CHAPTER 2

BASIC HEAT TREATMENT

As Steelworkers, we are interested in the heat treatment of metals, because we have to know what effects the heat produced by welding or cutting has on metal. We also need to know the methods used to restore metal to its original condition. The process of heat treating is the method by which metals are heated and cooled in a series of specific operations that never allow the metal to reach the molten state. The purpose of heat treating is to make a metal more useful by changing or restoring its mechanical properties. Through heat treating, we can make a metal harder, stronger, and more resistant to impact. Also, heat treating can make a metal softer and more ductile. The one disadvantage is that 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.

HEAT-TREATING THEORY

The various types of heat-treating processes are similar because they all involve the heating and cooling of metals; they differ in the heating temperatures and the cooling rates used and the final results. The usual methods of heat-treating ferrous metals (metals with iron) are annealing, normalizing, hardening, and tempering. Most nonferrous metals can be annealed, but never tempered, normalized, or case-hardened.

Successful heat treatment requires close control over all factors affecting the heating and cooling of a metal. This control is possible only when the proper equipment is available. The furnace must be of the proper size and type and controlled, so the temperatures are kept within the prescribed limits for each operation. Even the furnace atmosphere affects the condition of the metal being heat-treated.

The furnace atmosphere consists of the gases that circulate throughout the heating chamber and surround the metal, as it is 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 the mixture of gases that comes from the combination of the air and the gases released by the fuel during combustion. These gases contain various proportions of carbon monoxide, carbon dioxide, hydrogen, nitrogen, oxygen, water vapor, and other various hydrocarbons. Fuel-fired furnaces can provide three distinct atmospheres when you vary the proportions of air and fuel. They are called oxidizing, reducing, and neutral.

STAGES OF HEAT TREATMENT

Heat treating is accomplished in three major stages:

- Stage l—Heating the metal slowly to ensure a uniform temperature
- Stage 2—Soaking (holding) the metal at a given temperature for a given time and cooling the metal to room temperature
- Stage 3—Cooling the metal to room temperature

HEATING STAGE

The primary objective in the heating stage is to maintain uniform temperatures. If uneven heating occurs, one section of a part can expand faster than another and result in distortion or cracking. Uniform temperatures are attained by slow heating.

The heating rate of a part depends on several factors. One important factor is the heat conductivity of the metal. A metal with a high-heat conductivity heats at a faster rate than one with a low conductivity. Also, the condition of the metal determines the rate at which it may be heated. The heating rate for hardened tools and parts should be slower than unstressed or untreated metals. Finally, size and cross section figure into the heating rate. Parts with a large cross section require slower heating rates to allow the interior temperature to remain close to the surface temperature that prevents warping or cracking. Parts with uneven cross sections experience uneven heating; however, such parts are less apt to be cracked or excessively warped when the heating rate is kept slow.

SOAKING STAGE

After the metal is heated to the proper temperature, it is held at that temperature until the desired internal structural changes take place. This process is called SOAKING. The length of time held at the proper temperature is called the SOAKING PERIOD. The soaking period depends on the chemical analysis of the metal and the mass of the part. When steel parts are uneven in cross section, the soaking period is determined by the largest section.

During the soaking stage, the temperature of the metal is rarely brought from room temperature to the final temperature in one operation; instead, the steel is slowly heated to a temperature just below the point at which the change takes place and then it is held at that temperature until the heat is equalized throughout the metal. We call this process PREHEATING. Following preheat, the metal is quickly heated to the final required temperature.

When apart has an intricate design, it may have to be preheated at more than one temperature to prevent cracking and excessive warping. For example, assume an intricate part needs to be heated to 1500°F for hardening. This part could be slowly heated to 600°F, soaked at this temperature, then heated slowly to 1200°F, and then soaked at that temperature. Following the final preheat, the part should then be heated quickly to the hardening temperature of 1500°F.

NOTE: Nonferrous metals are seldom preheated, because they usually do not require it, and preheating can cause an increase in the grain size in these metals.

