

PRACTICAL | **INDUCTION HEAT TREATING**

Second Edition

Richard E. Haimbaugh



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To the memory of my father, Omer, who started my training in induction; for my youngest brother, Dave, who continues to practice commercial induction heat treating; my brother, Kurt, who has always been a leader; and my wife, Carol, who supports me and checks when my office is too quiet.

About the Author

Dick Haimbaugh's first practical experience with induction heat treating occurred in 1946 when he was eleven years old. With the purchase of two war surplus General Electric radio frequency induction heaters, his father had started a commercial heat treating company to specialize in induction heat treating. After pestering his father for work, Dick was shown how to load hub caps into a coil, push the "on" button, and then remove the hub caps from the coil when they had been induction heat treated. He took about 2 hours to induction anneal 250 hub caps.



He worked for his father through high school and college. In his senior year in college where he was majoring in metallurgical engineering, and while working as a lab assistant for graduate students, Dick asked his father for help with the coil design for a spark gap unit. The coil pulled so much power that the cables to the power supply started smoking.

Following graduation from the University of Illinois, Dick worked for a short time for Allison Division of General Motors. Then during his Army service, he worked as a mechanical engineer in the Army Rocket Guided Missile section at Redstone Arsenal. Upon leaving the Army, Dick returned to work for his father while also attending the University of Chicago where he earned an MBA degree. Since that time, he has been involved in all aspects of commercial induction heat treating, with active participation as a lifetime member of ASM International, chairing and participating in various ASM committees, working with Handbook Committees, as well as contributing to several of the MEI courses.

Over the years, Dick has trained the personnel at Induction Heat Treating Corp. in the knowledge needed for commercial heat treating production, and he has consulted for various companies including General Elec-

tric and the Center for Metals Fabrication. He has participated as an induction heat treating expert in two Heat Treating Conferences sponsored by ASM International and plans to remain active in the industry.

Dick retired in 2005 and lives in Florida with a great life of social activities, golf, tennis and just plain fun. He teaches ASM's *Practical Induction Heat Treating Course* at ASM's Metals Park, and he loves to help anyone having questions or problems involving induction heat treating.

Preface to the Second Edition

Throughout the years, many books and articles have been written about induction heat treating. In the author's opinion, *Induction Heat Treatment of Steel*, Lee Semiatin and Dave Stutz, 1986, was an excellent early source for induction heating and metallurgical theory. The First Edition of this book was published in 2001. Since then knowledge of the science and practice of induction heat treating has continued to grow. ASM Handbook Volume 4C, *Induction Heating and Heat Treatment*, was published in 2014 and is considered by the author to be the most complete and detailed handbook on induction heating and heat treatment published to date. Much of the material contained in this Second Edition was taken from this Handbook.

The author's company has the experience of processing more than 20,000 orders a year in commercial induction heat treating. This book is written to complete the tie-in of the metallurgy, theory, and practice of induction heat treating from a hands-on explanation of what floor people need to know. Explanations contain language and terms that need to be understood. Operating information and a progression from process analysis to standards and quality control are presented.

The early chapters, 1 through 7, provide explanations of theory to the detail that the author feels is needed in order to understand induction and the metallurgy of induction. Chapters 8 to 10 deal with production aspects of induction. Chapter 11 reviews and presents a process for analysis of applications, including selection of frequency, power requirements, and the selection of different types of fixturing to meet production requirements. Chapter 12 discusses standards and inspection for induction, while Chapter 13 deals with identification and resolution of problems found with induction hardened parts. The final chapters discuss quality control and maintenance.

The appendixes are meant to help more with design information and include some charts and data to help with production including tempering curves and hardenability curves. References are given for texts and authors to help those who desire a more detailed understanding of the theoretical aspects.

The author appreciates the help and material given by Bill Stueht, Robert Fuffini, George Welch, and Fred Specht.

Preface to the First Edition

Throughout the years, many books and articles have been written about induction heat treating. In the author's opinion, *Induction Heat Treatment of Steel*, Lee Semiatin and Dave Stutz, 1986, provides the best combination of induction heating and metallurgical theory to date.

There are many practical aspects that the books to date do not cover. The author's company has the experience of processing more than 20,000 orders a year in commercial induction heat treating. This book is written to complete the tie-in of the metallurgy, theory, and practice of induction heat treating from a hands-on explanation of what floor people need to know. Explanations contain language and terms that need to be understood. Operating information and a progression from process analysis to standards and quality control are presented.

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The author appreciates the help and material given by Bill Stuehr of Induction Tooling and the material furnished by Robert Ruffini of Fluxtrol and George Welch of Ajax Magnathermic.

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CHAPTER 1

History of Metallurgy and Induction Heating

THIS CHAPTER includes a brief history of metallurgy, followed by a discussion of the development of scientific theories involving the electrical nature of induction heating. The author incorporates personal experiences and memories throughout.

History of Metallurgy

The Egyptians are believed to have worked copper for centuries before 3500 B.C. A piece of heat-treated steel was found in one of the pyramids, and it is thought to date from 3000 B.C. Early metal workers found certain metals and ores could be refined, processed, and made into tools and weapons, but it was not until the Iron Age and the Hittites that metallurgical processes were developed that would consistently produce strong steel weapons. Although the art of metallurgy developed as early smiths found that heating and cooling iron in different ways could make iron either softer or harder, metallurgical theory lagged behind until relatively modern times. In 1864 Henry Clifton Sorby first used a microscope to study metals. This was followed by Albert Sauveur trying to convince American steelmakers that something practical was to be gained from microscopic examination. However, it has only been since about 1930, when x-ray diffraction with wave mechanics was applied to metals, that the science of metallurgy was born.

The first induction phenomenon was observed by Michael Faraday in the middle 1800s when the effect that caused the heating of transformer and motor windings was considered to be undesirable. The first constructive use of induction occurred in 1916 when it was used to melt metals. Induction heat treating came into prominence in the 1930s, when high-

frequency motor-generator sets were developed and used for the induction hardening of crankshaft journals and bearings. In 1938, Caterpillar installed a power supply for induction hardening track links, and by 1943 they had 16 induction-hardening units in production (Ref 1). In 1941 Vaughn, Farlow, and Meyer presented a paper titled “Metallurgical Control of Induction Hardening” at the convention of the American Society for Metals, which provided proof that alloy elements such as nickel and chromium were wholly unnecessary for maximum surface hardness and that carbon steels could be used in place of alloy steels. Caterpillar subsequently purchased a 500 kW, 9.6 kHz motor generator set for induction hardening their final drive gear with a 642 mm (25.7 in.) diameter by a 125 mm (5 in.) wide face. In an article in the July 1943 issue of *Metal Progress*, the Caterpillar process for contour hardening this gear was presented. Figure 1.1 shows the contour pattern produced at that time by Caterpillar. Caterpillar must be considered the early pioneer in the contour hardening of gear teeth.

Progress in research in metallurgical principles of induction hardening continued, and at the 26th annual meeting of the American Society for Metals in 1944, D.L. Marten and F. E. Wiley presented a paper that reported investigation of temperature, composition, and previous structure upon induction-hardening characteristics of plain carbon steel (Ref 2). The basic metallurgical theory as presented at that time is still being taught today.

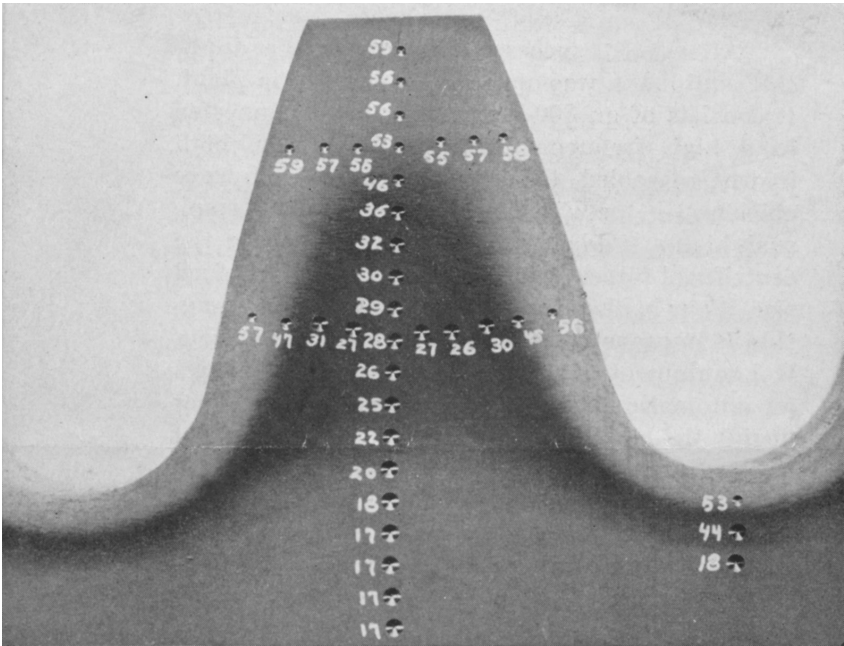


Fig. 1.1 Hardness survey (Rockwell C scale) of hardened tooth, sectioned on center. Magnified 2¾ diameters. Source: Ref 1

Induction Heating after World War II

In 1946, Edwin Cady listed the basic types of induction equipment (Ref 3) with frequencies ranging from 25 Hz to 50 MHz:

- Electronic circuit (vacuum tube, 300 to 530 kHz, and greater than 1 MHz)
- Spark gap (15 to 60 kHz and 125 to 450 kHz)
- Rotary converter (motor generator, 1 to 10 kHz)
- Mercury arc (400 Hz to 3 kHz)
- Standard power cycle (line frequency of 60 Hz, or 25 Hz as generated by some steel mills)

While other types of power supplies and converters have been used over the years, the intent of this book is to discuss those commonly used for induction heat treating.

The first induction heaters sold by General Electric during World War II had rectifier tubes for the conversion of the alternating current (ac) to direct current (dc). Output control and tuning were accomplished through a combination of different taps on the output of the tank coil and a control knob that tapped the plate transformer for different output voltages. The power was turned on and off through the use of a main solenoid-activated contactor. Cycle times were controlled through use of a mechanical, cam-driven timer. The output was the high voltage obtained directly from the tank voltage, and low-turn work coils could not be used.

Coil designs to heat small areas were developed in many creative ways. For example, to get around overloads, a shunt coil was used. This was a coil made of copper tubing that was placed directly across the high-voltage output from the tank circuit. The coils were typically wound to a 102 mm (4 in.) diameter; the number of turn shunts varied from 5 to 13. The shunts were water cooled, with the water coming from T connections on both sides of the shunt. While it seemed that all of the power would be lost in the shunts, they actually worked quite well. If power reduction to prevent a slight overload at the “heat on” position was needed, a 13-turn shunt could be installed and used. If the overload was severe, a 5-turn shunt could reduce the power substantially. Setup instructions would indicate what shunt was to be used.

The shunts, when used properly, actually leveled the power output so that the plate amperage was held more constant. As the workpiece on heating passed through the Curie temperature, the plate amperage with the use of a shunt did not drop as much.

The use and development of induction heat treating practices continued to grow after World War II, and output transformers were developed to help the power supplies and load match when using low-turn work coils. Around 1948, General Electric performed research on the optimum design

for output transformers for radio-frequency (RF) induction heaters. They ran tests on both the size of the transformer (settling on 152 mm, or 6 in.) and the stepdown ratio (11:1 found to be most desirable). The primary was sealed in beeswax, and the secondary was one turn, water-cooled, similar to current output transformers. The first transformer tops for sealing and mounting the outputs were Bakelite, which was later replaced by Micolex. In the 1950s General Electric went to a 279 mm (11 in.) diameter transformer with a 7:1 stepdown ratio. Because of the output transformers' single turn secondary, low turn work coils could now be used. In addition, the coils could be grounded on one side, so arcs that occurred with high-voltage coils were practically eliminated.

From the 1940s through the 1950s, the use and application of large motor generators and RF oscillator induction power supplies continued. In the mid-1950s General Electric introduced a new RF induction heater. It featured an aluminum-enclosed oscillator section; the internal bus components were silver plated. Rectifier tubes were still used for the dc conversion, but two of the models that were available had three triode rectifier tubes so that thyatron power controls could be used for stepless power control and for power turn-on. Two of the models featured an internal output transformer that was rigidly attached and had an air core. The output power ratings were proven through running a water load in a work coil. The induction heaters featured what was called a filament regulated transformer-capacitor network that provided about 3% regulation through swings of line voltage. Motor-driven voltage regulators could be furnished on request.

The induction hardening of air-to-air missile fuse bodies was developed during the Korean War. These were the striking end of the air-to-air missiles. The bodies required a soft nose to allow collapse on impact, to explode the missile. The requirement was for the body to be hard but the nose totally soft. At that time induction tempering did not produce parts in specification. A 20 kW RF induction heater was used for austenitizing with direct tank-loaded coils (high voltage). The coils themselves were contoured to the shape of the fuse body, starting with 6.35 mm (0.25 in.) copper tubing at the top for about four turns, moving into 4.18 mm ($3/16$ in.) copper tubing around the bottom to provide higher current concentration. The nose of the fuse body was placed onto a brass, water-cooled nest to prevent the nose from heating and hardening. Nitrogen atmosphere was used to prevent scale, with an austenitizing cycle of 9 s. The parts were oil quenched in mineral oil and then furnace tempered. The final surface finish was good enough that the fuse bodies could be plated afterward with any finish machining or polishing.

About 1959, International Harvester (IH) found that customers who purchased new tractors were replacing the track shoe bolts with Caterpillar bolts before use. The Caterpillar bolts were induction hardened and did not wear. The IH bolts were overall hardened and tempered but did

not have contour-hardened heads. The heads of the bolts wore in use, and the bolts had to be chiseled out for replacement. A track shoe bolt fixture was designed and built to handle production for IH. A 50 kW RF induction heater could run 2,500 bolts/h for a 14.3 mm ($\frac{9}{16}$ in.) diameter, 3,500 bolts/h for 12 mm ($\frac{1}{2}$ in.), and 5,000 bolts/h for 11 mm ($\frac{7}{16}$ in.).

Case hardening of full length bars for a steel company was developed in the early 1960s. A horizontal scanning system for case hardening of 38 mm (1.5 in.) diameter, 3.8 m (12 ft, 6 in.) long, AISI 1045 steel bars was developed. The scanner had fixed nylon rollers for a distance of about 4 m (14 ft) on each side of the induction coil. A pusher was used to move the bars through the coil, with pneumatically activated restraint wheels on each side of the coil. When one bar was done, the restraint rollers would elevate. The hardened bar was lifted up by pneumatic lifts and moved to the side so that another new bar could be loaded. Then, pusher direction was reversed, and the quench solenoids were switched so that the quench was applied on the exit side of the bar from the coil. The bar was austenitized and quenched in the opposite direction. The two-direction hardening produced high productivity.

Starter ring gear teeth were hardened for a locomotive manufacturer in the mid-1960s. A fixture was built to induction harden the 256 teeth of a starter ring gear that was made by a local gear company. A 20 kW induction heater was used with a remotely mounted transformer. The transformer was indexed into the tooth for tooth-by-tooth hardening. After austenitizing when the transformer and coil quickly moved back, the gear was indexed into an oil spray quench. An entire tooth was skipped during indexing each heating and quenching cycle. In order to harden all the teeth, the gear rotated around twice. After the teeth were all hardened, the gear was cleaned and moved over to a 50 kW, 10 kW motor generator set and single-shot induction tempered. About five gears per day were run over a period of about five years (the production of locomotives at that time). The production stopped when the manufacturing was moved to Canada.

Automotive wheel hubs were induction case hardened for a large bearing company. About 1990 a large bearing company that had been producing the hubs in Japan provided sample hubs for test. Tooling was developed, and tests were run using 10 kHz. The pattern with 10 kHz was better than the customer was producing in Japan. A decision was made to build a production line. At that time more research on frequency was done, with the decision made that 25 kHz would be a better frequency. Automatic fixturing was built using a 150 kW, 25 kHz power supply. At that time little research had been done on induction tempering, so the decision was made to furnace temper after induction hardening. This line was in 8 to 16 h production for about 20 years.

About 1999, a design of parking pawls needed to have the opposing faces case hardened. The parts were to be made of AISI 5160 steel that were Carbo-Austempered prior to induction hardening. Because the pawl

was considered a safety item, there were strict requirements on case depth at both faces of the pawl. The pawls quenched to a hardness of 66 HRC. This was followed by a 160 °C (325 °F) furnace temper. One nick on these parts could cause the transmission to jam. The tooling was built to work using a four-position dial fixture, heating both faces simultaneously, with automatic activation of position holddown and subsequent unloading after quenching. Since there were four nests, one part from each nest was cut every 4 h. This job ran for about 10 years until there was a redesign of the pawl by the automotive company using the pawl.

In the 1960s solid-state power supplies were invented for the conversion of line frequency into medium-frequency induction heating. Because of their higher efficiency and increased versatility as the reliability of the solid-state power supplies increased, solid-state power supplies started to replace motor-generator sets in the 1970s. The continued development trend of solid-state power supplies has been into higher frequencies as the solid-state devices have continued to increase in current-carrying and voltage-blocking characteristics. Today, while there is still a market for RF oscillators, most of the induction heating equipment sold is solid-state. Solid-state has made even the RF oscillators more efficient through replacement of the tube rectifiers by solid-state diodes. Development of better transformers for load matching will increase the potential use of solid-state RF power supplies. If the past is used as a basis for projection into the future, the probability is that transistors will continue to improve and at some time will convert the frequency for all RF power supplies.

Advantages of Induction Heating

Induction heating has the ability to rapidly heat specific areas of a part, such as the teeth of a gear or the bearing area of a shaft. Not only can superior mechanical properties be produced in such an area, but also the entire part does not have to be heated as is done with furnace heat treating. Significant benefits are produced, such as:

- *Superior mechanical properties:* A hard case and a soft core provide a good blend of strength and toughness not attainable with furnace through heating. Furthermore, because the hardness of as-quenched steels depends only on carbon content, carbon steels can be used instead of alloy steels for most applications. Induction-hardened tractor axles have a significant increase in bending fatigue over axles that are conventionally furnace hardened. Axles and shafts are also induction case hardened to produce high torsional strength, and many parts such as gears are selectively induction hardened to provide wear resistance on the gear teeth.
- *Lower manufacturing costs:* Total energy costs can be reduced because the entire part does not have to be heated. The costs of other

processes that are necessary for furnace-hardened parts are reduced because the lower distortion reduces the need for grinding and finishing for final net shape. Straightening can sometimes be eliminated.

- *Manufacturing compatibility:* Induction heat-treating systems can be automated for high production requirements and can be incorporated into manufacturing cells. Floor space requirements are reduced, and the workplace operating environment is improved.

The development and use of solid-state power supplies for induction heating continue today in all frequency ranges. There are many different applications for induction heating outside the heat-treating area, but only heat treating of steel is discussed in this book.

There are many other historic specific terms used for induction heating power supplies, such as converter, inverter, motor generator, vacuum tube oscillator, spark gap generator, and frequency tripler. These frequency converters change the 50/60 Hz line frequency to higher frequency. This book is concerned with the application of power supplies that are most commonly used in induction heat-treating practice that change or convert three-phase, 50/60 Hz line frequency into single-phase high frequencies above 3 kHz. While there are installations and systems that use frequencies below 3 kHz for heat treating, they relate to a smaller number of specific installations rather than wide and varied commercial use and deal with dedicated, through-heating type applications such as the heat treating of pipe. Induction is also used widely for forging, melting, and a good number of individual applications. For purposes of this book, the terms induction heater and power supply will essentially mean the same thing: An induction heater is a power supply that produces the high frequency for induction heating.

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CHAPTER 2

Theory of Heating by Induction

INDUCTION HEATING was first studied when it was found that heat was produced in transformer and motor windings, as mentioned in Chapter 1, “History of Metallurgy and Induction Heating,” in this book. Accordingly, the theory of induction heating was researched so that motors and transformers could be built for maximum efficiency by minimizing heating loss. The development of high-frequency induction power supplies provided a means of using induction heating for surface hardening. The early use of induction involved trial and error, with built-up personal knowledge of specific applications but a lack of understanding of the basic principles. Through the years the understanding of the basic principles has expanded, extending currently into computer modeling of heating applications and processes.

Induction heating occurs when a strong electromagnetic force field is produced from an induction coil close enough to a part to produce an electric current in the part. The part is heated mainly due to the resistance of the flow of this electric current. The actual heating is a complex function related to the relationship between the physical and electrical properties of the part as it is heated through rising temperatures. These functions include the properties of heat transfer such as thermal conductivity and specific heat, and electrical and magnetic properties such as resistivity, permeability, and frequency.

Resistance

All metals conduct electricity while offering resistance to the flow of this electricity. This resistance causes loss in power that shows up in the form of heat. This is because, according to the law of conservation of en-

ergy, energy not lost but, rather, is transformed from one form to another. The losses produced by resistance are based on the basic formula $P = i^2R$, where i is the amount of current and R is the resistance. Because the amount of loss is proportional to the square of the current, doubling the current significantly increases the loss (or heat) produced. Some metals, such as silver and copper, have very low resistance and, consequently, are very good conductors. Silver is expensive and is not ordinarily used for electrical wire (although some induction heaters built in World War II had silver wiring because of the copper shortage). Copper wires are used to carry electricity through power lines because of low heat loss during transmission. Other metals, such as steel, have high resistance to an electric current, so when an electric current is passed through steel, substantial heat is produced. The steel heating coil on top of an electric stove is an example of heating due to the resistance to the flow of the 60 Hz household electric current. In a similar manner, the heat produced in a part in an induction coil is due to the electrical current circulating in the part.

Alternating Current and Electromagnetism

Induction heaters are used to provide alternating electric current to an electric coil (the induction coil). The induction coil becomes the electrical (heat) source that induces an electrical current into the metal part to be heated (called the workpiece). No contact is required between the workpiece and the induction coil as the heat source, and the heat is restricted to localized areas or surface zones immediately adjacent to the coil. This is because the alternating current (ac) in an induction coil has an invisible force field (electromagnetic, or flux) around it. When the induction coil is placed next to or around a workpiece, the lines of force concentrate in the air gap between the coil and the workpiece. The induction coil actually functions as a transformer primary, with the workpiece to be heated becoming the transformer secondary. The force field surrounding the induction coil induces an equal and opposing electric current in the workpiece, with the workpiece then heating due to the resistance to the flow of this induced electric current. The rate of heating of the workpiece depends on the frequency of the induced current, the intensity of the induced current, the specific heat of the material, the magnetic permeability of the material, and the resistance of the material to the flow of current. Figure 2.1 shows an induction coil with the magnetic fields and induced currents produced by several coils. The induced currents are sometimes referred to as *eddy currents*, with the highest-intensity current being produced within the area of the intense magnetic fields.

Induction heat treating involves heating a workpiece from room temperature to a higher temperature, such as is required for induction tempering or induction austenitizing. The rates and efficiencies of heating depend on the physical properties of the workpieces as they are being heated. These properties are temperature dependent, and the specific heat, mag-

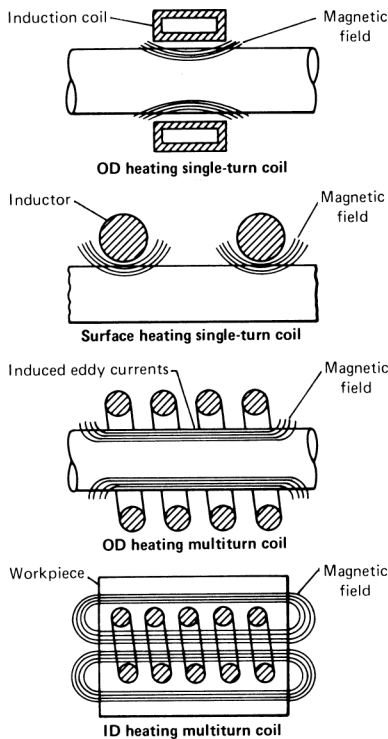


Fig. 2.1 Induction coils with electromagnetic fields. OD: outside diameter; ID: inside diameter. Source: Ref 1

netic permeability, and resistivity of metals change with temperature. Figure 2.2 shows the change in specific heat (ability to absorb heat) with temperature for various materials. Steel absorbs more heat with an increase in temperature. This means that more energy is required to heat steel one degree when it is hot than when it is cold. Table 2.1 shows differences in resistivity of different metals at various temperatures. *Note:* At room temperature steel has about 10 times more resistance to current flow than does copper. This is why copper is used for induction coils. Table 2.2 shows the thermal conductivity of copper and iron (steel). Thermal conduction of steel is at least 2 times lower at 760 °C (1400 °F) than at room temperature. Finally, the magnetic permeability of steel is high at room temperature, but at the Curie temperature, just above 760 °C (1400 °F), steels become nonmagnetic, with the effect that its permeability becomes the same as air.

Hysteresis

Hysteresis losses occur only in magnetic materials such as steel, nickel, and a few other metals. As magnetic parts, such as those made from car-

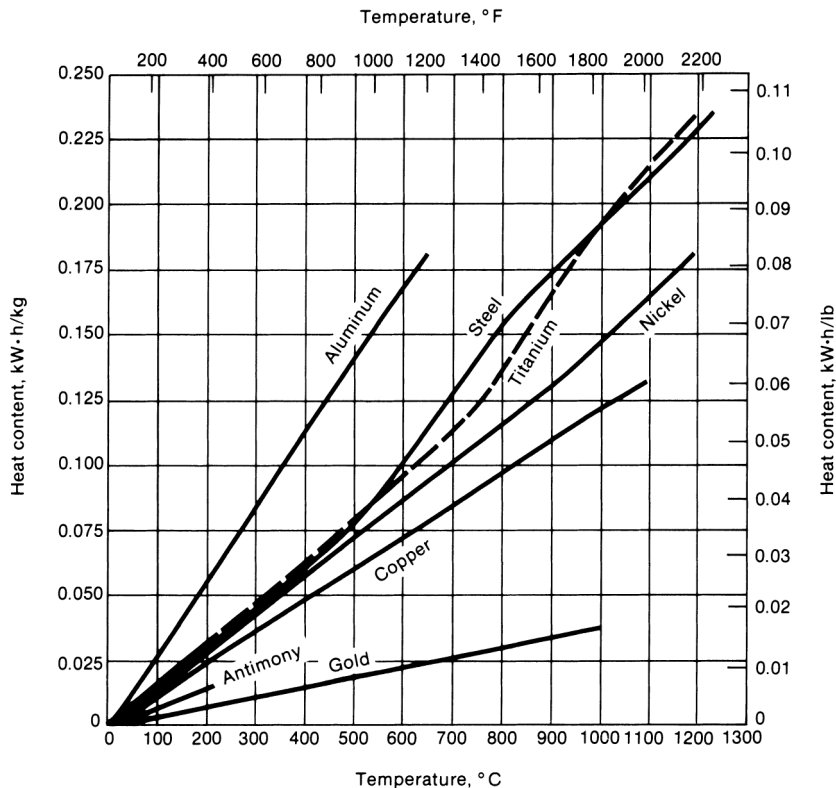


Fig. 2.2 Change in specific heat with temperature for materials. Source: Ref 2

bon steels, are heated by induction from room temperature, the alternating magnetic flux field causes the magnetic dipoles of the material to oscillate as the magnetic poles change their polar orientation every cycle. This oscillation is called *hysteresis*, and a minor amount of heat is produced due to the friction produced when the dipoles oscillate. When steels are heated above Curie temperature they become nonmagnetic, and hysteresis ceases. Because the steel is nonmagnetic, no reversal of dipoles can occur. Figure 2.3 shows an illustration of hysteresis and the effect on the magnetic flux field strength. Figure 2.4 shows the Curie temperature for carbon steels, as represented by the line ABCD. It is estimated that hysteresis produces in the range of 6 to 8% of the heat in steel below the Curie temperature.

Skin Effect and Reference Depth

Induction heating occurs when an electrical current (eddy current) is induced into a workpiece that is a poor conductor of electricity. For the induction heating process to be efficient and practical, certain relationships of the frequency of the electromagnetic field that produces the eddy

Table 2.1 Resistivity of different metals

Material	Approximate electrical resistivity, $\mu\Omega \cdot \text{cm}$ ($\mu\Omega \cdot \text{in.}$), at temperature, $^{\circ}\text{C}$ ($^{\circ}\text{F}$)							
	20 (68)	95 (200)	205 (400)	315 (600)	540 (1000)	760 (1400)	980 (1800)	1205 (2200)
Aluminum	2.8 (1.12)	...	...	6.9 (2.7)	10.4 (4.1)	...	...	...
Antimony	39.4 (15.5)	...	...	...	...	...	...	...
Beryllium	6.1 (2.47)	...	...	...	11.4 (4.5)	...	...	...
Brass (70Cu-30Zn)	6.3 (2.4)	...	...	...	...	...	...	...
Carbon	3353 (1320.0)	...	...	...	1828.8 (720.0)	...	...	...
Chromium	12.7 (5.0)	...	...	...	...	...	...	...
Copper	1.7 (0.68)	...	...	3.8 (1.5)	5.5 (2.15)	...	9.4 (3.7)	...
Gold	2.4 (0.95)	...	...	...	...	...	12.2 (4.8)	...
Iron	10.2 (4.0)	14.0 (5.5)	...	...	63.5 (25.0)	106.7 (42.0)	123.2 (48.5)	...
Lead	20.8 (8.2)	27.4 (10.8)	...	49.8 (19.6)	...	...	...	...
Magnesium	4.5 (1.76)	...	...	...	...	...	...	...
Manganese	185 (73.0)	...	...	...	...	...	...	...
Mercury	9.7 (3.8)	...	...	...	...	...	...	...
Molybdenum	5.3 (2.1)	...	...	...	...	...	...	33.0 (13.0)
Monel	44.2 (17.4)	...	...	...	...	...	...	...
Nichrome	108.0 (42.5)	...	...	114.3 (45.0)	...	114.3 (45.0)	...	...
Nickel	6.9 (2.7)	...	...	29.2 (11.5)	40.4 (15.9)	...	54.4 (21.4)	...
Platinum	9.9 (3.9)	...	...	...	...	...	...	...
Silver	1.59 (0.626)	...	...	...	...	6.7 (2.65)	...	...
Stainless steel, nonmagnetic	73.7 (29.0)	...	...	99.1 (39.0)	...	...	130.8 (51.5)	...
Stainless steel 410	62.2 (24.5)	...	...	...	101.6 (40.0)	...	127 (50.0)	...
Steel, low carbon	12.7 (5.0)	16.5 (6.5)	...	...	59.7 (23.5)	102 (40.0)	115.6 (45.5)	121.9 (48.0)
Steel, 1.0% C	18.8 (7.4)	22.9 (9.0)	...	...	69.9 (27.5)	108 (42.5)	121.9 (48.0)	127.0 (50.0)
Tin	11.4 (4.5)	...	20.3 (8.0)	...	...	...	...	...
Titanium	53.3 (21.0)	...	...	...	...	...	...	165.1 (65.0)
Tungsten	5.6 (2.2)	...	...	...	...	...	...	38.6 (15.2)
Uranium	32.0 (12.6)	...	...	...	...	...	...	...
Zirconium	40.6 (16.0)	...	...	...	...	...	...	...

Source: Ref 3

Table 2.2 Thermal conductivity of copper and iron versus temperature

Material	Thermal conductivity, $\text{W/m} \cdot \text{K}$						
	27 $^{\circ}\text{C}$ (81 $^{\circ}\text{F}$)	227 $^{\circ}\text{C}$ (441 $^{\circ}\text{F}$)	427 $^{\circ}\text{C}$ (801 $^{\circ}\text{F}$)	627 $^{\circ}\text{C}$ (1161 $^{\circ}\text{F}$)	827 $^{\circ}\text{C}$ (1521 $^{\circ}\text{F}$)	1027 $^{\circ}\text{C}$ (1881 $^{\circ}\text{F}$)	1227 $^{\circ}\text{C}$ (2241 $^{\circ}\text{F}$)
Copper	402	385	370	355	338	322	...
Iron	80	49	49	37	30	30	33

Source: Ref 4

currents, and the properties of the workpiece, must be satisfied. The basic nature of induction heating is that the eddy currents are produced on the outside of the workpiece in what is often referred to as “skin effect” heating. Because almost all of the heat is produced at the surface, the eddy currents flowing in a cylindrical workpiece will be most intense at the outer surface, while the currents at the center are negligible. The depth of heating depends on the frequency of the ac field, the electrical resistivity, and the relative magnetic permeability of the workpiece. For practical purposes of understanding, the skin heating effect (reference depth) is defined as the depth at which approximately 86% of the heating due to resistance of the current flow occurs. Figure 2.5 shows reference depths for various materials at different temperatures. The reference depths decrease with higher frequency and increase with higher temperature. The reference depth, as mentioned, becomes the theoretical minimum depth of

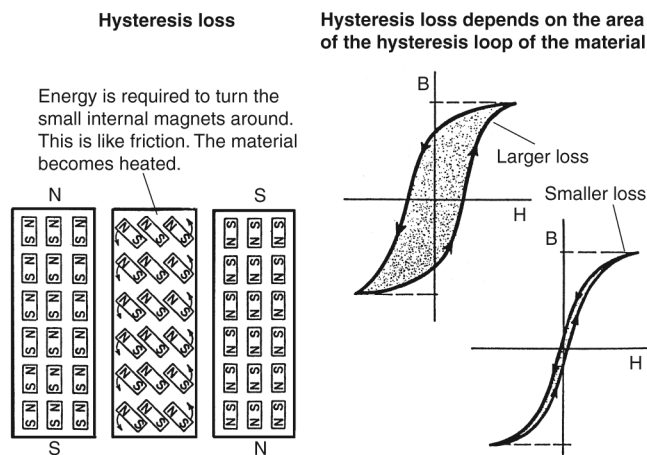


Fig. 2.3 Effect of hysteresis on heating rate. N: north; S: south; B: flux density in a ferromagnetic material; H: corresponding magnetic intensity. Source: Ref 5

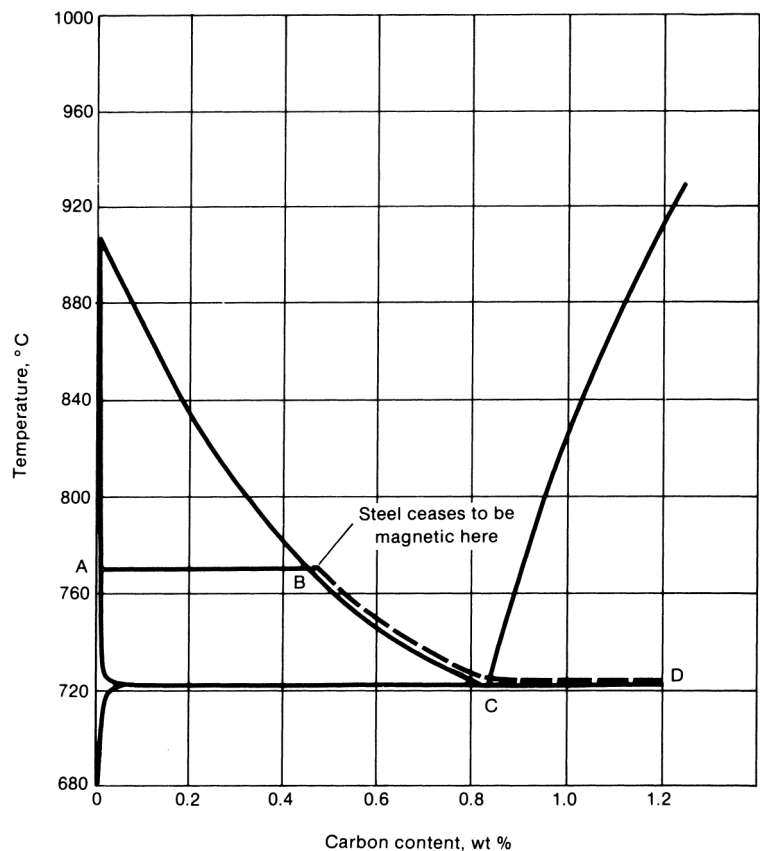


Fig. 2.4 Curie temperature for carbon steels. ABCD: Curie temperature for carbon steels. Source: Ref 2

heating that a given frequency will produce at a given power and work-piece temperature. The cross-sectional size of the workpiece being heated must be at four times the reference depth, or what appears to be current cancellation occurs. Figure 2.6 shows the critical frequency (or minimum frequency) for heating different bar diameters. Figure 2.7(a) illustrates three examples of ratios of workpiece thickness (*a*) and reference depth of

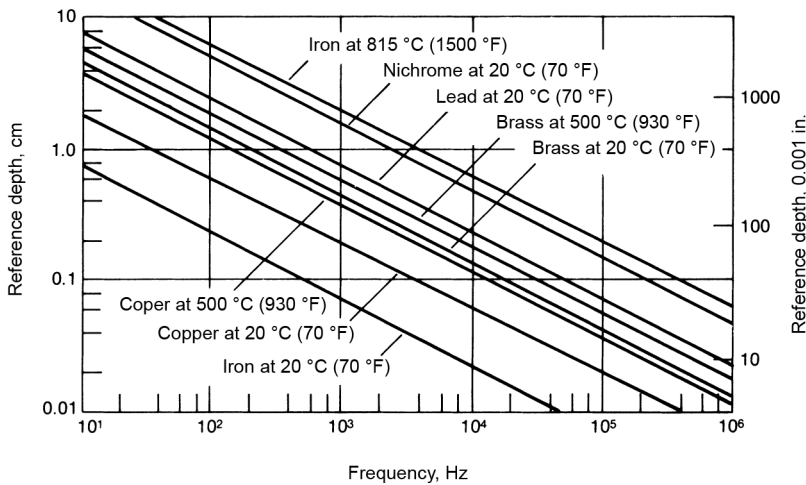


Fig. 2.5 Reference depth for various materials. Source: Ref 2

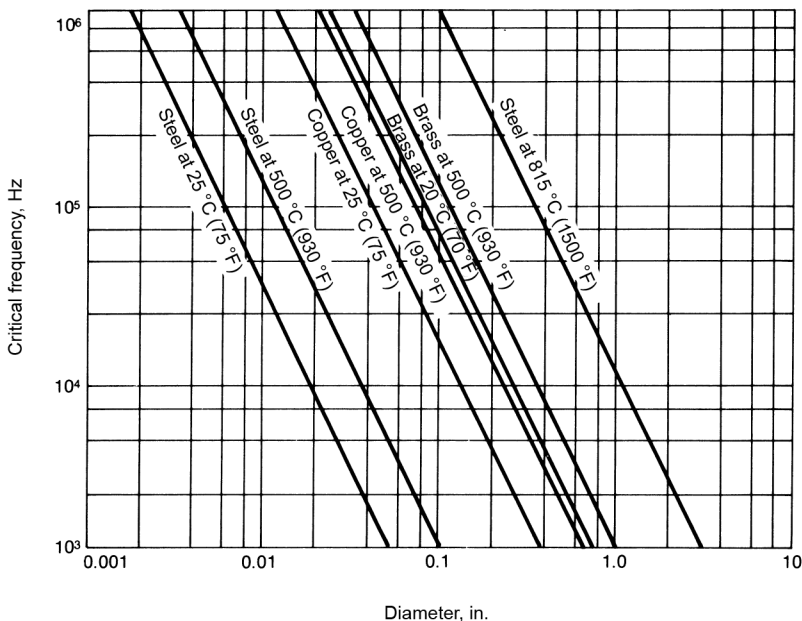


Fig. 2.6 Critical frequency for efficient heating of several materials. Source: Ref 2

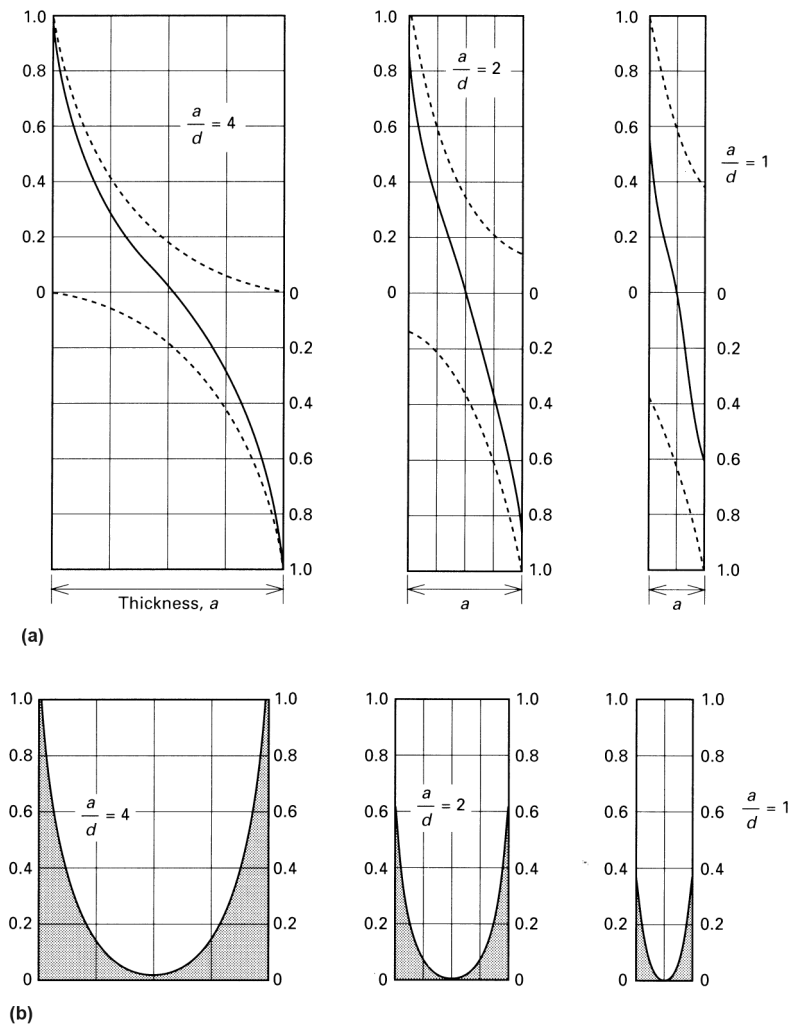


Fig. 2.7 (a) Ratios of object thickness, a , and reference depth, d . Dashed lines: exponential decay; solid lines: net current. (b) Net heating curves. Source: Ref 6

heating (d) with the respective current distribution. The dashed lines show exponential decay from either side; the solid line gives the net current from the summation of the two dashed lines. As the ratio of the workpiece thickness to reference depth of heating decreases below 4:1, the net current decreases. The net heating curves (Fig. 2.7b) are obtained by squaring the net current density, demonstrating that the best surface heat distribution occurs when $a/d = 4$.

For a fixed frequency, the reference depth varies with temperature because the resistivity of conductors varies with temperature. With magnetic

steels the magnetic permeability varies with temperature, decreasing to a value of 1 (the same as free space) at the Curie temperature, at which steel becomes nonmagnetic. Because the reference depth increases when steel is heated over the Curie temperature, when austenitizing $a/d = 4$ must be based on the reference depth when the steel is at a temperature above the Curie point. Figure 2.8 shows an illustration of the deeper depth of current penetration over the Curie point. Because of these effects, the reference depth of nonmagnetic materials may vary by a factor of 2 to 3 over a wide heating range, whereas for magnetic steels it can vary by a factor of 20. The net effect is that cold steel has a very shallow reference depth compared to hot steel.

Another very important result of the skin effect is evidenced in heating efficiency. Heating efficiency is the percentage of the energy put through the coil that is transferred to the workpiece by induction. As shown in Fig. 2.7, if the ratio of workpiece diameter to reference depth for a round bar drops below about 4:1, the heating efficiency drops. This ratio becomes what is defined for round bars as the critical frequency for heating. Figure 2.9 shows the minimum recommended bar diameter for efficient heating as a function of frequency, and Fig. 2.10 shows the efficiency of heating as a function of frequency. Higher frequencies are needed to heat small bars efficiently, but as Fig. 2.10 shows, once the critical frequency is reached, increasing the frequency has very little effect on relative efficiency.

For through heating, a frequency close to the critical frequency should be selected so that the workpiece will through heat faster. In contrast, for case hardening, frequencies higher than the 4:1 ratio will be selected that are both higher than the critical frequency and high enough to generate the desired skin effect heating for production of the specified case. Once the critical frequency is reached, the case depth requirements will help in frequency selection because lower frequencies have deeper reference depths, thereby producing deeper case depths. Note that the electrical depths of

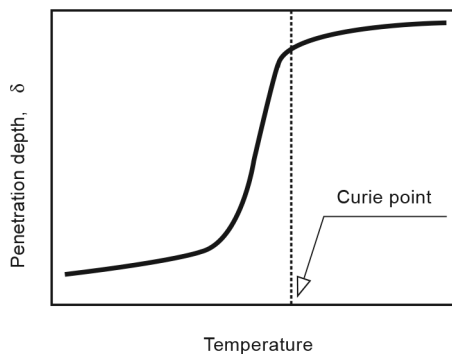


Fig. 2.8 Variation of current penetration depth through the Curie point.
Source: Ref 7

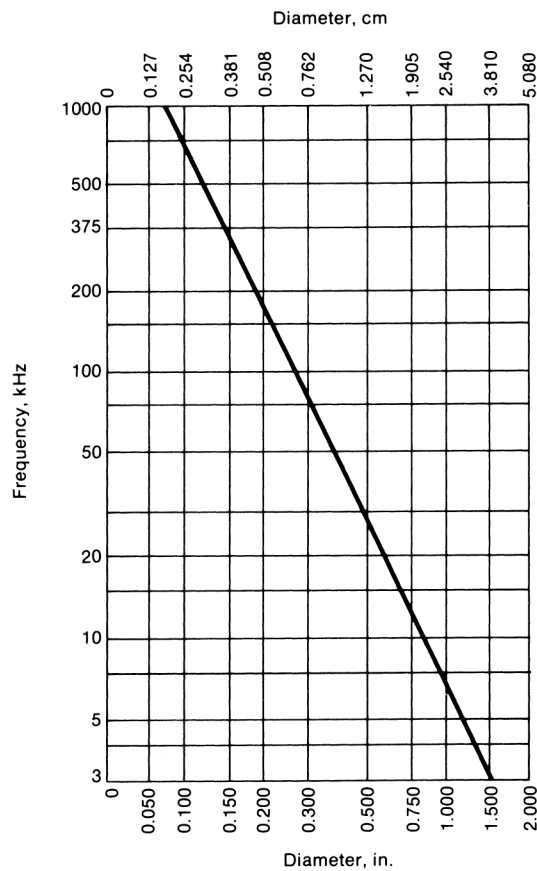


Fig. 2.9 Critical diameter as a function of diameter for round bars. Source: Ref 2

heating discussed so far have dealt only with solid cylinders. The depth of heating is deeper for hollow cylinders, with the electrical current distributed essentially throughout the entire cylinder wall. Figure 2.11 shows the higher heating efficiencies that are produced when heating cylinders.

See Chapter 11, “Induction Heat Treating Process Analysis,” in this book for a discussion of frequency selection.

Power Density

Selection of power is just as important as the selection of frequency. When case hardening is to be done, the short heat cycles that are necessary require higher power density (energy input per unit of surface) than through-heating applications. The power density at the induction coil is the metered output power divided by the amount of workpiece surface

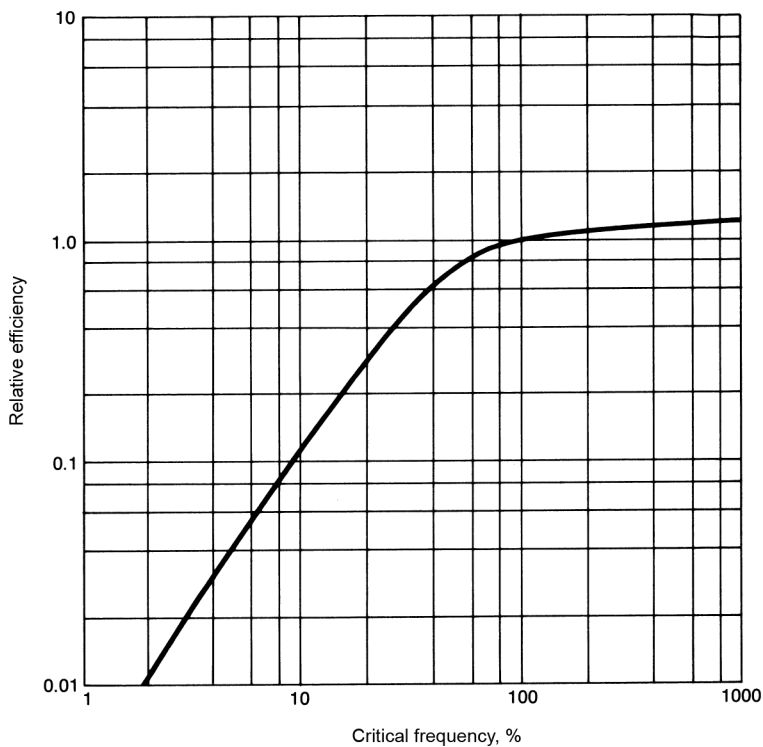


Fig. 2.10 Efficiency of heating as a function of frequency. Source: Ref 2

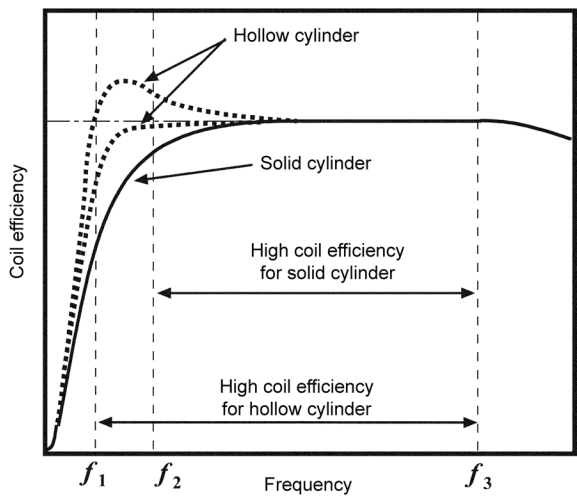


Fig. 2.11 Electrical efficiency of the coil vs. frequency when heating hollow and solid cylinders. Source: Ref 8

within the induction coil and is expressed in kW/cm² or kW/in.². Power density requirements, as shown subsequently, can be used to rate the power requirements for an application.

Power requirements are related to the amount of energy required to heat a workpiece and to the induction heating system power losses. The energy or heat content required to heat the workpiece can be calculated when the material, its specific heat, and the effective weight of material to be heated per hour are known.

The value in kilowatt-hours is (lb/h × specific heat × temperature rise)/3413, where the pounds per hour relate to (3,600 s × part weight)/actual heat cycle. Heat input required to heat a specific workpiece represents only the energy or power that needs to be induced from the coil into the workpiece. Other system losses such as coil losses, transmission losses, conversion losses, and the ability to load match for required output power determine the power supply rating. Table 2.3 shows the typical system losses for a typical solid-state power supply system and a radio frequency vacuum tube system. By calculating the heat content requirements of the workpiece at the coil, and with the system losses known, the power requirements for heating can be determined. If a heat content of 25 kWh is needed by the workpiece and system losses are 50%, then a minimum output power rating of 50 kW is needed from the power supply. As discussed in Chapter 3, “Induction Heat Treating Systems,” in this book, the ability of a power supply to produce rated output power depends on the ability to load match the power supply to the induction coil. When in doubt, it is advisable to use power supplies with higher output power ratings than needed. Chapter 11, “Induction Heat Treating Process Analysis,” deals with the determination of power supply ratings from tables that have been developed through calculation and correlation with surface power densities and for through heating. From calculation of the surface of the area to be heated in relationship to power, power density curves define power supply ratings. For instance, if a power density of 1.55 kW/cm² (10 kW/in.²) is needed, and the area to be heated is 5 in.², then the power required is 50 kW. In general, obtaining higher production rates for specific case depths for surface hardening requires higher power densities.

Through-heating systems can be defined from knowing the cross-sectional size and the weight of steel to be heated per hour. Lower power densities and frequencies are used for through heating because the work-

Table 2.3 Typical system losses for different induction power supplies

Power supply	Frequency	Terminal efficiency, %	Output transformer efficiency, %	Coil efficiency, %	System efficiency, %
Solid state	10 kHz	90	75	75	51
Radio frequency	450 kHz	65	60	85	33

Source: Ref 3

pieces need to have the heat soak and penetrate to the core. Higher productivity is obtained from using more power heating and from heating more workpiece area at the same time, thereby not increasing the power density. Higher power densities provide the ability to heat surfaces more rapidly. However, there may be limitations to the amount of power that an individual induction coil can handle. Induction coil design is discussed in Appendix 3, “Induction Coil Design and Fabrication,” in this book.

The amount of cooling water a given coil can carry defines the amount of power it can carry. Also, the fact that the power supply has a more than adequate power rating does not necessarily mean that the power can be induced into the workpiece. Only 125 kW of a 250 kW power supply may load into a given coil and part. Load matching and tuning are discussed in Chapter 3, “Induction Heat Treating Systems,” in this book. Tables of power densities are listed in Chapter 3 as well, and tables of scanning speeds are listed in Appendix 2, “Scan Hardening,” in this book.

Conduction of Heat

The primary mechanism of heat flow to the interior of a workpiece comes from the conduction of the heat first produced by the eddy currents on the surface. Hysteresis produces a secondary effect and is a small, second producer of heat. Losses due to hysteresis are usually ignored in the heat content calculations for induction processing because of the effect is minor. As previously discussed, the heating rate is mainly affected by:

- Field strength of the magnetic flux field
- Coupling of the induction coil to the workpiece
- The electrical and magnetic properties of the material being heated

The desired rate of heating varies with the application. Mathematical analysis of heat transfer can be quite complex because of the interaction of the intense heat produced due to the eddy-current heating of the surface, the rate of heat transfer toward the core, and the fact that the electrical, thermal, and metallurgical properties of most materials exhibit a strong dependence on temperature and vary during the heating cycle.

Steel is a much poorer conductor of heat than is copper. As noted in Table 2.2, copper conducts heat about 5 times faster than steel at room temperature and 10 times faster than steel at red hot temperatures. In fact as steel is heated, it conducts heat less rapidly.

One way to view heat propagation is as a wave. Using carbon steel as an example, high heat is first produced in the reference depth of the magnetic material. When the Curie temperature is passed, the depth being heated increases in a wavelike motion until the reference depth of the nonmagnetic material is reached. From that point most of the heat transfer occurs by the inward conduction of heat. Figure 2.12 shows the tempera-

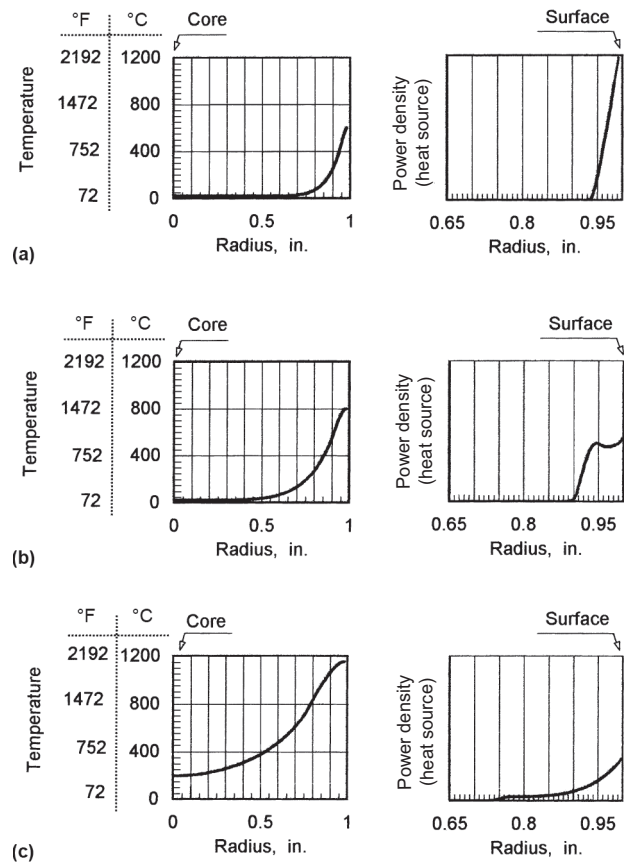


Fig. 2.12 Interrelationship of heating time, power density, and hardened depth at cycle times (a) 0.4 s, (b) 1.15 s, and (c) 6.5 s. Source: Ref 7

ture profile of heat for 25 kHz on a 50 mm (2 in.) cylinder. At 0.4 s (Fig. 12a), the surface being heated is under the Curie temperature and is nonmagnetic. At 1.15 s (Fig. 12b), the surface is nonmagnetic, and the surface is heating deeper, with minor temperature migration into the core. At 6.5 s (Fig. 12c), the austenitic portion of the surface has increased to about 0.200 in. deep, and there has been minor temperature migration to the core. It should be noted that, at this point, in order to accomplish the heat transfer, the surface temperature has increased to 1200 °C (2192 °F).

Heat transfer is a matter of temperature differential and the thermal conduction rate of the workpiece. When the material is austenitic, higher temperature differential is necessary at the surface to increase the speed of heat conduction and transfer toward the core. As soon as the power is turned off, the increase in temperature seems to stop at the edge of the austenitized area. When heat treating parts, the case depth produced during heating does not appear to penetrate any deeper while the part is being quenched (except with small-diameter parts). During case hardening,

cooling occurs from both the outer surface on which the quenchant is being applied and the core toward which the heat is migrating. Holes under the case can affect both the eddy-current distribution and heat transfer. This is discussed in Chapter 11, “Induction Heat Treating Process Analysis,” in this book.

The important things to remember in frequency selection are that smaller parts need higher frequencies and that the lowest frequency that will heat a given cross section is usually the most economical.

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CHAPTER 3

Induction Heat Treating Systems

THE ELEMENTS THAT make up an induction heat treating system are shown in Fig. 3.1. These elements are the cooling water for cooling the electrical components, power supply, heat station, work-handling fixture, controls, work coil, and quench system. Depending on the power supply and processing requirements, these elements may be furnished either separately or unitized. The power supply is the component that receives the line power from the utility and converts it into a high-frequency output. This Chapter begins with a discussion of the types of power supplies and discusses the system elements and their influence on system requirements.

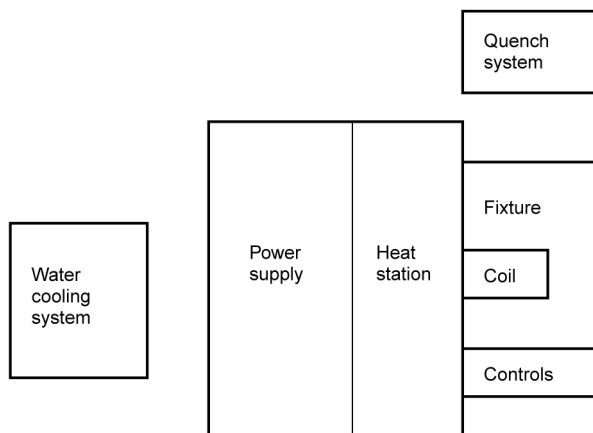


Fig. 3.1 Elements of an induction heat-treating system. Source: Ref 1

Types of Power Supplies

Induction power supplies for heat treating are measured using two major outputs. The output power is usually expressed in kilowatts, and the output frequency, in kilohertz. The output power is determined by the amount of energy required, and the frequency is determined by the requirements of the work load. For example, a power supply might be listed as 100 kW, 10 kHz. There are other considerations in power supply selection, such as the capacity to tune to all intended applications and the ability to heat in the required time.

The increase in power and frequency capabilities of power supplies is due to the continued technology advances in the ability of silicon-controlled rectifiers (SCRs, or thyristors) and transistors to operate at higher voltages, faster switching speeds, and higher temperatures with better operating characteristics. Newer induction systems are more efficient, more reliable, and more controllable due to magnetic components such as transformers, chokes, and reactors that reduce physical size and improve efficiency.

There are two types of direct current power supplies: rectification (ac/dc) and conversion of direct current (dc/dc). Internal circuits convert the dc current to high-frequency outputs. The two main types of circuits in the high-frequency output are parallel and series resonant. When the impedance of the output of the power supply (vector sum of resistance, capacitance, and inductance) matches the impedance of the load (output to work coil and workpiece), full power is produced.

As mentioned previously, there are many different types of induction-heating power sources, ranging from line frequency coils that heat for shrink fitting, to many different types of higher-frequency induction power supplies. Most induction power supplies sold for heat treating today are either some type of solid-state or oscillator (vacuum) tube. Many types and models of induction power supplies are made to meet the diverse requirements for different frequencies and output power requirements for induction heat treating. Regardless of the electronic technology, the power supplies perform a common function. Figure 3.2 shows a block diagram of modern high-frequency power supplies performing line frequency conversion into high frequency. The power supplies are basically frequency changers that change the 60 Hz (U.S.), three-phase current furnished by the electric utility into a higher-frequency, single-phase current for induction heating. These power supplies are often referred to as converters, inverters, or oscillators, depending on the circuits and electronic devices used. There are many possible combinations of conversion techniques. It can be difficult to distinguish the difference in operating characteristics between the power supplies sold by various manufacturers because the manufacturers' claims are technically difficult to verify. There is no current standard for rating the output power of solid-state power supplies.

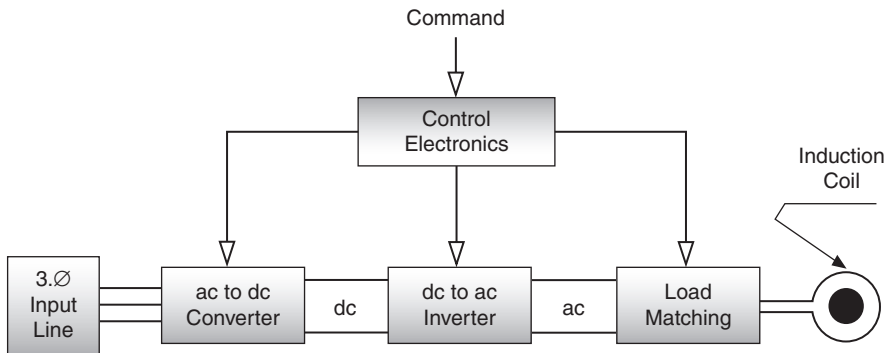


Fig. 3.2 Induction heat-treat power supply basic diagram. ac: alternating current; dc: direct current. Source: Ref 2

The input line voltage and current are often used as an indication of output of the power supply (which does not guarantee rated output power for specific applications or the actual power delivered out of the heat station). Radio frequency (RF) oscillator tube power supplies are supposed to be rated by water load at the coil.

Solid-state power supplies convert the line alternating voltage (ac) to produce single-phase, direct-current (dc) voltage. Inversion is then accomplished through use of thyristors (SCRs), or transistors such as isolated gate bipolar transistors (IGBTs) or metal-silicon-dioxide field-effect transistors (MOS FETs), to produce dc pulses that are then made sinusoidal to form high-frequency ac. (Some current source power supplies do this in one step.)

Solid-state diodes are used to convert the input ac to dc. Diodes permit the flow of current in only one direction and block current from the opposite direction. Silicon-controlled rectifiers turn on when an initial gating signal is provided and turn off only when a reverse voltage is applied to the SCR. This reverse voltage must be applied long enough to turn off the SCR. This is called load commutation. The maximum frequency to which the SCR can be used is often dictated by how long this reverse voltage must be applied. At frequencies below 10 kHz, SCRs can carry more current than transistors, so they are commonly used.

Transistors have the advantage of being able to conduct current as long as the gating signal is maintained. Thus, they can be operated at higher speeds, producing higher frequencies. Their inherent disadvantages are that they cannot carry as much current as an SCR, and their operating voltages are lower. It takes more transistors to make power. Transistors are more commonly used at approximately 10 kHz and up. Over 100 kHz it is more difficult to make output transformers that are needed for low-turn coils.

All of the solid-state devices are heated due to the current flow through in operation. The devices must be adequately cooled (generally through

water cooled heat sinks) so that they do not lose their operating capabilities.

The frequency furnished by the power supply is critical to the intended induction heat-treating process because of the relationships between the size of the part that is being heated and the depth of heating of the frequency being used. Other factors such as the output voltage, current, and power are all dictated by the type of resonant load the power supply is driving, the part and temperature to which the part is heated, the number of parts per hour to be heated, and any other relevant factors as related to the desired production. Chapter 2, "Theory of Heating by Induction," in this book mentioned that the higher the frequency, the shallower the hardened depth and the better the efficiency at the coil. For the purposes of this book, induction heat-treating practice will deal with most commonly used frequencies above 3 kHz, although there are some applications for lower frequencies. If a frequency below 3 kHz is needed for a particular application, the theory of frequency use and power requirements is similar to that for higher frequencies. One distinguishable feature below 3 kHz is that the coils have more mechanical vibration, so rigidity in the coil design can be very important.

Induction-heating power supplies are usually optimized for one maximum power and frequency range. The power, depending upon the circuit being used, can be controlled from 100% down to a lower setting. Power supplies are available in which the output frequency can have a range of tuning control from 3 to 10 kHz. Some power supplies can switch frequencies by turning the power off, using a contactor to change capacitor taps for tuning, and then turning the power back on again. The design trend for newer power supplies is the ability to switch power and frequency while under power. Finally, power supplies may be rated for intermittent duty. The components in the power supply may be capable of producing full power for duty cycles such as 50% (where the heating time is only half of the operating cycle). If the power is left on longer the internal, water-cooled components may overheat. Such a power supply would not be purchased for continuous duty (heating all the time). It can be very difficult to verify the power supply duty ratings strictly from the manufacturer's literature; it needs to be found in other published sources.

Figure 3.3 shows the use of SCRs, transistors (IGBTs and MOS FETs), and vacuum tube oscillators currently in use. The lower end of the frequency range, under 10 kHz, as previously mentioned, widely uses SCRs because of device cost versus current-carrying capabilities. In the medium frequencies IGBTs are used, and in the higher frequencies MOS FETs are used. In the future, as the current-carrying ability of transistors is increased and the cost is decreased, transistors are expected to come into wider use over the full frequency range. Solid-state and RF oscillator tube power supplies have considerable differences in efficiency, as shown in Table 3.1. The lower-frequency, solid-state power supplies are more efficient in en-

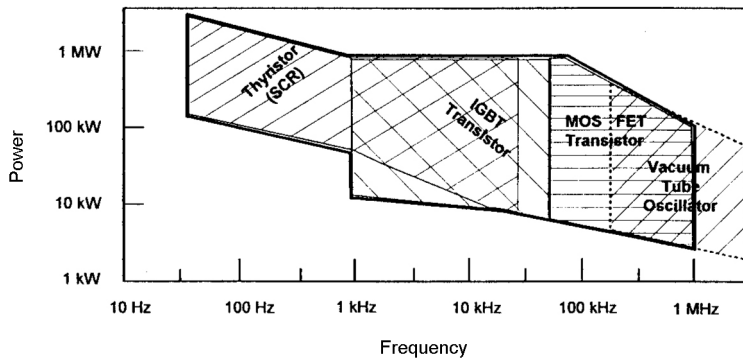


Fig. 3.3 Modern inverter power types for heat treating. SCR: silicon-controlled rectifier; IGBT: isolated gate bipolar transistor; MOS FET: metal-silicon-dioxide field-effect transistor. Source: Ref 3

Table 3.1 Comparative efficiencies of various power sources

Power source	Frequency	Terminal efficiency, %	Coil efficiency, %	System efficiency, %
Supply system	50 to 60 Hz	93 to 97	50 to 90	45 to 85
Frequency multiplier	50 to 180 Hz	85 to 90	50 to 90	40 to 80
	150 to 540 Hz	93 to 95	60 to 92	55 to 85
Motor generator	1 kHz	85 to 90	67 to 93	55 to 80
	3 kHz	83 to 88	70 to 95	55 to 80
	10 kHz	75 to 83	75 to 96	55 to 80
Static inverter	500 Hz	92 to 96	60 to 92	55 to 85
	1 kHz	91 to 95	70 to 93	60 to 85
	3 kHz	90 to 93	70 to 95	60 to 85
	10 kHz	87 to 90	76 to 96	60 to 85
Radio frequency generator	200 to 500 kHz	55 to 65	92 to 96	50 to 60

Source: Ref 4

ergy conversion. The RF oscillator tube has a filament that consumes energy by being heated all the time, and the switching losses in oscillator tubes are high.

The two main types of inverters used in solid state are voltage fed and current fed. These can be further subdivided by the dc source, as shown in Fig. 3.4. Versions of these different inverters are sold by the various induction-heating equipment manufacturers. Reference 3 goes into the theoretical explanation of the electrical circuits for each source. Figure 3.5 shows the electric features of a bridge inverter. Current source inverters operate better with what is termed high “Q” loads, which essentially are loads that are more loosely coupled or tuned. However, as discussed later in this Chapter, the main factor that needs to be examined when selecting a power supply is its ability to produce full power at the rated output power level over the band of impedance matching needed by the user.

Where two different frequencies are desired for an application, several different ways that the frequency and power changes can be made are:

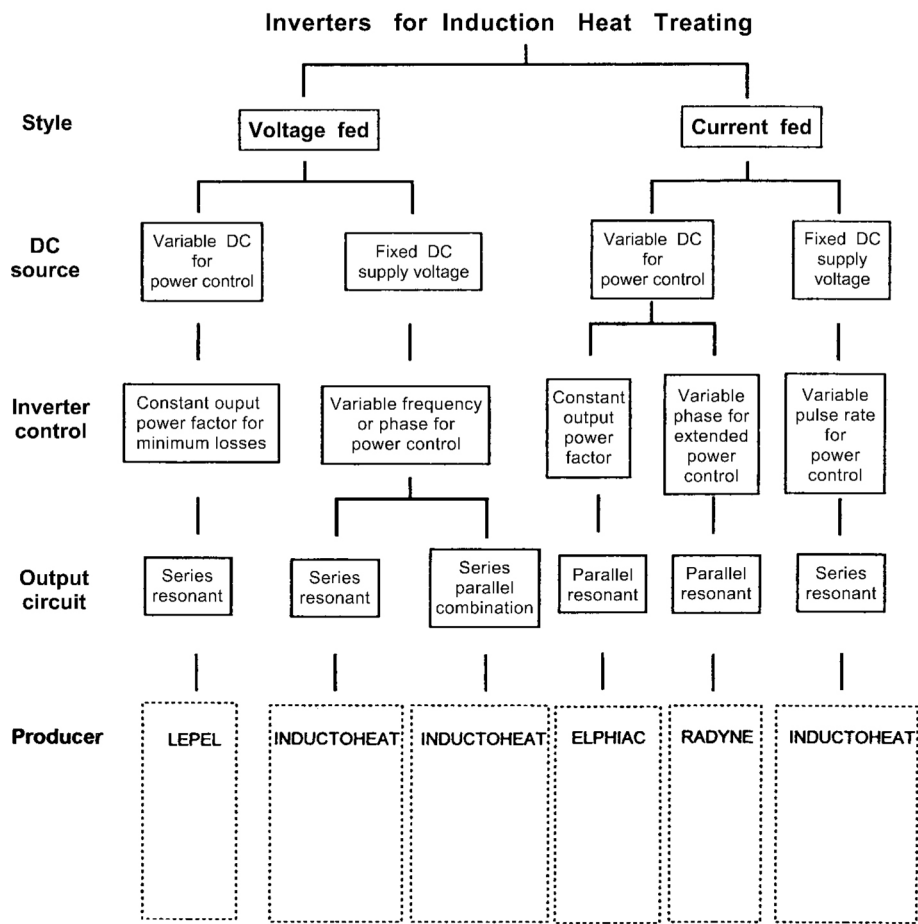


Fig. 3.4 Direct current (DC) source of main types of inverters. Source: Ref 3

Bridge	Inverter	Features
Voltage Fed	Current Fed	
DC Filter Capacitor	DC Inductor	
Square Wave Voltage	Sine Wave Voltage	
Sine Wave Current	Square Wave Current	
Series Resonant Output	Parallel Resonant Output	
Load Current = Output I.	Load Voltage = Output V.	
Voltage x "Q"	Current x "Q"	
Best For Low "Q" Loads	Best For High "Q" Loads	

Fig. 3.5 Electric features of bridge inverter. High "Q" loads are loads more loosely coupled or tuned. DC: direct current. Source: Ref 3

- Use solenoid or manually operated tap changers. The power supply is first operated at one frequency, such as 3 kHz; the power is then turned off, capacitance is switched in the heat station, and the power supply turned on at a higher frequency, such as 10 kHz.
- Use two different frequency power supplies, heating first with a lower frequency to preheat and then turning the power supply off, followed immediately by heating with a second, higher frequency power supply.
- Use two power supplies of different frequencies simultaneously, a method being used for some high-power contour hardening. The purpose is to use frequencies that will produce uniform heating of a gear with a very fast heat cycle. This is illustrated in the power circuit shown in Fig. 3.6.
- Use a power supply that can change frequency and or power on the fly (when under load). Technology has emerged that permits such operation. An example is shown in Fig. 3.7. There are some limitations on the frequency and the ability to make full power at the top frequency.

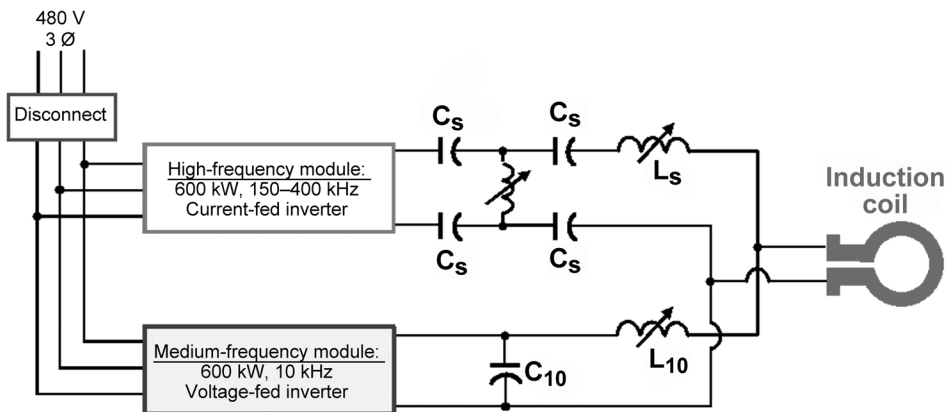


Fig. 3.6 Circuitry of a single coil dual-frequency inverter. Courtesy of Inductoheat, Inc. Source: Ref 5

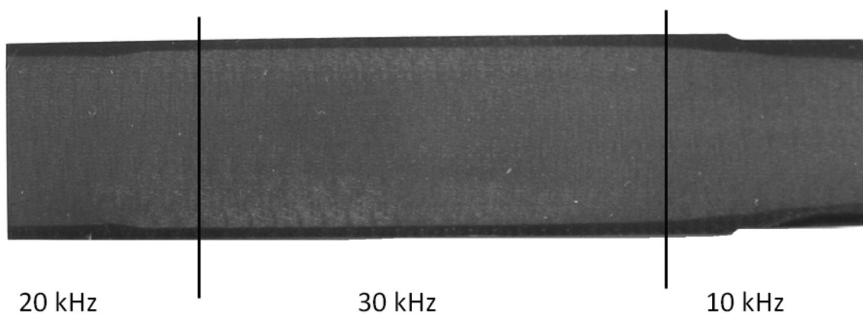


Fig. 3.7 Shaft hardened with independently controlled frequency and power (IPF) power supply showing the effect of varying frequency “on the fly” during the scan. Courtesy of Radyne Corporation. Source: Ref 6

Complete disclosure of all of the requirements for an operating system needs to be provided when new power supplies are being purchased. Engineers do not always agree on what should be provided, and some recommendations may be made based on what the supplier can furnish rather than what is best for the application. If more money is available for purchase, it enables the supplier to provide more sophistication in what is being furnished. The power supplies all come in increments of rated power output at given frequencies. For instance, a 10 kHz series may have power supplies rated at 25 kW, 50 kW, 75 kW, 100 kW, 250 kW, 400 kW, and on. These power outputs are generally dictated by the market and what competitors sell. As the power increases, for example, from 75 to 100 kW, the 100 kW unit may essentially have the same components as the 75 kW unit. One indication of this may be the number of SCRs used for inversion. As modules increase in power, additional SCR models are paralleled into the circuit.

Disruption and Distortion of Line Current. The switching action of solid-state devices can produce “notches” or harmonics back on the supply voltage. The extent of these distortions depends upon the type of circuits being used in the power supply and the protection provided for filtering or screening. The effect of these disruptions can affect controls and operation of other equipment in the plant. Line harmonics have been so bad that they have caused main breakers in plants to activate and power line carriers in other equipment to malfunction. Circuits that can produce these conditions need to have suitable filtering to prevent the feedback.

Solid-State Advantages. Solid-state power supplies are preferred when the workpieces are large enough to permit cost-efficient frequency selection. High-power units are less expensive and smaller in size than oscillator tube units while having higher efficiency in conversion from line frequency to terminal output. Solid-state power supplies require no warmup and have a high degree of reliability. Finally, solid-state power supplies inherently have better power regulation, with the ability to produce full power over an entire heating cycle. At the higher frequencies, such as above 50 kHz, the smaller MOS FET transistors are used. Higher frequencies cause more switching losses, resulting in reduction of the output power rating. With the higher frequencies, such as above 300 kHz, vacuum tube oscillators are still widely used.

Oscillator tube units operate in the 200 kHz up through 2 MHz frequency range and tend to have higher cost per kilowatt of power sold. Older power supplies used rectifier tubes to complete the rectification to dc, while modern units use solid-state diodes. (The only tube in a modern power supply is the oscillator tube.) Radio frequency (oscillator or vacuum tube) power supplies use a transformer to change the input voltage to high voltage before conversion to dc. The oscillator tube is used to produce dc pulses that are likewise changed into the high-frequency, ac current. Because the plate transformer converts the incoming ac to voltages

much higher than solid state, the tank output voltages are much higher than solid state. The higher output voltage of the RF tube power supplies is one of their more distinguishable features. Output transformers are used to lower the output voltages to the work coil. Smaller, low-turn tubing coils can be used for very efficient heating of small parts. The output power of an RF oscillator decreases slightly when magnetic steel parts are heated through the Curie temperature, so it is harder to maintain full power output. However, RF power supplies have been around for many years and have more versatility in impedance matching and tuning than solid-state power supplies. Radio frequency units are easy to tune, and when there is a component failure, they are easy to troubleshoot. Radio frequency tube power supplies have been in wide use for 75 years and have a good history of operation. Although oscillator tubes have 1,000 h warranties, tube life up to 25,000 h or more is not unusual.

While operating cost as determined by power supply cost and conversion efficiency to the workpiece is a consideration, other factors must also be reviewed. Once the desired frequency and power requirements have been calculated for a power supply, factors such as the recommended line utility requirements, cooling water requirements, system losses in the heat station and coil, power supply controls and regulation, and window for full power regulation should be reviewed.

Line Utility Requirements

In the United States the most common line utility is 480 V, three-phase, 60 Hz. There are some 220 V utilities in use; through the use of transformers almost any voltage can be used (other countries can have different utility sources, such as 380 V). The input kilovolt-amps and line voltage tolerance of the power supply should be reviewed. Local utilities are required to furnish a given range of line voltages. However, line voltage variation during a workday can produce output power fluctuations that may be a problem. Also, as previously mentioned, solid-state devices such as diodes and SCRs produce line harmonics back into the power line that can potentially affect other solid-state controls and equipment.

Cooling Water Requirements

Cooling water is required because all of the electrical energy consumed is essentially transferred in the form of heat to the cooling water. Except for small radiation losses and residual heat left after quenching, even the heat produced in the workpiece is absorbed by the quenchant, which in turn needs to be cooled through a heat exchanger. If the heat input into the workpiece is 50 kW in a 100 kW induction-heating system, then the other 50%, or 50 kW, represents system loss to be absorbed by the cooling water. Thus, at full power, a 100 kW system transmits 100 kW into cool-

ing water either through the cooling water in the electrical system or the cooling water that directly or indirectly cools the parts that are heat treated (indirect cooling is done by heat exchangers that cool the quenchant).

Water quality is extremely important in induction heat treating systems. A review of the maintenance problems of induction-heating systems shows poor water quality to be the leading cause of maintenance problems. Six sources of problems in water are:

- *pH level:* Cooling circuits consist mostly of brass and copper fittings and pipe. A range of 6 to 8 appears to be the best range for good results. Below 6 will produce corrosion of brass, and above 8 scale will form.
- *Suspended solids:* If allowed to accumulate, the suspended solids will tend to clog the small water passages in transformers and capacitors. Suspended solids tend to settle at the low points of cooling passages when the pumps are turned off, leading to eventual clogging.
- *Dissolved gases:* These are not generally a problem unless there is open air turbulence. Dissolved carbon dioxide can result in high corrosion rates by lowering the pH. Dissolved oxygen will increase electrolytic corrosion rates and can be a problem when pressurized systems are used without dissolved gas removers.
- *Biological contaminants:* While the systems that contain copper do not usually have a problem with biological contamination, it is possible for algae or microorganisms to “infect” a cooling system. The contamination can result in corrosion, plugging, and reduced heat transfer. Professional help should be used for assistance in dealing with suspected biological problems.
- *Dissolved solids:* These are the most significant factor in cooling electrical equipment. Total dissolved solids directly affect the conductivity of the cooling water. When the conductivity is too high, electrolysis will occur in the cooling passages that have dc voltage potential. Different original equipment manufacturers (OEMs) have different methods of dealing with dissolved solids according to the individual requirements of their power supply, including the use of sacrificial targets and calculated cooling hose lengths. Figure 3.8 shows an example of calcium-clogged cooling hoses. Deposits will form most often at the points that have the highest temperature or at the bottom of the cooling hose loops. The maximum dissolved solids may be stated, such as 250 ppm. However, because the content of dissolved solids can be determined through water conductivity, a conductivity range such as 60 to 400 $\mu\text{S}/\text{cm}$ may be recommended by the manufacturer. Conductivity ranges are covered later in this Chapter in the discussion of closed water recirculation systems.
- *Galvanic corrosion:* This is another cause of fitting deterioration and water contamination. Care must be taken in the connection of systems



Fig. 3.8 Calcium-clogged water paths due to high-conductivity water.
Source: Ref 7

not to place dissimilar metals in contact with each other without the use of a galvanic fitting. For example, if the heat exchanger has copper pipe but the inlet water connection is made with steel pipe, galvanic fittings should be used.

The different elements of the induction-heating system have different cooling water requirements. Thus, the cooling water needed to cool the electrical components in the power supply, heat station, induction coil, and quench system can have different specifications. This is particularly important in large power systems, so that cooling water costs can be minimized. Where large quantities of cooling water are needed, lower standards can be used to cool elements such as the quench system. The power supply OEMs give clear definitions of the quality, quantity, and maximum temperature of cooling water needed. While there has been a tendency to relax standards in some of the transistorized power supplies, over the long term high-quality water is recommended for continued equipment operation.

Available cooling water sources on the line or input side include well water, river water, and reservoir or lake water, feeding into various types of open and closed systems. In the circumstances where a natural source of cooling water is not available, refrigerated cooling packages can be used. When a natural source of cooling water is used for cooling the power supply and heat station, whatever the source, the water should be supplied at a temperature above the dew point to prevent excessive condensation. Open water recirculating systems that add line water as needed to maintain the recirculated temperature work quite well. The excess water passes through an overflow to the drain for other manufacturing processes. Most natural water sources that can be legally used do not have high enough purity for use in cooling the power supplies, heat stations, and work coils. Engineers have tried many times to reduce the cost of power supplies by reducing water purity requirements, only to be proven wrong after the

equipment is out of warranty. Purity and conductivity of the water for the power supply and heat station have historically proven important to reliable, long-term operation. The OEM specifications for water quality, flow, and minimum inlet temperature are the minimum specifications that should be met. It is the author’s opinion that quenchant should not be used to cool power supplies and heat stations.

Different induction system configurations of power supply, heat station, and coil can have different inlet water pressure, water flow, and maximum water inlet requirements. From these requirements systems can be designed from the available line water that will provide the necessary cooling. Most available water supplies do not meet the water purity criteria; therefore, the line water is used to cool a separate system of high-purity cooling water that is recirculated through the induction system, plus any other separate systems that need cooling, such as the quench systems.

Figure 3.9 shows the preferred and most common type of cooling system used in cooling induction equipment. The system has a closed loop of cooling water running through all of the induction system and returning to an open tank. The system is nonpressurized, with the tank open to the atmosphere. By running the return lines into the tank below the water line, dissolved gases are minimized. This system should have all nonferrous plumbing and fittings. The closed side of the system recirculates high-purity cooling water at the correct temperature and flow through the in-

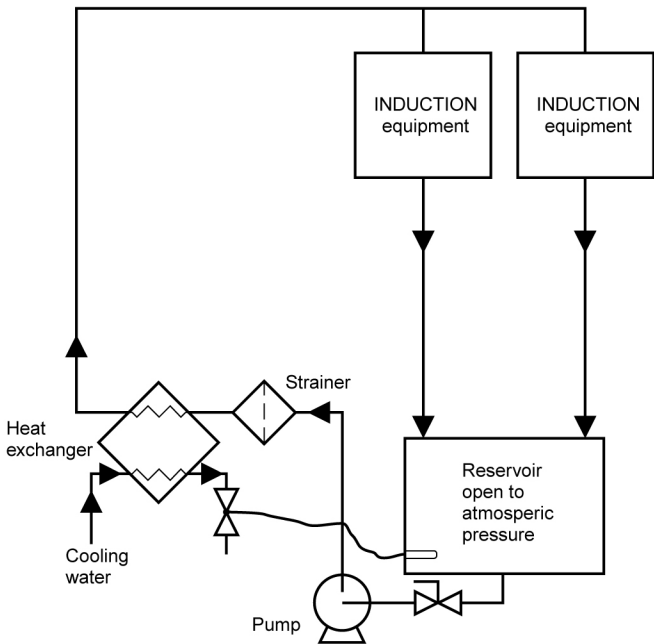


Fig. 3.9 Closed-loop recirculation system. Source: Ref 8

duction system, with the recirculated water cooled in a heat exchanger. The open side of the system uses line water obtained from natural sources or other sources such as cooling towers or chillers.

Figure 3.10 shows a common cooling system that uses an evaporative water tower to provide cooling for the line water side, adding makeup water as needed to counter evaporation losses. These systems are most efficient when the summertime dew point on hot muggy days does not exceed the maximum temperature required on the line water side. (Above the dew point, water will not evaporate.) When this happens, other sources of cooling need to be used, such as adding makeup water or using refrigerated coolers for supplemental cooling. The line water sources may need to have biocides added to prevent biological contamination, and filters may be needed to keep out solids such as leaves and wind-blown debris. In the wintertime, antifreeze may be needed to prevent freezing on the tower side.

Where high-purity water is needed, the internal closed systems of recirculated water commonly use distilled water or deionized water. When distilled water is used, the water should be changed on a periodic basis, such as every six months. New deionized water has a conductivity of about $20\ \mu\text{S}/\text{cm}$ and when first charged will dissolve some of the metallic components in the cooling system. The conductivity will increase very rapidly to about 180 to $200\ \mu\text{S}/\text{cm}$. After that, the conductivity will slowly increase to the $400\ \mu\text{S}/\text{cm}$ level, at which point the water should be changed.

