Quenching for Induction Heating

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Basics of Quenching

When induction hardening ferrous metals, quenching is just as important as the proper heating of the metal. Inadequate or improper quenching of the heated part results in low hardness values as well as spotty hardness and may cause quench cracking.

The intent of the quench is to cool the already austenitized material at a rate that converts most of the austenite to martensite.

Grain size of the material is a major factor in conversion of the metal into austenite and then martensite. The smaller the grain, the faster the material will go into solution. Smaller grain sizes reduce the time required at temperature and the temperature necessary to go into solution as well. Accordingly, rolled, forged, annealed or previously quench and tempered materials will all be affected differently by the heat and quench cycles.

There are a number of methods that can be used for determining the cooling rate for a given alloy. These include the Jominy Hardenability curve (JHT); the Time, Temperature, Transformation curve (TTT); and the Continuous Cooling Transformation (CCT) curve, all for the specific alloy being processed. Usually, the process at 704°C*(1300°F)* is used as a measure of the material's hardenability.

There are a number of quenchants that are used with induction heating and they are selected according to the materials being processed. This selection is based not only upon the material selected but by the mechanical configuration of the part as well. Where masses vary rapidly in volume (change from shape to shape) it may be necessary to use a less rapid quench to prevent cracking at the interface of the two shapes.

Quench cracking is caused by the formation of stresses within the part due to the normal contraction of the metal as it is cooled. In addition, microstructural stresses also occur as the steel expands with the formation of martensite.

Quenching is designed to remove the heat of the part as rapidly as possible. The quenchant must bring the material temperature below the knee of the TTT curve before the structure returns to an austenitic condition. The basic problem incurred during quenching is the formation of steam or vapor at the surface of the part as the quenchant comes in contact with the hot metal surface. It is important that the steam be broken down as rapidly as possible so that additional quenchant can contact the surface and reduce the part temperature. Breaking down the vapor barrier on the surface to be quenched eliminates soft areas and reduces residual stresses that may lead to quench cracking.

Quenchants are generally rated by their ability to remove heat, with brine being the most rapid and oil being the slowest. Where feasible, water is commonly used as a quenching medium. The key to adequate quenching lies in the thermal conductivity of the quenchant and its flow against the heated surface. Brine removes the heat at the fastest rate. Oil is considerably slower. The reaction time of certain steels precludes the use of rapid quenchants such as water which can produce cracking. Selection of the proper quenchant for each type of steel can generally be found in most metallurgical tables.

Oil can be used as a quenchant if it is used in sufficient flow so that the BTUs removed from the part, per gallon of quenchant, is kept below the ignition temperature of the oil. Thus, flow is more important than pressure in oil quenching. However, oil is rapidly being replaced as a quenchant due to its fire hazard and the smoke generated during the quenching cycle.

Plastic or polymer quenchant additives to water are replacing oil as a cooling medium. The “quenchability” of the system is dependent on the percentage of polymer in the water. The greater the polymer concentration, the slower the quenching action and the lower the BTU removal rate of the quenchant per gallon. Since heating of parts causes the water to evaporate during the quenching cycle the concentration must be monitored constantly. This is done utilizing a refractometer which can indicate percent concentration by measuring light diffraction through a sample of the quenchant. Some automatic systems are now available which will monitor the system and maintain the polymer concentration.

Polymer additives have a sticky residue and when used with automated equipment, cleaning of the quench system is important, especially if the equipment is not utilized for some period of time.

In all cases, quench flow is the important factor. High pressure causes the stream to impinge on the surface of the part and does not effectively remove BTUs from the surface. A high flow rate, at minimal pressure is more effective.

Selecting a Quenchant

Brine

Brine cooling rates are the most rapid of all the quenchants. While steam (vapor) breakdown is extremely rapid, higher cooling rates may increase the possibility of distortion and quench cracking of the part may occur. Where the part geometry permits rapid quenching, brine quenching can eliminate soft spots.

This rapid quenching action is caused by minute salt crystals that are deposited on the surface of the work. Localized high temperatures cause the crystals to fragment violently, creating turbulence that destroys the vapor phase.

A 10% solution of NaCl is usually an effective quench. The relationship of brine concentration to hardness is shown in Figure 1 below. Small variations in quench temperature will not greatly affect the cooling rate of the system. A temperature of 20°C*(68°F)* assures maximum effectiveness of cooling.