COOLING STAGE

After a metal has been soaked, it must be returned to room temperature to complete the heat-treating process. To cool the metal, you can place it in direct contact with a COOLING MEDIUM composed of a gas, liquid, solid, or combination of these. The rate at which the metal is cooled depends on the metal and the properties desired. The rate of cooling depends on the medium; therefore, the choice of a cooling medium has an important influence on the properties desired.

Quenching is the procedure used for cooling metal rapidly in oil, water, brine, or some other medium. Because most metals are cooled rapidly during the hardening process, quenching is usually associated with hardening; however, quenching does not always result in an increase in hardness; for example, to anneal copper, you usually quench it in water. Other metals, such as air-hardened steels, are cooled at a relatively slow rate for hardening.

Some metals crack easily or warp during quenching, and others suffer no ill effects; therefore, the quenching medium must be chosen to fit the metal. Brine or water is used for metals that require a rapid cooling rate, and oil mixtures are more suitable for metals that need a slower rate of cooling. Generally, carbon steels are water-hardened and alloy steels are oil-hardened. Nonferrous metals are normally quenched in water.

HEAT COLORS FOR STEEL

You are probably familiar with the term *red-hot* as applied to steel. Actually, steel takes on several colors and shades from the time it turns a dull red until it reaches a white heat. These colors and the corresponding temperatures are listed in table 2-1.

During hardening, normalizing, and annealing, steel is heated to various temperatures that produce color changes. By observing these changes, you can determine the temperature of the steel. As an example, assume that you must harden a steel part at 1500°F. Heat the part slowly and evenly while watching it closely for any change in color. Once the steel begins to turn red, carefully note each change in shade. Continue the even heating until the steel is bright red; then quench the part.

The success of a heat-treating operation depends largely on your judgment and the accuracy with which you identify each color with its corresponding temperature. From a study of table 2-1, you can see that close observation is necessary. You must be able to tell the difference between faint red and blood red and between dark cherry and medium cherry. To add to the difficulty, your conception of medium cherry may differ from that of the person who prepared the table. For an actual heat-treating operation, you should get a chart showing the actual colors of steel at various temperatures.

TYPES OF HEAT TREATMENT

Four basic types of heat treatment are used today. They are annealing, normalizing, hardening, and tempering. The techniques used in each process and how they relate to Steelworkers are given in the following paragraphs.

ANNEALING

In general, annealing is the opposite of hardening, You anneal metals to relieve internal stresses, soften them, make them more ductile, and refine their grain structures. Annealing consists of heating a metal to a specific temperature, holding it at that temperature for a set length of time, and then cooling the metal to room temperature. The cooling method depends on the

Table 2-1.—Heat Colors for Steel

Color	Temperature °F	Temperature °C
Faint red visible in dark	750	399
Faint red	900	482
Blood red	1050	565
Dark cherry	1075	579
Medium cherry	1250	677
Cherry or full 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

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

Thickness of Metal (inches)	Time of heating to Required Temperature (hr)	Soaking Time (hr)
Up to 1	3/4	1/2
1 to 2	1 1/4	1/2
2 to 3	1 3/4	3/4
3 to 4	2 1/4	1
4 to 5	2 3/4	1
5 to 8	3 1/2	1 1/2

metal and the properties desired. Some metals are furnace-cooled, and others are cooled by burying them in ashes, lime, or other insulating materials.

Welding produces areas that have molten metal next to other areas that are at room temperature. As the weld cools, internal stresses occur along with hard spots and brittleness. Welding can actually weaken the metal. Annealing is just one of the methods for correcting these problems.

Ferrous Metal

To produce the maximum softness in steel, you heat the metal to its proper temperature, soak it, and then let it cool very slowly. The cooling is done by burying the hot part in an insulating material or by shutting off the furnace and allowing the furnace and the part to cool together. The soaking period depends on both the mass of the part and the type of metal. The approximate soaking periods for annealing steel are given in tablc 2-2.

Steel with an extremely low-carbon content requires the highest annealing temperature. As the carbon content increases, the annealing temperatures decrease.

Nonferrous Metal

Copper becomes hard and brittle when mechanically worked; however, it can be made soft again by annealing. The annealing temperature for copper is between 700°F and 900°F. Copper maybe cooled rapidly or slowly since the cooling rate has no effect on the heat treatment. The one drawback experienced in annealing copper is the phenomenon called "hot shortness." At about 900°F, copper loses its tensile strength, and if not properly supported, it could fracture.