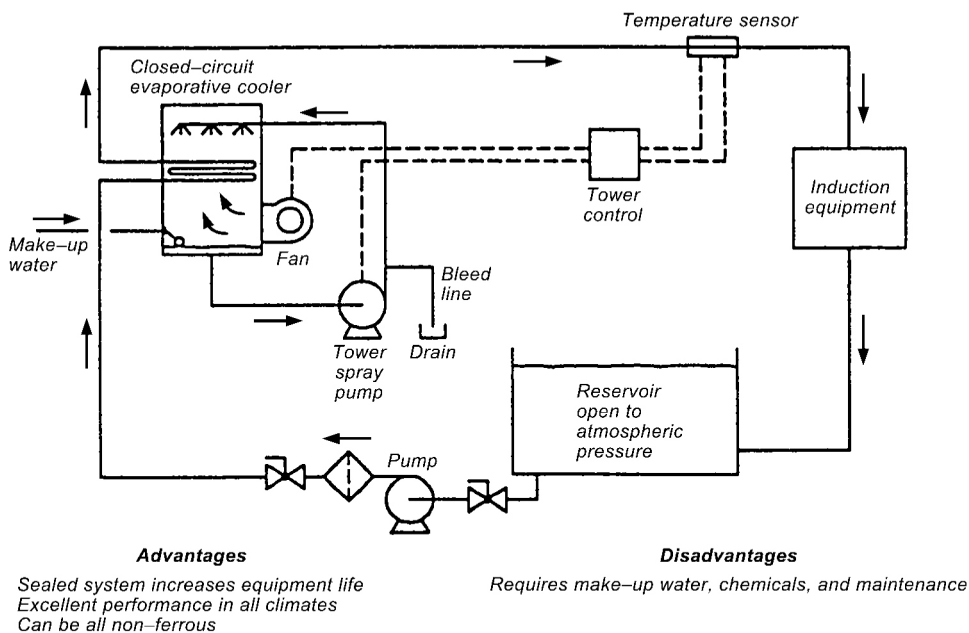


Fig. 3.10 Closed-loop recirculation system with tower. Source: Ref 8

Where deionized water is used with a closed-loop deionizing system, it is recommended that the water be maintained at a specified conductive range, such as 60 to 100 $\mu\text{S}/\text{cm}$. If the water is in a closed system, biocides may be needed, and filters are recommended. Quench system design is discussed in Appendix 4, “Quench System Design,” in this book. Also, if the closed system needs antifreeze because of low plant ambient temperature, commercial antifreezes (as are used with cars) must not be used. They will ionize and break down under voltage. Only pure ethylene or propylene glycol should be used.

Heat stations contain the transformers and capacitors, as needed by a given power supply, to help match the power supply voltage or impedance to the coil. The footprint available for an induction system can determine the best type of layout for the equipment. This includes things such as the heat station integral with the power supply or the ability to locate the power supply at a remote location from where the parts are being heated. When the power supply is remotely or balcony located, there may be requirements for minimizing power losses in the transmission of the high-frequency power to the heat station. Heat stations may have tank circuits with the tuning capacitors either in parallel or in series with the induction coil.

Transformers in the heat station are used to lower the output voltage of the power supply to match the work coil voltage. Figure 3.11 shows the operating data for an output transformer rated at 1200 kVA, 800V, 10 kHz. To match a 40 V work coil, the 20-1 tap would be used. The heat station transformers sold have become standardized in many respects to the standard voltage and frequency ratings of the power supplies being sold.

Tuning capacitors in the heat stations are installed with the taps reachable when the enclosure door is opened. The capacitors are tapped and are used for tuning purposes. Typical voltages for the capacitors used for solid state are 220 V, 440 V, 800 V, 1000 V, and 1200 V, and typical frequencies are 60 Hz and 1, 3, 9.6, 25, and 50 kHz. Operating a capacitor at a higher frequency than rated is not recommended because of the potential to exceed the current-carrying capacity of the capacitor. Taps may be manually changed or by the use of a manual switch or selector switch when the power is off. In some cases where tap change is needed during the heating process, this may be accomplished by turning off the power long enough for contactors to close. In the case of motor-generator sets, the switching is done under power to maintain a leading power factor.

The heat station tuning transformers and capacitors can be in the same enclosure as the power supply components, or they may be in a separate enclosure. High-frequency transformers tend to be inefficient, producing system power losses running from 10 to 40% of the output of the power supply. When the heat stations are furnished separately from the power supply, proper system design requires that the conductors carrying the high frequency be chosen and installed according to the instructions of the

JACKSON VARIABLE RATIO ISOLATION TRANSFORMER

MODEL 52V1-101 CHARACTERISTICS 52V1-101 C

RATING 800 VOLTS 10 KHZ 1200 KVA 300 KW

RATIO PRIMARY/SECONDARY	10-1	11-1	12-1	13-1	14-1	15-1	16-1	17-1	18-1	19-1	20-1	21-1	22-1
INPUT TAP CONNECTION	6-16	5-16	6-18	5-18	6-20	1-16	0-16	1-18	0-18	1-20	0-20	1-22	0-22
RESISTANCE-OHMS short circuit	.016	.018	.019	.021	.022	.024	.026	.027	.029	.030	.032	.034	.035
IMPEDANCE-OHMS short circuit	.065	.072	.078	.085	.091	.098	.104	.111	.117	.124	.130	.137	.143
LEAKAGE INDUCTANCE uH	1.03	1.14	1.24	1.34	1.45	1.55	1.66	1.76	1.86	1.97	2.07	2.17	2.28
(1) MAXIMUM KVA INPUT	1951	1860	1781	1711	1649	1593	1542	1496	1454	1415	1379	1346	1315
MAXIMUM WINDING LOSS-KW	95	95	95	95	95	95	95	95	95	95	95	95	95
WINDING LOSS-KW	36.0	39.6	43.2	46.8	50.4	54.0	57.6	61.2	64.8	68.4	72.0	75.6	79.2
CORE LOSS-KW	6.2	5.2	4.4	3.8	3.3	2.9	2.6	2.3	2.1	1.9	1.7	1.6	1.4
EXCITING CURRENT	22.1	18.3	15.4	13.1	11.3	9.8	8.6	7.7	6.8	6.1	5.5	5.0	4.6
(2) CORE DUTY CYCLE % TIME ON	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
SECONDARY VOLTS AT FULL LOAD	70	63	57	52	47	44	40	37	35	32	30	28	27
EFFICIENCY % (BASED ON KW)	85.9	85.1	84.1	83.1	82.1	81.0	79.9	78.8	77.7	76.6	75.4	74.3	73.1

(1) THE MAXIMUM KVA RATING IS BASED ON INLET WATER TEMPERATURE 35°C (95°F), OUTLET WATER TEMPERATURE 66°C (151°F).

WATER PRESSURE DROP 2.1 KG/CM² (30PSI) AND WATER FLOWS BELOW:

PRIMARY	1 INLET(S)	2 OUTLET(S)	2.9 GPM / Outlet	5.8 TOTAL GPM
SECONDARY	1 INLET(S)	2 OUTLET(S)	2.9 GPM / Outlet	5.8 TOTAL GPM
CORE	1 INLET	1 OUTLET	3.0 GPM / Outlet	3.0 TOTAL GPM

WATER REQUIREMENTS:

HARDNESS MAXIMUM 12 GRAINS/GALLON (205 ppm)

INLET TEMPERATURE: MAXIMUM 35°C (95°F)

INLET TEMPERATURE MUST BE HIGHER THAN DEW POINT TEMPERATURE TO AVOID CONDENSATION

THE ABOVE CALCULATIONS AND WATER FLOW ARE BASED ON A PRESSURE DROP OF 2.1 KG/CM² (30PSI)

(2) CORE DUTY CYCLE IS BASED ON MAXIMUM STEEL CORE TEMPERATURE OF 135°C (266°F) AND THE TIME POWER IS ON THE CORE

30 SECONDS ON AND 30 SECONDS OFF = 50% DUTY CYCLE, 60 SECONDS ON OR MORE = 100% DUTY CYCLE

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Date: 1/18/1978

Rev.: 7/27/2012

Fig. 3.11 Manufacturer's data sheet. Courtesy of Jackson Transformer Company. Source: Ref 9

manufacturer of the equipment. Remote location, even exceeding a meter or several feet, can produce system losses that reduce the output power available at the coil. Likewise, coil design, as discussed in Appendix 3, “Induction Coil Design and Fabrication,” in this book, is important in optimizing the amount of power available to be induced into a workpiece. Proper coil design reduces the power loss in the coil, enabling more power to be produced in the workpiece.

Power Supply Regulation

The ability to produce the same amount of power for each part during the heating cycle is important. The power supplies need to have regulation so that the power supply has constant output if there is a change of the line voltage during operation (not an unusual circumstance). The manufacturers normally rate their power supply over the range of input voltage for which constant output can be produced. The ratings of the voltage variation produced at a given plant location should be checked against the voltage range over which the manufacturer’s power supply is rated to operate. For instance, when the power supplies are being run at full power, regulation may not be achieved over large voltage swings, such as the line voltage ranging from 480 V down to 430 V in the same day. Radio frequency oscillator power supplies with front-end SCR power controllers are supposed to regulate, but they too may fail to handle large swings in line voltage. The RF oscillator power supplies may have other methods of regulation to help with small input-voltage fluctuations, such as filament voltage regulation. Radio frequency power supplies do not regulate the output through closed-loop feedback for frequency adjustment such as for solid-state power supplies. Plate amperage, the metered indication of output current of the oscillator tube, decreases when the temperature of the workpiece is passing through the Curie temperature. Solid-state power supplies regulate to constant output through closed-loop controls to hold constant power, constant voltage, or constant current. The firing rate of the semiconductors is changed to cause a frequency shift so that the constant output is maintained.

Each method of regulation of solid-state has areas of application. When the controls are set to hold constant power, there is no drop of power during heating. Voltage and current regulation tend to the output power better when there are wide variations in impedance during the heating cycle, such as when a scanner passes over different diameters of a workpiece when heating. Regulation of the power supply is important so that the total power produced into the workpiece during each heat cycle is the same during low-line voltage conditions or when the line voltage fluctuates. When purchasing a power supply, the buyer should be certain that the power supply regulates the output power for consistent output with

normal line voltage fluctuations that exist in the buyer's plant not only throughout the day but also throughout the year.

Controls. The development of power supply controls started with analog meters and dial pots (potentiometers) for setup and monitoring. Setup involved dialing the pot to a marked position and trying to catch the deflection of the analog meters during trial tuning. If one person was involved in the setup, it could take several tries to note and to record the movement of the analog meter. Switching between heat levels could require the switching of pots or contactors.

The operating controls can be as simple as the push-button controls shown in Fig. 3.12. The basic power on and off buttons are provided, output power control is provided, and features are present to provide status screens, as shown in Fig. 3.13. Programmable logic controls are available now in equipment with many units that offer a much more flexible approach to power supply control, power supply monitoring, and control of components of the induction heat-treating system. These can provide precise setup guides and capability along with data presentation and storage for quality control purposes.

The essential controls can be separated into three different groupings: the metering, the logic portion, and the operating control. The metering of

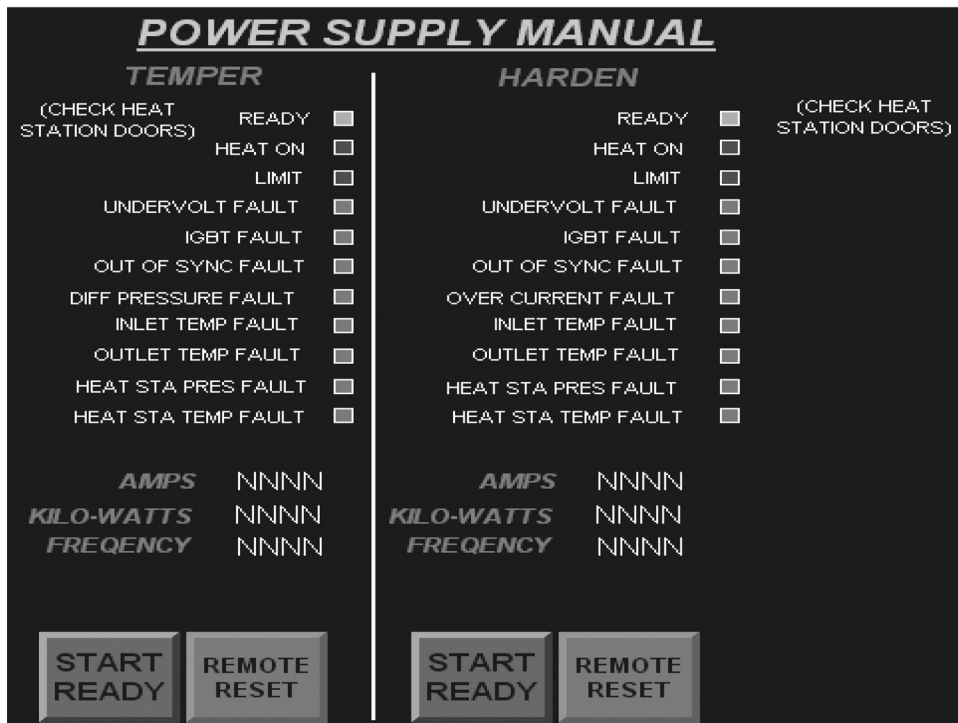


Fig. 3.12 Power supply start-stop and status screen. Source: Ref 10

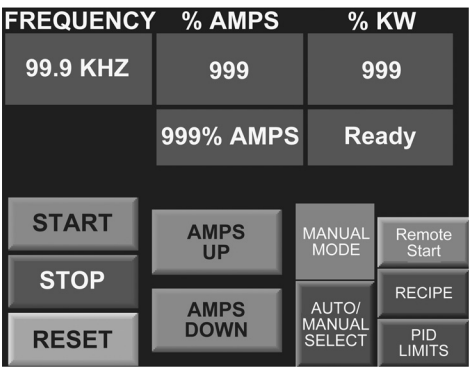


Fig. 3.13 Power supply control on simple machine. Source: Ref 10

the power supply provides the information not only for initial tuning but also for monitoring the power supply performance during operation. Use of the meters is discussed in this Chapter under “Load Matching.” Different types of power supplies have different metering requirements, and different manufacturers vary in meter output they furnish. Factors to be considered are the types of metering furnished and the location of the metering (for example, the meters from the control, “heat on,” “heat off” locations).

The logic types of control are internal in the power supply. These include the automatic controls within the power supply, such as various limit circuits, overload circuits, trip circuits, status indications, and power regulation circuits. Limit circuits serve to protect the power supply against conditions such as high frequency, high voltage, or high current. The overload circuits protect against detrimental or harmful conditions to the power supply such as short circuits, open circuits, and arcs. The internal control circuits also provide power regulation, such as constant power through both the heating cycles on solid-state equipment, to maintain a constant output. Also included in this type of control are any special circuits that tie in with remote-control feedback for automatic power control. Examples of control feedback circuits are those for which radiation pyrometers or linear speed feedback controllers provide signals that are used to regulate the output power back to the power supply.

The third type of control is the operating control, such as output power adjustment, the control that turns the power on and off. If 100% power is being produced and the workpiece is being heated too fast, adjustment of the power control will reduce power. Different types of power supplies do this differently, by either reducing the firing rate of the semiconductors or using front-end solid-state controllers to reduce the input voltage before rectification. It is possible to purchase some power supplies, such as RF tube sets, that do not have a stepless type of power control.

Turn-On Power Ramp. The first power supplies used mechanical-relay-type contactors that provided almost instantaneous turn-on after closure. Today most power supplies that are solid-state or with SCR front ends have a ramp in which the power is increased from low to full power to start the heat cycle. Slower ramps give more time for limit and trip circuits to operate. However, applications that have short heat cycles, such as less than 1 s, require fast power turn-on. The objective is to have the power supply operate at full power for the entire heating cycle, rather than to have a large portion of the heating cycle at less than full power. The manufacturers of the contour-hardening equipment (where the heat cycles are less than 0.25 s) not only use controls designed to provide very fast power ramps but also may even use controls that initiate turn-on at zero crossing in the line phasing. One example of fast turn-on is where RF was used to provide five heating cycles every second for automated sealing of pull tabs on cans.

Regulation and Control. Most induction heat-treating operations are based on a predetermined level of power applied for a given length of time. Repeatability is produced through accurate timing and through a consistent amount of power produced in the workpiece every heat cycle to produce exactly the same austenitizing cycle. Electronic timers are used to provide accurate heating cycles, often through use of programmable controllers. The requirement is that each workpiece must be processed so that the same total power is induced with the same heating time. The process is kept in control through regulation of the output power and accurate timing. However, the advent of Six Sigma quality control requirements has required more advanced monitors for quality assurance. The most common monitor is the energy monitor.

Energy Monitors and Monitoring of Process Variables. The basic energy monitor measures and displays the total energy delivered in the induction coil in kilowatt-seconds. Voltage and current feedback signals are fed from a point (the coil is the accurate location) into a monitor that displays the kilowatt-seconds used during the heat cycle. Once a workpiece heating pattern is developed with a heating cycle, the monitor can have upper and lower kilowatt-seconds limits entered into the control system so that there will be a system fault if the proper number of kilowatt-seconds is not reached. Test workpieces must be run to establish the proper limit settings. Another way that the energy monitor can be used is to actually control the length of the heat cycle through kilowatt-seconds, with a timer providing the high limit. The most precise use of the energy monitor is one in which the kilowatt-seconds are displayed on a monitor so that the actual kilowatt-seconds are displayed on a curve through the heating cycle. With this type of display, the high and low limits can be characterized for each application.

Figure 3.14 shows an example of monitor readings for an induction cycle with a low-power heating cycle and a high-power heating cycle in

kilowatt-seconds, with limits. Figure 3.15 illustrates readings from a kilowatt-second monitor that has the upper and lower power limits characterized. About halfway through the cycle a problem occurred and the power dipped below the lower bandwidth setting, indicating a potential process problem. While the monitors are a useful addition to quality control systems, they may not indicate all conditions that might produce a bad workpiece. Induction coils with magnetic flux concentrators will eventually produce workpieces out of tolerance due to deteriorating or spalling of the flux concentrator. The coil will produce the same kilowatt-seconds into the workpiece, but less energy will be induced into the workpiece while the coil losses are higher. Either periodic workpiece inspection or advanced nondestructive testing techniques (as discussed in Chapter 12, “Standards and Inspection,” in this book) must be used.

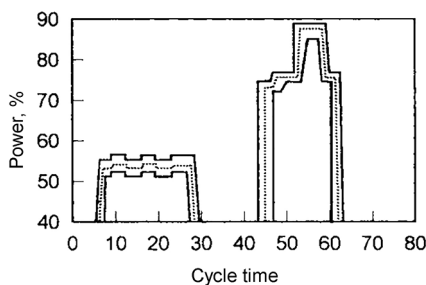


Fig. 3.14 Kilowatt-second process monitor. Source: Ref 3

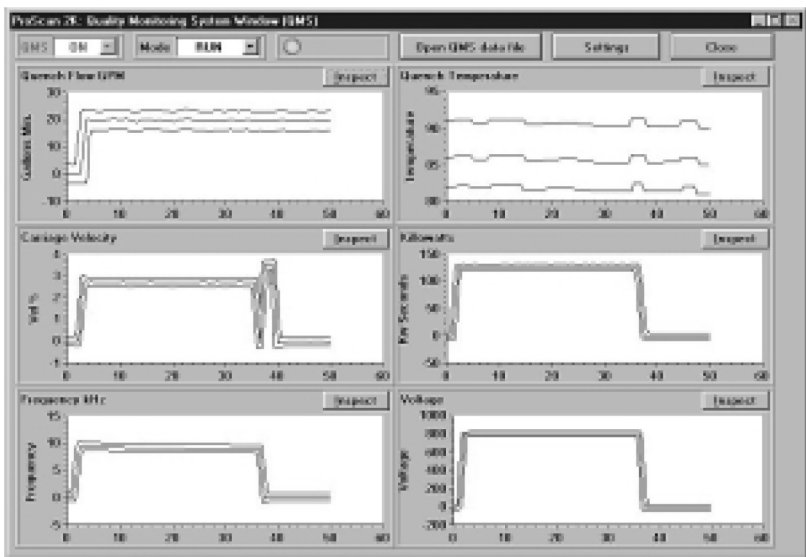


Fig. 3.15 Quality monitoring system main screen from a scan speed process monitor. Source: Ref 11

It is recommended that the power supply output mode monitored not be the same as the power supply control regulation mode. For instance, if a power supply is regulating on constant power, then either coil voltage or kilowatt-seconds during the cycle should be monitored. More advanced quality control monitors characterizing the expected output of all variables during the cycle so that high-low limits can be set for each individual process parameter. Data are collected from all variables at fixed time increments throughout the cycle and are compared to previously entered data and limits to ensure that process values always stay in limits and that the process is in control.

Figure 3.16 shows other measurement variables that can be monitored in a similar fashion. The more sophisticated monitors are used more often with dedicated induction process systems for specific parts because of the testing and qualification needed to characterize all of the variables for the process monitoring. One of the variables that is sometimes measured and monitored is the workpiece temperature throughout the heating cycle. In addition some insulated-gate bipolar transistor power supplies float the frequency to make tuning easier. It may be important for production part approval process validation that the output be fixed, once tuned, for frequency or other output characteristics that can provide variance in the process.

Temperature Control through Use of Pyrometers. While experienced operators can tell by the color and scaling of the workpiece during

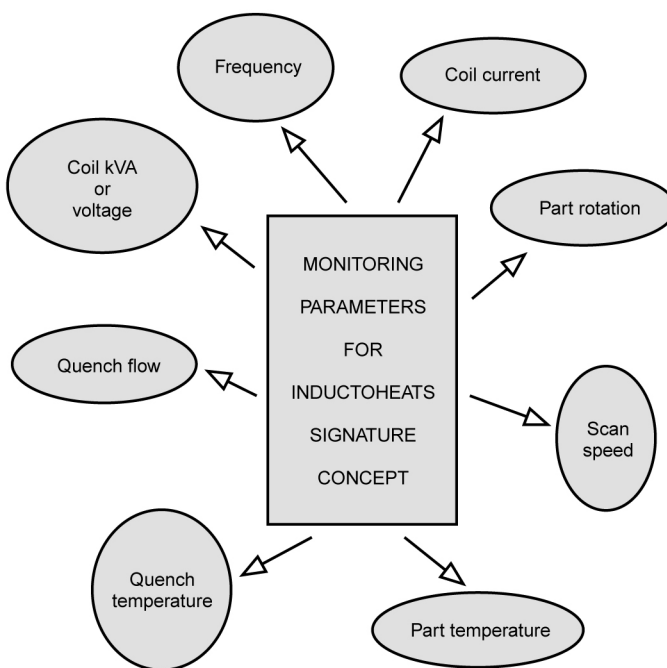


Fig. 3.16 Monitoring parameters for signature concept. Source: Ref 3

austenitizing that the workpiece temperature is approximately correct, temperature measurement can provide precise temperature readings. Infrared pyrometers and fiber optics are most widely used for temperature measurement with induction.

Infrared pyrometers are accurate to 0.5 to 1% of the reading. They can be used as portable sensors or as part of a permanent, continuous temperature monitoring or controlling system. The pyrometer heads or fiber optic pickups need a clear line of sight onto the area at which the temperature is being measured. Where the heat cycle has fast temperature changes, a digital readout is preferred because the analog type meters have a delay in indicating the metered output. The three types of infrared pyrometers are:

- Single-color or single-band pyrometers measure infrared radiation from a fixed wavelength. These are the most versatile because of their suitability to many applications. Their accuracy is affected by the presence of scale on the workpiece and any smoke coming off the workpiece, and by any changes in emissivity of the workpiece.
- Broad-band pyrometers measure the total infrared radiation emitted by the target. Similar to single-color pyrometers, the accuracy of these pyrometers is also adversely affected by the presence of scale and smoke.
- Two-band or two-color pyrometers measure the radiation emitted at two fixed and closely spaced wavelengths. The ratio of the two measurements is used to determine the temperature of the target. The adverse effects of other two pyrometers are largely eliminated by this pyrometer. Because of its accuracy this is the most widely used pyrometer. It is readily adaptable for measuring temperature in induction-heating systems using a variety of optical systems for focusing, including fiber optics.

Figure 3.17 shows a system schematic for the use of an infrared pyrometer during the induction hardening of a crankshaft. Systems such as this may be either closed loop, with the pyrometer controlling the heating cycle, or open loop, with the pyrometer acting as an over-temperature shutoff control. Most pyrometers are used for over-temperature control.

Diagnostic systems help to show the operating condition of the induction-heating system. Table 3.2 shows the typical capabilities of diagnostic control. With planning, the status of virtually every component of an induction system can be displayed with feedback for diagnostics where necessary. Figure 3.18 shows a flow diagram of a diagnostics control plan. The more advanced control systems allow the entry of all process parameters to be characterized in real time on a screen with limits set. Operators can enter, verify, and monitor power levels, heating time, the power supply output during the cycle, part temperature during the cycle, scan speeds

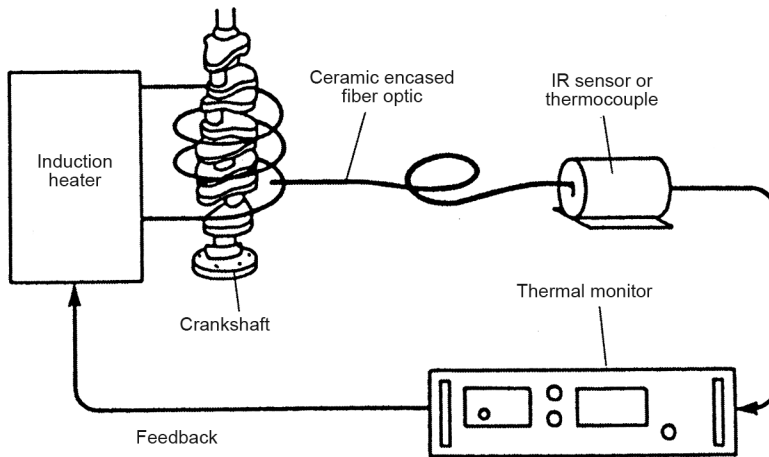


Fig. 3.17 Simple temperature control system. IR: infrared. Source: Ref 4

Table 3.2 Typical capabilities of diagnostic equipment

Machine diagnostics	Process diagnostics	Process signature capabilities
• Proximity switch failure • Limit switch failure • Liquid levels • Liquid temperatures • Inductor ground • Power supply status • Pump operation status • Guard/safety gate status • Coil water cooling pressure • Coil water cooling flow • Part position gaging • Part present indication	• Power level • Heat time • Scan speed • Rotation speed • Part temperature • Energy into a part • Quench flow • Quench pressure • Quench temperature • Quench concentration	• Quench pressure • Quench flow • Power level • Voltage level • Current level • Rotation speed • Part temperature

Source: Ref 12

during the cycle, and other conditions as desired, such as quenchant pressure, quenchant flow, and part rotation speed.

Window of Full Power Output. Figure 3.19 shows the effect of tuning to produce a frequency that results in full power. Once the resonant frequency is reached, the power output drops rapidly. (This is known as “going over the hill.”) The width of the frequency range that will produce rated power represents the “window” within which the power supply can be tuned to make rated power. The ability of a given power supply to make full power into a given work load and output impedance depends on the system design and application. However, the ability of different types of power supplies to broad-band tune and to make full power into different loads and coil impedance varies widely. Some power supplies need to have 100% over rating of power to essentially be a broad-band tuning unit. The ability of given power supplies to broad-band tune can some-

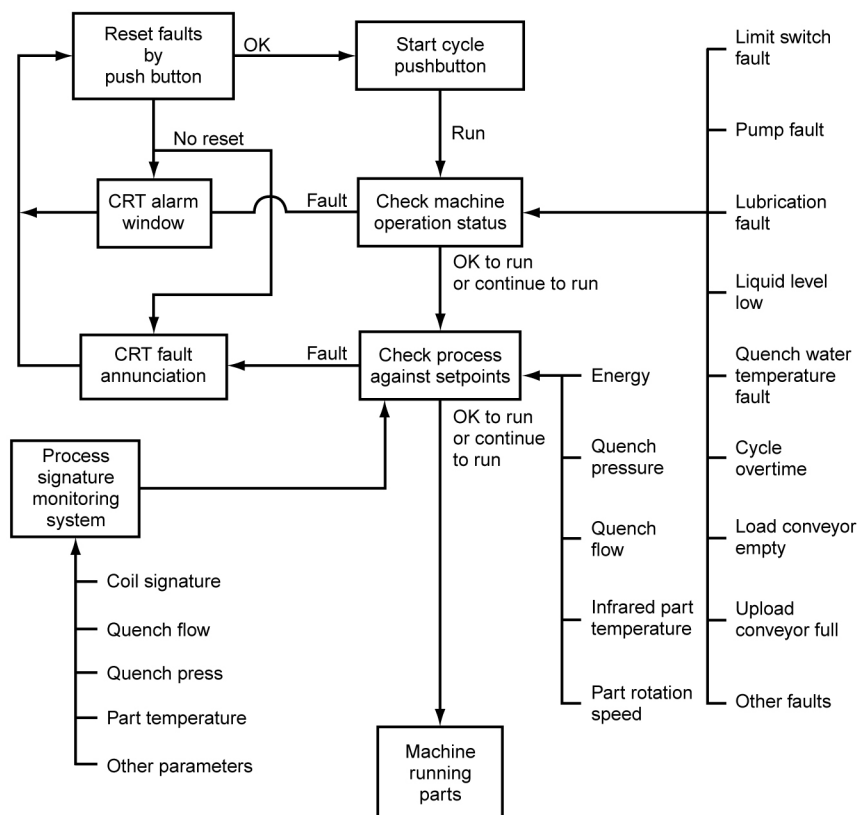


Fig. 3.18 Flow diagram of a diagnostics control plan. CRT: cathode ray tube.
Source: Ref 12

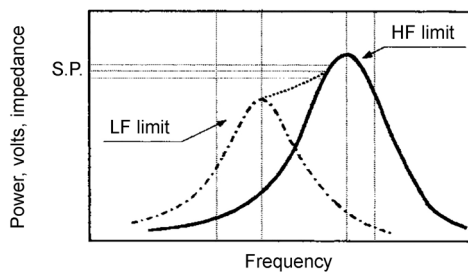


Fig. 3.19 Power supply output at resonant frequency. S.P.: set point; LF: low frequency; HF: high frequency. Source: Ref 3

times be increased by installing additional tuning capacitors, wider-range output transformers, and the use of auto transformers in the heat stations. If in doubt, the recommendation is to purchase a power supply with reserve power. It is easier to produce 100 kW at 50% with a 200 kW power supply than it is to run the 100 kW power supply at full power over all conditions.

Other conditions that should be reviewed in new equipment are overall equipment reliability, maintainability, and the service and parts organization.

Fixtures and Work Handling. Simple fixtures, such as worktables, sit in front of the heat stations and may require no interconnection. On the other hand, the fixtures and work-handling equipment may be very elaborate. Descriptions of lift-and-rotate mechanisms (an example is shown in Fig. 3.20), index tables, and scanners are described in Chapter 11, “Induction Heat Treating Process Analysis,” in this book. These devices provide whatever is necessary to locate the part in the induction coil and the means for moving parts into and out of the coil. There are many standard types of designations for this equipment, and there have been many unique mechanisms.

Design factors that should be considered in the design of fixturing are:

- The workpieces must be safely held in fixtures or nests that do not interfere with any part of the heat treating process. For example, nests

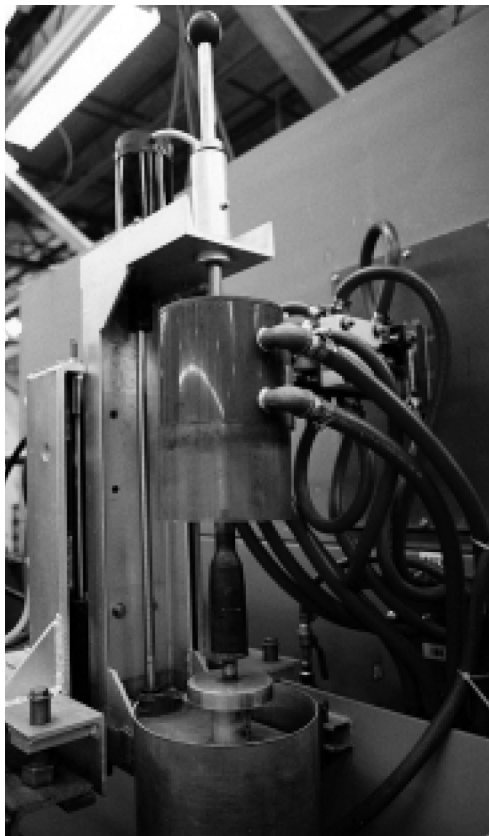


Fig. 3.20 Picture of lift-and-rotate mechanism. Source: Ref 13

that hold the parts may need to be made from nonmagnetic materials, or even cooled during and after hardening.

- Workpieces must be positioned positively with the degree of accuracy needed for each step of the process. Mechanized systems may need proximity devices to make certain that the workpiece is accurately located in the coil before the workpiece is positioned into the coil.
- Workpieces must be positioned properly and supported well enough to minimize distortion. For example, small-diameter workpieces held between centers can distort with excessive center pressure. Long workpieces may need mechanical restraint on each side of the coil.
- Frequencies below 10 kHz can cause some workpieces to levitate. The fixturing design must prevent levitation.
- Electrical conducting materials used in construction of the fixture should be kept away from the heating field, and stray, induced currents should be avoided in drives, bearings, and moving parts.
- Bearings and moving parts that are under the quenchant must be sealed to prevent entry of the quenchant into these bearings and parts.
- The necessary operating controls for cycle start and emergency stop must be in reach of the operator. Also, on induction hardening systems that have frequent setup change, it is desirable to have the power supply meters in sight of the operating position. This helps to facilitate safe tuning during setup.
- The working height of the fixture should be at a level conducive to efficient flow of workpieces in and out of induction hardening.
- Operational safety concerns as required by OSHA regulations must be met to prevent harm to the induction heater operator.
- The rotation speed of nests or spindles commonly range from 1 to 5 rps, with 2.5/5 rps being the most common. When using very fast heat cycles, such as under 1 s, the rotation speed may need to be faster if uniform patterns are not produced.
- When parts are being held between top and bottom centers or cups such as on scanners, the top spindle pressure must not stop the part being held from rotation. When this happens, one solution is to have both top and bottom spindles have positive rotation.
- Horizontal scanners sometimes use restraint mechanisms on each side of the coil to make certain the part being scanned is held concentric and the coil and to reduce distortion.
- Transfer switches are used in systems that desire to transfer the power from one power supply to one or more heat stations or fixtures for purposes of higher utilization of the power supply or versatility in operation. The very simple method used has been to change bolted bus connections. When the change is desired when alternating in production, transfer switches are used. It is recommended that the transfer be done before any load is applied. The conduction connections must not heat or arc, and they must not affect the electrical characteristics of the load circuit.

Quench Systems

Quenchant selection is discussed in Chapter 6, “Quenching,” in this book. Quench systems can vary from the simple use of line water, with the spent water going down the drain after the workpiece is quenched, to more sophisticated quenching systems with tanks, heat exchangers, pumps, filters, and temperature regulation controls.

In the past, dunk oil quenching and water-soluble oils were widely used. Today, although oil is still used for some applications, polymer quenches have widely replaced most of the oil quenches. Polymers are not flammable, so they provide no fire hazard. In addition, polymers are easily cleaned off after quenching. Polymer quenchants contain biocide and rust inhibitors. The vapor pocket reduction provided by low polymer-to-water ratios has been found to make polymer quenchants more desirable than straight water quenchants in many applications.

Proper quench system design considerations are:

- The quenchant must be selected for the characteristics desired. This includes the quenchant speed, desired operating temperature range, and additives. Some biocide additives contain chlorine, which can combine with alkaline glycol to form chlorethyl. If nitrosamine is prohibited, end users can also specify nitrate- or non-nitrate-based polymer quenchants to avoid the formation of nitrosamine. Because the smell of the quenchant can be obnoxious, venting of the quench tank is needed in cases where there is considerable vaporization.
- The quench system must be sized for both the volume of quenchant and the heat extraction needed. A source of line water, with given flow and input temperature, is needed for cooling the quenchant in the quench system heat exchanger. Sizing of the system is a function of the line water and quenchant flow, the temperature differentials of the line cooling water and the quenchant, and the size and heat removal capacity of the heat exchanger. Cooling towers, chillers, and city or well water systems can be used for the line water. (Chillers are expensive to operate.) Due to cost, in most locations cooling towers are used when substantial line cooling water is needed. Cooling towers have the limitation of not being able to cool the recirculated water below high outside temperatures and high humidity. As with the quenchant system, closed systems involving chillers or cooling towers may need to have biocides added, and they may need filtration to remove debris.
- The quench system must be able to provide the amount of quenchant needed at the coil. Design of quenchant outlets in coils, quench rings, and quench pads is discussed in Appendix 4, “Quench System Design,” in this book. The system design must be capable of maintaining the quenchant within the specified control range, as the range should normally not exceed 7 °C (10 °F). A typical control range is from 35 to 38 °C (90 to 100 °F). If the control range is higher than room tempera-

ture, heaters may be needed to bring the tank up to temperature. An over-temperature alarm or cutoff to prevent high-temperature operation is always recommended.

- The quench tank and piping must not react with the quenchant. Polymers are very hard on painted tanks. In addition, and to prevent galvanic corrosion, the piping should not be made of dissimilar materials. A tank capacity of three to four times the quench flow per minute is recommended.
- The quench system piping, solenoids, and manifold must be designed so that full volume of quenchant is supplied to the quenching position on command. Care must be taken so that the quenchant itself does not drain out of the quench ring. Ideally, when a quench solenoid opens, full flow must occur with no necessity to fill the quench ring itself before the quenchant can emerge.
- Suitable filtration must be put in the quench tank. The quenchant must be kept free of foreign material and scale. Y-type strainers are widely used because of the low cost. These are basket-type strainers, and they serve to trap only the larger particles. Cartridge- and bag-type filtration units can be specified to filter from 5 up to 100 mm. A differential pressure switch across the inlet and outlet sides will detect a clogged condition. If the filters are placed in a bypass configuration (similar to the oil filter in a car), separate flow is run through the cartridge continuously. In this case a flow switch can be used to indicate the flow. A wide variety of controls and systems are available to help “foolproof” these systems. When quench flow is being monitored as one of the process variables, the usual requirement is for monitoring the pressure at the pump outlet or manifold and for monitoring the quenchant flow into the quench ring. Continuous automatic, indexing media-style filters work well if manual replacement of filter media is a problem. These are sometimes called dragout-style filters because the filter paper is dragged across a perforated plate. When the pressure differential is too high, the filter is automatically indexed into a hopper. These filters are good for applications that are high in scale and chips because their large volume and automatic indexing assures good filtration. Positive pressure is used for filtration, and a “clean tank” is required on applications that cannot afford to have the quenchant flow disrupted for cleaning the filter.

Load Matching

It is necessary to match or tune the load impedance with the output impedance of the power supply in order to obtain the delivery of full power from the power supply to the workpiece. Electrically, impedance is the vector sum of the resistance, current, and voltage. Coil voltage is normally used for matching reference. Figure 3.21 shows illustrations of volt-

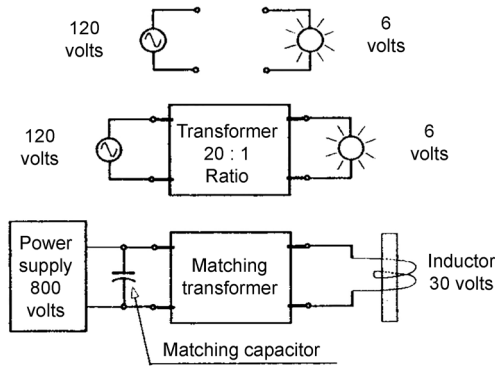


Fig. 3.21 Load matching/impedance matching. Source: Ref 3

age matching, starting with matching a 6 V light bulb to a 120 V household circuit to an 80 V output from an induction power supply. If the induction coil shown has a 30 V requirement and the power supply has an 800 V output, then a transformer can be used to match the coil to the power supply. The electrical components used for load matching, such as transformers and capacitors, are located in the heat station. Heat stations may be either built into the power supply or furnished separately. This book does not discuss older technology power supplies used for heat treating, such as motor-generator sets and spark gap units. More information for these power supplies can be obtained in Ref 4 and 14.

When purchasing equipment or when designing for new applications, it is important to know the capability of the particular power supply in order to match to the proposed induction coil. Because of the significant differences in power supplies, the specifications of the individual power supply must be reviewed. There is a wide variety in the capabilities of different power supplies, as furnished by different manufacturers, to produce full power over a wide range of different loads. While this may not be significant in the case of the power supply and process that are designed for one specific part, it may be significant where different types of parts need to be induction hardened and versatility is needed. The ability to produce full output is dictated by the type of power supply and heat station, the transmission line to the induction coil, and the induction coil and load. Power losses occur in the transmission of power from the terminals of the heat station to the induction coil. Coil lead lengths, lead design, and transmission line design must be considered in equipment layout.

Tuning of Solid-State Inverters

A discussion of power supplies is not complete without mention of the most dreaded work to many: tuning. However, tuning is not hard to do if the proper sequence is performed. Solid-state inverters are easier to tune

than the older motor-generator sets because of the faster limit and control circuits in solid-state units. Before tuning, set up a log for recording the meter results during tuning, so that any changes in meter readings can be used to decide what to change for the next step. Optimal tuning depends upon the specific circuit requirements for a given inverter. It requires a combination of using transformer taps to tune for voltage while using capacitor taps to tune for a frequency range. Tuning on the floor involves trial and error, although some of the power supplies currently sold indicate recommendations in the meter displays.

The object of tuning is to match the voltage and current to achieve maximum power at the desired frequency. The tuning used for previous setups for the same type of application, where there is a coil change, is normally good. When the tuning is for a new application and data are available for similar applications, the previously used tuning is a good starting point. However, it can be wise to start with less than full power for the first test. The meters are used to monitor the output for tuning purposes. Ideally the instruments should indicate power, voltage, current, and frequency. A power supply operating in a limit condition is not considered properly tuned. The power supply is not harmed by operation, but the output may not be consistent because operation in a limit condition can cause the heat produced in the work part to vary slightly. Anytime there is a possibility there could be danger to the inverter or coil on a coil change or new application, conservative procedures during tuning are recommended. Always refer to the manufacturer's instructions for tuning. A sample tuning instruction is:

1. Use the tuning for a similar part if available. Start with a low amount of capacitance tapped in and the power control set at a low level. Turn on the heat and observe the meters. If none of the meters is running into a limit, slowly increase the power in steps until an observation can be made at which the meter reads higher than the others (i.e., is the voltage running high while the current is low?). Turn the power off and record the readings. If the power is sufficient to overheat the workpiece, cool it before reheating. Care must be taken not to overheat the workpiece during these tests.
2. If the voltage is high, take out some turns on the transformer ratio. For example, go from a ratio of 16 to 1 to a ratio of 12 to 1. If the current is high, add turns to the transformer ratio. If the frequency is high, add capacitance. On power supplies with a large frequency range, match voltage and current through the transformer before attempting to force the frequency change through the addition or subtraction of capacitance.
3. After changing taps, turn the power down again and repeat the low-power step, gradually increasing the power until either full power or a limit is reached. Again, record the readings.

Repeat these processes until the voltage and current readings are similar and the frequency is within the desired range.

Theoretical tuning can be done by using a load frequency analyzer, as applied to a given work coil, to determine the resonant frequency of the induction heater without heating the workpiece. In this case, the transformer matching ratio is either calculated or estimated by rule of thumb. After obtaining the resonant frequency, capacitance is added or subtracted from the circuit to match the tuned frequency of the work station to the rated frequency of the power source.

Radio frequency, oscillator tube power supplies may use tap changes in the tank coil or a means of adjustment of the grid current output for tuning purposes. The power supplies require that the grid current be kept between specified range at full power. These power supplies tend to have wider bands of impedance matching than do solid-state power supplies. If tuning is needed during setup, it is generally very easy to do. Stepless power control is usually accomplished through the use of SCR power controllers that vary the output power through variation of the input line voltage. However, depending on the particular circuit used, the operator can use changes in grid current or taps on the tank coil circuit to change the output power.

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CHAPTER 4

Induction Coils

THE COIL, also known as inductor or induction work coil, is basically a transformer primary that induces high-frequency output of an induction power supply into a workpiece, which is effectively the transformer secondary. Coil design is application specific, so the type of coil to be used should be selected before designing fixturing. The type of process used, such as whether the workpieces are heated single shot or scanned, influences coil selection. Coil design and construction principals are discussed in Appendix 2, “Scan Hardening,” in this book. This Chapter deals with general theory, types, and applications of coils.

Classifications of Coils by Electromagnetic Field

The two coil classifications relate to the direction of eddy currents produced by the coil in the workpiece: longitudinal flux and transverse flux.

Longitudinal flux (reverse current flow) induction coils are by far the most widely used type of coil, with solenoid types of coils most commonly used. Longitudinal flux coils should not be confused with channel coils, which are orientated in the longitudinal direction of a workpiece. The workpiece is surrounded or enveloped, with the turns on opposite sides so that induced current flows around the workpiece, as shown in Fig. 4.1. When the air gap between the coil and workpiece is reasonable for the frequency and load conditions involved, heating can be quite efficient because the flux lines tend to be confined. Figure 4.2 illustrates the confinement of the flux field between two conductors with opposing current. Solenoid coils come in many different forms, shapes, and adaptations, with the circular or enveloping coil the simplest form. As previously discussed in Chapter 2, “Theory of Heating by Induction,” in this book, solenoid types of coils require the workpiece thickness to be at least four times the reference depth for efficient operation. The coils can be oriented so that long workpieces are either encircled by a solenoid coil, with the cur-

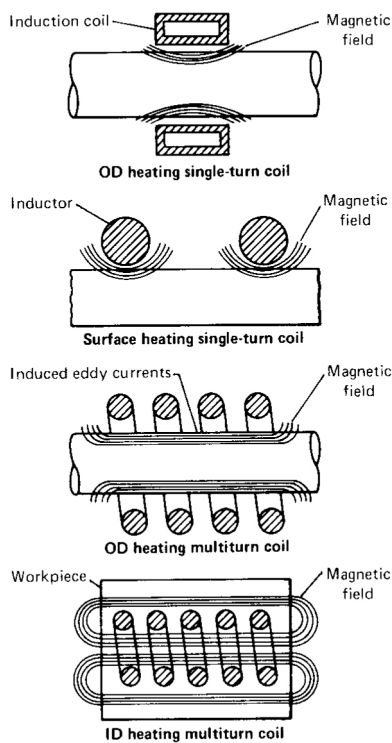


Fig. 4.1 Magnetic fields and induced current produced. ID: inside diameter; OD: outside diameter. Source: Ref 1

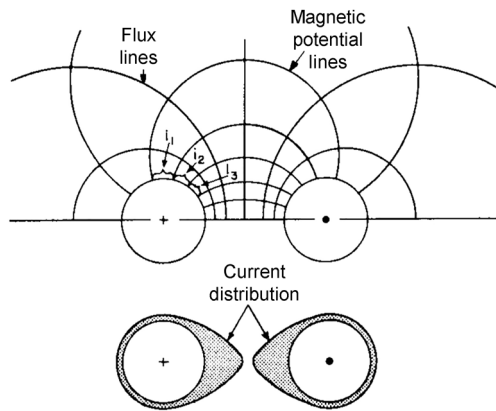


Fig. 4.2 Flux plot of two parallel conductors carrying current in opposite directions. Source: Ref 2

rent flowing around the circumference of the part, or, in the case of channel coils, oriented perpendicular to the workpiece so that the current flows along the longitudinal direction. Solenoid coils have many subclassifications, which are discussed in this Chapter.

Transverse flux (sometimes called proximity) coils are not as widely used. They are used to heat work pieces where the cross-section thickness is less than four times the reference depth. Figure 4.3 shows an example of a transverse coil. The workpiece is essentially placed between turns of the induction coil, in which the current is flowing in the same direction. By doing this, there is no current cancellation effect and thin pieces can be heated efficiently.

Coil Design

Factors that influence coil design and selection include the dimensions and shape of the workpiece, number of workpieces to be heated, hardness pattern desired, production process to be used (such as single shot or scanning), frequency and power input, how the workpiece is to be quenched, and coil-life considerations. Table 4.1 shows the efficiency of different style coils that do not have flux concentrators applied. In some circumstances, depending on the process used, different types of coils can be used. The same part may be scanned on a lower-power system that is single-shot hardened on a high-power system. Many coils are built based on knowledge of coil design principles and on experience, while other coils need development programs in order to produce conforming work-

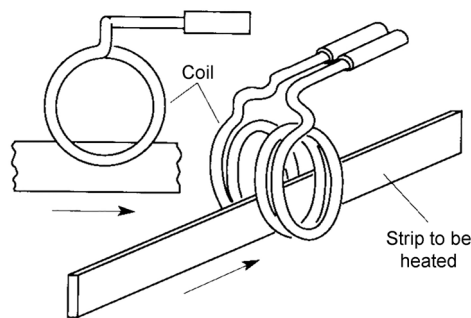


Fig. 4.3 Example of transverse flux coil, with arrows showing direction of feed of the strip. Source: Ref 3

Table 4.1 Efficiency of different types of coils

Type of coil	Coupling efficiency at frequency of:			
	10 Hz		450 kHz	
	Magnetic steel	Other metals	Magnetic steel	Other metals
Helical around workpiece	0.75	0.50	0.80	0.60
Pancake	0.35	0.25	0.50	0.30
Hairpin	0.45	0.30	0.60	0.40
One turn around workpiece	0.60	0.40	0.70	0.50
Channel	0.65	0.45	0.70	0.50
Internal	0.40	0.20	0.50	0.25

Source: Ref 4

pieces. Computer simulation for coil modeling is discussed in Appendix 2, “Scan Hardening,” in this book.

Coil design considerations for efficiency and use:

- The coil should be coupled as close to the workpiece as possible. Table 4.2 shows recommended coil-coupling distances. The coil coupling requirements may depend on other factors, such as how the part is to be loaded or positioned in the coil, and the shape of the area to be heated.
- The leads into the coils must be designed for the best efficiency.
- The coils must be designed so that they are rigid and do not move when power is applied.
- The coils must be designed so that they do not overheat during use and do not develop stress fractures during use. As a rule, lower-frequency coils generally operate with higher-power inputs, so they require more rigidity and better cooling.
- All coils have significant power losses and need good cooling. Separate high-pressure cooling systems may be necessary for high-power applications.
- The coil must be designed so that the magnetic flux lines produce eddy currents that heat the desired areas. The highest concentration of flux lines is inside the coil, producing the maximum heating rate there. Coils can be made with different contours and shapes or can be made with more than one turn. Radio frequency (RF) coils need closer coupling and concentricity around workpieces than do lower frequencies. Flux concentrators are used to increase coil efficiency or to concentrate the flux to specific areas in the workpiece.

Magnetic flux concentrators or intensifiers are used very effectively to increase the efficiency of some coils. In other cases, flux concentrators are necessary to produce the pattern required in the workpiece. Figure 4.4(a) shows the current distribution in a conductor. When a workpiece is placed under the conductor, the current is redistributed (Fig. 4.4b). Because of proximity effect, a significant part of the conductor’s current flows near the surface of the conductor that faces the workpiece. The remainder of the current is concentrated on the sides of the conductor, with

Table 4.2 Recommended coil coupling distances

Frequency (kHz)	Coupling to workpiece	
	in.	mm
1–3	0.12–0.24	3–6
10–25	0.08–0.15	2–3.8
50–450	0.06–0.09	1.5–2.25

Source: Ref 5

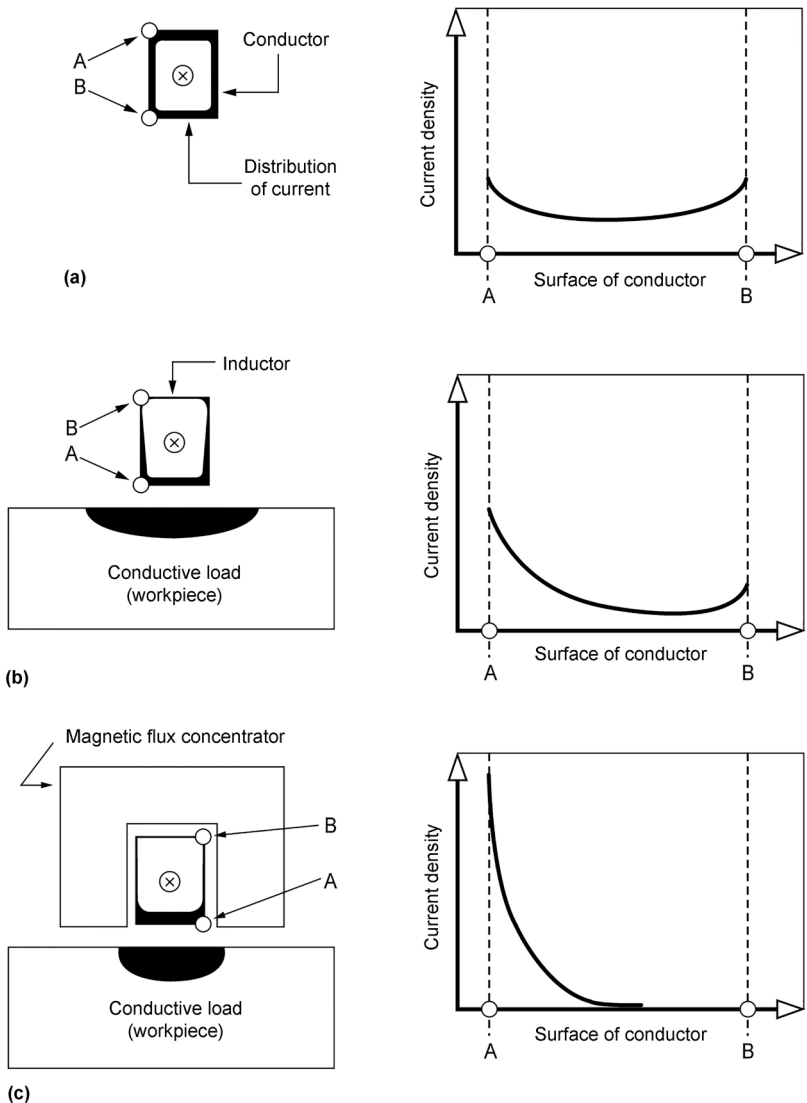


Fig. 4.4 Current distribution in straight conductor. Source: Ref 6

a current induced in a general area in the workpiece close to the conductor. After a flux concentrator is placed around this conductor (Fig. 4.4c), practically all of the conductor's current is concentrated on the surface facing the workpiece. A significantly larger current is induced in the workpiece directly next to the conductor. Some applications such as bore heating show substantial increase in efficiency. Correctly applied, the benefits are:

- Reduction of operating power levels required to obtain the desired heating of workpieces

- Improvement of process efficiency and decrease in the amount of energy used
- Increasing the productivity rate of the heat-treating system
- Heat pattern improvement because of the control of the distribution of heat in the workpiece
- Protection of the workpiece or fixture components against unintended heating by stray flux
- Improvement in coil load matching to the power supply

The use of flux concentrators usually provides several of the previously mentioned benefits. Table 4.3 shows the efficiency of internal coils with and without concentrators. When the power supply is tuned for the same coil voltage, the bare coil has a coil efficiency of 68%, compared to an efficiency of 87% of the coil with flux concentrators. Figure 4.5 shows increases in case depth that can be with a 28 mm (1.13 in.) inside diameter (ID) by 6.25 mm (0.25 in.) wide coil heating a 1 in. round bar with a 380 kHz and a 8.3 kWh power supply at the energy levels shown. At the same energy level the coils with concentrators had increased case depths over the coils without concentrators. The technical and economical significance of each effect depends on the specific conditions of the particu-

Table 4.3 Effect of flux intensifiers on inside-diameter coil efficiency

	Coil voltage, V	Workpiece power, kW	Coil losses, kW	Coil efficiency, %	Power factor, kVA	Apparent power
Power coil	88.6	68.0	10.4	87	0.22	354
Bare coil	30.6	8.4	4.0	68	0.10	122
Bare coil(a)	87.0	68.0	32.4	68	0.10	992

Note: (a) Bare coil with the same workpiece power as the power coil. Source: Ref 7

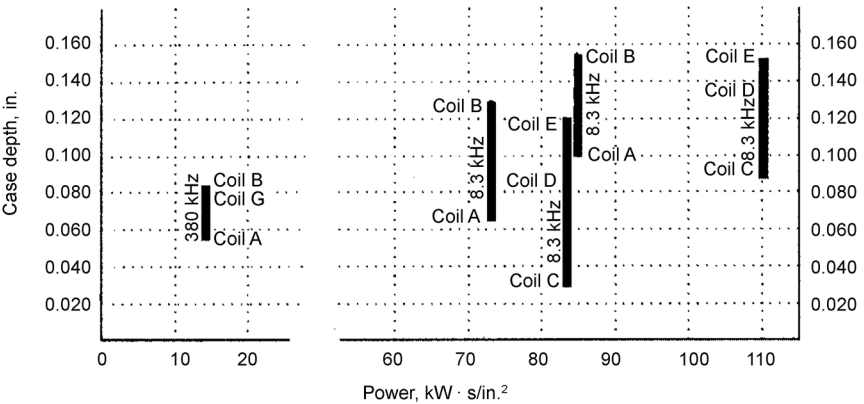


Fig. 4.5 Increase in case depth with concentrators in inside-diameter coils. Coils A, C: without concentrator; coils B, D, E, F: with concentrator. Source: Ref 8

lar application. Using computer simulation and full-scale experimentation, the Centre for Induction Technology conducted detailed studies on the influence of flux concentrators (Ref 9). The results show that the proper application of flux concentrators is always beneficial in an induction heating process.

In many cases the requirements needed for magnetic materials used for flux concentrators for coils are severe. The materials must work in a very wide range of frequencies and must possess high magnetic permeability and saturation flux densities. When magnetic materials saturate, they lose their ability to concentrate magnetic flux. Stable mechanical properties with resistance to the elevated temperatures caused by hysteresis and heat transfer from the workpiece are important. Because of the nature of heat treating processes, the material must withstand an attack of hot water, quenchants, or active products. The circumstances that should be considered in the selection of concentrator material include:

- The frequency selected
- The magnetic flux field intensity
- The geometry of the coil and part to be heated
- The aggressive nature of the applied quenchant
- The temperature to which the part will be heated
- How the material is to be installed
- The brittleness of the selected concentrator material
- How the concentrator material is to be formed
- How the concentrator is to be cooled if necessary

Whereas early materials were used only with frequencies below 10 to 15 kHz, flux concentrator materials are being made and developed on a regular basis for use with higher frequencies. Both hard materials, which retain some magnetic field on power turn-off, and soft materials, which retain no magnetic fields on power turn-off, are used. The soft materials are machinable and formable. Three groups of magnetic materials are used for intensifiers: laminations, ferrite, and magnetodielectric materials. The formability and machinability can be important in the decision of which type of intensifier to use.

Laminations are manufactured from grain-oriented nickel-steel and cold-rolled and hot-rolled silicon-steel alloys. Mineral and organic coatings provide the insulation of the laminations. The lamination thickness used for induction coils ranges from 0.1 to 1.0 mm (0.004 to 0.040 in.), with the thin laminates being used for the highest frequencies. The main frequency use of laminations application is below 10 kHz, although at times they are used at frequencies up to 30 kHz with reduced flux density and intensive cooling. Laminations have the highest possible permeability and saturation flux density, so at frequencies below 10 kHz they are the most efficient. One of the main advantages of laminates is that they can

withstand higher temperatures than other materials. Laminations need to be tightly stacked together. They have overheating problems when they are stacked in sharp radii such as the ends of single-shot coils.

Ferrites have high permeability only in weak flux fields with low losses. Ferrites work in a wide range of frequencies when properly selected and applied. The drawbacks that restrict application as a good material for flux controllers include low saturation flux density and Curie temperature, high sensitivity to thermal and mechanical shock, and the inability to be machined except by grinding and cutting with diamond tools.

Magnetodielectric (electrolytic and carbonyl iron-based) materials are made from soft magnetic particles and dielectric materials that serve as a binder and electric insulator of the particles. Different grades of the materials are currently used for most applications. The materials are produced by compacting different magnetic powders and binders, followed by thermal treatment. The compacted materials are machinable with standard tools, and they have excellent thermal, chemical, magnetic, and mechanical properties.

Moldable materials made from insulated micro iron particles suspended in a polymer base have been developed. These materials are sold in a soft, flexible form. A catalyst is added before forming on a coil, and the coil and composite are baked in a low-temperature oven.

Flux concentrators are often soldered, fastened, or glued to the induction coil. Degradation, loosening, chipping, or arcing can affect the amount of energy induced into a part. The suppliers of the flux concentrators provide instructions regarding use. The disadvantage of flux intensifiers is that substantial cost can be added to the coil. In addition, coil life is reduced. Bare coils without concentrators have long life expectancies and usually fail because of a workpiece hitting the coil or an arc. Coils with concentrators have shorter life cycles, with some producing as few as 10,000 parts before failure. When coils with concentrators fail, the failures may be very gradual over a period of time, or they can be catastrophic. Dedicated production lines using coils with concentrators often have a number of coils on hand so that coils can be removed and rebuilt when necessary. Many induction processes use flux concentrators only when the overall benefits exceed the disadvantages. Bare coils work quite well in many applications.

Coil Characteristics versus Frequency

Coils in the lower frequencies of 1 to 10 kHz can have mechanical vibration that requires rigid restraint and mounting techniques, particularly in the 1 kHz region. Close space multiturn coils will spread apart when power is applied unless they are restrained. These lower frequencies are used for deeper case hardening and for larger-diameter through-heating applications. The coils used for heat treating in the 3 to 25 kHz frequency

range tend to be low-turn coils, although coils used for continuous heating of bars and tubes can use multiturn coils such as those used in the forging industry. Machined coils are more likely to be used with the low frequencies, while coils made from tubing are more likely to be used with high frequencies. Figure 4.6 shows the current produced in three areas in relationship to coil position at the end of a bar for high frequency (Fig. 4.6a) and for low frequency (Fig. 4.6b). High frequency has higher edge effect, in which current concentrates more at the end of a bar that produces deeper heating. This can affect coil selection and location because higher frequency coil design and placement can be more limited than lower frequencies.

Coil characterization is the technique of adjusting the coil design so that the induced eddy currents produce a uniform heating pattern in the workpiece. The number of turns, the spacing between turns and the workpiece, the power density, and the frequency determine the heating effect and final austenitized pattern. The shaded area in Fig. 4.7 shows the current produced by placement of a coil at various locations. The position and overlap of the coil affect the heating effect at the edges. Coils are designed with overlap and then positioned so that the heating at the edge produces

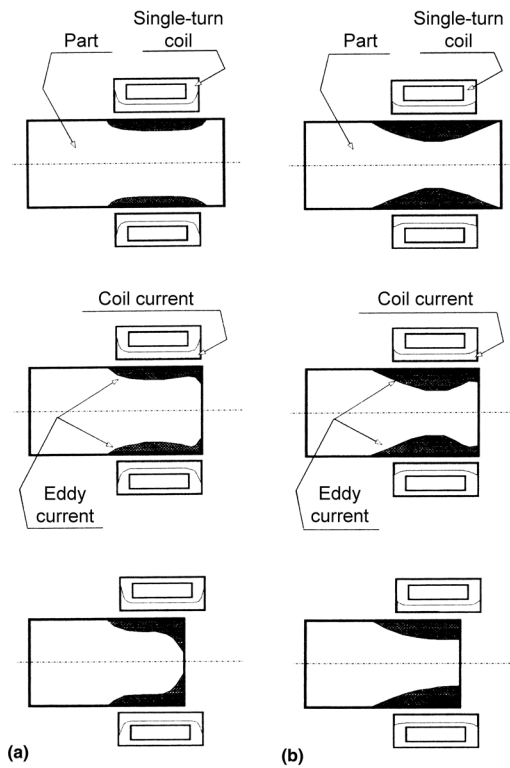


Fig. 4.6 Electromagnetic end effect for (a) high and (b) low frequency. Source: Ref 10

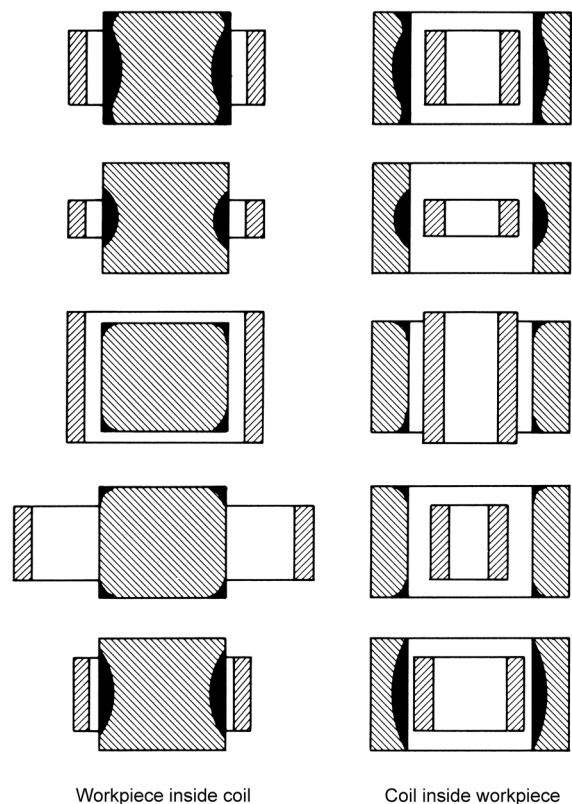


Fig. 4.7 Effect of relative proportions of workpiece and coil. Source: Ref 11

the same depth of pattern as produced in the center. The lower the frequency, the more overlap is required because of the edge-heating effect. Standard close-coupled coils with flux concentrators operating at 10 kHz require approximately 3 mm (0.120 in.) overlap, while only 1.5 mm (0.060 in.) overlap is required for 450 kHz. The closer the coupling between the turns and the workpiece, the more intense the magnetic flux field. Intense flux fields produce more intense eddy currents and, consequently, faster heating. Machined coils can have different machined ID dimensions in the same coil that affect the energy input into the workpiece, similar to the effect that can be accomplished by winding multiturn coils with the turns having different IDs. Table 4.3 shows the efficiency of different types of induction coils. Note that the efficiency increases when two turns are used to heat the same width instead of one turn.

Coil Leads and Dead Spots. The magnetic flux field in a coil is not entirely symmetrical because the points at which the coil leads are attached distort the flux field. The effect is that the flux field is off-center. This effect is more significant with the RFs and with single-turn coils. Rapid rotation of the parts helps to produce uniform heating of the workpiece. In short cycles, higher speed rotations of up to 10 times in the cycle

are necessary, while for time cycles of 4 s or longer, a minimum rotation speed of at least 2 rps is recommended.

Coils for Static Heating. Static heating is heating the workpiece in place with a timed heat cycle. The coil shape depends on the geometry of the workpiece or part being heated. Round parts such as fine-pitch gears use encircling coils. Other parts, such as the tips of tools or specific-wear areas, use odd-shaped coil designs, such as those shown in Fig. 4.8, which are individualized to the type of area to be heated.

Coils for Single-Shot Heating. Single-shot and static heating are often used to define the same type of heat cycle. Coils for high-intensity, single-shot heating are designed to locate horizontally on the workpiece so that current is induced in the longitudinal direction. Round workpieces are rotated at high speed so that a case can be produced around the diameter. Coils for single-shot heating generally require characterization and usually have flux concentrators to help improve the coil efficiency. The size limitation of a workpiece for single-shot hardening is limited by the amount of power available in the power supply. Single shot is used on large workpieces when high production rates justify the equipment cost. Coils for single-shot hardening have coil designs that permit either quenching in place through the coil or movement of the part out of the coil for quenching.

Coils for Scanning or Progressive Hardening. Scanning requires the workpiece to delay in position at the start of the heating cycle and then to

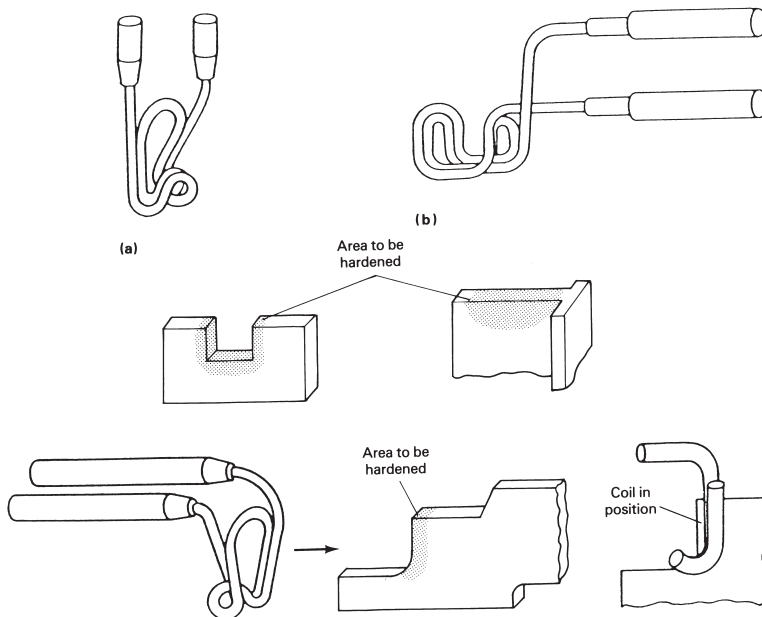


Fig. 4.8 Localized heating coils, (a) and (b) are examples of coils. Source: Ref 3

start moving through the coil, progressively heating and quenching. The major difference in coil design between static heating and scanning occurs when quenching is integrated into the coil, with separate chambers built into the coil for the quenchant and for the cooling water for the coil. Depending on the application, both encircling and longitudinal coils are used. The most common scanners are fixtures designed for vertical scanning. Figure 4.9 shows two coils connected in series heating workpieces on a dual-spindle, vertical scanner.

Basic Types of Coils

Solenoid encircling coils are the most efficient coils used with typical applications such as heating the outsides of workpieces. The number of turns depends on the load-matching characteristics of the power supply (as discussed in Chapter 3, “Induction Heat Treating Systems,” in this book), the heat treating pattern required, and the process requirements. Workpieces with high production requirements tend to use much larger coils that require more power to produce the required power density. Multiturn coils tend to be used more with the RFs, while one- and two-turn coils tend to be used with the lower frequencies. Solenoid coils are designed with and without integral quenches and are also used for scanning. Examples of these coils are shown in:

- *Figure 4.10:* Single-turn coil with rigid construction, as commonly used for medium and low frequency, that was designed for annealing a welded tube. The same coil design could be used for heating any



Fig. 4.9 Dual-spindle scanner with coils. Source: Ref 2

round shape, gear, or sprocket of appropriate width. Quenching is done externally to the coil.

- *Figure 4.11:* Single-turn coil with rigid construction and integral quench. This coil would be used for static heating, with quenching in the coil following austenitizing.
- *Figure 4.12:* Single-turn RF coil with stud providing rigidity and aluminum oxide protective coating. This particular coil was designed for induction brazing. The same coil could be used for a number of differ-

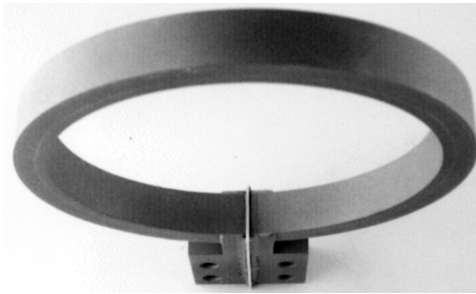


Fig. 4.10 Single-turn inductor. Source: Ref 12



Fig. 4.11 Single-turn outside-diameter single-shot inductor. Source: Ref 12

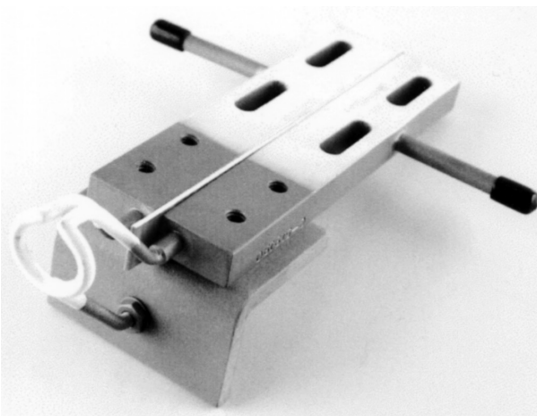


Fig. 4.12 Single-turn radio frequency tubing coil. Source: Ref 12

ent types of applications, such as austenitizing the end face of a workpiece.

- *Figure 4.13:* Single-turn machined coil with integral quench designed for rigidity. The ID of a workpiece is austenitized, followed by jogging into position from the integral quench.
- *Figure 4.14:* Single-turn machined coil with integral quench for scanning designed for close impingement of quenchant after scanning. The machined taper at the quench holes provides the desired angle of quenchant impingement. This particular coil was designed for axle shaft hardening.
- *Figure 4.15:* Single-turn machined coil with integral quench for scanning designed with quench holes in the bottom. This coil was designed for splined shaft hardening. The method of attaching the outer plate at

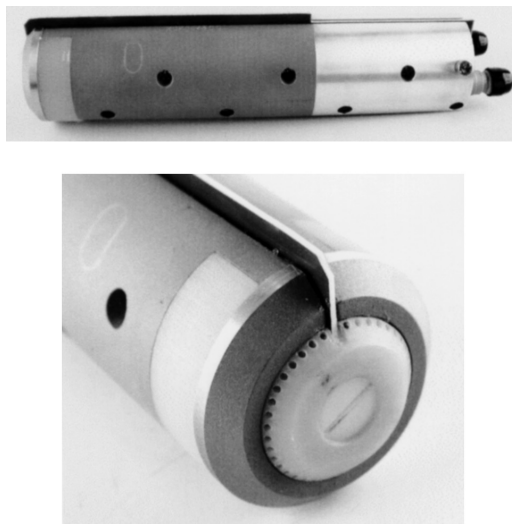


Fig. 4.13 Single-turn machined coil. Source: Ref 12



Fig. 4.14 Single-turn scanning coil. Source: Ref 12

the quenchant outlet permits easy access for cleaning the quenching orifices.

- *Figure 4.16:* Single-turn tube coil shaped for single-shot, contour hardening. This coil was designed for thin-wall tube hardening and tempering.
- *Figure 4.17:* Single-turn machined coil with integral quench for static heating and hardening gear teeth on a shaft.
- *Figure 4.18:* Single-turn machined coil that is contoured to the shape of the workpiece for scan hardening a gear rack.
- *Figure 4.19:* Single-turn machined coil with integral quench that is contoured to shape for static hardening a cam.

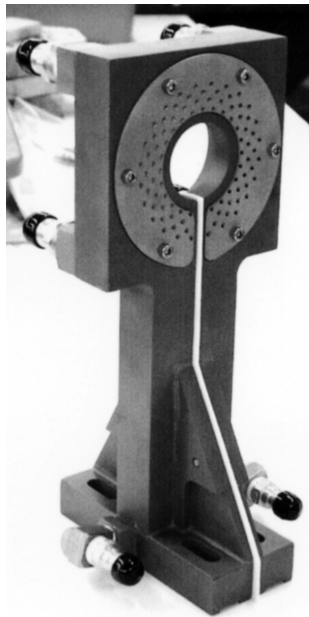


Fig. 4.15 Single-turn scanning coil with quench. Source: Ref 12

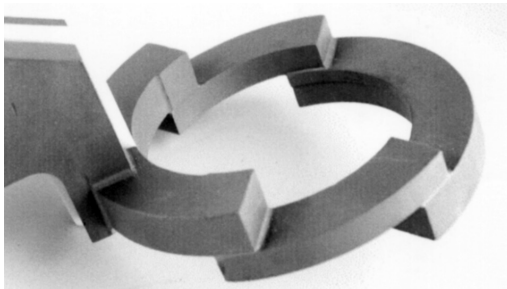


Fig. 4.16 Single-turn, single-shot-contoured coil. Source: Ref 12

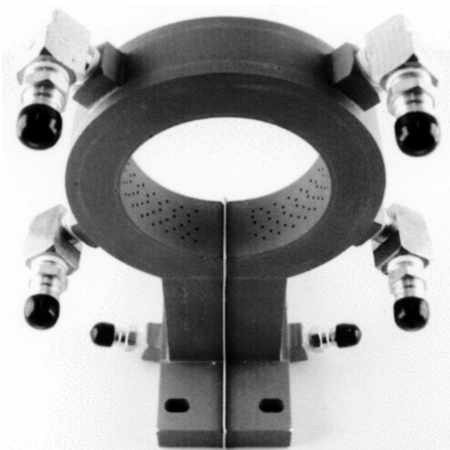


Fig. 4.17 Single-turn machined static heating coil. Source: Ref 12

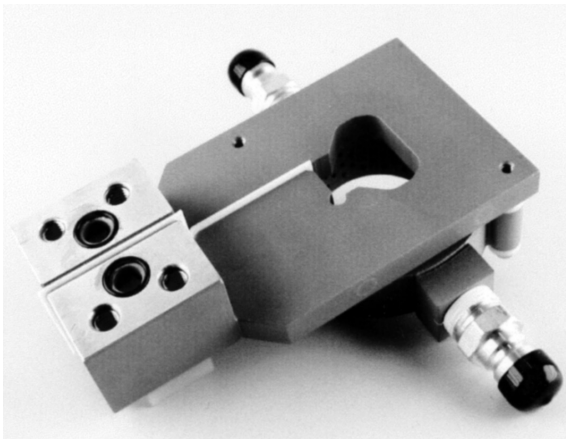


Fig. 4.18 Single-turn machined contour-to-part coil. Source: Ref 12

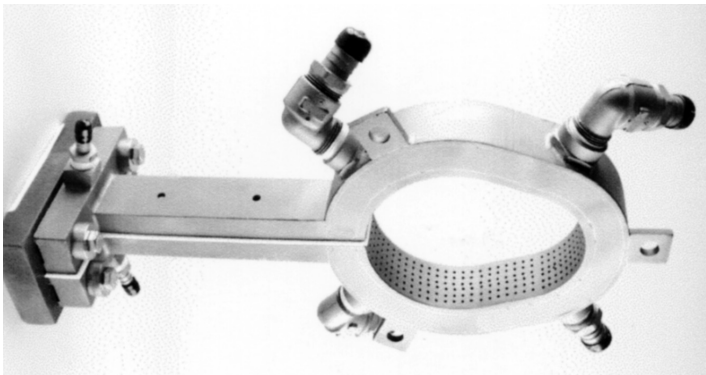


Fig. 4.19 Single-turn machined contour coil, integral quench. Source: Ref 12

- *Figure 4.20:* Two-turn tubing coils such as this are commonly used for RF scan heating of a tube.
- *Figure 4.21:* Two-turn series coil with quench for scanning to produce deep case hardening of a shaft.
- *Figure 4.22:* Low-turn shaped coil from tubing with rigid mounting for tempering a wheel spindle.
- *Figure 4.23:* Multiturn shaped coil from tubing coated with plastisol for dielectric compound for RF heating of nuclear fuel.
- *Figure 4.24:* Multiturn coil with rectangular tubing for through heating prior to forging. The same coil can be used for through heating for hardening with quenching external to the coil.
- *Figure 4.25:* Multiturn coil for RF, with direct tank connection (high voltage) for preheating above a fluidized bed.

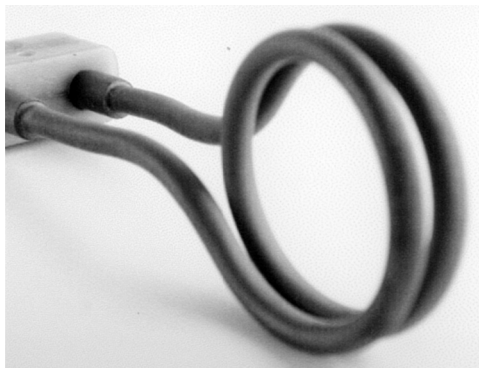


Fig. 4.20 Two-turn tubing coil. Source: Ref 12

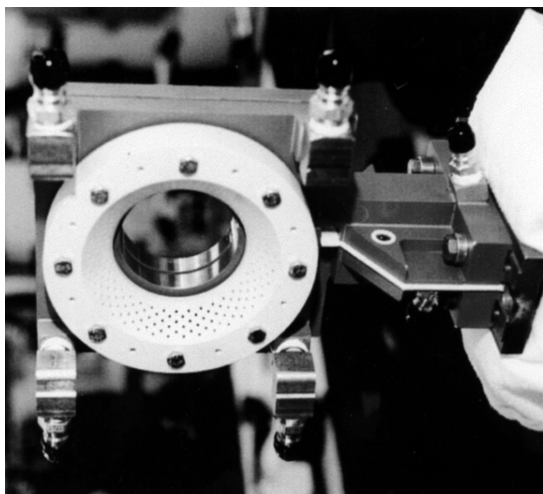


Fig. 4.21 Two-turn series coil with quench. Source: Ref 12

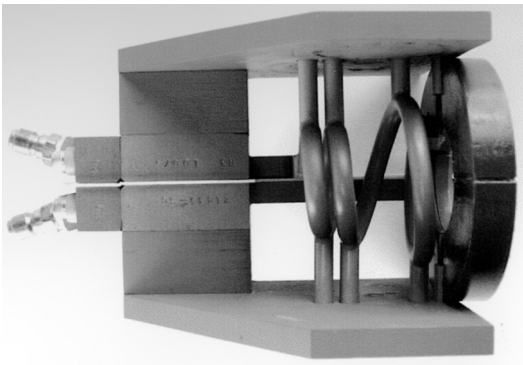


Fig. 4.22 Multiturn tube-shaped coil with concentrator. Source: Ref 12



Fig. 4.23 Multiturn shaped coil. Source: Ref 12

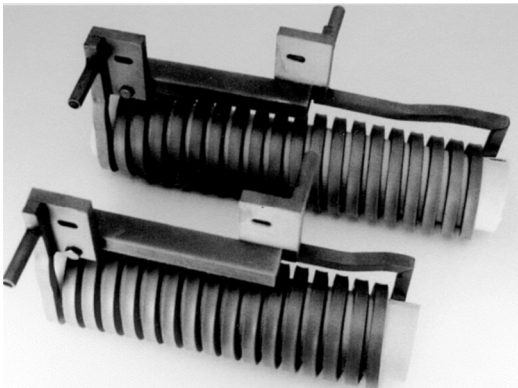


Fig. 4.24 Multiturn solenoid coil. Source: Ref 12

- *Figure 4.26:* Multiturn rectangular tube coil with flux concentrators for hardening a brake pin.

Channel or Hairpin Coil. These coils are in effect solenoid coils, flattened and elongated. Most channel coils are single-turn coils. Workpieces can be oriented both perpendicular and longitudinal to the coil, and with proper fixturing can harden a number of workpieces at one time. When the ends are cupped, this type of coil can be used to heat parts that are trayed or conveyorized. When a workpiece is inserted longitudinally, round parts are rotated and heated single shot. Workpieces that have edges, such as cutters, can be heated by this coil design. Examples of these coils are shown in:

- *Figure 4.27:* Single-turn channel, curved coil with flux concentrator so that parts on a wheel can pass through. This coil was used for the continuous heat of bolt threads.

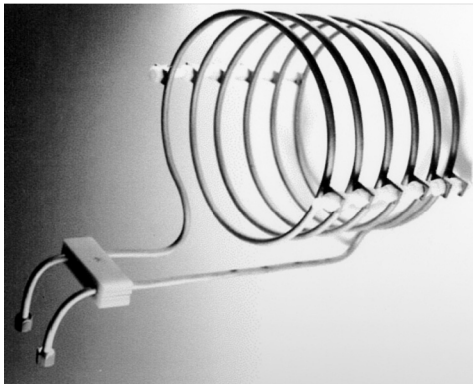


Fig. 4.25 Radio frequency multiturn coil. Source: Ref 12

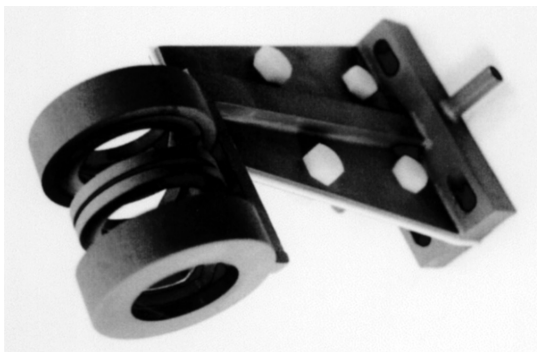


Fig. 4.26 Multiturn coil with concentrators. Source: Ref 12

- *Figure 4.28:* Multiturn channel coil designed for high-voltage terminal connection designed for tempering axle shafts.

Internal Coil. Single- or multiturn coils can be used to heat the bore of a workpiece. Internal coils tend to be less efficient, particularly at small diameters, which require the current path in the coil to come up through the lead in the center of the coil. The operating efficiency of internal coils

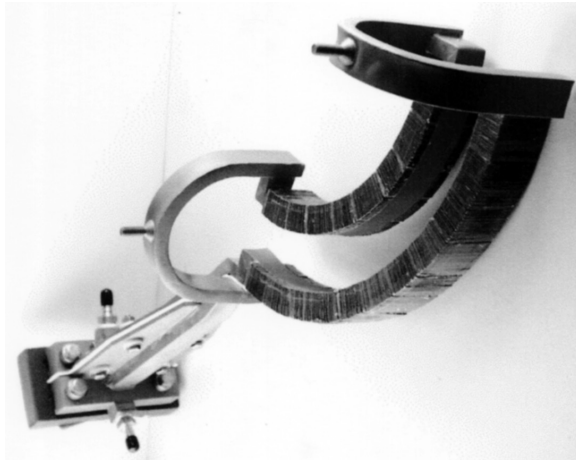


Fig. 4.27 Curved channel coil with concentrators. Source: Ref 12

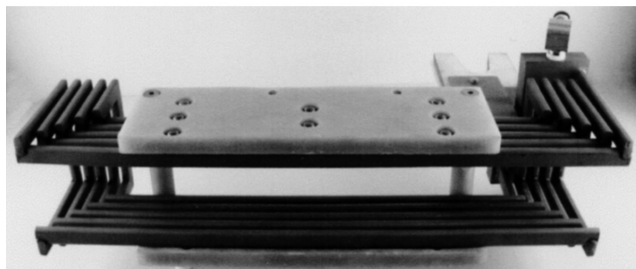
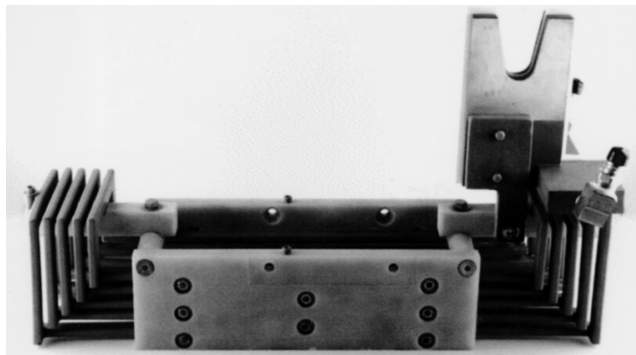


Fig. 4.28 Multiturn channel coil. Source: Ref 12

tends to be the lowest, but flux concentrators help greatly to increase the operating efficiency. It is difficult to wind a coil under 12.5 mm (0.5 in.) in overall diameter; however, special hairpin coils have been designed to fit into smaller bores. For all practical purposes, 12.5 mm (0.5 in.) is the smallest bore that can be heated with 450 kHz, while 250 mm (1 in.) is the smallest bore that can be heated with 10 kHz. Examples of these coils are shown in:

- *Figure 4.29*: Single-turn machined coil with integral quench designed for ID scanning of cylinder liners.
- *Figure 4.30*: Multiturn tube coil wound around Ferrotron flux intensifier designed for ID annealing a threaded hole after the workpiece was first carburized.
- *Figure 4.31*: Multiturn rectangular tube coil wound on rigid support designed for ID hardening of an internal spline.