Relation of hardness to brine concentration when still-quenching, end quench specimens 90 °C (195 °F) brine solution. Number above curves indicate distance from quenched end in units of 1⁄16 in. (Ref 2).

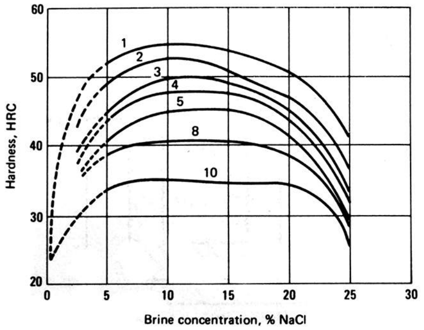


Figure 1

Water

Water quenching is the most common of induction quenchants. Cold water is one of the most severe of the quenchants and rapid agitation allows it to approach the maximum capabilities of the liquid quenchants. If the temperature of the water is allowed to increase, its capabilities for reducing the vapor phase drops and the cooling rate will also decrease at a rapid rate.

Water quench temperatures should be in the range of 15-25°C*(60-75°F)* as shown in Figure 2 below. To maintain adequate cooling provide agitation of the fluid to create a velocity in the order of 0.25 m/s *(50 ft/min)*.

Effect of temperature on quenching properties of water. Source: E.F. Houghton & Co.

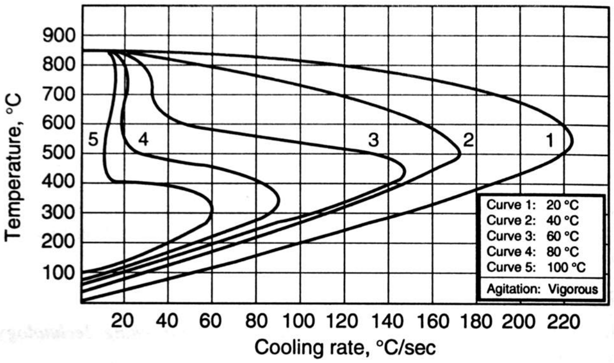


Figure 2

It is usually recommended that along with rust inhibitors, biocides should be added to water quench systems to eliminate biological growth in the water.

Oils

Oils are characterized by quenching speed and operating temperature among other factors. Oils range from normal speed for quenching high hardenability steels to high speed for steels with low hardenability (see Figure 3).

Cooling rate curves for quenching oils. Source: E.F. Houghton & Co.

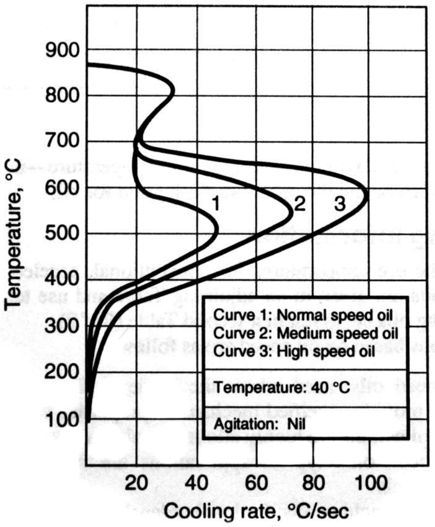


Figure 3

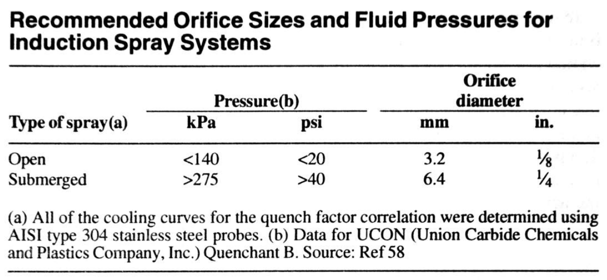
A major factor in selection of oils is the flash point or temperature at which the oil vapors will ignite if an ignition source is present. Ignition occurs if the part is not quenched rapidly or if the oil does not remove heat fast enough. Rapid agitation of the oil together with an adequate cooling means in the quench tank are necessary to reduce the possibility of fire.