Aluminum reacts similar to copper when heat treating. It also has the characteristic of "hot shortness." A number of aluminum alloys exist and each requires special heat treatment to produce their best properties.

NORMALIZING

Normalizing is a type of heat treatment applicable to ferrous metals only. It differs from annealing in that the metal is heated to a higher temperature and then removed from the furnace for air cooling.

The purpose of normalizing is to remove the internal stresses induced by heat treating, welding, casting, forging, forming, or machining. Stress, if not controlled, leads to metal failure; therefore, before hardening steel, you should normalize it first to ensure the maximum desired results. Usually, low-carbon steels do not require normalizing; however, if these steels are normalized, no harmful effects result. Castings are usually annealed, rather than normalized; however, some castings require the normalizing treatment. Table 2-2 shows the approximate soaking periods for normalizing steel. Note that the soaking time varies with the thickness of the metal.

Normalized steels are harder and stronger than annealed steels. In the normalized condition, steel is much tougher than in any other structural condition. Parts subjected to impact and those that require maximum toughness with resistance to external stress are usually normalized. In normalizing, the mass of metal has an influence on the cooling rate and on the resulting structure. Thin pieces cool faster and are harder after normalizing than thick ones. In annealing (furnace cooling), the hardness of the two are about the same.

HARDENING

The hardening treatment for most steels consists of heating the steel to a set temperature and then cooling it rapidly by plunging it into oil, water, or brine. Most steels require rapid cooling (quenching) for hardening but a few can be air-cooled with the same results. Hardening increases the hardness and strength of the steel, but makes it less ductile. Generally, the harder the steel, the more brittle it becomes. To remove some of the brittleness, you should temper the steel after hardening.

Many nonferrous metals can be hardened and their strength increased by controlled heating and rapid cooling. In this case, the process is called heat treatment, rather than hardening.

To harden steel, you cool the metal rapidly after thoroughly soaking it at a temperature slightly above its upper critical point. The approximate soaking periods for hardening steel are listed in table 2-2. The addition of alloys to steel decreases the cooling rate required to produce hardness. A decrease in the cooling rate is an advantage, since it lessens the danger of cracking and warping.

Pure iron, wrought iron, and extremely low-carbon steels have very little hardening properties and are difficult to harden by heat treatment. Cast iron has limited capabilities for hardening. When you cool cast iron rapidly, it forms white iron, which is hard and brittle. And when you cool it slowly, it forms gray iron, which is soft but brittle under impact.

In plain carbon steel, the maximum hardness obtained by heat treatment depends almost entirely on the carbon content of the steel. As the carbon content increases, the hardening ability of the steel increases; however, this capability of hardening with an increase in carbon content continues only to a certain point. In practice, 0.80 percent carbon is required for maximum hardness. When you increase the carbon content beyond 0.80 percent, there is no increase in hardness, but there is an increase in wear resistance. This increase in wear resistance is due to the formation of a substance called hard cementite.

When you alloy steel to increase its hardness, the alloys make the carbon more effective in increasing hardness and strength. Because of this, the carbon content required to produce maximum hardness is lower than it is for plain carbon steels. Usually, alloy steels are superior to carbon steels.

Carbon steels are usually quenched in brine or water, and alloy steels are generally quenched in oil. When hardening carbon steel, remember that you must cool the steel to below 1000°F in less than 1 second. When you add alloys to steel, the time limit for the temperature to drop below 1000°F increases above the l-second limit, and a slower quenching medium can produce the desired hardness.

Quenching produces extremely high internal stresses in steel, and to relieve them, you can temper the steel just before it becomes cold. The part is removed from the quenching bath at a temperature of about 200°F and allowed 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 following paragraphs, we discuss the different methods of hardening that are commercially used. In the Seabees, we use a rapid surface hardening compound called “Case” that can be ordered through the Navy supply system. Information on the use of “Case” is located in the *Welding Materials Handbook*, P-433.

Case Hardening

Case hardening produces a hard, wear-resistant surface or case over a strong, tough core. The principal forms of casehardening are carburizing, cyaniding, and nitriding. Only ferrous metals are case-hardened.