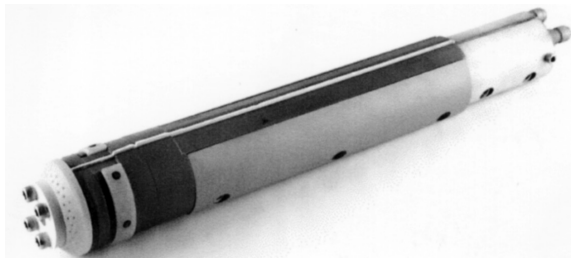


Fig. 4.29 Single-turn bore coil. Source: Ref 12



Fig. 4.30 Multiturn inside-diameter coil with concentrator. Source: Ref 12

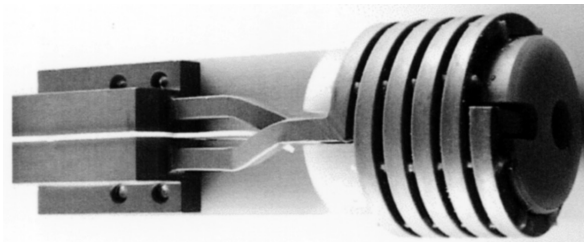


Fig. 4.31 Multiturn coil rectangular tubing. Source: Ref 12

- *Figure 4.32:* Single-turn machined coil with integral quench, rigid mounting, and with a shorting slide for tuning (trombone) designed for internal hardening of a bearing. The trombone adjusts the coil impedance to help with tuning for output power.

Pancake coils are wound in a circular manner that resembles the heating elements on a stove and are used to produce round or oblong patterns on flat surfaces. If a full circular pattern is needed, there will be a dead spot in the center of the coil unless a flux concentrator is used, or unless the workpiece is rotated off center or oscillated. Figure 4.33 shows a two-turn pancake coil designed for heating the edges of a thin plate. The pancake coils can be wound so that the concentric turns produce a complete spiral pattern, with the center lead extending upward out of the coil.

Butterfly Coil. Figure 4.34 shows an example of a butterfly coil designed for brazing a fitting to a tube. This is wound so that the outside vertical turns, which produce the heating, have their current flow in the

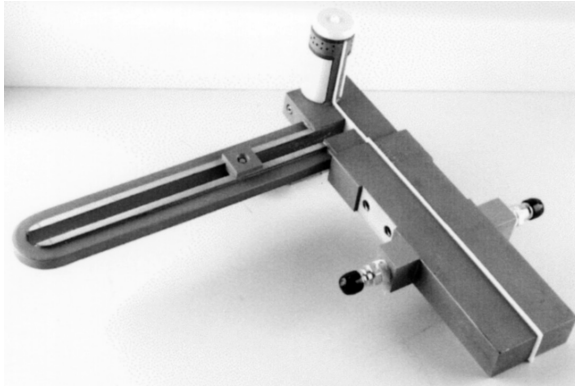


Fig. 4.32 Single-turn bore coil with trombone. Source: Ref 12

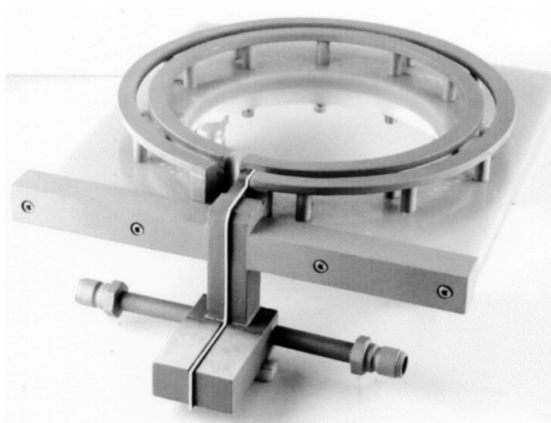


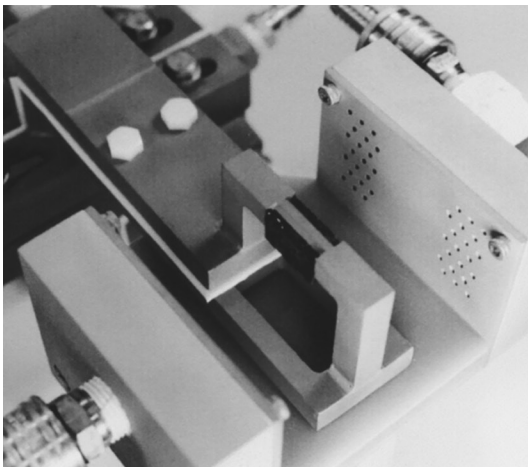
Fig. 4.33 Two-turn pancake coil. Source: Ref 12

same direction. This coil is an example of a transverse flux coil, and it is used to heat flats and thin cross sections. Because the induced current flows in the same direction, there is no dead spot as found with a pancake coil.

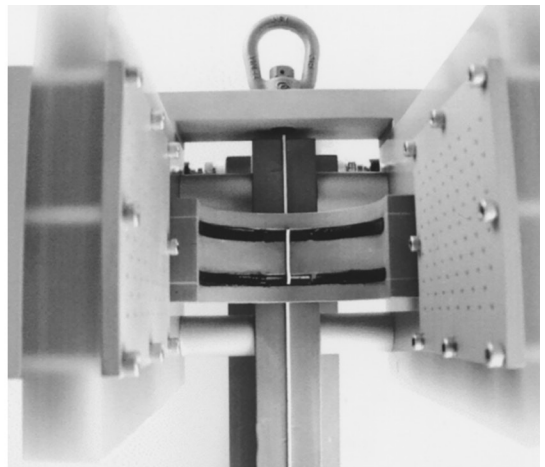
Split-Return Coil. Figure 4.35 shows two split-return coils. The coil is designed so that it has three leads. Two leads on the outside are parallel, with each lead passing half the current, and the lead in the center is in series carrying the full return current. Split-return coils are used for hardening parts such as the ends of shafts or bolts where a channel-type coil would not heat the end face. Figure 4.35(a) shows a split return with the return offset, providing a large window for the workpiece that was designed for hardening a groove. Figure 4.35(b) shows a split return with the return in the center and flux concentrator between the turns; quench pads are on the outside. This coil was designed for hardening a lobe on a camshaft.



Fig. 4.34 Butterfly coil. Source: Ref 12



(a)



(b)

Fig. 4.35 Split-return coil. (a) Return offset. (b) Return in center, flux concentrator between turns, quench pads on the outside. Source: Ref 12

Reverse-Turn Coil. Figure 4.36 shows two coil designs that use the same coil to heat two different areas of the same workpiece. In Fig. 4.36(b), the design shows the coil wound so that the current travels in both sets of turns in the same direction. The design in Fig. 4.36(c) shows the upper turns with the current traveling in the opposite direction to the lower turns. The flux density between the two groups of turns increases as the spacing decreases, producing less heat between the two groups. When static heating cycles, this effect can be used to keep shoulders of parts from overheating where there are changes in diameter between the two areas. Figure 4.37 shows an example of a split return with opposing loops. A single-turn loop is at the top of the coil, with three turns of the opposing loop down inside the coil. The coil quenches through the flux concentrator.

Special Coils. Virtually any of the above coil configurations can be wound into special shapes to heat specific areas of parts. Figure 4.38 shows a single-shot coil oriented for longitudinal, single-shot hardening. Figure 4.39 shows an example of a coil built for single-tooth gear hardening by scanning. The coil is profiled to the pitch of the gear tooth, and it hardens one side of a tooth to the root, and back up the side of the adjacent tooth. Figure 4.40 shows a nonencircling U-shaped coil that is used for crankshaft hardening where the coil floats on a water-cooled guide as the entire crankshaft is rotated. Figure 4.41 shows a multiturn solenoid type coil used in a dual frequency heating application. Note the offset in the tubing so that the turns are parallel to the stud mounting for rigidity. Figure 4.42 shows a tray assembly of the coil and quench for a CV joint

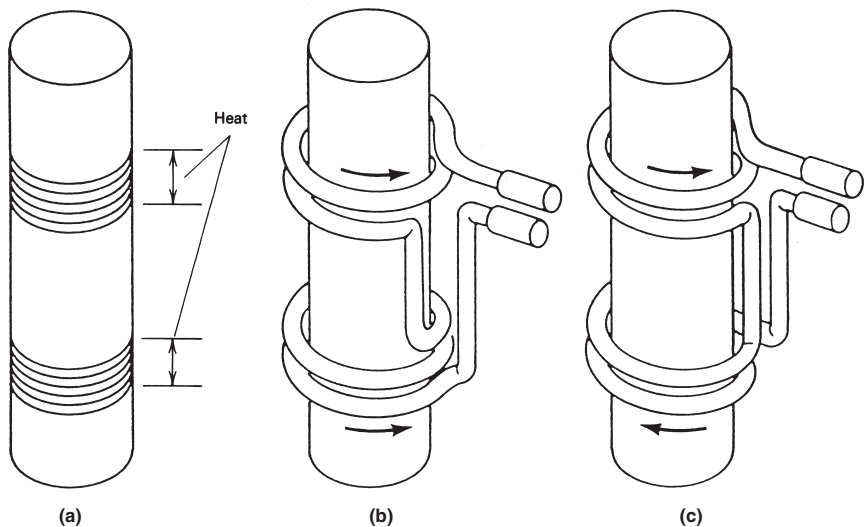


Fig. 4.36 Control of heating patterns in two different regions of a (a) workpiece by winding the turns in opposite directions. (b) Current travels in both sets of turns in same direction. (c) Upper turns with current traveling in opposite direction to lower turns. Source: Ref 3

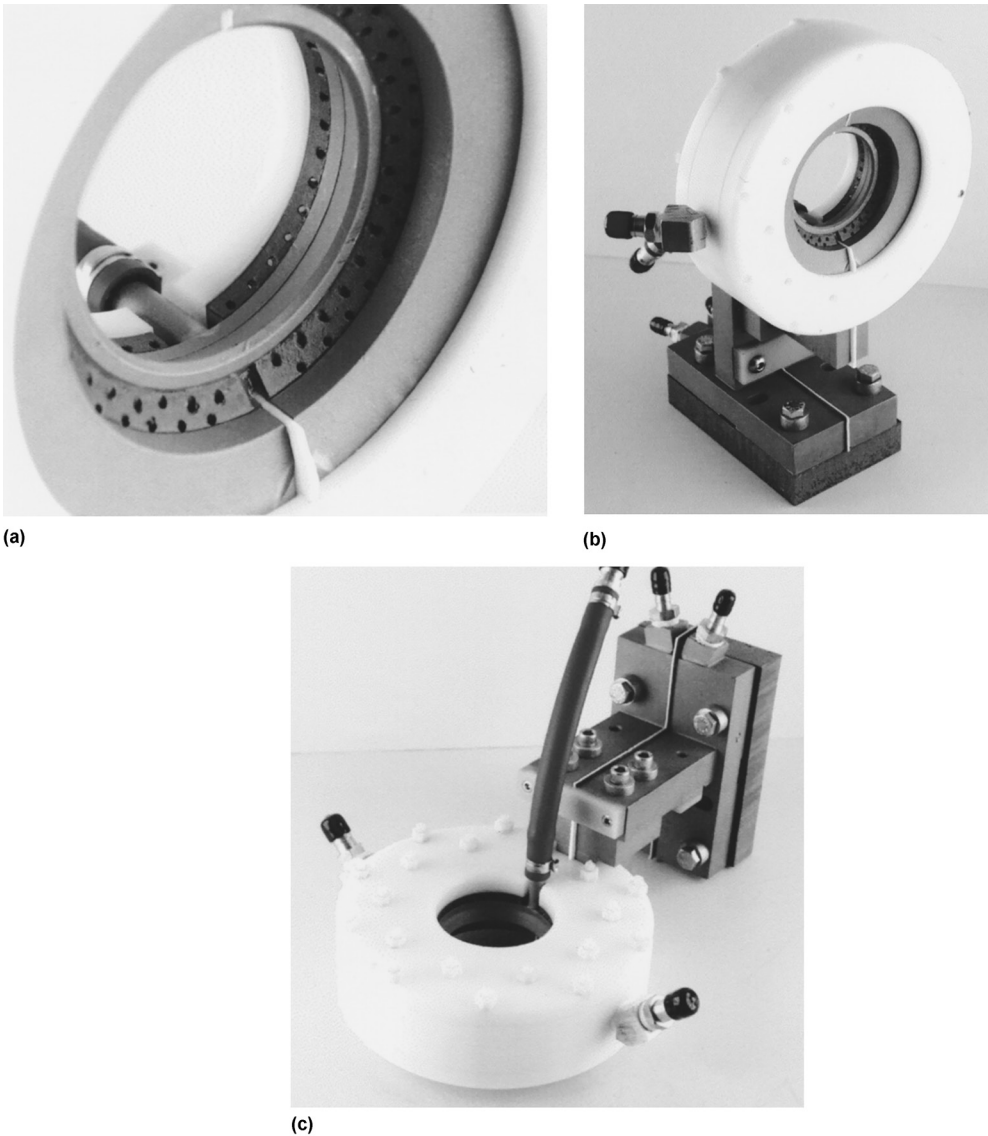


Fig. 4.37 Two-turn coil with opposing leads. Source: Ref 12

in which the tray fastens directly onto the output transformer to provide a complete, simple tooling change. Figure 4.43 shows a helical gear coil, which is a right- and left-hand scanning coil set used for tooth-by-tooth hardening. There are flux concentrators between the turns, and quench impingement is provided on the adjacent sides of the tooth being heated. Figure 4.44 shows a special coil for hardening jaw teeth. The coil is designed to hold a pipe wrench jaw above the teeth to be hardened. Figure 4.45 shows a progressive scanning coil with a Ferrotron 550H intensifier quench plate that is used to block the induced current from the adjacent flanged shoulder. Figure 4.46 is a laminated-concentrator, three-turn ID

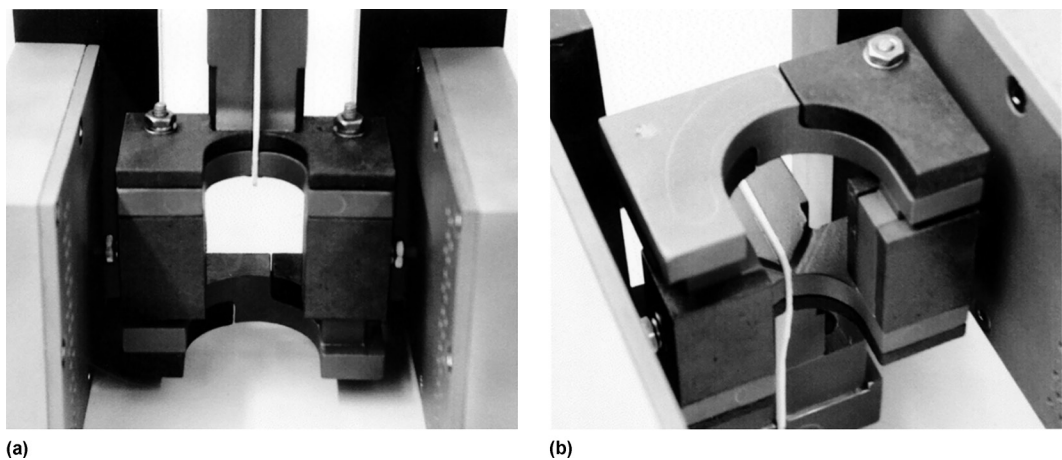


Fig. 4.38 Longitudinal heating coil, single shot with quench. Source: Ref 12

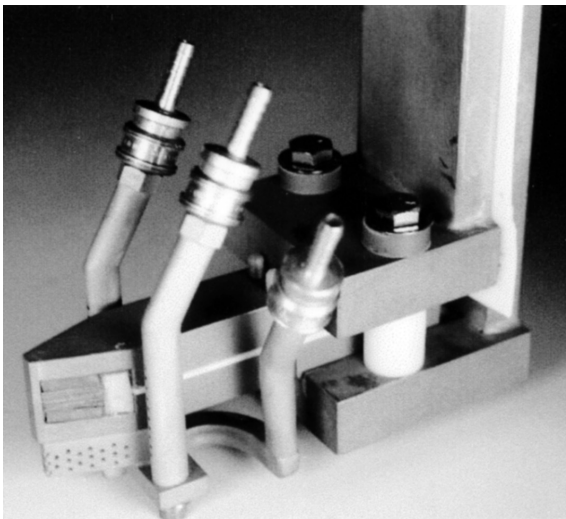


Fig. 4.39 Single-tooth gear coil. Source: Ref 12

coil designed to harden a bore. Figure 4.47 is a single-turn coil designed to heat a spherical ball. A high-power, long heating cycle was needed to provide deep hardening. Each half of the coil has its own cooling water to keep the coil from overheating. Figure 4.48 is a coil and quench pad designed for hardening loop tow hitches for a heavy-duty truck-trailer eye. Figure 4.49 is a coil for single-shot hardening the stem of a CV joint using a multi-intensifier technique. Figure 4.50 is a coil with ID cooling so that the outside diameter of a part can be case hardened without through heating and hardening. Figure 4.51 is a special bevel gear inductor used for single-shot hardening. The slots in the side force the current around the

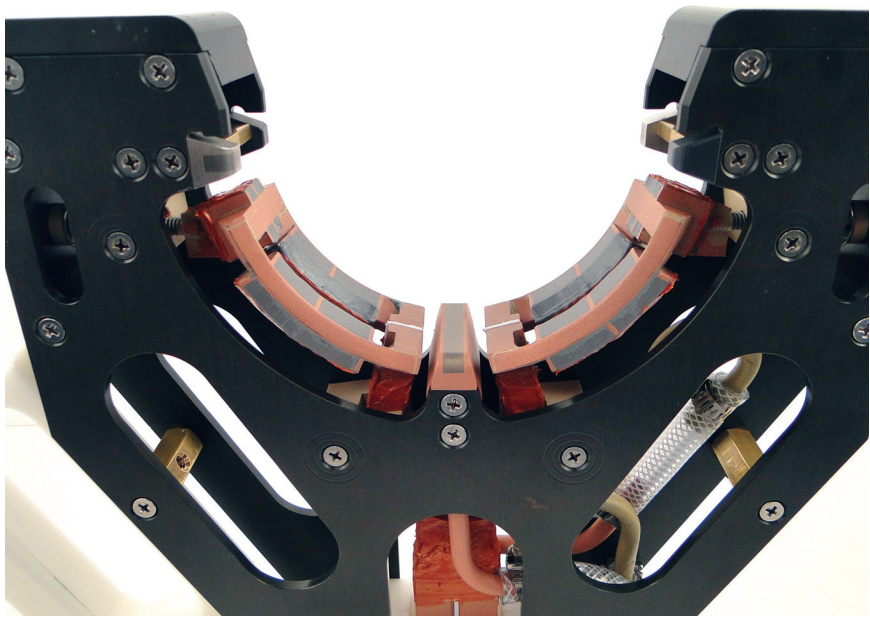


Fig. 4.40 Nonencircling U-shaped inductor coil. Courtesy of Bill Stuehr at Induction Tooling.

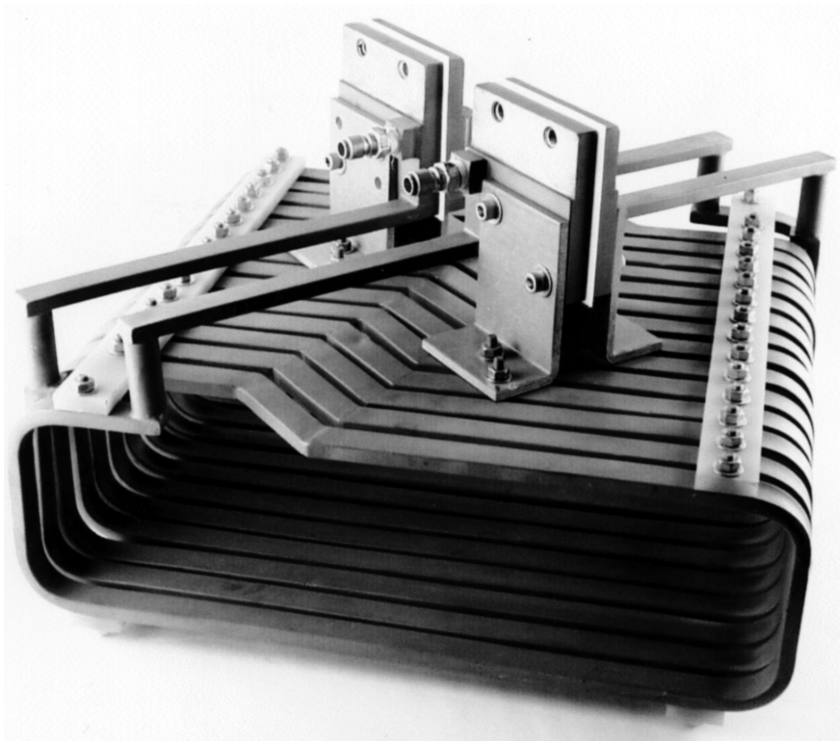


Fig. 4.41 Multiturn solenoid coil with dual frequency. Source: Ref 12

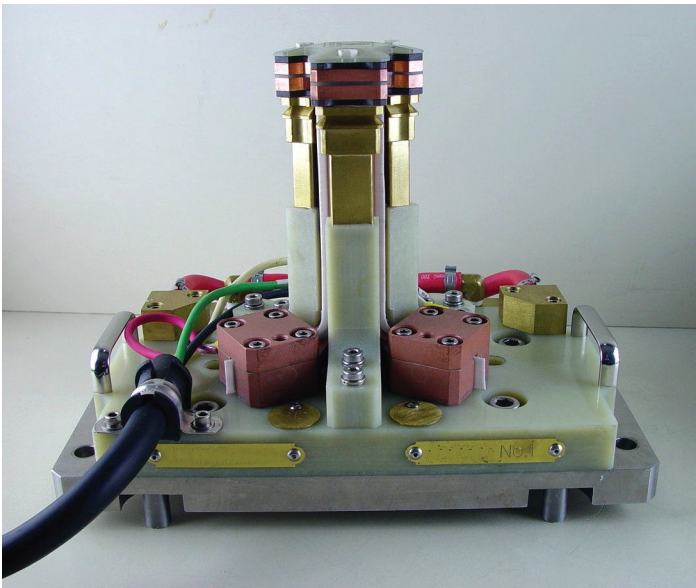


Fig. 4.42 CV tray assembly. Source Ref 12

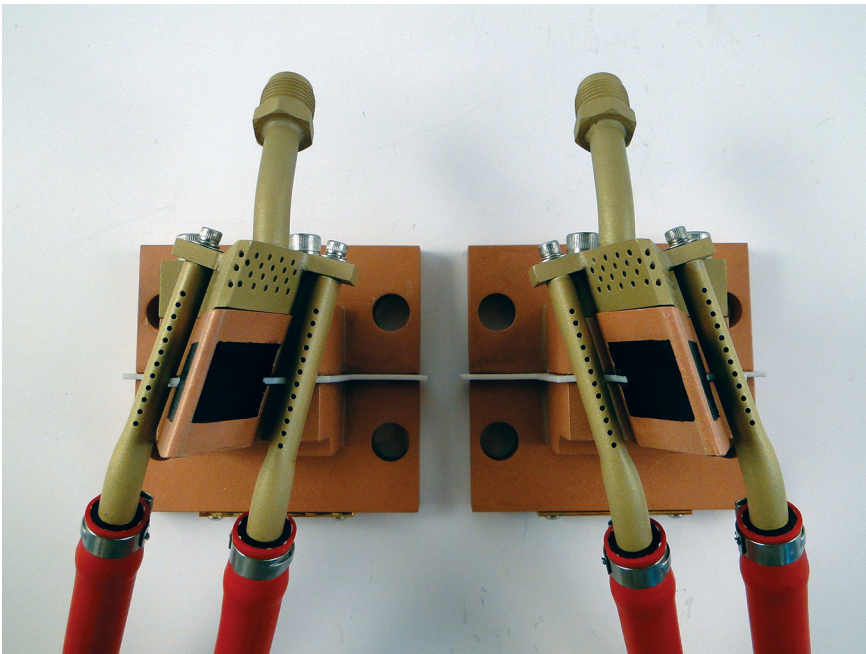


Fig. 4.43 Helical gear inductor. Source Ref 12

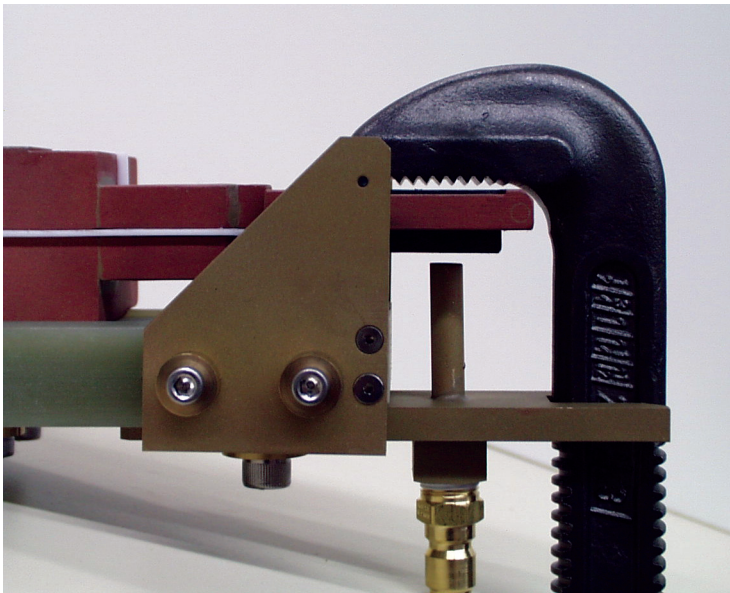


Fig. 4.44 Hook jaw special. Source Ref 12

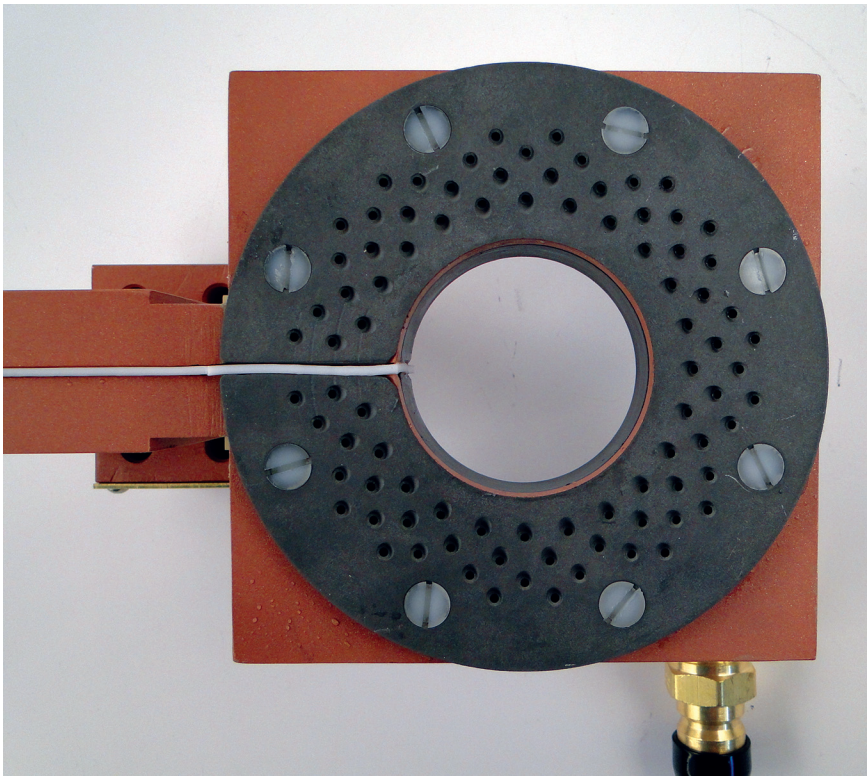


Fig. 4.45 Intensifier-blocker quench. Source Ref 12

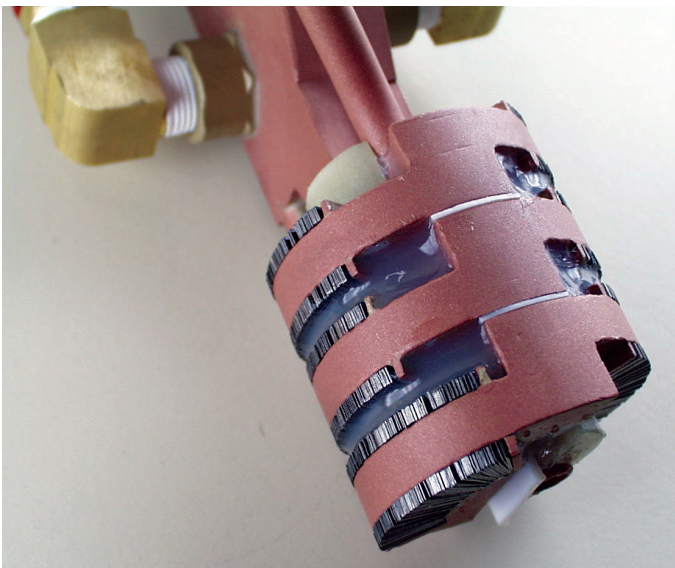


Fig. 4.46 Laminated three-turn inside diameter coil. Source Ref 12

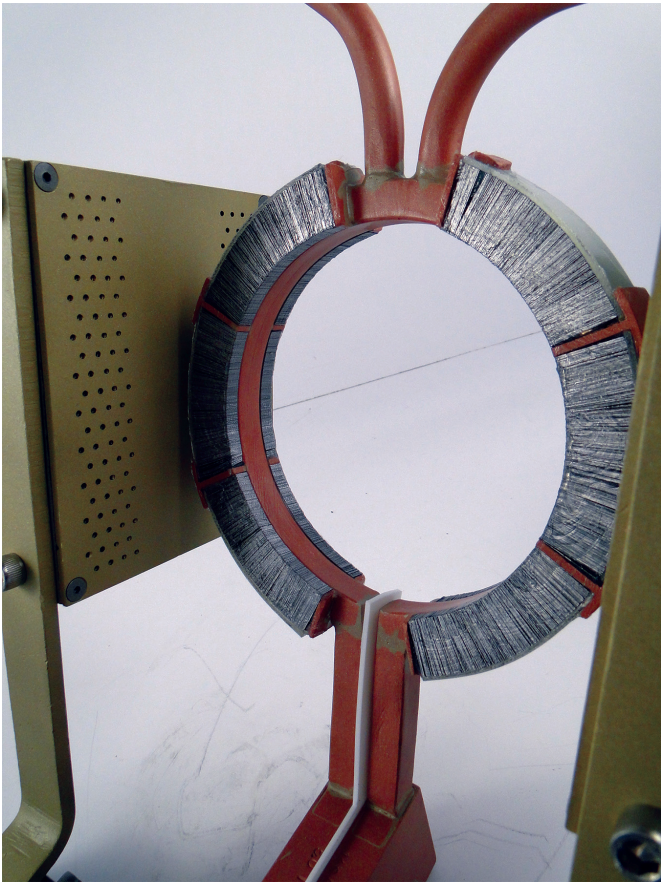


Fig. 4.47 Laminated loop. Source Ref 12

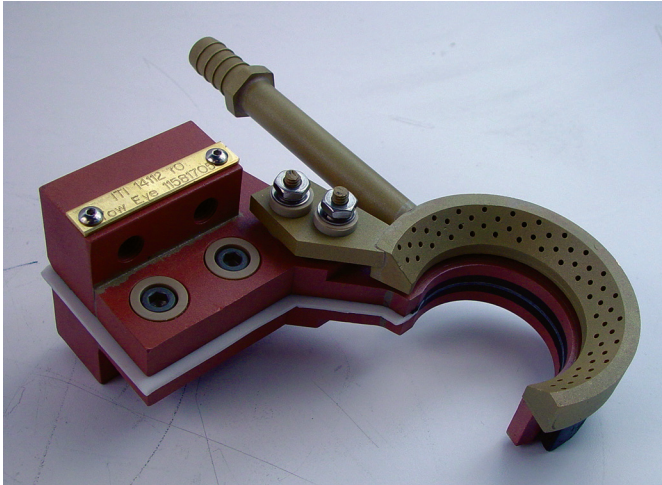


Fig. 4.48 Loop tow hitch coil. Source Ref 12

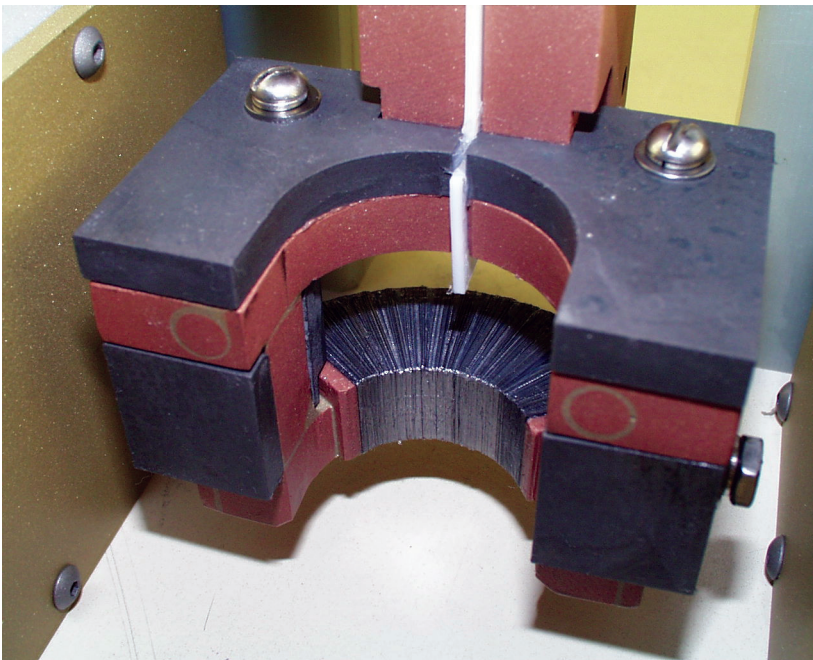


Fig. 4.49 Multi-intensifier. Source Ref 12

coil to be induced in the gear in a serpentine manner so that the gear teeth are uniformly heated.

Bus Bars for Power Transmission. The bus bars used for power transmission from the terminal of the output transformer to the connection point of the coil need to be built rigidly and have adequate cooling. Wide bus bars with close spacing between them will prevent power losses. Fig-

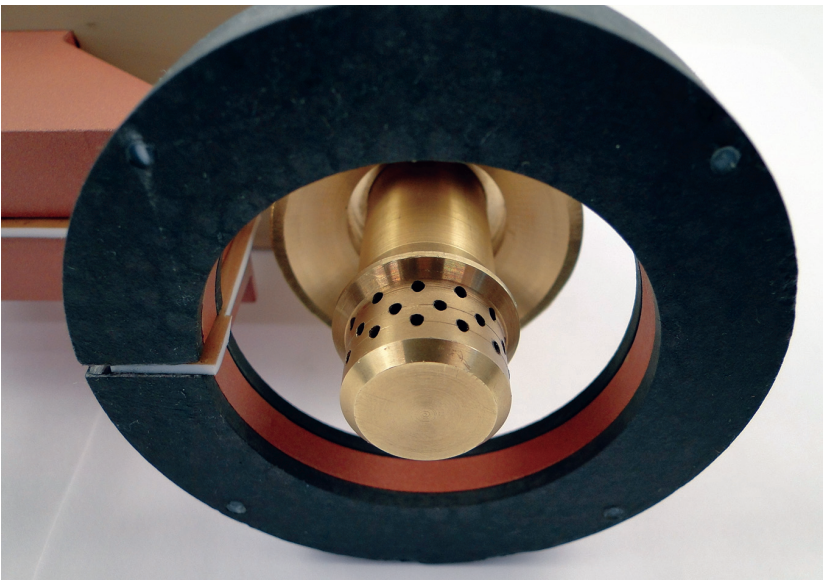


Fig. 4.50 Outside-diameter heat, inside-diameter quench. Source Ref 12

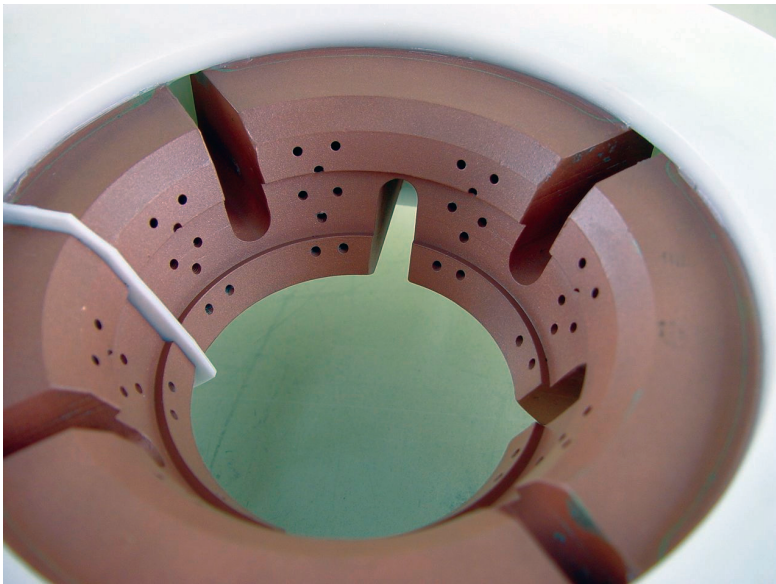


Fig. 4.51 Special bevel gear inductor. Source Ref 12

ure 4.52 provides examples of two bus bars. One is jogged so that the coil connection point is raised. This would be used in applications such as the bore hardening of cylinder lines in which the coil needs a high locating point so that it can extend down into the liner when scanning. The adjustable y-axis bus bar permits adjustment of the coil height on the y-axis.

Quick Connects. All coils need to be attached to the high-frequency output of the power supply, usually a transformer or copper bus bar connection. Historically this means of attachment has required the use of a mating connecting point so that each coil locates the same way (such as the bolt holes found in the Jackson-type transformer) and the use of cooling water interconnection points. Quick-connecting coil terminals have been developed to permit relatively simple and fast methods of connecting a coil. Figure 4.53 shows examples of several quick connects for RF; Figure 4.54 shows a quick connect for medium or low frequency.

Tempering Coils. Where the workpieces are magnetic, induction tempering is performed at temperatures below the Curie point. The heating rate is slower, and possible heating should be done from the opposite side of the area to be tempered. Coils can be coupled more loosely, and in order to provide deeper heating, lower frequencies are used than would be

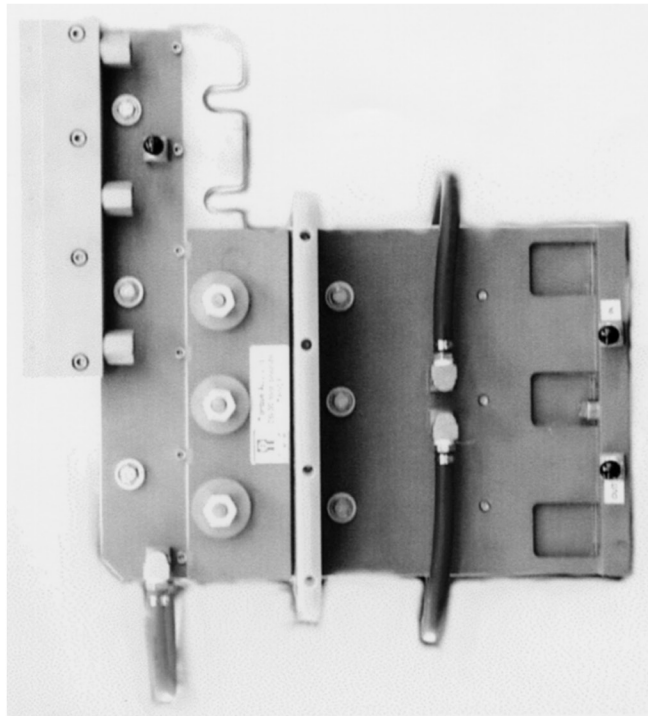


Fig. 4.52 Bus bar extensions. Source: Ref 12

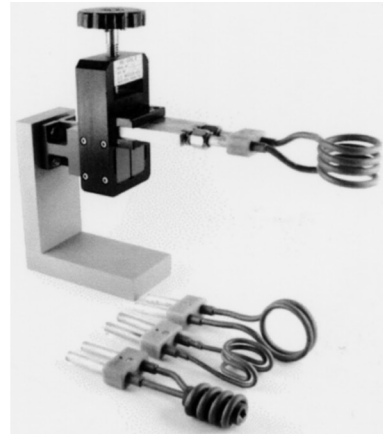
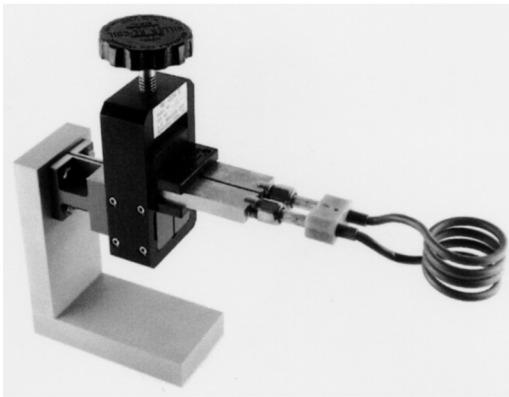


Fig. 4.53 Adapters with coils. Source: Ref 12

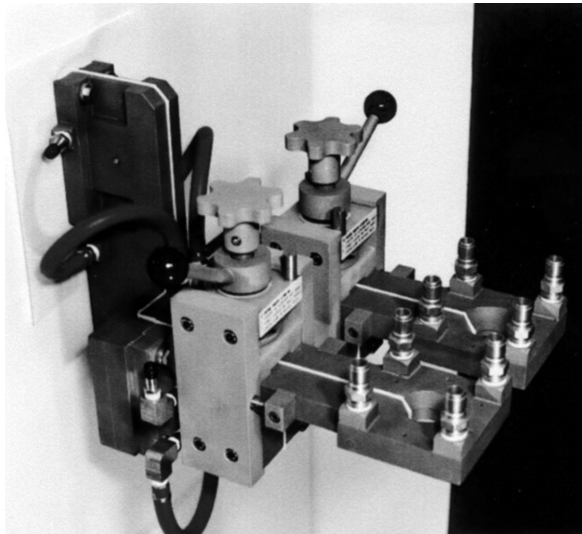


Fig. 4.54 Dual bus bar with coils. Source: Ref 12

used with austenitizing. Figure 4.55 illustrates coil returns for the induction tempering of wheel spindles and wheel hubs. The wheel spindle is tempered from the same side as the case because internal heating is too difficult. If possible, however, the wheel hub can be heated from the opposite side of the area to be tempered. Induction tempering is discussed in Chapter 7, “Tempering” in this book.

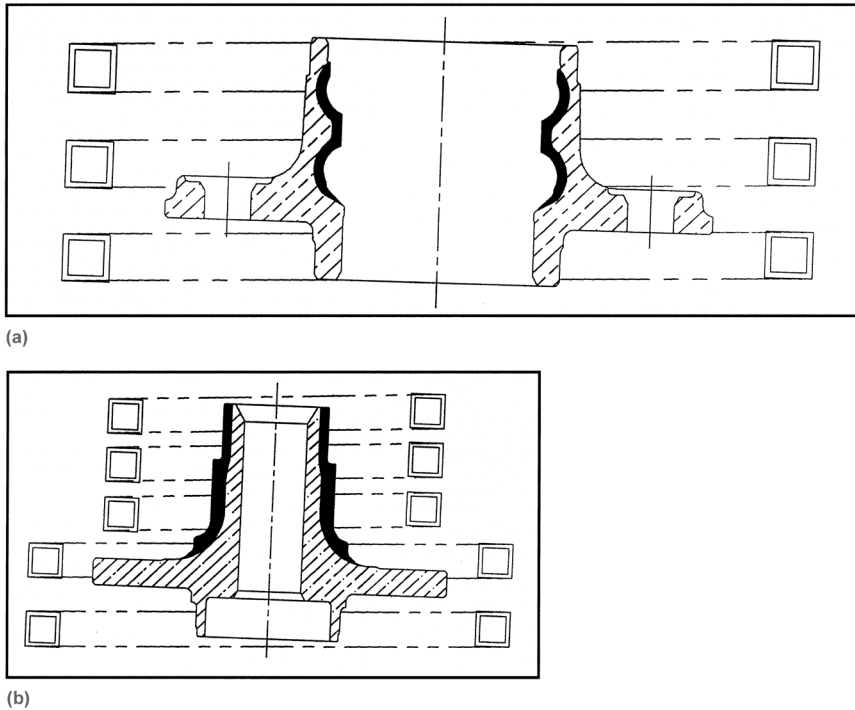


Fig. 4.55 Induction tempering of a part that has been (a) hardened on the inside surface and (b) hardened on the outside surface. Source: Ref 13

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CHAPTER 5

Heat Treating Basics

THE INTENT OF this Chapter is to provide the basic metallurgical theory necessary to understand the induction heat-treating practice. Heat treating is the treatment of metals by heating and cooling in a prescribed manner so as to obtain specific conditions and/or properties. Almost all metals and metal alloys respond to some form of heat treatment. While almost any pure metal or alloy can be softened by means of a suitable heating and cooling cycle, only certain alloys can be strengthened or hardened by heat treatment. The reason that steels account for more than 80% of total metal production is that practically all steels respond to one or more types of heat treatment. The heat treatment of a specific steel part may involve several different types of heating and cooling processes in sequence. The heating can be accomplished in a wide variety of ways, ranging from the use of heat-treating furnaces to lasers, while cooling methods can range from cooling in air to quenching with water. Regardless of the method of heating and cooling used, metallurgical processes can be described scientifically.

Iron and Steel

Fundamentally, all steels are alloys of iron and carbon with carbon as the principal ingredient. The amount of carbon present in steel has a pronounced effect on the properties of steel and on the selection of suitable heat treatments to produce desired properties. So-called plain carbon steels have low amounts of carbon while also having small but specified amounts or percentages of manganese and silicon, as well as unavoidable small but measurable and limited amounts of phosphorus and sulfur. In all carbon steels, small quantities of alloying elements or residual elements such as nickel, chromium, and molybdenum are present. These residual elements are unavoidable because they are retained from the raw materials used in melting. However, as a rule, small amounts of these elements have

little or no disadvantage to the intended use. To impart special characteristics or properties for engineering applications, one or more of several other elements may be added to alloy steel.

Standard carbon and alloy grades established by the American Iron and Steel Institute (AISI) or the Society of Automotive Engineers (SAE) have now been assigned designations in the Unified Numbering System (UNS) by ASTM (ASTM E 527) and SAE (SAE J 1086). There are a number of different systems, although the AISI numbering system is the most commonly accepted. Table 5.1 shows the types and approximate percentages of identifying elements in standard carbon and alloy steels that are induction hardened. Most numbers are four digits long, with a few, such as AISI 52100, being five digits long. The last two digits of the carbon steel indicate the carbon content. Most induction-hardened parts in the four-digit series will have a carbon content under 0.60%. Other U.S. numbers such as ASTM and SAE designations may be used, and there are various international designations with the AISI correlation. A general cross-reference to the other types of designations is listed in Ref 2.

Carbon Steel. Carbon steels, referred to as plain carbon steels, are classified in four distinct series in accordance with the AISI system. All four series can be discussed in terms of their carbon content in general response to heat treating:

- The 1000 series are plain carbon steels containing not more than 1.00% manganese maximum.
- The 1100 series are resulfurized carbon steels for machinability (sulfur is added).

Table 5.1 Classification of carbon and steel alloys

AISI designation	Description C	Composition, %				
		Mn	Cr	Mo	Ni	Va
Carbon steels						
10xx	xx	0.30–1.50	...	...	...	...
11xx	xx	1.30–1.65	...	...	...	...
15xx	xx	1.25–1.75	...	...	...	...
Alloy steels						
41xx	xx	0.40–1.00	0.80–1.10	0.15–0.25	...	...
43xx	xx	0.45–0.80	0.40–0.90	0.20–0.30	1.65–2.00	...
52100	0.98–1.10	0.25–0.45	1.30–1.60	...	...	...
6150	0.48–0.53	0.70–0.90	0.80–1.10	...	...	0.015 min.
H-steels						
4150H	0.65–1.10	0.65–1.10	0.75–1.20	0.15–0.25	...	...
Boron steels						
10Bxx	xx	0.70–1.20	...	...	...	...
15B35	0.31–0.39					
Stainless steels						
416	0.15 max	1.25 max	12.0–14.0	...	...	...
420	Over 0.15	1.00 max	12.0–14.0	...	...	...
440C	0.96–1.20	1.00 max	16.0–18.0	0.75 max	...	...
The xx in the last two digits stands for the carbon content by weight. Steel 1045 has 0.45% carbon. Source: Ref 1						

The xx in the last two digits stands for the carbon content by weight. Steel 1045 has 0.45% carbon. Source: Ref 1

- The 1200 series are resulfurized and rephosphorized carbon steels.
- The 1500 series have up to 1.65% manganese.

Plain carbon steels are divided into three groups depending upon carbon content.

Group I—Low Carbon (0.08 to 0.25% Carbon). The three principal types of heat treatment used on these low-carbon steels are (a) process treating of material to prepare it for subsequent operations, (b) treating of finished parts to improve mechanical properties, and (c) case hardening by carburizing or carbonitriding to develop a hard, wear-resistant surface. Some parts containing more than 0.18% carbon are induction hardened to improve wear and strength.

Group II—Medium Carbon (0.30 to 0.55% Carbon). Because of the higher carbon content, quenching and tempering become increasingly important when steels of this group are considered. They are the most versatile of the carbon steels because their hardenability (response to quenching) can be varied over a wide range by suitable controls. In this group of steel there is a continuous change from water-hardening to oil-hardening steels. The hardenability is very sensitive to changes in chemical composition, particularly to the content of manganese, silicon, and residual elements, as well as grain size. These steels are also very sensitive to changes in cross section.

Carbon steels may be purchased as modified steels in which small amounts of specific elements, such as manganese, are added to increase the hardenability. There is also widespread use of the resulfurized grades such as AISI 1141 and 1144, which are readily induction hardened. Some of these grades are cold drawn at room temperature or at elevated temperatures using heavier-than-normal drafts with a following stress relief and are used in place of quenched and tempered bars. The heavier drafts produce higher tensile and yield strengths. While parts made from bar stock are generally given no prior heat treatment before induction hardening, the medium-carbon steels need homogeneous microstructures for the best response to the fast austenitizing cycles. Heat treatment for the refinement of the microstructure is often desirable.

Group III—High Carbon (0.60 to 0.95% Carbon). Oil or polymer quenches are used to minimize distortion and the potential for quench cracking. As with the medium-carbon steels, prior heat treatment may be necessary to provide a microstructure that will give the best response with induction.

Alloy steels are those steels containing specified percentages of other elements in their chemical compositions. The elements most commonly alloyed with steel are nickel, chromium, molybdenum, vanadium, and tungsten. Manganese also falls into this category when it is specified in percentages generally in excess of 1%. As mentioned in Chapter 1, “History of Metallurgy and Induction Heating,” in this book, induction heating came into prominence because of its ability to use carbon steels for the

replacement of alloy steels. Alloy steels are not normally used unless they are first quenched and tempered to provide core hardness, or the hardenability is needed for deep case depths. Hardenability is discussed later in this Chapter.

H-Steels. H-steels are guaranteed by the supplier to meet established hardenability limits for specific ranges of chemical composition. An example of designation of an H-steel would be 1045 H. This is 1045 steel warranted for hardenability. When an H-steel is specified, the steel producer shows on the shipping papers or by some other acceptable means the hardenability characteristics of the heat of steel involved.

Boron Steel. Boron is a potent and economical alloying element that markedly increases hardenability when added to fully deoxidized steel. The effects of boron on hardenability are unique in two respects: (a) a very small amount of boron (about 0.001%) has a powerful effect on hardenability, and (b) the effect of boron on hardenability is much less in high-carbon than in low-carbon steels. Very small amounts of boron are sometimes added to the medium-carbon steels to increase their hardenability.

Stainless Steel. Stainless steels are best defined as alloy steels containing at least 10% chromium, with or without other elements. Chromium is added to increase corrosion resistance. Stainless steels are commonly divided into four groups, of which only the martensitic family is induction hardened. The martensitic grades have AISI classifications composed of three numbers or three numbers and a letter. The numbers are all in the 400 series, but not all 400 series grade designations are martensitic. (Some are ferritic.) The grades most commonly induction hardened are 416, 420, 440C, and 440F. Figure 5.1 shows the family relationships for standard martensitic stainless steels.

Cast Iron. The term *cast iron*, like the term *steel*, identifies a large family of ferrous alloys. Cast irons primarily are alloys of iron that contain more than 2% carbon and from 1 to 3% silicon. Cast irons have more carbon present than can be retained in solution in solid metal. The carbon is found both combined with iron as iron carbide (cementite) and as graphite (one of the crystalline forms of carbon). Wide variations in properties can be achieved by varying the balance between carbon and silicon, by alloying with various metallic or nonmetallic elements, and by varying melting, casting, and heat-treating practices. Table 5.2 shows the general classification of cast irons by tensile strength according to ASTM class numbers. There are six basic types of cast irons and several varieties of each type. The types of iron are classified by how excess carbon occurs in the microstructures. Figure 5.2 shows the types of cast iron in relationship to the carbon and silicon content. The three types of cast iron most commonly induction hardened are malleable iron, gray iron, and ductile iron. Gray and ductile irons are sometimes confused. Identification is important in heat treating because of the typically lower silicon content and wider alloy content in the higher strength grades of gray iron.

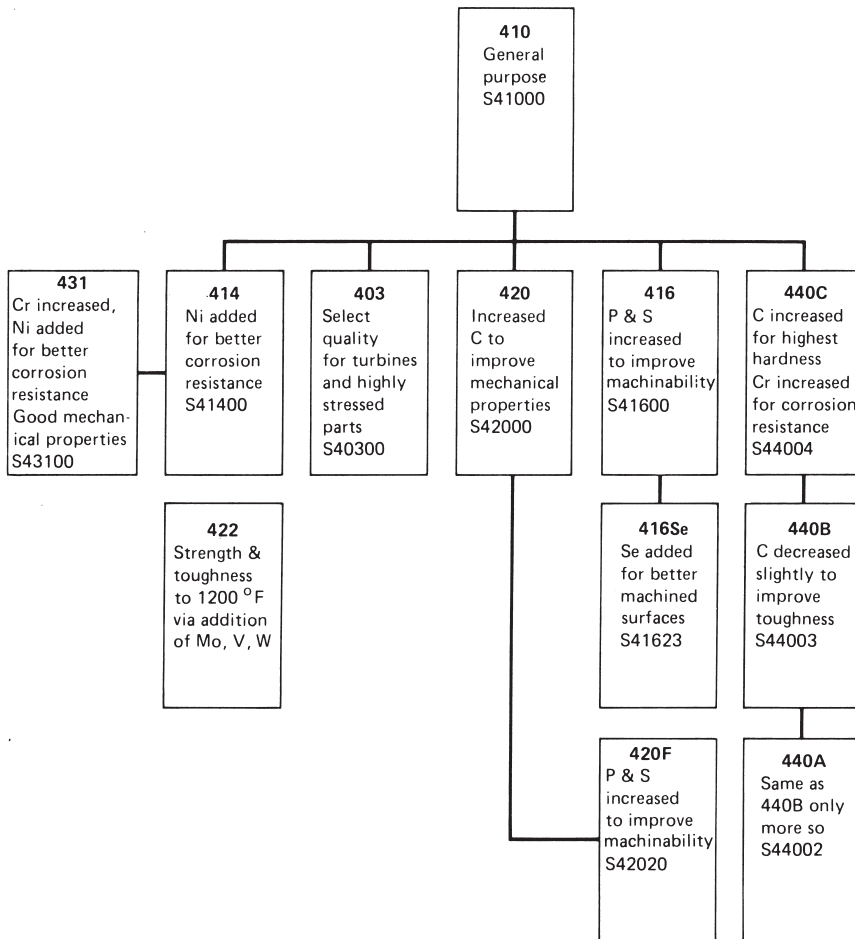


Fig. 5.1 Family relationships for standard martensitic steels. Source: Ref 3

Table 5.2 Classification of cast irons by tensile strength

ASTM class	Approximate tensile strength	
	MPa	ksi
20	138	20
25	172	25
30	207	30
35	241	35
40	276	40
45	310	45
50	345	50
60	414	60

Source: Ref 1

Malleable iron contains compact nodules of graphite flakes in the form known as temper carbon. As opposed to the spheroidal nodules found in ductile cast iron, these nodules are somewhat irregular aggregates. Numbers such as 40010, as shown in Table 5.3, classify the pearlitic and martensitic ASTM grades that can be induction hardened.

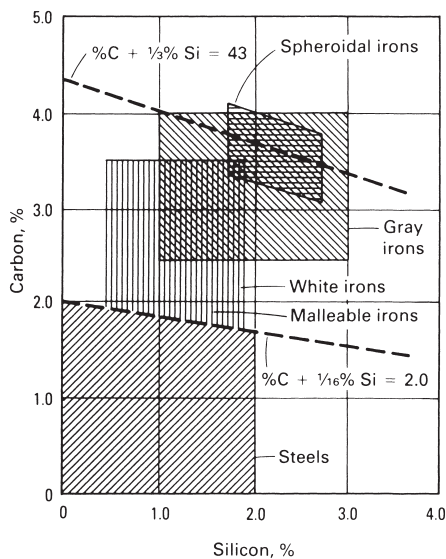


Fig. 5.2 Cast iron in relationship to carbon and silicon. Source: Ref 4

Table 5.3 Classification of malleable iron by mechanical properties

ASTM A220 class or grade	Hardness, HBN	Tensile strength	
		MPa	ksi
40010	149–197	414	60
45008	156–197	448	65
45006	156–207	448	65
50005	179–229	483	70
60004	197–241	552	80
70003	217–269	586	85
80002	241–285	655	95
90001	269–321	724	105

Source: Ref 1

Gray iron contains carbon in the form of graphite flakes. Gray cast irons are classified by ASTM specification A48, which classifies the various types in terms of tensile strength. The ASTM class numbers range from class 20 to class 60.

Ductile iron, also known as spheroidal graphite iron, contains spherulitic graphite in which the graphite flakes form into balls. Ductile iron is so named because in the as-cast form it exhibits measurable ductility. Most of the specifications for standard grades of ductile iron are based on properties—that is, strength and/or hardness is specified for each grade. Composition is either loosely specified or made subordinate to the mechanical properties. Table 5.4 shows the classification and numbering system according to average mechanical properties. Note that the classifications are in three segmented numbers, such as 60-40-18.

Table 5.4 Average mechanical properties of ductile cast iron

Nearest standard grade	Hardness, HB	Ultimate strength, MPa	ksi
60-40-18	167	461	66.9
65-45-12	167	464	67.3
80-55-06	192	559	81.1
120-90-02	331	974	141.3

Source: Ref 1

Tool steels are any steels used to make tools for cutting, forming, or otherwise shaping a material into a part or component adapted to a definite use. The earliest tool steels were simple, plain carbon steels. Beginning in 1868 and, to a greater extent, early in the 20th century, many complex, highly alloyed tool steels were developed. These complex alloy tool steels contain relatively large amounts of other elements such as tungsten, molybdenum, manganese, and chromium. Very precise production practices and stringent quality controls are used to fabricate tool steels. With few exceptions, all tool steels must be heat treated to develop specific combinations of physical and mechanical properties. The induction hardening of tool steels is limited to a few types of tool steels and specific, uniform geometry. While induction is used to heat some tool steels, the complex shapes and heating requirements for most tools and dies do not represent a good application for induction. Table 5.5 shows the classifications of tool steels that are most commonly induction hardened. Induction tempering can be done on some tool steels for slight reduction of the as-quenched hardness to help increase ductility.

Powdered metal parts are formed by compressing precisely mixed metal powders of iron and desired alloying elements in a shaped die to produce what is termed a green compact. The compacts are then sintered (diffusion bonded) at elevated temperature in a furnace with a protective atmosphere. During sintering, the powdered metal is effectively fused together. By pressing and sintering only, parts of more than 80% theoretical density of iron can be produced. By repressing, the density can be increased to 90%.

Iron, iron-copper, iron-copper-carbon, and prealloyed steels are among the materials used for powder metallurgy parts. Parts made from many of these materials respond to heat treatment. Powder metallurgy materials customarily are designated by the specifications or standards to which they are made, such as those listed in Table 5.6. The ASTM and SAE designations use the term *class* to indicate the carbon content of the finished part. The term *grade* is used to differentiate between related alloys bearing the same designation. Metal Powder Industries Federation (MPIF) designations for ferrous powder metallurgy materials include a prefix of one or more letters (the first of which is “F” to indicate an iron-based material), four numerals, and a single-letter suffix.

Table 5.5 Tool steel classification by major elements

AISI class	Composition(a), %								
	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Air-hardening, medium-alloy cold-work steels									
A2	0.95–1.05	1.00 max	...	4.75–5.50	...	0.90–1.40	...	0.15–0.50	...
A3	1.20–1.30	0.40–0.60	...	4.75–5.50	...	0.90–1.40	...	0.80–1.40	...
A4	0.95–1.05	1.80–2.20	...	0.90–1.20	...	0.90–1.40	...	...	...
A6	0.65–0.75	1.80–2.50	...	0.90–1.20	...	0.90–1.40	...	...	...
A7	2.00–2.85	0.80 max	...	5.00–5.75	...	0.90–1.40	0.50–1.50	3.90–5.15	...
A8	0.50–0.50	0.050 max	0.65–1.10	4.75–5.50	...	1.15–1.65	1.00–1.50	...	...
A9	0.45–0.55	0.050 max	0.95–1.15	4.75–5.50	1.25–1.75	1.30–1.80	...	0.80–1.40	...
A10	1.25–1.50	1.60–2.10	1.00–1.50	...	1.55–2.05	1.25–1.75	...	...	...
High-carbon, high-chromium cold-work steels									
D2	1.40–1.60	0.60 max	...	11.00–13.00	...	0.70–1.20	...	1.00 max	1.00 max
D3	2.00–2.35	0.60 max	...	11.00–13.00	1.00 max	...	1.00 max	...	...
D4	2.05–2.40	0.60 max	...	11.00–13.00	...	0.70–1.20	...	...	...
D5	1.40–1.60	0.60 max	...	11.00–13.00	...	0.70–1.20	...	2.50–3.50	2.50–3.50
D7	2.15–2.50	0.60 max	...	11.50–13.50	...	0.70–1.20	...	...	...
Oil-hardening cold-work steels									
O1	0.85–1.00	1.00–1.40	...	...	0.40–0.60	...	0.40–0.60	...	...
O2	0.85–0.95	1.40–1.80	...	...	...	...	...	...	...
O6	1.25–1.55	0.30–1.10	...	...	...	...	...	...	...
O7	1.10–1.30	1.00 max	...	...	1.00–2.00	...	1.00–2.00	...	...
Shock-resisting steels									
S1	0.40–0.55	0.10–0.40	0.15–1.20	1.00–1.80	1.50–3.00	0.050 max	1.50–3.00	...	...
S2	0.40–0.55	0.30–0.50	0.30–0.50	...	...	0.30–0.60	...	...	...
S5	0.50–0.65	0.60–1.00	0.60–1.00	...	...	0.20–1.35	...	...	...
S6	0.40–0.50	1.20–1.50	1.20–1.50	1.20–1.50	...	0.30–0.50	...	...	...
S7	0.40–0.55	0.20–0.80	0.20–0.80	3.00–3.50	...	1.30–1.80	...	...	...

(a) “...” indicates only present as a very small amount or residual amount. Source: Ref 1

Table 5.6 Ferrous powdered metal compositions

	MPIF composition ranges, %				
Description	MPIF class	C	Ni	Cu	Fe
Iron	F-0000	0.30 max	...	...	97.70–100.00
Steel	F-0005	0.30–0.60	...	...	97.40–99.70
Steel	F-0008	0.60–1.00	...	...	97.00–99.10
Copper iron	FC-0200	0.30 max	...	1.50–3.90	93.80–98.50
Copper steel	FC-0205	0.30–0.60	...	1.50–3.90	93.50–98.20
Copper steel	FC-0208	0.60–1.00	...	1.50–3.90	93.10–97.90
Copper steel	FC-0505	0.30–0.60	...	4.00–6.00	91.40–95.70
Copper steel	FC-0508	0.60–1.00	...	4.00–6.00	91.00–95.40
Copper steel	FC-0808	0.60–0.90	...	6.00–11.00	86.00–93.40
Nickel steel	FN-0205	0.30–0.60	1.00–3.00	2.50 max	91.90–98.70
Nickel steel	FN-0208	0.60–0.90	1.00–3.00	2.50 max	91.60–98.40
Nickel steel	FN-0405	0.30–0.60	3.00–3.50	2.00 max	89.90–96.70
Nickel steel	FN-0408	0.60–0.90	3.00–3.50	2.00 max	89.60–96.40
Nickel steel	FN-0705	0.30–0.60	6.00–8.00	2.00 max	87.40–93.70
Nickel steel	FN-0708	0.60–0.90	6.00–8.00	2.00 max	87.10–93.40
Infiltrated steel	FX-1005	0.30–0.60	...	8.00–14.00	80.50–91.70
Infiltrated steel	FX-1008	0.60–1.00	...	8.00–14.00	80.10–91.40
Infiltrated steel	FX-2005	0.30–0.60	...	15.00–25.00	70.40–84.70
Infiltrated steel	FX-2008	0.60–1.00	...	15.00–25.00	70.00–84.40

MPIF, the Metal Powder Industries Federation. Source: Ref 5

Iron/Iron Carbide

Carbon in Iron. Pure iron by itself is very limited in engineering usefulness. Carbon is the main alloying element in the different crystalline forms of iron that are called steel, and it produces the superior physical properties that make steel so useful. Even in the highly alloyed stainless steel, it is the quite minor constituent carbon that virtually controls the engineering properties. Furthermore, due to the manufacturing processes, carbon in effective quantities persists in all irons and steels unless special methods are used to minimize it. Iron alloyed with carbon forms the phase called iron carbide, commonly called cementite in metallurgical terms. In induction heat-treating practice, it is common to use iron carbide or carbide instead of cementite.

Carbon in iron has the capability of forming a solid-state solution that makes possible the successful heat treating of steel. Carbon atoms are 1/30th the size of iron atoms. Carbon is almost insoluble in the ferritic stage but very soluble in the austenitic phase that exists above 725 °C (1340 °F). Carbon actually dissolves; that is, the individual atoms of carbon lose themselves in the interstices among the iron atoms. The solid solution of carbon in iron can be visualized as a pyramidal stack of basketballs with golf balls between the spaces in the pile. In this analogy the basketballs would be the iron atoms, and the golf balls interspersed between them would be the smaller carbon atoms. The austenitic phase is much more accommodating to carbon than the ferritic phase, with the explanation of this based on fundamental theory involving electron bonding and the balance of the attractive and repulsive forces.

Phases of Iron-Carbon. A phase is a portion of an alloy—physically, chemically, or crystallographically homogeneous throughout—that is separated from the rest of the alloy by distinct boundary surfaces. The following phases occur in iron-carbon alloys: molten alloy, austenite, ferrite, cementite, and graphite. Any of these phases may likewise be called constituents (ingredients in a system). Therefore, not all constituents, such as pearlite and bainite, are phases because they are mixtures of phases and not homogeneous throughout. A phase diagram is a graphical representation of the equilibrium temperature and composition limits of phase fields and phase reactions in an alloy system. Figure 5.3 shows the iron-cementite phase diagram. Phase diagrams have the temperature plotted vertically and composition (percent carbon in iron), horizontally. The left side of the diagram is 100% iron. Proceeding from left to right, carbon increases from 0 to 6.67%. Phase diagrams should be viewed mainly from an equilibrium viewpoint. The phases, as shown, consider that time is not a factor and that the phases exist at the temperature shown. This diagram is very important in understanding the basic nature of the phases and is important in understanding the beginning basic theory of heat treating.

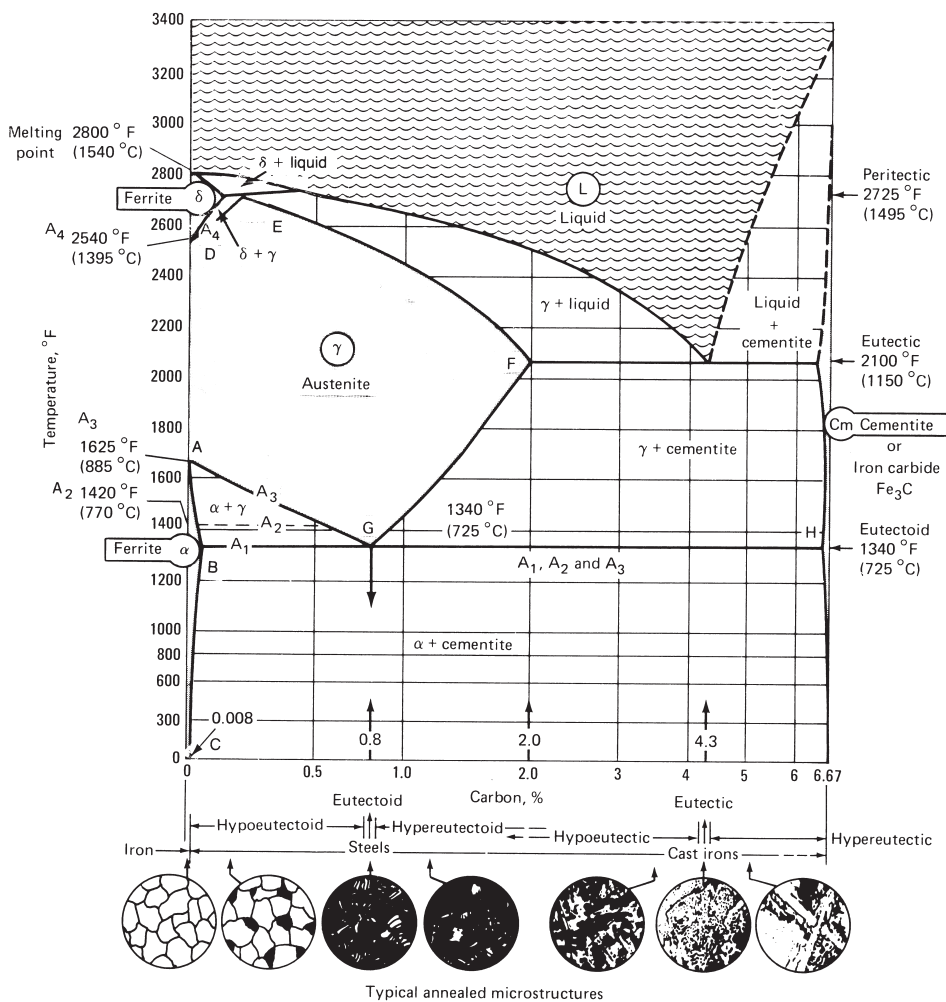


Fig. 5.3 Iron-cementite diagram. See text for details. Source: Ref 2

The iron-cementite diagram is usually called the iron-carbon diagram. Technically this is incorrect because iron carbide is the phase called cementite. Since cementite under equilibrium conditions decomposes into iron and graphite, the technically correct diagram is that shown in Fig. 5.4: the iron-graphite diagram. This diagram has significance only in the heat treating of some cast irons and powdered metal parts where graphite is present.

The process by which iron changes from one atomic arrangement to another when heated or cooled is called a transformation. Transformations that occur at very slow rates of heating and cooling are known as equilibrium transformations. Transformations of this type occur not only in pure iron but also in many of its alloys. Ferritic iron alloyed with carbon is

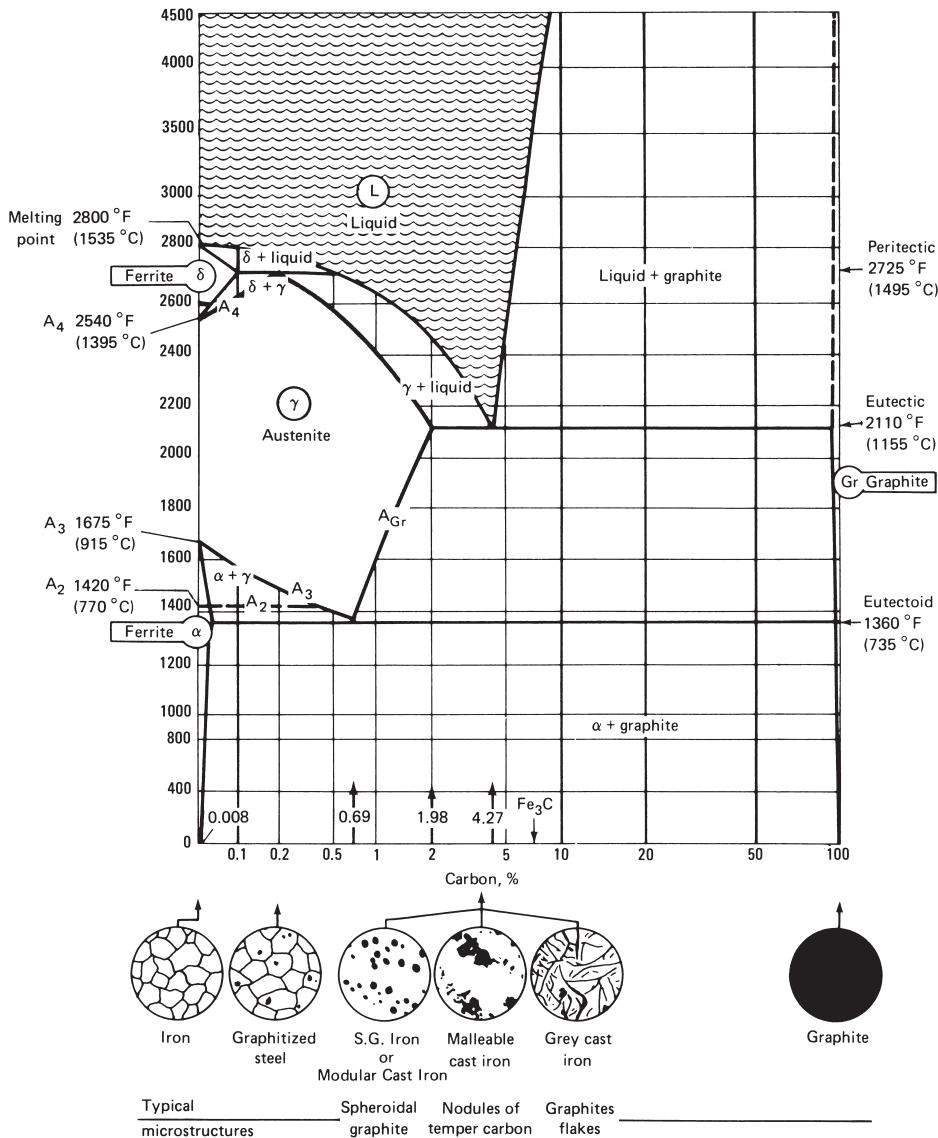


Fig. 5.4 Iron-graphite diagram. Source: Ref 2

transformed to austenitic iron above the upper transformation temperature. It is this transformation that makes possible the variety of properties that can be achieved to a high degree of reproducibility through the use of carefully selected heat treatments.

When carbon atoms are present in iron, two changes occur. First, depending on the carbon content, transformation temperatures are changed; second, transformation takes place over a range of temperatures rather than at a single temperature. Although the iron-cementite phase diagram as shown in Fig. 5.3 extends from a temperature of 1870 °C (3400 °F)

down to room temperature, note the part of the diagram that lies below 1121 °C (2050 °F). Steel induction heat-treating practice rarely involves the use of temperatures above 1121 °C (2050 °F).

Austenite is the term applied to the phase that is a solid-state solution of carbon in iron. The solubility of carbon in austenite depends on temperature and can range from 0 to 2%. Under normal equilibrium conditions austenite cannot exist in carbon steel at room temperature. (It may be present in alloy and stainless steels.)

Classification of Heat-Treating Processes

The intent of this book is to cover induction heat-treating practices. In some instances, heat treatment procedures are clear-cut in terms of technique and application. In other instances, descriptions or simple explanations are insufficient because the same technique frequently may be used to obtain different objectives. For example, the processes of stress relieving and tempering are often accomplished with the same equipment and by using the identical time and temperature cycles. The objectives, however, are different for the two processes.

It is important that the heat treater understand the general classifications of heat-treating processes and their importance before induction hardening, and where these processes fit into the practice of induction heat treating. The following descriptions of the principal heat-treating processes are arranged according to their interrelationships. The processes are discussed in relationship to induction heat treating, along with the metallurgical aspects.

Annealing is a generic term denoting a heat treatment that consists of heating to and holding at a suitable temperature, followed by cooling at a suitable rate. The cooling rates at high temperature are slow, and the cycle during cooling may involve holding times at elevated temperatures. Cycles are used to produce a microstructure that provides high softness and high machinability. The microstructures in steel obtained by annealing are not generally desirable for induction heating.

When the term *induction anneal* is used, it generally means to soften the metal by heating with induction. Because there is no holding at temperature time for induction, steel parts that are induction annealed are in reality induction tempered (see “Tempering” in this Chapter). Induction is used to anneal nonferrous metals or alloys such as copper or brass. However, with nonferrous alloys, the annealing cycles involve heating the workpiece to full solution and quenching fast enough to anneal. Electrical contacts made from beryllium copper are solution hardened in the furnace and induction annealed on the barrel ends so that the ends can be crimped.

Normalizing consists of heating a ferrous alloy to a suitable temperature above its specific upper transformation temperature and holding at temperature for time sufficient to complete transformation. Cooling at a

predetermined cooling rate and cycle follows this. The cooling rate is usually faster than that used for annealing, and there is not generally a holding time at elevated temperature during the cooling cycle. Normalizing is usually used as a conditioning treatment for strength and machinability or to produce a microstructure that is better for induction hardening.

Austenitizing is defined as the process of forming austenite by heating steel above the transformation range. This term will be widely used in the remaining chapters of this book. When used without qualification, the term implies complete austenitizing. Workpieces that are to be induction hardened are first austenitized. Austenitizing is also the initial step prior to normalizing, full annealing, and quench hardening of ferrous alloys.

Quenching is the rapid cooling of a steel or alloy from the austenitizing temperature through contact with a quenching medium. Induction heat treating uses dunk immersion into a quench tank, spray quenches, or mass quenching. Most common quenching media include water, water-polymer solutions, and oil. When selecting a quenchant, in order to minimize the possibility of quench cracks and distortion, it is best to avoid a solution that has more cooling power than is needed to achieve the results. Selection of the quenchant may require a complete analysis of all the factors involved in the induction heat-treating practice. Chapter 6, “Quenching,” in this book discusses quenching practices, and Chapter 11, “Induction Heat Treating Process Analysis,” presents a method for process analysis.

Tempering consists of the reheating of ferrous alloys to some preselected temperature that is below the lower transformation temperature. Tempering is used to increase the ductility of heat treated parts. Most parts are tempered from 107 to 538 °C (225 to 1000 °F). Parts may be furnace tempered or induction tempered. Chapter 7, “Tempering” in this book discusses tempering.

Stress relieving for steels and irons, like tempering, is always done by heating to some temperature below the transformation temperature. The primary purpose of stress relieving is to relieve (make uniform throughout the cross section) mechanical stresses that have been imparted to parts from such processes as forming, rolling, machining, welding, or heat treating. Stress relieving is normally a batch, furnace type of heat treatment. The parts are heated and are held at the established temperature only long enough to reduce the residual stresses to an acceptable level. Then the parts are cooled at a relatively slow rate to avoid creation of new stresses.

Stress relieving is normally performed at higher temperature ranges, such as from 538 to 650 °C (1000 to 1200 °F). However, the term is also used where hardened parts are heated at the 120 to 150 °C (250 to 300 °F) range for purposes of making the parts more ductile without causing a decrease in hardness.

Carburizing consists of absorption and diffusion of carbon into low-carbon steels or alloys by heating to some temperature above the upper

transformation temperature of the specific alloy. Temperatures used for carburizing are generally in the range of 900 to 1040 °C (1650 to 1900 °F). Heating is done in a carbonaceous environment (liquid, solid, or gas). This raises the carbon content at the surface, producing a carbon gradient extending inward from the surface. The surface layers can then be hardened to a high hardness either by quenching from the carburizing temperature or by cooling to room temperature, followed by re-austenitizing and quenching. Parts that have been carburized can be induction tempered in localized areas, and parts that have been carburized and slow cooled or tempered can be induction hardened in localized areas.

Carbon restoration is a process in which gas carburizing is used to restore the decarburized surface of a steel or alloy part. The carbon potential is controlled so that the carbon content of the decarburized surface is increased to the same or slightly higher carbon content compared to the carbon content of the part. For instance, an AISI 1050 steel with surface decarburization may have the carbon restored 0.50%. (See discussion of decarburization in Chapter 9, “Decarburization and Defects,” in this book.)

Carbonitriding is a case-hardening process in which a ferrous alloy, generally low-carbon steel, is heated above the transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen on the surface. This process is used to produce cases that are shallower than those produced by carburizing. Thin, hard, wear-resistant cases are produced because of the formation of complex carbides and nitrides in the case. The nitrides can be resistant to induction tempering.

Nitriding is a shallow, case-hardening process in which a ferrous alloy is heated at a temperature below the transformation temperature in a nitrogenous atmosphere, usually ammonia, generally in the 565 °C (1000 °F) region. Quenching is not required to create a hard, wear-resistant and heat-resistant case. Alloy steels, such as the AISI 4000 series steels, may be used. To produce the benefits of the induction-hardened case combined with the high hardness benefits of the nitrided case, parts may be induction hardened under nitrided cases, with no effect on the nitrided case.

Nitrocarburizing is a very shallow, case-hardening process done through contact with both nitrogen and carbon at temperatures below the transformation temperature. The purpose is to provide a low-distortion method for producing shallow cases that improves the anticuffing characteristics of ferrous parts.

Hardness and Hardenability

There are several methods for measuring or evaluating the results of the physical properties produced as a result of heat treating, such as tension testing, impact testing, bend testing, and various types of shear testing. However, most of these tests require special equipment and destruction of

the part being tested, and the tests cannot be performed quickly in-line. By far, hardness testing is the most universally used method for measuring the conformance to specifications for heat treating because hardness tests are:

- Simple to perform
- Do not usually impair the usefulness of the workpiece being tested
- Correlate to other physical properties, when accurately tested and properly interpreted.

Hardness varies directly with strength and inversely with ductility.

Hardness. Hardness is a matter of interpretation. To some people, a hard substance does not wear, while to others hardness is something that will not bend, resists penetration, or has the ability to scratch an object (such as diamond on glass). The definition provided in most dictionaries is “the relative capacity of a substance for scratching another.”

Many different systems have been devised for testing the hardness of metals, but only a few have achieved commercial importance. These are the Brinell, Rockwell, Vickers, rebound-type, and various microhardness testers. Except for the rebound type, all of these testers depend on the principle of indentation for measurement. In practice, induction heat-treating hardness testing uses Rockwell, Vickers, rebound-type, and microhardness testers, with the Rockwell “C” test scale being the most versatile and widely used scale for specification of hardness. Chapter 12, “Standards and Inspection,” in this book discusses in more detail the principles behind the different testers. Figure 5.5 shows a bench-type Rockwell hardness tester.

Hardenability is a term used widely throughout this book, and it is important that the reader understand its precise meaning. One might think that hardenability means the ability to be hardened. Although true to a degree, the precise meaning of hardenability is much broader. In classes on heat treating, two questions are asked: (a) If a specific steel, after being heated above the upper critical temperature and then quenched in water, has a hardness of 65 HRC (near the limits for most steels as measured by Rockwell testing), does this establish it as a high-hardenability steel? (b) If, after heating and quenching, a specific steel is only 35 HRC, is it a low-hardenability steel? Invariably a student will answer yes to the first question and no to the second. The correct answer for both is “not necessarily.” In each instance, information on section thickness is required before either question can be correctly answered. Therefore, hardenability does not necessarily mean the ability to be hardened to a certain Rockwell or Brinell value.

For example, just because a given steel is capable of being hardened to 65 HRC does not necessarily mean that it has high hardenability. Also, a steel that can be hardened to only 35 HRC may have very high harden-



Fig. 5.5 Rockwell tester. Source: Ref 6

ability. Hardenability refers to the capacity of a steel to harden to a specified hardness or hardness range at given depths. Deep-hardening steels, such as alloy steels, are said to have high hardenability.

The Jominy hardenability (end-quench) test is one of the most commonly used hardenability tests for predicting the ability of induction heat treating to produce minimum specified case depths. In this test, test bars of normally 25.4 mm (1 in.) in diameter by 102 mm (4 in.) long are fully austenitized. The bars are then removed from the furnace and placed into the test fixture as shown in Fig. 5.6. Water flow from underneath is controlled so that the amount striking the end of the specimen is constant in volume and velocity. The water impinges on the end of the specimen only, cooling the part. Thus, the end with quench impingement quenches the fastest. When the bar has completely cooled, the bar is removed from the fixture and parallel, opposite flats are ground so that the hardness can be checked down the longitudinal direction of the bar. Hardness tests are made every 1.5 mm ($1/16$ in.). Figure 5.7 shows an example of test results.