Polymers

Polymer quenchants are aqueous PVA materials that are added to water to simulate the quenching characteristics of oil. This is obtained by varying the concentration of the polymer in the water. Benefits of this system include the elimination of smoke as well as possible hazard of ignition and fire.

The polymer helps develop a film at the interface of the heated material and the quenchant and acts as an insulator to slow down the cooling rate to approach that of oil. This film eventually collapses and the quenchant comes in contact with the part being processed. This results in nucleate boiling and a high heat extraction rate. The balance of the cooling is due to convection and conduction in the liquid.

The polymer film on the surface of the heated area dissolves into the fluid when the surface temperature of the part falls below the separation temperature of the polymer quenchant (see Figure 4).



Recommended Orifice Sizes and Fluid Pressures for Induction Spray Systems

Type of spray(a)	Pressure(b) kPa	Pressure(b) psi	Orifice diameter mm	Orifice diameter in.
Open	<140	<20	3.2	⅛
Submerged	>275	>40	6.4	¼

(a) All of the cooling curves for the quench factor correlation were determined using AISI type 304 stainless steel probes. (b) Data for UCON (Union Carbide Chemicals and Plastics Company, Inc.) Quenchant B. Source: Ref 58

Figure 4

A range of quench characteristics can be achieved through variations in the concentration of the polymer, quenchant temperature and agitation of the quenchant.

As the water vaporizes due to contact with the heated surface it will vaporize and turn to steam. Accordingly the concentration of the polymer tends to increase in the quenchant over time. This will change the characteristics of the quench and the addition of water and/or polymer must be adjusted regularly by checking for proper concentration.

Polymers are completely soluble in water at room temperatures but insoluble at temperatures ranging from 60-90°C*(140-195°F)*. Adequate cooling of the quench fluid to remove heat must be provided to keep the quenchant in this range.

Agitation of the polymer quenchant solution will also aid in maintaining uniformity of quench.

Selecting a Quench Method

Mechanical considerations of the handling system usually determine the method for applying the quench. The main purpose of the quench, however applied, is to remove the heat from the part as rapidly as possible while minimizing any stresses that may occur in the process.

Critical factors in designing a proper quench are flow, temperature variance in the quenchant and, degree of filtration and heat removal. Flow, not pressure, is the key to a successful quench.

Drop Quenching

Drop quenching is the most common of all quench techniques. The part is heated above the upper critical temperature and then dropped into a tank containing the quenchant. In many manual processes the operator will simply take the heated part and immerse it in the quench, moving it about to provide agitation.

The time interval between the completion of the heating and the immersion in the quenchant can affect the hardness of the part being processed. Long parts, if heated by single shot technique and dropped vertically into the quench may attain different temperatures from one end to the other during the drop cycle. Similarly, if the part is very thin or the heated depth is shallow, temperature may drop below the critical by the time the part enters the quench. This may create a variation in hardness in the part and possibly create distortion as well.

In the case of a long part, an auxiliary spray quench, energized as the part drops into the tank (Figure 5) should be utilized. The distance the part travels when it passes in to the quench should be minimized.

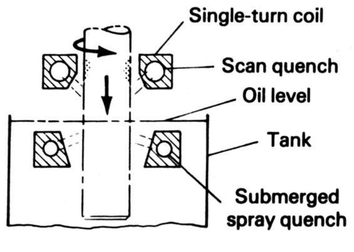


Figure 5

When the part drops into the quench, there should be sufficient agitation to break the vapor barrier. Figures 6A and 6B depict a system used to harden plane blades for woodworking. As each blade is stripped from the magazine it is heated. An escapement then drops the part in to the quench tank. Initially, cold spots were created as the flat blades fell and surface tension caused the parts to adhere to each other bottom of the tank. This prevented insufficient cooling of the blade. A spray ring was inserted into the tank so that the blades passed through the agitation created and were sufficiently cooled by the time they reached the bottom of the tank.