Case hardening is ideal for parts that require a wear-resistant surface and must be tough enough internally to withstand heavy loading. The steels best suited for case hardening are the low-carbon and low-alloy series. When high-carbon steels are case-hardened, the hardness penetrates the core and causes brittleness. In case hardening, you change the surface of the metal chemically by introducing a high carbide or nitride content. The core remains chemically unaffected. When heat-treated, the high-carbon surface responds to hardening, and the core toughens.

CARBURIZING.— Carburizing is a case-hardening process by which carbon is added to the surface of low-carbon steel. This results in a carburized steel that has a high-carbon surface and a low-carbon interior. When the carburized steel is heat-treated, the case becomes hardened and the core remains soft and tough.

Two methods are used for carburizing steel. One method consists of heating the steel in a furnace containing a carbon monoxide atmosphere. The other method has the steel placed in a container packed with charcoal or some other carbon-rich material and then heated in a furnace. To cool the parts, you can leave the container in the furnace to cool or remove it and let it air cool. In both cases, the parts become annealed during the slow cooling. The depth of the carbon penetration depends on the length of the soaking period. With today's methods, carburizing is almost exclusively done by gas atmospheres.

CYANIDING.— This process is a type of case hardening that is fast and efficient. Preheated steel is dipped into a heated cyanide bath and allowed to soak. Upon removal, it is quenched and then rinsed to remove any residual cyanide. This process produces a thin, hard shell that is harder than the one produced by carburizing and can be completed in 20 to 30 minutes vice several hours. The major drawback is that cyanide salts are a deadly poison.

NITRIDING.— This case-hardening method produces the hardest surface of any of the hardening processes. It differs from the other methods in that the individual parts have been heat-treated and tempered before nitriding. The parts are then heated in a furnace that has an ammonia gas atmosphere. No quenching is required so there is no worry about warping or other types of distortion. This 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.

Flame Hardening

Flame hardening is another procedure that is used to harden the surface of metal parts. When you use an oxyacetylene flame, a thin layer at the surface of the part is rapidly heated to its critical temperature and then immediately quenched by a combination of a water spray and the cold base metal. This process produces a thin, hardened surface, and at the same time, the internal parts retain their original properties. Whether the process is manual or mechanical, a close watch must be maintained, since the torches heat the metal rapidly and the temperatures are usually determined visually.

Flame hardening may be either manual or automatic. Automatic equipment produces uniform results and is more desirable. Most automatic machines have variable travel speeds and can be adapted to parts of various sizes and shapes. The size and shape of the torch depends on the part. The torch consists of a mixing head, straight extension tube, 90-degree extension head, an adjustable yoke, and a water-cooled tip. Practically any shape or size flame-hardening tip is available (fig. 2-1).

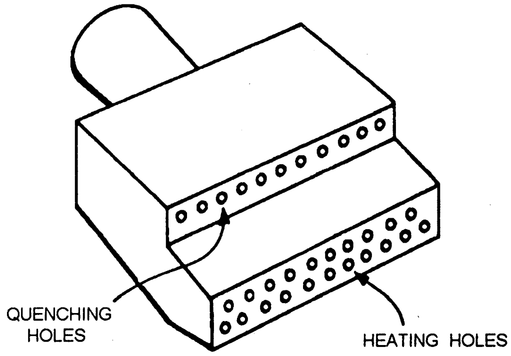

Figure 2-1.—Progressive hardening torch tip.

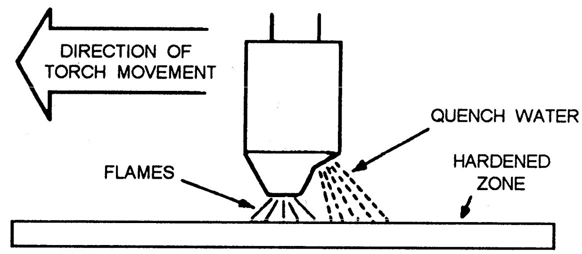

Figure 2-2.—Progressive hardening.

Tips are produced that can be used for hardening flats, rounds, gears, cams, cylinders, and other regular or irregular shapes.