Workpieces that are induction hardened will generally have a minimum case depth specified. The hardenability curves are significant in that they present data that can be used to predict whether a given steel can meet specifications, providing the prior microstructure is present. Figure 5.8 shows the hardenability curve for 1045 steel. The hardness shown at the first $1/16$ in. (J1), is representative of surface hardness, and the deeper hardnesses are representative of hardnesses that can be produced deeper with

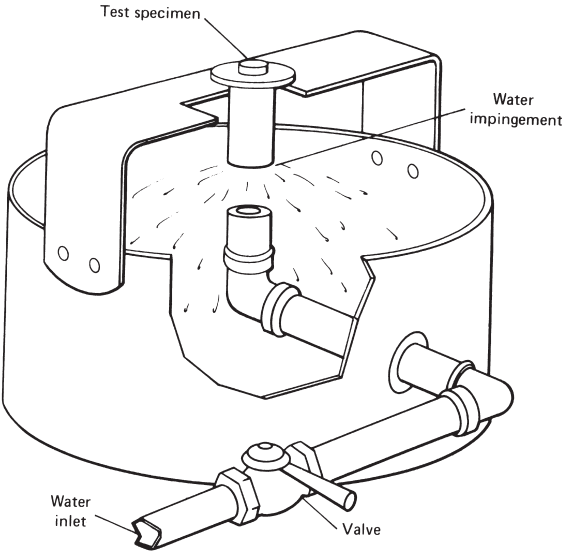


Fig. 5.6 Standard end-quench (Jominy) test specimen and method of quenching in quenching jig. Source: Ref 2

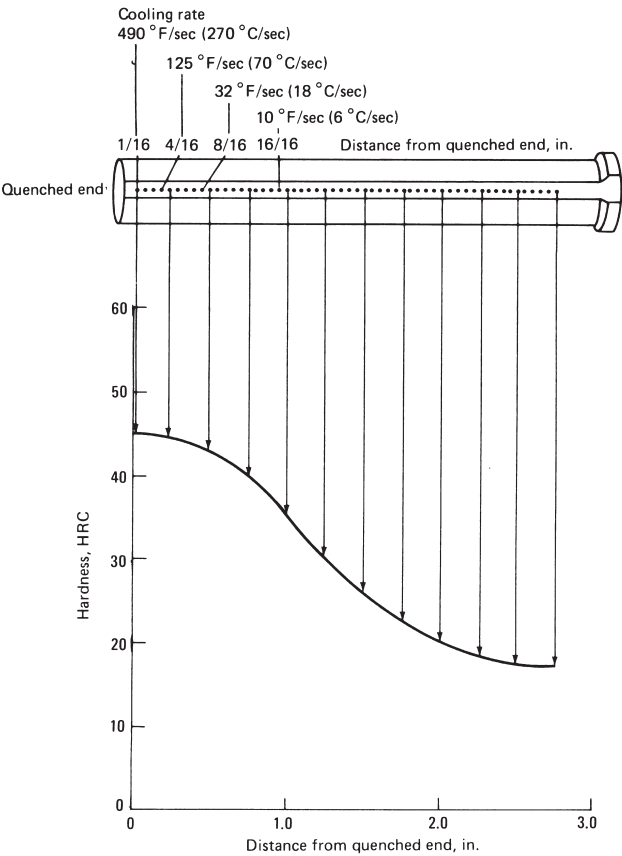


Fig. 5.7 Plotting of hardness vs. distance for end quench. Source: Ref 2

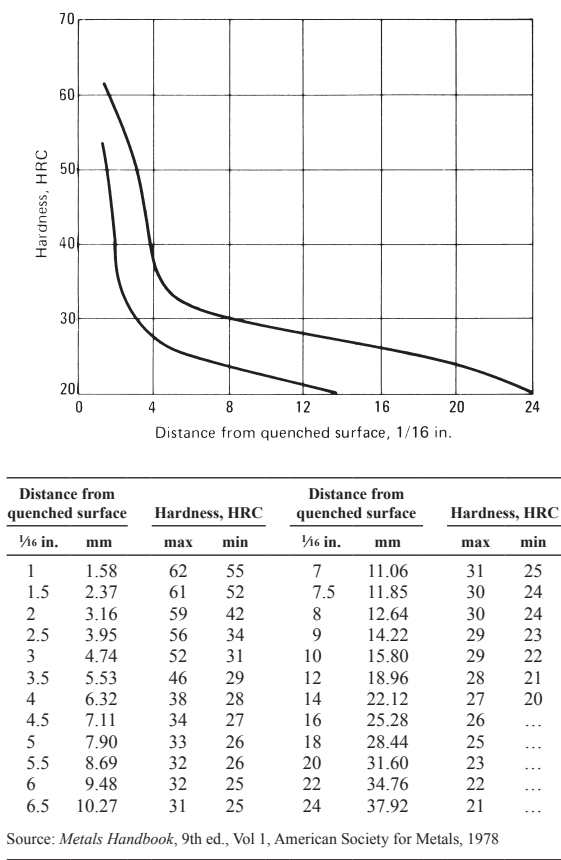


Fig. 5.8 End quench hardenability for 1045 steel. Source: Ref 2

good quenching. If a workpiece specification called for the hardness to be HRC 64 at the surface or the hardness to be above 50 HRC at 6 mm (0.250 in.), the specification is not likely to be met. The hardenability charts of steel alloys commonly induction hardened appear in Appendix 6, “Hardenability Curves,” in this book.

Role of Carbon in Hardened Steels. Carbon is the key to the hardening of steels by the heating and quick cooling (quenching) mechanism. The carbon content of a steel determines the maximum hardness attainable. The effect of carbon on attainable hardness is demonstrated in Fig. 5.9. The maximum attainable hardness requires only about 0.60% carbon, which probably seems odd to the reader. From the iron-cementite diagram (Fig. 5.3), it would seem logical that hardness would not become a straight line until about 0.77% C is reached. However, there is essentially no change in attainable hardness above about 0.60% C according to the data shown in Fig. 5.9. This can be accounted for through some unavoidable deficiencies concerned with indentation hardness testing. Despite this apparent oddity, these data are accurate and absolutely reproducible for extremely thin sections of carbon steel.

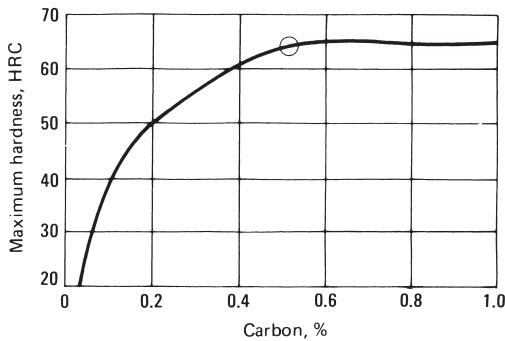


Fig. 5.9 Relationship between carbon content and hardness.

In fact, the data shown in Fig. 5.9 are precise to the extent that they sometimes are used in reverse. The hardness to which a specimen quenches can be used as a quick means of determining carbon content of an unknown steel. For example, a properly austenitized and quenched workpiece that tests to low hardness during setup can be the first indication of low carbon content in the steel. In conventional heat-treating practice, it should be remembered that the data shown in Fig. 5.9 are based on heat treating wafer-thin sections that are cooled from their austenitizing temperature to room temperature within a matter of seconds, thus developing 100% martensite. In practice the cross sections are usually larger, and less than optimum quenching speed may be used to avoid quench cracking. Also, the workpiece size may be so large that it cannot be quickly quenched.

The most important factor influencing the maximum hardness that can be attained is the mass of the metal being quenched. In a small section, the heat is extracted quickly, thus exceeding the critical cooling rate of the specific steel. The critical cooling rate is the rate of cooling that must be exceeded to prevent formation of nonmartensitic products (transformation products). As section size increases, it becomes increasingly difficult to extract the heat fast enough to exceed the critical cooling rate and thus avoid formation of transformation products. A typical condition is shown in Fig. 5.10, which illustrates the effect of section size on surface hardness and is a good example of the mass effect. For small sections up to 13 mm (0.5 in.), full hardness of about 63 to 65 HRC is attainable. As the diameter of the quenched piece is increased, cooling rates and hardness decrease because the critical cooling rate for this specific steel is not exceeded.

Induction Austenitization

Transformation to Austenite. The initial step in heat treating steel is austenitization, the process of transforming the microstructure to austenite. Figure 5.3 shows that when a steel alloy is heated, the transformation to austenite under equilibrium conditions starts at A_{c1} and completes at the A_{c3} (sometimes referred to as the critical temperature). Equilibrium

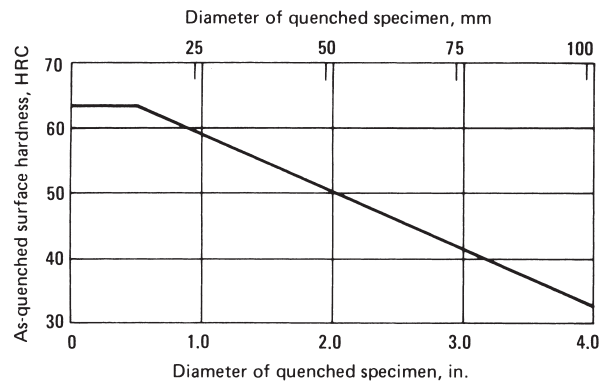


Fig. 5.10 Effect of section size on surface hardness of 0.54% carbon steel.
Source: Ref 2

means that there is sufficient time at the specific temperature for transformation to complete. For example, when a 0.40% carbon steel is heated to 725 °C (1340 °F), its crystalline structure begins to transform to austenite. If held for a long period of time at 725 °C (1340 °F) according to the phase diagram, the resulting microstructure will be a mixture of ferrite and austenite. No matter how long it is held at 725 °C (1340 °F), transformation to austenite is not complete until a temperature of approximately 815 °C (1500 °F) is reached.

In contrast, as shown in Fig. 5.3, steel containing 0.80% carbon transforms completely to austenite when heated to 725 °C (1340 °F) at what is called the eutectoid composition. The eutectoid composition is the only composition at which the A_{c1} and A_{c3} are at the same temperature. If the amount of carbon is increased to above 0.80%, such as to 1.0% carbon, and the steel is heated to 725 °C (1340 °F) or just above, austenite is formed. However, because only 0.80% carbon can be completely dissolved at this temperature, 0.20% carbon remains as cementite unless the temperature is increased to above 1040 °C (1450 °F). Increasing the austenitization temperature will increase the amount of carbon that can be taken into solution, up to 2.00% carbon. The solution and diffusion of carbon are dependent on both time and temperature. Carbon is found in the cementite or carbide particles. Larger carbides take longer to dissolve, so that the practical effect on induction heating is that the fast heating cycles of induction heating may not dissolve all of the carbides. The difference between heat treatment temperatures for induction heating and furnace heating is specifically the inherent short austenitizing times when using induction. Three metallurgical factors affect the transformation temperatures for austenitization with induction heating: (a) the chemical composition, (b) the prior microstructure, and (c) the rate of heating.

Effect of Chemical Composition on Transition Temperatures. The A_1 and A_3 transformation temperatures shown in Fig. 5.3 are for steel alloyed

with carbon only. The addition of other elements has the effect of changing the effective phase diagram into a multidimensional diagram with movement of the A_1 and A_3 temperatures. All important alloying elements decrease the eutectoid iron:carbon composition ratio and shift A_1 and A_3 . These shifts do not have much effect on induction austenitizing because workpieces must be heated through and over the A_3 temperature. The prior microstructure and heating rate have more effect.

Effect of Prior Microstructure and Grain Size. As described in Fig. 5.3, heating for transformation into austenite has so far involved equilibrium conditions. When the prior microstructure does not have a uniform distribution of phases or elements, complete austenitization requires more time at temperature, or a higher austenitizing temperature. Induction normally uses a timed heat cycle that does not hold the workpiece at temperature. Workpieces are heated to a specific temperature and are then cooled. Large carbide particles and some elements, such as manganese or nickel, diffuse very slowly. Accordingly, due to lack of time for solution and diffusion, complete transformation into a homogeneous austenitic phase can be difficult with the fast austenitizing cycles of induction heating. While the carbides may be in solution, there may not be complete diffusion particularly with steels that have some nickel. The result may be a martensitic matrix that has slight variations of hardness or the appearance of what is termed ghost pearlite. Higher austenitizing temperatures help because the rate of diffusion roughly doubles for every 6 °C (10 °F) that carbon steels are heated over the A_1 temperature. Therefore, higher austenitizing temperatures are used when induction heat treating than when furnace heat treating. Figure 5.11 shows the effect of both prior structure and rate of heating on A_{c3} , the upper critical temperature, for complete transformation of 1042 steel. Note that induction austenitizing often requires temperatures 91 to 114 °C (150 to 200 °F) higher than recommended furnace austenitizing temperatures. Table 5.7 shows examples of approximate induction austenitizing temperatures for carbon. The prior grain size has little effect on how well a part will induction harden (Ref 7).

Austenitizing of Various Steels. The chemical composition and the prior microstructure affect required austenitizing temperature for various steel alloys. The influence on particular grades varies considerably and affects induction heat-treating practice.

Carbon Steel. The development of induction heating pioneered the substitution of case hardened carbon steels for through-hardened alloy steels. One of the oldest rules in steel selection is to select the grade of steel in which carbon content is chosen to produce the hardness and physical properties that are needed. The use of lower-carbon steels maximizes ductility while reducing quench-cracking tendencies. In principle, if a hardness range of only 40 HRC is needed, the carbon content can be below 0.30 carbon. However, if the hardness needs to be greater than 60 HRC, a carbon content greater than 0.50 is preferred. From a machinability view-

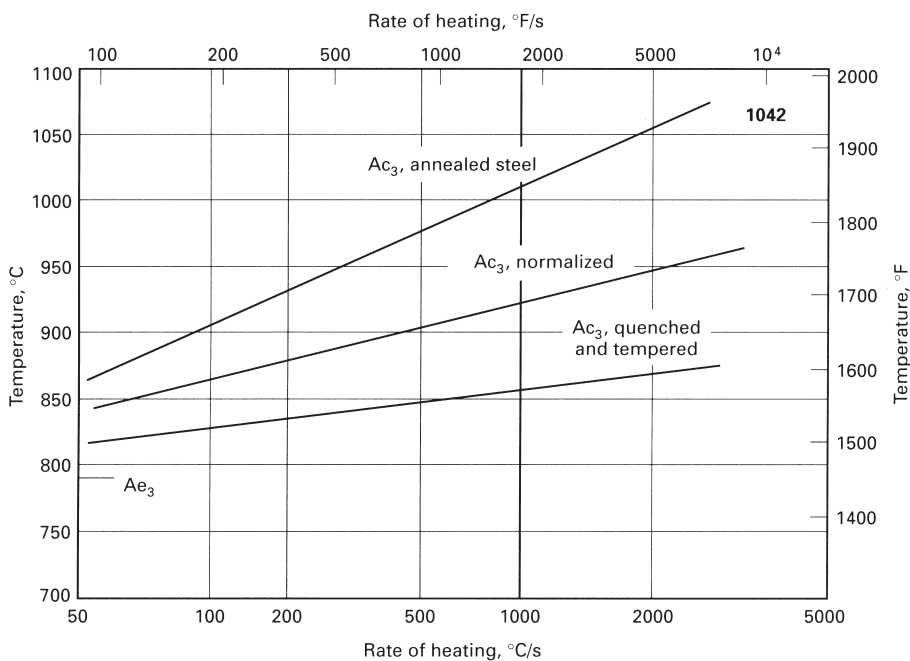


Fig. 5.11 Effect of prior structure on A_{c3} transformation temperature of 1042 steel. A_{c3} , temperature at which transformation of ferrite to austenite is completed on heating. Source: Ref 4

Table 5.7 Approximate induction austenitizing temperatures for carbon and alloy steels

Carbon content, %	Temperature for furnace heating		Temperature for induction heating	
	°C	°F	°C	°F
0.30	845–870	1550–1600	900–925	1650–1700
0.35	830–855	1525–1575	900	1650
0.40	830–855	1525–1575	870–900	1600–1650
0.45	800–845	1475–1550	870–900	1600–1650
0.50	800–845	1475–1500	870	1600
0.60	800–845	1475–1550	845–870	1550–1600
>0.60	790–820	1450–1510	815–845	1500–1550

Recommended austenitizing temperatures for a specific application will depend on heating rates and prior microstructure. Free-machining and alloy grades are readily induction hardened. Alloy steels containing carbide-forming elements (for example, niobium, titanium, vanadium, chromium, molybdenum, and tungsten) should be austenitized at temperatures at least 55 to 100 °C (100 to 180 °F) higher than those indicated. Source: Ref 4

point, higher carbon in steel increases the difficulty of machining. For this reason, there is considerable use of resulfurized steels, such as 1141 and 1144, in which the sulfide inclusions produce a remarkable increase in machinability. The austenitizing temperature selected needs to be high enough for complete solution of the carbon and complete diffusion. Segregation will increase the required austenitizing temperature. Grain growth is not usually a problem unless the steel is substantially overheated.

Alloy steels require a prior microstructure that is quenched and tempered in order to quench to optimum hardness and to produce the case depths that are projected by the hardenability curves. Overheating produces a higher tendency toward quench cracks.

Gray Cast Iron. Because irons can vary significantly in total carbon content, a minimum combined carbon content of 0.40 to 0.50% (as pearlite) is recommended. During austenitizing, the pearlite will behave essentially the same as the carbon in steel of similar carbon content. Care needs to be taken when austenitizing because the melting point of gray iron is much lower than that of steel. A phosphide constituent (steadite) melts at 954° to 982 °C (1750 to 1800 °F). The melting is not easily visible during heating, and a melted part is usually nonconforming and not salvageable. While as-cast parts can be heat treated to lower hardnesses, some shapes and parts will crack during heating unless stress relieved prior to induction hardening.

Ductile Cast Iron. The response of nodular iron is dependent upon the amount of pearlite in the matrix. The recommended microstructure is normalized and tempered with the hardness from 225 to 280 BHN.

Stainless steels and tool steels usually require up to 110 °C (200 °F) higher than the furnace austenitizing temperatures, and they generally quench 1 to 2 points HRC lower than when furnace austenitizing. Overheating produces retained austenite with resulting lower as-quenched hardness. Parts with retained austenite must be cryogenically processed as soon as possible for reduction of the retained austenite. Because of the combination of high austenitizing temperature that is required throughout the entire case, deep case depths with full transformation are difficult to produce without overheating the surface temperature in order to austenitize deeper into the case.

The Transformation of Austenite

Thus far, the discussion has been confined to heating of steel and the effects of various alloys, heating times, and austenitizing temperatures. Following austenitization, steel can be hardened to various degrees by the control of cooling rate and temperature at which the steel is held below the A_1 temperature for a given period of time before further cooling. The transformation of steel from austenite when cooled is discussed here.

The temperatures at which the transformations occur on cooling are determined for conditions of slow cooling and for given carbon contents. Although there are only three phases in steels, there are many different structures. The eutectoid composition is the only composition to which carbon steels, on slow cooling, transform simultaneously into one constituent, pearlite. For the objectives of this book the precise amount of carbon denoted as eutectoid is of no particular significance and will be considered to be 0.80%. To better understand the transformation of aus-

tenite on cooling, these three definitions of carbon steel according to carbon content will be used: under 0.80%, 0.80%, and above 0.80%. The hardening reaction and the resulting microstructures, or transformation products, are best understood by studying the transformation theory as related to the effect of cooling rapidly and holding at temperature for various times, or continuous cooling and varying the cooling rate. The isothermal transformation (IT) diagrams show the effect of equilibrium conditions on cooling, whereas the continuous cooling transformation (CCT) diagrams show the effects of continuous cooling.

The isothermal cooling diagram, also known as the time/temperature transformation diagram (Fig. 5.12), uses thin slices of the steel alloy that are cut and austenitized. The slices are then very rapidly quenched and are held at the quenched temperature for fixed time periods, with time increased until transformation is complete. At the end of the fixed time periods the slices are rapidly quenched below the M_f (martensite finish) temperature so that any remaining austenitic microstructure is transformed

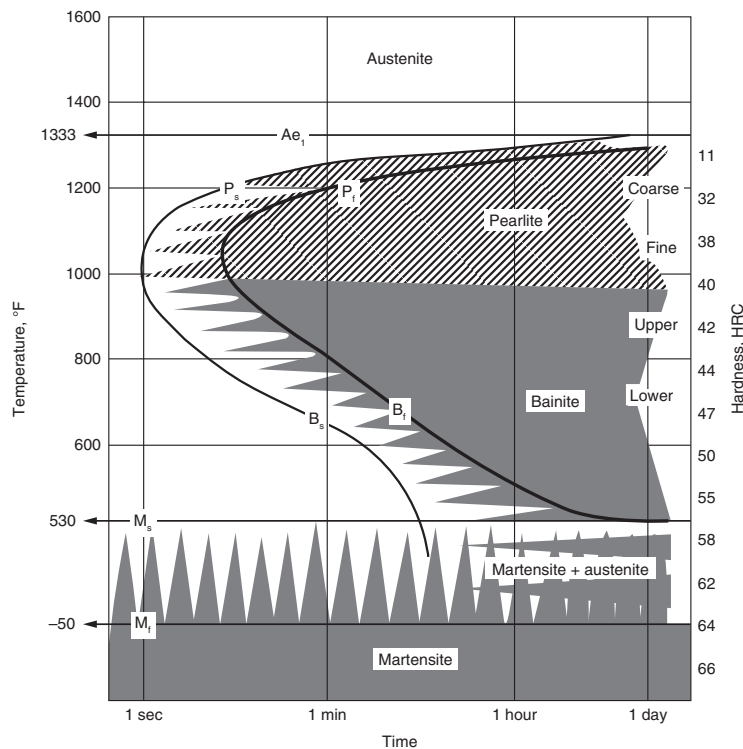


Fig. 5.12 Complete isothermal transformation diagram for 0.80% carbon steel. All of the transformation products are named. Bainite transformation takes place isothermally between 275 °C and about 525 °C (530 °F and about 975 °F). If austenite is rapidly cooled from above A_1 past the nose of the curve and to temperatures below 275 °C (530 °F), M_s , martensite starts to form. As long as cooling continues, more martensite forms. Transformation of austenite to martensite is not complete until M_f is reached. Ae_1 , equilibrium transformation temperature in steel. Source: Ref 2

to martensite. The final microstructure will consist of whatever microstructure was produced during the time period when the slice was held at higher temperature, plus martensite. Many test specimens need to be processed in order for the results of all temperatures and times held at temperature to be tested. Note that transformation at temperatures just under the equilibrium transformation temperature in steel (A_{e1}) require extensive time, while at 540 °C (1000 °F) only 1 s is needed. Pearlite is produced when quenched and held above 540 °C (1000 °F), and bainite is produced when held at lower temperatures. Quenching fast enough to miss the knee of what is termed the “C-curve,” where transformation starts, produces the desired martensitic microstructure. Notice also that according to equilibrium conditions, the test parts need to be quenched and to be held beneath the M_f temperature in order to have 100% martensite on final cooling. The importance of this diagram is that it shows the relative temperatures at which the different transformation products are produced and the importance of quenching fast enough to miss the “knee” of the diagram.

Transformation of Austenite for Steels under 0.80% Carbon (Hypoeutectoid Steels). In Fig. 5.3, the area shown on the diagram that is bounded by AGB is of significance to room temperature, that is, microstructures of the steels with carbon contents under 0.80%. Within this area the two phases of ferrite and austenite, each having different carbon contents, can exist at the same time.

Assume that a 0.40% carbon steel has been slowly heated until its temperature throughout the piece is 870 °C (1600 °F), thereby ensuring a fully austenitic structure. Upon slow cooling, free ferrite begins to form from the austenite when the temperature drops across the line AG in Fig. 5.3 into the area AGB, with increasing amounts of ferrite forming as the temperature continues to decline while in this area. Ideally, under very slow cooling conditions, all of the free ferrite separates from austenite by the time the temperature of the steel reaches A_1 (the line BG) at 725 °C (1340 °F). The austenite islands, which remain at about 725 °C (1340 °F), now have the same amount of carbon as the eutectoid steel, or about 0.80%. At or slightly below 725 °C (1340 °F), the remaining austenite transforms to pearlite. Upon cooling to room temperature there are no further changes in the crystalline structure. The final microstructure is a mixture of the ferrite and pearlite for a 0.56% carbon steel, as shown in Fig. 5.13. The ferrite does not etch and remains white, while the iron-carbide plates in the pearlite etch black.

Transformation of Austenite for 0.80% Carbon Steels (Eutectoid). The 0.80% carbon steels transform to austenite at one transformation temperature, 725 °C (1340 °F), as shown in Fig. 5.3. The eutectoid temperature represents the lowest temperature of any carbon content in which complete transformation to austenite can occur. When the austenitic solid solution is slowly cooled, several changes occur at 725 °C (1340 °F) (the transformation temperature or critical temperature of the iron-cementite

system). At this temperature, a 0.80% carbon steel transforms from a single homogeneous solid solution simultaneously into two distinct new solid phases of ferrite and cementite that are called pearlite. The change occurs at constant temperature and with the evolution of heat. This simultaneous formation of ferrite and cementite occurs only at the eutectoid composition point G in Fig. 5.3.

The microstructure of a typical eutectoid steel is shown in Fig. 5.14. This represents a polished and slightly etched specimen at a magnification of 250×. The white matrix is alpha-ferrite, and the dark platelets are cementite. All grains are pearlite—no free ferrite grains are present under these conditions. Cooling rates and temperatures govern the final condition of the particles of cementite that precipitate from the austenite at 725 °C (1340 °F). With normal cooling, the microstructure will be entirely pearlitic. Under specific cooling conditions under which the cooling is sufficiently slow or interrupted, the cementite particles become spherical instead

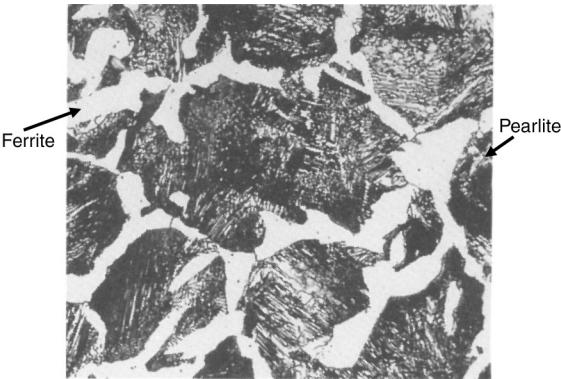


Fig. 5.13 Microstructure of pearlite and ferrite. 0.55% carbon steel slow cooled to form ferrite and pearlite. Picral etch. 500×. Source: Ref 8

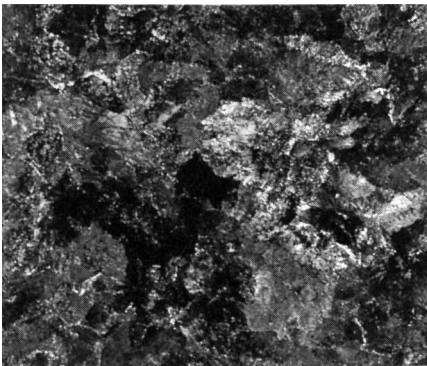


Fig. 5.14 Pearlite. 0.55 carbon steel austenitized at 860 °C (1580 °F), transformed at 650 °C (1202 °F) for 70 s. 300 HV steel. Picral etch. 250×. Source: Ref 8

of elongated platelets, as shown in Fig. 5.15. The microstructure appears as a matrix of ferrite with cementite or iron carbide globules.

Transformation of Steels from 0.80 to 2.0% Carbon (Hypereutectoid Steels). Steels of more than 0.80% carbon transform differently under equilibrium conditions. Assume that a steel containing 1.0% carbon has been heated to 845 °C (1550 °F), thereby ensuring a 100% austenitic microstructure. When cooled, no change occurs until the line GF in Fig. 5.3, known as the A_{cm} , is reached. At this point cementite begins to separate out as the temperature of the steel descends below the A line. The composition of austenite changes from 1.0% carbon down toward 0.80% carbon as the carbon content is depleted by the formation of cementite. At a temperature slightly below 725 °C (1300 °F), the remaining austenite will all transform to pearlite because it is then at the eutectoid composition. No further changes occur as cooling proceeds toward room temperature, so the room temperature microstructure consists of pearlite and free cementite. In this case the free cementite exists as a network around the pearlite grains (Fig. 5.16).

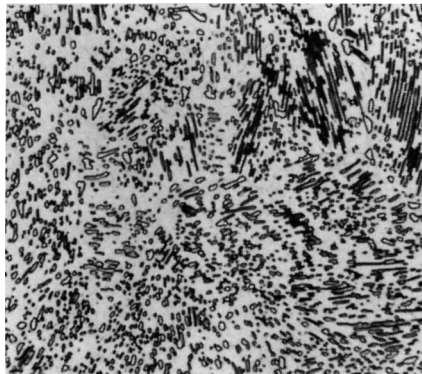


Fig. 5.15 Spheroidizing. Picral etch. 1000 $\times$. Source: Ref 8

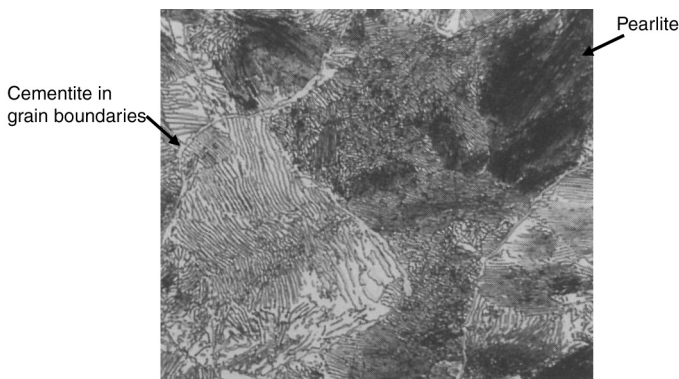


Fig. 5.16 Cementite network around pearlite. Proeutectoid cementite and pearlite formation. Picral etch. 500 $\times$. Source: Ref 8

Fast Cooling of Austenite

The previous transformation products, as described, were produced under very slow cooling or equilibrium conditions. Induction heat-treating practice uses rapid cooling (quenching) from the austenitic condition. With fast cooling, workpieces can be quenched to the preferred martensitic microstructure. If the cooling is not sufficiently fast, the final microstructures may have pearlite or bainite in the martensite. The effect of cooling rates and their effect on the transformation of austenite and formation of the various transformation products are described here.

Continuous Cooling Transformation (CCT) Diagram. As mentioned above, the IT diagram shows the microstructures produced by cooling and holding under equilibrium conditions. The diagrams have typically a C-shape in the curve, with time for transformation decreasing below the A_1 and then increasing again below the C of the curve. With induction hardening, the cooling or quenching of the alloy needs to be fast enough that the knee of this C-curve is missed. The IT diagrams can illustrate the need for quenching fast enough to miss the “knee” of the C-curve, but they do not provide the dynamic model that is needed. Continuous cooling transformation (CCT) diagrams show the microstructures produced by various rates of cooling. They help in selection of quenchants with fast enough quenching speeds to produce the cooling rates needed for martensitic microstructures. The CCT in Fig. 5.17 shows the continuous cooling of two different section sizes of 4340 steel, with the surface and center rates of cooling measured, and the final microstructure as quenched. Note that the cooling rate of both the surface and center of the smaller-diameter bar is fast enough to produce martensite (Fig. 5.17a); however, the center of the larger bar did not cool fast enough, and some bainite was produced (Fig. 5.17b). The larger section size quenched more slowly in the core, thus producing a slower cooling rate. Each steel alloy has its individual IT and CCT diagram, with the location and size of the C-curve depending upon the alloy content. Higher-alloyed steels, completely austenitized, do not need to be cooled as fast as the carbon steels to quench to martensite. The theory and importance of quenching rate are discussed in Chapter 6, “Quenching” in this book.

Microstructures Produced during Cooling. The products formed during cooling from austenite are called transformation products. The products that are formed depend upon the steel alloy used and the cooling rate. Martensite is the microstructure normally desired for optimum mechanical properties. The other transformation products are considered undesirable. Transformation products, discussed in the order of their potential formation when cooled from austenite, are:

- *Pearlite* is normally produced during slow cooling. The mechanism of formation is as described previously in the transformation of steels under 0.80% carbon. Pearlite is a mixture of the two phases of ferrite

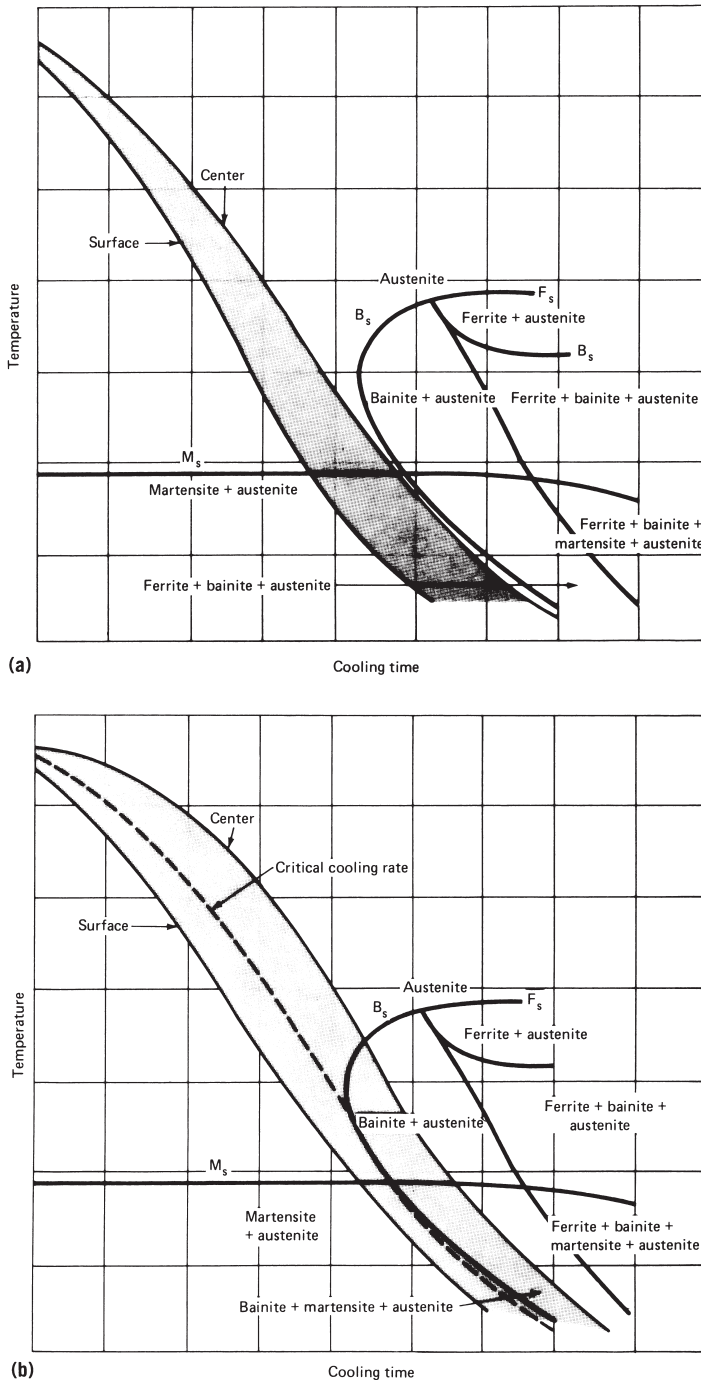


Fig. 5.17 IT diagram and cooling curve for 4340 steel: effect of section size.

(a) The cooling curve for a 25.4 mm (1 in.) diam AISI 4340 steel bar in relation to the CCT curve for AISI 4340 steel. The cooling rate is sufficiently rapid to quench the entire bar to martensite. (b) A 76 mm (3 in.) diam bar is shown in relation to the same CCT curve. It cools more slowly under identical quenching conditions, and because of the mass, the center consequently transforms partially to ferrite and bainite. Source: Ref 2

and cementite, with the cementite formed as lamellar plates in a matrix of ferrite. Pearlite can be found in the microstructure of a quenched part if the austenitization was not complete. Most quenching rates are fast enough to avoid pearlite formation. The experience of the author is that pearlite is not normally found in induction-hardened parts unless there is interrupted or slack quenching or unless diffusion of the pearlite was not completed during austenitization.

- *Bainite* can be produced in two forms: upper bainite and lower bainite. At temperatures lower than 565 °C (1050 °F) the urge for the austenite to transform is overcome by the lack of mobility of the carbon atoms. The austenite would like to transform, but the carbon atoms cannot move fast enough. Because the carbon atoms cannot move freely, the time necessary for transformation to begin is longer as the temperatures fall lower than 565 °C (1050 °F). Fig. 5.12 shows the region for bainite formation for a 0.80% (eutectoid) carbon steel to be between 525 to 275 °C (975 to 530 °F). Bainite is similar to pearlite in that it has a lamellar mixture of ferrite and cementite, but the mixture is much finer. High magnification is often needed to accurately define bainite microstructures, as opposed to pearlitic microstructures. Upper bainite, formed at higher temperatures, has a feathery appearance. Lower bainite, formed at temperatures under upper bainite, has an acicular appearance. Fig. 5.18 shows a microphotograph of lower bainite, which has the appearance of flakes. Because many manufacturers do not want bainite in induction-hardened parts, further discussion of bainite is given in Chapter 14, “Quality Control,” in this book.
- *Martensite* is a transformation product formed spontaneously by the rapid cooling of a steel alloy past approximately 275 °C (530 °F), the M_s temperature, to form a phase that is essentially a supersaturated solution of carbon in ferrite. A martensite crystal is formed by a mechanism that can be thought of in terms of shear that moves iron atoms cooperatively and almost simultaneously from their original sites in

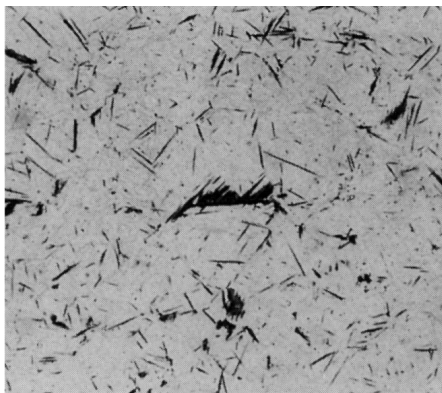
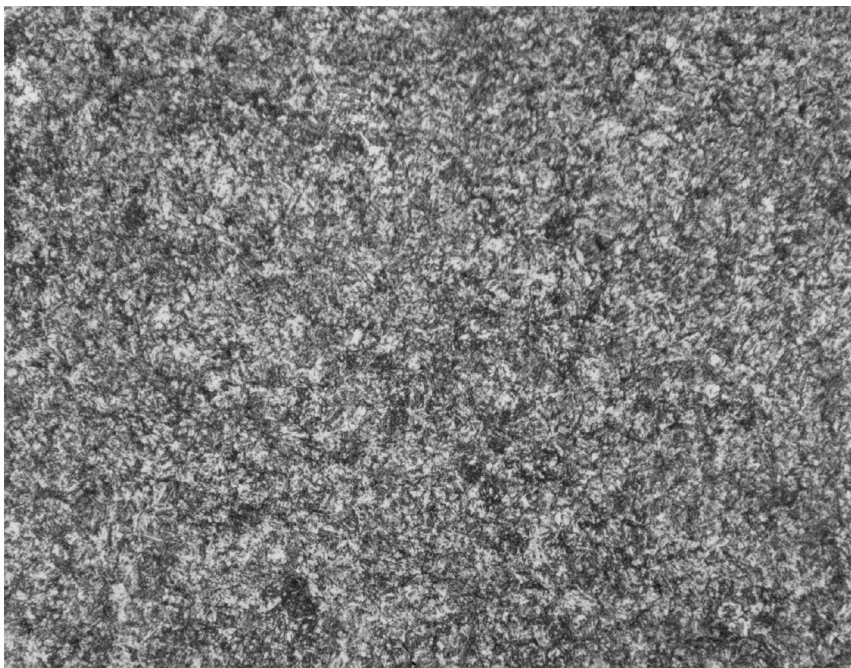


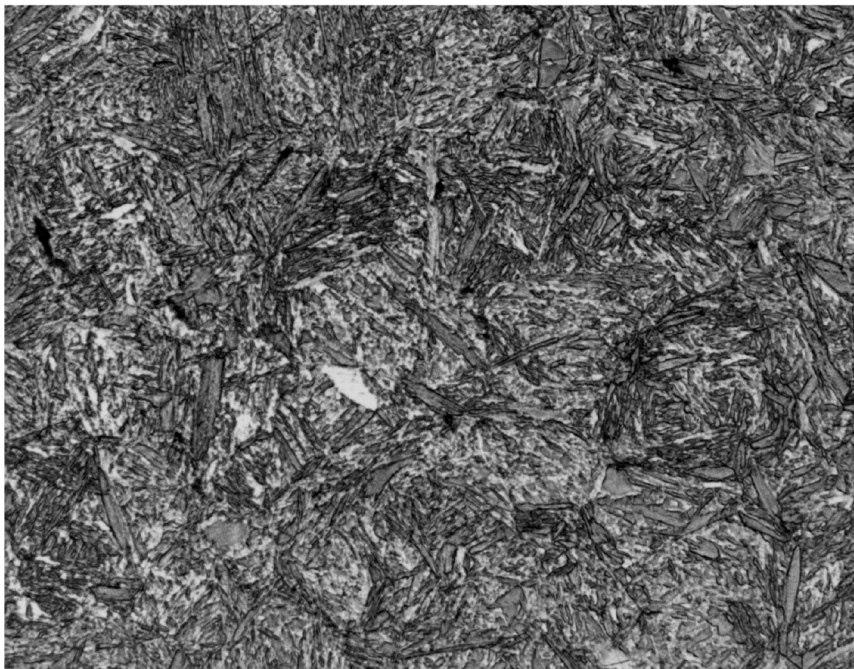
Fig. 5.18 Lower bainite. Picral etch. 250 $\times$. Source: Ref 8

the austenite structure to the nearest available site in the final structure. Martensite plates have a needle-like or acicular outline when viewed by a microscope. The amount of transformation is essentially independent of time. On the IT and CCT diagrams martensite formation starts at the M_s temperature and completes at the M_f temperature. Transformation to martensite is accompanied by a marked volume increase. It is difficult, if not impossible, to determine the M_f temperature with any accuracy because it is hard to distinguish small volumes of untransformed austenite by light microscopy. The end of the transformation is therefore often arbitrarily defined by either 90% or 95% transformation, which in the case of eutectoid steels happens to be close to room temperature. The M_f temperature of some steels is below room temperature. In a quenched eutectoid steel some austenite, at 5 to 10 volume percent, is usually retained at room temperature. As quenched and etched, the appearance is that of a white matrix that will have only oxide or sulfide inclusions showing. Figure 5.19(a) and (b) shows an induction-hardened 1052 steel wheel-hub that quenched to 62.1 HRC. The as-quenched martensite at 200 $\times$ (Fig. 5.19a) has little definition, while at 1000 $\times$ (Fig. 5.19b) the acicular structure is prominent, and the clusters show some evidence of the original austenitic grain size plus a small titanium carbide inclusion just off center, which is actually slightly golden in color. Chapter 13, “Nonconforming Product and Process Problems,” in this book discusses etching and inspection methods for martensitic microstructures.

- *Tempered Martensite.* The recommended heat-treating practice for optimum physical properties is to quench a workpiece to a fully martensitic microstructure and then, if the hardness is higher than specified, to temper to reduce the hardness into the specified range. Chapter 7, “Tempering,” in this book discusses tempering theory. Upon reheating a workpiece above 121 °C (250 °F), the martensite is not stable, and the carbon in solution in the martensite starts to precipitate. This microstructure after tempering is called *tempered martensite*, and it etches to a darker color with increasing tempering temperature. Figure 5.20(a) and (b) shows a specimen of the same steel that was shown in Fig. 5.19 that was tempered at 206 °C (400 °F), reducing the hardness to 56 HRC.
- *Retained Austenite.* For most steels above 0.60% carbon the M_f temperature, which is the temperature at which formation to martensite is complete, is below room temperature. Therefore, for these alloys a small percentage of residual, or retained, austenite is found when the alloys are quenched to room temperature. Small amounts of retained austenite are impossible to see by microscopy. Methods for reduction of retained austenite are discussed in Chapter 14, “Quality Control,” in this book in the discussion of materials and process problems that are involved when the amount of retained austenite after quenching is objectionable.

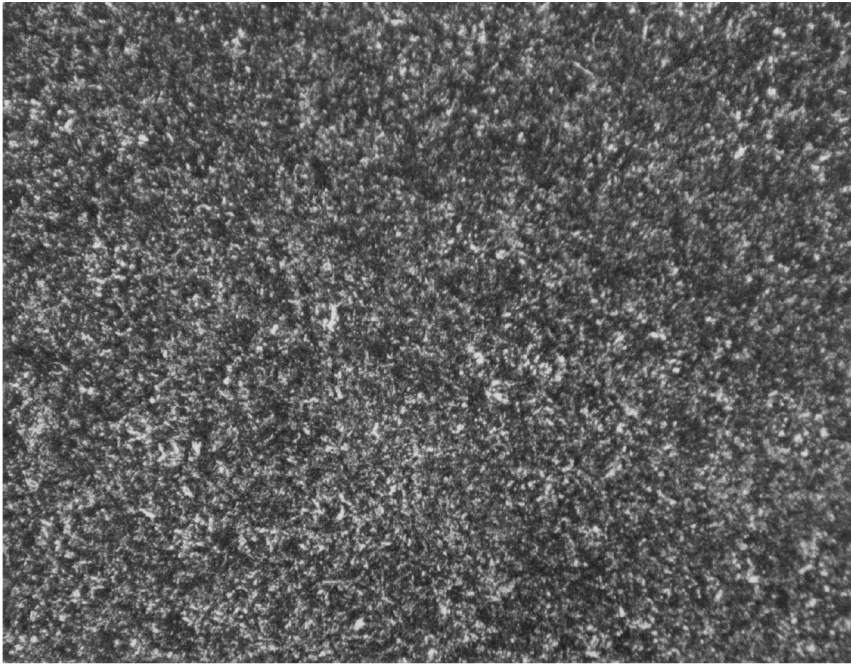


(a)

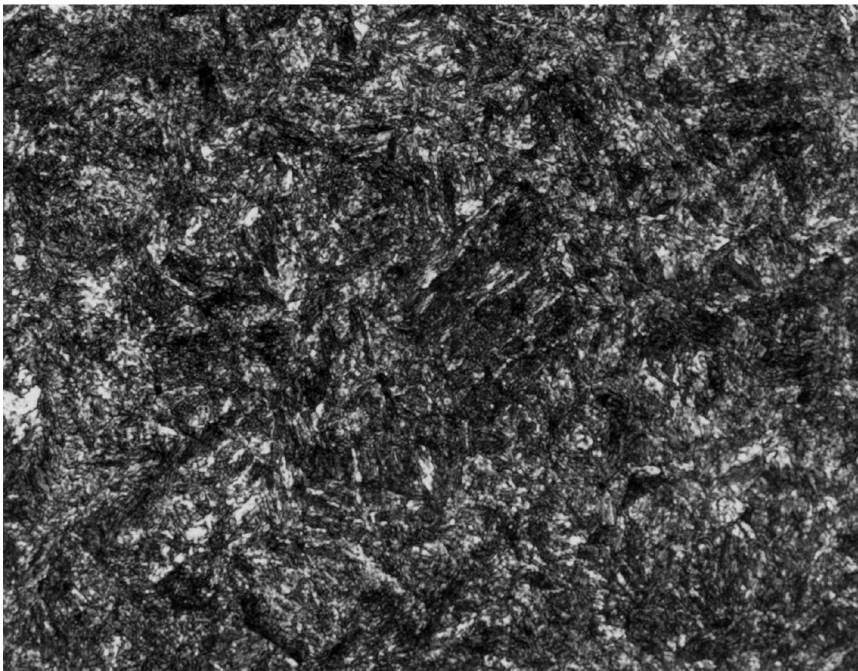


(b)

Fig. 5.19 Untempered martensite: 1052 steel induction hardened with 14% polymer quench. The as-quenched hardness is HRC 62.1. Nital etch. (a) 200 $\times$. (b) 1000 $\times$. Source: Courtesy of Aston Metallurgical Services, Inc.



(a)



(b)

Fig. 5.20 Tempered martensite: 1052 steel induction hardened with 14% polymer quench and tempered at 206 °C (400 °F). The as-quenched hardness is HRC 56.2. Nital etched. (a) 200×. (b) 1000×. Source: Courtesy of Aston Metallurgical Services, Inc.

Residual Stress and Induction Heat Treating

Residual stresses are stresses that exist in a solid body without an imposed external force. Factors such as cold working, phase changes while heat treating, and temperature gradients that occur during heating or cooling produce the stresses. The nature of stresses in a workpiece before induction hardening can influence distortion and cracking tendencies during heating and quenching. Often individuals question what can cause these effects. The answer is a lot. Table 5.8 shows a summary of the effects of compressive and tensile residual stresses at the surface of the parts created by common manufacturing processes.

There are two basic types of residual stresses: macrostresses, which are an average of body stresses over all large regions as compared to grain size; and microstresses, which are the average stress across one grain, or part of the grain, of the material. These two types of residual stresses may be classified further as tensile or compressive stress, with their locations starting at the surface and moving toward the center of a part.

Heat treatment can result in the development of residual stresses (both compressive and tensile), dimensional change (with respect to size and shape), and quench cracking. The major benefit of reduction of the overall residual stresses in a part is the elimination of dimensional change during manufacturing. The major benefit of producing compressive residual stress through induction hardening includes improved fatigue life and increased resistance to crack initiation. Tensile residual stresses at the surface of a part are generally undesirable because they can effectively increase the stress levels, as well as cause fatigue failure, quench cracks, and grinding checks and reduce the strength of a part. Excessive tensile residual stresses in the interior of a component may also be damaging because of the exis-

Table 5.8 Summary of compressive and tensile residual stresses at the surface of the parts created by the common manufacturing processes

Compression at the surface	Tension at the surface
Surface working: shot peening, surface rolling, lapping, and so on	Rod or wire drawing with deep penetration
Rod or wire drawing with shallow penetration(a)	Rolling with deep penetration
Rolling with shallow penetration(a)	Swaging with deep penetration
Swaging with shallow penetration(a)	Tube sinking of the outer surface
Tube sinking of the inner surface	Plastic bending of the shortened side
Coining around holes	Grinding: normal practice and abusive conditions
Plastic bending of the stretched side	Direct-hardening steel (through hardened)(b)
Grinding under gentle conditions	Decarburization of steel surface
Hammer peening	Weldment (last portion to reach room temperature)
Quenching without phase transformation	Machining: turning, milling
Direct-hardening steel (not through hardened)	Built-up surface of shaft
Case-hardening steel	Electrical discharge machining
Induction and flame hardening	Flame cutting
Prestressing	
Ion exchange	

(a) Shallow penetration refers to ≤1% reduction in area or thickness; deep penetration refers to ≥1%. (b) Depends on the efficiency of quenching medium. Source: Ref 4

tence and consequence of defects that serve as stress raisers. Subsurface quench cracks can initiate due to excessive tensile stresses.

Measurement of residual stresses is generally done after a part is manufactured. There are two broad methods for the measurement: mechanical and physical. The mechanical methods include the stress relaxation methods of layer removal, cutting, hole drilling, and trepanning that incorporate the use of strain gauges and measurement of the movement of a part as the stressed layers are removed. The physical methods include x-ray diffraction, neutron diffraction, acoustic, and magnetic, with x-ray diffraction probably being the most widely used.

Processes That Influence Dimensional Change and Residual-Stress Patterns. A number of factors affect the residual stresses found in a completed part. Broad classifications are:

- Forming or metalworking processing before heat treating
- Heat-treating operations before induction heat treating
- Effect of temperature gradients during heating and cooling
- Phase transformation during cooling
- Postquench tempering

Residual Stresses in Cold-Drawn Steel. The process of cold drawing steel produces mechanical stresses that depend on the shape of the dies and draft reduction as well as the prior microstructure, hardness, and grade of steel. Figure 5.21 shows the distribution of stresses in 1045 steel reduced by 20%. Also shown are the effects of both rotary straightening and stress relieving after cold drawing because there are significant effects on the residual stress pattern of the resulting products. The graphs in Fig. 5.21 indicate the center of the bar and the stress levels toward the surface. Negative levels are compression, and positive levels are tension. The overall balance in a bar before machining is zero. All tensile levels balance with the compressive levels. However, once a part is machined, the levels are changed. The surface can be left in either compression or tension, depending on the previous stress condition and how much machining is done.

Residual Stresses Caused by Machining. Many complex parts are made from machining forgings, castings, bars, or plates. Stresses that are present from either castings or forgings that are machined without prior heat treatment can affect the final residual stress balance in a machined part. The presence of residual stresses in the workpiece affects its machinability; on the other hand, the machining process also creates and changes the residual stresses and produces undesired distortions in the part. Machine-shop personnel may have to experiment with a number of process parameters to minimize detrimental residual stresses, such as the prior heat treatment, type of cutting tool, depth of cut, speed of turning,

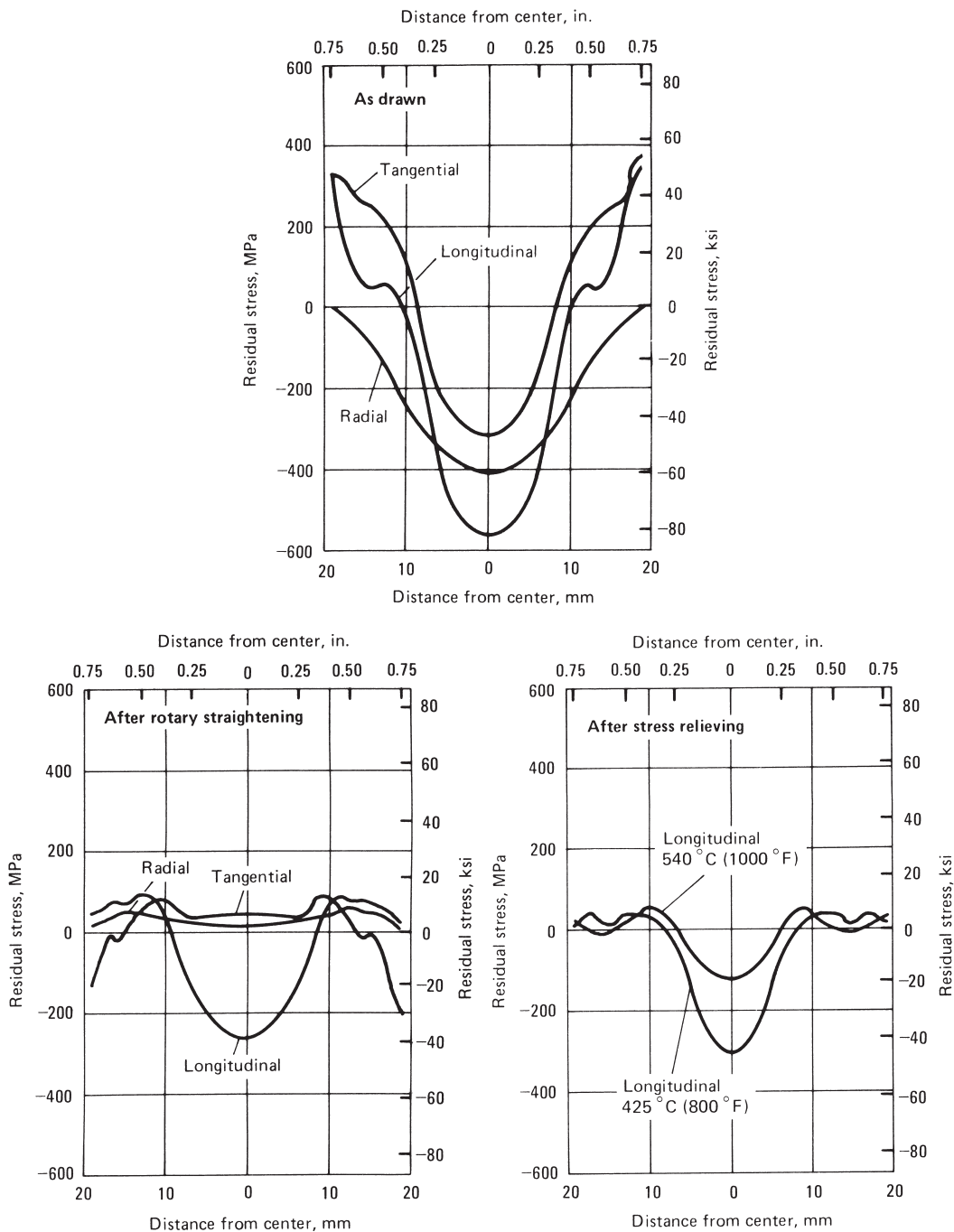


Fig. 5.21 Residual stress patterns in cold-drawn 1045 steel bars. Bars were cold drawn 20% from 43 to 38 mm ($1\frac{1}{16}$ to $1\frac{1}{2}$ in.). Source: Ref 5

coolant, clamping/unclamping techniques, machining sequence, and even the frequency of tool sharpening or change.

Stress Relief. The basic objective of stress relieving is to produce the rearrangement of atoms or molecules from their momentary equilibrium position to more stable positions associated with lower potential energy or stress state. Stress relieving operations for parts that are to be induction hardened involve heating the part to a certain temperature and holding at the elevated temperature for a specified length of time, followed by cooling to room temperature. Stress relief of parts to relieve cold-worked stresses is usually done in the 370 to 649 °C (700 to 1200 °F) range. Low-temperature tempering of quenched steels is sometimes done at 120 to 150 °C (250 to 300 °F) and is called stress relieving because ductility is increased. If parts are machined after quenching and tempering, the stress relieving must not be done at a temperature higher than the original tempering condition, or there will be a decrease in hardness.

Stress Relieving of Cold-Drawn Bars. The process of heating for stress relieving (thermal processing) of cold-drawn bars is also known as strain drawing, strain tempering, strain annealing, strain relieving, preaging, or stabilizing. Thermal stress relieving is probably the most widely used treatment applied to cold-drawn bars. Its purpose is to modify the magnitude and distribution of residual stresses in the cold-finished bar and thereby to produce a product with the desired combination of mechanical properties for field service. When at the stress-relieving temperature, the elastic-strain energy is released in small but significant amounts of plastic deformation. Temperatures up to 650 °C (1200 °F) are used, with most of the commercial temperatures ranging from 370 to 480 °C (700 to 900 °F). When stress relieving is performed at relatively low temperatures, hardness, tensile strength, and elastic properties of most cold-drawn steels are increased. At higher temperatures, however, hardness, tensile strength, and yield strength are reduced. The choice of a specific time and temperature depends on chemical composition, cold-drawing practice, and the final properties required in the bar.

Residual Stresses due to Heating and Cooling. Thermal stresses are produced first during the heating and then during the cooling of a part. Figure 5.22 shows the stresses at the surface of a carbon steel cylinder during heating and quenching. During heating, the surface remains in compression until the temperature reaches 1000 °C (1830 °F), when the surface becomes plastic. During cooling, the surface stresses are in tension until the surface is in the martensite formation range. The level of stress produced depends on the modulus of elasticity and the thermal coefficient of expansion of the material. The very basic nature of induction heating involves the conduction of heat from the surface toward the core. The rate of heating and the amount of heat transfer determine the thermal stresses during heating, as well as any stress relief of preexisting stresses in the core. Residual stresses on heating have little effect, except when

tensile stresses are high on the inside of a part, and the outside compressive stresses are relaxed through subsequent plastic deformation so that the inside remaining tensile stresses are large enough to cause the part to crack. Induction heating can cause cracks when heating cold-drawn bar stock, when the bar is not stress relieved uniformly and there are still large tensile stresses inside the core.

During the cooling of induction-hardened parts, different stress conditions are set up. First, due to thermal contraction, the outside surface is increasing in tensile strength (the ductility is decreasing), while trying to decrease in volume. The resultant net residual stresses in the part after cooling depend on the contraction of the core and its effect on contraction of the surface. If the parts are case hardened fast enough that the core has little heat, the core may have little effect on surface stresses. If the part is through heated so that the core has heat and can contract when cooled, there may be substantial effect. The final residual stress distribution with induction heating is more complex when the quenched parts undergo phase transformation to martensite.

Changes in Volume due to Phase Transformation. Figure 5.23 shows the compressive stresses in the case of an induction-hardened part. The most important change is the change of austenite into martensite, in that there is an approximate increase in volume of 4% times the carbon content. The area that is martensitic tries to increase in size, producing the compressive stress as the core cools. Surfaces can quench in tension when there is very little temperature variation between the surface and center of the part.

Residual stress patterns due to thermal and transformation volume changes are complex because the change in stresses due to thermal volume is independent of the changes caused by phase formation. During quench hardening of a steel workpiece, hard martensite forms at the surface layers, associated with thermal volume contraction and phase-volume

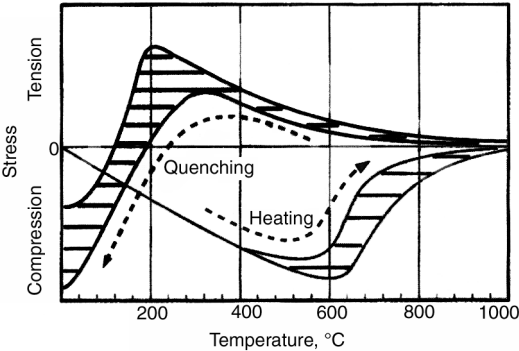


Fig. 5.22 Stresses at the surface of a carbon steel cylinder during heating and quenching. Martensite formation results in a final compressive residual stress state. Source: Ref 9

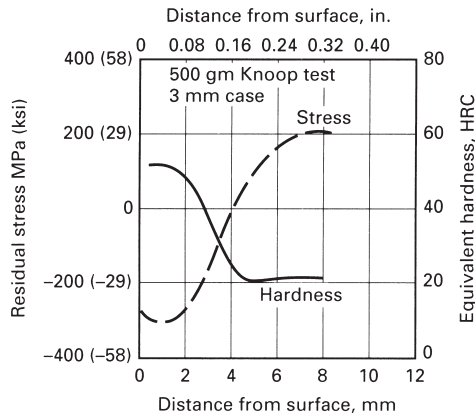


Fig. 5.23 Typical hardness and residual stress profile in induction-hardened (to 3 mm, or 0.12 in., case depth) and tempered (at 260 °C, or 500 °F) 1045 steel. Source: Ref 4

increase. The remainder of the workpiece under the surface is still hot and ductile austenite (assuming the entire part was austenitized). Later, the remaining austenite transforms to martensite, but its volumetric expansion is restricted by the hardened surface layer. This restriction causes the central portion to be under compression, with the outer surface under tension. During the final cooling of the interior core, surface contraction is hindered by the hardened surface layers. This restraint in contraction produces tensile stress in the core and compressive stress at the outer surface. Figure 5.24 illustrates the complex pattern of residual stress distribution over the diameter of a quenched bar, showing residual stresses after quenching in the longitudinal and radial directions in relationship to the coil and area heated. In some particular conditions, the volumetric changes can produce sufficiently large residual stresses that can cause plastic deformation on cooling, leading to warping or distortion of the steel part. Also, while plastic deformation appears to reduce the severity of quenching stresses, with severe quenching the quenching stresses are so high that they do not get sufficiently released. Consequently, the large remaining residual stresses can reach or even exceed fracture stress of steel and can cause quench cracks.

Residual Stresses in Induction Hardening. After quenching an induction-hardened part, compressive residual stresses may develop at the surface when martensite forms on the surface. Development of these compressive stresses depends on the nature of the hardened case and the stresses developed during quenching. The magnitude of the compressive stress effectively increases the yield strength, permitting the application of significantly higher stresses than could normally be possible in fatigue loading. There is a sharp transition to a tensile state in the transition zone between the case and unhardened core material. In induction hardening,

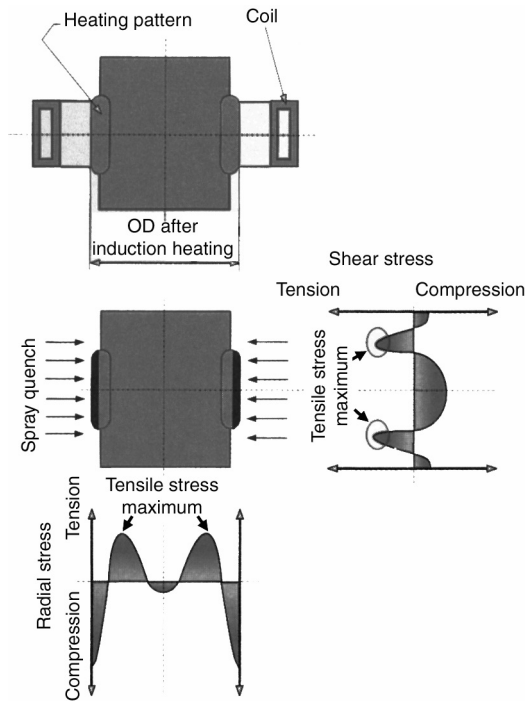


Fig. 5.24 Complex pattern of residual stresses forms in a carbon steel cylinder after induction heating and spray quenching. One of the goals of tempering is to relieve the subsurface tensile stresses that can cause cracking in service. Surface compressive stresses are beneficial. Stresses shown are on a macroscopic scale. OD: outside diameter. Source: Ref 9

an increase in hardenability changes the depth at which transition from compressive to tensile stress can occur. In some applications an initial preheat to increase the core temperature, followed by increase in the rate of heating, can optimize and produce the maximum compressive stress at the surface while minimizing tensile stress under the case.

While the compressive residual stress on the surface is considered to be beneficial, the maximum tensile residual stress is located just beneath the hardened case. This is a zone of potential danger, because it is where most subsurface cracks initiate. The result is that the overall residual stress condition in the as-quenched part promotes brittleness that reduces the part reliability. Tempering is needed to relieve some of these stresses, ideally to remove or substantially reduce subsurface tensile stresses, while retaining the beneficial surface compressive stresses. Finally, where compressive surface stresses are important, machining or grinding operations after induction hardening may need to be examined so that the compressive stresses are not removed, with the part left in an essentially tensile mode. Special attention should be paid to the selection, application, and use of the grinding wheel, to keep the tensile stresses at the surface as low as

possible. Abusive grinding can cause grinding cracks or overheating of the surface.

Distortion

Distortion can be defined as an irreversible and usually unpredictable dimensional change in the part during heat treating. The term *dimensional change* is used to denote changes in both size and shape. For purposes of induction heat treatment, distortion is an uncontrolled, irreversible movement that occurs in a part as a result of the induction heat-treating process. The intention of the induction heat treating is to keep the distortion within allowable limits that will enable the part to be completed as designed in the manufacturing process. However, sometimes processes such as tempering, cryogenic processing, straightening, machining, and grinding operations must be used to put the part back into usable tolerances. Figures 5.25 and 5.26 show two different types of parts with distortion problems. Both gears have distortion due to size change and shape change. Note that the recommendation for eliminating the distortion in Fig. 5.25 is to change the design of the gear, whereas for the gear in Fig. 5.26 the weight holes should be located deeper or should be drilled after the part is induction hardened.

Size Distortion. Changes in size in the micro constituents due to the volumetric changes that occur during a phase change were previously discussed. Limiting size change can be very important when semifinished parts are induction hardened and zero net change in size is an objective.

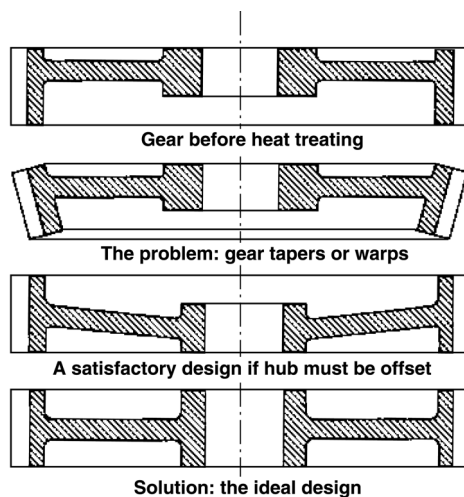


Fig. 5.25 Distortion caused by lack of symmetry in a gear: a typical problem caused by lack of symmetry in design, illustrated by a gear that warped during heat treating. Design modification can solve the problem. Source: Ref 10

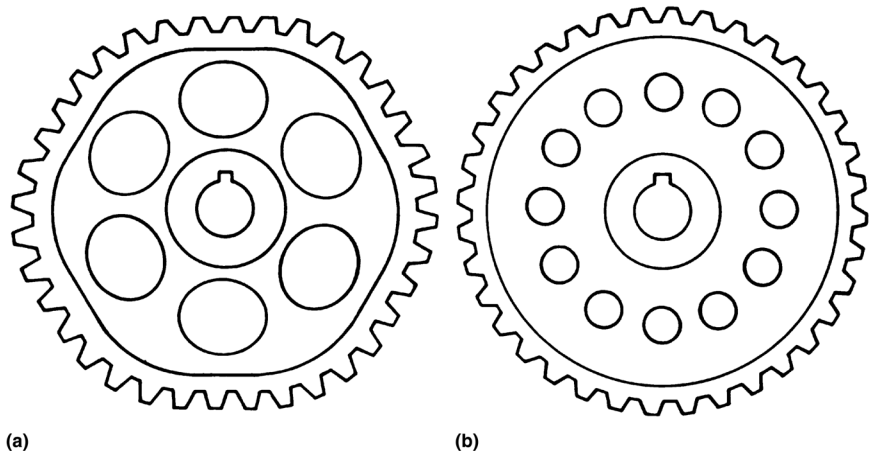


Fig. 5.26 Distortion caused by lack of symmetry in a gear: problem caused by the use of holes to reduce weight of a gear. (a) If the designer specifies large holes in the web, heat treatment may produce a flat spot for each hole. (b) Keeping the hole diameter to one-third of the web width eliminates the problem. Source: Ref 10

Shape Change, Bending, or Warpage. The effects of the residual stresses in parts before they are induction hardened and the induction-hardening process itself can cause distortion due to shape change. Spiral gears may straighten, and shafts may bend. Bores may close, and overall lengths may change. Potential methods for reduction of distortion are discussed in Chapter 11, “Induction Heat Treating Process Analysis,” in this book.

Grain Size

Grain size refers to the number of grains per unit area in terms of average diameter. Grain size can be important both before and after the induction hardening of a part. The grain size before hardening influences the hardenability of a material. The hardenability of a carbon steel may increase as much as 50% with an increase in austenite grain size from ASTM 8 (fine grained) to ASTM 3 (coarse grained). Grain-size requirements after induction hardening are important if there are specifications on the martensitic grain size after quenching. (In this case the martensitic grain size is the only way to measure the austenitic grain size before quenching.)

While a number of different procedures can be employed to measure grain size, one of the more common methods is comparison with standard charts. The standard chart allows the parts to be viewed at 100 $\times$ and compared to the charts or calibrated objectives to determine the grain size, as illustrated in Fig. 5.27 and 5.28. Figure 5.29 shows microphotographs of four austenitic grain sizes ranging from grain size 5 to 0. It is often diffi-

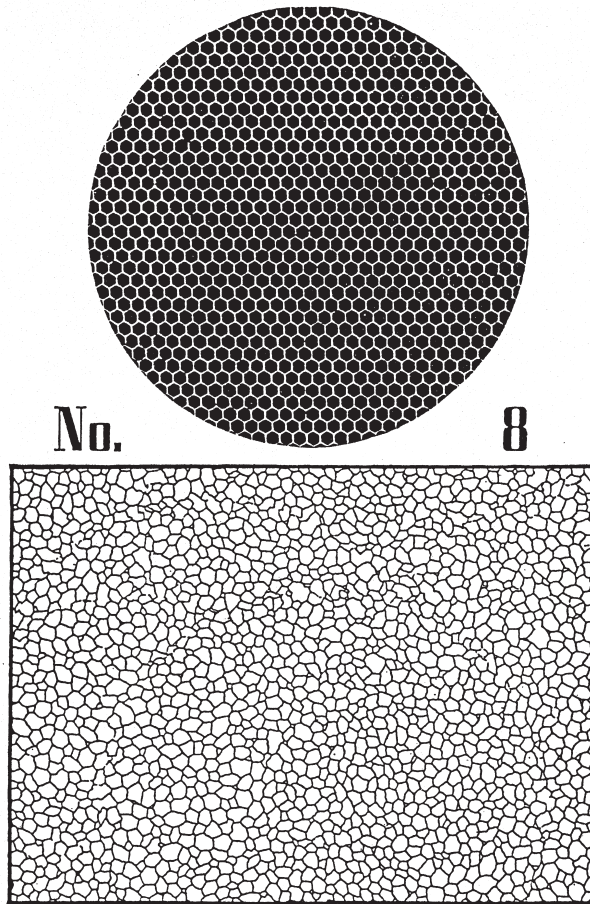


Fig. 5.27 Grain size No. 8. Upper, idealized hexagonal network for mean grain size No. 8, ASTM scale, 128 grains/in.². Lower, ASTM standard grain size No. 8, 96 to 192 grains/in.². 50 $\times$. Source: Ref 11

cult to determine the prior austenitic grain size in a fully martensitic microstructure. When the austenitic grain size becomes large enough, sometimes the vague previous austenitic grain size can be seen through the orientation of different packets of martensite. Figure 5.30 shows an example of martensite packets. The specimen needs to be tempered so that the martensite etches darker than that shown as quenched. Precise determination of the prior austenitic grain size can be difficult because there are no distinct martensitic grain boundaries and because the martensite packets may have different sizes because of different orientations. Too large a martensitic grain size is not usually a problem if normal induction-hardening austenitizing temperatures are used.

The parts are prepared metallurgically for grain size measurement. Preparation is discussed in Chapter 12, “Standards and Inspection,” in this book.

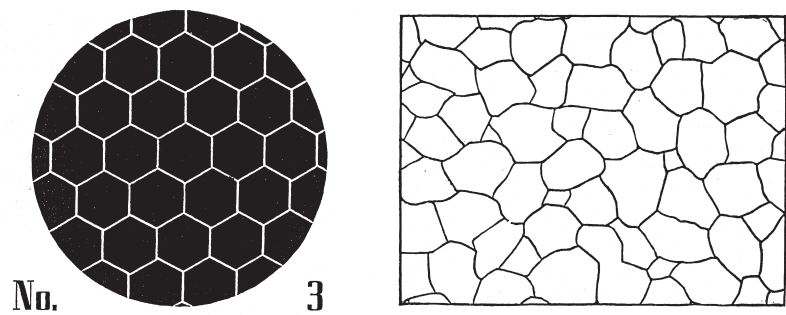


Fig. 5.28 Grain size No. 3. Left, idealized hexagonal network for mean grain size No. 3, ASTM scale, 4 grains/in.². Right, ASTM standard grain size No. 3, 3 to 6 grains/in.². 50x. Source: Ref 11

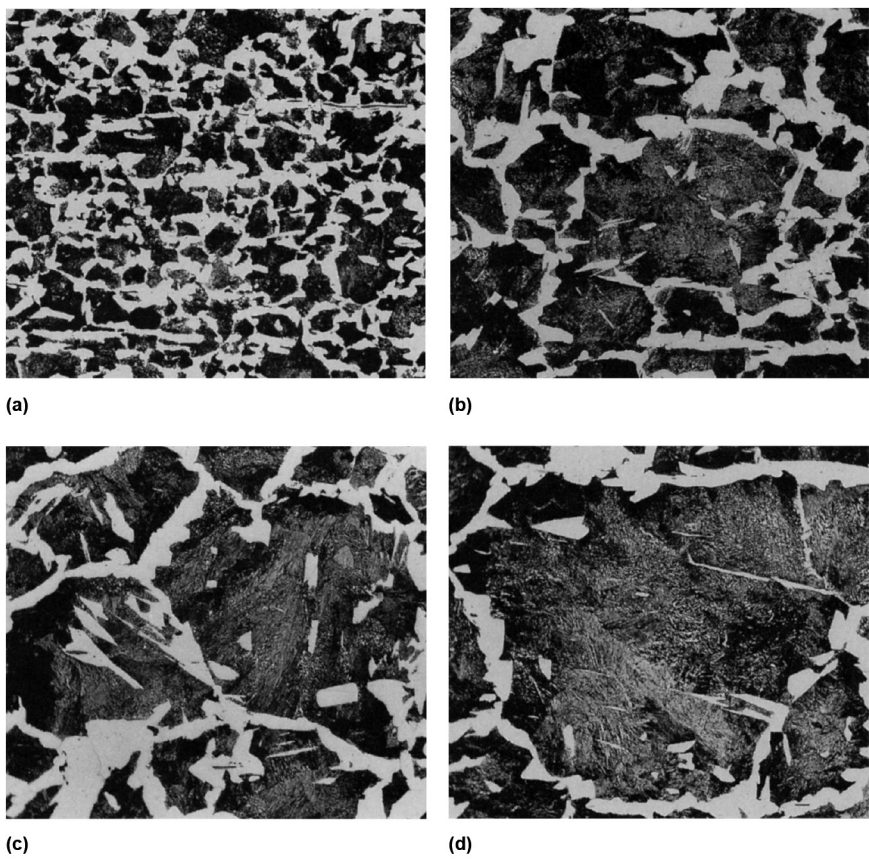


Fig. 5.29 Microphotographs of grain sizes. Austenite grain growth in a normal 0.5% C hypoeutectoid steel (silicon deoxidized). 180 HV steel, 0.50C-0.06Si-0.7Mn (wt%). Picral etch. (a) Austenitized for 1 h at 850 °C, cooled at 300 °C/h. Austenite grain size, ASTM No. 5. 100x. (b) Austenitized for 1 h at 900 °C, cooled at 300 °C/h. Austenite grain size, ASTM No. 3. 100x. (c) Austenitized for 1 h at 1100 °C, cooled at 300 °C/h. Austenite grain size, ASTM No. 1. 200x. (d) Austenitized for 1 h at 1200 °C, cooled at 300 °C/h. Austenite grain size, ASTM No. 0. 100x. Source: Ref 12

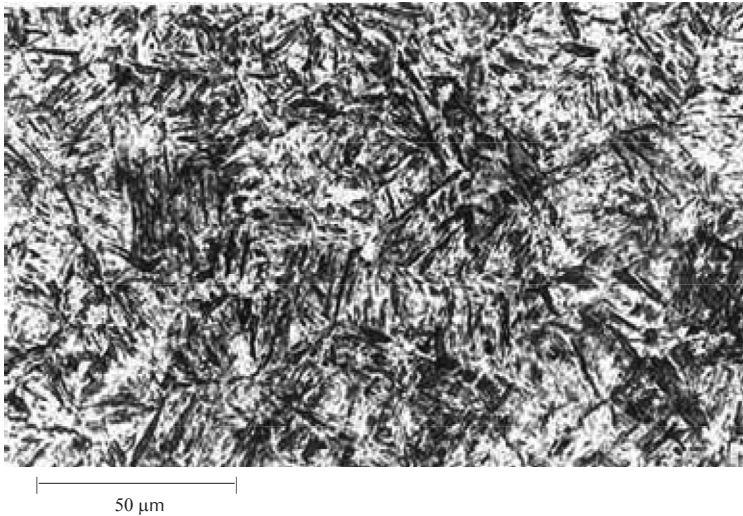


Fig. 5.30 Photomicrograph of martensitic structure. 500 $\times$.

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CHAPTER 6

Quenching

WHEN INDUCTION HARDENING, the workpieces are cooled by surrounding, spraying, or immersing the part in a quenchant, with the exception of a steel workpiece that has had its heat removed by air or self-quenching. Quenching is the cooling of a workpiece at a controlled rate in order to obtain the desired microstructure and hardness. Chapter 5, “Heat Treating Basics,” in this book covers the cooling of austenite and the subsequent transformation of austenite when cooled, with the microstructure produced during cooling dependent on cooling rate and steel composition. Hardness and hardenability are determined by the chemical composition of the steel, the microstructure when austenitized, and the cooling rate of the quenchant. Selection of the quenchant is governed by the cooling rate that is needed to quench the workpiece to full hardness without producing quench cracks and that will minimize distortion (if distortion is a factor). This Chapter discusses the theory and selection of quenchants.

Three Stages of Quenching

During the quenching of steel in liquid media, the process may be split into the following three stages: (a) the vapor blanket stage, (b) the boiling stage, and (c) the convection stage. Figure 6.1 gives examples of the three stages of quenching.

The vapor blanket stage occurs when the workpiece is first quenched for cooling from austenite. The very hot surface temperature of the workpiece vaporizes the quenchant, and a thin vapor pocket forms around the workpiece. Heat transfer occurs by radiation and conduction through the vapor blanket, which acts essentially as an insulating layer because of the relatively poor conductivity of a vapor. The vapor stage is a period of relatively slow cooling, and the cooling effect of various quenchants varies greatly due to the differences in the thickness of vapor pockets that are formed. Vapor pocket formation is reduced through the use of cold water,

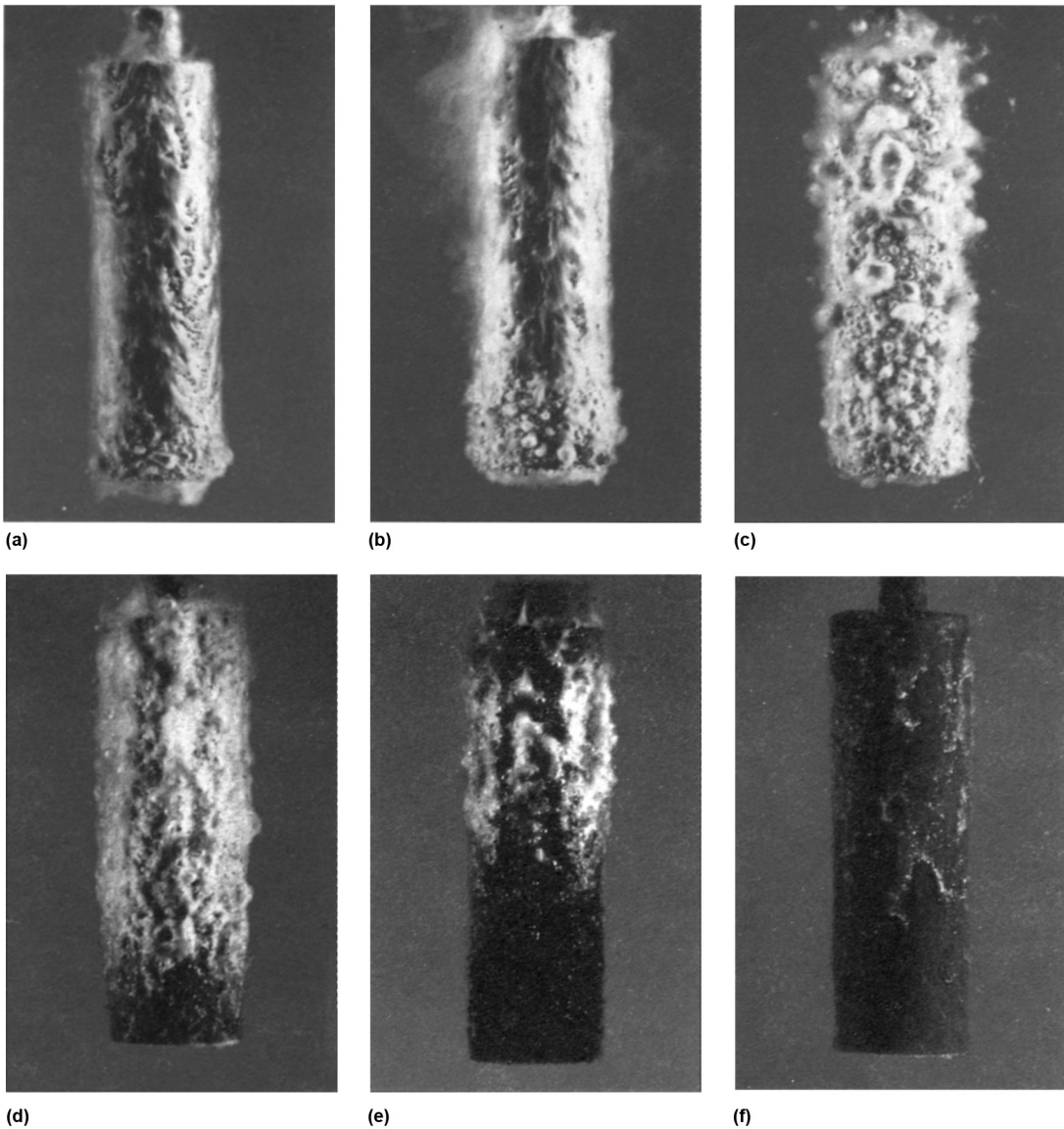


Fig. 6.1 Photo sequence of a hot steel rod being quenched in a 25% polyalkylene glycol polymer in water solution. (a) When the rod is immersed, a polymer film forms on its surface. (b) After 15 s, polymer activates and begins to boil. (c) After 25 s, boiling occurs over the entire rod as the cooling rate increases. (d) After 35 s, boiling collapses and the convection stage begins. (e) After 60 s, the polymer starts to redissolve. (f) After 75 s, polymer film has completely redissolved, and the heat removal is achieved entirely by convection. Source: Ref 1

spray quenches, or addition of additives to the water, such as salt and polymers. Oil quenches produce virtually no vapor pocket. The initial heat extraction of oil quenches is fast, but the quenching speed slows substantially in the other stages of quenching.

The boiling stage is the second stage of cooling. The vapor pocket collapses, and the quenchant comes into contact with the hot metal surface of

the part, resulting in nucleate boiling to cool the part. This stage of quenching typically has the highest rate of heat extraction.

The convection stage, the third stage of cooling, starts when the surface temperature of the part being cooled decreases below the boiling point of the quenchant. Heat transfer occurs by direct contact between the surface of the part being cooled and by convection of heat through the quenchant. The cooling rate is low because of the low temperature differential between the part being cooled and the quenchant. The cooling rate is affected primarily by the quenchant viscosity, agitation, and convection rate.

Factors for Selection of Quenchant

The main factors for the selection of a quenchant are:

- The quench speed needed to produce the required hardness and case depth
- Minimizing the potential for distortion and quench cracks
- The capability of keeping the quenchant in the desired operating temperature range
- Environmental requirements such as restrictions on rust inhibitors or biocides in the quenchant, venting requirements, cleaning of the quenchant from parts after quenching, and disposal of used quenchants

Types of Quenchants

In the early years of induction heat treating, water was widely used for quenching, with salt additives used when severe quenchants were needed. In the 1950s the introduction of fast-speed oil quenchants permitted the use of oil as a quenchant for medium-carbon steels where there were cracking tendencies because of small section size. Later, various water-soluble oils and plastic quenchants were introduced, followed by the introduction of the polymer-based water quenchants that continue to be in heavy use today. Polymer quenchants have eliminated spotty hardnesses that were caused by vapor pocket formation. Polymers also provide more flexibility when used for quenching induction-austenitized workpieces.

The various quenchants used have different cooling characteristics in cooling rates. Different materials and part geometry have different quenching rate requirements in order to produce a fully martensitic microstructure. The quench severity of various quenchants versus cooling rates needed for different steel alloys is shown in Fig. 6.2. Low-carbon steels need high cooling rates, whereas high-alloy steels can have slow cooling rates. (Workpieces made from 4340 steel will quench to high hardness in air.) The characteristics of quenchants vary.