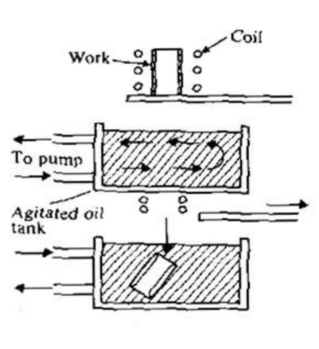


Figure 6A

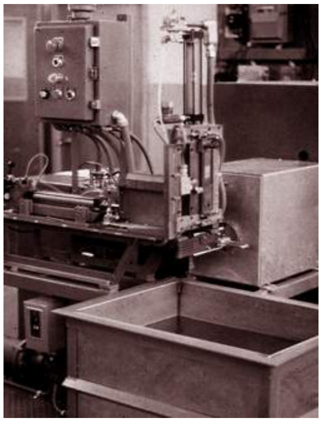


Figure 6B

Drop quenching consists of the part being physically transferred to a tank by a gravity device or conveyor. Selection of technique depends on the mechanical handling as well as the mass of the part vs. the surface area to be cooled. In some instances it is preferable to spray quench the part as it exits the coil and then use a drop quench for further heat removal.

The capacity of quench fluid in the tank is calculated on the amount of BTU's to be removed from the work each hour. A general rule of thumb is one gallon of oil for each pound of heated material per hour.

In production systems, the quench tank must be cooled by a heat exchanger. Gradual build up in temperature of the quench medium by continued use will cause its temperature to rise. This increased quench temperature will reduce part hardness obtainable.

A heater should be supplied in the quench tank to bring the quenchant to the normal operating temperature after a cold start i.e. Monday mornings. Normal quench temperature is 70ºF to 100ºF +/- 5º.

The quench tank should have a propeller or other mechanism for creating a continuous circulation during operation. This helps to remove steam pockets that may form at the face of the hardened area when there is no movement of the quenchant.

Spray Quench

Spray quenching is the most common form of application with induction heating. With this technique, the quenchant is applied to the part at the completion of the heating cycle by a ring or head with perforations, through which quenchant is passed directly on to the part.

In static heating, where the part is held in position during the heat and quench cycles, a solenoid valve is actuated to start the quench flow when the part is at the desired temperature. In cases where the part is small or the case depth is shallow, the solenoid valve is actuated shortly before the end of the heat cycle so that the quench pressure can build sufficiently.

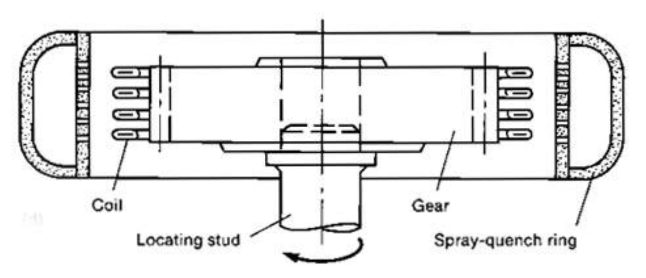


Figure 7

When using a multi-turn coil, a quench ring surrounding the coil applies the quenchant through the space between the coils turns (see Figure 7). Because of its proximity to the work coil, quench heads of this type may experience heating. Quench head should be made of plastic, ceramic or low resistivity materials such as brass. Where a metal quench ring surrounds the coil, heating can be additionally reduced by placing a split in the ring to prevent the ring from being a closed loop. The split should be filled with insulating material and sealed to prevent leakage.

With single turn coils an integral quench may be utilized.

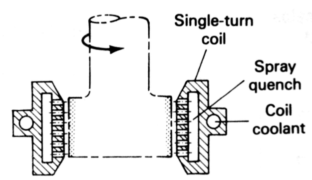


Figure 8

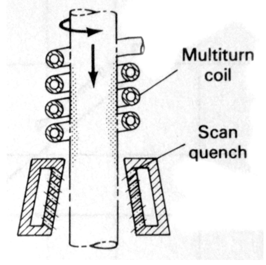


Figure 9

As shown in Figure 8, integral quench coils are double chambered. The outer chamber contains the coil cooling water. The inner chamber channels the quench fluid through perforations in the wall closest to the part. Since this face also carries the coil current, the number and size of the holes, as well as their spacing must be designed so that there is minimal resistance to the flow of the current. Quench hole area should be no more than 10-15% of the face of the coil. Integral quench coils are also utilized in vertical scanning systems. Here, the quench chamber is below the coil water chamber. As shown in Figure 9, the quench is oriented at 30º from the vertical axis. This provides for an area for the temperature to soak uniformly before it is quenched. It also prevents the quenchant from rising up the part into the heating area and thus causing soft spots in the work.