In hardening localized areas, you should heat the metal with a standard hand-held welding torch. Adjust the torch flame to neutral (see chapter 4) for normal heating; however, in corners and grooves, use a slightly oxidizing flame to keep the torch from sputtering. You also should particularly guard against overheating in comers and grooves. If dark streaks appear on the metal surface, this is a sign of overheating, and you need to increase the distance between the flame and the metal.

For the best heating results, 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. Sometimes it is necessary to change this angle to obtain better results; however, you rarely find a deviation of more than 30 degrees. Regulate the speed of torch travel according to the type of metal, the mass and shape of the part, and the depth of hardness desired.

In addition, you must select the steel according to the properties desired. Select carbon steel when surface hardness is the primary factor and alloy steel when the physical properties of the core are also factors. Plain carbon steels should contain more than 0.35% carbon for good results inflame hardening. For water quenching, the effective carbon range is from 0.40% to 0.70%. Parts with a carbon content of more than 0.70% are likely to surface crack unless the heating and quenching rate are carefully controlled.

The surface hardness of a flame-hardened section is equal to a section that was hardened by furnace heating and quenching. The decrease in hardness between the case and the core is gradual. Since the core is not affected by flame hardening, there is little danger of spalling or flaking while the part is in use. Thus flame hardening produces a hard case that is highly resistant to wear and a core that retains its original properties.

Flame hardening can be divided into five general methods: stationary, circular band progressive, straight-line progressive, spiral band progressive, and circular band spinning.

STATIONARY METHOD.— In this method the torch and the metal part are both held stationary.

CIRCULAR BAND PROGRESSIVE METHOD.— This method is used for hardening outside surfaces of round sections. Usually, the object is rotated in front of a stationary torch at a surface speed of from 3 to 12 inches per minute. The heating and quenching are done progressively, as the part rotates; therefore, when the part has completed one rotation, a hardened band encircles the part. The width of the hardened band depends upon the width of the torch tip. To harden the full length of a long section, you can move the torch and repeat the process over and over until the part is completely hardened. Each pass or path of the torch should overlap the previous one to prevent soft spots.

STRAIGHT-LINE PROGRESSIVE METHOD.— With the straight-line progressive method, the torch travels along the surface, treating a strip that is about the same width as the torch tip. To harden wider areas, you move the torch and repeat the process. Figure 2-2 is an example of progressive hardening.

SPIRAL BAND PROGRESSIVE METHOD.— For this technique a cylindrical part is mounted between lathe centers, and a torch with an adjustable holder is mounted on the lathe carriage. As the part rotates, the torch moves parallel to the surface of the part. This travel is synchronized with the parts rotary motion to produce a continuous band of hardness. Heating and quenching occur at the same time. The number of torches required depends on the diameter of the part, but seldom are more than two torches used.

CIRCULAR BAND SPINNING METHOD.— The circular band spinning method provides the best results for hardening cylindrical parts of small or medium diameters. The part is mounted between lathe centers and turned at a high rate of speed pasta stationary torch. Enough torches are placed side by side to heat the entire part. The part can be quenched by water flowing from the torch tips or in a separate operation.

When you perform heating and quenching as separate operations, the tips are water-cooled internally, but no water sprays onto the surface of the part.

In flame hardening, you should follow the same safety precautions that apply to welding (see chapter 3). In particular, guard against holding the flame too close to the surface and overheating the metal. In judging the temperature of the metal, remember that the flame makes the metal appear colder than it actually is.

TEMPERING

After the hardening treatment is applied, steel is often harder than needed and is too brittle for most practical uses. Also, severe internal stresses are set up during the rapid cooling from the hardening temperature. To relieve the internal stresses and reduce brittleness, you should temper the steel after it is hardened. 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, and then cooling it, usually instill air. The resultant strength, hardness, and ductility depend on the temperature to which the steel is heated during the tempering process.

The purpose of tempering is to reduce the brittleness imparted by hardening and to produce definite physical properties within the steel. Tempering always follows, never precedes, the hardening operation. Besides reducing brittleness, tempering softens the steel. That is unavoidable, and the amount of hardness that is lost depends on the temperature that the steel is heated to during the tempering process. That is true of all steels except high-speed steel. Tempering increases the hardness of high-speed steel.