Water has continued to be an excellent quenchant when used appropriately. Water is cheap and readily available. Figure 6.3 shows cooling rate

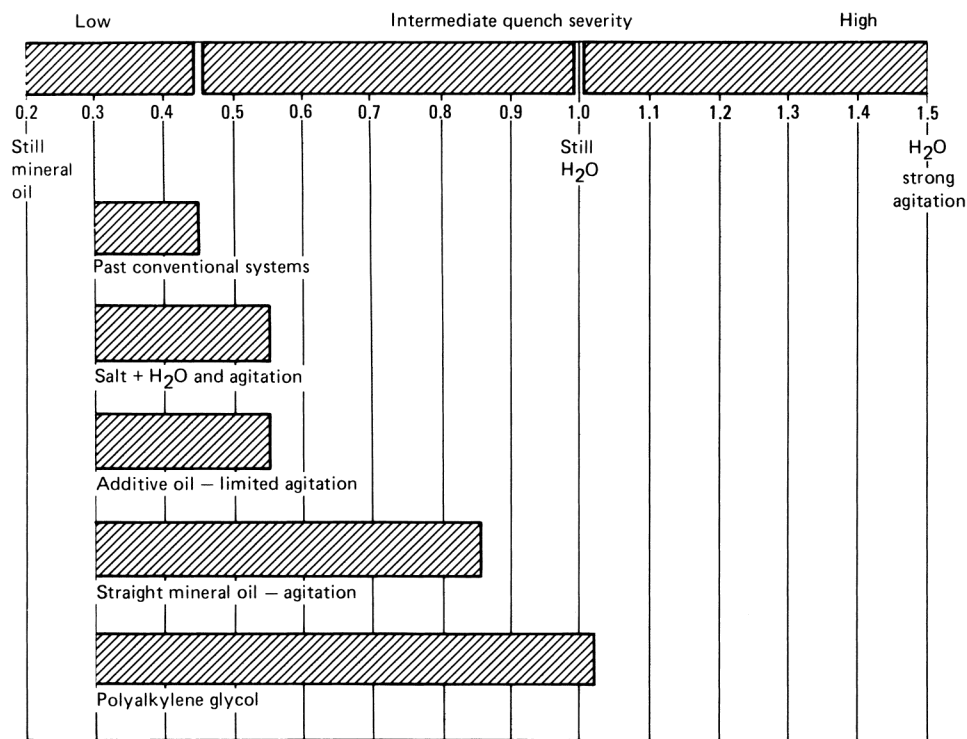


Fig. 6.2 Approximate quench severities for quenching mediums containing additives to improve cooling capacity. Source: Ref 2

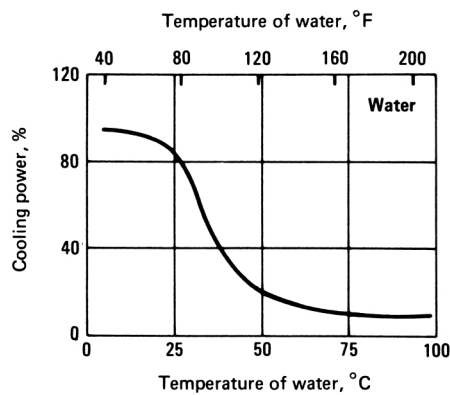


Fig. 6.3 Relation of surface cooling power of water with moderate agitation and water temperature. Source: Ref 3

versus temperature for water quenchants with moderate agitation of the water. Note the substantial drop in cooling rate from 26 to 40 °C (80 to 100 °F). Figure 6.4 shows the effect of cooling rates of water at different temperatures throughout decreasing workpiece temperature. The fastest cooling rates are produced with the coldest water in the boiling stage. The

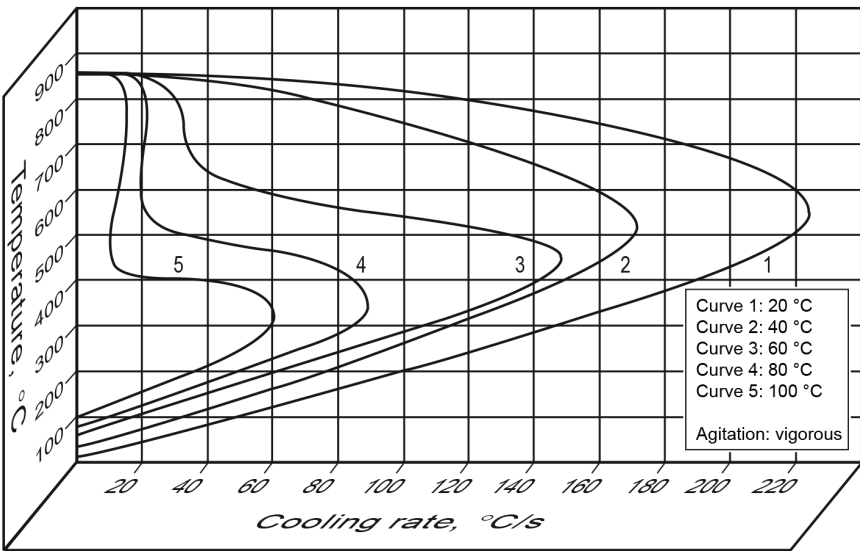


Fig. 6.4 The effect of temperature on the quenching characteristics of water.
Source: Ref 4

quenching speed of water is much faster at or below 26 °C (80 °F). However, in practice, where the quench water is recirculated through a water-to-water heat exchanger, the recirculated water temperature is more likely to be above the 32 °C (90 °F) range, unless the line-cooling water is obtained from a cool source, such as a well or a chiller. Even 6 °C (10 °F) can make a big difference in the quenching ability of water. Appendix 4, “Quench System Design,” in this book discusses system design requirements for keeping quenchant temperatures in a controlled range in order to maintain the same cooling rate throughout the workday.

Brine-based quenching systems have been used in place of water for the very high quenching-rate requirements. Brine is made through the addition of salts to water quenching systems. Commonly used materials include sodium chloride (NaCl), typically at 10%, and sodium hydroxide (NaOH), typically at 3%. When a workpiece is first quenched, salt crystals form and deposit on the surface of the workpiece, as shown in Fig. 6.5. Then the crystals fragment and cause disruption of the vapor film. Figure 6.6 shows an example of the effect of salt and the quenching characteristics of various salt solutions compared to water. The use of brine is limited because of high maintenance required for brine quenching systems, along with corrosion problems on the equipment and workpieces.

Soluble oil quenchants in water were more widely used before the introduction of the polymer-water-based quenchants. Soluble oil-water quenchants produce a quenching rate similar to that of water but are very difficult to use and produce inconsistent results. Oil-in-water emulsions

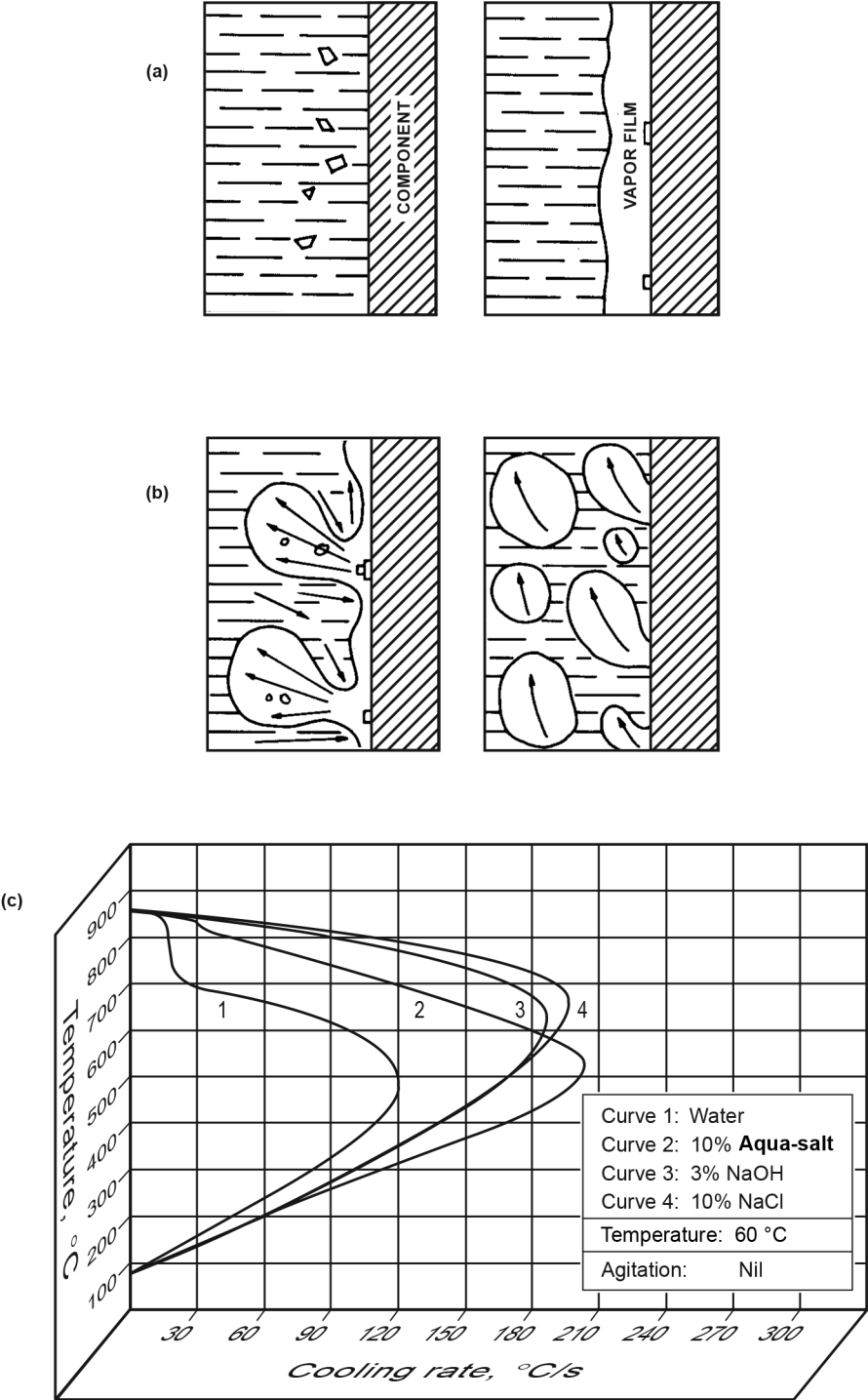


Fig. 6.5 (a) Salt crystals form and deposit on the component surface. (b) Crystals fragment, causing disruption of the vapor film. (c) The quenching characteristics of various salt solutions. Source: Ref 4

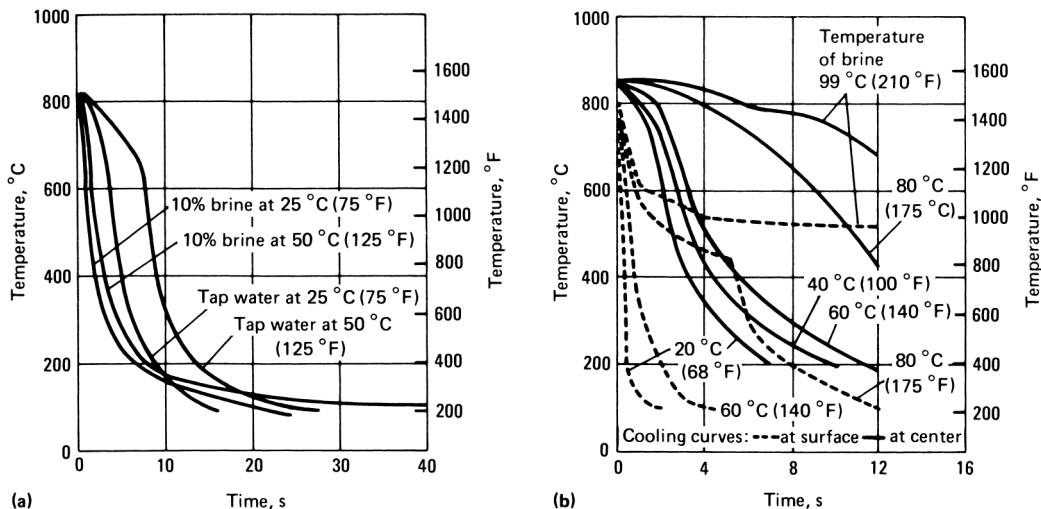


Fig. 6.6 Cooling curves showing effect of temperature on cooling power. (a) Center cooling curves for water and 10% NaCl solution in quenching 18-8 stainless steel specimens 13 mm (0.5 in.) diam by 64 mm (2.5 in.). No agitation. (b) Center and surface cooling curves for 5% NaCl solution at 0.9 mm/s (3 ft/s) in quenching 0.95% C steel specimens 13 mm (0.5 in.) diam by 50 mm (2 in.). Source: Ref 3

are effective as a final coolant for tempered parts to provide a black surface and rust protection (Ref 5).

Oil quenching can produce a wide range of quenching characteristics through careful formulation and blending. Quenching oils for conventional heat treating are classified by three quenching speeds: normal speed, medium speed, and high speed. Oils were traditionally used to avoid distortion or cracking problems, because of the slow cooling speeds of oil during the M_f - M_s transformation to martensite. As discussed in Chapter 5, “Heat Treating Basics,” in this book, a workpiece is least likely to crack when the entire cross section being hardened transforms to martensite at the same time. Oil quench systems, compared to the other quench systems, have a wide temperature range of operation in which the quenching speed does not vary enough to affect the hardness of the workpiece. The viscosity of quench oil increases up to the 66 °C (150 °F) region, producing faster cooling. Quench bath temperatures can range without any problem from room temperature to over 100 °C (212 °F).

When workpieces are immersed in oil, flames appear at the point of immersion. At that time the workpiece needs to be quickly, completely immersed in the oil bath so that the flame around the workpiece self-extinguishes. The flash point of quench oils is as high as 182 °C (360 °F), so the quench bath will not ignite as long as the bath temperature is below this point and the workpiece is plunged into the quench tank. During the immersion of the workpiece, smoke is produced that may need to be exhausted. When used for spray quenching, however, the workpiece itself

needs to be quenched below the flash point to prevent fires. After quenching with oil, the workpieces are normally cleaned to remove the oil dragout.

Oil quenching still has use in small production lots where polymer-based quenching testing is not feasible but the prevention of quench cracks and minimized distortion are important. Polymer-water-based quenchants in production have taken the place of most oil quenches because of the smoke produced with oil, the need to clean the oil before tempering, and the versatility of the polymers in adjusting quenching speed. Some suppliers of polymer quenchants claim they have the same cooling rate as oil in the martensitic transformation range. Note that, when interpreting the curves, the data are based on dunk quenching. Testing is recommended when making a change from oil to polymer.

Polymer quenches consist of solutions of organic polymers in water. They also contain corrosion inhibitors and other additives and are produced as concentrates that are further diluted to give ready-to-use quenching solutions. Polymer quenches eliminate the danger of fire hazard that exists with oil. At low concentrations the polymer quenches eliminate the soft spotting due to vapor pocket formation that is found with water quenches. (Note that proper quenching techniques must still be used, or self-tempering of martensite can occur because of improper quenchant impingement.)

One of the major advantages of polymer quenches is the ability to mix concentrations that cool anywhere from the quenching speed of water to the quenching speed of oil. Polymers can be selected and concentrations can be mixed to produce the quenching speeds and characteristics needed for specific parts made of specific steels. Cooling curves furnished by the manufacturers for polymer quenchants cover concentrations typically from 0 to 30% in concentration. Normal polymer quenchant temperatures in induction heating systems are held within 6 °C (10 °F) of the bath temperatures between 32 and 43 °C (90 and 100 °F).

Types of polymers used include:

- PAG—polyalkylene glycol
- ACR—sodium polyacrylate
- PVP—polyvinyl pyrrolidone
- PEO—polyethyl oxazoline

PAG and PEO are the most commonly used polymers with induction. They have similar characteristics in that their quenching speed decreases with increasing concentration and decreases with an increase in quenching temperature. All polymers have an increase in cooling rate with increased agitation.

PAG polymers have what is termed *inverse separation*. Depending on the chemical structure, the polymer that is first deposited on the steel part

during cooling goes back into solution in the quenchant in the 60 to 90 °C (140 to 194 °F) region. Figure 6.7 shows the cooling rates of PAG quenchants as a function of concentration, temperature, and agitation. The PAG polymers have dragout, and with heavy concentrations not only do the workpieces feel “slimy,” but also the fixturing in contact with the quenchant becomes coated.

The polymer-to-water ratio of PEOs is highly efficient in modifying quenching characteristics and required properties at low polymer concentrations. The inverse dragout is at 65 °C (150 °F), and PEOs have less dragout after quenching. Figure 6.8 shows the cooling rates of PEOs as a function of concentration, temperature, and agitation. PEOs have a faster cooling rate at low concentrations than do PAGs while having a lower cooling rate in the martensite-formation temperature range. The PEO polymers are rated to have the most oil-like quenching characteristics of the polymer quenchants.

Comparison of Quenchant Curves

One of the common modes for evaluating different quenchants is through the use of a quenchometer. Fixed-diameter balls have thermocouples inserted so that the cooling rate can be measured as the balls are quenched. The cooling curves produced from tests give comparisons among the speeds of different quenchants under different conditions. The basis for initial selection of a quenchant for an induction-hardened part is provided by these curves. Figure 6.9 shows the cooling curves of water, a 20% PAG polymer quench, and oil quench. These curves are all based upon dunk quenching of 25.4 mm (1 in.) diameter steel bars. Since most induction quenches are spray quenches, the effect of the direct impingement of the spray quench on larger workpieces may cause the quenchant to cool not only differently but also faster—at least in the vapor cooling stage. Polymer quenchants in polymer-to-water ratios ranging between 1.0% and 25% are extensively used to produce quenching speeds between those of water and fast oil. As the polymer-to-water concentration is reduced, the faster cooling rate decreases the overall time of quenching, thereby increasing productivity. Testing is necessary with many workpieces so that the quench concentration is characterized to a controllable range in which the leanest ratio of quenchant can be used without fear of cracking.

Quenching Methods

Many methods of quenching are used for induction heat treating, from simple dunking to spray impingement from high-velocity quench rings.

Dunk and Submerged Quenching. Parts that are not quenched by spray quenching from the coil, quench ring, or pad may be quenched directly by dropping or moving the parts into a quench tank. Dunk quench-

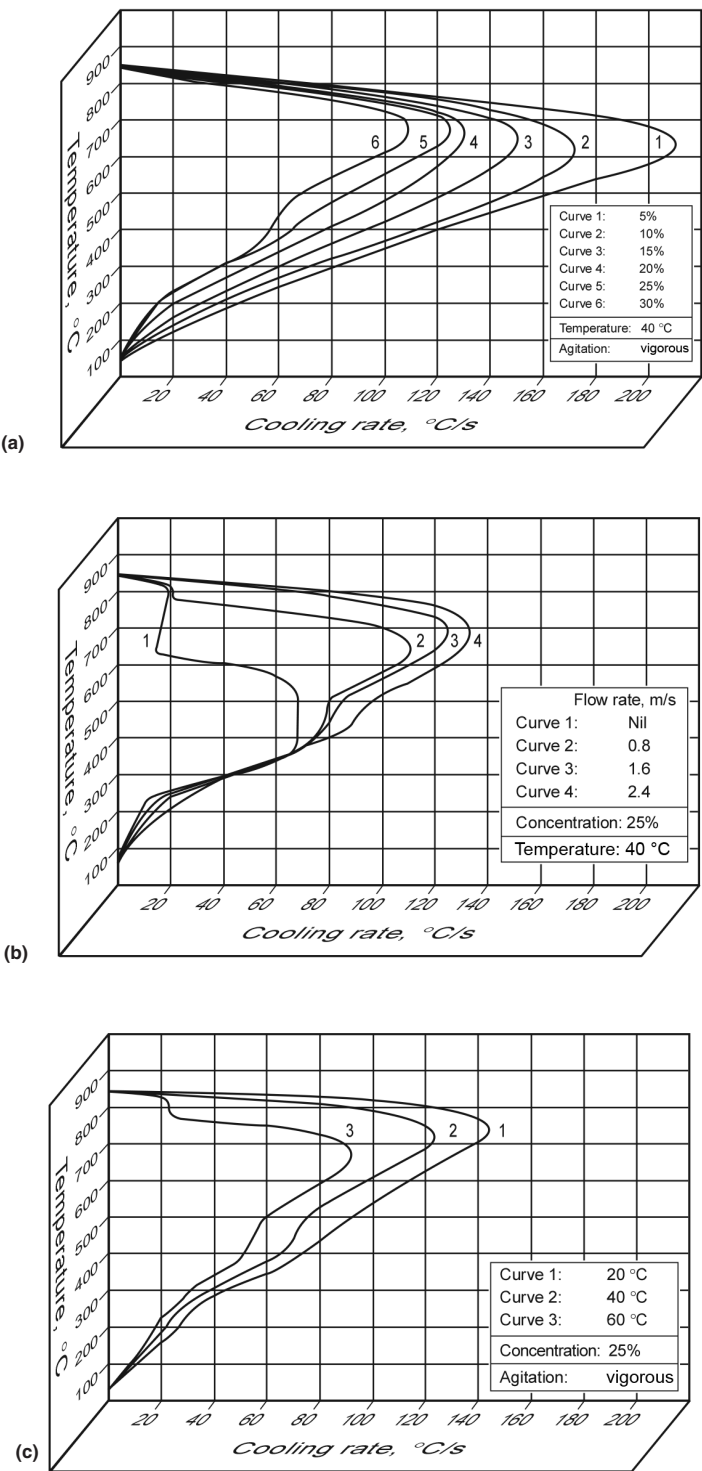


Fig. 6.7 Polyalkylene glycol quenchant: effect on quenching characteristics of (a) concentration, (b) agitation, and (c) temperature. Source: Ref 4

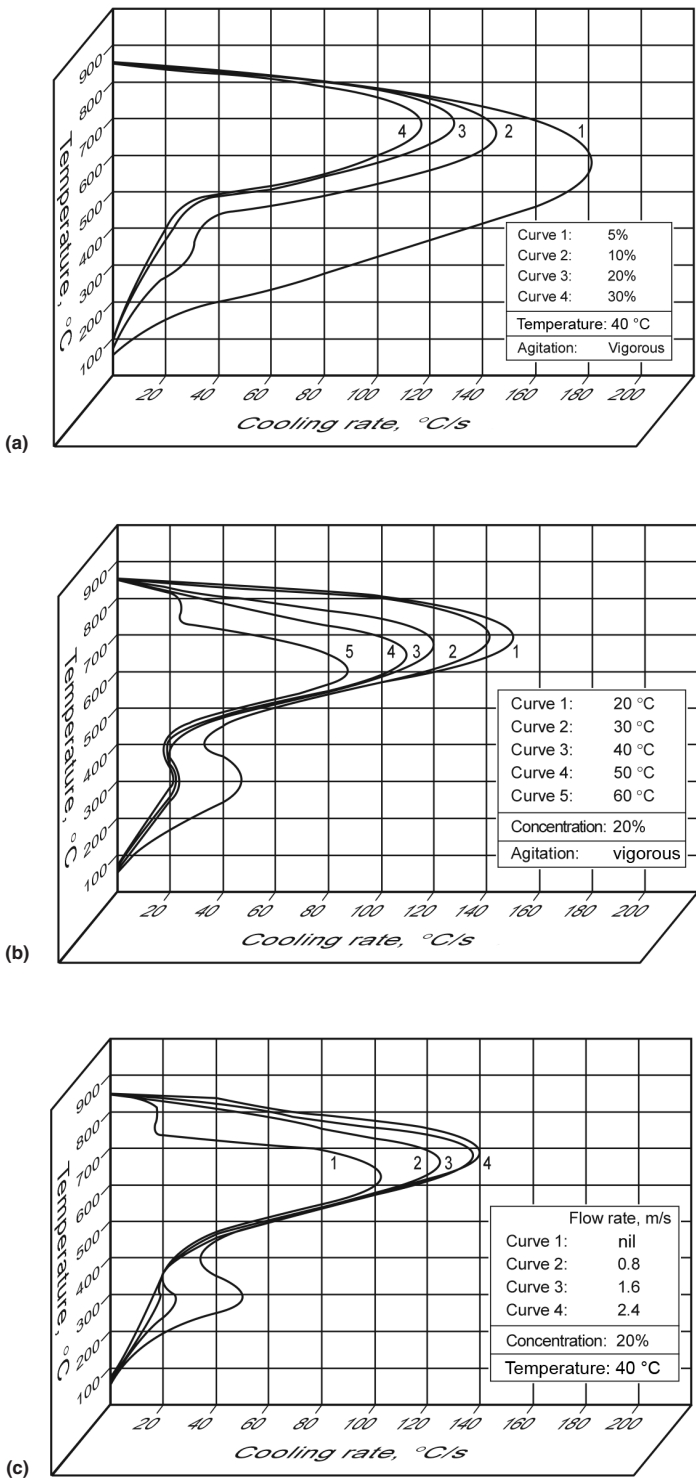


Fig. 6.8 Polyethyl oxazoline quenchant: effect on quenching characteristics of (a) concentration, (b) temperature, and (c) agitation. Source: Ref 4

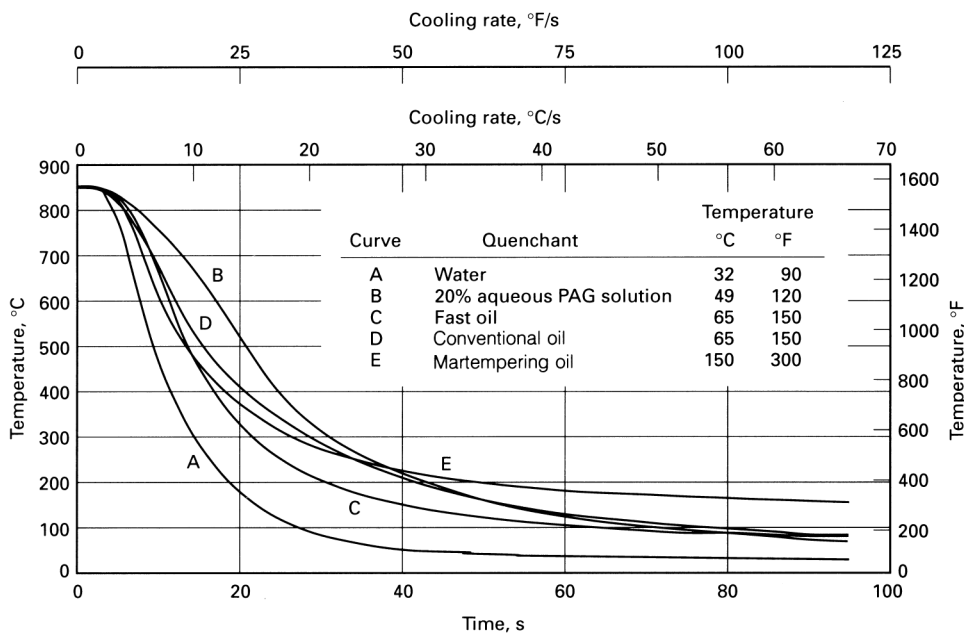


Fig. 6.9 Effect of selected quenchants on the cooling curve of a 25.4 mm (1.0 in.) diam steel bar. All quenchants flowing at 0.50 m/s (100 ft/min). PAG: polyalkylene glycol. Source: Ref 1

ing usually means the parts are dropped or quickly moved into a quench tank (with good agitation) and quenched through contact with the quenchant. In submerged quenching the parts may have impingement added through the use of quench rings. Finally, there are applications such as the tooth hardening of fine-pitch gears in which the parts are heated under water. The initiation of power heats the tooth sufficiently to cause a vapor pocket next to the area being heated. The tooth is then heated enough to provide complete austenitization while contact with the water prevents heating of the adjacent sides of the tooth. When the heat cycle is done, quenching is virtually instantaneous due to the water collapsing the vapor pocket and quenching the parts.

Mass Quenching. When the steels have any combination of sufficient mass to rapidly cool the part being heated or high hardenability of the steel, the cooling can be fast enough to produce the desired martensitic microstructure. AISI 4340, D2, and some of the stainless steels can air harden.

Forced Air Quenching. Forced air has been used where the hardenability was sufficient with the slower cooling effect of air, yet fully quenched. This is used in some cases where cracking was a problem and the mass of the part was small enough to permit adequate quenching.

Spray Quenches. This approach is used in both static heating and single-shot heating, where the workpiece is heated at one time, and in progressive hardening or scanning. The spray quenches can be located

either within the coil itself or in an external quench ring or blocks. When workpieces are induction scanned, they are moved progressively through the induction coil, heating first for austenitization and then quenching as the part passes through the coil.

Examples of Basic Quench Methods. Figure 6.10 shows 11 basic arrangements for quenching induction-hardened parts. Note that several common methods are used: submersion, heat and quench in place with

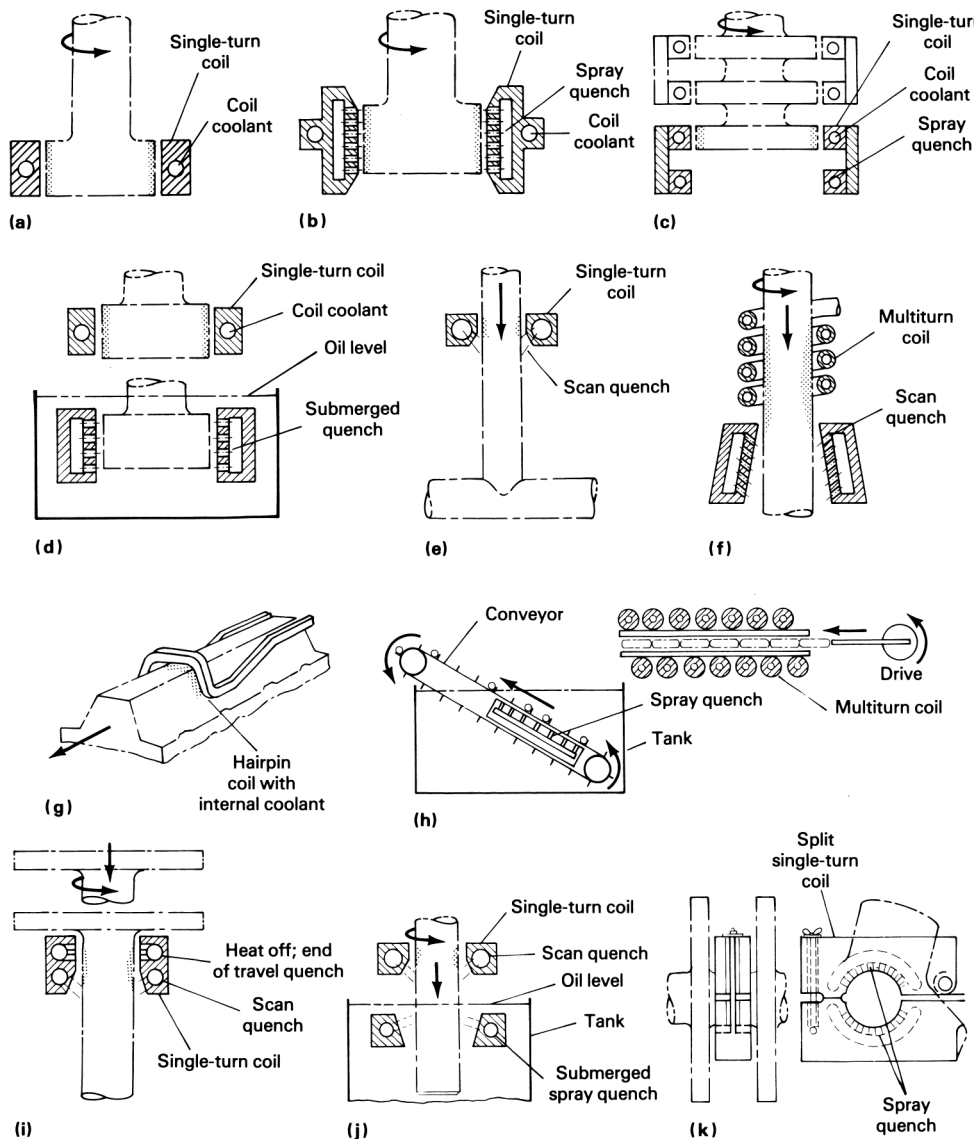


Fig. 6.10 Eleven basic arrangements for quenching induction hardened parts. See text for details. Source: Ref 1

quench integrated into the coil, and heat and quench either in place or out of coil with a separate directed quench:

- The workpiece is removed from the coil for quenching (Fig. 6.10a). Some workpieces that are hardened on index tables can be heated in position and then indexed into a spray quench.
- The workpiece is quenched in place from the coil after heating by a spray quench (Fig. 6.10b). In this case the coil has two different cooling passages: one on the outside diameter for cooling the coil, with the cooling water on all the time, and the second admitting quenchant through opening of a quench solenoid at the end of the heat cycle.
- The workpiece is lowered into a spray quench ring at the end of the heat cycle (Fig. 6.10c). This is commonly done with lift-and-rotate devices. At the end of the quench cycle, the workpiece may be either lowered or raised for removal.
- The workpiece is lowered into a quench tank for submerged quenching (Fig. 6.10d). If oil is used, as in the example in Fig. 6.10(d), the part must be lowered rapidly and completely into the oil to prevent fire. Polymer may also be used. As previously discussed, polymers will have no fire hazard, but tank temperature control and uniform agitation are much more important. Quench rings can be used in tanks to increase the quenching speed.
- A scanning coil is used, where the quenchant cools the work coil (Fig. 6.10e). The quenchant must be flowing during the entire heating cycle.
- A multiturn scanning coil is used with a separate quench ring on the exit side of the workpiece (Fig. 6.10f). This technique can also be used with single- and low-turn coils. One quench ring can be used over a number of different coil diameters. The quench ring can also be spaced at a distance below the coil to permit more equalization of the austenitized temperature before quenching, providing more system versatility.
- The mass of a workpiece is used to self-quench the part (Fig. 6.10g). A 4340 steel will quench very effectively in some applications using this technique.
- Workpieces are pushed horizontally through an induction coil, dropping into a quench tank to be brought out by a conveyor (Fig. 6.10h). Rotary wheel fixtures can use the same technique.
- Vertical scanning can be combined with two quenches (Fig. 6.10i). When hardening onto the faces of workpieces such as spindles, the cycle initiates with stationary heating of the face, followed by scanning of the body. When the scanner starts to move away from the face, it is necessary to quench the face. A lower quench is used to quench the body during the scanning travel. Sometimes with deep case hardening a secondary quench is necessary below the primary quench because

after the workpiece has passed out of the primary quench, the residual heat in the core can cause the surface to reheat and temper if a secondary quench is not used.

- Vertical scanning can use as the primary quench a spray quench from the coil and as secondary quench a quench tank (Fig. 6.10j). The effectiveness of the tank quench is increased through the use of a submerged spray quench.
- A split-type coil such as is used in hardening a crankshaft journal can have built-in spray quench (Fig. 6.10k).

Selection of Quenchant

A review of Fig. 6.11 shows the metallurgical basis required to verify the selection of quenchant, that is, to pick a quenchant for the particular part and alloy being cooled that will cool fast enough to permit transformation to martensite without cracking or distortion. Therefore, the general recommendation for selection of a quenchant for induction heat treating is to select the fastest speed quenchant that will produce the desired hardness and case depth without cracking the part. In general with temperature and agitation as a constant, lower-carbon steels require the faster cooling rates that are produced by water or low-polymer-concentration quenchants. Since the low-carbon steels do not produce quench cracks, the selection of a high-speed quenchant is obvious. Also, fairly fast quenchants are used

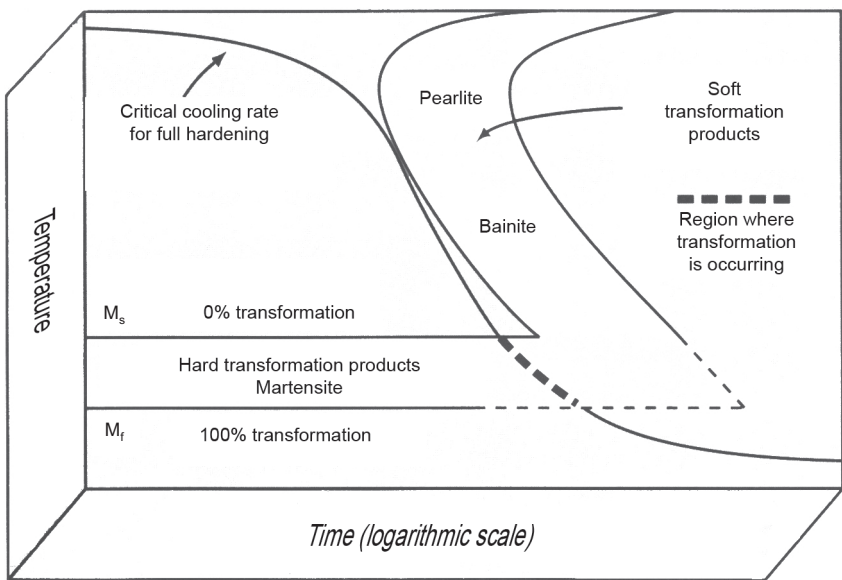


Fig. 6.11 Continuous cooling transformation diagram illustrating the critical cooling rate for complete martensitic transformation. M_s : temperature at which transformation of austenite to martensite starts; M_f : temperature at which transformation of austenite to martensite is completed. Source: Ref 4

very effectively in some applications with alloy steel parts where the application involves shallow case depths or small areas to be hardened.

Higher-carbon steels, generally over 0.45% carbon, may require slower quenchants, and the alloy steels may require high polymer concentrations or oil quenchants. To keep alloy steels from cracking, cooling through the M_f to M_s temperatures must be uniform. Sometimes testing is needed to determine the use of the in-between concentrations of polymers on specific applications for suitability. The higher concentrations of polymers have more dragout, adding cost. From a productivity viewpoint, keeping the concentrations as low as practical reduces cost by decreasing the overall cycle time. Finally, the nature of the mechanical handling may help dictate the type of quenchant to be used, while the nature of the part and process may dictate the type of quenchant to be used, quenchant concentration, and temperature.

Methods of Reducing Contamination of Quenchants

- Clean the parts prior to induction hardening.
- Make certain there is no leaking of hydraulic fluids into quenchant.
- Use lubricants that are not readily soluble in the quenchant.
- Make certain any forging compounds left on the parts will not contaminate the quenchant.
- When water is used as a quenchant, make certain it does not become contaminated or have too high of a concentration of dissolved salts due to make-up water being added.

See also Appendix 4, “Quench System Design,” in this book.

In summary, induction heat treating not only requires proper austenitization but also the correct quenching quenchants and techniques to produce good parts.

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CHAPTER 7

Tempering

STEELS ARE TEMPERED to obtain specific values of mechanical properties, to relieve quenching stresses, and to ensure dimensional stability. The highest hardness produced for any given steel without any other surface process is obtained by quenching to a fully martensitic microstructure. The high hardness characteristic of a martensitic microstructure is produced from the straining of the iron lattices by the carbon. Because hardness is directly related to tensile strength, steel composed of 100% martensite is at its strongest possible condition. However, the condition of highest strength is also the condition at which steel is most subject to brittle fracture due to lack of ductility. Except at low carbon contents, fully martensitic steels have insufficient toughness for many applications. Therefore, martensitic steels produced by medium-carbon and high-carbon steels are usually tempered after induction hardening in order to increase their ductility. During tempering, martensitic microstructures supersaturated with carbon are decomposed into more stable, ductile microstructures. Figure 7.1 shows the increase in ductility (greater reduction in area and more elongation) and lowering of hardness for 4340 steel as it is tempered with increasing temperature. Figure 7.2 shows how increasing the tempering temperature for 4140 steel lowers the hardness and increases the notch toughness, a measure of ductility.

The variables associated with tempering after induction hardening that affect the microstructure and the mechanical properties include tempering temperature, time at temperature, and the composition of the steel (including carbon content, alloy content, and residual elements). On heating a martensitic microstructure, the carbon atoms diffuse and act over increasing temperature and time in a series of distinct steps that eventually form iron carbide or alloy carbide of iron in a ferrite matrix. This gradually decreases hardness, tensile strength, and yield strength while increasing ductility and toughness. The properties of the tempered steel are determined primarily by the size, shape, composition, and distribution of the

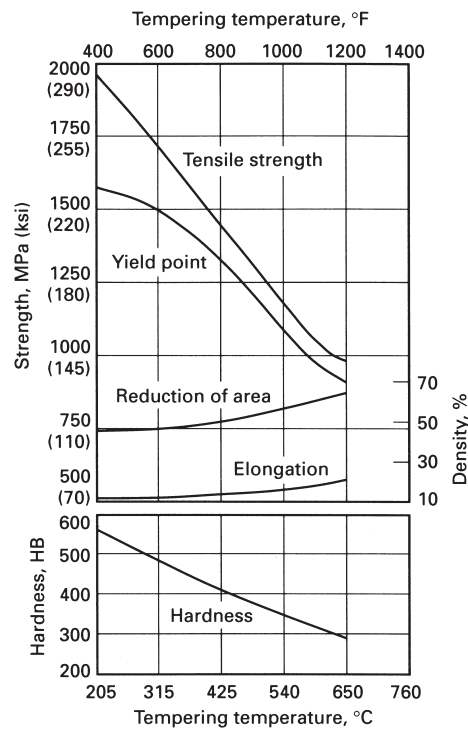


Fig. 7.1 Effect of tempering temperature on the mechanical properties of oil-quenched 4340 steel bar. Single-heat results: ladle composition, 0.41C-0.67ΔMn-0.023ΔP-0.018ΔS-0.26ΔSi-1.77ΔNi-0.78ΔCr-0.26Mo; grain size, ASTM 6 to 8. Critical points: A_{c1} , temperature at which austenite begins to form on heating, 730 °C (1350 °F); A_{c3} , temperature at which transformation of ferrite to austenite is completed on heating, 770 °C (1475 °F). A_{r3} , 475 °C (890 °F); A_{r1} , 380 °C (720 °F). Treatment normalized at 870 °C (1600 °F), reheated to 800 °C (1475 °F), quenched in agitated oil. Cross section, 13.46 mm (0.530 in.) diam; round treated, 12.83 mm (0.505 in.) diam; round tested; as-quenched hardness, 601 HB. Source: Ref 1

carbides that are formed, with a relatively minor contribution from solid-solution hardening of the ferrite. Diffusion of carbon and the alloying elements necessary for the formation of the carbides are temperature and time dependent.

Structural Changes and Stages of Tempering

Based on x-ray diffraction, dilatometric, and microstructural studies, although the temperature ranges may have some overlap, most steels are considered to have three distinct stages of tempering (while some tool steels have a fourth stage).

- *Stage I:* 100 to 250 °C (210 to 480 °F), the formation of transition carbides and lowering of the carbon content of the martensite to 0.25%

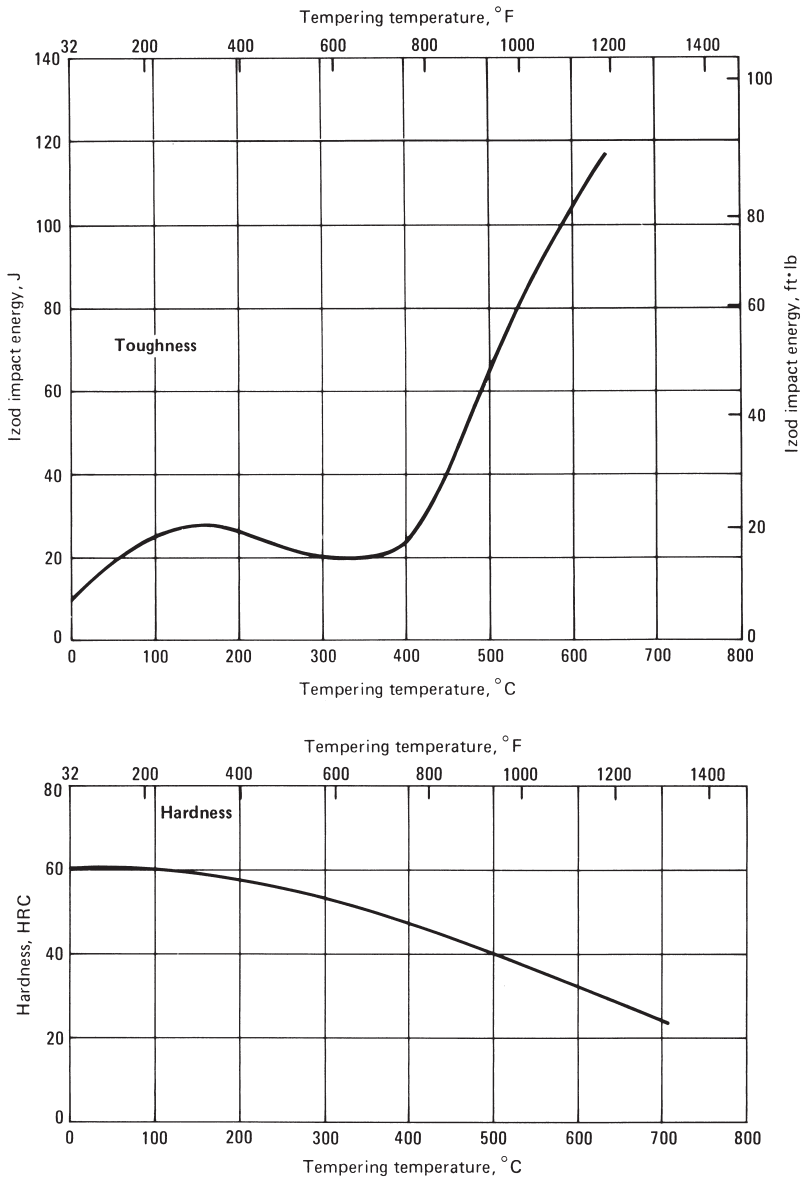


Fig. 7.2 Hardness and notch toughness of 4140 steel tempered 1 h at various temperatures. Source: Ref 2

- *Stage II:* 200 to 300 °C (390 to 570 °F), the transformation of retained austenite into ferrite and cementite
- *Stage III:* 250 to 350 °C (480 to 660 °F), the replacement of transition carbides and low-temperature martensite by cementite and ferrite
- *Stage IV:* 250 to 700 °C (480 to 1290 °F), the precipitation of finely dispersed alloy carbides and growth in carbide particle size

Dimensional Changes. During tempering, martensite decomposes into a mixture of ferrite and cementite, with a resultant decrease in volume as the tempering temperature increases. Any retained austenite transforms to bainite, with an increase in volume in stage II of tempering. When certain alloy steels are tempered, a precipitation of finely distributed alloy carbides occurs, along with an increase in hardness. With the precipitation of these alloy carbides, the M_s temperature of the retained austenite will increase, such that the remaining retained austenite is transformed to martensite during cooling. This tempering, called secondary hardening, does not usually start until over 425 °C (800 °F). After cooling to room temperature, the hardness can be higher than as-quenched hardness.

Tempering Temperature

The tempered hardnesses for several furnace-austenitized and quenched steels are presented in Table 7.1. Temperature and time are interdependent variables in the tempering process. Minor temperature changes have more effect than minor time changes. Figure 7.3 shows the decrease in hardness

Table 7.1 Typical hardnesses of various carbon and alloy steels after tempering

Grade	Carbon content, %	Hardness, HRC, after tempering for 2 h at °C (°F):									Heat treatment
		205 (400)	260 (500)	315 (600)	370 (700)	425 (800)	480 (900)	540 (1000)	595 (1100)	650 (1200)	
Carbon steels, water hardening											
1030	0.30	50	45	43	39	31	28	25	22	95(a)	Normalized at 900 °C (1650 °F); water quenched from 830 to 845 °C (1525 to 1550 °F); average dew point, 16 °C (60 °F)
1040	0.40	51	48	46	42	37	30	27	22	94(a)	
1050	0.50	52	50	46	44	40	37	31	29	22	Normalized at 885 °C (1625 °F); water quenched from 800 to 815 °C (1475 to 1500 °F); average dew point, 7 °C (45 °F)
1060	0.60	56	55	50	42	38	37	35	33	26	
1080	0.80	57	55	50	43	41	40	39	38	32	Normalized at 900 °C (1650 °F); water quenched from 830 to 855 °C (1525 to 1575 °F); average dew point, 13 °C (55 °F)
1095	0.95	58	57	52	47	43	42	41	40	33	
1137	0.40	44	42	40	37	33	30	27	21	91(a)	
1141	0.40	49	46	43	41	38	34	28	23	94(a)	
1144	0.40	55	50	47	45	39	32	29	25	97(a)	
Alloy steels, water hardening											
1330	0.30	47	44	42	38	35	32	26	22	16	Normalized at 900 °C (1650 °F); water quenched from 800 to 815 °C (1475 to 1500 °F); average dew point, 16 °C (60 °F)
2330	0.30	47	44	42	38	35	32	26	22	16	
3130	0.30	47	44	42	38	35	32	26	22	16	Normalized at 885 °C (1625 °F); water quenched from 800 to 855 °C (1475 to 1575 °F); average dew point, 16 °C (60 °F)
4130	0.30	47	45	43	42	38	34	32	26	22	
5130	0.30	47	45	43	42	38	34	32	26	22	
8630	0.30	47	45	43	42	38	34	32	26	22	
Alloy steels, oil hardening											
1340	0.40	57	53	50	46	44	41	38	35	31	Normalized at 870 °C (1600 °F); oil quenched from 830 to 845 °C (1525 to 1550 °F); average dew point, 16 °C (60 °F)
3140	0.40	55	52	49	47	41	37	33	30	26	
4140	0.40	57	53	50	47	45	41	36	33	29	Normalized at 870 °C (1600 °F); oil quenched from 830 to 845 °C (1525 to 1575 °F); average dew point, 13 °C (55 °F)
4340	0.40	55	52	50	48	45	42	39	34	31	
4640	0.40	52	51	50	47	42	40	37	31	27	Normalized at 870 °C (1600 °F); oil quenched from 830 to 870 °C (1525 to 1600 °F); average dew point, 13 °C (55 °F)
8740	0.40	57	53	50	47	44	41	38	35	22	
4150	0.50	56	55	53	51	47	46	43	39	35	Normalized at 870 °C (1600 °F); oil quenched from 815 to 845 °C (1500 to 1550 °F); average dew point, 13 °C (55 °F)
5150	0.50	57	55	52	49	45	39	34	31	28	
6150	0.50	58	57	53	50	46	42	40	36	31	
8650	0.50	55	54	52	49	45	41	37	32	28	
8750	0.50	56	55	52	51	46	44	39	34	32	
9850	0.50	54	53	51	48	45	41	36	33	30	

(a) Hardness, HRB. Data were obtained on 25 mm (1 in.) bars adequately quenched to develop full hardness. Source: Ref 2

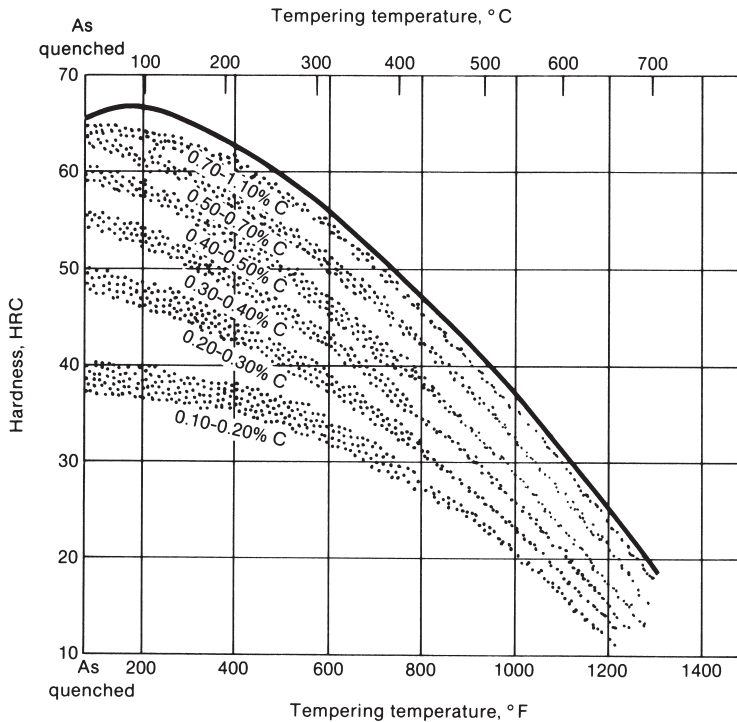


Fig. 7.3 Decrease in hardness with increasing tempering temperature (1 h tempering time) for carbon steels of various carbon contents. Source: Ref 3

with increasing tempering temperature for carbon steels of various carbon contents. Induction-hardened parts are normally tempered between 150 to 540 °C (300 and 1100 °F), with most induction-hardened parts probably tempered below 260 °C (500 °F). However, tempering at 150 °C (300 °F) can sometimes drop the hardness below specification. In this case, tempering at 121 °C (250 °F) can produce what is termed *stress relief* and increase the ductility without lowering the hardness.

Tempering Time

The decrease in hardness with time at four tempering temperatures for a 0.82% carbon steel is shown in Fig. 7.4. Time is shown on a logarithmic scale. Most of the hardness decrease occurs in the first hour at heat; the second hour at heat has a very small decrease. The hardness decrease beyond 2 h is negligible. Because of this type of response, tempering temperature, rather than time, is usually best used as the variable for producing the required hardness. Time is used mainly in three applications. First, continuous furnaces, as described later, need to have the parts in the furnace for minimum times. For example, it may be experimentally verified

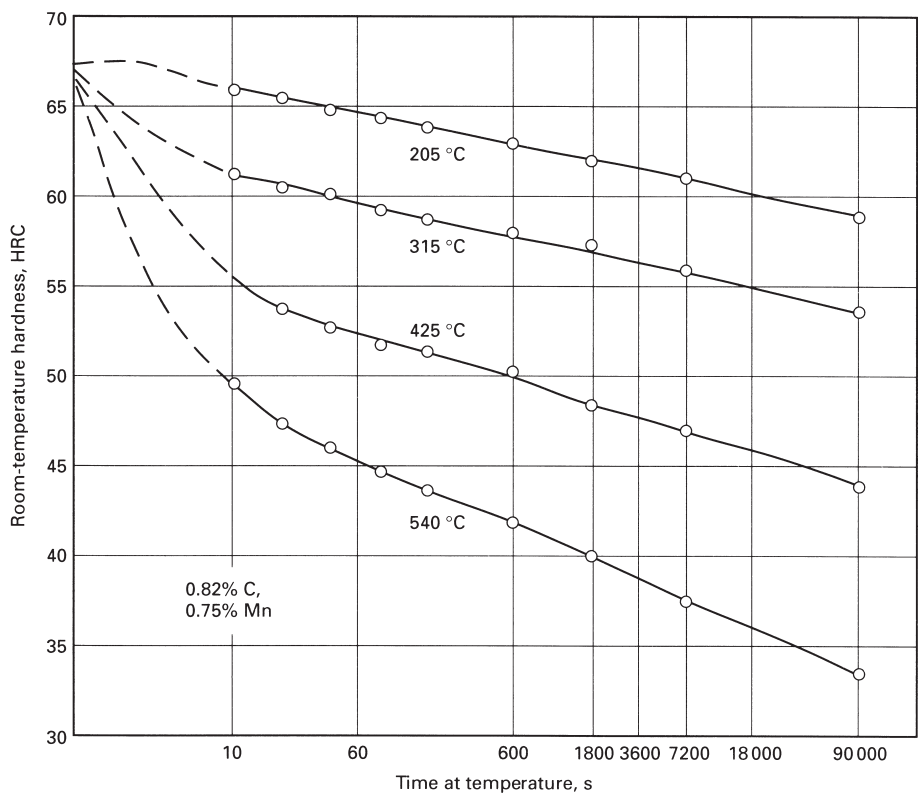


Fig. 7.4 Effect of time at four tempering temperatures on room-temperature hardness of quenched 0.82% C steel. Note the nearly straight lines on the logarithmic time scale. Source: Ref 1

that 20 min in a continuous furnace produces the desired hardness. Second, batch furnaces may have the times at heat increased because of the load density. The mass or weight of the load affects time for the load to uniformly heat to tempering temperature. Typical batch loads run at heat from 1 to 2 h. Finally, induction tempering requires sufficient time for heat transfer in the workpiece, so that the entire hardened area is heated to tempering temperature. Typical tempering times for induction tempering may run from 10 to 20 s.

Tempering Processes

Three types of tempering processes are commonly used after induction hardening a workpiece: furnace tempering, induction tempering, and residual heat tempering.

Furnace Tempering

Batch tempering is most commonly done in an oven. Steel workpieces are loaded into baskets or retorts, so that the entire load is tempered in one heat at the temperature and time required for lowering the surface hard-

ness into the specified range. The most uniform heating in batch ovens is accomplished with ovens that have fans to provide high air recirculation through the load. The heating characteristics of the furnace being used should be considered when selecting the time to use for tempering. Load density and convection in the furnace change the time required to bring the entire load up to temperature. Depending on the load density, intensity of air recirculation, and type of oven, the normal rule for tempering time is from 1 to 2 h at heat. Once the heating time cycles are established, tempering temperature is normally used to determine the required change in hardness.

The tempering curves for several common induction-hardened 0.45% carbon steels are shown in Fig. 7.5. These tempering curves are used as

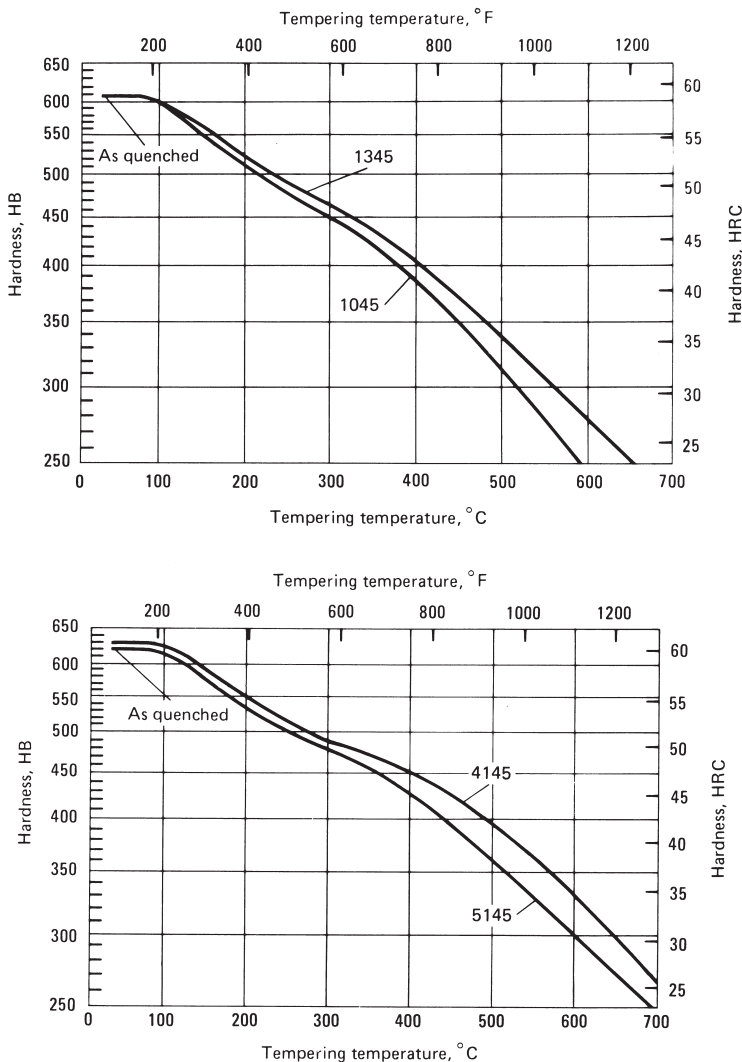


Fig. 7.5 Tempering characteristics of four 0.45% carbon and alloy steels tempered 1 h. Source: Ref 2

the model for selection of tempering temperature by batch furnace tempering. As previously mentioned, there is usually no drop in hardness in induction-hardened workpieces when tempered at 121 °C (250 °F). When workpieces quench harder or softer than the curves, interpolate using the drop in hardness with change in temperature to calculate a revised tempering temperature. For instance, if a 4145 steel workpiece quenches to 58 HRC and needs to be tempered to 50 to 55 HRC, a 4.5 point drop in hardness requires a tempering temperature of about 205 °C (400 °F). A workpiece can be run through in a pilot test to verify the temperature that is correct for the hardness drop. Then, if the hardness is off by only a point or two, a minor adjustment in temperature is needed. Carbon steels have a nearly linear decrease in hardness over 149 °C (300 °F), with a drop of one point HRC for roughly every 13 °C (25 °F) increase in temperature. This rule is useful when there are variations in the as-quenched hardness and minor adjustments need to be made in the tempering temperature. Caution must be used when tempering alloy steels. Many of the textbook curves may not show the decrease in hardness that may occur below 204 °C (400 °F), and the decrease in hardness may not be linear. Additional tempering curves for steels commonly induction hardened are shown in Appendix 5, “Tempering Curves,” in this book.

Continuous furnaces or ovens use higher tempering temperatures than do batch furnaces to reduce the as-quenched hardness because the workpieces are not held at temperature as long. Because of this, the time and temperature relationships for the needed drop in hardness have to be more closely reviewed before processing. Again, the tempering of pilot workpieces is recommended.

If workpieces are run through at a lower temperature that does not produce the necessary drop in hardness, the workpieces can be retempered at a higher temperature without any detrimental effect on properties. For example, assume that a specification calls for HRC 51 to 55. If a load of 0.45% carbon steel is tempered at 204 °C (400 °F) to produce a final hardness of HRC 55, the load can be rerun at 232 °C (450 °F) to produce an expected hardness of HRC 53. The drop in hardness reacts to the temperature of the tempering operation in the second heating cycle, almost as if the first lower tempering operation had not been done.

Metallurgy of Short-Time Tempering. Cellular manufacturing layouts require all processing for the manufacturing of a part to be in-line. Before induction tempering, continuous tempering ovens were used, which required substantial floor space. With induction installed in-line for tempering, floor-space requirements are reduced substantially. The metallurgical fact behind induction tempering is that short-time, higher-temperature tempering cycles can produce the same hardness as conventional long-time tempering. Higher tempering temperatures increase the diffusion-controlled precipitation of carbon from a martensitic microstructure.

Induction Tempering

The major differences between induction and furnace tempering are the times and temperatures involved. When workpieces are tempered by induction, they are heated to a given surface temperature with no holding time at temperature. Figure 7.6 shows hardness as a function of tempering temperature and time, for furnace- and induction- treated 1050 steel. The shorter cycle of an induction-tempered workpiece requires higher tempering temperatures. In Fig. 7.6 the austenitized and quenched hardness of the steel was 62 HRC. A 1 h furnace tempering cycle at 425 °C (800 °F) produced the same 40 HRC hardness as the same steel heated for 5 s to 540 °C (1000 °F). The faster tempering cycle requires a higher temperature for diffusion of the carbon atoms to form iron carbide. Because other mechanical properties, such as yield and tensile strength, elongation, reduction in area, and fracture toughness, often correlate with hardness, these two different treatments produce similar products. However, the mechanical properties may be different in induction-tempered workpieces than in furnace-tempered workpieces, because of the difference of time at temperature and the resulting differences in microstructure and residual stress.

Tempering always involves a reasonable compromise between maintaining the required hardness and obtaining a low-stress, tough, and ductile microstructure. Because stress relief is an important goal of tempering, it is imperative to know how internal stresses are relieved during induction tempering. Prior macrostresses, thermal stresses, and transformation

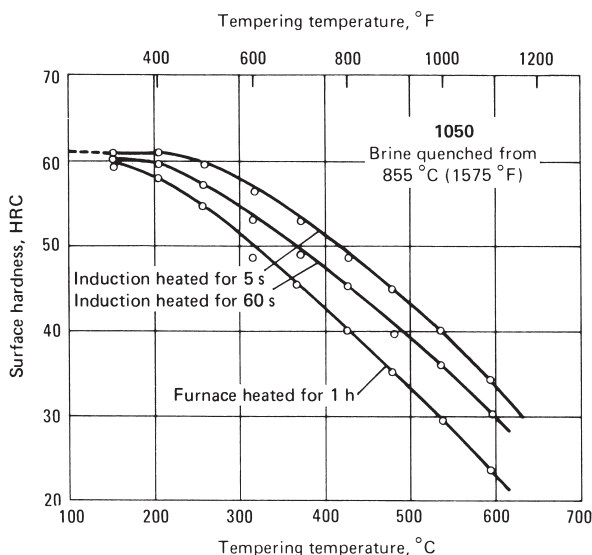


Fig. 7.6 Variation of hardness with tempering temperature for furnace and induction heating. Source: Ref 4

stresses are discussed in Chapter 5, “Heat Treating Basics,” in this book. The overall macrostresses may not be the same, and the microstructure may not be totally identical when comparing induction tempering to furnace tempering. Figure 7.7 plots temperature versus time for the induction tempering of a bar. The temperature distribution over heating and cooling is not as uniform as that produced during furnace tempering. It is important to examine the mechanical properties and part performance when induction tempering. These could be such properties as torsional strength, torsional fatigue life, bending strength, impact strength, and rotating-bending fatigue life. In some circumstances the torsional strength of a 1038 shaft tempered at 150 °C (300 °F) is better than an untempered shaft, even though the bending strength is higher in the untempered shaft.

Figure 7.8 shows the tempering temperature effect on bending strength and impact energy (brittleness) for an induction hardened and tempered SAE 15B35. Up to 150 °C (300 °F) there is very little drop in hardness, while the impact bending yield strength increases up to 260 °C (500 °F). Figure 7.9 shows the bending life fatigue of SAE 15B35 induction-hardened spindles versus the power setting. Each setting is equated to the furnace tempering temperature. The maximum fatigue life is in the untempered condition up to 180 °C (350 °F). Above this temperature the fatigue life drops rapidly.

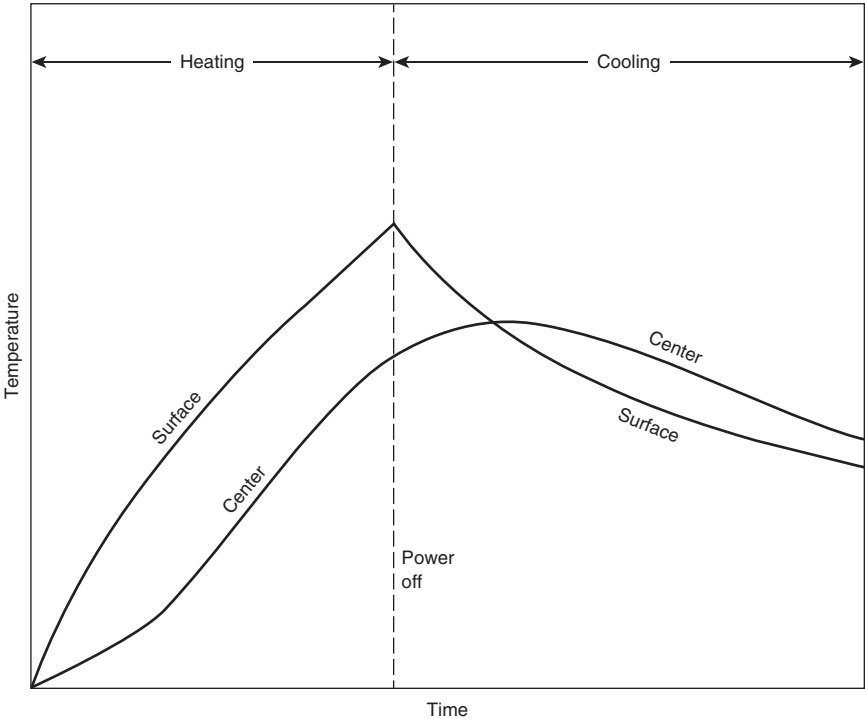


Fig. 7.7 Temperature vs. time plot at the surface and center of an induction-heated, solid bar. Source: Ref 5

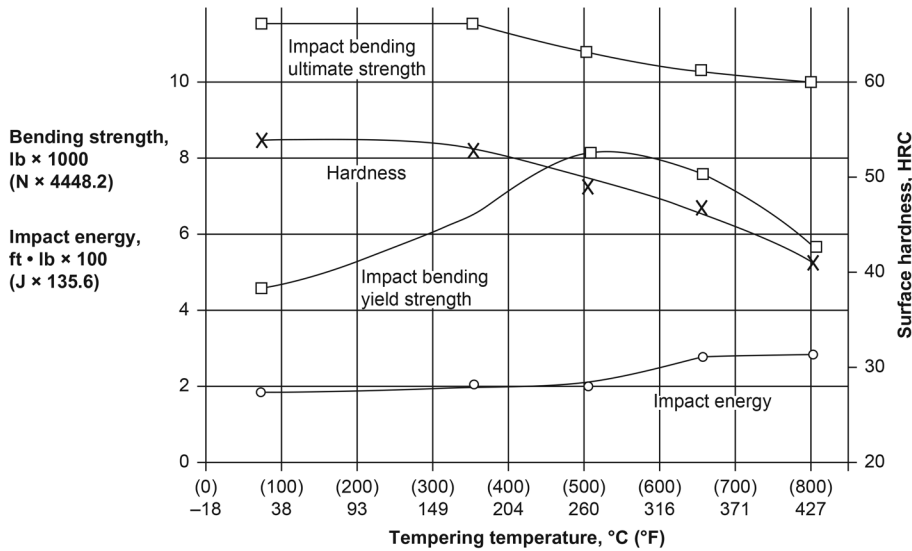


Fig. 7.8 Bending impact data from U-notched bar of SAE 15B35 steel, quenched and tempered to 229 to 269 HB. Induction-hardened effective case depth of 2.54 mm (0.100 in.) to 40 HRC. Source: Ref 6

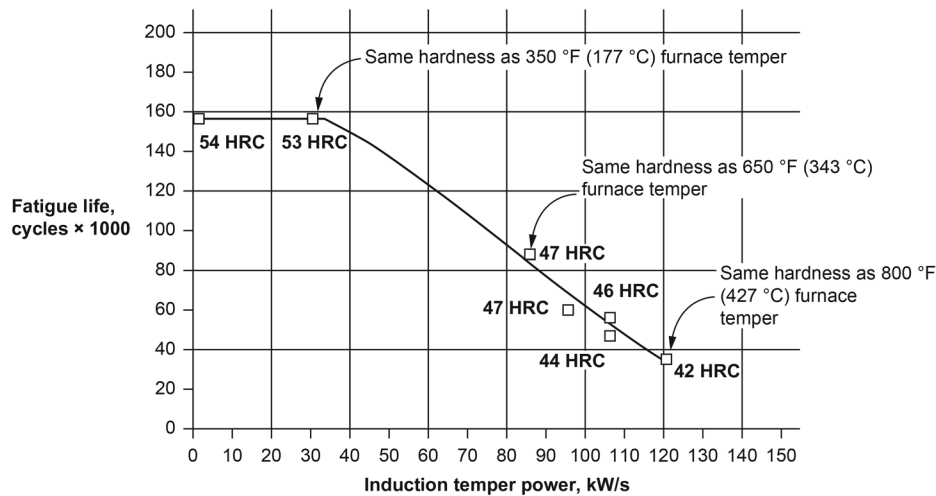


Fig. 7.9 Bending fatigue life of actual SE 15B35 induction-hardened spindles vs. the induction power setting. Source: Ref 6

The controls needed for induction tempering must be very stringent in terms of both time and temperature. The consistency of producing the same tempered hardness needs to be examined from all process variables. This includes variables such as different heats of steel, the effects on nonuniform geometry of the workpieces, and the ability of the induction heating system to provide precisely the same amount of power into the workpiece throughout the day.

Table 7.2 shows the effect of heating rate (the input power affects the heating rate) on the induction-tempered hardness of steels heated from 525 to 550 °C (980 to 1020 °F). Variance of the heating rates appears to be less important than the tempering temperature reached. For a given heating rate and cooling rate produced by air versus water, the major effect of the cooling rate on the effective tempering characteristics is to reduce the effective tempering time. This suggests that, for best process control, when induction tempering the heating rate should be slow enough to provide the uniform temperature needed throughout the cross section, and the cooling rate should be replicated when in production.

Single-Shot Tempering. In this process, neither the part nor the coil moves, although the part may be rotated. The entire part is heated in one heating cycle, which is substantially longer than the austenitizing cycle so that there is more time for conduction of heat into the entire part. This produces a lower temperature differential, which produces a uniform tempered hardness and minimizes residual stresses in the part. The single shot can be performed in a sequenced number of coils to provide the final uniform tempering desired.

Progressive or Continuous Heating. In this process, the workpiece moves though the coil or the coil moves along the workpiece in a continuous process. This is ideal for wires, rods, cylinders, and so forth. Figure 7.10 diagrams time versus temperature for induction tempering 18 mm (0.7 in) diameter medium-carbon steel rods traveling at a speed of 100 mm/s (4 in./s.). The induction-tempering line consists of four in-line multiturn coils with a profiled power distribution. The frequency is 1 kHz. Prior to induction tempering the rods were induction surface hardened; the case depth is 1.75 mm (0.07 in.). The length of the entire induction tempering systems was approximately 0.5 m (20 in.), representing a substantial reduction of floor space.

Scan tempering is done generally on outside diameters (ODs) and inside diameters (IDs) of cylindrical-shaped parts as well as flats. The parts are not generally very long, so the amount of residual heat in the part is the same.

Static tempering is used to temper many shapes of workpieces. Both single-position and multiposition holding nests are used; the parts are in-

**Table 7.2 Effect of heating rate (power input)
on hardness of induction-tempered steels**

Alloy	Hardness, HRC, at power input of:		
	2.5 kW	5 kW	10 kW
1020	30.2	30.7	31.3
1042	35.0	35.6	36.6
1095	44.5	44.6	46.4
4130	38.4	39.0	40.0
4340	41.4	41.8	41.4
4620	30.6	31.9	31.7
8620	32.2	32.8	33.0

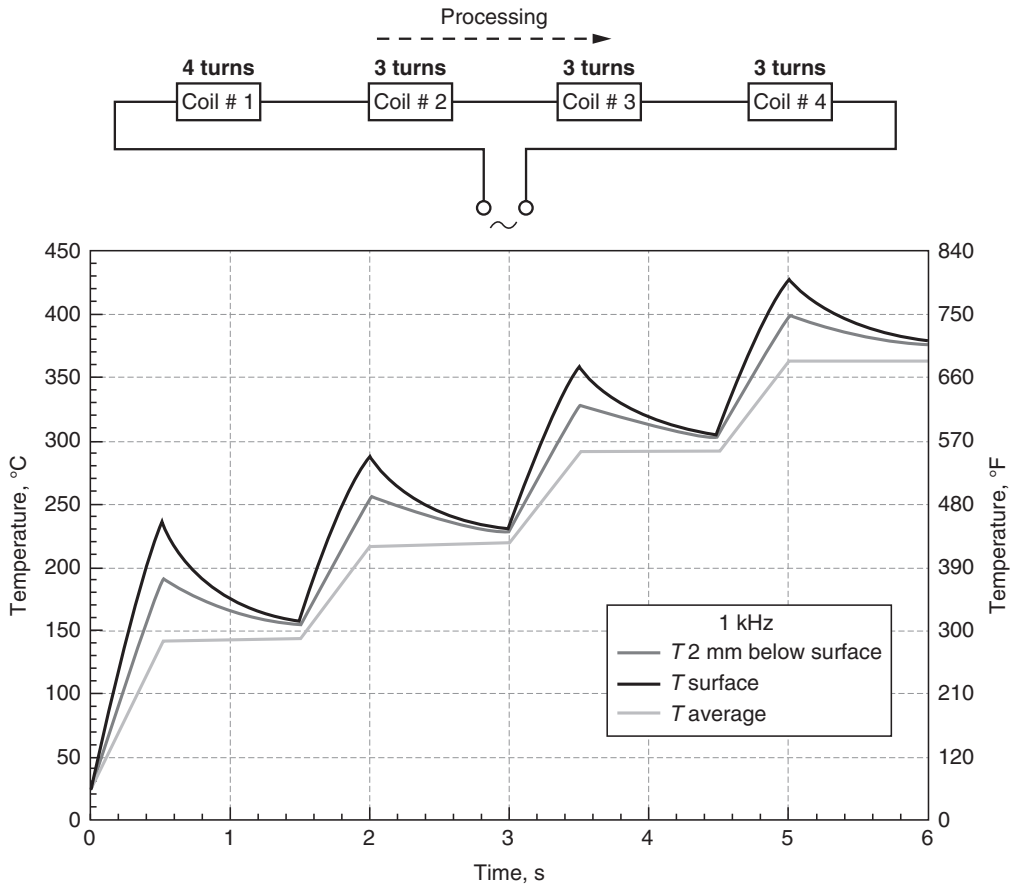


Fig. 7.10 Computer simulation of time-temperature diagram for induction tempering of 18 mm (0.7 in.) diameter medium-carbon steel rods traveling at 100 mm/s (4 in./s). Each coil is 50 mm (2 in.) long, and the distance between coils is 100 mm (4 in.). Source: Ref 6

dexed into different coils. The coils are generally coupled more loosely so that the parts heat over the entire length of the part. By loosely coupling, the rate of heat input into edges, shoulders, and holes is reduced so that the final heat in the tempered part is more uniform.

Process variables include:

- **Heating rate:** The heating rate during induction tempering can be varied over a wide range without noticeably affecting the final tempered hardness. This is a result of the slow air cooling that typically follows heat treatment. Because cooling occurs at a much lower rate than heating, the contribution of the cooling cycle to the effective tempering time is ordinarily more than that of the heating portion of the tempering treatment. As mentioned with induction tempering, the temperature to which the part was heated seems to have more effect than the heating rate.

- *Cooling method:* Similarly for a given heating rate, the method of cooling has a second-order effect on the effective tempering parameter and thus on tempered hardness levels. Its major effect is to reduce the effective tempering time. Just air-cooled or water-cooled parts heated to the same peak temperature with different power settings have tempered hardnesses that are nearly the same.
- *Power densities:* Tempering calls for much lower power densities (6 to 15 times lower) than hardening.
- *Power supplies:* Because the output power needed for hardening is substantially greater than for tempering, the use of the same power supply for both hardening and tempering may not be possible. Some types of power supplies cannot operate at very low power settings, such as 3 to 5% of their rated power.

The general recommendation, where possible, is that a workpiece that is outside-diameter (OD) induction hardened should be inside-diameter (ID) induction tempered whenever the ID is large enough to accept a work coil. Conversely, ID induction-hardened workpieces should be OD induction tempered. The reason for this is the shallow reference depth that is produced in steel under the Curie temperature, as previously described in Chapter 2, “Theory of Heating by Induction,” in this book. The initial high heat buildup is in the reference depth, which is usually less than the case or cross section, being tempered. At tempering temperatures, the rate of heat conduction is relatively slow, and it is harder to provide uniform tempering temperatures with the short heating time throughout the martensitic area. By heating from the opposite side, where higher temperatures have no effect on the properties of the workpiece, the heat flow provides a more gradual buildup of the temperature in the martensitic area and provides more uniform tempering temperature. Because of the slower rate of heat conduction, it is not unusual for the induction tempering heating time to exceed twice or more the austenitizing time for the same workpiece.

An induction-hardening process may have an indexing fixture with one heating position and frequency for austenitizing and quenching, and two other positions of a lower frequency for tempering. The heating time for an individual tempering position is equal to the austenitizing time. However, because the power density of each position is in the range of 6 to 15 times lower than when austenitizing, less heating occurs at each position. The total tempering time for a given part is the sum of the times for heating in all of the positions plus transfer time between positions, with the highest tempering temperature being produced at the last position. The total time for tempering is the total of the time spent in both tempering positions and the index in-between. Through a process such as this, the effective production rate as produced by the time of the austenitizing cycle is not reduced by the requirement for longer tempering time.

Additional care must be taken with regard to the selection of frequency, coil design, and technique of heating. Table 7.3 provides information regarding selection of power source and frequency for various applications of induction tempering. Lower frequencies are best used because of the deeper penetration into the surface of the part being tempered due to the tempering temperature being below the Curie temperature. The geometry of the workpiece obviously must be considered to recognize the effect of thermal mass on the induced energy. For instance, in the case of induction tempering of gears, it is very important that the tooth and the root of the tooth have identical heating times/temperatures. Because of this, most gears are usually furnace tempered.

Equivalent time/temperature cycles for tempering are determined in several ways. For example, tempering experiments can be conducted at a variety of temperatures for a range of times. The relationship for induction is determined and then plotted to establish the time/temperature relationship for the workpieces being heated. Table 7.4 provides operating and production data for progressive induction tempering.

Residual Heat Tempering or Self-Tempering

Residual heat tempering uses heat in the core of the workpiece after quenching to raise the surface heat back to tempering temperature after the surface is quenched below the M_f temperature. It is essential when self-tempering that residual heat be closely controlled, which can be challenging. It can be difficult to control the application and the quenching process so that the same heat balance is present in a part after quenching. The limitations are:

- Usually used for parts that have symmetrical, noncomplex geometry such as round cylinders or tubes

Table 7.3 Selection of power source and frequency for various applications of induction tempering

Section size		Maximum tempering temperature		Rating(a) for:					
				Power lines, 50 or 60 Hz	Frequency converter, 180 Hz	Solid-state systems or motor generators			Vacuum tube over 200 kHz
cm	in.	°C	°F			1000 Hz	3000 Hz	10,000 Hz	
0.32 to 0.64	1/8 to 1/4	705	1300	...	...	...	...	...	Good
0.64 to 1.27	1/4 to 1/2	705	1300	...	...	...	...	Good	Good
1.27 to 2.54	1/2 to 1	425	800	...	Fair	Good	Good	Good	Fair
1.27 to 2.54		705	1300	...	Poor	Fair	Good	Good	Fair
2.54 to 5.08	1 to 2	425	800	Fair	Fair	Good	Good	Fair	Poor
2.54 to 5.08		705	1300	...	Fair	Good	Good	Fair	Poor
5.08 to 15.24	2 to 6	425	800	Good	Good	Good	Fair	...	...
5.08 to 15.24		705	1300	Good	Good	Good	Fair	...	...
Over 15.24	Over 6	705	1300	Good	Good	Good	Fair	...	...

(a) Efficiency, capital cost, and uniformity of heating are considered in these ratings. "Good" indicates optimum frequency. "Fair" indicates frequency higher than optimum that increases capital cost and reduces uniformity of heating, thus requiring lower heat inputs. "Poor" indicates frequency substantially higher than optimum that substantially increases capital cost and reduces uniformity of heating, thus requiring substantially lower heat inputs. Source: Ref 3

Table 7.4 Operating and production data for progressive induction tempering

								Work temperature									
								Entering coil		Leaving coil							
Section size		Material	Frequency, Hz	Power(a), kW	Total heating time, s	Scan time		°C	°F	°C	°F	Production rate		Inductor input(b)			
cm	in.					s/cm	s/in.					kg/h	lb/h	kW/cm²	kW/in.²		
Rounds																	
1.27	½	4130	9600	11	17	0.39	1	50	120	565	1050	92	202	0.064	0.41		
1.91	¾	1035 mod	9600	12.7	30.6	0.71	1.8	50	120	510	950	113	250	0.050	0.32		
2.54	1	1041	9600	18.7	44.2	1.02	2.6	50	120	565	1050	141	311	0.054	0.35		
2.86	1⅛	1041	9600	20.6	51	1.18	3.0	50	120	565	1050	153	338	0.053	0.34		
4.92	1⅝ ₁₆	14B35H	180	24	196	2.76	7.0	50	120	565	1050	195	429	0.031	0.20		
Flats																	
1.59	⅝	1038	60	88	123	0.59	1.5	40	100	290	550	1449	3194	0.014	0.089		
1.91	¾	1038	60	100	164	0.79	2.0	40	100	315	600	1576	3474	0.013	0.081		
2.22	⅞	1043	60	98	312	1.50	3.8	40	100	290	550	1609	3548	0.008	0.050		
2.54	1	1043	60	85	254	1.22	3.1	40	100	290	550	1365	3009	0.011	0.068		
2.86	1⅛	1043	60	90	328	1.57	4.0	40	100	290	550	1483	3269	0.009	0.060		
Irregular shapes																	
1.75 to 3.33	1⅝ ₁₆ to 1⅝ ₁₆	1037 mod	9600	192	64.8	0.94	2.4	65	150	550	1020	2211	4875	0.043	0.28		
1.75 to 2.86	1⅝ ₁₆ to 1⅞	1037 mod	9600	154	46	0.67	1.7	65	150	425	800	2276	5019	0.040	0.26		

(a) Power transmitted by the inductor at the operating frequency indicated. For converted frequencies, this power is approximately 25% less than the power input to the machine, because of losses within the machine. (b) At the operating frequency of the inductor. Source: Ref 3

- Is more difficult to use where the parts have specific case-hardened regions and the tempering temperature cannot be uniformly distributed
- Very difficult to control when trying to temper small parts that do not retain much residual heat during quenching
- Hard to use in vertical scanning because of the effect of different amounts of residual heat in the top and bottom of a scanned part

Conclusion

The Hollomon-Jaffe tempering correlation and Grange-Baughman tempering correlation research provides formulas and discussion regarding mathematical determination and modeling of tempering temperatures. These calculations use formulas that involve time/temperature relationships for both furnace and induction tempering (Ref 6).

The decisions to temper or not to temper an induction-hardened part and what tempering process to use are application specific. In general, tempering decreases hardness and residual stress but increases ductility and impact strength. The effect of tempering on other mechanical properties is harder to define in advance and can vary depending upon the geometry of the part and its specific conditions of use. For this reason it is best to validate the effects of tempering by testing using actual service conditions. The best method of tempering is application specific.

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CHAPTER 8

Cleaning and Rust Protection

WORKPIECES MAY NEED CLEANING both before and after induction hardening. Machining fluid residues not only smoke during austenitizing but also can severely contaminate quenchants. This contamination will cause the quenchant's cooling rate to change, which of course is an undesirable condition. Furthermore, experience has shown that the workpieces need to be cleaned before furnace tempering. Finally, after tempering, unless the workpieces are processed in-line in a manufacturing cell, some sort of rust protection is advisable. With in-line processes, the necessity for cleaning and rust protection depends on the other in-line processes.

Cleaning

Different types of quenchants have different types of cleaning requirements before tempering. Oil quenchants need to be removed before tempering. Quench oils burn in the tempering furnaces, and if they are not removed, the parts in a tempering retort can actually glue together. The oil can coat the parts, similar to a thin lacquer, making cleaning very difficult after removal from the tempering furnace. While many types of solvent cleaners can be used, environmentally it is easy to use an industrial washer to remove the oil.

Surface Finish

Surface finish after quenching an induction-hardened part can be important. Parts that are heated with high austenitizing temperature can have surface defects such as blisters or solidified melts. Another common effect

is the formation of scale during austenitizing. Scale formation is a natural product of all steel parts that are heat treated by induction without protective atmosphere or vacuum. Oil quenches tend to produce a higher degree of scale retention than do water or polymer quenches, and the higher the temperature of austenitization, the greater the amount of scale. Removal of scale and any resulting surface defects may be needed to produce the finished part.

Some induction heat-treating processes use protective atmospheres to prevent scale formation. The protection involves preventing the oxygen from contacting the surface of the part being heated and quenched. Processes with atmospheres that are potentially explosive need to be carefully designed to prevent infiltration of oxygen. Flame curtains, such as used with furnaces, can be used. When inert atmospheres such as argon, helium, or nitrogen are used, the envelope surrounding the part being heated must be kept free of oxygen for complete protection. Another method uses a slightly reduced inert mixture. This has been done by adding hydrogen under 4%. A mixture of inert gas and hydrogen at less than 4% is not explosive.

Water quenches will leave the parts with a tendency to rust unless chemical rust inhibitors are used in the quench water. Sometimes enough residual heat can be left in the parts that any remaining water evaporates. Under continuous conditions, air blasts may remove the water. Rotating spindles with workpieces can have a rotation speed high enough to spin off the water.

Polymer quenches present a different situation. While the manufacturers state in their literature that parts can be tempered without washing, experience shows that the polymers must be rinsed or washed off before tempering. Several things can happen when parts are tempered without polymer removal. First, evaporation and burning of the polymer in the tempering process create obnoxious odors. Second, the polymers form adherent coatings that are difficult to remove after tempering. Third, polymers seem to make parts more susceptible to rusting at a later date—even if rust preventives are applied after tempering.

Rust Protection

A number of rust preventives can be applied for temporary protection. Keep in mind that when removed from the tempering furnace, the parts have clean surfaces. Rust can form very quickly, particularly in humid weather. Rust that is not visible can form in the pores, which over a period of several months will nucleate and grow. Therefore, it is recommended that rust preventives be applied to the parts as soon as possible after they have cooled.

CHAPTER 9

Decarburization and Defects

DECARBURIZATION MAY OR MAY NOT be a defect on a workpiece. The potential for decarburization needs to be understood so that workpieces are not rejected for low hardness during inspection. The intent of this Chapter is to explain decarburization and the importance of recognizing decarburization when induction hardening. Also, the nature and origin of various defects are explained so that proper analysis can be used to identify defects, both before and after induction hardening, that may make workpieces nonconforming.