Spray quench heads, whether separate or integral to the coil should have a total hole area of 10-20% of the area being quenched. The ratio of surface area to the total orifice area is typically 10% for systems with narrow coils and 20% for systems with wide coils. Hole size is a function of part diameter.

Part Diameter	Quench Hole Size	Flow at 20 PSI
0.5 in.	1/16 in.	1/3 GPM
1.0 in.	1/8 in.	1.5 GPM

Doubling of the quench pressure approximately quadruples the flow through the hole.

The holes must be properly placed and sized to provide a uniform quench and eliminate the “barber poling” or spiral hardness pattern that can result from improper cooling.

Typical orifice sizes for single shot induction systems			
Orifice size		Part diameter	
mm	in.	mm	in.
1.6	0.06	6.4-12.7	0.25-0.50
3.2	0.13	12/07/38	0.50-1.5
6.4	0.25	>38	>1.5

The total area of the quench holes should equal the area of the quench inlet.

The total area of the incoming quench line should be close to the total area of all of the quench holes. The preferred ratio is no more than 2:1. The total area of the quench holes should be a minimum of 10% or more of the surface area being treated.

Quench hole size is related to part diameter. Typically on a ½” diameter part, quench hole diameter would be 1/16”. With a 1” diameter part the quench hole size would be 1/8”. Hole spacing should be twice the hole diameter or less.

When working with an annular ring, the incoming water flow should be tangential to the spray path. This will provide a more even flow to the quench which might create an uneven hardening pattern.

Quench tanks are used to contain the quenchant either as a open vessel for drop quenching or as a supply for a spray quench. Capacity of the tank is usually calculated as a minimum of 3-4 times quench flow or a capacity sufficient to contain 5 minutes of the normal flow rate of the system. An old heat treaters adage is “One gallon of quench for one pound of heated material per hour”.

Quench filtration is also a key to consistent operation. Chips from the part, particles from the air and similar contaminants all are possible problems which could prevent a consistent, trouble free quench.

A strainer should be used to remove particles which are of a size to block quench holes. Weir tanks are utilized to remove floating particles and a cartridge filter of 75-100 micron size is recommended in the quench line to remove additional contaminants.

Face Quenches

By utilizing a double chamber coil (two tubes brazed together to form an inner and outer section) a face quench can be created. Sufficient metal must exist between the quench holes to permit the current to flow easily. The wall thickness of the quench facing the heated area must also be of sufficient thickness to carry the current at this point and not deform due to overheating during the quenching cycle. When the quench fluid is applied, further cooling will occur, thus bringing the coil face resistivity back to the original temperature condition.

Scan Quenching

On scanning type coils, the quench chamber is below the cooling chamber for the coil. It is normally angled down in the direction at which the part exits the scanner. This provides an opportunity for the heat to equalize in the part prior to quenching and prevents the quench from running up into the heat zone. In some applications scan quenching is performed by a separate quench ring located below, and separate from, the quench coil. This ring should utilize the same design technique as regular spray rings.

Air Quench

Air quenching is sometimes acceptable on certain grades of steel where transition back to martensite is slow due to the presence of alloying agents. While it is generally utilized with tool steels that are not induction hardened it can be beneficial in some induction heating applications. Air quenching can be in still air or can be accelerated with a fan or compressed air. Care must be taken to control the cooling rate to prevent quench cracking.

Mass Quenching

Mass quenching can occur when the total mass of the part is far less than the mass or volume of the adjacent material. The unheated volume absorbs the heat at a great rate by conduction acting as a heat sink to allow the heated layer to convert to martensite. Generally this is used where the part has an extremely thin case or where induction pulse hardening is used. Where there is sufficient cool mass behind the heated area, the temperature of this mass reduces the temperature of the heated zone below the AC3 value before the knee of the T-T-T curve is reached. This is sometimes referred to as Self Quenching.

Press Quenching (Die Quenching)

Where tolerances on flatness of a product are critical i.e. knives, gears, it is sometimes required to place the heated part in a press when it is above the critical temperature. The press is then closed on the part and fluid quenchant is applied through holes in the press dies. The dies keep the part flat as the material is brought down in temperature by the quenchant. Flatness can be kept to a minimum with this technique even thought he parts have been heat treated.

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