Tempering is always conducted at temperatures below the low-critical point of the steel. In this respect, tempering differs from annealing, normalizing, and hardening in which the temperatures are above the upper critical point. When hardened steel is reheated, tempering begins at 212°F and continues as the temperature increases toward the low-critical point. By selecting a definite tempering temperature, you can predetermine the resulting hardness and strength. The minimum temperature time for tempering should be 1 hour. If the part is more than 1 inch thick, increase the time by 1 hour for each additional inch of thickness.

Normally, the rate of cooling from the tempering temperature has no effect on the steel. Steel parts are usually cooled in still air after being removed from the tempering furnace; however, there are a few types of steel that must be quenched from the tempering temperature to prevent brittleness. These blue brittle steels can become brittle if heated in certain temperature ranges and allowed to cool slowly. Some of the nickel chromium steels are subject to this temper brittleness.

Steel may be tempered after being normalized, providing there is any hardness to temper. Annealed steel is impossible to temper. Tempering relieves quenching stresses and reduces hardness and brittleness. Actually, the tensile strength of a hardened steel may increase as the steel is tempered up to a temperature of about 450°F. Above this temperature it starts to decrease. Tempering increases softness, ductility, malleability, and impact resistance. Again, high-speed steel is an exception to the rule. High-speed steel increases in hardness on tempering, provided it is tempered at a high temperature (about 1550°F). Remember, all steel should be removed from the quenching bath and tempered before it is complete] y cold. Failure to temper correctly results in a quick failure of the hardened part.

Permanent steel magnets are made of special alloys and are heat-treated by hardening and tempering. Hardness and stability are the most important properties in permanent magnets. Magnets are tempered at the minimum tempering temperature of 212°F by placing them in boiling water for 2 to 4 hours. Because of this low-tempering temperature, magnets are very hard.

Case-hardened parts should not be tempered at too high a temperature or they may loose some of their hardness. Usually, a temperature range from 212°F to 400°F is high enough to relieve quenching stresses. Some metals require no tempering. The design of the part helps determine the tempering temperature.

Color tempering is based on the oxide colors that appear on the surface of steel, as it is heated. When you slowly heat a piece of polished hardened steel, you can see the surface turn various colors as the temperature changes. These colors indicate structural changes are taking place within the metal. Once the proper color appears, the part is rapidly quenched to prevent further structural change. In color tempering, the surface of the steel must be smooth and free of oil. The part may be heated by a torch, in a furnace, over a hot plate, or by radiation.

Table 2-3.—Oxide Colors for Tempering Steel

Color	Temperature	
	°F	°C
Pale yellow	428	220
Straw	446	230
Golden yellow	469	243
Brown	491	255
Brown dappled with purple	509	265
Purple	531	277
Dark blue	550	288
Bright blue	567	297
Pale blue	610	321

Cold chisels and similar tools must have hard cutting edges and softer bodies and heads. The head must be tough enough to prevent shattering when struck with shammer.The cutting edge must be more than twice as hard as the head, and the zone separating the two must be carefully blended to prevent a lineof demarcation. A method of color tempering frequently used for chisels and similar tools is one in which the cutting end is heated by the residual heat of the opposite end of the same tool. To harden and tempera cold chisel by this method, you heat the tool to the proper hardening temperature and then quench the cutting end only. Bob the chisel up and down in the bath, always keeping the cutting edge below the surface. This method air-cools the head while rapidly quenching the cutting edge. The result is a tough head, fully hardened cutting edge, and a properly blended structure.

When the cutting end has cooled, remove the chisel from the bath and quickly polish the cutting end with a buff stick (emery). Watch the polished surface, as the heat from the opposite end feeds back into the quenched end. As the temperature of the hardened end increases, oxide colors appear. These oxide colors progress from pale yellow, to a straw color, and end in blue colors. As soon as the correct shade of blue appears, quench the entire chisel to prevent further softening of the cutting edge. The metal is tempered as soon as the proper oxide color appears and quenching merely prevents further tempering by freezing the process. This final quench has no effect on the body and the head of the chisel, because their temperature will have dropped below the critical point by the time the proper oxide color appears on the cutting edge. When you have completed the above described process, the chisel will be hardened and tempered and only needs grinding.