Decarburization

Decarburization is a surface condition that is common to all hot-rolled steel products to some extent. It is produced during heating and rolling operations when oxygen in the atmosphere at temperature reacts with and removes carbon from the hot surface. Decarburization can also be produced when parts are furnace austenitized in air or incorrect protective atmospheres. The depth of decarburization depends on temperature, time at temperature, nature of furnace atmosphere, reduction of area between the bloom and the finished size, and the type of steel. Figure 9.1(a) and (c) show two examples of decarburization. Figure 9.1(a) shows surface decarburization and the increase in surface hardness, with hardness readings taken from the surface inward. Figure 9.1(c) shows the completely ferritic surface layer in a commercial 1.0% carbon strip in the austenitized and quenched condition. From an induction heat-treating viewpoint, any time plate or strip steel is being used as the material for a workpiece, there is potential for surface decarburization. Figure 9.2 shows the decarburization in a normalized, 0.8% carbon steel. Picral etchants define pearlite and

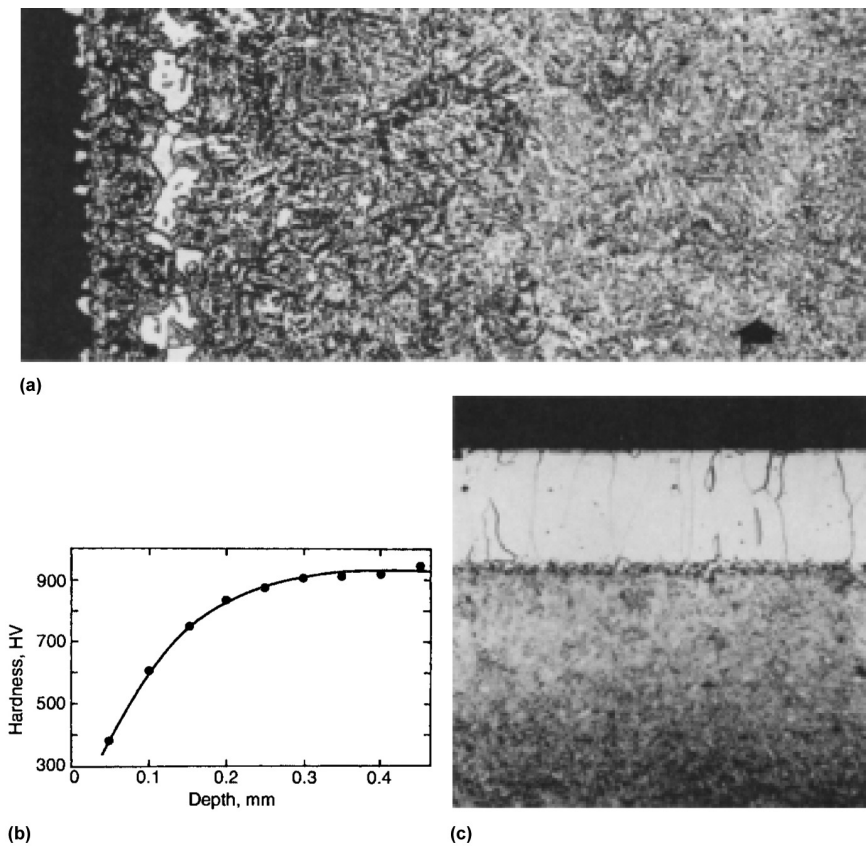
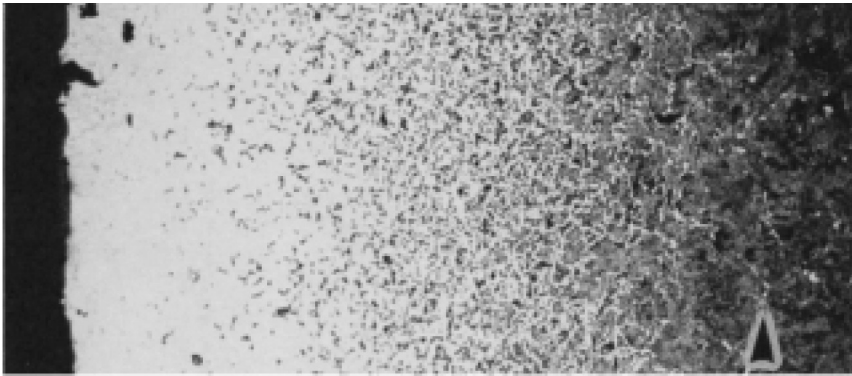


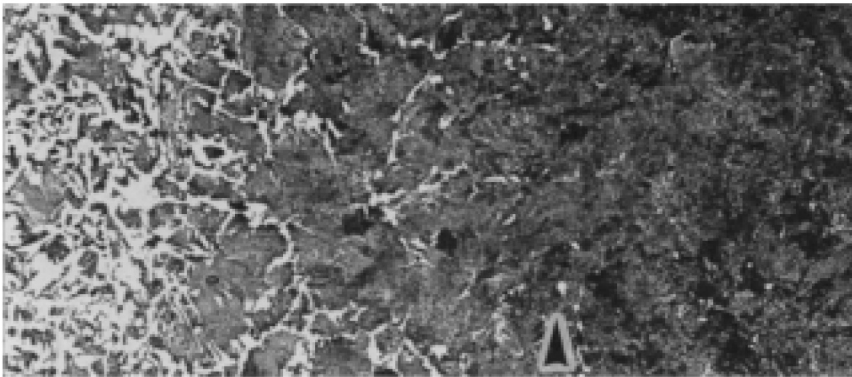
Fig. 9.1 Decarburization in a 1.3% C hypereutectoid steel in the quench-hardened condition. 1.20C-0.17Si-0.40Mn. Austenitized at 850 °C (1562 °F), water quenched, tempered at 175 °C (347 °F). (a) 1% nital. 250×. (b) Variation of hardness with depth in the quenched and tempered hypereutectoid steel. (c) Completely ferritic surface layer in a commercial 1% C strip in the quench-hardened condition. 3% nital. 250×. Source: Ref 1

show the ferrite (the decarburized area) as white. The nital etchants that are used for defining induction-hardened cases will not define decarburization very well unless the workpieces are tempered at a sufficiently high temperature to produce dark, tempered martensite when etched. Decarburization lowers surface hardness, producing a soft, low-strength area, and permits plastic deformation at the root of a notch without crack initiation. Thus, it will not lower, but may slightly increase, notch toughness. Decarburization also lowers the fatigue resistance of steel. Figure 9.3 illustrates the effect of decarburization on fatigue behavior of a steel. The decarburized parts have average lower fatigue lives. For this reason, critical parts, or at least critical areas of parts with decarburized surfaces, are usually machined to remove the decarburized material.

Depth of Decarburization Produced by Induction. For a typical 5 s heat cycle to 950 °C (1760 °F), the decarb depth is calculated to be 0.00197



(a)



(b)

Fig. 9.2 (a) Decarburization in a 0.8% C eutectoid steel, 0.78C-0.30Mn. Picral. 50 $\times$. (b) Transverse section of a hot-rolled bar; normalized. Picral. 100 $\times$. Arrowheads indicate total depth of decarburization. Source: Ref 1

cm (0.00078 in.). This depth is so shallow that decarburization with induction heat treating has never been a problem. Castings, forgings, cold-drawn stock, and hot-rolled products may all have decarburization unless the decarburization is removed, or unless there is a carbon restoration heat-treating process. Another source of decarburization occurs when parts are heat treated in nonprotective atmospheres or in atmospheres in which the carbon potential is such that decarburization is not prevented during austenitizing.

Castings. Decarburization is a normal product found on the surface of castings. Even investment castings, with the close finished tolerances, may have decarburization.

Forgings. Parts before forging are normally heated to forging temperatures without the benefit of protective atmospheres. Therefore, unless a carbon restoration process has been done, the forgings are likely to have decarburization. Table 9.1 shows the amount of stock removal recom-

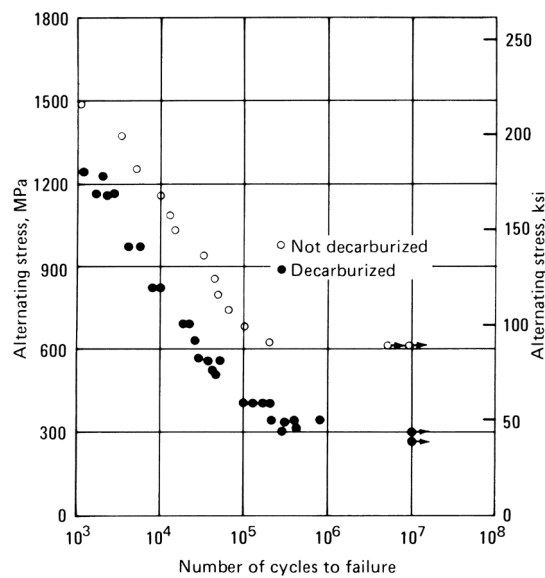


Fig. 9.3 Effect of decarburization on fatigue behavior of a steel. Source: Ref 2

Table 9.1 Typical decarburization limits for steel forgings

Range of section size		Typical depth of decarburization	
mm	in.	mm	in.
<25	<1	0.8	0.031
25 to 100	1 to 4	1.2	0.047
100 to 200	4 to 8	1.6	0.062
>200	>8	3.2	0.125

Source: Ref 2

mended for machining in highly stressed areas. Low surface hardness may result unless all the decarburization is removed.

Stock Removal for Cold-Finished Steel. Standard quality cold-finished bars are produced from hot-rolled steel. Therefore, the original decarburization that was present on the hot-rolled stock is still present on the steel, although it has been reduced in thickness as the bar diameter was reduced by cold drawing. Guidelines provide recommendations for stock removal of surface decarburization and any other surface defects that might be present. The recommended stock removal for all nonresulfurized grades is 0.025 mm per 1.59 mm (0.001 in. per $\frac{1}{16}$ in.) of cross section, or 0.254 mm (0.010 in.), whichever is greater. For example, for a 25 mm (1 in.) bar, recommended stock removal is 0.254 mm (0.016 in.) per side. For the re-sulfurized grades, recommended stock removal is 0.038 mm per 1.59 mm (0.0015 in. per $\frac{1}{16}$ in.) or 0.38 mm (0.015 in.), whichever is greater.

Stock Removal for Hot-Rolled Stock. Stock removal of 3.18 mm ($\frac{1}{8}$ in.) is recommended for diameters of 38 through 76 mm ($1\frac{1}{2}$ through 3 in.), and 6.35 mm ($\frac{1}{4}$ in.) for larger-diameter bars.

Significance on Induction Hardening. Prints, as provided for parts that are to be induction hardened, do not generally indicate whether sufficient stock has been machined to remove any potential surface decarburization. The induction-hardening process by itself is not affected by decarburization. However, the lower surface hardness produced after quenching can cause the quenched workpieces to be in nonconformance. Chapter 13, “Nonconforming Product and Process Problems,” in this book presents methods of checking for decarburization. Proper product design must make allowances for removal of decarburization, or carbon restoration of decarburization. In some instances in which there are finishing operations after induction hardening, stock removal can be completed after heat treating. In these cases surface hardness specifications must allow for the low hardnesses produced by decarburization.

Defects and Flaws

The objective of induction heat treating is to produce defect-free workpieces that are hardened to specifications. However, defects can be present in the workpieces before induction hardening. These defects may cause problems that no amount of proper heat-treating technique can overcome. Defects can also be produced by the induction heat-treating process itself.

By definition, a defect is a discontinuity in size, shape, or orientation, the location of which makes it detrimental to the useful service of the workpiece in which it occurs. Flaws are a detectable imperfection in a workpiece. A flaw may not make a workpiece nonconforming. Fractures initiate at localized nonhomogeneities or defects in the material, such as inclusions, microcracks, and voids. Defects and flaws are detrimental if they lead to stress concentrations that cause a fracture anytime in the manufacturing cycle or life cycle of a part. The different manufacturing processes for workpieces that are induction hardened have different types of defects.

Defects or flaws most likely to be found in workpieces before induction hardening include casting defects, cold heading defects, and defects in bar stock. Figure 9.4 shows 10 different types of flaws that may be found in rolled bars.

- *Porosity* is the result of trapped gaseous bubbles in the solidifying metal, causing porous structure in the interior of the ingot. On rolling, these structures are elongated and interspersed throughout the cross section of the bar product. The major casting imperfections that affect

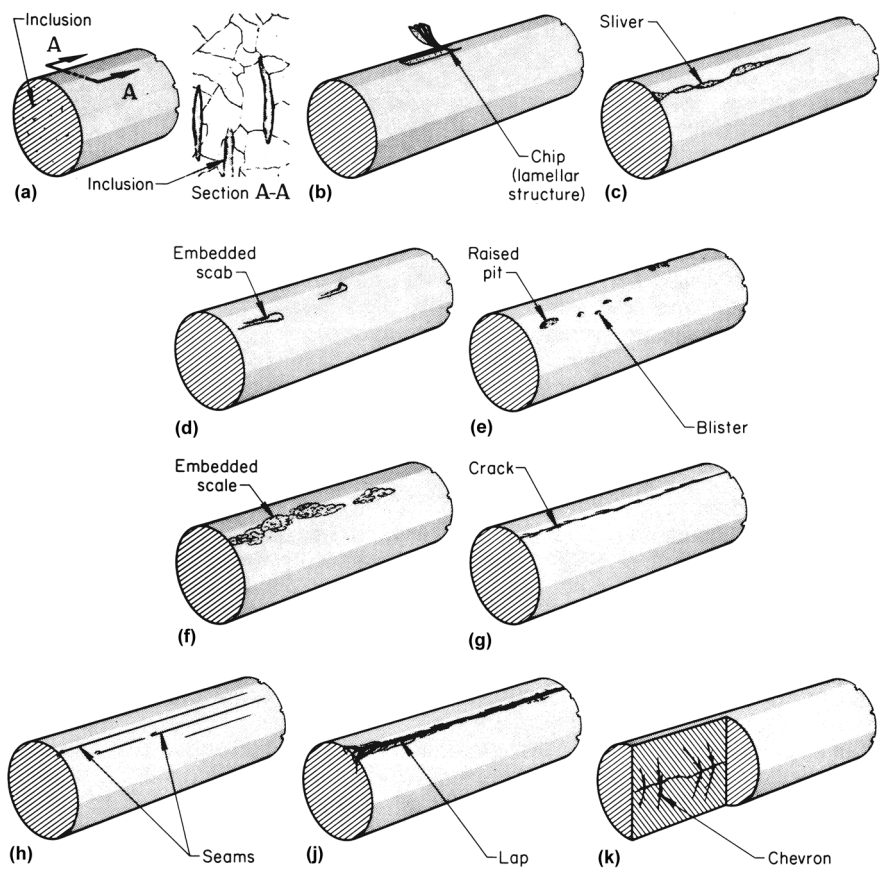


Fig. 9.4 Ten different types of flaws that may be found in rolled bars. See text for details. Source: Ref 3

induction-hardened workpieces are blowholes or gas holes, which may appear as subsurface voids. These voids can cause nonuniform heating and hot spots.

- *Inclusions* (Fig. 9.4a) may occur from spatter (entrapped splashes) during the pouring of the steel into the mold. They are elongated during rolling and are usually subsurface in the bar, showing a lamellar structure of inclusions that is seen in the longitudinal or rolling direction. The inclusions can be oxide in nature, or they can be from sulfur that is added to form manganese sulfide for machinability. Figure 9.5 shows a micrograph of manganese sulfide inclusions. Microinclusions are almost always present in steel to some degree. In general they cause few problems when induction hardening steel. The exceptions are when the inclusions act as stress risers when they are strung out in a subsurface line, or in the case of a forging parting line that exits at the surface.

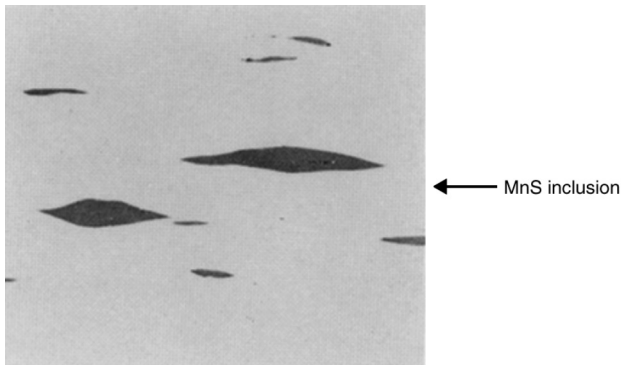


Fig. 9.5 Manganese sulfide inclusions in 0.39% carbon steel, unetched, 250X. Source: Ref 1

- *Chips* (laminations, Fig. 9.4b) occur from spatter (entrapped splashes) during the pouring of steel into a mold.
- *Slivers* (Fig. 9.4c) most often are caused by a rough mold surface, overheating before rolling, or abrasion during rolling. Usually slivers are found with seams.
- *Embedded scabs* (Fig. 9.4d) are caused by metal that is removed from the wall of the mold, which becomes embedded in the surface of the rolled bar.
- *Pits and blisters* form during subsequent rolling, when gaseous pockets in the ingot become pits or blisters (Fig. 9.4e) on the surface or slightly below the surface of bar products.
- *Embedded scale* (Fig. 9.4f) may result from rolling or drawing of bars that have become excessively scaled during prior heating operations.
- *Cracks* (Fig. 9.4g) are often confused with seams (Fig. 9.4h). Cracks with little or no oxide present on their edges may occur when the metal cools in the mold, setting up highly stressed areas, whereas seams that develop from these cracks during rolling are heavily oxidized. Cracks also result from highly stressed planes in cold-drawn bars or from improper quenching during heat treatment. Cracks created from these latter two causes show no evidence of oxidized surfaces (Fig. 9.4g). The defects that show up in fasteners are usually cracks caused by overstressing the metal during heading or other forming operations. Typical locations of forging cracks from cold forging are shown in Fig. 9.6.
- *Seams* result from elongated, trapped gas pockets or from cracks. The surfaces generally are heavily oxidized and decarburized. Depth varies widely, and surface areas sometimes may be welded together in spots. Seams may be continuous or intermittent, as indicated in Fig. 9.4(h). A micrograph of a typical seam is shown in Fig. 9.7. Stock removal, mentioned earlier in this chapter for the removal of decarburization,

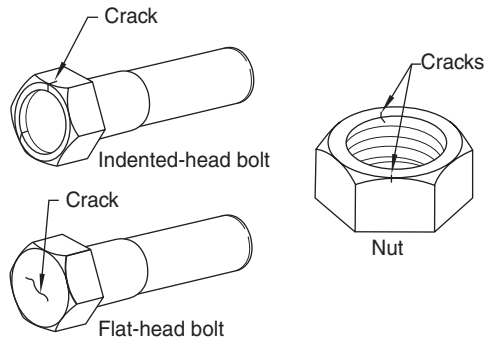


Fig. 9.6 Typical locations of forging cracks in bolt heads and in nuts. Source: Ref 3



Fig. 9.7 Micrograph of a seam in cross section of a $\frac{3}{4}$ in. diam medium carbon steel bar, showing oxide and decarburization in the seam. 350x. Source: Ref 3

generally removes all seams. However, occasionally seams are found in bar stock that is used to make workpieces for induction hardening.

- *Laps* are most often caused by excessive material in a given hot roll pass being squeezed out into the area of the roll collar. When turned for the following pass, the material is rolled back into the bar and appears as a lap on the surface (Fig. 9.4i), somewhat similar to seams that result from rolling fins or protrusions into the surface of the bar. The net effect is about the same as far as imperfections are concerned. Stock removal, mentioned earlier in this chapter for the removal of decarburization, generally removes all laps.

- *Chevrons* (Fig. 9.4k) are internal flaws named for their shape. They often result from excessively severe cold drawing and are even more likely to occur during extrusion operations. The severe stresses that build up internally cause transverse subsurface cracks. Most of the bar stock sold will have the seams removed either during manufacturing or during machining.

Surface Defect and Seam Detection. Sometimes surface defects can be seen visually without magnification. When a defect is found, workpieces should be inspected before induction processing. Seams appear as fine lines or cracks that extend longitudinally. There may be more than one seam around the diameter, and the seams may be discontinuous, appearing and disappearing down the length of the workpiece. Most of the time the seams are shallow. Seams and cracks smaller than approximately 0.013 mm (0.005 in.) can be detected through the use of die penetrants as used with fluorescent light. Larger defects can be detected by Magnafluxing.

Another method for seam detection is visual observation of the heated area during induction austenitizing. The current concentration produced by the eddy currents flowing perpendicular to a seam will cause the seam itself to heat hotter than the balance of the workpiece. The seam appears as a hot, white line inside the induction coil. Operators can be trained to watch for this.

Seams, when detected after heat treating, have the appearance of a heat-treating crack. At this point it can be difficult to visually determine whether the crack is a true heat-treating crack or a seam. Seams can initiate quench cracks that extend deeper than the initial depth of the seam. If a crack extends into a ductile area that is not heat treated, a seam is usually indicated. However, with some of the high-tensile-strength steels, cold-drawn steel seams can initiate a heat-treating crack that extends the full length of the workpiece. As previously stated, the best time for positive detection and identification of seams is before induction hardening.

Stress and Quench Cracks

Stress cracks can be produced in cold-drawn bars that crack during heating up to austenitizing temperature. High nonuniform residual stresses, as discussed in Chapter 5, “Heat Treating Basics,” in this book, can cause the workpiece to crack during heating due to the expansion caused by high stresses toward the core, with resulting lower yield strength.

Quench cracks occur after a workpiece is heated and quenched. Quench cracks initiate most commonly in the hardened case when the brittle martensitic case cracks due to stresses produced in the later transformation of austenite to martensite under the case. Quench cracks can also initiate at stress risers, such as keyways, holes, or fillets. Figures 9.8 to 9.13 show typical locations of some of these areas. Figure 9.14 shows

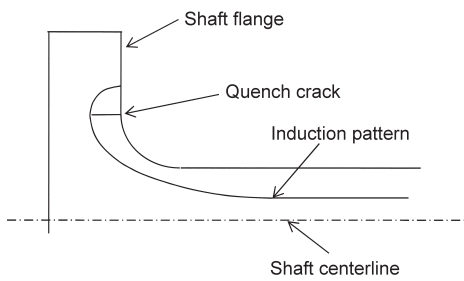


Fig. 9.8 Quench cracks in axle shaft flange radius. Source: Ref 4

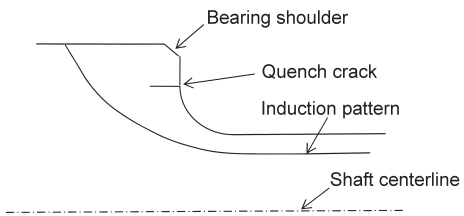


Fig. 9.9 Quench crack in induction-hardened shoulder. Source: Ref 4

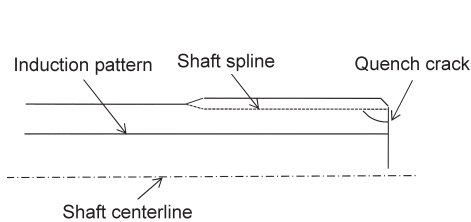


Fig. 9.10 Quench crack at spline end of axle shaft. Source: Ref 4

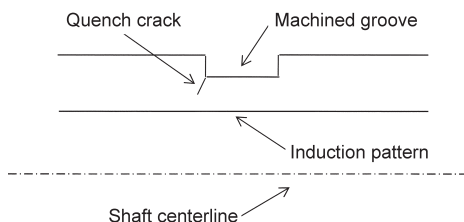


Fig. 9.11 Quench crack in machined groove on a shaft. Source: Ref 4

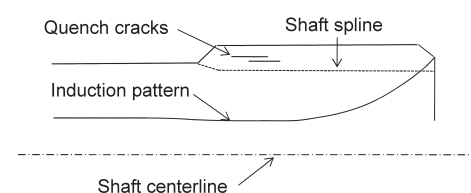


Fig. 9.12 Quench cracks on spline surface. Source: Ref 4

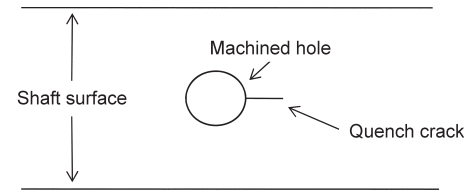
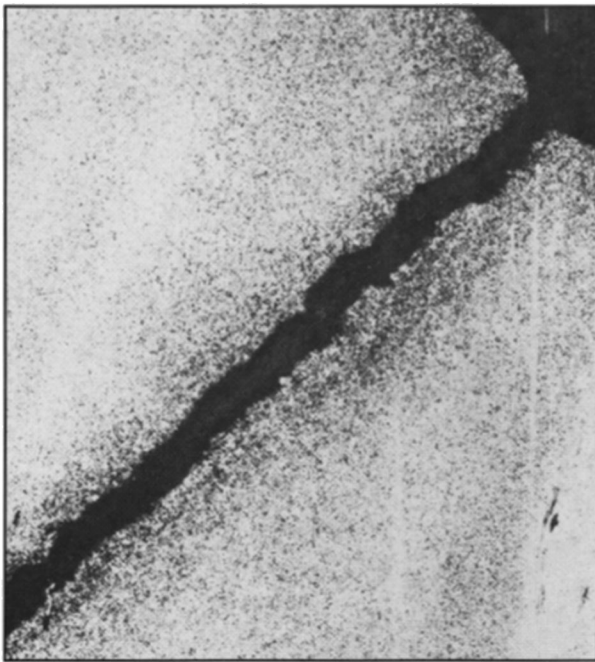


Fig. 9.13 Quench cracks in machined hole on a shaft. Source: Ref 4

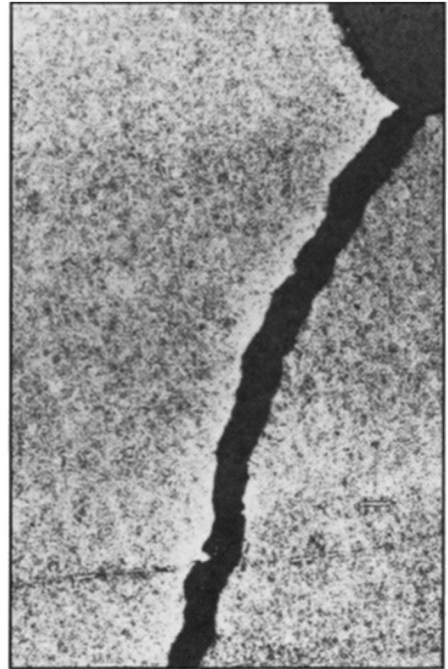
photomicrographs of several types of quench cracks. Unless the quench cracks are extremely tight, they may be visible as the workpiece is polished, before etching.

Quench cracking is mostly intergranular (along the grain boundaries). There have been instances of cracking at the boundary of the induction-hardened case and the unhardened core. The main reasons for cracking in heat treatment are workpiece design, grades of steel used, workpiece defects, heat treating practice, and tempering practice.

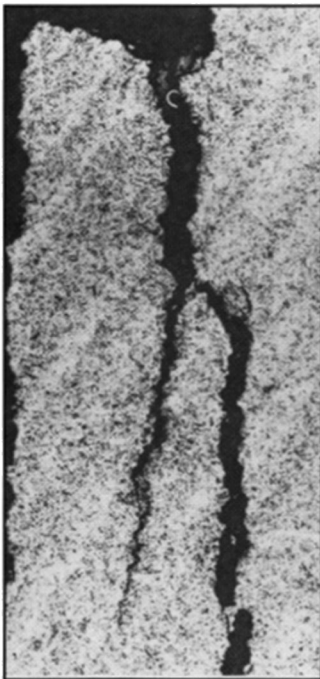
Workpiece Design. Features such as sharp corners, fillets, radii, tooling marks, keyways and the number, location, and size of holes are termed *stress risers*. Abrupt changes in section thickness within a workpiece can promote nonuniform cooling during quenching and can initiate quench



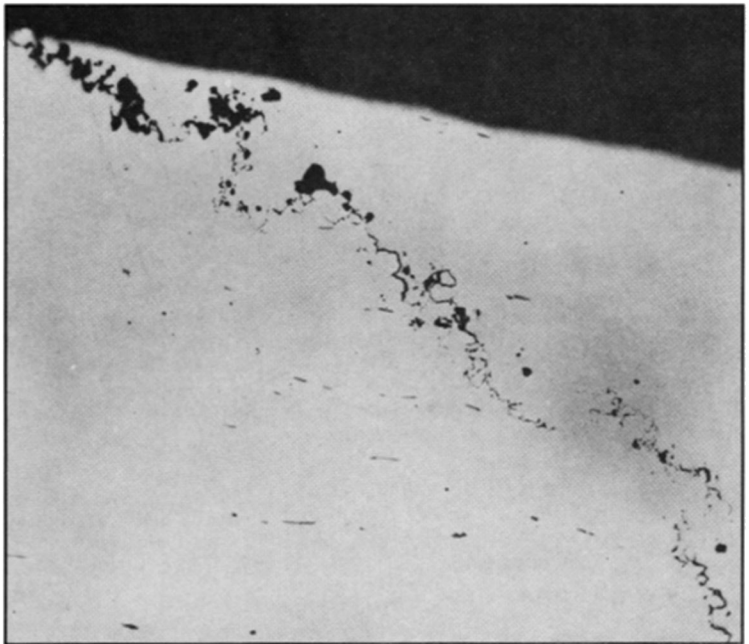
(a)



(b)

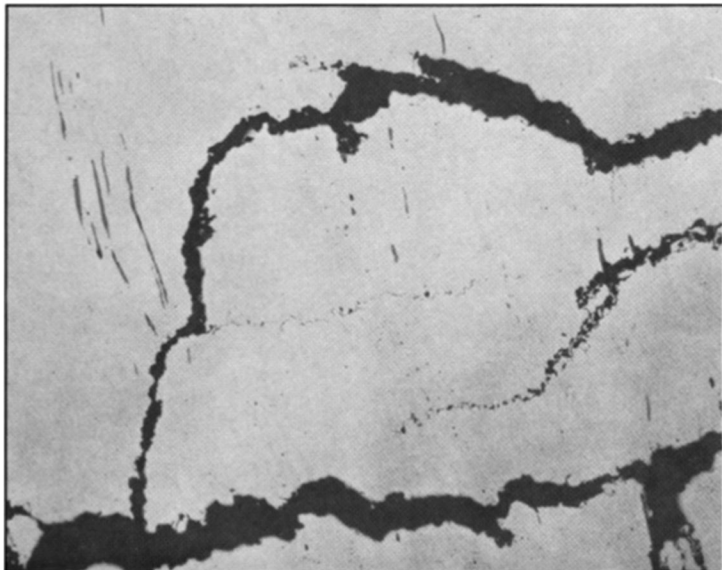


(c)

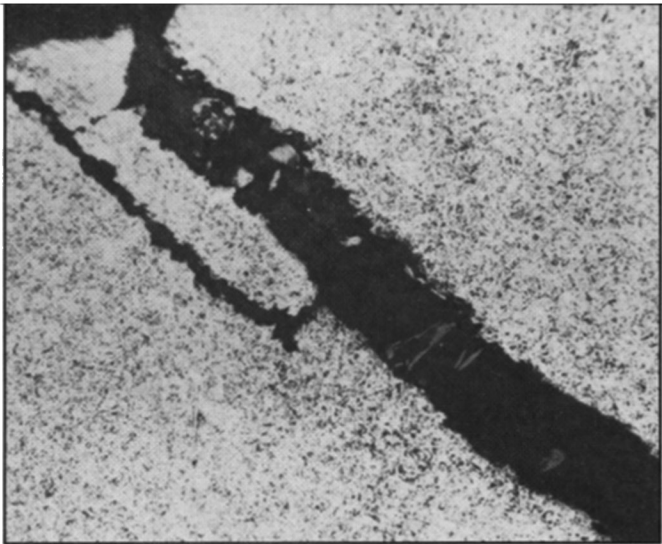


(d)

Fig. 9.14 Micrographs of cracks. (a) SAE 4140 steel as quenched and tempered; microstructure is tempered martensite with quench crack at area of dimensional change. 2% nital. 100 $\times$. (b) SAE 4142H steel as quenched and tempered; microstructure is tempered martensite with quench crack at the radius. 3% nital. 100 $\times$. (c) SAE 4150 steel as quenched and tempered; cracking initiates from silicate and sulfide inclusions. 2% nital. 100 $\times$. (d) SAE 4140 steel as quenched and tempered; microstructure is tempered martensite with cracking at inclusions. Unetched. 100 $\times$.



(e)

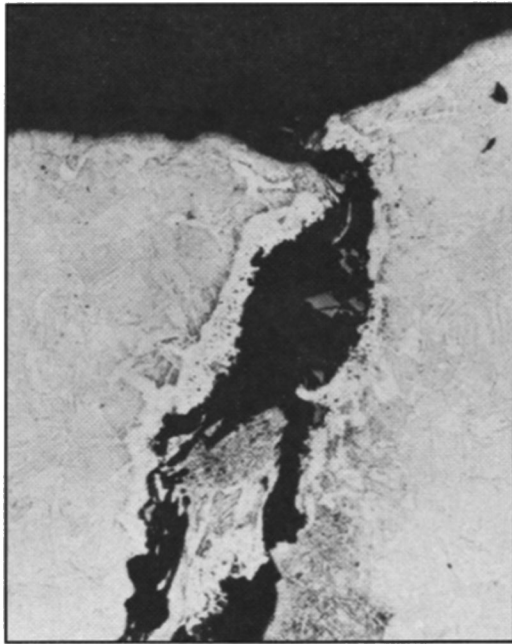


(f)

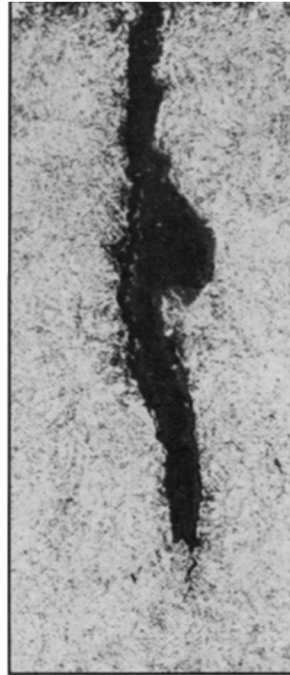


(g)

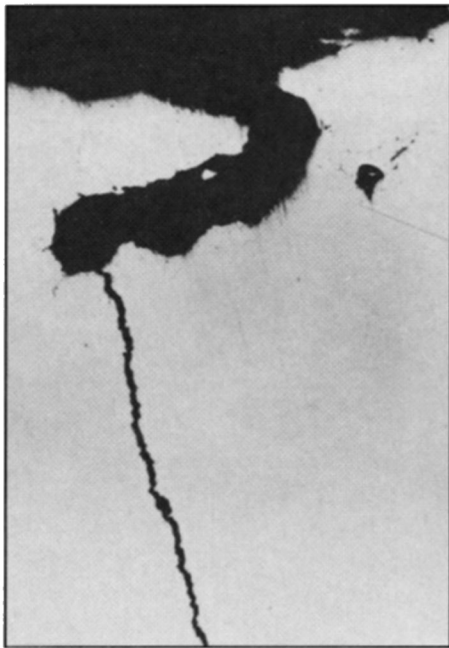
Fig. 9.14 (continued) Micrographs of cracks. (e) SAE 4140 steel as quenched and tempered; microstructure is tempered martensite with quench cracking promoted by nonmetallic inclusions. Unetched. 100 $\times$. (f) SAE 1144 steel as quenched and tempered; microstructure is tempered martensite where cracking is aided by inclusion defects. 2% nital. 200 $\times$. (g) SAE 1144 steel as quenched and tempered; microstructure is tempered martensite where cracking is aided by inclusion defects. Unetched. 100 $\times$.



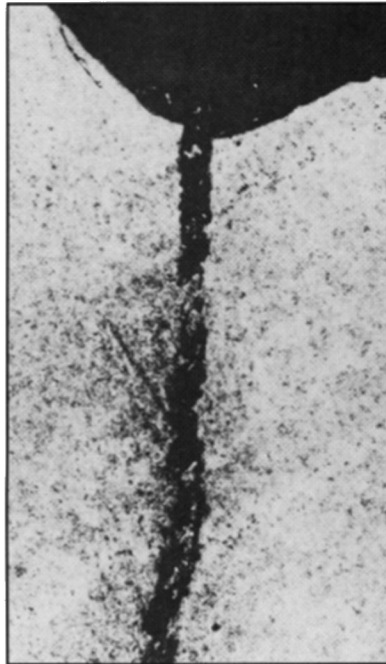
(h)



(i)



(j)



(k)

Fig. 9.14 (continued) Micrographs of cracks. (h) SAE 8630 steel as quenched; microstructure is martensite where cracking initiated from rolling seam. (i) SAE type 403 stainless steel as quenched and tempered; microstructure is predominantly tempered martensite with cracking promoted by the seam. Vilella's reagent. 100 $\times$. (j) SAE 4118 carburized steel as quenched and tempered; microstructure is tempered martensite with quench crack propagating from machine burr. Unetched. 200 $\times$. (k) SAE 4140 steel as quenched and tempered; microstructure is tempered martensite with quench crack initiating from machine groove. 2% nital. 100 $\times$. Source: Ref 5

cracks in the section that hardens first. Wherever possible, workpieces should be designed to reduce the stress risers that initiate quench cracks. Radii and corners should be rounded. Holes should have chamfer relief, and keyways should not be hardened unless necessary. When hardening of keyways is necessary, careful selection of the induction power supply frequency is required. The quench selected needs to cool the quenched area uniformly as slowly as possible. Sometimes holes and keyways in bores can be machined after the workpieces are induction hardened.

Workpiece Defects. Workpiece defects that are detrimental include both surface and subsurface conditions in material before induction heating or defects due to the induction-heating process. An example of a problem that can occur when heating gray cast iron is that it has a low melting constituent called steadite that melts at about 1049 °C (1920 °F). When heated too hot, small puddles form due to melting. Another surface condition, mentioned in Chapter 8, “Cleaning and Rust Protection,” in this book, is pitting due to scale. Scale forms on the surface and increases as workpieces are heated in air over the A_1 point. After the workpieces are quenched, a network can occur on the surface when the scale is removed. Increasing the austenitizing temperature increases the amount of scale, which may cause the heat-treated workpiece to not have the required final surface finish. Subsurface conditions can produce weaknesses that lead to product failure, such as found with blisters or melting. Blisters or melting occur when heating at too high an austenitizing temperature, producing subsurface melting and oxides (Fig. 9.15). Other conditions in the material that can cause cracking in the subsurface include inclusions, internal ruptures as found in forgings, casting defects, and high residual stresses under the surface.

Heat Treating Practice. In furnace heat treating, higher austenitizing temperatures are thought to increase the propensity toward formation of quench cracks. Similarly, steels with coarser grain size are expected to be more prone to cracks than fine-grain steels because the fine-grain steels possess more grain-boundary area to stop the movement of cracks and to redistribute residual stresses. However, recent induction practices in heat treating show there is little difference in quench crack propensity between a fine-grained and a coarse-grained steel.

Medium-carbon steels are often quenched with water or low-polymer water quenchants to produce high hardness, and they are susceptible to cracks if they are not handled properly. At high hardness levels, martensite is very brittle and can easily crack on quenching, particularly when the workpiece is not uniform. Another problem occurs with design tendencies that try to keep the carbon content low to increase machinability. Such workpieces may need faster quenchants to produce the specified hardness, leading to quench cracking. One steel that is very prone to producing a quench crack when a quenched hardness of over 57 HRC is needed is 4140.

When quench cracking occurs, the workpiece and crack should be examined very carefully. If workpieces are available that have not yet been heat treated, they should be examined for flaws. If possible, Magnaflux the workpieces and then harden them. If quench cracks are found after Magnafluxing, then the likelihood is that the cracking is occurring during quenching. The cracks may need to be examined microscopically to look for subsurface defects and flaws. To eliminate the cracking, first improve the quenching. A slower-speed quenchant should be selected. The quenching speed can be slowed only to the point that there is a loss of either case depth or surface hardness. When deep case quenching, other factors need to be examined. Sometimes the workpieces need to be held in the quenchant longer so that the heat is extracted from the core faster. Workpieces that are scanned can need secondary quenching (another quench ring applying quenchant below the first area). Sometimes substantial testing of various quenchants and quenching rates is necessary. There have been instances in which a faster quench stopped the cracking, apparently by producing a deeper martensitic case that had sufficient strength to withstand the stresses produced by the deeper core transformation to martensite.

Good metallurgical practice has always been to temper quenched workpieces as soon as possible. Immediate tempering reduces the martensite brittleness and stops quench cracking. Because immediate tempering is difficult for workpieces that are batch tempered, the best practice is to temper as soon as possible, at least in the same shift. The longer that steel workpieces are kept at room temperature after transformation to martensite, assuming that the M_f temperature has not been reached, the more likely the occurrence of quench cracking from the volumetric expansion

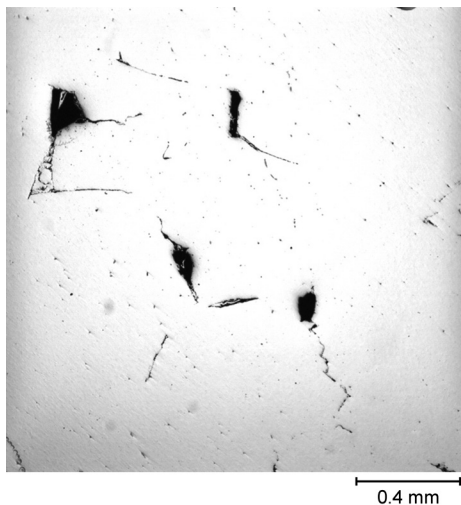


Fig 9.15 Grain-boundary oxidation and melting due to overheating during forging. Unetched. Source: Ref 4

caused by isothermal transformation of retained austenite into martensite. This is more of a process problem with some of the alloy and tool steels that can have considerable retained austenite.

Finally, workpieces that are induction tempered should have the cased area cooled below the M_f temperature before being reheated for tempering. If workpieces are reheated before passing the M_f temperature, the final microstructure should be reviewed for complete transformation to tempered martensite.

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CHAPTER 10

Applications of Induction Heat Treatment

SINCE ITS INTRODUCTION in the 1930s, induction heat treatment has been applied to a large variety of mass-produced commercial products. The initial applications involved hardening of the surfaces of round steel parts such as shafts. Subsequent surface-hardening techniques were developed for other parts whose shapes are not so simple. Most recently, induction-hardening and tempering techniques have been developed for purposes of heat treating to large case depths and heat treating entire cross sections. Induction is commonly applied to several types of parts.

Typical parts that are induction surface hardened include:

- *Transportation field*: crankshafts, camshafts, axle shafts, transmission shafts, splined shafts, universal joints, gears, valve seats, wheel spindles, and ball studs
- *Machine-tool field*: lathe beds, machine beds, transmission gears, and shafts
- *Metalworking and hand-tool fields*: rolling-mill pliers, hammers, diagonal pliers, armature shafts, and so forth

Through-hardening applications include:

- Oil-country tubular products
- Structural members
- Spring steel
- Chain links

This Chapter discusses applications and advantages of induction methods of heat treatment for some of the parts listed above.

Surface-Hardening Applications

Crankshafts for internal-combustion engines were probably the first parts to which induction-hardening techniques were applied. Because the explosive forces of the engine must pass through the crankshaft, severe demands in terms of strength and wear resistance are placed on the steel used in manufacturing the crankshaft. These demands are ever increasing with the rising horsepower ratings of engines used in automobiles, tractors, and other vehicles.

The most stringent demands are placed on the journal and bearing surface. Journals are the parts of the rotating shaft that turn within the bearings. Before the advent of induction heating, methods such as furnace hardening, flame hardening, and liquid nitriding were used. However, each of these processes presented problems, such as inadequate or nonuniform hardening and distortion. Induction hardening overcomes many of these problems. Through proper selection of frequency, power, and the particular induction process, low-distortion case hardening can be accomplished. In one of the most common steels used for crankshafts, 1045, case hardnesses over 55 HRC are readily obtained. Other advantages of the induction process for crankshafts include:

- Only the portions that need to be hardened are heated, leaving the remainder of the crankshaft relatively soft for easy machining and balancing. Figure 10.1 shows the two typical hardness patterns produced

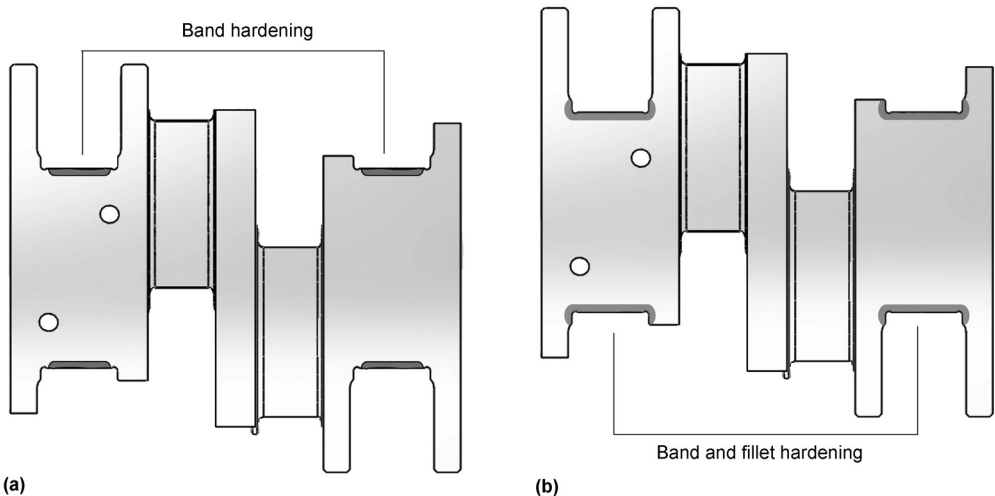


Fig. 10.1 Profile of induction-hardened patterns of journals in crankshaft. (a) Band hardening pattern. (b) Band and fillet hardening pattern. Source: Ref 1

in induction hardening crankshaft journals. Figure 10.1(a) presents the hardness pattern on the journal surface. Figure 10.1(b) illustrates the hardness extended into the adjacent fillets.

- Induction hardening results in minimum distortion and scaling of the steel. The rapid heating associated with induction heat treating is advantageous in avoiding heavy scaling in other applications as well.
- Because induction heat-treating processes can be automated, an induction tempering operation immediately following the hardening treatment can be done in manufacturing cells.
- The properties of induction-hardened crankshafts are superior to those of crankshafts produced by other techniques. These properties include high strength, fatigue resistance, geometrical accuracy, low vibration, light weight, and short length.

Several types of inductors and processes are used. *Clamshell inductors* are a type of split inductor that is typically hinged on one side so that the inductor can be closed after the crankshaft is loaded. The crankshafts are held in place with no rotation. Locating pins can be used when it is necessary to maintain position of the crankshaft in the inductor when other fixtures will not hold the position reliably. The quench can be applied either in the coil or from outside quench blocks. Short coil life is a problem, because the high current through the contact points of the coil where the two halves meet develops oblation and pitting of the contact surfaces. This produces maintenance and reliability problems. Also, because closing the coil is usually done manually, the production rates are not high. This type of coil is best for low-production use.

Split inductors completely separate in two for loading and unloading. They have pneumatic, hydraulic, or mechanical type closing mechanisms. These must be designed so that there is no deformation in the inductor due to the clamping pressure and to ensure consistent electrical contact is maintained when closed. Silver plating is commonly used to increase the life of the inductor in the clamping areas. However, the contacts where the coil halves pass the current tend to degrade with time. Coil life can be 10,000 cycles or lower.

U-Shaped Inductors with Crankshaft Rotation. This technology was developed in the 1960s. A nonencircling inductor with carbide guides rides the crankshaft journal while the crankshaft is rotated during heating and quenching. Coil gaps ranging from 0.25 to 0.04 mm (0.010 to 0.160 in.) are needed. The heat is applied to the journal only in the area of the inductor, and rapid rotation varies typically from 24 to 32 rpm to produce a symmetrical hardness pattern. The heating time ranges from 8 to 20 s, depending on the process variables. Heating of the fillets can be accomplished through the use of flux concentrators, along with power adjustments as needed during the heating cycle. The drawbacks to this process include excessive wear of the guides or locators, the expertise necessary

for maintenance and adjustment of the guides, coil degradation due to heat and operating conditions, and overheating of the coil due to coil design and cooling, among others.

Stationary (Nonrotational) Technology. This is a patented technology developed where the crankshaft is not rotated. The inductor is made from two sections machined from a copper block. The bottom block is the “active” block that receives the power from the power supply. The top block is the “passive” block, an electrically closed loop. When the bottom block induces current into the journal, it will tend to flow around the entire diameter of the journal because of the electrical effect. The shorted top block reinforces the flow of current around the journal so that a uniform, hardened pattern is produced in the journal after quenching. After the crankshaft is loaded in position, as with split coils, the top block is lowered into position. Because there is no electrical contact with the lower block, as would happen in a split coil, there is no problem with degradation of the contacts, nor does the crankshaft need to be rotated.

Presently the great majority of crankshafts are being made from steel forgings as well as from cast iron (high-performance race cars are machined from solid billets). In the latter case, surface hardness levels of higher than 50 HRC are easily obtainable after induction heating and air quenching. The resultant microstructure is a mixture of bainite and martensite, with 100% martensite avoided to minimize the danger of crack formation at holes, eliminating the need for chamfering and polishing in these regions. The air quench allows the initial formation of bainite during cooling. After a prescribed period of time, the air quench is followed by a water quench, during which the martensite phase is produced from the remaining austenite. Sufficient residual heat is left in the part to self-temper the martensite.

Axle shafts used in cars, trucks, and farm vehicles are, with few exceptions, surface hardened by induction. Although in some axles a portion of the hardened surface is used as a bearing, the primary purpose of induction hardening is to put the surface under a state of compressive residual stress. By this means, the bending and torsional fatigue life of an axle may be increased by as much as 200% over that for parts conventionally heat treated (Fig. 10.2). Induction-hardened axles consist of a hard, high-strength, tough outer case with good torsional strength and a tough, ductile core. Many axles also have a region in which the case depth is kept very shallow so that the part can be readily straightened following heat treatment. In addition to substantially improving strength, induction hardening is also very cost-effective. This is because most shafts are made in inexpensive, unalloyed medium-carbon steel that is surface hardened to case depths of 2.5 to 8 mm (0.10 to 0.30 in.), depending on the cross-sectional size. As with crankshafts, typical hardness (after tempering) is

around 50 HRC. Such hard, deep cases improve yield strength considerably as well.

Modern transmission shafts, particularly those for cars with automatic transmissions, are required to have excellent bending and torsional strength, as well as surface hardness for wear resistance. Under well-controlled conditions, induction-hardening processes are most able to satisfy these needs, as shown by the data in Fig. 10.3, which compares the fatigue resistance of through-hardened, case-carburized, and surface-induction hardened axles. The induction-hardening methods employed are quite varied and include both single-shot and scanning techniques.

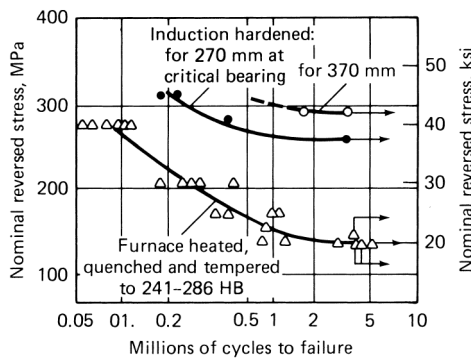
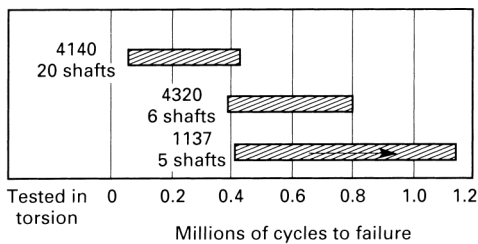


Fig. 10.2 Bending fatigue response of furnace-hardened and induction-hardened medium-carbon steel tractor axles. Shaft diameter: 70 mm (2.75 in.). Fillet radius: 1.6 mm (0.063 in.) Source: Ref 2



Steel	Surface hardness, HRC	Method of hardening
4140	36–42	Through-hardened
4320	40–46	Carburized to 1.0–1.3 mm (0.040–0.050 in.)
1137	42–48	Induction hardened to 3.0 mm (0.120 in.) min effective depth and 40 HRC

Fig. 10.3 Comparison of fatigue life of induction surface-hardened transmission shafts with that of through-hardened and carburized shafts. Arrow in lower bar (induction-hardened shafts) indicates that one shaft had not failed after testing for the maximum number of cycles shown. Source: Ref 2

Induction hardening of crankshafts, axles, and transmission shafts is becoming an increasingly automated process. Often parts are induction hardened in-line. One such line for heat treating of automotive parts is depicted schematically in Fig. 10.4. It includes an automatic handling system, programmable controls, and fiber-optic sensors. Mechanically, parts are fed by a quadruple-head, skewed-drive (QHD) roller system after being delivered to the heat-treatment area by a conveyor system. The roller drives, in conjunction with the check guides, impart both rotational and linear forward movement of the workpiece through the coil. Once a part enters the “ready position,” the fiber-optic sensor senses its position and initiates the heating cycle for austenitization, subsequent in-line quenching, and then induction tempering. The workpieces are round bars that are fed end-to-end continuously.

In the hardening cycle of the QHD system, the induction power-supply frequency is generally either in the radio frequency (RF) range (approximately 500 kHz) for shallow cases or in the range for 3 to 10 kHz if deeper cases are needed. For rejection purposes, a temperature monitor senses if the workpiece has been either underheated or overheated. Assuming that the workpiece has been heated properly, it then passes through a quench ring. After quenching, the workpiece is moved into the induction-tempering part of the heat-treating line. Again, a fiber-optic sensor senses the presence of the workpiece and begins the heating cycle, generally using a lower-frequency power supply (lower frequency can be used because the workpiece is still magnetic during tempering and thus has a shallower reference depth). Depending on the surface hardness as quenched and the desired final hardness, the desired tempering temperature can be as high as approximately 400 °C (750 °F). As discussed in Chapter 7,

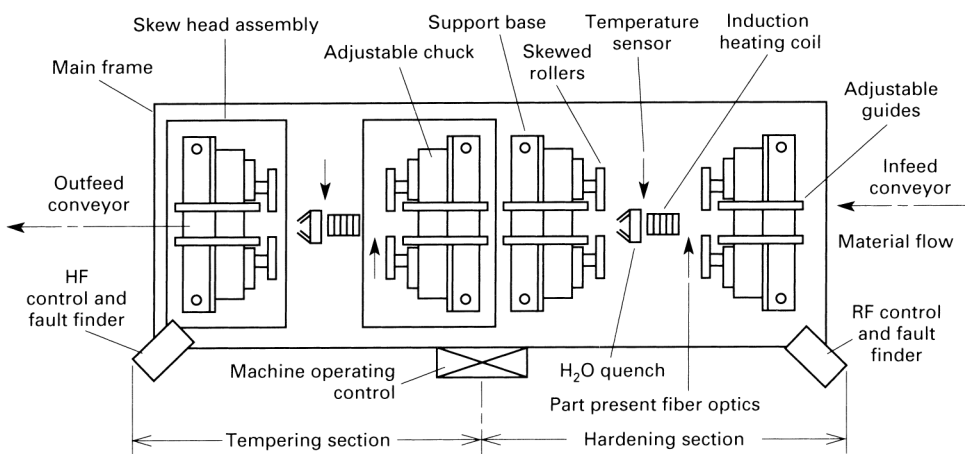


Fig. 10.4 Automated, quadruple-head, skewed-drive roller system used for in-line induction hardening and tempering of automotive parts. HF: high frequency; RF: radio frequency. Source: Ref 2

“Tempering,” in this book, induction tempering requires a higher tempering temperature than does furnace tempering because of the short heat cycle. When the tempering is complete, the workpiece is moved onto a conveyor for transportation to grinding.

The control system of this line is designed to allow decision making by a programmable controller. Thus, all aspects of the heat-treating process and mechanical operations are preprogrammed and may be changed easily to accommodate different part sizes and heat-treating parameters. With such a process, users have been able to increase production rates more than threefold over those obtainable with conventional heat-treating lines.

Gears. Reliability and high dimensional accuracy (to ensure good fit) are among the requirements for gears, necessitating the importance of keeping distortion as low as possible during heat treatment. Induction heat treating is one of the very important processes used for heat treatment of gears. Gears, because of the wide varieties, sizes, and differences in tooth profiles, represent unique applications. External spur and helical gears, bevel and worm gears, internal gears, racks, and sprockets are good examples of the kinds of gears of which the size can range from less than 6 mm (0.25 in.) to greater than 3 m (12 feet). As with shafts, the hardened pattern may be through the cross section, as with small armature shafts, to single-teeth case hardening, as is done with large gears. A wide variety of frequencies and induction processes are used because of the way the induced currents are produced in gear teeth with different profiles, sizes, and pitches. The heat-treating processes use single-shot heating techniques and a variety of scanning techniques. A wide number of different frequencies are used to accommodate the different patterns and tooth profiles.

The size of gear, the hardening requirements, and the production requirement influence the type of induction-hardening process used. High-quantity production lots can be induction hardened single shot, whereas small quantities of large gears need to be run one tooth at a time to keep the capital equipment costs low.

Single-shot through hardening of the gears of small armature shafts has been done since the 1950s. In addition, a wide variety of different types of case patterns are produced on gear teeth. Figure 10.5 shows eight different induction patterns that can be produced. Patterns A, B, and C are similar in that a portion of the tooth is hardened but not the root. These patterns were originally used on gears with large pitch teeth. Pattern A uses channel-type coils that heat each tooth single-shot, one tooth at a time, either statically or by scanning. If no maximum case depth is specified, small gears may have the teeth through hardened. Use of a frequency high enough that root penetration does not occur produces patterns B and C. Figure 10.6 shows how high frequencies tend to heat the tips of teeth, whereas low frequencies tend to heat the root. Pattern D in Fig. 10.5 shows the root-heating effect of a frequency that is too low. Patterns like this are

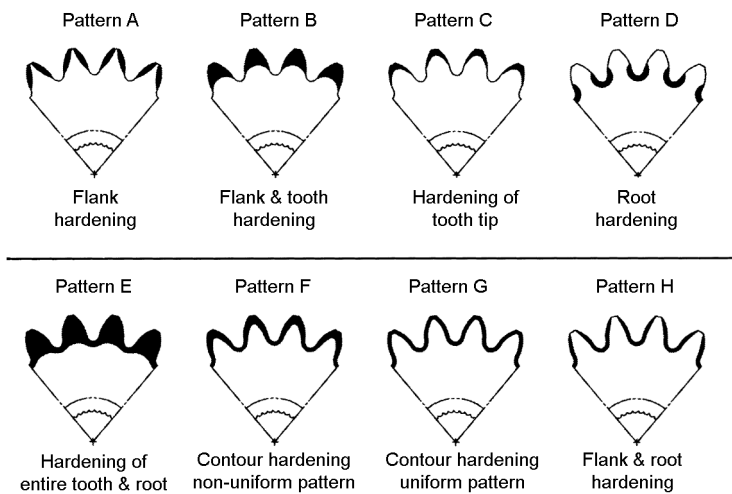


Fig. 10.5 Induction-hardening patterns for gears. Source: Ref 3

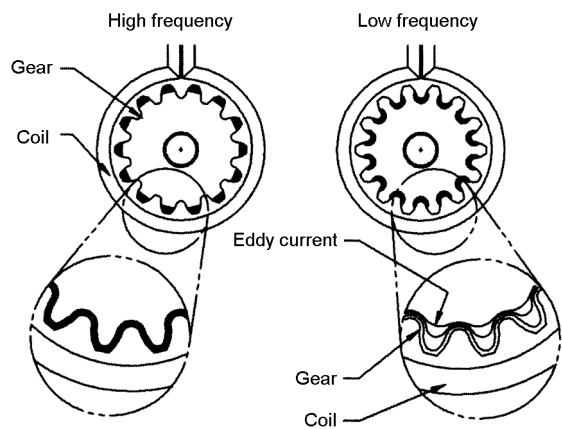


Fig. 10.6 Frequency influence on hardness profile with an encircling induction coil. Source: Ref 3

not acceptable because the upper portion of the tooth is not hard and will be subject to wear.

The American Gear Manufacturers Association currently recognizes 36 modes of gear failure. However, they find that the greatest stress on a gear is from the pitch diameter through the fillet of the root. Failure is most likely to occur at these points. Therefore, it is highly desirable that the wear surface and the root of gearing be hard. Patterns E, F, G, and H in Fig. 10.5 meet these criteria. Pattern E represents one of the most common patterns produced by induction, by either single-shot heating or scanning. The specifications commonly call for the gear to be induction hardened to

a minimum hardness below the root. Figure 10.7 shows the frequencies versus gear pitch that are used to produce this type of pattern. A frequency of 450 kHz has difficulty in producing case depths below 1.5 mm (0.060 in.) on even the fine-pitch gears. Single-shot hardening is limited by the power available on the power supply. Larger gears can be scanned to keep the power requirements reasonable. When distortion is excessive, requirements may be changed to those shown in patterns F and G in Fig. 10.5. With pattern F, the frequency is lowered and the power density is increased. The case depth at the root is 30 to 40% of the case depth at the tip of the tooth. Pattern F attempts to produce a near contour pattern, whereas pattern G attempts to produce a uniform contour. Pattern F uses pulsed or dual-frequency heating techniques. These patterns attempt to produce gears that not only quench to net shape without distortion but also have the surface in compression so that the overall physical properties are increased.

Tooth-by-tooth hardening is used almost exclusively with large gears. It can be used to harden tip-by-tip or gap-by-gap. Tip-by-tip hardening can be done by single-shot heating or scanning. Gap-by-gap hardening uses the scanning mode of processing. With single-tooth hardening, the production requirements are generally lower. The output power requirements are lower because there is less area of the single tooth than the entire gear. Figure 10.8 shows two examples of gap-by-gap single-tooth hardening. Figure 10.8(a) shows the correct pattern. Figure 10.8(b) is the pattern obtained on the last tooth scanned where one side of the first tooth hardened is tempered during the heating of the last tooth due to insufficient cooling. Figure 10.9 shows correct application of quenchant on the side of the tooth to prevent tempering or drawback.

Research performed by the Gear Research Institute has shown that contour-hardened gears performed better than carburized gears in single-

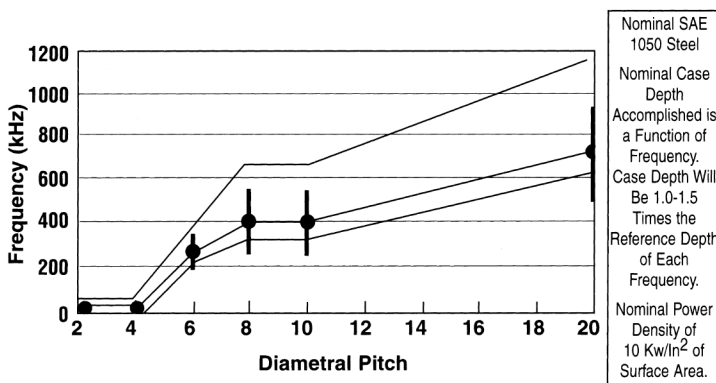


Fig. 10.7 Proper frequency selection is needed to accomplish even heating. Too low a frequency will result in field cancellation and inadequate heating; too high a frequency could overheat the surface. SAE, Society of Automotive Engineers. Source: Ref 4

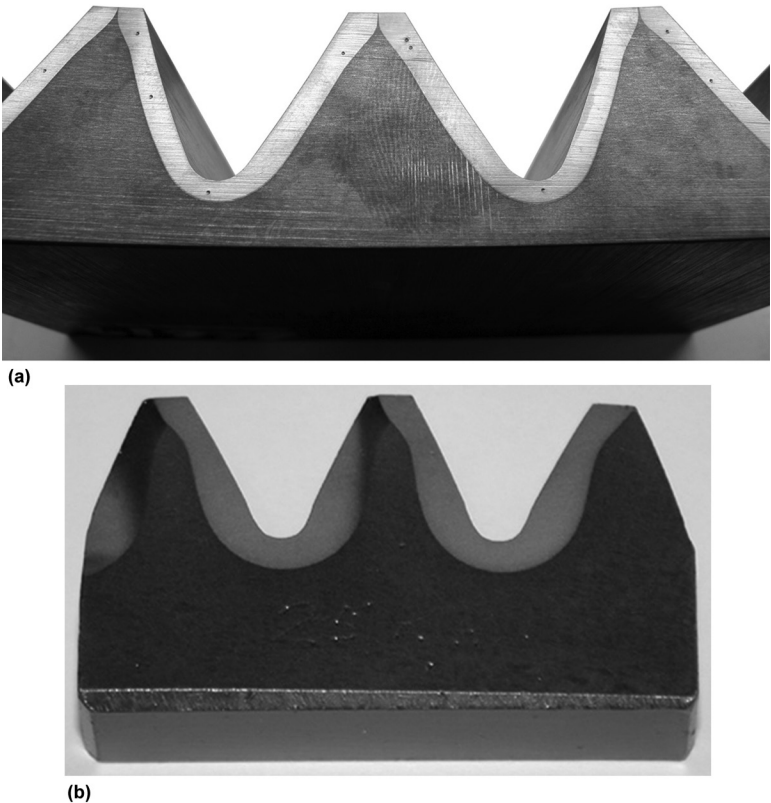


Fig. 10.8 Hardness patterns from gap-by-gap induction hardening. (a) Typical pattern. (b) Inconsistent pattern. Source: Ref 5

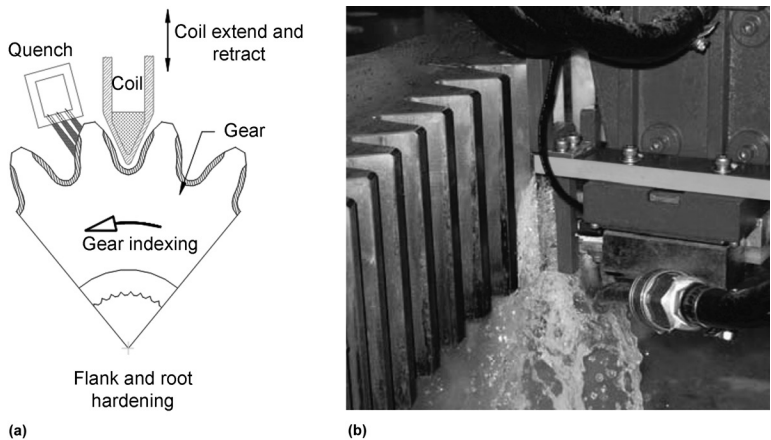


Fig. 10.9 Control of tempering back part. (a) Schematic. (b) Special cooling spray blocks. Courtesy of Inductoheat, Inc. Source: Ref 5

tooth and power-circulating bending strength tests. Carburized gears are better in rolling contact. Note that carburized gears do have higher surface hardness. Figure 10.10 shows the locations at which patterns can be specified on a gear. The pattern can be measured from any combination from the tip, at the pitch line, or at the root. Figure 10.11 shows a comparison in hardening pattern between single-frequency and dual-frequency spin hardening.

The single power-supply pulsing process uses a preheat of low or moderate power followed by a high power, for a very short pulse that can be 0.2 to 0.5 s. Experimentation may be needed to select the optimum frequency for a given pitch gear. The preheat performs two functions. First, the tip of the gear is preheated, producing an increase in the temperature at the tip of the tooth so that a lower temperature rise is needed to complete austenitization. Second, the preheat produces heat in the core that after quenching and cooling produces compressive residual stress on the surface of the case. The dual-frequency process uses a medium frequency

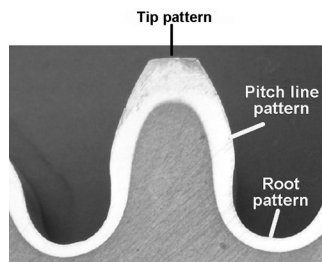


Fig. 10.10 Root, pitch line, and tip patterns. Courtesy of Contour Hardening, Inc. Source: Ref 5

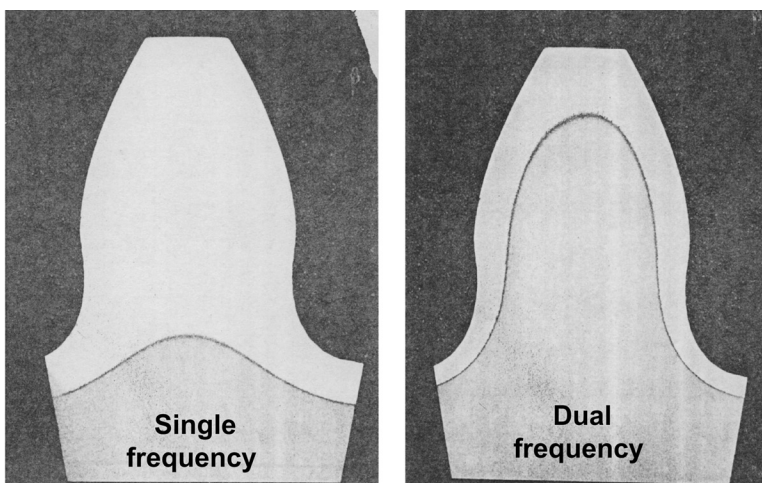


Fig. 10.11 Comparison of single- and dual-frequency patterns of the same tooth geometry. Source: Ref 5

to produce the preheat, followed by an extremely fast, high-frequency austenitizing cycle. The frequencies and heating times are optimized to produce a contoured case. The dual-frequency process was developed to enable induction heat treating to replace furnace carburizing.

Figure 10.12 shows graphically the dual-frequency process along with an example of an internal gear that was hardened. Figure 10.13 shows the pattern obtained on a medium-size tooth using a dual-frequency power supply that first uses a low-frequency preheat followed by a fast high-frequency austenitizing cycle. The contour is not exact, but the gear has

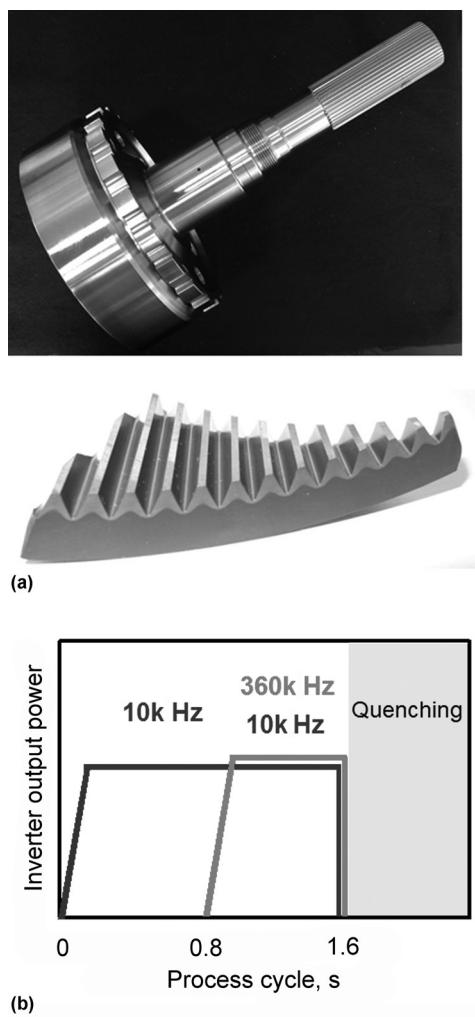


Fig. 10.12 Dual-frequency process for hardening of a shaft/helical wide-face internal gear from normalized AISI 4340. (a) Component with the teeth located on inside and an etched portion of as-hardened section. Minor gear diameter, 175 mm (6.9 in.); major circular diameter, 186 mm (7.3 in.). (b) Process recipe for induction hardening of the gear. Courtesy of Inductoheat, Inc. Source: Ref 5

the desired case. The heating cycle will be slightly faster because there is no need to turn off the lower-frequency power supply and then turn on the higher-frequency power supply.

The final technique used for contour hardening and producing compressive stresses on the surface of the case is where the gear or workpiece is austenitized during through heating and quenched. By using material that has selected hardenability along with very fast quenching, hardness patterns are produced on the entire part. Figure 10.14 shows examples of this

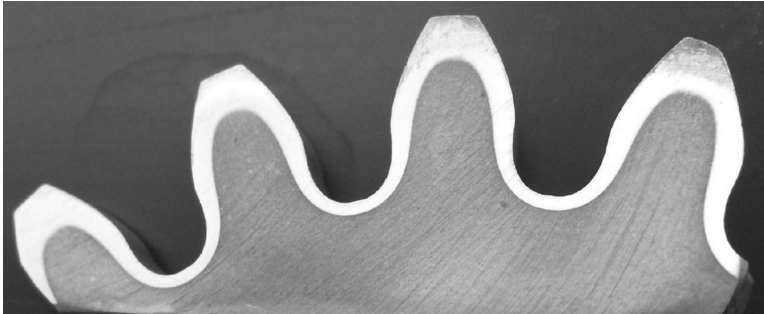


Fig. 10.13 Dual-frequency induction-hardening pattern. Courtesy of Contour Hardening Inc. Source: Ref 5

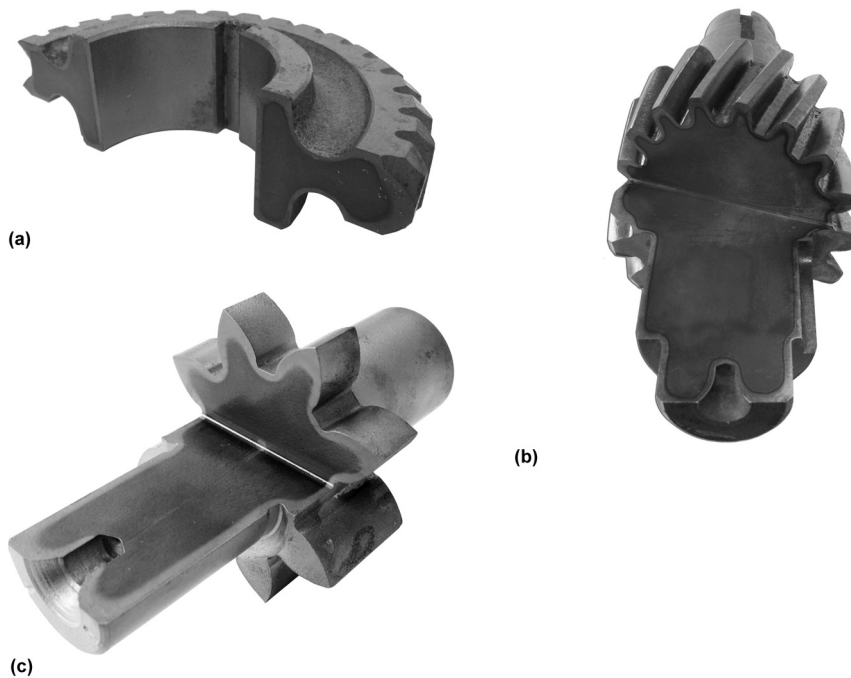


Fig. 10.14 Examples of surface-hardened gears using through surface hardening definition. (a) Transmission gear pinion. (b) Shaft/helical gear. (c) Pump gear. Courtesy of ERS Engineering, Inc. Source: Ref 5

process being performed on a transmission gear pinion, a shaft with helical gear, and a pump gear.

There are several types of dual frequency systems. Figure 10.15 shows a dual-frequency system using one induction coil. This system uses the delay between the preheat and the fast heat cycle to transfer the coil's electrical connections from the medium-frequency power supply to the RF power supply. The static heating cycle for a gear run by this system includes (Ref 6):

- Load position
- Scan up to preheat position
- Preheat 3 s
- Delay to RF 3.5 s
- RF heat 0.16 s
- Quench on, no delay (polymer based quench media)
- Quench time 8 s
- Return to load position

Figure 10.16 shows a dual-frequency setup where each of the two power supplies has its own induction coil. The gear preheated with low frequency is then dropped to the high-frequency coil, and finally austenitized and quenched in the RF coil. Figure 10.17 shows a hypothetical setup in which the gear is scanned in both the preheat position and the austenitizing position. Scanning permits the use of lower power densities. The preheat is accomplished by scanning through the coil of a medium-frequency power

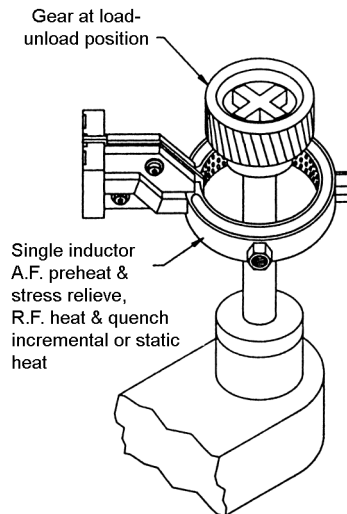


Fig. 10.15 Dual-frequency contour, one coil. A single induction coil provides for heating and quenching, as employed for the thermal treatments indicated. AF, audio frequency; RF, radio frequency. Source: Ref 6

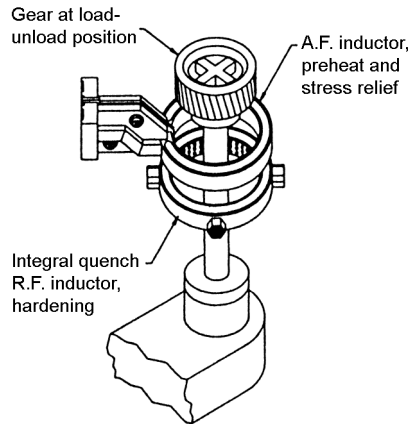


Fig. 10.16 Dual-frequency contour, two power supplies with coils: multi-frequency induction-hardening machine with coils designed for static heating of gear. AF: audio frequency; RF: radio frequency. Source: Ref 6

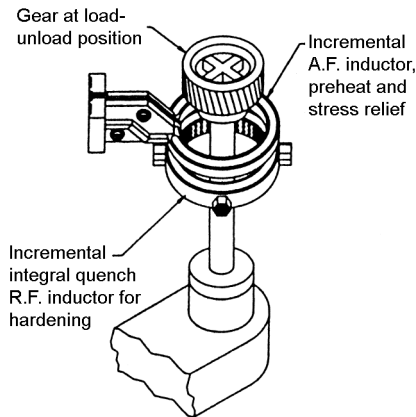


Fig. 10.17 Dual-frequency contour, two-power scan: multifrequency induction hardening machine with coils designed for scan (incremental) heating of gear. AF, audio frequency; RF, radio frequency. Source: Ref 6

supply. The scanning permits the power supply to have a lower output-power rating than that which would be required for static heating. After the preheat scan, the gear is lowered into the high heat coil of the RF power supply. Table 10.1 shows a comparison of preheat scanning versus preheat static heating. The limitations on this process are based mainly on the size of the gear to be hardened. If the gear has a small face width, 20 mm ($\frac{1}{2}$ in.) or smaller, the static approach may be desired. Note that the power requirements are substantial for large gears. The high power requirements may limit the ability of a user to install and use this type of process. Also, with larger gears and where a perfect contour is not desired,

Table 10.1 Incremental (scan) versus static contour gear hardening by dual-frequency induction heating: Sample gear development data

Characteristic	Data
Gear dimensions	
Major diameter	12.676 in.
Root diameter	12.00 in.
Face width	2.800 in.
Diametral pitch	8
Surface area	112 in. ²
Material	4150
Process requirements	
Surface hardness	58–62 RC after 300 °F temper
Case depth	0.030 in.; minimum in root
Pattern	Contour, no more than ⅔ of tooth height
Phase I power requirements	
Low frequency	1176 kW
High frequency	784 kW
Phase II power requirements	
Low frequency	480 kW
High frequency	170 kW
Source: Ref 6	

gears can be scanned for austenitizing in the single-coil, dual-frequency configuration.

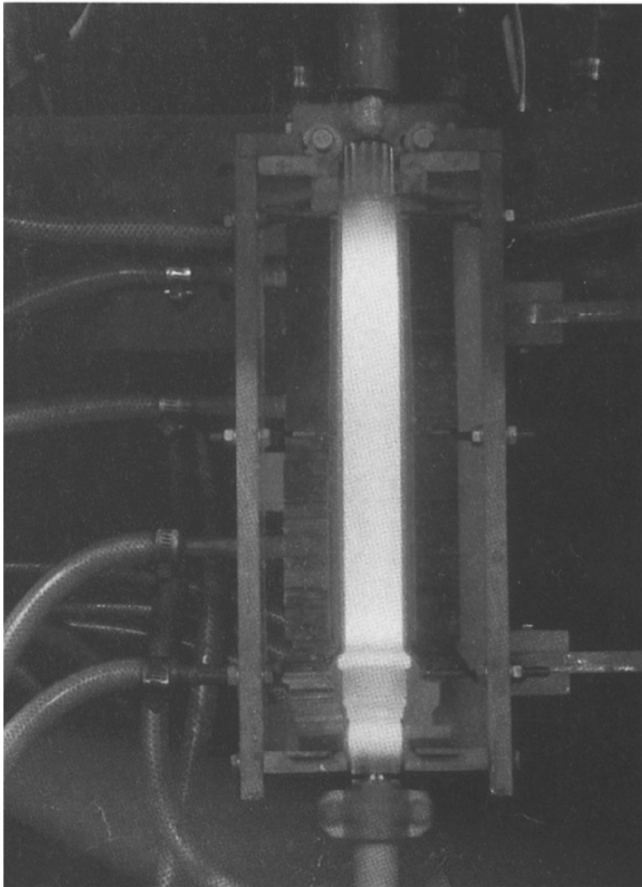
In all single-shot applications and where the overall diameter of the gear can be scanned, the gear is rotated. During the quenching of large-tooth gears, the rotation speed may need to be slowed so that the gear teeth do not spin out the quenchant through a paddle-like effect. Substantial flow must be used during oil quenching to eliminate any fire hazard. Polymer quenches are widely used with quench rings and spray quenching in concentrations appropriate for the material, required hardness, and geometry of the gear. Contour-hardened gears may need very rapid and accurate application of the quenchant to force immediate and rapid quenching.

The power requirements are dictated by the power required for the application. Small through-heating applications such as the small armature shafts can be run on RF power supplies as low as 5 kW. The large, contour-hardening power supplies may require powers into the 500 to 1000 kW region.

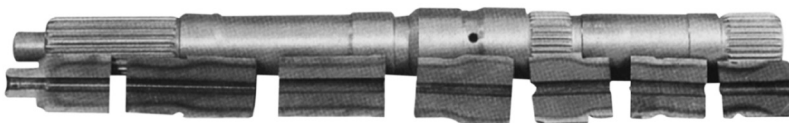
Sprockets generally require heating patterns similar to pattern E in Fig. 10.5. Because of the tooth profiles, even small-diameter sprockets produce the most uniform heating, with frequencies of 25 to 50 kHz. Sprockets are hardened single shot up to 381 to 508 mm (15 to 20 in.) in diameter, with the power-supply frequency decreasing as the diameter increases. The tendency is for root heating, followed by conduction of heat into the tip. Dual-frequency heating techniques have been used in which the power supply first heats the root at 3 kHz, then turns off for a couple of seconds so that the power supply’s heat station can switch capacitance, and then turns on again at 10 kHz to top off the heat at the tooth tip. Large sprockets, such as those greater than 635 mm (25 in.) in diameter, are generally hardened by single-tooth techniques.

Powdered metal gears are usually statically induction hardened with the same types of coils as would be used on steel gears. The powdered metals heat better with high frequency, and care needs to be taken that the gears are not overheated because more porosity is produced.

Shafts, as shown in Fig. 10.18, can require that the induction-hardened pattern pass over a larger diameter and around the corner and extend around the fillet into the smaller diameter. The basic frequency used will depend upon the material and the required case depth. The ideal situation is one in which the change in diameters is not greater than the frequency



(a)



(b)

Fig. 10.18 Shaft with changes in diameter. (a) A single-shot coil vertically heats the output shaft in 8 s. (b) Cutaway view of single-shot shaft showing contoured pattern. Source: Ref 7

used. Because of the potential for overheating at the corner between the two diameters and the need to harden the fillet, the lowest possible frequency should be selected to provide deep heating. When the hardening pattern starts at the edge of the larger part, a lower-power heating dwell can be used to bring the cross section up to heat, and then the scanning cycle starts over the smaller diameter. Another technique is to use a longitudinal coil that is designed to produce the necessary power density to scan the parts. Scanning speeds and output power may need to be changed as the part moves from the larger diameter to the smaller diameter. Finally, there is substantial application of horizontal scanners to full-length induction hardening of full-length bars and for ball screws.

Miscellaneous Applications. There are many other applications of induction surface hardening. These include uses in the ordnance, hand-tool, and automotive fields.

In the ordnance area, induction heating has been used for both surface hardening and through hardening of armor-piercing projectiles. The induction process allows a very uniform microstructure to be obtained. Induction produces a more uniform microstructure than that produced by furnace heat treating on some parts.

Induction heating has also been used for selective through hardening and surface hardening of heads for tools such as hammers, axes, picks, and sledges. These tools are usually made of 1078/1090 steel. Lead baths were once used for heat treating of such parts, but environmental regulations have almost eliminated the use of lead baths. Figure 10.19 shows an installation for the induction hardening of hammers. The claws are being austenitized, two at a time, using a 50 kW, 50 kHz power supply. The split design of the claws requires that a unique coil design be used to produce uniform heating. After austenitizing, the heads are moved downward into quench pads for polymer quenching. The faces of the striking end are austenitized on another power supply operating at 10 kHz.

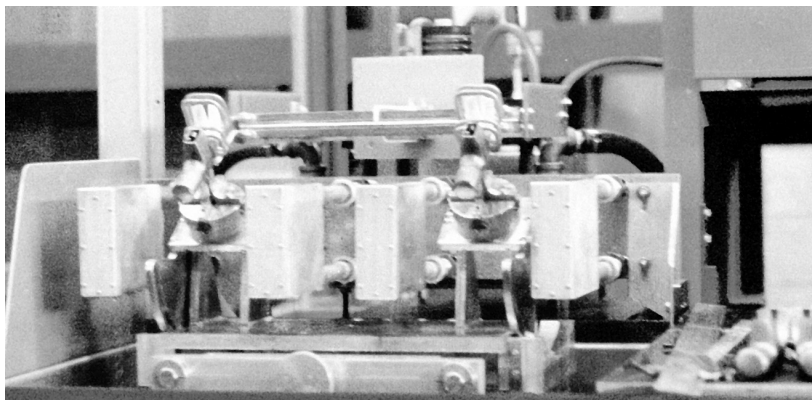


Fig. 10.19 Hammer head hardening: hammer claws being heated to hardening temperature in a Lepel, two-position load coil and quench facility. Covers have been removed from machine. Source: Ref 8

Figure 10.20 shows a camshaft lobe that is being induction hardened with high-intensity power. Using 25 kHz instead of 10 kHz, the heat cycle was 1.2 s. The shallower case depth increased the production rate, produced straighter camshafts, and improved the lobe crowning. Vertical scanners are used to move and to position the cams in the coil on a programmed basis. Other automotive applications include torsion bars, wheel spindles, wheel hubs, and tulips for front-end drives. Figure 10.21 shows two camshafts of different lengths that were induction hardened using the same

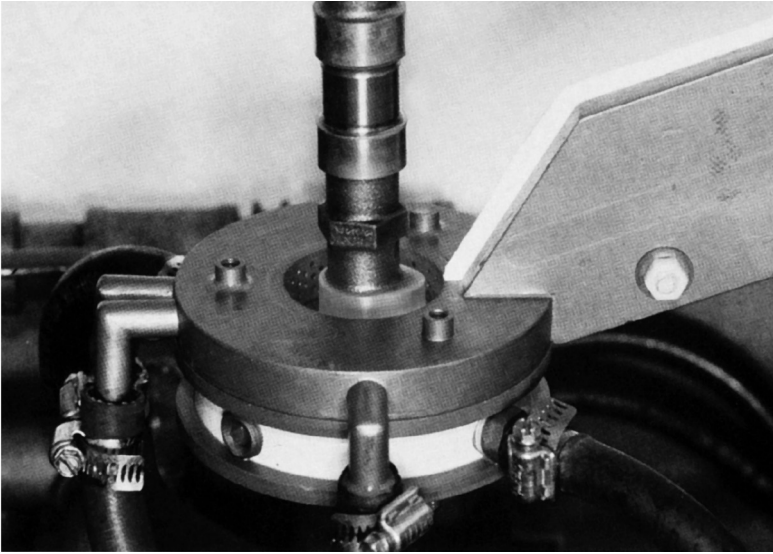


Fig. 10.20 Camshaft lobe: high-intensity induction heating one lobe at a time (7 kW/cm^2 or 45 kW/in.^2). Source: Ref 7

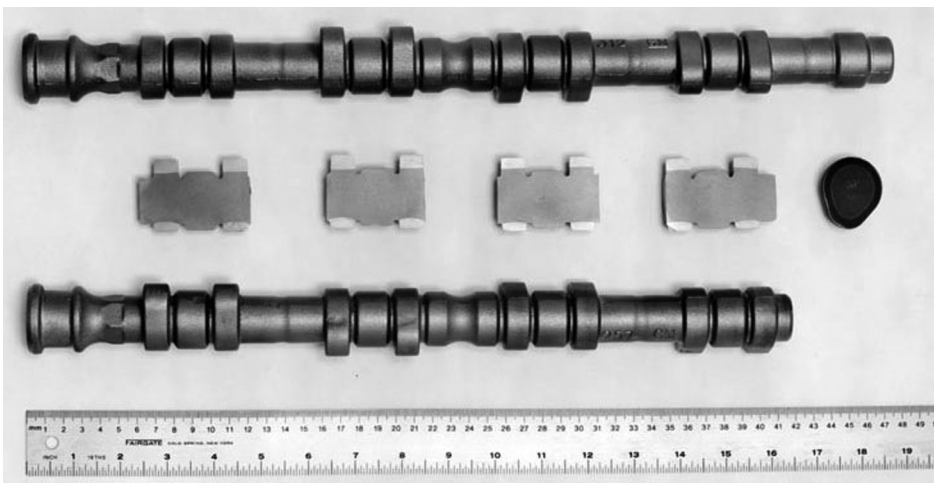


Fig. 10.21 Two camshafts having different lengths that were induction hardened using the same single-shot inductor that hardens multiple lobes. Source: Ref 5

same induction coil that was designed to heat two lobes at once. Figure 10.22 shows examples of cam lobe shapes that are not symmetrical and their induction hardened patterns. Note that the lower the frequency, the easier it is to obtain uniform hardened patterns even though the coupling between the lobe and induction coil can vary considerably.

