening method produces the hardest surface of any of the hardening processes?
- A. Nitriding
 - B. Cyaniding
 - C. Carburizing
 - D. Halogenizing
17. If the steel parts are placed in a container packed with charcoal and heated in a furnace, what case-hardening process is being used?
- A. Cementation
 - B. Pack hardening
 - C. Carburizing
 - D. Atmospheric cementation
18. On what areas of a part being flame hardened should a slightly oxidizing flame be used?
- A. Flat surfaces
 - B. Corners and grooves
 - C. Rounded surfaces
 - D. Edges and elongated sections
19. Which of these factors determines the rate at which you move the welding torch when flame hardening a steel part?
- A. Mass of the part
 - B. Shape of the part
 - C. Depth of the hardness desired
 - D. All of the above

20. **(True or False)** Flame hardening can produce a hard case that resists wear while the core retains the metal's original properties.
- A. True
 - B. False
21. What term is used to describe the process of heating steel to a specific temperature (below its hardening temperature), holding this temperature for a certain length of time, and then cooling the steel in still air to room temperature?
- A. Annealing
 - B. Hardening
 - C. Tempering
 - D. Case hardening
22. **(True or False)** Steel can be tempered provided some hardness remains after it has been normalized.
- A. True
 - B. False
23. In which of the following metals are the softness, ductility, and resistance to impact NOT increased?
- A. Aluminum
 - B. High-speed steel
 - C. Low-carbon steel
 - D. Already hardened steel
24. What are the most important properties to be obtained in tempering permanent steel magnets?
- A. Stability and malleability
 - B. Softness and malleability
 - C. Hardness and stability
 - D. Ductility and resistance to wear
25. Why should you agitate the part or the quenching medium when cooling a part?
- A. To break up gases that form
 - B. To induce oxidation
 - C. To reduce the cooling rate
 - D. To raise the temperature of the liquid

26. For which of the following reasons is the flush method of quenching better than other quenching methods for parts having cavities or recesses?
- A. It enables formation of gases that enhance the hardening process.
 - B. It introduces oxygen into the process to increase the temperature.
 - C. It ensures a thorough uniform quench as liquid is sprayed all over the parts.
 - D. It facilitates the formation of gases that help reduce the temperature.
27. What temperature should water not exceed when used as a quenching medium?
- A. 65°F
 - B. 75°F
 - C. 85°F
 - D. 95°F
28. Which of these quenching media has the highest cooling rate compared to water?
- A. Fuel oil
 - B. Prepared oil
 - C. Brine, 10% solution at 65°F
 - D. Caustic soda (sodium hydroxide), 10% solution
29. What is the correct solution for a brine quench medium?
- A. 3.8% salt for every 3 gallons of water at 65°F
 - B. 3/4 pound of salt per gallon of water at 65°F to 100°F
 - C. 20% salt solution for the entire mix
 - D. 3/4 pound of salt per 100 gallons of water
30. **(True or False)** Caustic soda requires special handling because of its harmful effects on skin and clothing.
- A. True
 - B. False
31. **(True or False)** Air quenching should only be used for nonferrous metals
- A. True
 - B. False

Trade Terms Introduced in this Chapter

Case hardened	Case hardening or surface hardening is the process of hardening the surface of a metal, often a low-carbon steel, by infusing elements into the material's surface, forming a thin layer of a harder alloy. Case hardening is usually done after the part in question has been formed into its final shape.
Caustic Soda	Sodium hydroxide (NaOH), also known as lye and caustic soda, is a caustic metallic base. It is used in many industries, mostly as a strong chemical base in the manufacture of pulp and paper, textiles, drinking water, soaps and detergents, and as a drain cleaner.
Cementite	Hard, brittle iron carbide (Fe_3C) in steel, cast iron, and iron-carbon alloys.
Cooling medium	Any gas, liquid, solid, or combination used specifically to cool a metal to room temperature during a heat-treating process.
High-speed steel	High-speed steel is a general name for high alloy steels that retain their hardness at very high temperatures and are used for metal-cutting tools. All high-speed steels are based on either tungsten or molybdenum (or both) as the primary heat-resisting alloying element. These steels require a special heat so that their unique properties can be fully realized. The manufacturing process consists of heating the steel to a temperature of 2,150°F to 2,400°F (1,175°C to 1,315°C) to obtain solution of a substantial percentage of the alloy carbides, quenching to room temperature, tempering at 1,000°F to 1,150°F (535°C to 620°C), and again cooling to room temperature.
Hot-shortness	Brittleness in metals during high temperature deformation.
Quenching	Quench hardening is a mechanical process in which steel and cast iron alloys are strengthened and hardened. This is done by heating the material to a certain temperature, differing upon material, and then rapidly cooling the material. This produces a harder material by either surface hardening or through-hardening, varying according to the rate at which the material is cooled. The material is then often tempered to reduce the brittleness that may increase from the quench- hardening process.
Spalling	To break up into chips or fragments; to chip or crumble.

Tool steel

A variety of carbon and alloy steels particularly well suited for making into tools. Their suitability comes from their distinctive hardness, resistance to abrasion, ability to hold a cutting edge, and/or resistance to deformation at elevated temperatures (red-hardness). Tool steel is generally used in a heat-treated state. With a carbon content between 0.7% and 1.4%, tool steels are manufactured under carefully controlled conditions to produce the required quality and are made to a number of grades for different applications.