During the tempering, the oxide color at which you quench the steel varies with the properties desired in the part. Table 2-3 lists the different colors and their corresponding temperatures. To see the colors clearly, you must turn the part from side to side and have good lighting. While hand tempering produces the same result as furnace tempering, there is a greater possibility for error. The slower the operation is performed, the more accurate are the results obtained.

QUENCHING MEDIA

The cooling rate of an object depends on many things. The size, composition, and initial temperature of the part and final properties are the deciding factors in selecting the quenching medium. A quenching medium must cool the metal at a rate rapid enough to produce the desired results.

Mass affects quenching in that as the mass increases, the time required for complete cooling also increases. Even though parts are the same size, those containing holes or recesses cool more rapidly than solid objects. The composition of the metal determines the maximum cooling rate possible without the danger of cracking or warping. This critical cooling rate, in turn, influences the choice of the quenching medium.

The cooling rate of any quenching medium varies with its temperature; therefore, to get uniform results, you must keep the temperature within prescribed limits. The absorption of heat by the quenching medium also depends, to a large extent, on the circulation of the quenching medium or the movement of the part. Agitation of the liquid or the part breaks up the gas that forms an insulating blanket between the part and the liquid.

Normally, hardening takes place when you quench a metal. The composition of the metal usually determines the type of quench to use to produce the desired hardness. For example, shallow-hardened low-alloy and carbon steels require severer quenching than deep-hardened alloy steels that contain large quantities of nickel, manganese, or other elements. Therefore, shallow-hardening steels are usually quenched in water or brine, and the deep-hardening steels are quenched in oil. Sometimes it is necessary to use a combination quench, starting with brine or water and finishing with oil. In addition to producing the desired hardness, the quench must keep cracking, warping, and soft spots to a minimum.

The volume of quenching liquid should be large enough to absorb all the heat during a normal quenching operation without the use of additional cooling. As more metals are quenched, the liquid absorbs the heat and this temperature rise causes a decrease in the cooling rate. Since quenching liquids must be maintained within definite temperature ranges, mechanical means are used to keep the temperature at prescribed levels during continuous operations.

LIQUID QUENCHING

The two methods used for liquid quenching are called still-bath and flush quenching.

Instill-bath quenching, you cool the metal in a tank of liquid. The only movement of the liquid is that caused by the movement of the hot metal, as it is being quenched.

For flush quenching, the liquid is sprayed onto the surface and into every cavity of the part at the same time to ensure uniform cooling. Flush quenching is used for parts having recesses or cavities that would not be properly quenched by ordinary methods. That assures a thorough and uniform quench and reduces the possibilities of distortion.

Quenching liquids must be maintained at uniform temperatures for satisfactory results. That is particularly true for oil. To keep the liquids at their proper temperature, they are usually circulated through water-cooled coils. Self-contained coolers are integral parts of large quench tanks.

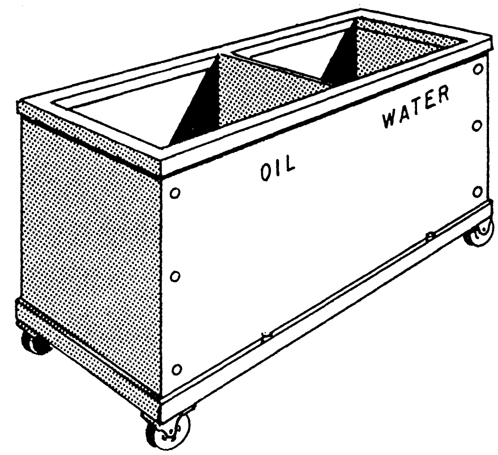

Figure 2-3.—Portable quench tank.

A typical portable quench tank is shown in figure 2-3. This type can be moved as needed to various parts of the heat-treating shop. Some tanks may have one or more compartments. If one compartment contains oil and the other water, the partition must be liquid-tight 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. A portable electric pump can be attached to the rim of the tank to circulate the liquid. This mechanical agitation aids in uniform cooling.