Through-Hardening Applications

Through hardening and tempering are commonly done on a variety of parts through the use of induction. Through hardening occurs either when a portion of a part is through heated and hardened or when the entire part



Fig. 10.22 Examples of cam lobe shapes showing nonsymmetrical geometry. Source: Ref 5

is induction hardened. Hairpin coils are used to through harden the gripping teeth and cutting edges of many tools and cutters, with RF being very effective. Although the final effect appears to be a case such as the cutting edge of diagonal pliers (Fig. 10.23), hairpin coils through heat in the area of the cutting edge only. Many parts are through heated on one wear area or cutting edge, while the balance of the part is not affected.

Figure 10.24 shows an induction heating application in which track pins are through hardened, furnace tempered, induction case hardened, and furnace tempered in one line. Two hundred links per hour for diameters ranging from 41 to 65 mm (1.6 to 2.6 in.) and lengths ranging from 224 to 345 mm (9 to 13.8 in.) are horizontally moved through induction hardening, quenching, and induction tempering. The pins are progressively moved by a walking-beam mechanism through three different heating zones to provide a uniform austenitizing temperature. After exiting from the last austenitizing coil, the pins are conveyed to a location for pickup, where dual-grip overhead gantry picks up and carries the hot pins to one of three quench spindles. The dual grip enables the previously quenched pin to be removed from centers, with the hot pin then placed into the centers. The pin is rotated and quenched uniformly with a polymer quenchant. During quenching the gantry moves back to pick up the next hot pin and deposits the quenched pin on a ramp for acceptance into the tempering furnace. After leaving the tempering furnace, the pins are conveyed through a cool-down chamber and located into position for pickup by a second overhead gantry. This gantry places the pins into one of three spindles for static induction heating for case hardening, with austenitizing in the coil and quenching outside of the coil. After leaving the tempering furnace, the pins are cooled and conveyed to a grinding operation.



Fig. 10.23 Diagonal pliers. Source: Ref 9

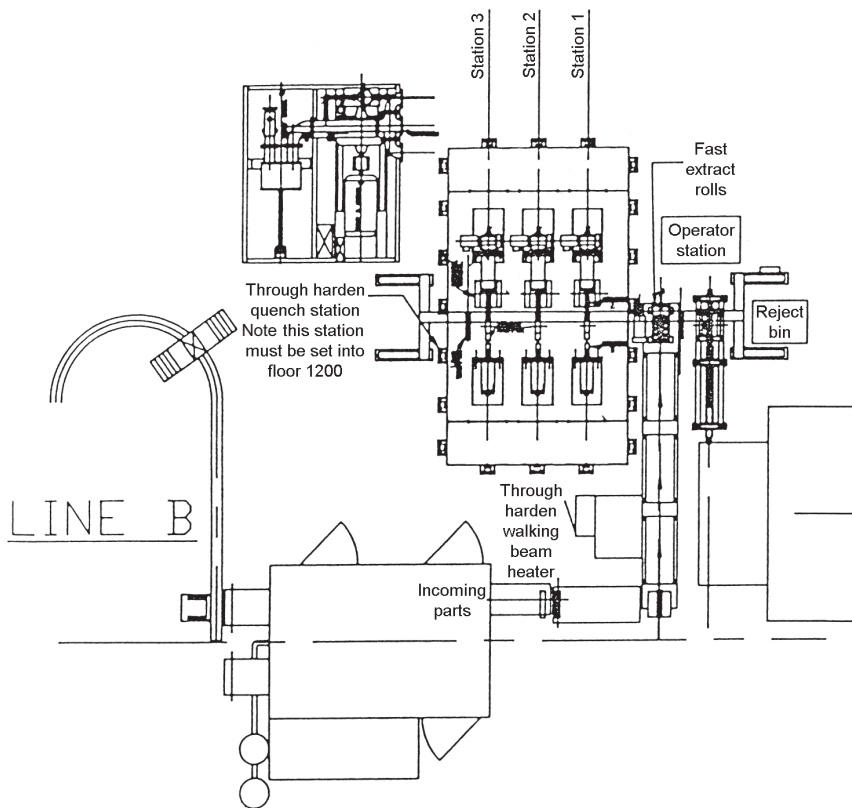


Fig. 10.24 Track pins. Source: Ref 10

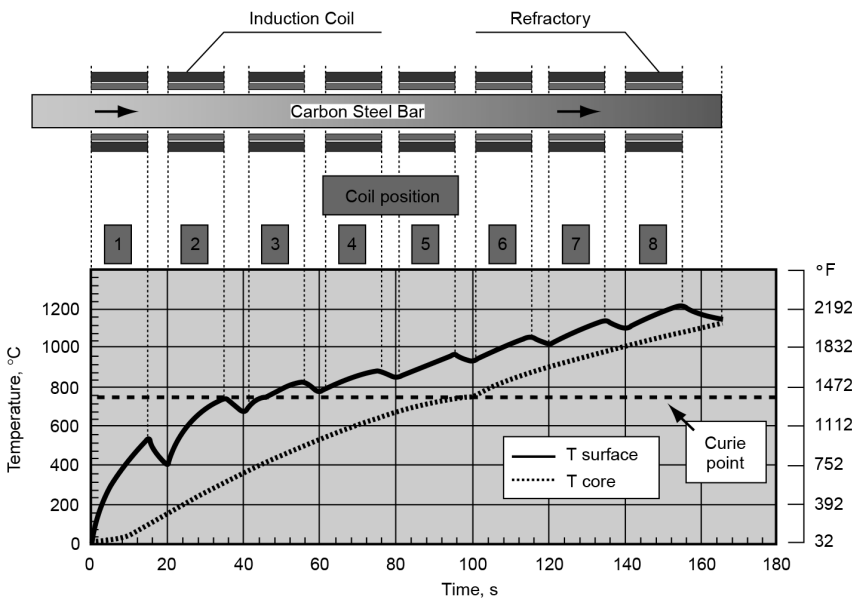


Fig. 10.25 Continuous bar heating: thermal profile of a steel bar as processed through an eight-coil induction line. Source: Ref 11

Modern techniques for producing long products such as cylindrical bars and rods combine the former three stages of production, casting, reheating, and rolling, into a continuous line. Reheating is used to provide the bar/rod at the rolling stage with the desired temperature profile across the thickness, diameter, and length. In some cases the initial temperature of the bar/rod is uniform; in other cases the initial temperature is nonuniform due to uneven cooling as the material progresses from the caster. In recent

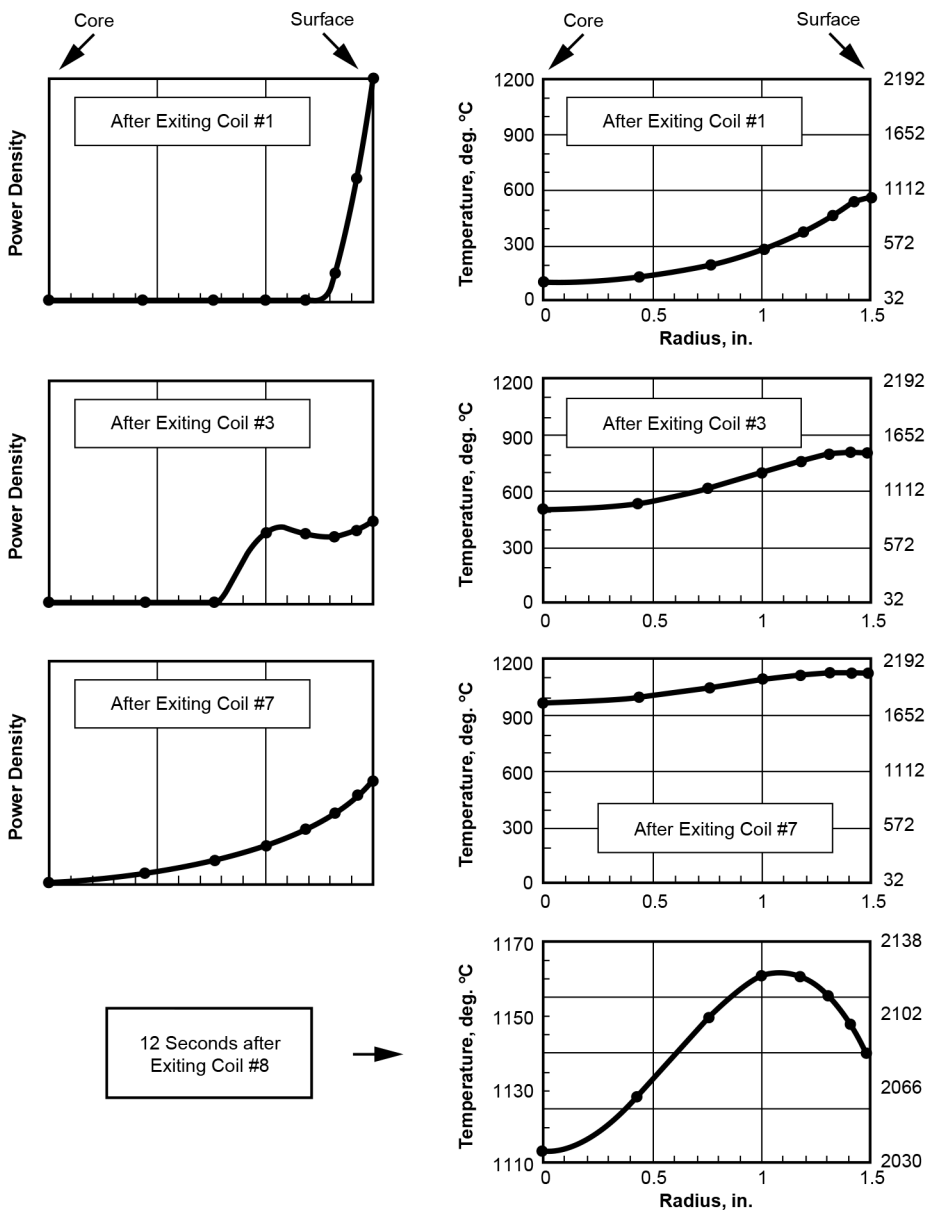


Fig. 10.26 Models of power density on continuous bar heating. Power density and temperature profiles of a bar at different positions in an in-line induction heater. Source: Ref 11

years the bar/rod producers are selecting induction heating in the place of gas-fired furnaces. The large reduction in floor space required by induction is significant, and induction improves the bar surface quality.

Depending on the requirements for throughput and bar size, the induction systems may consist of one or several induction coils, as shown in Fig. 10.25. Computer modeling can be used to analyze the complex technological problems, so that not only is the surface-to-core temperature uniform, but also the leading and trailing bar ends are not overheated. Figure 10.26 shows models of power density and temperature profiles of a bar at different positions in an in-line induction heating system.

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CHAPTER 11

Induction Heat Treating Process Analysis

IN A FORMALIZED quality system, a clear understanding of the requirements for the part to be induction hardened is not just necessary but is even required under preproduction planning. This Chapter provides application and processing analysis for the induction hardening of a new part, or the review of an old part. The complete specifications for processing should be clearly stated either on the print or in a specification in an accompanying document that is referenced on the print. The material and any previous heat treatments need to be known. If a part is being designed, the factors that promote good design of a part can be considered. Potential critical stress points such as keyways, cross holes, and any nonuniform cross sections need to be identified. If the part is already designed, then these stress points need to be reviewed to see what effect they may have on successfully induction hardening a part to print specifications. Figure 11.1 provides a step-by-step guide with the most important factors reviewed first so that the application can be qualified before completion of the analysis. By first qualifying the application, it can be determined if the application can be done by induction and if any changes or clarifications are needed. Please note that after the initial qualification, as the analysis precedes some of the choices, such as frequency selection and power selection, may be changed or modified because of economic factors and production requirements.

Process Qualification

Material and Prior Heat Treatment. The selection of the wrong material, or a material with a prior microstructure that is not recommended, can prevent the induction hardening process from producing good parts.

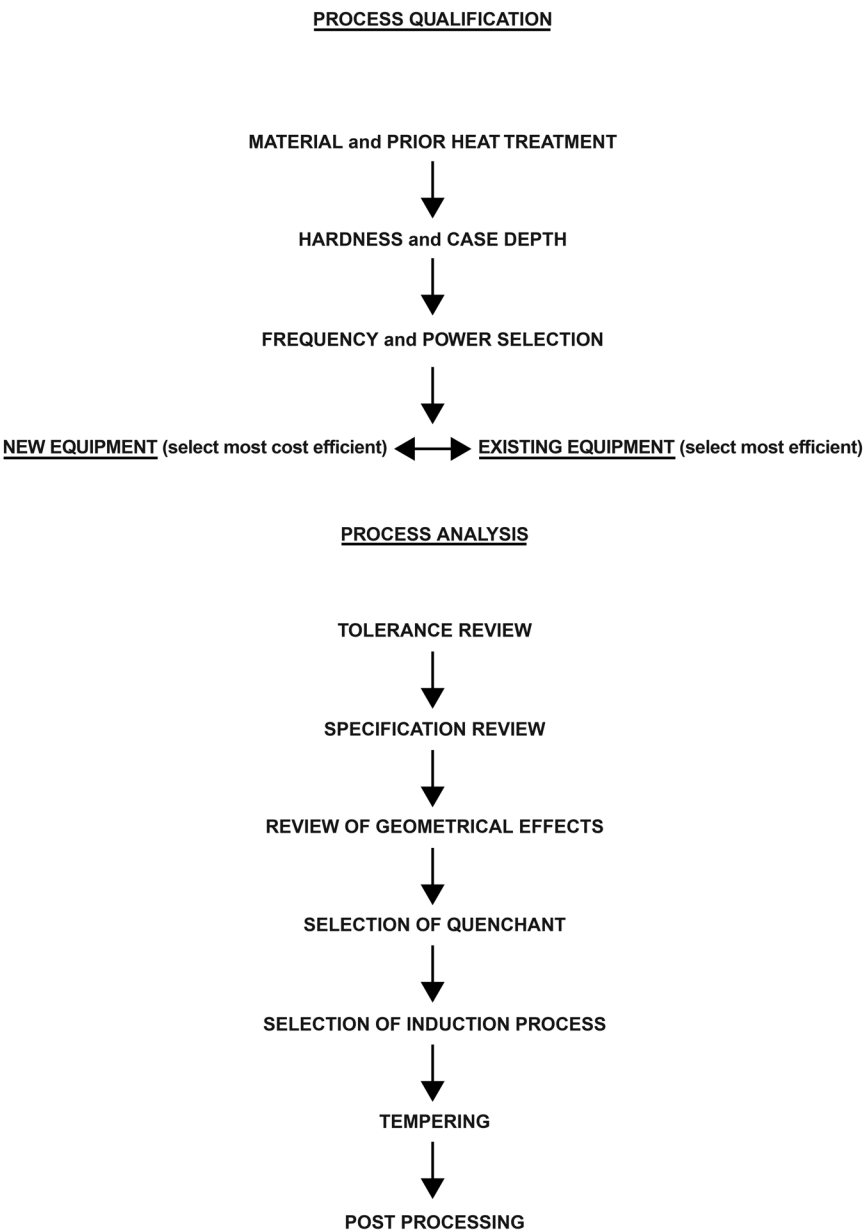


Fig. 11.1 Process qualification and analysis. Source: Ref 1

Therefore, the first step is to determine the material and any prior heat treatment from the workpiece print. This print should define the material itself, such as American Iron and Steel Institute (AISI) 1045. Reference 2 has tables in the appendix that cross-reference to different standards and numbering systems. Next, review the manufacturing source of the material. The workpiece could be made from cold-rolled stock or hot-rolled

stock or forged or cast. Finally, if noted on the print, determine any prior heat treatment. This includes thermal processes such as annealing, normalizing, quench and tempering, or carbon restoring.

Hardness and Case Depth. The next step in analysis is to determine whether the specified hardness can be produced. Figure 11.2 shows the relationship between carbon content and the hardness range that can be produced. The carbon content determines whether the workpiece is capable of being quenched within the hardness ranges shown. A common error in material selection is the use of low-carbon steel, unless carburized, or a steel with lower than needed carbon content. If there is any doubt about the effect of the carbon content for a particular alloy, the J1 hardenability hardness (at 1.5 mm, or $\frac{1}{16}$ in.) is a good indication of the surface hardness to which an alloy with a good prior microstructure will quench. Chapter 5, “Heat Treating Basics,” in this book discusses in detail that the best prior microstructure for induction hardening is the microstructure produced by quenching and tempering. AISI 4150 steel has high enough carbon to quench optimally to a surface hardness of 63 HRC. However, if 4150 is fully annealed, it may not quench over 54 HRC when induction hardened.

After determining if the part will quench to or above the desired hardness, the case depth specifications must be reviewed. The part must have material that is capable of quenching over the desired minimum case depth. To determine this, review the hardenability chart for the material. Typical hardenability charts for some of the steels commonly induction hardened are in Appendix 6, “Hardenability Curves,” in this book. Also, the ASM Handbooks may be used to find the charts for other steels not listed in Appendix 6 in the book. Keep in mind that hardenability charts show the expected hardenability for a broad number of heats. Because of purchasing leverage, some manufacturers may be able to purchase better grades of steel than those obtainable through warehouses. However, the

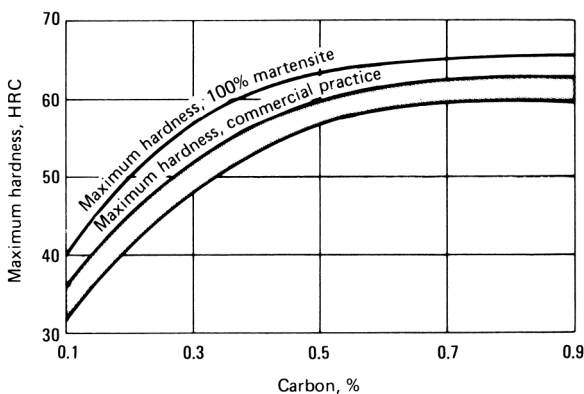


Fig. 11.2 As-quenched hardness vs. carbon content. Source: Ref 2

assumption can be made that if the specified case depth, such as defined by HRC 50 or other hardness value, meets the specified depth for all heats, the workpiece will quench to the specified case depth with the correct prior microstructure.

At this point, if the qualification has shown that the part and material could not be induction hardened to the specification, three different options can be selected: (a) stop the analysis until a change in material or heat treatment is made, (b) list the specifications that the intended material is expected to produce, or (c) specify the material and/or prior heat treatment needed and proceed with the qualification noting this assumption in writing. An example of this would be to specify that the carbon content of the material needs to be a certain minimum value. If an AISI 1040 steel is specified with the requirement that the surface hardness is to be 61 HRC, the use of 1050 steel will readily produce this hardness. Once the conclusion has been made that the material is capable of being induction hardened to the given specifications, the first steps in qualification are complete. Further discussion is given to hardness and case depth specifications later in this Chapter. The next step in qualification is to make the initial power supply frequency and power requirements.

Frequency selection (Ref 3) is the first parameter considered for induction heating. Primary considerations in the selection of frequency are depth of heating efficiency, type of heat treatment (such as surface hardening vs. through hardening), and the size and geometry of the part.

The frequency and power supplies commonly used in the induction hardening of steel are listed in Table 11.1. The lower frequencies are more suitable as the size of the part and the case depth increases. However, because power density and heating time also have an important influence on

Table 11.1 Frequency selection

Case depth		Diameter		Frequency				
mm	in.	mm	in.	1 kHz	3 kHz	10 kHz	50 kHz	450 kHz
0.38–1.27	0.015–0.050	6.35–25.4	¼–1	...	...	...	...	Good
1.29–2.54	0.051–0.100	11.11–15.88	⅜–⅝	...	...	Fair	Good	Good
1.29–2.54	0.051–0.100	15.88–25.4	⅝–1	...	...	Good	Good	Good
1.29–2.54	0.051–0.100	25.4–50.8	1–2	...	Fair	Good	Good	Good
1.29–2.54	0.051–0.100	>50.8	>2	Fair	Good	Good	Good	Poor
2.56–5.08	0.101–0.200	19.05–50.8	1–2	...	Fair	Good	Good	Poor
2.56–5.08	0.101–0.200	50.8–101.6	2–4	Fair	...	Good	Good	Poor
2.56–5.08	0.101–0.200	>101.6	>4	Good	Good	Fair	Good	Poor
5.08–10.0	0.200–0.400	>8	>2	Good	Good	Fair	Poor	Poor
Through hardening								
		1.59–6.35	⅛–1	...	...	...	...	Good
		6.35–12.7	¼–½	...	...	Fair	Fair	Good
		12.7–25.4	½–1	...	Fair	Good	Good	Fair
		25.4–50.8	1–2	Fair	Good	Fair	Poor	...
		50.8–76.2	2–3	Good	Good	Poor	...	...
		76.2–152.4	3–6	Good	Poor	Poor	...	...
		>152.4	>6	Poor	Poor	Poor	...	...

“Good” indicates most efficient frequency. “Fair” indicates the frequency is less efficient. “Poor” indicates not a good frequency for this depth. The coil power density must be kept within the recommended ranges. Source: Ref 1

the depth to which the part is heated, wide deviations from Table 11.1 may be made with successful results. This interrelationship is shown in Fig. 11.3 in terms of case depth, frequency, and power density for surface-hardened steel. In some instances, the determining factor in selecting the frequency is the power required to provide power density sufficient for successful hardening, as lower frequency induction equipment is available with higher power ratings and lower cost.

The equation given for reference depth, d , in Chapter 2, “Theory of Heating by Induction,” in this book can be used to estimate the optimal power supply frequency for induction hardening of steel. For surface hardening, the desired case depth is typically taken to equal about one-half the reference depth required for austenitizing for selection of minimum frequency. Table 11.1 shows the practical effect of frequency selection for hardening to various case depths. By contrast, when through hardening is desired, the frequency is usually chosen such that the reference depth is a fraction of the bar radius (or an equivalent dimension for parts that are not round). This is necessary in order to maintain adequate “skin effect” and to enable induction to take place at all. If the reference depth is chosen to be comparable to or larger than the bar radius, there will be two sets of eddy currents near the center of the bar induced from diametrically opposed surfaces of the bar. From a practical viewpoint, it is as if the induced currents cancel each other. To avoid this, frequencies for through hardening are often chosen so that the reference depth does not exceed approximately one-half the thickness for plates and slabs when using solenoid coils. When the bar diameter is less than four reference depths, or slab thickness is less than two reference depths, the electrical efficiency drops sharply. By contrast, little increase in efficiency is obtained when the bar diameter or slab thickness is many times more than the reference depth.

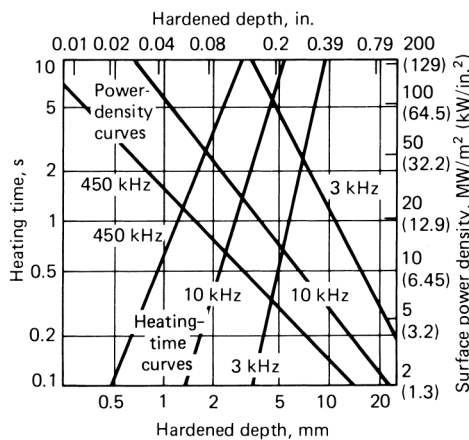


Fig. 11.3 Interrelationship among heating time, surface power density, and hardened depth for various induction generator frequencies.
Source: Ref 3

Typical frequency selections for induction hardening of steel workpieces are listed in Table 11.1 and Fig. 11.4. Those for surface hardening are examined first. For very thin cases such as 0.40 to 1.25 mm (0.015 to 0.050 in.) on small-diameter bars, which are easily quenched to martensite, relatively high frequencies are best. If the reference depth is equated to the case depth, the best frequency for a 0.75 mm (0.030 in.) deep case

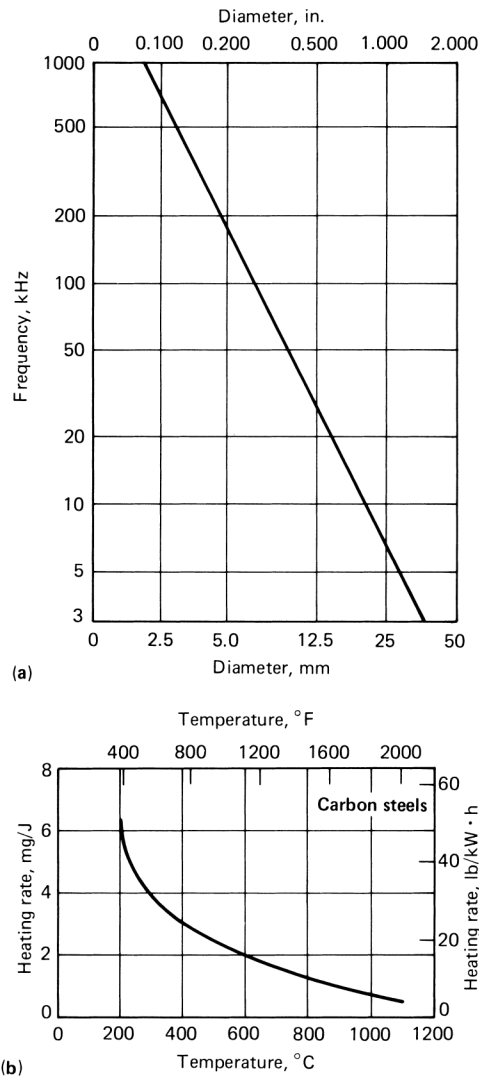


Fig. 11.4 Typical frequency selections and heating rates for induction hardening of steel parts. (a) Relationship between diameter of round steel bars and minimum generator frequency for efficient austenitizing, using induction heating. (b) Heating rate for through heating of carbon steels by induction. For converted frequencies, the total power transmitted by the induction to the work is less than the power input to the machine because of converter losses. See also Fig. 11.1. Source: Ref 3

on a 13 mm (0.05 in.) diameter bar is around 450 kHz. When the surface of a larger-diameter bar is hardened, particularly when the case is to be deep, the frequency is often chosen so that the reference depth is several times the desired case depth. This is because the large amount of metal below the surface layer to be hardened represents a large thermal mass that draws heat from the surface. Unless very high power densities are employed, it is difficult to heat only the required depth totally to the austenitizing temperature. As an example, consider the recommended frequency for imparting a 3.8 mm (0.15 in.) hardened case to a bar 75 mm (3 in.) in diameter. If reference depth were equated to the case depth and a frequency of about 10 kHz were selected, only “fair” results would be produced. A frequency of 3 kHz, with its deeper reference depth, is more efficient at producing the deeper case depth on large diameters and is accordingly rated at “good.”

For through hardening of a steel bar or section, the optimum frequency is often based on producing a reference depth about one-fourth of the bar diameter or section size. For instance, through heating and through hardening a 64 mm (2.5 in.) diameter bar would entail using a power supply with a frequency of about 1 kHz. If lower frequencies were employed, inadequate skin effect (current cancellation) and lower efficiency would result. On the other hand, higher frequencies might be used. In these cases, however, the power supply output would have to be low enough to allow conduction of heat from the outer regions of the steel part to the inner ones. Otherwise, the surface may be overheated, leading to grain growth or even melting.

Power Density and Heating Time. Once the frequency has been selected, varying the power density and heating time can produce wide ranges of temperature profiles. Selection of these two heating parameters depends on the inherent heat losses of the workpiece (from either radiation or convection losses) and the desired heat conduction patterns of a particular application.

In through-heating applications, the power needed is generally based on the amount of material that is processed per unit time, the peak temperature, and the material’s heat capacity at this temperature. Power specification for other operations, such as surface hardening of steel, is not as simple because of the effects of starting material condition (prior microstructure) and the desired case depth.

Surface heating is used primarily in the surface hardening of steel parts such as shafts and gears. In this type of application, high power densities and short heating times are used when thin case depths are desired.

Typical power density recommendations for surface hardening of steel are given in Table 11.2. These are based on the need to heat very rapidly to the austenitizing temperatures shown in Table 11.3 and have proven through years of experience to be appropriate. When using these or other fixed ratings, however, the effect of heating time and frequency on case

Table 11.2 Power density required for surface hardening

Frequency, kHz	Depth of hardening(a)		Input					
			W/mm ²			kW/in. ² (c)		
	mm	in.	Low(b)	Optimum(c)	High(d)	Low(b)	Optimum(c)	High(d)
500	0.38–1.14	0.015–0.045	10.9	15.5	18.6	7	10	12
	1.14–2.29	0.045–0.090	4.7	7.8	12.4	3	5	8
10	1.52–2.29	0.060–0.090	12.4	15.5	24.8	8	10	16
	2.29–3.05	0.090–0.120	7.8	15.5	23.3	5	10	15
	3.05–4.06	0.120–0.160	7.8	15.5	21.7	5	10	14
3	2.29–3.05	0.090–0.120	15.5	23.3	26.35	10	15	17
	3.05–4.06	0.120–0.160	7.8	21.7	24.8	5	14	16
	4.06–5.08	0.160–0.200	7.8	15.5	21.7	5	10	14
1	5.08–7.11	0.200–0.280	7.8	15.5	18.6	5	10	12
	7.11–9.14	0.280–0.360	7.8	15.5	18.6	5	10	12

Note: This table is based on use of proper frequency and normal overall operating efficiency of equipment. Values may be used for static and progressive methods of heating; however, for some applications, higher inputs can be used when hardening progressively. (a) For greater depth of hardening, a lower-kilowatt input is used. (b) Low kilowatt input may be used when generator capacity is limited. These kilowatt values may be used to calculate largest part hardened (single-shot method) with a given generator. (c) For best metallurgical results. (d) For higher production when generator capacity is available. (e) Kilowattage is read as maximum during heat cycle. Source: Ref 3

Table 11.3 Approximate induction austenitizing temperature

Steel	Carbon, %	Austenitizing temperature	
		°C	°F
1022	0.18/0.23	900	1650
1030	0.28/0.34	875	1600
10B35	0.32/0.38	855	1575
1040	0.37/0.44	855	1575
1045	0.43/0.50	845	1550
1050	0.48/0.55	845	1550
1141	0.37/0.45	845	1550
1144	0.40/0.48	845	1550
1541	0.36/0.44	845	1550
Stress proof	0.36/0.44	845	1550
Fatigue proof	0.36/0.44	845	1550
4130	0.28/0.33	870	1600
4140	0.38/0.43	875	1600
4150	0.48/0.53	845	1550
ETD 150	0.48/0.53	845	1550
4340	0.38/0.43	845	1550
5160	0.56/0.64	845	1550
52100	0.98/1.1	800	1475
8620	0.18/0.23	875	1600
1018 carbon	0.9 nom	815	1500
1118 carbon	0.9 nom	815	1500
8620 carbon	0.9 nom	815	1500
5120 carbon	0.9 nom	815	1500
416 SS	<0.15	1065	1950
420 SS	>0.15	1065	1950
440C SS	0.95/1.2	1065	1950
O1	0.9	815	1500
D2	1.5	1020	1875
D3	2.25	980	1800
A1	1	980	1800
S1	0.5	955	1750

The induction austenitizing temperature can be up to 200 °F (110 °C) higher depending upon the prior microstructure and the rate of heating. Source: Ref 1

depth (Fig. 11.3) must be considered. Higher frequencies and higher power densities produce smaller case depths. Thus, lower frequencies at higher power densities can be used to produce the minimum possible case depth for that frequency.

Through Heating. To allow time for the heat to be conducted to the center of the workpiece, power ratings for through hardening of steel are much lower than those for surface hardening. After a while, the rate of increase of the surface and center temperatures becomes comparable due to conduction, and a fixed temperature differential persists during further heating. On larger workpieces the entire cross section can be austenitized, but temperature differential will always be present from surface to core center. Table 11.1 shows frequency efficiency versus diameter of a round bar. In addition to the methods used by Tudbury (Ref. 4), the allowable temperature differential permits the power supply output ratings to be selected. The process involves selecting the frequency and calculation of the bar diameter (or section size) to reference depth, a/d . For most through-heating applications this ratio will vary from around 4 to 6. Then the values of the thermal conductivity are used to estimate the induction thermal factor. Finally, the total power required to heat the bar is calculated.

In addition to these estimates, if total accuracy is needed radiation heat loss must also be considered when calculating power requirements. At 875 °C (1600 °F) the losses are 0.010 kW/cm² (0.065 kW/in.²) of surface. The losses double when heating to 1100 °C (2000 °F). On the continuous heating of large surfaces, these losses should be added to the power requirements.

However, through the use of tables and knowing the effective weight of steel to be heated per hour, it is easy to determine the power supply requirements. From knowing the effective heat cycle time, the effective weight of steel to be heated per hour can be calculated. If the process is not continuous, the effective heat cycle can be calculated by knowing the operating efficiency and number of parts to be heated per hour. If the required heating time is 10 s, then divide 1 h (3600 s) by this heat cycle of 10 s to get an effective heating rate per hour of 360 parts. Then multiply by the effective weight to be heated to obtain the pounds per hour. If the 360 parts have an effective weight of 600 lb and need to be heated to 875 °C (1600 °F), then 0.8 mg/J (4 lb/kW-h) or 250 kW is needed (Fig. 11.4b). Table 11.1 can be reviewed to determine frequency ranges that can be used. Finally, the approximate power densities required for the through heating can be obtained from Table 11.4. When through heating is desired, lower power densities are used than those used for surface hardening. Because the price of power per kilowatt of power supply decreases with frequency, sometimes there are trade-offs between the optimum frequency and the frequency selected. On large-capacity, through-heating installations such as the continuous hardening of bar stock, more than one power supply with different frequencies may be used in-line to promote the most efficient heating. Large-tonnage installations may use frequencies ranging down to line frequency for preheating below the Curie temperature (also providing reduced thermal shock) and higher frequencies above the Curie point. Also, lower frequencies are best for induction tempering because

Table 11.4 Approximate power densities required for through heating of steel for hardening, tempering, or forming operations

Frequency(a), Hz	Input(b)									
	150–425 °C (300–800 °F)		425–760 °C (800–1400 °F)		760–980 °C (1400–1800 °F)		980–1095 °C (1800–2000 °F)		1095–1205 °C (2000–2200 °F)	
	kW/cm ²	kW/in. ²	kW/cm ²	kW/in. ²	kW/cm ²	kW/in. ²	kW/cm ²	kW/in. ²	kW/cm ²	kW/in. ²
60	0.009	0.06	0.023	0.15	(c)	(c)	(c)	(c)	(c)	(c)
180	0.008	0.05	0.022	0.14	(c)	(c)	(c)	(c)	(c)	(c)
1000	0.006	0.04	0.019	0.12	0.08	0.5	0.155	1.0	0.22	1.4
3000	0.005	0.03	0.016	0.10	0.06	0.4	0.085	0.55	0.11	0.7
10,000	0.003	0.02	0.012	0.08	0.05	0.3	0.070	0.45	0.085	0.55

(a) The values are based on use of proper frequency and normal overall operating efficiency of equipment. (b) In general, these power densities are for section sizes of 13 to 50 mm (½ to 2 in.). Higher inputs can be used for smaller section sizes, and lower inputs may be required for larger section sizes. (c) Not recommended for these temperatures. Source: Ref 1

the deeper penetration of the induced current during heating requires less heat conduction to produce a uniform temperature.

Frequency and power selection can have two objectives. First, if the purpose of the analysis is for the selection of new equipment, the lowest-cost frequency will need to be determined. If the purpose of the analysis is to determine which equipment in-house should be used, then the selection can be made from the viewpoint of the equipment with the most efficient production processing cost. As discussed above, a shallow case depth might be more efficiently produced with higher frequency, while a deeper case depth is more efficiently produced by lower frequency.

Tolerance review is the next step of analysis. At this point of the review process, the broad qualification objectives of material review and power supply selection have been completed. Following is a review of the print of the part to be induction hardened, along with any pertinent specifications. The print should indicate the area to be induction hardened, and any specifications should be either listed directly on the print or referred to by a specification number.

- *Machining tolerances* may be shown either on the print dimension lines or in one of the information boxes at the bottom of the print. If the machining tolerances are in a box, the number of decimals defines the machining tolerance. For example, 0.xxx dimension might have a 0.05 mm (0.002 in.) tolerance. The machining tolerances are important because the pattern length tolerance may be indicated from a location that in itself has a machining tolerance that can affect the pattern tolerance. Induction pattern lengths should not be specified to the same tolerances as machining tolerances.
- *Overall part dimensions* should be clearly shown. Locations for holding the workpiece should be determined.
- *Pattern length location and tolerances:* Pattern starting locations need to be clearly indicated from a machined surface, preferably from the location at which the part will be held or located. Induction pattern

locations and tolerances need to be stated separately from machining tolerances. The pattern length, depending on the frequency of the induction power supply, needs as large a tolerance as possible. One to two mm (0.040 to 0.080 in.) or greater is tight for radio frequencies, and tolerances can range up to 6.1 mm (0.25 in.) for the lower frequencies. Because tighter tolerances represent more setup and quality control cost, the pattern tolerances should be reasonably specified. Some parts require only minimum pattern length tolerances.

Specification Review. ASTM testing standards are discussed in Chapter 12, “Standards and Inspection,” in this book as related to hardness testing. Chapter 13, “Nonconforming Product and Process Problems,” in this book discusses testing and inspection for induction. There are currently no national standards for the other induction heat-treating specifications. This includes such items as definition of case depth (apparent or effective), pattern tolerances, microstructure requirements, special inspection requirements, or standards as listed in separate individual company standards. A wide number of companies have individual standards for the measurement of case depth and their own microstructural requirements. These specification numbers should be referenced somewhere on the print of the part to be induction hardened.

Case Depth Required and Definition. When no method of case depth specification is given, the most economical method of case depth verification is through the use of an etchant to define the total (or apparent) case with measurement of the etched depth. When the case depth is measured by determining a hardness value, the method of measurement is called effective case. For this definition, medium-carbon steels most often use HRC 50 or its equivalent. There is no standard on effective case depth for induction-hardened cases, so the definition will vary by manufacturer. Most manufacturers use a hardness value below 50 HRC when the carbon drops below 0.45%. The different types of common case depth specifications are:

- Minimum total case or effective case depth, no maximum (part can be through hardened)
- Minimum and maximum total case
- Minimum and maximum effective case
- Minimum effective case, maximum total case
- Minimum effective case at HRC 50, minimum transition case at another hardness value such as HRC 35 (this is for deep case requirements)

Geometrical Effects. The shape of the workpiece and the corresponding shape of the induction coil affect the induction heating process. The ideal shape is a round workpiece, such as a bearing. When the shape or

required hardness patterns become nonuniform, the analysis needs to be more detailed because of both overheating and underheating tendencies. This next section discusses the effects of some of the different types of workpieces and complex shapes.

Part Shape with Regard to Location of the Pattern. The easiest application of induction is where there is symmetry in respect to the workpiece and the induction pattern required. Round workpieces are ideal because the induction coil can be contoured around the diameter (or in the inside diameter of a hollow workpiece). Square and rectangular cross sections tend to have deeper heating at the corners, with the higher frequency producing more heat at the corners. Workpieces, such as diagonal pliers, easily have the cutting edge hardened. Dies that have an edge hardened on one side over a long length set up bending stresses that will tend to make the part bow, even if restrained during heating (some cutters and ways have opposing sides hardened to minimize this tendency toward bowing). Hairpin and channel coils can sometimes be contoured to follow the outline of the workpiece. Other times thin cross sections are prone to overheating. There are times when the best information on the ability to heat a given workpiece is that obtained from running test heats. The different types of coil design are discussed in Chapter 4, "Induction Coils," in this book.

Part Shape with Regard to Any Changes in Diameter or Cross Section in the Area to Be Heated. Changes in diameter require analysis to determine whether the desired induction pattern can be produced. Difficulty occurs where the change in cross section is greater than the reference depth. Although in some circumstances a timed dwell can be used to initially soak in the heat at the junction between the two diameters, if the diameter change is not too great, conventional encircling coils tend to skip and not to heat the fillet between the two diameters. Longitudinally oriented coils may need to be used in this situation. Workpieces such as shafts, which require both a flange face and the adjacent diameter to be hardened, may require the "Z"-type coils as shown in Chapter 4, "Induction Coils," Fig. 4.16. These coils are single-shot coils, but they induce the current into the flange around the circumference while inducing the current into the shaft longitudinally.

Tapered shafts or shafts with changes in diameter greater than 26 mm (1 in.) are difficult to harden. The coil losses will increase to the point that not enough power is induced into the workpiece to effectively heat the smaller diameters. Another difficult example is the scan hardening of the diameter while trying to harden the face at the end. Not enough current can be induced to heat the face without overheating the diameter adjacent to the face.

Holes. When under an induction coil, the current flow around a hole heats nonuniformly with more heat produced around the hole area. Small holes, such as 1.5 mm (0.060 in.), are not affected. As the hole size and the

frequency increase, the overheating effect increases as well. The overheating produces a tendency toward quench cracking or even melting. Machining chamfer relief on the edge of a hole will reduce this overheating tendency. Figure 11.5(a) and (d) shows the overheating effect of holes in a round bar. When holes overheat, metal plugs inserted before heating will stop the current concentration and overheating. The plugs must be inserted tight enough that they do not fly out when the part is heated. If the plugs are made of soft material, they can be drilled out. Copper or brass plugs can be used, but they have a tendency toward producing nonuniform heat,

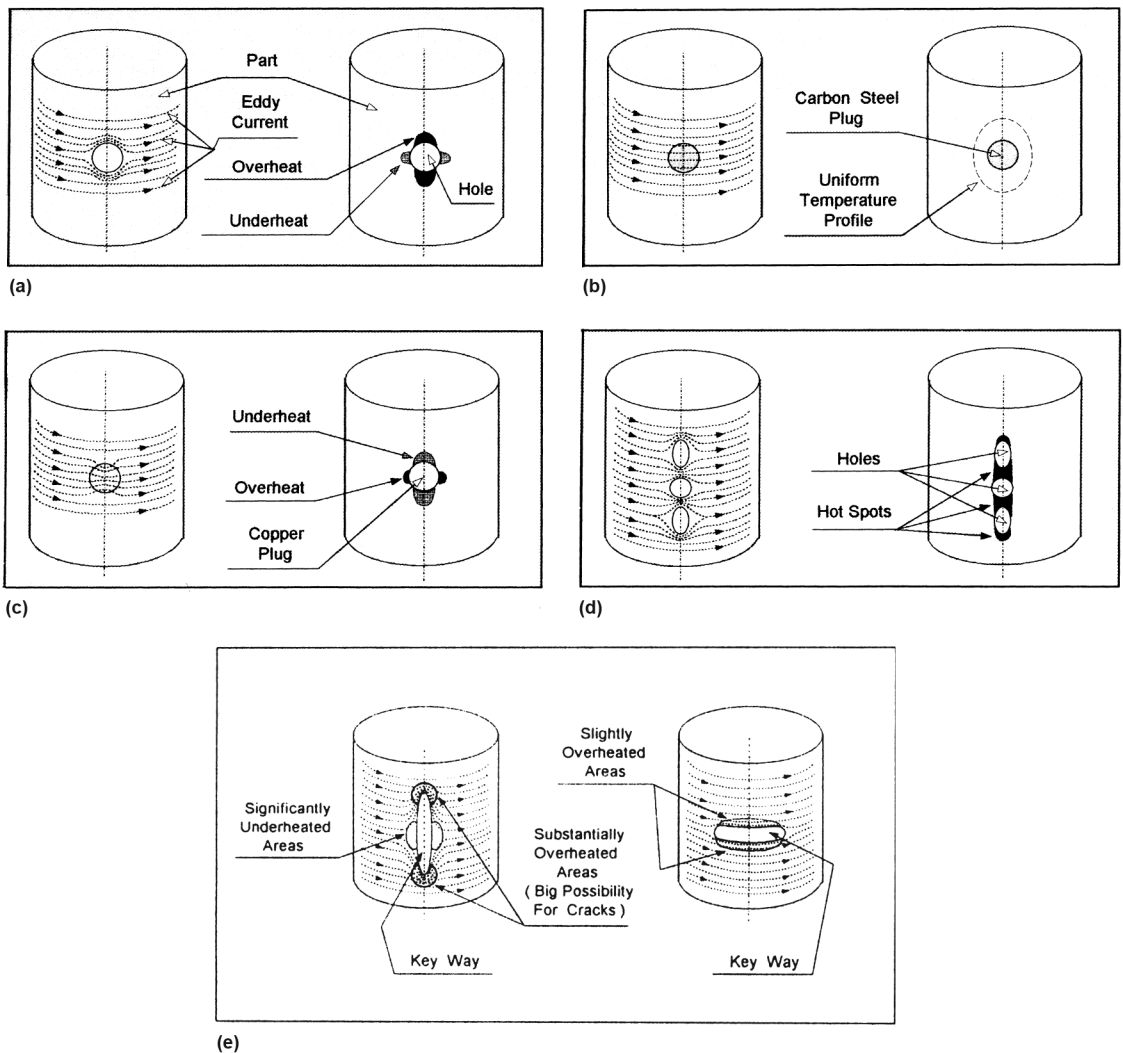


Fig. 11.5 Cross-hole overheating: eddy-current distribution and heat nonuniformities due to presence of transverse holes. (a) Transverse hole, no plug. (b) Carbon steel part and carbon steel plug. (c) Carbon steel part and copper plug. (d) Multiholed part, no plugs. Source: Ref 5

as shown in Fig. 11.5(c). Low-carbon steel, because it is similar in resistivity and conductivity to carbon steel, will tend to negate the effects of the hole, as shown in Fig. 11.5(b). Because low carbon will not harden, the low-carbon plugs can be drilled out after quenching. Small pilot holes can even be put in the plugs to help with their removal. Some use has been made of nonmetallic plugs, but they are difficult to use on a production basis. Finally, there have been installations in which air is blown into a longitudinal hole in the part that connects to the cross hole. The air prevents quench cracking.

- *Cross holes in the pattern* are sensitive to overheating as the hole size increases and frequency decreases. For instance, at 450 kHz, holes less than 1.5 mm (0.060 in.) in diameter do not generally provide any problems. As the holes size approaches 3.0 mm (0.125 in.) in diameter, the tendency toward overheating increases. At diameters greater than 3 mm (0.125 in.), the holes may need to be plugged. At 10 kHz, the critical hole size is about 6 mm (0.375 in.) in diameter. At 3 kHz the critical hole size is about 12.5 mm (0.500 in.).
- *Cross holes close to the edge of the pattern* can cause a localized overheating effect at the edge of the pattern, with the effect that the pattern becomes elliptical at the areas of the holes. If holes are present, the pattern tolerance needs to be larger than that required if the holes were not present.
- *Longitudinal holes close to the bottom of the pattern* cause distortion of the magnetic flux field because the normal heat flow into the core of the part is upset. Because there is no material in the hole to conduct heat, the area between the hole and the case will be hotter. If the hole is close enough to the austenitized area, the longitudinal area in the case will actually form a hot spot that is overheated. Cracking and distortion can result. Whenever possible, these holes should be drilled after the parts are induction hardened. If this cannot be done, it may be necessary to plug these holes. If the holes are threaded, bolts can be inserted to help with the heat flow and to reduce the overheating.
- *Longitudinal holes in the core (under the case)*, except on centerline, tend to promote distortion, as discussed in Chapter 5, “Heat Treating Basics,” in this book. Figure 11.6 shows the overheating effect of longitudinal holes. The drilling of these holes after the parts are induction hardened will promote lower distortion. If distortion is excessive and the holes are threaded, bolts can be inserted to reduce distortion.

Keyways, unless required by the specifications, should not be hardened. However, some parts require the strength that is needed in the area of keyways. Keyways will always promote nonuniform heating. Figure 11.5(e) shows the heating effect of keyways, with the particular tendency toward overheating in one area while underheating in another. Nonconcentric

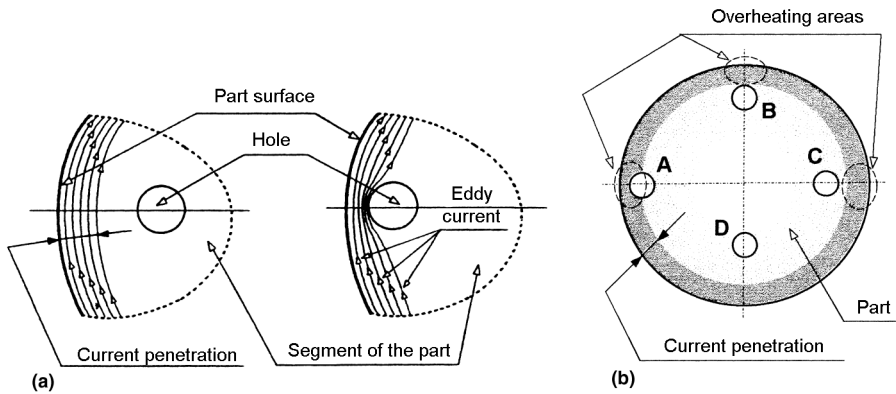


Fig. 11.6 Longitudinal holes overheating: (a) eddy-current redistribution due to presence of longitudinal hole; (b) overheating areas due to presence of longitudinal holes. Source: Ref 5

hardened cases are produced, leading to bowing or distortion. In addition, the fillet areas of the keyways are stress risers that serve to initiate quench cracks. It is usually better to use a frequency that will harden the entire keyway cross section than to use a higher frequency and not harden the bottom of the keyway. There have been other ingenious ways that the keyways have been plugged, including fastening in metal plugs and molding various materials. However, these techniques are used more as a salvage technique than for steady production. Whatever plug is used must not come out of the keyway during austenitizing and quenching.

Bores and Inside Diameters. If the part is a tube or has a bore with a thin cross section, there may be a problem with through heating unless secondary cooling is used on the outside diameter during heating. The bore must be large enough that an induction coil can fit inside the bore. While some induction coils have been developed to heat diameters under 12 mm (0.50 in.), larger diameters are preferred. If possible keyways in bores, even if the outside diameter is being hardened, should always be broached after induction hardening because they are stress risers and may promote cracking during quenching. Finally, heat transfer does not occur as rapidly when heating a bore. It is easier to control shallow cases and, correspondingly, is more difficult to produce deep cases.

Tubes and Sleeves. Hollow workpieces act differently in an induction coil than do solid workpieces. The hollow core reacts differently with the electromagnetic flux field such that tubular cross sections tend to through heat. Lower frequencies can be used to heat hollow parts than are required for solid parts of the same diameter.

Selection of Quenchant. The selection of the quenchant is important because quenching is part of the process cycle and affects the hourly production rate. In order to calculate the hourly production rate, as outlined next, the method of quenching must be determined. Quenching a work-

piece generally takes as long as or longer than hardening it. With alloy steels and slow quenchants this becomes even more pronounced. The theory of quenching is discussed in Chapter 6, “Quenching” in this book. Table 11.5 lists recommended quenchants for the various steels commonly induction hardened and where there is danger of quench cracking. When a particular grade of steel has a propensity toward quench cracking, the shape of the parts and the metallurgical characteristics influence quenchant selection and quenching technique. The selection of the quenchant will influence the selection of the induction process that is going to be used. Longer quenching times may require outside-the-coil quenching, multiple heating and quenching positions, and the use of secondary quenching in order to optimize production rates.

Selection of Induction Process. The number of workpieces to be run per hour and the operating efficiency help to determine the fixturing and type of induction process. From this information, hourly production rates

Table 11.5 Quench response

Steel	Carbon(a), %	As-quenched hardness, HRC	Quenchant type(b)		Tendency for quench cracks
			Static heating	Scanning	
1022	0.18/0.23	30/44	Water	Water	No
1030	0.28/0.34	40/52	Water	Water	No
10B35	0.32/0.38	55/58	Water	Water	No
1040	0.37/0.44	50/60	Water	Water	No
1045	0.43/0.50	54/64	Water/P	Water/P	Yes
1050	0.48/0.55	55/65	Water/P	Water/P	Yes
1141	0.37/0.45	48/56	Water/P	Water/P	No
1144	0.40/0.48	55/62	Water/P	Water/P	Yes
1541	0.36/0.44	53/60	Water/P	Water/P	No
Stress proof	0.36/0.44	55/62	Oil/P	Water/P	Yes
Fatigue proof	0.36/0.44	55/62	Oil/P	Water/P	Yes
4130	0.28/0.33	49/56	Oil (24% P)	Water/P	No
4140	0.38/0.43	53/60	Oil/P	Water/P	Yes
4150	0.48/0.53	59/64	Oil (24% P)	Water/P	Yes
ETD 150	0.48/0.53	59/64	Oil (24% P)	Water/P	Yes
4340	0.38/0.43	53/60	Oil	24% P	Yes
5160	0.56/0.64	58/65	Oil	P	Yes
52100	0.98/1.1	60/66	Oil/P	P	Yes
8620	0.18/0.23	36/46	Oil (24% P)	P	No
1018 carbon	0.9 nom	60/66	Water	...	No
1118 carbon	0.9 nom	60/66	Water	...	No
8620 carbon	0.9 nom	60/66	2/20% P	...	No
5120 carbon	0.9 nom	62/66	2/20% P	...	No
416 SS	<0.15	36/45	Oil	...	No
420 SS	>0.15	46/55	Oil	...	No
440C SS	0.95/1.2	58/62	Oil	...	No
O1	0.9	59/63	Oil	...	Yes
D2	1.5	61/64	Oil	P	Yes
D3	2.25	63/66	Oil	P	Yes
A1	1	61/65	Oil	...	Yes
S1	0.5	56/59	Oil	...	Yes
Gray cast iron		>50	P	...	No
Ductile cast iron		>50	P	...	No

(a) nom: nominal. (b) P is polymer quench, with the concentration depending on the part geometry and hardness requirements. Caution must be used in selection of the quenchant where there is a tendency toward quench cracking because of the part geometry and hardness requirements. A 24% polymer quenchant is considered in this table to produce the same rate as that produced by a fast-speed oil. These recommendations are from commercial practice. Optimum hardness can be produced when the microstructure before induction hardening is optimum. Source: Ref 1

need to be established. Low production requirements will generally require less mechanization unless there is a workpiece weight or handling problem. Various induction-hardening techniques and processes are discussed later in this Chapter. With high production requirements, production rate calculations may need to be made with several types of production modes versus cost of equipment and operation. An example of this is the use of several scanners, each hardening parts with low-kilowatt power supplies as opposed to one single-shot system using a large-kilowatt power supply. As discussed above, the area to be induction hardened should be calculated in square inches. An examination of the available power will determine the power density and the type of processing that should be done (i.e., single-shot vs. scanning). The higher productivity produced by single-shot induction hardening may be needed. Also, at this time different frequencies may be considered at different power levels to try to best meet the production requirements. Higher power, lower frequency may be used, although more inefficient, because the overall economics are superior.

Coil design is discussed in Chapter 4, “Induction Coils,” in this book. Different designs of coils, particularly if magnetic flux concentrators are used, operate with different efficiencies. Select the type of induction coil that will best produce the desired induction pattern, keeping in mind the desired production rate. The coil selected must produce the required pattern, or no amount of unique mechanization will produce a good part. Through the use of flux concentrators, coils can be designed for specific patterns that were formerly very difficult to produce. After the coil design is selected, determine the process and fixturing that will work best. An example is a spindle (Fig. 11.7) with small production requirements that

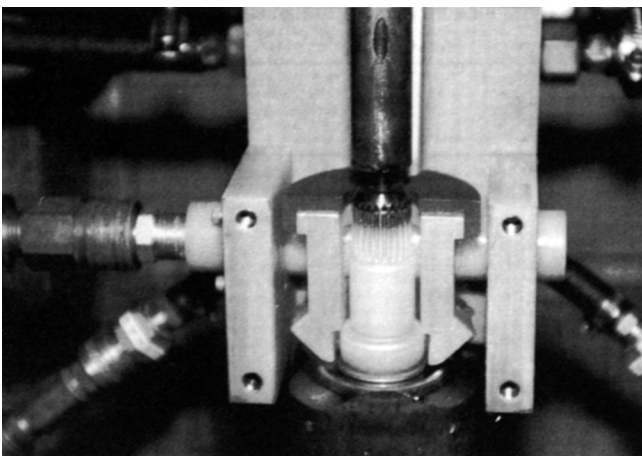


Fig. 11.7 Example of shaft with changes in diameter. Source: Ref 5

has a substantial change in diameter. Figure 11.7 shows a nonencircling induction coil with flux concentrator that is used for single-shot hardening. However, a shorter nonencircling coil can be designed to be used with a scanner and a lower-output power supply. This system would start with a heat dwell at the fillet and would then scan the rest of the shaft. The shorter coil uses the same power density. Some new parts that have no processing history require development programs for the process and coil design.

Distortion may or may not be important. Some workpieces are finish machined or ground after induction hardening. One technique is to preestablish the distortion and then to machine the workpiece with a tolerance that allows for distortion. Another technique is to establish a heating-quenching cycle that produces no distortion. This can involve preheating and the timed use of primary and secondary quenchants.

Holding Locations for the Workpieces. Maintaining process control and producing conforming induction-hardened parts usually require that the workpieces be positioned in exactly the same way in the induction coil for each heating cycle. Thus, it is important to determine what surfaces on the workpiece can be used to hold the part. As discussed above under “Tolerance Review,” the location point must have tight tolerances in reference to the area to be heated. Machined surfaces are preferred. The holding fixture or nest must not interfere with the magnetic flux field of the coil. When the workpieces are held by cupping nests, the ends must be flat and free of burrs. If the workpieces are held between centers, the center holes must be drilled to the same depth.

Automotive safety items require special, “bulletproof” processing. The production process must ensure that every part that is shipped is in specification. If statistical process control (SPC) is required, decisions must be made regarding the critical specifications that are to be tested and to be recorded for SPC purposes.

Tempering is discussed in Chapter 7, “Tempering,” in this book. The requirement for tempering may be stated in the print or specifications. Where parts are austenitized and quenched to a hardness that is above the specified hardness range on the print, the parts must be tempered. If the parts quench within the specified hardness range, but tempering is optional or not listed, tempering should be considered if the parts have designs that might promote brittle failures or if the parts are ground after induction hardening. If the parts are to be furnace tempered, the number of parts per load for batch tempering or the number of parts per hour for continuous tempering should be calculated. If the parts are to be induction tempered, the induction-tempering process needs to be designed and the parts tested.

Postproduction Processing. Some parts may require straightening. For all parts after processing, requirements need to be reviewed for cleaning or for applying a rust preventive.

Work-Handling Equipment Selection

In order to induction harden a workpiece with a controlled process, the workpiece must be located consistently in the exact same location in the induction coil. Most workpieces are rotated when possible. Depending on process requirements, workpieces may be loaded and unloaded manually or mechanically (or a combination of both). Many different types of mechanical fixtures can be used to accomplish this. Low production is more likely to involve manual loading and unloading, whereas high production is more likely to involve mechanized loading. Furthermore, some of the fixtures move the parts through the induction coil. If the application is being analyzed for new equipment, then the process can be optimized for whatever criteria are needed. This could range from the cheapest equipment to do the job, from a capital equipment cost, to what equipment in-house can do the job.

General Types of Work-Handling Fixtures. There are two broad classifications of heating: in-place heating and scanning. In-place heating is usually called static heating or single-shot heating. The workpiece is positioned in the coil, a timed cycle is used for heating, and then the workpiece is quenched. The difference between static heating and single-shot heating is that single-shot heating involves the use of a longitudinally orientated coil with the workpiece rotated in the coil. When an encircling coil is used during static heating, the part is usually rotated. However, static heating may use hairpin or channel-type coils in which the workpiece is not rotated. Depending on the application, the coil design, and the fixturing, one or more workpieces or areas of a workpiece may be heated at a time. Most workpieces that can be heated statically can be heated single shot through the use of higher power with single-shot tooling. Scanning usually involves a timed heat dwell to start the heat cycle, followed by scanning one or more workpieces through the coil, heating and quenching progressively. A variation of scanning is where the part is oscillated in the coil and quenched at the end of the heating cycle. With either classification, a number of different fixturing techniques and part orientations are possible. For instance, parts may be scanned with either vertically or horizontally orientated fixtures.

One Position, Heating. The workpiece is manually placed in a location in the coil; the operator depresses the “heat on” push button; the workpiece is heated and then either quenched in place or manually removed for quenching. A rotating spindle with holding nest can be used to hold the workpieces that need to be rotated. When a number of workpieces are heated at one time in a channel coil, nonmetallic holding fixtures or trays can be used. This represents one of the lowest-cost fixturing techniques.

One position, lift fixtures can be designed for top or bottom loading. On vertical fixtures, nests are used to hold the workpieces, or the workpieces are held between centers. Different versions of horizontal fixtures exist

with different types of feed mechanisms. The main difference between the one position fixture is that the workpiece is loaded outside of the coil. Depressing the “start” push button causes any rotation to start and the workpiece to move into the coil. At the completion of the heat cycle, the workpiece may either quench in place or be moved into the quench.

Scanning, Workpiece Moves. The standard vertical scanner is basically a lift-and-rotate fixture that is designed to move the part progressively through the coil so that it can heat and quench progressively. In a typical cycle the workpiece is loaded into the starting position. Upon depression of the “cycle start” push button, the workpiece is rapidly moved to the “heat on” position. The heat cycle starts with a timed dwell to bring the workpiece up to austenitizing temperature. The workpiece is then scanned and quenched for the desired pattern length. At the conclusion of quenching, the workpiece is moved back to the unloading/reloading position. Horizontal scanners are also used with the parts that are held and rotated on rollers. In some cases, the rollers are skewed so that the bars are moved through the coil by the rotation process. Other scanners use pushing mechanisms that push the bars through the coil. Finally, some scanners have beds or mechanisms that move the workpiece through or under the coil.

Scanning, Coil Moves. Scanners have been developed on which the coil and heat station are mounted on a mechanism that moves. The workpiece is held stationary, while the coil moves. This type of scanner is used more commonly when very heavy parts are to be induction hardened.

Higher degrees of automation use the same concepts at the coil position using index fixtures, wheeled fixtures, conveyors, shuttles, and walking-beam mechanisms to move the parts in and out of the coil. Some installations use multiple heat stations operating in sequence on the same power supply through the use of power transfer switches. Other installations heat more than one part with the same power supply, such as is done with multiple-spindle scanners, or with the use of channel- or hairpin-type coils where the workpieces can be conveyed through the coil. Considerable ingenuity exists in fixture designs, with all sorts of shuttles, robotic arms, and special mechanization used.

Examples

Information was provided earlier regarding frequency selection. Figures A2.1 and A2.2 in Appendix 2, “Scan Hardening,” in this book gives heating rates for scan hardening. However, some rules of thumb can be readily used to provide a good estimate of the power selections. Note that the actual power requirements depend on the total system losses and the ability to load match the power supply to produce the required power. If in doubt, double the power required for power supply output. It is much easier to use a power supply at 50 to 75% output than to obtain 100%

output power in a given coil. For the purposes of the following examples, it will be assumed that the optimum power density is being used. Table 11.6 gives some rules of thumb that are used in the following examples for heating rates. Common rated output power supplies are then applied. A couple of models of applications are presented, followed by qualification of the examples and an analysis of simple hardening systems, and then moving into more complex systems to increase production.

Example 1: Pin Hardening. A 1045 steel pin that is 50 mm (2.0 in.) in diameter by 150 mm (6 in.) long is to have a minimum pattern length of 100 mm (4 in.) in the center of the length induction hardened to surface hardness of HRC 50 to 60 with an effective case depth of 1 to 2 mm (0.040 to 0.080 in.). In the first steps in qualification, as shown in Table 11.7, the material qualifies for both hardness and case depth. The specifications can be met with power supply frequency ranging from 10 to 450 kHz. The workpiece can be heated by single shot or scanning. Single shot, because of the power density required, will require a much higher power supply rating than scanning. Table 11.8 shows production estimates of both 10 kHz and 450 kHz, single shot heating versus scanning.

Induction power supply frequencies from 10 kHz to 450 kHz will produce the required production rates. The 450 kHz will produce less total heat in the workpiece because of the shallower reference depth and lower power density required. This in turn allows the workpiece to quench faster.

Table 11.6 Rules of thumb for estimating induction heating rates

Frequency	Case depth		Power density		Single-shot heat time, s	Scanning rate, progressive	
	mm	in.	kW/cm ²	kW/in. ²		mm/s	in./s
3 kHz	3.80	0.150	1.55	10	4.0	0.60	0.25
			3.10	20	2.0	1.25	0.50
10/25 kHz	2.50	0.100	1.55	10	2.5	1.00	0.40
		0.100	3.10	20	1.0	2.50	1.00
450 kHz	1.25	0.050	3.10	5	4.0	0.50	0.20
			1.55	10	2.0	1.25	0.50

The scanning rate is roughly inversely proportional to the case depth. For instance, a 10% increase in case depth will require a 10% reduction of scanning rate. Source: Ref 1

Table 11.7 Example 1

Step	Item	Description	Ref no	Analysis	Comments
1	Material	1045 cold drawn	...	...	No special or unusual geometry
2	Surface	50 mm (2 in.) diameter by 100 mm (4 in.)	...	12.56 in. ²	Total surface single shot
3	Hardness	HRC 55	Table 11.5	OK	Will quench OK
4	Case depth	1.0/2.0 mm (0.040/0.080 in.)	Figure 5.8	OK	Will quench OK
5	Min frequency	50 mm (2.0 in.)	Figure 5.8	10 kHz	...
	Opt frequency	50 mm (2.0 in.)	Figure 5.8	450 kHz	...
6	Power density	For 10 kHz	Table 11.6	20 kW/in. ²	Optimum
		For 450 kHz	Table 11.6	10 kW/in. ²	Optimum
7	Power	10 kHz	Calculated	250 kW	Needed for single shot
		10 kHz	Calculated	62 kW	Needed for scanning
		450 kHz	Calculated	125 kW	Needed for single shot
		450 kHz	Calculated	30 kW	Needed for scanning

Source: Ref 1

Table 11.8 Example 1 with different processes

Heating process	Power supply		Cycle, s	Comments
Scan	100 kW, 10 kHz	Load	3	...
		Position	2	...
		Heat	5	1 s dwell plus 4 s scan
		Quench	12	...
		Return	6	At 50 mm/s (2 in./s)
		Unload	3	...
		Total	31	93/h at 80% efficiency
Single shot	250 kW, 10 kHz	Load	3	...
		Position	0	Load in position
		Heat	1	Might need slightly longer
		Quench	12	...
		Return	0	...
		Unload	3	...
		Total	19	150/h at 80% efficiency
Scan	40 kW, 450 kHz	Load	3	...
		Position	2	...
		Heat	9	1 s dwell plus 8 s scan
		Quench	10	Less heat sink, quenches faster
		Return	6	At 2 in./s
		Unload	3	...
		Total	33	87/h at 80% efficiency
Single shot	125 kW, 450 kHz	Load	3	...
		Position	0	...
		Heat	2	...
		Quench	10	Faster when quenching
		Return	0	...
		Unload	3	...
		Total	18	160/h at 80% efficiency

Source: Ref 1

The coil development of the 450 kHz, single-shot system is technically more difficult because of potential flux-intensified degradation. Both power supplies produce about the same production rate. If new equipment is being considered, the total capital equipment cost might be the deciding factor in frequency selection.

Next, consider the effect of equipment selection for this same application, but with the production requirement increased. Higher operation efficiency from mechanization will not be enough to produce this rate. Higher power, by itself, will not significantly increase the production rate unless more than one part is heated at a time. One 200 kW, 10 kHz power supply can be used to scan two parts at a time. The power can be reduced from the single-shot heating as shown in Table 11.8 because the encircling coils used for scanning are more efficient than single-shot coils. The same output power, 40 kW on the 450 kHz power supply is used to operate alternately through use of a power transfer switch to two heating fixtures. The analysis of this is shown in Table 11.9. The operating efficiency is still estimated at 80%. It takes slightly longer to load and unload two parts at a time when done manually on the dual-spindle scanner of the 10 kHz power supply. It is very important that the materials-handling aspect of production be reviewed so that this efficiency can be maintained as the required production rate increases. The production rate of the single-shot, 250 kW, 10 kHz power supply was increased from 150 parts per hour to 164, while the rate of the 40 kW, 450 kHz power supply as single shot was

increased from 87 parts per hour to 151 parts per hour. When using two heat stations with transfer switch, the power supply is kept in operation almost all of the time. As long as the heating cycle is longer than the load and unload time, the operating efficiency can be increased. The factor that controls the production rate is that a workpiece cannot be unloaded from its position until the quenching is completed. In order to optimize production rate, the second heat station must be ready to have its workpiece in position for heating when the heat cycle of the first station is complete. With radio frequencies, about 1 s is needed for the actual power transfer.

Example 2: Gear Hardening. A fine-pitch steel gear made from 1144 steel that is 5.0 mm (2.0 in.) in diameter by 12.5 mm (0.50 in.) wide is to be induction hardened. The gear teeth are to be hardened to a surface hardness of HRC 50/55 and a total case depth of 1 mm (0.040 in.) minimum below the root. The qualification is shown in Table 11.10. The power supply frequency can range from 25 kHz to 450 kHz. A 50 kW, 25 kHz and a 30 kW, 450 kHz power supply have been selected.

The analysis will first start with the simplest fixturing or handling equipment. Then examples will show how higher production rates can be produced by changing the fixturing and power supply ratings. Table 11.11 shows the production rate that can be produced with simple fixturing con-

Table 11.9 Example 1 for higher productivity

Induction process	Power supply		Seconds	Comments
Scan (two parts)	200 kW, 10 kHz with dual-spindle scanner	Load	6	...
		Position	2	...
		Heat	5	1 s dwell plus 6 s scan
		Quench	12	...
		Return	6	At 2 in./s
		Unload	4	...
		Total	35	164/h at 80% efficiency
Scan	40 kW, 450 kHz two station with transfer switch for alternating cycle	Position	0	8 s needed to unload and reload;
		Heat	9	part loaded during cycle of opposing
		Quench	10	station; 1 s dwell plus 8 s scan
		Return	6	
		Transfer	1	
		Total	19 average	151/h at 80% efficiency

Source: Ref 1

Table 11.10 Example 2

Step	Item	Specification	Ref No.	Analysis	Comments
1	Material	1144 cold drawn	...		...
2	Surface	2 in. diam by 0.50 in. wide	...	1.57 in. ²	Surface to be heated
3	Hardness	HRC 50	Table 11.5	OK	Will need tempering
4	Case depth	0.040 in. (1.0 mm) min	Figure 5.8	OK	...
5	Min frequency	2.0 in. (50 mm) diam	Figure 5.8	25 kHz	...
	Opt frequency		Figure 5.8	450 kHz	...
6	Power density	For 25 kHz	Table 11.6	15 kW/in. ²	Optimum
		For 450 kHz	Table 11.6	10 kW/in. ²	Optimum
7	Power	25 kHz	Calculated	50 kW	Rec. power supply
		450 kHz	Calculated	30 kW	Rec. power supply

Rec.: recommended. Source: Ref 1

sisting of single-shot, lift-and-rotate operation with 25 kHz, 50 kW and 450 kW, 30 kW power supplies, each with lift-and-rotate fixtures. At this point, production rate of both frequencies is about the same. A 3 s, static heat cycle is about correct for this steel. The 25 kHz power supply would not be operating at full power to produce a 3 s heat cycle, but as mentioned, the power supply should not be rated too close to the actual power requirements. Total system losses for both frequency power supplies would vary a little but not significantly enough to be a factor in equipment selection. Other factors for consideration might be the reduced maintenance requirements for solid state, plus the type of other applications that might be run on the equipment.

Next, examples will be given for increasing the productivity of the same power supplies on the same workpiece through mechanization and different setup. The effect of running two workpieces at a time on the 450 kHz power supply versus operating the 450 kHz with two alternating heat stations is presented in Table 11.12. In either operation, one operator is used. The production rate is slightly higher on the 450 kHz unit, but

Table 11.11 Example 2 with simple fixturing

Induction process	Power supply		Seconds	Comments
Single shot lift and rotate	50 kW, 25 kHz	Load	3	...
		Position	1	...
		Heat	3	...
		Quench	6	...
		Drop	1	...
		Unload	2	...
		Total	16	180/h at 80% efficiency
Single shot lift and rotate	30 kW, 450 kHz	Load	3	
		Position	1	
		Heat	3	
		Quench	6	
		Drop	1	
		Unload	2	
		Total	16	180/h at 80% efficiency

Source: Ref 1

Table 11.12 Example 2 with more complex fixturing

Induction process	Power supply		Seconds	Comments
Single shot (two parts)	50 kW, 25 kHz one spindle	Load	4	...
		Position	1	...
		Heat	3	...
		Quench	6	...
		Drop	1	...
		Unload	4	...
		Total	19	303/h at 80% efficiency
Single shot	30 kW, 450 kHz two station with transfer switch for alternating cycle	Heat	3	Loading and unloading done during heating of other station
		Quench	6	
		Total:	9	
		Unload	2	
		Load	3	
		Position	1	
		Drop	1	
		Total	7	320/h at 80% efficiency

Source: Ref 1

probably not high enough to justify the two-position fixturing. The two-position setup becomes more effective when the heating and quenching times are long enough that the power supply can be effectively kept in production more than 90% of the time. Index tables make up another type of fixturing that can be used to further increase the production.

Index fixtures are a fairly simple way to increase the production rate running one or two parts at a time. An index fixture requires that the workpiece be either manually loaded or mechanically loaded, indexed into the coil location, heated, quenched, and moved out of the coil for unloading (either manual or mechanical). The overall cycle can be replicated on a timed basis, which tends to improve the operating efficiency because the operators have to maintain the pace set by the process. Processes that are totally mechanized can approach 90 to 95% operating efficiency due to the ability to keep the induction power supply in production consistently.

The design recommendations for fixtures are discussed in Chapter 3, “Induction Heat Treating Systems,” in this book. Index fixtures vary from rotary index tables to conveyorized and walking-beam mechanisms. Index tables are more common, and rotation is usually needed at the coil and primary quenching positions. The fixtures can be designed for a second quenching position. Quenching can be done either in or below the coil until the workpiece is quenched to a temperature sufficiently low that the quenching can be completed when the workpiece is then indexed to the second position. The second quenching may be done primarily so that either the operator can handle the workpiece or the workpiece is cooled sufficiently for in-line induction tempering next. The use of a secondary quench also permits the workpiece to be removed from the coil position so that another workpiece can be indexed into the coil and the heat cycle initiated while final quenching is done on the previous part at the secondary quench position. Using the same gear application and requirements of Example 2, changing the fixturing to a rotary index fixture will increase the production on the same power supply to the required level of 480 workpieces per hour. Table 11.13 shows the production increase from an index fixture.

Use of an index fixture increases the production rate higher than that obtained by a lift-and-rotate fixture. Also, as mentioned, index fixtures, because of their mechanization and ability to run faster through the use of

Table 11.13 Example 2 with index fixture

Induction process	Power supply		Seconds	Comments
Static heating, index, two gears	30 kW, 450 kHz	Load	0	Loading is done during heating and quenching
		Position	3	
		Heat	4	
		Drop	1	
		Quench	4	Plus 4 s secondary quench 480/h at 80% efficiency
		Total	12	

Source: Ref 1

secondary quenches, can operate at a high efficiency. An increase of 80 to 90% efficiency is expected with optimization of workpiece production flow.

Example 2 involves static heating. Scanners are used when progressive heating is required. Scanners are built for both vertical and horizontal hardening. Vertical scanners hold the workpieces either in a bottom nest or between vertical spindles, and heat and quench the workpiece on a continuous basis as it is passed through the induction coil. As mentioned above, through the use of the scanning technique, the power requirements of the power supply are minimized. This technique is necessary for very long workpieces because the power requirements are not feasible. Rotation of the parts is generally required in a scanner. When the workpiece length is excessive, scanners may be designed for horizontal scanning rather than vertical scanning. There are other applications in which horizontal scanners are used because the hardened workpieces tend to be straighter, particularly on small-diameter bars.

Scanning Applications. Instead of scanning a straight shaft, the gear hardening application will be used to show the increase in production that can be obtained through fixture change. When scanning gears on rods, good setup techniques need to be used to make certain that uniform cases and hardnesses are produced at the start and the end of the heating cycle. The gears must have precise dwells when the heating cycle is initiated, and the coil must be designed so that, when the heat is turned off at the end of the cycle, the trailing edge does not overheat while leaving a soft zone just before the edge. Furthermore, someone other than the operator must load the gears on the rods because the operator cannot load them fast enough. Table 11.14 shows an example of the high production rate that can result.

Examples 1 and 2 are meant to show the versatility of processing that can be accomplished. With good definition of the production requirements, the production of the same workpiece can be accomplished in many ways. In Example 2, from the same power supply, through more complex fixturing, the production rate has been increased from 180 parts per hour to 886 parts per hour. Sufficient organization and planning have been done so that workpieces can be taken from storage or the prior manufacturing process and removed from the area. For instance, as mentioned, one operator cannot load the gears on rods fast enough to keep the scanner

Table 11.14 Example 2 with scanner

Induction process	Power supply		Seconds	Comments
Scanning with gears on rods (16 gears)	50 kW, 25 kHz	Load	5	...
		Position	3	...
		Heat	9	1 s dwell plus scan 8 in. at 1 in./s
		Quency	12	...
		Return	5	...
		Unload	4	...
		Total	39	886/h at 60% efficiency(a)

(a) The operating efficiency will tend to be lower because of the time required to handle the gears on rods. Source: Ref 1

in operation. Furthermore, the types of skids or pallets used to store the workpiece and even the workpiece stacking and orientations can affect production.

Vertical scanners may have one or more spindles holding workpieces, so that more than one workpiece can be hardened at a time. While there is no theoretical number of heating positions, the loading and unloading of the workpieces dictate the economical number to be run at a time. Generally a dual-spindle scanner becomes more economical if the operator can load and unload two workpieces at a time. Because heavier parts are most often loaded one at a time, it may be more economical to run these on only one spindle.

There are many other types of mechanical handling devices of which the only limit is ingenuity. Anything that has the ability to move parts into the coil without being affected itself by the magnetic flux field of the coil can be used. Examples or other types are trap fixtures, bowl feeders, conveyors, rotating wheels, shuttles, and cam-operated devices.

Tempering will be required if the parts, as with the prior gear illustrations, quench to a hardness higher than the specification. The theory of tempering is discussed in Chapter 7, “Tempering,” in this book. Workpieces may be tempered by induction or furnace. If tempered by induction, tempering on the same power supply will slow production substantially because tempering heat cycles are generally at two to three times the cycle time required for austenitizing. (As previously discussed, slower heat input is needed to provide surface-to-core uniformity of heat.) If tempering can be done with the same power supply, coil, and fixture, and if reduction of the overall production rate is not a consideration, then the overall cycle adjustment for tempering can be made. If not, a second power supply and coil can be used, sometimes transferring the part so that the tempering is done as the workpiece is sequenced through a series of coils. For instance, if a tempering time of 24 s is needed, tempering the workpiece at 8 s each in three coil positions will produce the overall 24 s. In fact, the tempering might be more uniform because the transfer time between the coils produces some soaking and temperature equalization.

Postproduction analysis must consider the removal of quenchant from the workpieces before tempering. Oils must be removed. Polymers, as previously discussed in Chapter 5, “Heat Treating Basics,” in this book, when heated produce a strong, noxious smell. In addition, if the burning is not complete, the polymers bake on in hard-to-remove deposits. Various washing processes are available. Standard hot-water washers will remove quenchants. Disposal of the removed quenchants from the washer is an issue that must be addressed in accordance with environmental regulations.

Rust preventive application and packaging of the parts that were hardened are final considerations. The parts, as removed from tempering, are very susceptible to rust. Decisions should be made as to how the rust preventive will be applied, such a spraying or dipping.

Setup Instructions and Operating Procedures. Replication of the processing is important, whether a power supply and heating system are in production continuously on one application or whether many setups are made over a period of time. Written process instructions must be made, including all specifications, prints, coils, fixtures, tuning instructions, specific process instructions, and inspection procedures and requirements. An example of the instructions for setup personnel follows. (If the operator is doing the setup, then these would apply to the operator.)

Setup Instructions. Good setup is critical for successful induction heat treating. The setup person is responsible not only for producing a first article part, which is completely in specification, but also for making a setup on which an operator can safely run the parts on a production basis. The setup person is responsible for making setups that provide optimum production rates. Finally, the setup person is responsible for operator training and for timely response to any production problem.

Setup procedures are:

1. Read work order, setup sheet, prints, and any other instructions enclosed in the work order packet. Make certain everything is clear and all information needed is on hand. Verify the core hardness is correct if there is a core hardness requirement, and record it on the work order.
2. Remove and take the old setup tooling to the tool room for cleanup and inspection. Find the tooling on the new setup as indicated on the setup sheet. Bring the tooling and parts to the machine.
3. Check the quenchant concentration and condition so that if a change is needed, it can be done while the setup is in process. Record the quenchant concentration on the setup sheet.
4. If the job has been processed before, make the setup according to instructions. If the setup has not been run before, find a similar part for initial tuning of the power supply. If similar tuning cannot be found, tune according to the instructions of the power supply being used, starting out at low power.
5. Make certain the coil attachment point on the bus or transformer is clean before installing the induction coil. Turn on the coil water. Check the coil for water flow and for leaks.
6. Install adapters and fixtures, as specified. Make certain the coil is centered on the workpiece.
7. If information is needed regarding operating instructions for a given machine or fixture, check the operating manual at the machine or in the engineering office.
8. Check the setup sheet for control settings. If the proper program for that machine is indicated, as with numerical control (NC) fixtures, enter the program. If a new NC program needs to be entered, begin in the following order:

- Establish start position, heat position, quench position, and index position if applicable (most often the same as the start position).
 - Enter the scan speed if it is a scanning application (note that slightly too fast is best if in doubt), and set a power level (start low and increase as needed). Enter an approximate heat time, remove the workpiece, and run a cycle (no heat) to make certain it runs properly.
 - Put a setup piece in place, and try a cycle with heat and quench.
 - Adjust the scanning speed, power, and/or time for optimum heating.
9. Run the first article part.
 10. Check the part for conformance on hardness, length, case depth, surface finish, and so on, and qualify the first article.
 11. Record all setup information if new. Indicate any changes, if made, to a previous setup.
 12. After the first article part is qualified as in specification, let production know the setup is ready for production.

Stop production immediately on any induction heater that has production potentially in nonconformance. If a nonconformance exists, any nonconforming parts must be identified and segregated. Work with production control and quality control to investigate and remedy any problems with nonconforming parts. Make suggestions for continuous improvement as appropriate. Report any injuries to the shift foreman promptly.

Operator Instructions. The induction heater operator is very important to the induction heat treating process. The operator is a critical link in both production control and quality control. Operator responsibilities are:

- Make certain the quality control has approved the part for production.
- Make certain that all operating instructions are clearly understood. (Questions may be asked any time before, during, or after processing to help in understanding induction heat treating.)
- Handle parts carefully. Parts with machined surfaces such as gears, threads, and bearings are not to be dropped on another part.
- Make certain that all parts loaded onto spindles or into fixtures are properly located.
- Shut off the induction heater if any type of operating problem or induction heater fault is suspected. This includes parts not properly locating, coil arcs, or any change of process. This also includes detecting any problem that might be in the parts before hardening, such as cracks or poor machining.
- Make certain that parts that are partially heat treated (because of a machine fault), and/or parts that have not been heat treated are not mixed with parts that have been heat treated.

- Learn and memorize the heat color (temperature) on the part being heated. Look at each part after quenching, whenever possible, to make certain the part has been heat treated, that the discoloration is as expected in both the heated and unheated areas, and that there are no visible cracks or melts.
- Follow all safety regulations and practices. Advise anyone in management about any condition you feel is unsafe. Use proper and safe work-handling techniques when handling parts and skids of parts.
- Complete and attach job/flow tags to containers of hardened parts before they are transported.
- When the order is complete, verify the order is complete. If there is a count difference, note it on the work order. Verify that there are no unprocessed parts inside the containers in which the parts were sent to induction hardening.

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CHAPTER 12

Standards and Inspection

INSPECTION IS required in order to provide assurance of conformance to process specifications. This chapter covers both the relevant standards and practices and the inspection techniques for induction-hardened parts. Inspection involves two different types of testing: destructive testing (DT) and nondestructive testing (NDT). The names define what they mean; for instance, when a workpiece is destructively tested, the workpiece is destroyed for practical use. Specifications for induction-hardened parts will always require some sort of hardness measurement and may require case depth verification, microstructural requirements, and possibly some sort of physical measurement such as straightness.

Hardness testing may involve DT or NDT, depending upon the hardness scale used and the method of preparation for testing. For example, a Rockwell C indent on a final ground surface may be detrimental to further use of the part, whereas a Rockwell 15N indent at the same location may not roughen the surface finish enough to prevent use. Any preparation such as grinding the surface may be destructive, and of course a part is destroyed when sectioned. While most hardness testing uses a hardness tester that produces an indent on the part, there are still a few specifications that incorporate hardness testing through use of test files. Table 12.1 lists the advantages and limitations of NDT and DT.