Water

Water can be used to quench some forms of steel, but does not produce good results with tool or other alloy steels. Water absorbs large quantities of atmospheric gases, and when a hot piece of metal is quenched, these gases have a tendency to form bubbles on the surface of the metal. These bubbles tend to collect in holes or recesses and can cause soft spots that later lead to cracking or warping.

The water in the quench tank should be changed daily or more often if required. The quench tank should be large enough to hold the part being treated and should have adequate circulation and temperature control. The temperature of the water should not exceed 65°F.

When aluminum alloys and other nonferrous metals require a liquid quench, you should quench them in clean water. The volume of water in the quench tank should be large enough to prevent a temperature rise of more than 20°F during a single quenching operation. For

Table 2-4.—Properties and Average Cooling Abilities of Quenching Media

Quenching Medium	Cooling Rate Compared To Water	Flash Point (°F)	Fire Point (°F)
Sodium Hydroxide (10%)	2.06		
Brine (10%) at 65°F	1.96		
Caustic Soda (10%)	1.38		
Water at 65°F	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		

heavy-sectioned parts, the temperature rise may exceed 20°F, but should be kept as low as possible. For wrought products, the temperature of the water should be about 65°F and should never exceed 100°F before the piece enters the liquid.

Brine

Brine is the result of dissolving common rock salt in water. This mixture reduces the absorption of atmospheric gases that, in turn, reduces the amount of bubbles. As a result, brine wets the metal surface and cools it more rapidly than water. In addition to rapid and uniform cooling, the brine removes a large percentage of any scale that may be present.

The brine solution should contain from 7% to 10% salt by weight or three-fourths pound of salt for each gallon of water. The correct temperature range for a brine solution is 65°F to 100°F.

Low-alloy and carbon steels can be quenched in brine solutions; however, the rapid cooling rate of brine can cause cracking or stress in high-carbon or low-alloy steels that are uneven in cross section.

Because of the corrosive action of salt on nonferrous metals, these metals are not quenched in brine.

Oil

Oil is used to quench high-speed and oil-hardened steels and is preferred for all other steels provided that the required hardness can be obtained. Practically any type of quenching oil is obtainable, including the various animal oils, fish oils, vegetable oils, and mineral oils. Oil is classed as an intermediate quench. It has a slower cooling rate than brine or water and a faster rate than air. The quenching oil temperature should be kept within a range of 80°F to 150°F. The properties and average cooling powers of various quenching oils are given in table 2-4.

Water usually collects in the bottom of oil tanks but is not harmful in small amounts. In large quantities it can interfere with the quenching operations; for example, the end of a long piece may extend into the water at the bottom of the tank and crack as a result of the more rapid cooling.

Nonferrous metals are not routinely quenched in oil unless specifications call for oil quenching.

Caustic Soda

A solution of water and caustic soda, containing 10 percent caustic soda by weight, has a higher cooling rate than water. Caustic soda is used only for those types of steel that require extremely rapid cooling and is NEVER used as a quench for nonferrous metals.

WARNING

CAUSTIC SODA REQUIRES SPECIAL HANDLING BECAUSE OF ITS HARMFUL EFFECTS ON SKIN AND CLOTHING.

DRY QUENCHING

This type of quenching uses materials other than liquids. Inmost cases, this method is used only to slow the rate of cooling to prevent warping or cracking.

Air

Air quenching is used for cooling some highly alloyed steels. When you use still air, each tool or part should be placed on a suitable rack so the air can reach all sections of the piece. Parts cooled with circulated air are placed in the same manner and arranged for uniform cooling. Compressed air is used to concentrate the cooling on specific areas of a part. The airlines must be free of moisture to prevent cracking of the metal.

Although nonferrous metals are usually quenched in water, pieces that are too large to fit into the quench tank can be cooled with forced-air drafts; however, an air quench should be used for nonferrous metal only 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 quench.

Solids

The solids used for cooling steel parts include cast-iron chips, lime, sand, and ashes. Solids are generally used to slow the rate of cooling; for example, a cast-iron part can be placed in a lime box after welding to prevent cracking and warping. All solids must be free of moisture to prevent uneven cooling.