Standards

Reference 2 provides standards, practices, and recommendations for inspection. Workpiece hardness is always verified. The ASTM standard for hardness testing is the current version for Rockwell testing, ASTM E18-88, and for microhardness testing, ASTM 384. Rockwell testers are most commonly used, while microhardness testers are used for specific applications. SAE J423 applies to the destructive method of determining case depth, whereas ASTM E3 is the standard for polishing procedures to mea-

Table 12.1 Advantages and limitations of nondestructive testing and destructive testing

Nondestructive testing	Destructive testing
Advantages • Can be done directly on production items without regard to part cost or quantity available, and no scrap losses are incurred except for bad parts. • Can be done on 100% of production or on representative samples. • Can be used when variability is wide and unpredictable. • Different tests can be applied to the same item simultaneously or sequentially. • The same test can be repeated on the same item. • May be performed on parts in service. • Cumulative effect of service usage can be measured directly. • May reveal failure mechanism. • Little or no specimen preparation is required. • Equipment is often portable for use in field. • Labor costs are usually low, especially for repetitive testing of similar parts. Limitations • Results often must be interpreted by a skilled, experienced technician. • In absence of proven correlation, different observers may disagree on meaning and significance of test results. • Properties are measured indirectly, and often only qualitative or comparative measurements can be made. • Some nondestructive tests require large capital investments.	Advantages • Can often directly and reliably measure response to service conditions. • Measurements are quantitative, and usually valuable for design or standardization. • Interpretation of results by a skilled technician is usually not required. • Correlation between tests and service is usually direct, leaving little margin for disagreement among observers as to meaning and significance of test results. Limitations • Can be applied only to a sample, and separate proof that the sample represents the population is required. • Tested parts cannot be placed in service. • Repeated tests of same item are often impossible, and different types of tests may require different samples. • Extensive testing usually cannot be justified because of large scrap losses. • May be prohibited on parts with high material or fabrication costs, or on parts of limited availability. • Cumulative effect of service usage cannot be measured directly, but only inferred from tests on parts used for different lengths of time. • Difficult to apply to parts in service, and usually terminates their useful life. • Extensive machining or other preparation of test specimens is often required. • Capital investment and manpower costs are often high.

Source: Ref 1

sure case depth. Chapter 5, “Heat Treating Basics,” in this book discusses the general interpretations of hardness. Case-depth measurement is discussed later in this Chapter. The American Society of Testing and Materials publishes an annual volume on NDT called *Nondestructive Testing* (Ref 2) that covers many NDT procedures.

Test Equipment

Hardness Testing. The hardness scale specified on the print should be used unless inappropriate. The most common condition found where a scale might be inappropriate is one in which the part being tested or the case depth is not thick enough to support the test scale being used. As an example, most prints specify hardness using the Rockwell C scale. However, the C test scale is inappropriate for very small rounds because an accurate indent cannot be made. Hardness scales are also inappropriate in cases where the hardness being tested is less than 10 times the depth of the indenter penetration. Table 12.2 should be used to determine the minimum case or cross-sectional thickness needed to support different hardness scales at various hardness test ranges. The C-scale has the heaviest weight, penetrates the deepest, and tends to give the most accurate readings for a

Table 12.2 Minimum cross-section size to support hardness scale

Thickness		Rockwell scale		
		A		C
		Dial reading	Approximate hardness C-scale	Dial reading
mm	in.			
0.36	0.014	...	...	...
0.41	0.016	86	69	...
0.46	0.018	84	65	...
0.51	0.020	82	61.5	...
0.56	0.022	79	56	69
0.61	0.024	76	50	67
0.66	0.026	71	41	65
0.71	0.028	67	32	62
0.76	0.030	60	19	57
0.81	0.032	...	...	52
0.86	0.034	...	...	45
0.91	0.036	...	...	37
0.96	0.038	...	...	28
1.02	0.040	...	...	20

Thickness		Rockwell superficial scale					
		15N		30N		45N	
		Dial reading	Approximate hardness C-scale	Dial reading	Approximate hardness C-scale	Dial reading	Approximate hardness C-scale
mm	in.						
0.15	0.006	92	65	...	...	...	...
0.20	0.008	90	60	...	...	...	...
0.25	0.010	88	55	...	...	...	...
0.30	0.012	83	45	82	65	77	69.5
0.36	0.014	76	32	78.5	61	74	67
0.41	0.016	68	18	74	56	72	65
0.46	0.018	...	...	66	47	68	61
0.51	0.020	...	...	57	37	63	57
0.56	0.022	...	...	47	26	58	52.5
0.61	0.024	...	...	...	...	51	47
0.66	0.026	...	...	...	...	37	35
0.71	0.028	...	...	...	...	20	20.5
0.76	0.030	...	...	...	...	...	...

A guide for selection of scales using the diamond penetrator. Source: Ref 2

variety of surface conditions and parts. Some of the general ASTM standards important to testing are:

- *Distance between indents:* Hardness indents must be three indentation diameters apart.
- *Distance to the edge of a part:* Hardness indents must be 2.5 indentation diameters from the edge of a part.
- *Number of readings for a good test:* The recommended number is three valid readings. If a part rocks or has movement, the reading should be discarded and another reading taken.
- *Round correction:* When a round or curved workpiece is tested, there are two sources of error. First, the Rockwell tester being used has what is called anvil error. The diamond indenter may flex just a little bit when a round is measured, moving it off the true centerline. This type of error can vary from testing machine to testing machine. If anvil

error is in question, measure the hardness on two different hardness scales. The lighter test scale will tend to have less error, and comparison of the results of the two different hardness scales can indicate whether there is testing error. Second, because a round is being tested instead of a flat, the depth of penetration is slightly different. Above 25 mm (1 in.) in diameter, the tests are fairly accurate. However, below this round, correction must be added to the test readings. Table 12.3 lists the round correction that should be added to the reading. Note that parts should not be tested below 6.25 mm ($\frac{1}{4}$ in.) in diameter on the C- and A-scale and below 3.12 mm ($\frac{1}{8}$ in.) in diameter on the 15N test scale. Flats should be ground on small diameters to provide accurate testing surfaces.

Always record any test records when round corrections are used. If the test scale is being converted to another scale, always add the round correction to the test result before correlating to another scale. Finally, always note on inspection records the scale from which the conversion was made. Correlation is not always totally accurate and is intended to give an approximation of readings from one test scale to another. Figure 12.1 shows the use of steady rests for long workpieces. Figure 12.2 shows the correct use of a V-block anvil for checking a round part. Workpieces that have irregular test surfaces may need to be cross-sectioned so that the surface hardness can be tested just beneath the surface on the cut cross section.

Microhardness testing, as discussed in Chapter 5, “Heat Treating Basics,” in this book, is not used as widely for induction-hardened parts as

Table 12.3 Round correction tables

C D A Scale	Diamond “brale” penetrator: diameter of specimen, in.						
	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	$\frac{7}{8}$	1
80	0.5	0.5	0.5	0	0	0	0
70	1.0	1.0	0.5	0.5	0.5	0	0
60	1.5	1.0	1.0	0.5	0.5	0.5	0.5
50	2.5	2.0	1.5	1.0	1.0	0.5	0.5
40	3.5	2.5	2.0	1.5	1.0	1.0	1.0
30	5.0	3.5	2.5	2.0	1.5	1.5	1.0
20	6.0	4.5	3.5	2.5	2.0	1.5	1.5
15N 30N 45N Scale	Diamond “N” brale penetrator: diameter of specimen, in.						
	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	$\frac{7}{8}$	1
90	0.5	0.5	0	0	0	0	0
85	0.5	0.5	0.5	0	0	0	0
80	1.0	0.5	0.5	0.5	0	0	0
75	1.5	1.0	0.5	0.5	0.5	0.5	0
70	2.0	1.0	1.0	0.5	0.5	0.5	0.5
65	2.5	1.5	1.0	0.5	0.5	0.5	0.5
60	3.0	1.5	1.0	1.0	0.5	0.5	0.5
55	3.5	2.0	1.5	1.0	1.0	0.5	0.5
50	3.5	2.0	1.5	1.0	1.0	1.0	0.5
45	4.0	2.5	2.0	1.0	1.0	1.0	1.0
40	4.5	3.0	2.0	1.5	1.0	1.0	1.0

Source: Ref 2

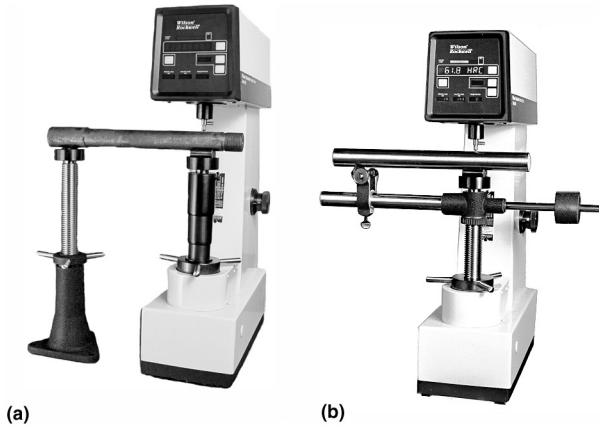


Fig. 12.1 Steady rest support for long workpieces. Source: Ref 3

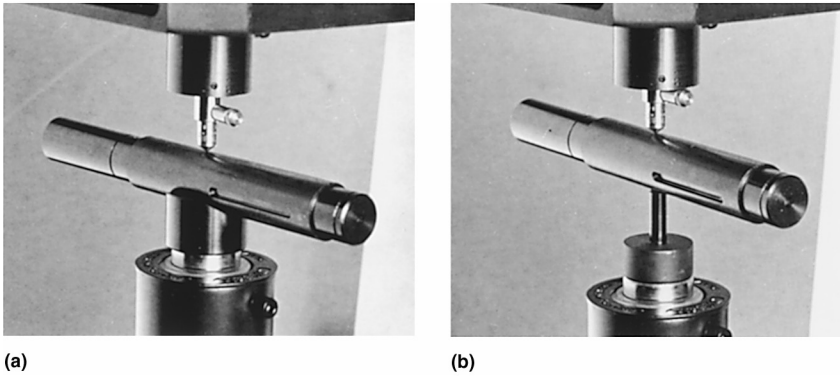


Fig. 12.2 Anvil support for cylindrical workpieces. (a) Correct method places the specimen centrally under indenter and prevents movement of the specimen under testing loads. (b) Incorrect method of supporting cylindrical work on spot anvil. The test piece is not firmly secured, and rolling of the specimen can cause damage to the indenter or erroneous readings. Source: Ref 3

Rockwell testing. Most specifications for case depths do not require microhardness. When microhardness is required, the Vickers indenter is recommended. This makes testing of the HRC 50 equivalent easier in the relatively large hardness transition zones produced during induction hardening. With the Vickers test, polishing to 600 grit will produce a specimen surface smooth enough for a good test. (The actual standards for metallographic test specimen surface preparation are given in ASTM E3.) Some powdered metal hardness specifications permit the use of apparent hardness tests that read the average hardness as tested rather than the true hardness of the matrix. Average hardness is then correlated, through tests, to the core hardness and listed in their specifications. For instance, a test

producing 35 Rockwell C may indicate a matrix hardness when tested by microhardness of 50 Rockwell C as correlated from Vickers to Rockwell C. Powdered metals, because of porosity, may require clusters of indentations made, with obvious low readings discarded and the other readings averaged. Microhardness testing is necessary for accurate testing of the cast irons that have graphite, such as ductile cast iron, and microhardness is also used for the measure of case depths on automotive parts such as wheel hubs.

Microstructures can be seen through a microscope after workpieces are properly prepared and etched. The preparation techniques will be discussed later in this Chapter.

Nondestructive Testing (NDT)

Nondestructive testing is used for quality-control purposes for the obvious intention of not destroying good parts while testing and evaluating for conformance to specifications. Many quality considerations must be applied to the control on NDT processes to ensure that the information being supplied from them is accurate, timely, and germane. One of the greatest problems of nondestructive inspection has been misapplication, which usually means that the wrong information was supplied. Louis Cartz, in the ASM book *Nondestructive Testing* (Ref 4), cites that liquid penetrant and magnetic particle inspection account for about 50% of all NDT testing, with ultrasonic and x-ray methods accounting for about another third. Eddy current accounts for approximately 10%. All other methods were about 2%. Table 12.4 provides examples on the relative uses and merits of various NDT methods from an operational viewpoint, and Table 12.5 lists

Table 12.4 Relative use and merits of various nondestructive testing methods

	Test method				
	Ultrasonics	x-ray	Eddy current	Magnetic particle	Liquid penetrant
Capital cost	Medium to high	High	Low to medium	Medium	Low
Consumable cost	Very low	High	Low	Medium	Medium
Time of results	Immediate	Delayed	Immediate	Short delay	Short delay
Effect of geometry	Important	Important	Important	Not too important	Not too important
Access problems	Important	Important	Important	Important	Important
Type of defect	Internal	Most	External	External	Surface breaking
Relative sensitivity	High	Medium	High	Low	Low
Formal record	Expensive	Standard	Expensive	Unusual	Unusual
Operator skill	High	High	Medium	Low	Low
Operator training	Important	Important	Important	Important	
Training needs	High	High	Medium	Low	Low
Portability of equipment	High	Low	High to medium	High to medium	High
Dependent on material composition	Very	Quite	Very	Magnetic only	Little
Ability to automate	Good	Fair	Good	Fair	Fair
Capabilities	Thickness gauging; some composition testing	Thickness gauging	Thickness gauging; grade sorting; case depth hardness	Defects only	Defects only

Source: Ref 4

Table 12.5 Characteristics of some nondestructive testing methods

Method	Characteristics detected	Advantages	Limitations	Example of use
Ultrasonics	Changes in acoustic impedance caused by cracks, nonbonds, inclusions, or interfaces	Can penetrate thick materials; excellent for crack detection; can be automated	Normally requires coupling to material either by contact to surface or immersion in a fluid such as water. Surface needs to be smooth.	Adhesive assemblies for bond integrity; laminations; hydrogen cracking
Radiography	Changes in density from voids, inclusions, material variations; placement of internal parts	Can be used to inspect wide range of materials and thicknesses; versatile; film provides record of inspection	Radiation safety requires precautions; expensive; detection of cracks can be difficult unless perpendicular to x-ray film.	Pipeline welds for penetration, inclusions, voids; internal defects in castings
Visual-optical	Surface characteristics such as finish, scratches, cracks, or color; strain in transparent materials; corrosion	Often convenient; can be automated	Can be applied only to surfaces, through surface openings, or to transparent material.	Paper, wood, or metal for surface finish and uniformity
Eddy current	Changes in electrical conductivity caused by material variations, cracks, voids, or inclusions	Readily automated; moderate cost	Limited to electrically conducting materials; limited penetration depth.	Heat exchanger tubes for wall thinning and cracks
Liquid penetrant	Surface openings due to cracks, porosity, seams, or folds	Inexpensive, easy to use, readily portable, sensitive to small surface flaws	Flaw must be open to surface. Not useful on porous materials or rough surfaces.	Turbine blades for surface cracks or porosity; grinding cracks
Magnetic particles	Leakage magnetic flux caused by surface or near-surface cracks, voids, inclusions, material or geometry changes	Inexpensive or moderate cost, sensitive both to surface and near-surface flaws	Limited to ferromagnetic material; surface preparation and post-inspection demagnetization may be required.	Railroad wheels for cracks; large castings

Source: Ref 4

the characteristics of the same NDT methods. Eddy current, magnetic particle, and liquid penetrant are the most widely used methods for testing induction-hardened parts.

Successful application of NDT methods to the inspection of induction hardened parts requires that:

- The test system and procedures be suited to both the inspection objectives and types of flaws to be detected
- The operator have sufficient training and experience
- The standard for acceptance appropriately define undesirable characteristics of a nonconforming part

Indications obtained during NDT testing need to be interpreted and evaluated. Any indication that is found is called a discontinuity. Discontinuities are not necessarily defects, but they need to be identified and evaluated to decide whether the part is at or below specification. Table 12.6 lists the various NDT processes and the types of defects that can be indicated.

Magnetic particle inspection is probably the most versatile in the types of defects that can be revealed. The Magnaflux tester is used for this type of inspection. Magnetic-particle inspection is a method for locating surface and subsurface discontinuities in magnetic steels. When a part under test is first magnetized with any magnetic discontinuities, cracks that lie in a direction that is generally transverse to the direction of the

Table 12.6 Selection of nondestructive testing process (visual examination is always useful)

Defect	Method	Comments
Bursts (wrought metals)	Ultrasonic testing	Internal bursts produce a sharp reflection; able to differentiate types of bursts
	Magnetic particle testing	Surface and near-surface bursts only of ferromagnetic materials
Cold shuts (casts)	Liquid penetrant inspection x-radiography	Surfaces of most metals; smooth regular line; casts difficult Distinct dark line
Fillet cracks (bolts) (wrought metals)	Ultrasonic testing	Extensively used; sharp reflection
	Liquid penetrant inspection	All metals; sharp, clear indications; necessary to remove all penetrant subsequent to testing
Grinding cracks	Liquid penetrant inspection	All metals; irregular pattern fine cracks; may require long penetrant dwell times
Convolution cracks nonferrous	Magnetic particle inspection	Ferromagnetic metals only
	x-radiography	Extensively used
Heat-affected zone cracking	Magnetic particle inspection	Ferromagnetic metals only; demagnetization may be difficult; must avoid electric arc from prods
	Liquid penetrant inspection	Nonferrous welds; depends on surface processing
Heat-treat cracks (near areas of stress)	Magnetic particle inspection	Ferromagnetic materials; straight, forked, or curved indications
	Liquid penetrant inspection	Nonferrous metals
Surface shrink cracks	Liquid penetrant inspection	Nonferrous metals; avoid regions such as press fittings
	Magnetic particle inspection	Ferromagnetic materials
Thread cracks (wrought metals)	Eddy current	Nonferrous welded piping
	Liquid penetrant inspection	Use fluorescent penetrant
Tubing cracks (nonferrous)	Magnetic particle inspection	Ferromagnetic metals; nonrelevant indications from threads
	Eddy current	Recommended if tube diameter is less than 1 in. and wall thickness is less than 0.15 in.
Hydrogen flake (ferrous)	Ultrasonic testing	Suitable for tubing; couplants may affect certain alloys
	Ultrasonic testing	Extensively used
Inclusions (welds)	Magnetic particle inspection	Used on finished part; appearance of short discontinuities (hairline cracks)
	x-radiography	Indications appear as randomly oriented cracks
Inclusions (wrought metals)	Eddy current	Used extensively; sharp well-defined round or other shaped spots; relatively large inclusions
	Ultrasonic testing	Thin-wall welded tubing
	Eddy current	Used extensively; large inclusions act as good reflectors; smaller give rise to background “noise”
	Magnetic particle inspection	Thin-wall, small-diameter rods; difficult for ferromagnetic metals
Lack of penetration (welds)	x-radiography	On machined surfaces, indicators are straight intermittent or continuous line
	Ultrasonic testing	Extensively used
	Eddy current	Used but some geometries difficult
	Magnetic particle inspection; liquid penetrant inspection	Nonferrous welded tubing
Laminations (wrought metals)	Ultrasonic testing	If rear of weld is visible
	Magnetic particle inspection; liquid penetrant inspection	Extensively used; sharp signals with loss of rear wall signal
	Liquid penetrant inspection; magnetic particle inspection (ferrous)	Indication straight, broken lines
Laps and seams (rolled metals)	Liquid penetrant inspection; magnetic particle inspection (ferrous)	All metals; fluorescent LPI; indications curved, continuous or broken lines
Laps and seams (wrought metals)	Magnetic particle inspection (ferrous); liquid penetrant inspection	Straight, spiral, or curved indications
	Ultrasonic testing	Extensively used; good signals
Microshrinkage (magnesium castings)	Eddy current	Tubing and piping
	x-radiography	Extensively used; elongated feathery streaks
Gas porosity (welds)	Liquid penetrant inspection	Extensively used on finished surfaces where machining opens micropores
	x-radiography	Extensively used; round and elongated spots on radiograph
Unfused porosity (aluminum)	Ultrasonic testing	Very sensitive, but depends on grain size
	Ultrasonic testing	Thin wall tubing
Stress-corrosion cracking	Liquid penetrant inspection	Extensively used
	x-radiography	Machined article; straight line indications
Hot tears (ferrous coatings)	Magnetic particle testing	Extensively used
	Liquid penetrant inspection	Surface only
Intergranular corrosion (nonferrous)	x-radiography	Extensively used
		Advanced stages of intergranular corrosion

Source: Ref 4

magnetic field cause a leakage field to be formed at and above the surface of the part. Next, finely divided ferromagnetic particles are applied over the surface to hold some of the particles in place over the cracks. When ultraviolet light (black light) is applied to the parts, the forms will fluoresce, with their outline generally indicating crack location, size, shape, and extent. Small and shallow surface cracks greater than 0.125 mm (0.005 in.) can be detected, as long as the part is located in a magnetic field that will intercept the crack. Cracks below the surface are difficult to detect.

Magnafluxing is operator dependent, and the reliability is not always 100% because interpretation is subjective. Inspection depends on the good eyesight, acuity, and experience of the inspector. Where a powder indication of uneven shape occurs, the inspector may need to repeat the process to see if the indication is reproducible. Some general comments are:

- Surface defects tend to give rise to sharp, narrow particle patterns held tightly together. The deeper the crack, the greater the buildup.
- Subsurface defects give rise to broad, fuzzy particle patterns because the magnetic particles do not adhere as tightly. False indications are not the result of magnetic forces. Some patterns of particles are formed by surface roughness or are held together mechanically. These indications will often not reappear on reprocessing.

False indications can result from the presence of lint, hair, fingerprints, or surface tension drain patterns. Resulfurized steels such as AISI 1144 will have particle buildups around the surface sulfide inclusions. Nonrelevant indications are caused by flux leakage that has no relation to a discontinuity that is considered to be a defect. When it is necessary to recheck lots of parts in which a defect has been found, the parts should be held for at least 5 days, and each part should then be tested three times to provide a reasonable assumption that all of the defective parts have been found.

Accumulations of powder occur at corners, where there is a change in the cross section of the part or change of shape. Care and discretion must be exercised because cracks are also likely to occur in these regions. Magnetic labeling and external magnetic fields occur when a part is partially magnetized by a neighboring electric current or by a permanent magnet. Sharp indications may result, though these will disappear after demagnetization. Residual magnetization may result from prior use of a magnetic chuck, and this will usually give a fuzzy indication. In this case, demagnetization is required first. Sharp corners, thread roots, keyways, and fillets give rise to a magnetic leakage field that can produce fuzzy indications. The magnetizing force should be reduced, and the process should be repeated. Metal path constrictions occur when size reductions give rise to apparent magnetic leakage fields with resulting fuzzy indications. Deep machine grooves can accumulate powder residue during draining; this

provides false indications. One method of verification is to gently wipe off the excess and see if the indication reappears.

After establishing a suitable Magnafluxing technique for inspection of a particular part, the process must then be maintained by adequate controls. These controls include periodic calibration of equipment, maintaining an adequate concentration of magnetic particles in the carrier solution, uniformity of preinspection part preparation, careful attention of postinspection requirements such as removal of residual magnetism, and, most important of all, periodic evaluation of personnel to maintain a suitable level of proficiency.

Spray-on and liquid penetrants are common methods of NDT in use. They are relatively simple to use for finding cracks that are open to the surface of a part. The spray-on process involves a kit with aerosol containers in which the part is first cleaned, a penetrant is sprayed onto the area to be examined and wiped off by a cloth, and a developer is sprayed on. The inspection process is fairly simple where limited inspection resources are available. Liquid penetrants can be used for faster and more precise inspection. Liquid penetrants containing fluorescent dyes are applied to the surface of a clean part to effectively wet the surface and to form a continuous and reasonably uniform coating. During this process the penetrant migrates into cavities that are open to the surface. After setting long enough, the excess penetrant is removed from the surface, and a developer is applied. When the dye is removed from the surface, the penetrant remaining in the cracks will fluoresce under black light. Dye penetrants do not need to put a magnetizing current through them, and they can detect cracks less than 0.125 mm (0.005 in.) in depth. There are several forms of this type of inspection, including the application of powders and developers, water-washable systems, postemulsifiable systems, and solvent-removable systems. The quality of penetrant inspection is highly dependent on strict compliance with the inspection procedure and on careful cleaning of the parts so that any cracks are open and exposed before being subjected to the penetrant. The penetrant method is generally found to be more sensitive than x-radiography or ultrasonics for fine surface cracks.

The observation of indications on the developed surface after a penetrant-developer treatment is very dependent on the individual inspector and is therefore quite subjective. The three general types considered to be true indications are (Ref 4):

- Continuous lines are observed generally as jagged lines; cold shuts appear as smooth, narrow, straight lines; forging laps appear as smooth wavy lines; and scratches tend to be shallow.
- Broken lines result from continuous lines becoming partially closed by working, such as grinding, peening, forging, or machining, and appear as a discontinuous line.

- Small, round holes are typically general porosity, gas holes, pinholes, or very large grains.

Ultrasonic inspection involves introducing a beam of high-frequency sounds into the material being inspected to detect surface and subsurface flaws. A transducer probe is placed against a test piece, with a coupling liquid used to provide a suitable sound path between transducer and test surface to increase the transmission of the ultrasonic pulse energy into the test piece. This is done to avoid having a layer of air between the probe and solid surface, which would transmit only a very weak beam. The sound waves travel through the material with some attendant loss of energy and are reflected at interfaces. The reflected beam is then detected and analyzed to define the presence and location of flaws. Previous heavy use of ultrasonic testing was used in areas such as inspection of casting, primary-mill products, forgings, flat-rolled products, rolled shapes, and welded joints. In addition, ultrasonic inspection techniques have been used for monitoring the initiation and presence of fatigue cracks.

Ultrasonics are being used to measure the case depth of induction-hardened parts such as axles, shafts, rollers, and bearings. An ultrasonic microstructural analyzer (Fig. 12.3) uses a transducer to apply the sound-to-measure case depths from 1 to 20 mm (0.040 to 0.80 in.). The analyzer measures the hardness depth by looking at the ultrasonic backscatter generated from the grain boundaries of the pearlitic core material and the transition zone between the martensitic case. The time of flight (horizontal distance between the two lobes) is proportional to the case depth. Parts that have sharp transition zones produce the best accuracy of case depth measurement. Figure 12.4 shows the ultrasonic response from front-wheel-drive shafts induction hardened to different depths ranging from 3.2 to 5.3 mm (0.13 to 0.21 in.). As the case depth increases, the time of flight is linear in respect to the case depth. Direct case-depth readings can be made in seconds and are not sensitive to surface roughness, material properties, dimensional tolerances, small changes in temperature, or magnetic fields.

Eddy-current instruments operate by measuring impedance changes in a test coil. The instruments use wire-wound coils (Fig. 12.5) placed around or in the part to be tested. Any change in the test part, such as electrical conductivity and magnetic permeability, affects the coil impedance. These changes can be measured and monitored in the instrumentation, with inspection results used mainly to make “go, no-go” decisions. Most eddy-current testing processes are designed for application on a particular part for inspection, such as checking cracks within 1 cm (0.4 in.) of the surface, surface hardness, and case depth.

Similar to induction heating, the depth of eddy-current penetration is determined by frequency. Current testing equipment uses computer based

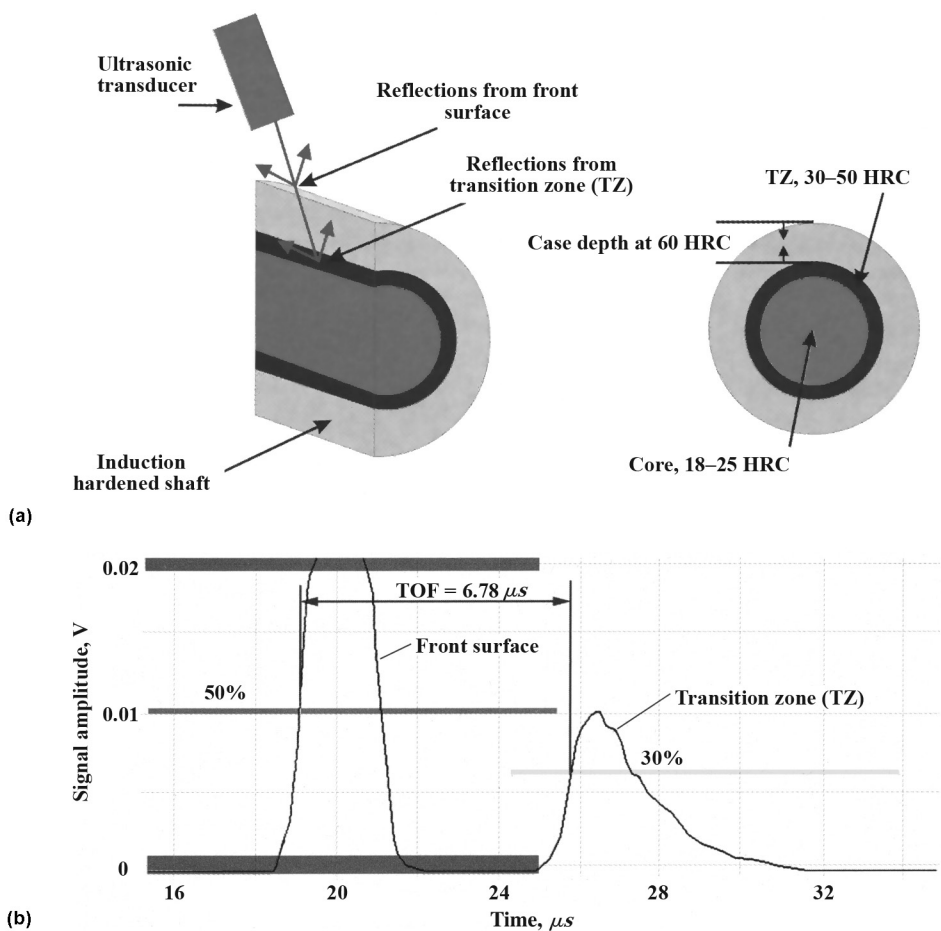


Fig. 12.3 How the ultrasonic microstructural analyzer works. (a) Schematic of principle of operation. (b) Ultrasonic response for a hardened steel shaft. The time of flight (TOF) between the front surface and the transition zone (TZ) lobes is measured and then converted to a case depth accurate within 5%. Source: Ref 5

multifrequency, in-line test stations for the monitoring of case depth, cracks, hardness, and other various induction-hardened parts. Table 12.7 lists some of these applications of eddy-current testing. Table 12.8 lists some of the possible hardening errors that the equipment is capable of monitoring during induction heating. In-line processing requires the development of application-specific, eddy-current coils and extensive pilot testing of parts to develop the computerized test program. One of the main problems for use is that, while nonconforming parts are identified, false trips occur because of the difficulty of developing programs that are accurate enough to handle all material and process conditions.

Radiographic inspection is the technique of obtaining a shadow image of a part using penetration radiation. The contrast in a radiograph is a result of different degrees of absorption of x-rays in the part, depending on

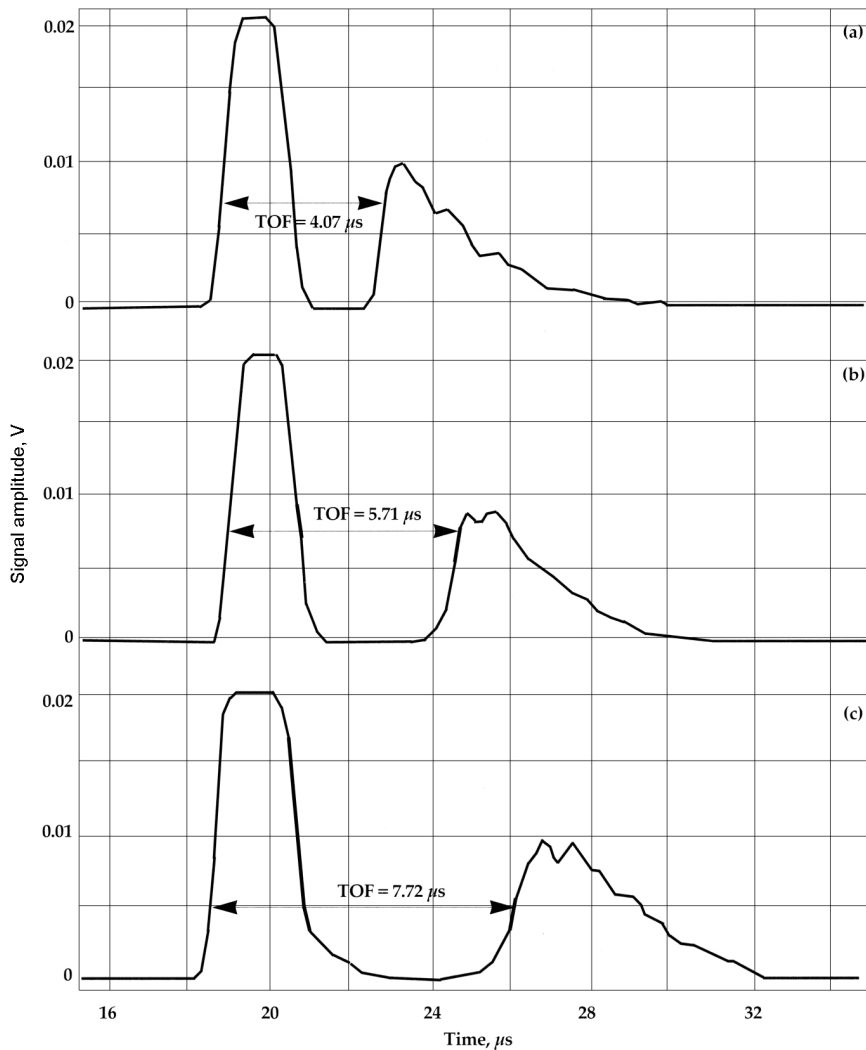


Fig. 12.4 Ultrasonic responses from front-wheel-drive half shafts made of SAE 1050 steel and induction hardened to different depths: (a) 3.2 mm (0.13 in.), (b) 4.3 mm (0.17 in.), and (c) 5.3 mm (0.21 in.). As case depth increases, the transition zone lobe moves to the right; its position is linear with respect to case depth due to the relatively constant velocity of the sound waves. TOF: time of flight. Source: Ref 5

variations in part thickness, chemical constituents, nonuniform densities, flaws, discontinuities, or scattering processes with the part. Several closely related techniques are used for different purposes. X-ray and sometimes neutron diffraction are used on induction heat treated parts for the determination of residual stresses, as discussed in Chapter 5, “Heat Treating Basics,” in this book. X-ray inspection can also be used for the determination of internal flaws, such as voids and cracks, but the orientation of the part being tested is very important in finding flaws such as cracks.

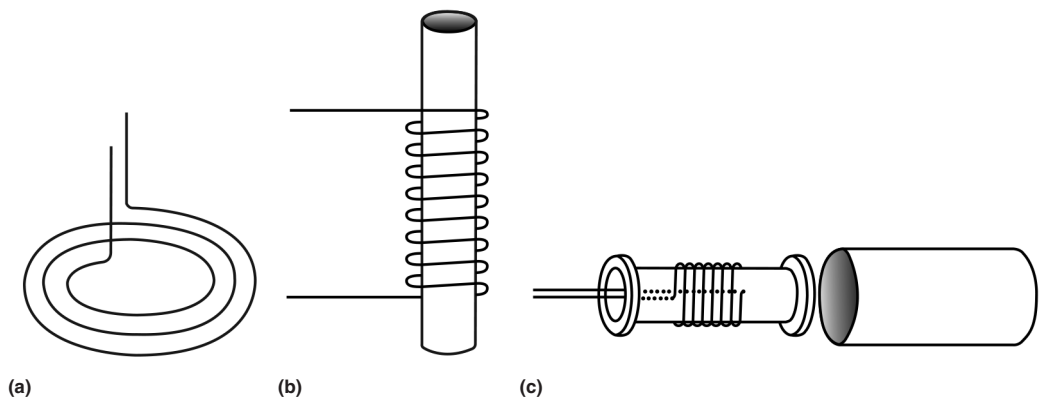


Fig. 12.5 Inspection coil configurations for eddy-current testing, depending on the specimen shape. (a) A flat surface is normally examined by a flat, pancake-type coil. (b) A cylindrical specimen is examined using an encircling coil. (c) The interior of a tube can be examined by an inside, inserted, or bobbin coil. Source: Ref 2

Table 12.7 Application examples of material testing by means of eddy-current testing

Component	Parameters to be tested
Bearing parts	Case depth, structure, and hardness pattern
Axle components	Case depth, structure, and hardness pattern
Pinion pins and axles	Case depth, structure, and hardness pattern
Linear guide components	Case depth, structure, and grinder burn
Steering racks and the like	Case depth, structure, and hardness pattern

Source: Ref 4

Table 12.8 Possible hardening errors during induction hardening

Which parameter was incorrect?	In which way was it incorrect?	What are the effects of this?
Austenitizing temperature	Too high	Overhardening, incorrect structure martensite + residual austenite
	Too low	Underhardening, incorrect structure martensite + bainite + ferrite
Austenitizing time	Too long	Overhardening, case too high, incorrect structure martensite + residual austenite
	Too short	Underhardening, shallow case, incorrect structure martensite + bainite + ferrite
Quenching	Too fast	Incorrect structure martensite + residual austenite
	Too slow	Incorrect structure martensite + bainite + ferrite
Annealing temperature	Formation of vapor bubbles	Soft spots not defined
	Too high	Hardness too low
Annealing time	Too low	Hardness too high
	Too short	Hardness too low
Rate of feed	Too long	Hardness too high
	Too slow	Shallow case, misplaced case, Austenitizing time too short
Damaged inductor	Too fast	Case too high, misplaced case, austenitizing time too long
	Undefined	Undefined
Malpositioning	Undefined	Unsymmetrical hardening pattern, overheating, melting

Source: Ref 4

Inspection for Induction

Inspection plans should be completed for each induction-hardening process that incorporates all appropriate standards and should specify what is to be inspected, the method of inspection, and the frequency of inspection. At first article inspection, all heat-treating requirements need to be inspected. Once in production, it is common for hardness to be checked only once per hour, and case depth once per shift. Inspection frequency is application specific, and testing programs should be designed to meet the individual part requirements. The amount of statistical process control used for in-line testing will affect the requirements of off-line sampling frequency. Personnel using the test equipment need to be trained and tested in the operation of all testing equipment. Finally, proper workpiece preparation for testing is necessary for obtaining valid test results, with testing instructions provided to the personnel performing inspection.

Inspection of workpieces that are induction hardened requires the use of standard preparation techniques. This section presents tried and proven techniques for preparing and inspecting induction-hardened parts. This includes preparation for inspecting, hardness testing, and case-depth measurement.

Workpiece Preparation for Surface Testing. The surface of the workpiece must be free from oil, scale, and pits. According to the standards, test parts should be smooth and free of machining marks; however, the Rockwell C-scale is not affected by shallow machining grooves, whereas the A- and 15N-scales are more affected. Standardized test blocks traceable to the National Institute of Standards and Technology must be used to calibrate Rockwell testers. Therefore, the most accurate testing is done with parallel surfaces. If the part is round, a V-block can be used, and special anvils can be used to hold the part to be checked directly under the indenter.

Removal of the quenchant and any other coatings or deposits, including, scale is necessary to prepare an induction-hardened part for inspection. The quenchant and any machining oils can be removed by immersion in an appropriate solvent. Glass bead is a quick method for scale removal that will not only clean but also produce etching or polishing that outlines the hardness pattern. If glass bead is not available, wire brushing, steel wool, or Scotch-Brite (3m Co., St. Paul, MN) can be used. At this point the part should be viewed for any nonconformances, such as quench cracks, melts, or pits. Next, the bottom surface of the part that is under the area to be checked should be inspected to make certain it is flat and free of burrs. Parts that do not have parallel surfaces need to have the bottom ground parallel to the surface to be checked. Parts that are round can be checked on V-blocks with round correction added to the reading. Long workpieces may need to have the ends held by a steady rest for accurate, flat location of the workpiece on the anvil.

Decarburization as a Source of Error. The lighter test scales produce softer hardness readings with decarb than do the heavier scales. Therefore, when two different test scales are used, and the hardness between the two scales does not correlate, decarb becomes a possibility. Decarb is not generally found over 0.25 mm (0.010 in.) on cold-drawn stock, and sanding or grinding easily removes most decarb. When the stock removal is not complete, or when there is slight decarburization, carbon depletion from the surface may be only partial. Carbon gradients may not show decarburization through etching. However, microhardness testing will verify the hardness increase that indicates carbon depletion. An increase in surface hardness after slight stock removal is also an indication of surface decarburization.

Minimum Case-Depth Verification by Surface Hardness. Occasionally workpieces have minimum case depth specified only. An example would be where a 0.5 mm (0.020 in.) case depth is specified. When a Rockwell test scale is used that will support the indent, the minimum case depth could be certified without checking. An example would be obtaining an HRC 62 reading on the surface of a part. This is a clear indication that the case depth must be at least 0.7 mm (0.028 in.), and the case depth can be certified to 0.7 mm (0.028 in.) minimum. However, most of the time the case-depth range is specified, so the workpieces have to be cross-sectioned for case depth determination.

Cross-sectioning requires the use of a water-cooled metallurgical cutoff saw. (Water-jet cutoff has also been used.) Because hardened parts are being cut, soft-bonded cutoff wheels must be used. Parts must be clamped so that they can be cut without causing binding of the cutoff wheel during cutting. In addition, parts with thin cross sections need to be mounted vertically so that the side of the part opposite the cutting wheel is adequately cooled during cutting. When effective case depth is measured (by hardness), either the first cut must be parallel to the bottom, the second cut must be parallel to the first cut, or the cut section must be parallel to the ground. Any time a workpiece is cut, there is a possibility of producing wheel burns (grinding burns). These are localized areas in which the martensite is heated during cutoff to a high enough temperature for tempering. The wheel burns will produce low hardness readings, and they may be detected by etching as described later in this Chapter.

Etching for Total Case-Depth Measurement. Figure 12.6 lists the procedures for mixing etchants. Lab procedures should be established for the safe mixing and handling of these etchants, including the wearing of protective eyeglasses when mixing. The commonly used etchants in induction heat treating are weak solutions of nitric and hydrochloric acids. Nital, a mixture of nitric acid and alcohol, is used most commonly for case-depth measurement, with small nitric acid concentrations ranging from 2 to 5% safely used. A weak solution of 5% hydrochloric acid and alcohol is used to define wheel burns. The process of etching for burns requires first overetching with nital until the etched area is as dark as pos-

Etchants:

Two principal etchants are used for etching in induction heat treating:

Nital (5%): 5% nitric acid, 95% alcohol

Mild Hydrochloric (5%): 5% hydrochloric acid, 95% alcohol

Procedure:

A protective rubber apron is recommended, and protective glasses are mandatory. Laboratory grades of alcohol can be purchased with ethanol ($\text{CH}_3\text{CH}_2\text{OH}$) recommended. Methyl alcohol, (CH_3OH) should not be used because of potential toxicity. Nitric acid and hydrochloric acid can be purchased in gallon or smaller bottles. The areas where the etchants are mixed should be well ventilated.

Acid is always added to the alcohol. Try to keep the acid off of your hands, and wash any etchant off the skin as soon as possible. If any irritations occur after use, the affected individuals should wear rubber gloves when etching. The etchants can be placed in plastic or glass bottles. Etchants are applied onto the top of the surface to be etched by whatever technique seems best with test specimens immersed, sprayed, doused, or swabbed. (Cotton swabs may be used.) When the etching is complete, the surface is first cleaned with water, then alcohol, and finally blown dry. Once dry, the test specimen must be examined to make certain that there are no water spots or etching stains. Thereafter, the etched surface must not be touched. If the specimens need to be stored, plastic containers or cotton taped over the top is recommended.

Fig. 12.6 Laboratory procedures for etching in induction heat treating. Source: Ref 6

sible. Then rinse with water, followed by alcohol, and blow dry. Finally, etch a second time with 5% hydrochloric acid. Any burned areas caused by tempering will remain dark, with the martensitic areas white.

After it has been determined there is no wheel burn (the double-etching test can be eliminated if you have determined from previous experience that no wheel burning occurs during the cutting of a particular part), polish the surface and etch with nital. After the etching process outlines the hardened case and provides definition of the core microstructure, the case depth can be optically measured.

Measuring Effective Case Depth. Effective case depth is the case depth as defined by a given hardness reading, most commonly HRC 50 or the equivalent. Individual specifications by different manufacturers sometimes provide their own definition of the hardness that is to be used. On parts for which the case depth exceeds 1.5 mm (0.060 in.), the easiest method of testing, if permitted, is to cut a parallel section. Then take HRC readings at the surface, extending toward the center in a spiral pattern, and the effective case depth at which HRC 50 is reached. Lighter cases such as the HR15N-scale can be used with shallower cases as long as the hardness indent is 2.5 times the indenter diameter from the surface of the cut workpiece. Some workpieces are hard to measure, and if a parallel cut cannot be made, the workpieces can be mounted in epoxy for testing by microhardness.

Crack Detection. Cracks can often be seen on the workpieces after cleaning. The very first step in inspection, as previously mentioned, is to look for cracks. However, NDT methods such as Magnafluxing may be needed to detect fine cracks. When the workpiece is inspected for cracks, it should be cooled to room temperature in the same manner as it will cool in production. (Setup personnel have a tendency to take a warm or hot

workpiece out of the coil and then water cool so that testing can be done.) As discussed above, various types of NDT have been used to test for conformance to specifications, including Magnaflux, dye-penetrant, eddy-current, and ultrasonic testing. Magnaflux and dye penetrant were used off-line to check for cracks, while eddy-current and ultrasonic testing can be used either on-line or off-line.

Sometimes the frequency of cracking is so low that, without evidence of special cause, cracking must be considered a statistical event. In those instances, diagnosis by process variables might be more effective than diagnosis by inspection. An example is the cracking of roller lifter axles that were prehardened, tempered, and then induction hardened. The axles were 100% eddy-current inspected after final grinding, and approximately 3 to 5 parts per lot of 30,000 pieces were found to be cracked. No abnormality or cause was found when the finished parts were metallurgically examined, and adjustment to the induction-hardening parameters was ineffective at preventing the cracks. Because the induction process did not appear to influence the frequency of cracking, the prehardening process was examined. It was known that very low carbon potential in the prehardening operation could cause cracking in the induction-hardening operation. Even though the carbon potential was verified and appropriate and the microstructure showed no signs of decarburization, the carbon potential was increased slightly. After testing, the carbon potential was adjusted upward to a level that brought the frequency of cracking down to zero (Ref 7).

The *ASM Handbook* on mechanical testing (Ref 3) has very good detail on hardness testing and a detailed list of the ASTM standards for hardness testing. The ASM book *Nondestructive Testing* (Ref 4) outlines in detail ASTM and other standards relating to NDT methods.

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CHAPTER 13

Nonconforming Product and Process Problems

THIS CHAPTER is designed to provide a step-by-step problem-solving sequence to help analyze the causes of nonconforming workpieces and to provide potential solutions. Workpieces can be out of tolerance for not meeting a hardness specification, case depth specification, or pattern length or for having a defect such as melting or a quench crack. Recommendations for inspection and testing are discussed in Chapter 12, “Standards and Inspection,” in this book, along with methods for valid and reliable test results. Anytime workpieces are checked with hardness testers and are found not to be in conformance with the required hardness, specimen preparation and testing methods should be reviewed for conformance to ASTM standards. This Chapter describes some of the more prominent causes encountered during testing that produce bad test readings.

Improper Testing Procedures

The Hardness Test Penetrates through the Case. ASTM Standard E 18-14A (see Table 12.2 in Chapter 12, “Standards and Inspections,” in this book) shows the maximum depth of case that a given hardness scale can correctly check. Sometimes the hardness specifications shown on prints are used for the testing but are not the scale that should correctly be used according to the ASTM standards. In such a case, the standards permit the use of the appropriate lighter scale, with the reading then correlated through the ASTM table (see example in Fig. 13.1). The recording of the test results should include the scale readings tested and the appropriate scale correlation.

Round Correction Is Not Being Added to the Test Reading. Rounds greater than 6.25 mm ($\frac{1}{4}$ in.) in diameter need to have a round correction factor added (see Table 12.3 in Chapter 12 of this book).

ROCKWELL®
HARDNESS TESTER

ROCKWELL®
SUPERFICIAL
HARDNESS TESTER

C	A	15-N	30-N	DPH	Knoop	Br'l	TENSILE STRENGTH
150 Kg. Brale	60 Kg. Brale	15 Kg. N Brale	30 Kg. N Brale	10 Kg. 136° Dia- mond	500 Gr. & Over	3000 Kg. 10mm Ball	
ROCKWELL	ROCKWELL	ROCKWELL Superficial	ROCKWELL Superficial	136° Diamond Pyramid	KNOOP	Brinell (Hultgren Ball)	Thousand lbs. per sq. in.
70	86.5	94.0	86.0	1076	972	—	INEXACT AND ONLY FOR STEEL
69	86.0	93.5	85.0	1004	946	—	
68	85.5	—	84.5	942	920	—	
67	85.0	93.0	83.5	894	895	—	
66	84.5	92.5	83.0	854	870	—	
65	84.0	92.0	82.0	820	846	—	
64	83.5	—	81.0	789	822	—	
63	83.0	91.5	80.0	763	799	—	
62	82.5	91.0	79.0	739	776	—	
61	81.5	90.5	78.5	716	754	—	
60	81.0	90.0	77.5	695	732	614	
59	80.5	89.5	76.5	675	710	600	
58	80.0	—	75.5	655	690	587	
57	79.5	89.0	75.0	636	670	573	
56	79.0	88.5	74.0	617	650	560	
55	78.5	88.0	73.0	598	630	547	301
54	78.0	87.5	72.0	580	612	534	291
53	77.5	87.0	71.0	562	594	522	282
52	77.0	86.5	70.5	545	576	509	273
51	76.5	86.0	69.5	528	558	496	264
50	76.0	85.5	68.5	513	542	484	255

Fig. 13.1 Hardness conversion card

Specimen Preparation. The specimen surface is not smooth, and the surface is not perpendicular to the diamond indenter.

The Rockwell diamond indenter is chipped or the Rockwell is not in calibration.

Workpiece Has Defects as Received

The induction heat-treating process can cause defects that were originally in the parts to become more apparent. Examples of these are seams, porosity (in castings), cold shuts and cracks produced by cold heading, and other casting and forming defects. Seams and laps are discussed later in this Chapter under “Cracks.” Anytime something unusual is seen, the workpiece should be carefully examined to make certain that the condition is not caused by a defect in the material. Most of the time the nonconformance will occur when one or more of the heat-treatment specifications are not be met, as in the case of low surface hardness, wrong case depth, cracks, surface defects, and distortion. High surface hardness is not considered a problem because proper procedures call for tempering if the workpiece is over the specified hardness. The balance of this Chapter focuses on the typical types of defects found during induction heat treating and possible remedies. Inspection normally starts with first article inspection, followed by a system for periodic testing of the workpieces for conformance to specification. First article inspection will normally reveal more of the problems that can cause nonconformance than those that appear during production, because it identifies some of the preexisting conditions that can cause the nonconformances. The conditions that can cause nonconformance are discussed in the order of inspection frequency of occurrence.

Low hardness probably is one of the largest areas of nonconformance. It is important to remember that hardness testing needs to be correctly done and that a quick examination of the hardness testing performed on a sample can find the wrong testing techniques used, such as placing the indents too close together. If no other cause can be found for the low hardness, examination of the calibration and performance can determine that the hardness testing machine itself is producing accurate results.

Low surface hardness or soft spots are found on first article inspection. As previously outlined, the inspection techniques are verified for correctness and appropriateness. If the individual doing the testing does not see the workpiece when austenitized, another workpiece should be heated and quenched to visually verify that the austenitizing temperature was high enough and that the quenching looked good. Inspection techniques for determining soft spots are outlined in Chapter 12, “Standards and Inspection,” in this book. Table 13.1 shows suggested remedial actions for these surface conditions of low surface hardness or soft spots:

Decarburization. Check for decarburization (decarb) by the most appropriate method. Simple surface-material removal sometimes is the fastest method. Decarb exists if the carbon content of the surface is lower than the nominal carbon content of the workpiece. In some cases the surface decarb can be difficult to detect because the decarb layer is very thin or

Table 13.1 Remedial actions for nonconformance of low hardness as quenched

Possible cause	Remedial action
Improper inspection	Make certain tester is in calibration Verify hardness scale used is appropriate Make certain surface of part is prepared for testing correctly Make certain part being tested was correctly seated Use round correction correctly for rounds Make certain hardness scale is appropriate of case depth
Decarburization	Remove enough of the surface to get below the decarb Verify if decarb will be removed in a subsequent operation Carbon restore
Quenching speed is too slow	Lower temperature of water or polymer quenchant Lower concentration of polymer quenchant Increase impingement of change method of application Change type to faster-speed quenchant
Austenitizing temperature is too low	Use a longer heat cycle time Increase power output of induction power supply Improve coil design
Carbon % too low	Improve output bus design to increase efficiency Obtain variance for lower hardness that is produced Carbon restore or carburize surface
Poor prior microstructure	Scrap parts Austenitize at hotter temperature Use lower output power with longer time Austenitize followed by quench and temper or normalize before induction
Spotty hardness	If water quenchant, lower temperature Improve quenchant flow or impingement Add up to 1% polymer if using water Use faster-speed quenchant
Removed from quench too soon	Hold in quench longer
Barberpole	Improve quench impingement Increase quenching speed
Retained austenite	Reduce heat cycle time Reduce power Deep freeze after quenching (cryogenic processing)
Cutoff wheel or grinding burn	Improve cooling during cutoff Reduce wheel pressure during cutoff Go to softer cutoff wheel Reposition part in cutoff for better cooling

Source: Ref 1

has a carbon content just under the average workpiece content, leading to slightly lower hardness just at the surface. This layer may quench to 100% martensite but of a lower hardness. In this case a slight grind or a micro-hardness test may be the only test that can determine that the decarb layer exists. Determine if further machining will be done. If so the decarb may not be detrimental to the use of the workpiece. Check the hardness below the decarb, and if the workpiece is in specification, note on the inspection record that decarb was present and that the hardness reading was taken below the decarb. Decarb does not always have a uniform distribution. Workpieces made from cold-drawn steel may be machined with more stock removed on one side of a bar than on the other. In this case the decarburized area would run longitudinally down one side of the workpiece. Also, cast or forged workpieces may not have the decarb totally removed in the machined areas.

Workpiece Not Quenched Fast Enough. If the overall surface hardness is low, the quenchant speed may need to be increased. Quenching speed

depends on the quenchant being used, quench temperature, and quench impingement. If polymer is being used, decrease the concentration (this is most often easier and more controllable than trying to change the temperature). If oil is being used, increase the oil impingement or temperature. Chapter 6, “Quenching,” in this book covers the selection and use of quenchants.

Workpiece Not Heated Hot Enough. Increasing the austenitizing temperature is a matter of increasing the power output of the power supply, increasing the heating time, or both. Usually when making the setup, the power is adjusted and set for the approximate time desired to heat the part. Then the heating time is used for fine adjustment of the cycle. The use of electronic timers and programmers makes adjustment of time cycles easy. If more power cannot be provided and adjusting the time does not help, the tuning of the power supply and heat station should be examined to make certain that maximum power is being produced. If the tuning is correct and more power is needed, then the bus design used to attach the induction coil, as well as the induction coil design itself, should be reviewed. Better lead construction on the bus attachment and better coil design for coil efficiency may be needed. Figure 13.2 shows white ferrite grains in a longitudinal cut from a workpiece that was not austenitized hot enough.

Material Has Carbon below Specifications. If the low hardness is not due to decarb, check to make certain that the material is not a low-carbon heat of steel. This can be done quickly by spark testing. As mentioned in Chapter 12, “Standards and Inspection,” in this book, low-carbon steel produces very few sparks when held against a grinding wheel. Sometimes where there is decarburization, such as with parts that have been quenched and tempered in a neutral atmosphere, keeping the atmosphere slightly

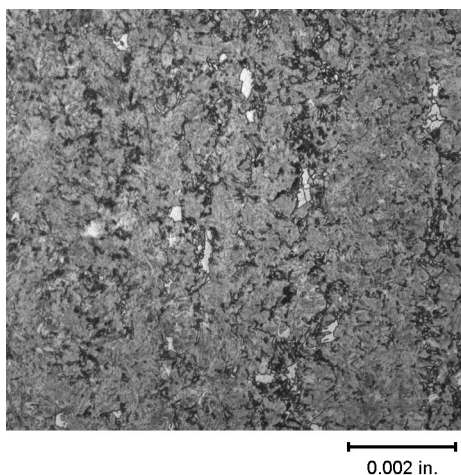


Fig. 13.2 Microstructure at low power setting, longitudinal direction. See text for details. Source: Ref 2

rich can make the difference in the ability to quench the surface hardness above specification.

Prior microstructures for induction heat treating need a fine, homogeneous distribution of the elements and phases (see Chapter 5, “Heat Treating Basics,” in this book). Analysis of the microstructure is needed to define the steps necessary, if possible, to produce the fully martensitic microstructure. Examples of poor prior microstructures are workpieces that are found to be fully annealed, that have ferrite banding, that have segregation of some of the elements such as manganese, or that have a mixture of coarse and fine grains. All require higher austenitizing temperatures.

Fully annealed microstructures are difficult to fully austenitize and to diffuse the carbon. For example, 4150 steel annealed may oil quench only to 53 HRC, while a prior microstructure that is quenched and tempered may quench to 58 HRC or higher.

Ferrite banding is described in Chapter 5, “Heat Treating Basics,” in this book in the discussion of undesirable microstructures. If the banding is severe enough, complete austenitization with uniform diffusion of carbon may not be possible. Problems also occur with mixed heats of steel where the first article workpiece does not have banding, but other heats with banding are mixed in later production. Workpieces with ferrite banding running at the same austenitizing temperature will quench to a lower hardness because the carbides are not fully dissolved and dispersed in the matrix. In addition, the manganese segregation in banded steels produces areas in the core that austenitize at a lower temperature than the remainder of the part. This can result in martensite formation in the core below the effective case depth. If possible, heat identification and separation should be implemented.

Coarse-grained microstructures can be produced when hot rolling produces nonuniform grain sizes around the diameter that affect the quenched surface hardness. Workpieces in which the soft area runs longitudinally in a slow spiral are an indication of this condition. When higher austenitizing temperatures are needed, the heating time is normally made longer. However, if the austenitizing temperature becomes excessive and produces other undesirable effects, as discussed later in this Chapter in the section “Overheating Resulting in Pitted or Deformed Surface,” then lower power and longer time cycles may need to be used. If the material cannot be purchased with a microstructure good enough for induction hardening, then the material needs to be normalized or quenched and tempered to produce a uniform microstructure prior to the induction heat treating practice.

The Carbide Particles Are Too Large for Solution. This is often the nature of carbide particles (cementite) in fully annealed steels. The best prior microstructure for induction heat treating is one that has a fine, uniform carbide distribution. When the carbides are large and coarse, they may not completely dissolve when the part is austenitized. The workpiece reacts like a lower-carbon steel and does not produce the hardness ex-

pected. Sometimes this can be easily discovered by rehardening the same part. If it quenches harder with the second heat cycle, then the prior microstructure is not good enough. Further proof of this can be found by microscopic examination. Under the microscope the hardened area can be examined to make certain that there was fully austenitic solution. A 52100 steel, with its high carbon content, austenitizes very well if the steel is purchase annealed with the carbides in a homogeneous, granular form.

Vapor pocket formation (steam pocket) is produced by poor quenchant contact with the workpiece when first quenched. Water quenchants, particularly warm water, are prone to produce vapor pockets. These pockets permit transition products to form, producing localized soft spots. The vapor pockets produce small soft spots that can be determined by etching, hardness tests, or microstructural analysis. The remedy is to redesign and improve the quenching. Cold water quenches much faster than warm water; however, water quench systems need to have an economical way to keep the water cold. Refrigerated chillers can be expensive to operate, and unless there is cheap availability of cold makeup water, it may be hard to keep the water temperature low enough to be effective. A slight addition of polymer up to about 1% in water will decrease vapor pocket formation without slowing the quenching rate so that a warmer quenchant can be used. Other techniques such as better impingement designs and submerged quenching with impingement are also used. Appendix 4, “Quench System Design,” in this book discusses quench cooling systems.

Transformation products occur during quenching, producing low hardness. Transformation products are an indication that the quenching speed is too slow. When workpieces do not quench hard enough and decarb is ruled out, the quenchant speed needs to be examined and increased, if possible. In general practice, the quenchant speed can be increased until the workpiece either cracks or has excessive distortion. If oil is being used, general practice is to change to a polymer quenchant (see Chapter 6, “Quenching,” in this book). Polymer quenchants have become widely used, with concentrations ranging from 1 to 28%. Concentrations of 1% quench with the approximate speed of water, while concentrations of 28% quench with the approximate speed of oil. In addition, there are special polymers that are reported to quench as fast as brine. Quenching curves, as supplied by the manufacturers, are based upon immersion quenching. Polymer quenchants, as used for induction, generally involve the use of spray quenching. Spraying polymer on the surface of a workpiece being quenched tends to decrease the thickness of the polymer layer. Therefore, it is not unusual to need to test the range of concentration that can be safely used for a particular workpiece. Too low of a concentration can produce quench cracks, while too high of a concentration can produce low surface hardness of case depth.

Removal from Quench Too Soon. Workpieces can self-temper if removed from the quenchant too soon. Examples of this are conveyORIZED

fixtures in which the conveyor speed is too fast, or scanning where the quench is not applied for a long enough distance to fully quench the part. The remedy is to slow the conveyor or to modify the quench ring or pad to increase the quenching impingement and efficiency. Design factors that are to be changed include increasing the number of inlets, putting baffles inside the inlets if the output flow varies around the quench ring, changing the outlet hole size and locations, and possibly changing the impingement angle. Another design change that can be made is to add a secondary quench below the primary quench.

Barberpole. Spiral patterns produced during quenching of alternate light and dark stripes often seen in workpieces that are scanned. When properly quenched, barberpole is a visual condition, and there is no effect on the hardened characteristics. However, if the quenching is not sufficient, two effects can occur. First, flakes of bainite may appear on the surface of the workpiece in a spiral pattern. The flakes can be seen in the microstructure. The bainite is not normally considered detrimental; however, if the round bar is centerless ground after induction hardened, the resulting surface finish and tolerance can be affected. Second, barberpole can be the result of self-tempering of a martensitic area as it passes from one quench impingement area to another. When microscopically viewed, the workpiece may have a fully hardened case with a very shallow tempered area spiraling down the workpiece. In both cases the quenching must be improved.

Retained Austenite. Stainless steels, 52100 steel, and tool steels such as those in the D-series, when austenitized too hot, will have the quenched microstructure consisting of martensite, small carbide particles, and retained austenite. 52100 will normally have up to 10% retained austenite that is not visible and can be detected only through x-ray diffraction. When the retained austenite exceeds approximately 10%, some retained austenite starts to become visible in the microstructure. As the retained austenite increases, the quenched hardness will start to drop. An indication of overheating and retained austenite can be found by performing hardness tests from the unhardened area into the hardened area. The hardness first increases, then peaks, and then drops as the testing progresses into the overheated area. The peak in hardness is the point at which the austenitizing temperature was correct. The solution, of course, is to decrease the austenitizing temperature.

Pattern Length Not in Conformance. If the workpieces are being scanned, then the distance for scanning needs to be adjusted. If the workpieces are being heated single shot and the pattern length is long enough but off center, the workpiece needs to be repositioned. If the coil length is not correct, then the coil needs to be recharacterized or rebuilt to produce a longer or shorter pattern as necessary.

Low hardness in a cut workpiece is a condition that is commonly produced by metallurgical cutoff wheels during cutting or overheating during subsequent grinding. Although the wheels are water cooled, if soft

wheels are not used on hard materials, sufficient temperature can be produced during cutting to locally temper the parts. Anytime low hardness is found after a workpiece is cut, the workpiece should be double etched, as described in Chapter 12, “Standards and Inspection,” in this book to check for burning. It may take some experimentation to find the best part orientation and clamping technique to prevent burns. Thin parts give particular problems, and it is best to cut thin sections standing vertical to prevent burns.

Shallow case depth is normally an indication that a longer heat cycle is needed. If a longer heat cycle does not produce a deeper case, then more detailed review is needed. Hardenability curves as shown in Appendix 6, “Hardenability Curves,” in this book are based on a furnace-austenitized part and a fixed water quench. The furnace austenitizing done for the hardenability curve negates any effect of prior microstructure because there is full time for austenitization. However, with induction hardening, hardenability is a function of the chemistry of the part, the prior microstructure, and the rate of quenching.

The hardenability curves indicate a part is capable of hardening to the hardness depths shown, as tested by the Jominy hardness test. The curves themselves provide an indication of specific capability of large number of heats of steel ranging from surface hardness to the hardnesses at depths below the surface. It is prudent to be wary of specifications for steels that have case depths greater than the maximum case depth produced for a particular grade of steel. The purchase of specified hardness grades may be possible. Finally, because induction can use quenchants and processes more violent than those used in producing the hardenability curves, induction may be able to produce greater case depths than those shown.

Hardenability is discussed Chapter 5, “Heat Treating Basics,” in this book. If a part does not produce a deep enough hardness with a longer heat cycle while appearing to have a large hardness transition zone, verify that the material is right and that the grade of material has the hardenability needed. Then check the quenchant. If polymer is being used, add water to the quenchant to increase the quenching speed. To increase quenching efficiency, the quenchant impingement can also be changed. Finally, if quenching is optimal, verify that the prior microstructure is not having an effect. Sometimes this can be done by simply reheating the same workpiece two or three times and seeing if the surface hardness and case depth both increase. (If the prior microstructure is having an influence, it should also produce a lower surface hardness.) The sequence as mentioned considers that the power supply frequency was fixed. If the power supply has variable frequency, lower the frequency. This will produce a deeper heating effect. Make certain that the frequency selection is capable of producing the case depth requirements as discussed in Chapter 2, “Theory of Heating by Induction,” in this book. Table 13.2 shows possible remedies when the case depth is too shallow.

The Microstructure Is Not 100% Martensite. This can be an indication that the workpiece was not austenitized at a high enough temperature, or it was not quenched fast enough. 100% martensite can be a requirement particularly for carbon steel. Because positive verification can be done only by microscopic examination, the requirements should be clearly stated. Carbides can be present with steels over 0.8% carbon because they were not taken into solution. In addition, up to 10% retained austenite is not visible in the microstructure, so it is wise if limitations are specified, to request the method of inspection for retained austenite. As previously noted, the prior microstructure has a significant influence on the ability to produce a fully martensitic microstructure. The influence of the prior microstructure, as discussed previously in the section “Low Surface Hardness or Soft Spots” in this Chapter has the same impact and resolution. Review of the microstructure to determine whether the workpiece has quenched to 100% martensite will define the problem. Comparison to the core microstructure that is not affected by the austenitizing cycle will clarify whether the nonconformance is due to incomplete solution or due to quenching too slowly. Table 13.3 shows remedial actions for improving the microstructure.

Case Depth Too Deep. This is one of the easy-to-remedy nonconformances. Decreasing the austenitizing temperature by reducing the cycle time or power output will reduce the case depth (assuming that the desired

Table 13.2 Remedial actions for nonconformance case depth too shallow

Nonconformance	Remedial action
Case depth too shallow	Heat hotter using longer time Lower power and use longer heating time Heat part second time if permitted Furnace heat treat before to produce better microstructure Increase quenching speed Lower frequency if possible Use steel with higher hardenability

Source: Ref 1

Table 13.3 Remedial actions for nonconformance of poor microstructure after quenching

Possible cause	Remedial action
Quench was too slow Part not heated hot enough Segregation in steel AR\aq4\	Use faster quenchant or better application of quenchant Increase austenitizing temperature by heating longer Increase austenitizing temperature by using more power Furnace heat treatment prior to induction Reduce austenitizing temperature by reducing cycle time
Has visible retained austenite	Reduce austenitizing temperature by reducing power Deep freeze (cryogenically process)
Has untransformed components	Induction austenitize with hotter temperature or overall furnace austenitize with quench and temper before induction austenitizing

AR: as received. Source: Ref 1

transformation and hardness still occur). Also, if possible, increasing the frequency of the power supply will reduce the case depth.

Cracks. Cracks are discussed in Chapter 9, “Decarburization and Defects,” in this book. Sometimes a “ping” can be heard during the heating or quenching of a workpiece, providing a clear statement that a crack has occurred. Most of the time cracks are found on inspection after quenching. Then it is important to determine the nature of the crack and when it occurred.

Seams, Laps, or Defects. Inspect the workpieces before induction hardening in order to determine whether the crack is from a seam or defect that is present in the workpiece. Figure 13.3 shows a crack that can be seen near the end of a 35 mm (1.40 in.) diameter shaft after induction hardening. The “V” at the left hand side of the workpiece is of significance because it clearly indicates that the crack is present during heating. It is the effect of the overheating that occurs when the current jumps across the crack in front of the main heating as the workpiece enters the coil. At this point of investigation the assumption can be made that the crack was either in the part or opened at the start of heating and propagated. Additional testing was done. Figure 13.4 shows a micrograph of the cross section from the same workpiece. A light line of surface decarburization can be seen running along the inside of the crack, a clear indication that the crack was produced in the workpiece during previous hot processing. Magnafluxing before induction hardening should have also defined the crack. Sometimes these cracks are not continuous in the bar stock and are present in only a small portion of the workpieces. Then the decision needs to be made as to whether to scrap the material or to run and to separate all cracked workpieces with appropriate inspection after hardening.

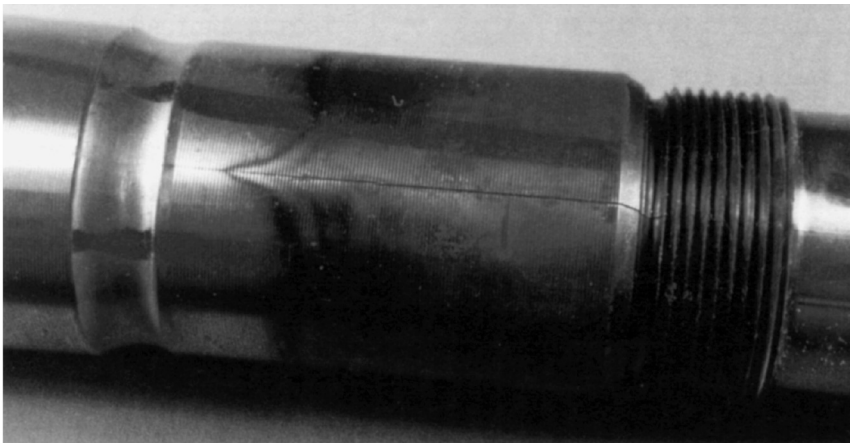


Fig. 13.3 Crack propagating longitudinally: view of induction-heated area showing “flaring” of the heat pattern at the crack, and the crack propagating past the heated area. Approx. 1.5 $\times$. Source: Ref 3

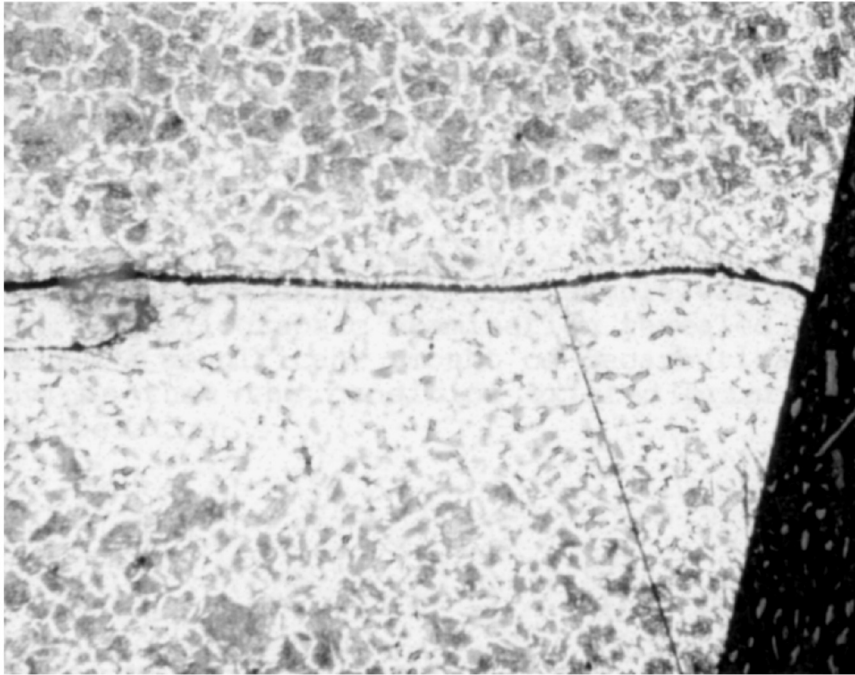


Fig. 13.4 Microphotograph of the crack in Fig. 13.3 showing decarburization on both edges. Nital etch. 130x. Source: Ref 3

Stress cracking during heating occurs due to high, nonuniform residual stress distributions in the workpiece. Heating a workpiece without quenching (if possible) and inspecting for cracks is one procedure that may help. Other times, the distribution of these cracks in the workpieces, such as 1 to 5%, is so small that the cause is hard to determine. When stress cracks occur during heating, furnace stress relieving a workpiece from 455 to 538 °C (850 to 1100 °F) may reduce the residual stresses enough to eliminate the cracking. On large parts the technique of using a low-temperature preheat from the induction coil followed by a high-heat austenitizing cycle has been known to eliminate cracking after induction hardening.

Quench Cracks from Cooling Too Fast. When the entire cross section being hardened passes through martensitic transformation at the same time, the potential for quench cracking is reduced. If a workpiece has a quench crack, the quenchant may be too fast or too cold. The first standard technique employed is to use a slower-speed quenchant. When polymer quenchants are being used, the polymer concentration should be increased. A second technique is to increase the quenchant temperature. When this is done, however, the quench tank needs to have heaters so that the quenchant is brought up to temperature before the start of production. Increasing the quench temperature of fast-quench oils up to the region of 78 °C (175 °F) actually increases the quenching speed. Some quench oils need

to be heated up into the 120 °C (250 °F) region to slow the quenching speed. In applications for which timed spray quenches are used, the quenching time can be reduced so that the part is brought out hotter. If the timing is such that the part is 120 to 150 °C (250 to 300 °F), quenching can be stopped and the part can be removed hot. The workpiece is then air cooled with both the mass of the part and convection to the air doing the cooling. Full transformation to martensite occurs because the workpiece is in the middle of the martensite-transformation temperature region. Whatever temperature is used, the process must be able to replicate the same as-quenched temperature throughout the daily production.

One of the main problems in removing workpieces hot is that, unless the process is mechanized, induction heater operators like to have the workpieces cool enough to handle without burning themselves. The other objection would be that where the workpiece is being subsequently induction tempered in-line, it would not be fully martensitic before the tempering operation. The potential then exists that after cooling from tempering, untempered martensite may be produced from incomplete austenitic transformation in the first cooling cycle.

In contrast to the technique of removing workpieces from quenching in the middle of the martensitic transformation range, there have been some workpieces for which intensive quenching techniques were used for very rapid quenching. The intention is to transform a case depth of martensite deep enough that the yield strength of the case is high enough to ensure that rupture does not occur when there is subsequent expansion of the workpiece caused by transformation or thermal expansion of the core. Table 13.4 shows a summary of the remedial actions for eliminating cracks.

Oxide inclusions can nucleate quench cracks (as seen in Chapter 9, “Decarburization and Defects,” in this book). If a slower quenchant does not stop the cracking, then contact should be made with the steel supplier to see if the inclusion content can be reduced.

Table 13.4 Remedial actions for nonconformance of cracks found in induction-hardened workpieces

Nonconformance	Remedial action
Seams, laps, or other defects as received	Inspect parts before induction hardening; review the material as received and segregate when possible
Quench cracks	Increase polymer concentration Increase polymer temperature Stop quenching part sooner and remove hot Quench part longer to remove core heat Change machining design to reduce stress concentrators Change machining order to complete machining after hardening Use lower-carbon steel if design permits Change frequency to promote more uniform heating Increase quenching speed (intensive quench) Contaminated quenchant; purge and change Change coil type or design
Cracks due to residual stresses in parts as received	Stress relieve parts before induction hardening Use low-power preheat before austenitizing

Source: Ref 1

Workpiece Shape. The basic geometry of some workpieces can cause the initiation of quench cracks. For example, keyways may have sharp fillets at the bottom that can act as stress risers, which can initiate cracks. If possible, keyways should always be machined after induction hardening. Sometimes variation of the frequency of the power supply, such as lowering the frequency to produce a deeper case, will help. Another technique is to change the orientation of the coil so that it is longitudinal to the keyway, producing less heat at the edges.

Lower the Carbon Content of the Workpiece. Some material specifications have excessive carbon. When the as-quenched hardness is considerably higher than the specified hardness range, lowering the carbon content will decrease the potential for quench cracks.

Prompt Tempering. Prompt tempering is always suggested to minimize quench cracking after the parts have been removed from the power supply.

Overheating Resulting in Pitted or Deformed Surface. As the austenitizing temperature is increased in air, heavier scale forms on the workpiece being heated. When workpieces are heated too hot, the scale formation can result in an actual pitting of the surface. Unless there are final metal removal operations, pitting may be detrimental to the point that the final desired surface finish is not produced. Workpieces with holes, keyways, or changes in cross section should always be examined for melting in these areas. Also, the parts may be overheated to the point that actual sparking and melting of the surface can be seen. Finally, gray cast irons have a phase that starts to melt at about 1049 °C (1920 °F). The melting appears visually as an actual flow or fusion in locations on the part. This is normally only a problem when the austenitizing temperature is raised to try to increase the quenched hardness. Overheating of the workpiece is an indication that time or power needs to be reduced, or the setup needs to be changed.

Too-Large Martensitic Grain Size. Martensitic grain size can be hard to define by microscopy. The workpieces must be tempered at a high enough temperature so that when the martensite is etched, the contrast is dark enough that the martensite packets and their orientation produce a cluster effect that will show the prior austenitic grain size. The specification should define the magnification to be used so that there is agreement in grain size definition. If the martensitic grain size is too large, the austenitizing temperature must be reduced.

Excessive Distortion. Reduction of distortion moves more into a trial-and-error process. First the part limitations for distortion should be clearly defined on prints. Chapter 5, “Heat Treating Basics,” in this book discusses distortion. Workpieces need to be designed so that the potential for distortion is reduced. Then the impact of items such as holding nests or fixtures, the quenchant used, timing of quenchant application (including primary and secondary quenchants), and the potential for machining to

final size after induction hardening must be reviewed and tested. Sometimes if distortion is constant from workpiece to workpiece, the machining tolerances before induction hardening can be set so that the final net shape desired after hardening is produced. Table 13.5 shows possible remedial actions for excessive distortion.

Workpieces Are Not Heating the Same in Production (Variance in Hardness, Case Depth, Pattern, etc.). Conditions occur under which all of the previous potential problems have been reviewed and have been found to be in control or in proper range during setup, but inspection during production is occasionally finding nonconforming workpieces. Physical conditions that occur outside the fixturing and materials are:

- Variation in line voltage is causing the power supply output to change. In times of high power consumption it is not unusual to have fluctuation and variation of the incoming line voltage. The utilities are commonly allowed plus or minus 10% on a 480 V supply. The manufacturers of power supplies design the power supplies to be able to produce constant output power over some variation in line voltage. The common type of output regulation is constant power, constant voltage, or constant current. However, particularly if tuned and operating at full output power, not all power supplies will produce constant output over severe line voltage fluctuations. If the output power is not constant for a given heat cycle time, the part being heated will not heat to the same temperature. The use of coil signature monitors with process characterization will indicate whether a part is heating to the identical desired parameters during each cycle. Some purchasers of new equipment specify that the power supply must operate at a given percent, such as 50 or 75%, of the rated output to give a wider window of operating power control.
- The workpieces are not locating accurately from heat cycle to heat cycle. All workpieces heated on a setup must be located in the same position in the induction coil. While the lower frequencies are more forgiving of eccentric rotation, the locations for the heat on (and, if scanning, the heat off) must be the same. It is highly recommended

Table 13.5 Remedial actions for nonconformance of excessive distortion

Possible cause	Remedial action
Austenitizing more area than required	Heat less area
Austenitizing too hot	Austenitize at lower temperature
Case depth deeper than necessary	Reduce case depth
Part design	Change design such as machine weight holes or keyway
Method of locating or holding part	Improve locating method
Parts quenching too fast	Use slower quenchant (such as lower polymer % or oil)
Induction process being used	Change process (such as static to scan)
Coil design being used	Change coil design (add flux concentrators, etc.)

Source: Ref 1

that workpieces have machined surfaces with consistent, accurate dimensioning to the surface to be heated. The workpieces to be heated must be machined the same. On high-volume production, sensors should be present to make certain the workpieces are correctly seated on the holding mechanism. The sensors should also monitor that all mechanical operations have occurred in the correct sequence. Finally, all workpieces must be free from chips and burrs because these can interfere with proper seating.

- The timing cycle is not accurate enough. Modern power supply controls provide through their programmable logic controller's very accurate timers. However, some older power supplies use analog-type timers that are not very accurate for short heating cycles. The shorter the heat cycle, the higher the degree of timer setting that is necessary. For heat cycles of less than 0.5 s, the timer should have settings to 0.001 s. For heat cycles between 0.5 and 2 s, the timer setting should be to 0.01 s, and for heat cycles greater than 2 s, timer settings to 0.10 s are generally sufficient for most applications. Note that on high-power, single-shot applications, higher accuracy might be desirable. Good design would be to have the timer accuracy higher than is needed.
- The concentration material in the coil has deteriorated. Many of the specialized induction coils today use flux concentrators. While there are varying types of materials used, the common factor among the different materials is that degradation occurs. After a point, the degradation will cause the coil efficiency and flux concentration to change to the point that the parts being induction heated will no longer quench into specifications. The coils need to be examined, sometimes on an hourly basis, until some useful estimate of minimum coil life can be determined. Maintenance cycles can be established for the rebuilding of these coils.
- The coil is moving. Induction coils can vibrate and flex due to the electromagnetic fields established and due to the heating of the coil itself because of the high-frequency alternating current (ac) current. Rigid design is important; lower frequencies tend to produce higher degrees of vibration. Techniques to improve the coil rigidity range from the use of studs on multiturn coils to machined coils with better cooling passages. It is important to cool the coil so that heating does not occur. Booster pumps can be placed on the inlet side of the coil to increase the water flow through the coil.
- There are mixed heats of material. Whenever possible in production, it is desirable to keep parts made from different heats of steel in the same production lot. The heats should be identified and kept separate. When the steel is purchased in smaller than heat quantities, there may be no guarantee that mixed heats are not being purchased. When there are different heating results and mixed heats are suspected, sometimes the difference in the two heats can be seen by simply checking the core

hardness. Spectroscopic examination can be used for accurate chemical analysis.

- There is internal heating of components in the power supply or heat station. Restrictions or debris in the cooling lines of the internal components can cause overheating and change in the output of the power supply. Infrared sensors have been used, and any unusual oxidation or signs of overheating can indicate restrictions.
- There is oxidation in the electrical connections on the coil or output power transmission bus. Occasionally, heating a component that carries the high-frequency current from the power supply to the induction coil will cause a bolt to loosen, with the result that either the bolt starts to carry the current and overheat or the electrical connections themselves will oxidize. The electrical resistance is changed, and the output power to the induction coil will change. During maintenance, inspect for any signs of discoloration in the bus, the coil, or bolts.
- There is a short circuit in the output transformer. Radio frequency output transformers are very susceptible to failure due to internal arcing on the primary side. Usually the electrical short will be violent and sudden and will cause a power supply overload fault. However, there are times when the arcs start out as a small electrical leakage and are not obvious. Arcing may occur at the induction coil, and the power supply may have an overload trip with no visible reason. Sometimes the power supply will reset and operate for a period of time before faulting again. The lower-output voltage solid-state power supplies can also have output transformers short. This will normally produce an overload or trip.
- Consistent geometry and machining tolerances are important. The machined tolerances must be tight enough that the apparent load in the work coil to the power supply is the same. Also, the tolerances of the distance from location points must be tight enough that the heat treated area is not out of tolerance due to parts positioned at different locations while heating.
- Modern power supplies have limit circuits for protection. A limit circuit may limit the frequency of output but not cause a fault that trips the unit. It is not recommended that a power supply operate in a limit condition because, although the power supply may not be damaged, the output power might not be consistent.
- A change of rotation speed of a workpiece can affect the processing. In one case noticed by the author in the induction hardening of gray iron drill bits, changing the rotation speed during scanning actually changed the loading of the radio frequency induction heater. Also, the higher the frequency and the shorter the austenitizing cycle, the more important it is that rotation speed of the workpiece is consistent.

Table 13.6 shows a quick reference to the remediation of these problems.

Table 13.6 Remedial actions for nonconformances found of variance in quenched workpieces

Possible cause	Remedial action
Parts not positioned accurately or the same	Retune to operate power supply at lower line voltage Remove any burrs or hold part at better location Retool fixturing
Coil is damaged	Repair any coil arcs Repair any coil leaks Repair coil and improve rotation concentricity Improve coil water flow Replace coil
Timers not accurate enough	Replace with more accurate timer
Coil changes position during heating	Make coil more rigid
Different heats of steel	Keep heats of steel separate Increase austenitizing temperature if possible Inspect and separate heats; run separately
Internal components in power supply overheating	Check cooling lines for blocked water flow
Bus connections overheating	Check and remove any oxidation; check tightness
Electrical short in output transformer	Repair or replace transformer
Workpiece geometry is not the same	Sort parts
Power supply is operating in limit condition	Retune so that a limit does not occur
Rotation is changing speed or not concentric	Retool
Source: Ref 1	

REFERENCES

1. R.E. Haimbaugh, personal communication, 2001
2. G. Fett, A. Griebel, and J. Tartaglia, Defects and Abnormal Characteristics of Induction Hardened Components, *Induction Heating and Heat Treating*, Vol 4C, *ASM Handbook*, ASM International, 2014, p 228–240
3. Ajax Magnathermic, unpublished data, 2001

CHAPTER 14

Quality Control

EFFECTIVE SYSTEMS of quality control/quality assurance are essential for modern-day heat-treating practices. The essentials of an effective control program include:

- An independent quality assurance department
- Standards of quality that reflect customer needs
- Written procedures covering all phases of the heat treating process, starting with prototype qualification through inspection approval for shipment
- Process control documentation
- Methods of maintaining part identification through heat treating and keeping written inspection records
- Inspection procedures, including frequency sampling, and identification and segregation procedures for nonconforming products
- Written procedures to be followed when nonconforming product is found
- Schedules for calibration of test equipment
- Schedules and procedures for record retention
- Identification of training needed and implementation of training programs
- Systems for control of documentation, including review and distribution
- Periodic audits

Formalized Quality Control

Formalized programs, such as International Organization for Standardization (ISO) and Quality System (QS), containing all the elements in the preceding list plus more are now in place worldwide. These programs require that businesses be established and operated in a manner that satis-

fies specific requirements. Independent certified trainers and auditors have been established to help businesses operate according to the principles of the programs. The ISO certification requirements are based on the European and now worldwide standards. The QS programs, based on U.S. automotive standards, are more stringent than ISO. This Chapter deals with the essence of quality systems and presents methods for design of quality induction heat-treating systems.

Formalized quality control is required by many companies in industry, with the goal of developing fundamental quality systems that provide for continuous improvement. Defect prevention is emphasized, along with a reduction of variation and waste in the supply chain. Quality System 9000, ISO/TS 16949, or new versions of ISO 9000 define the fundamental QS-expectations. In addition, many companies have their own versions of requirements for formalized quality control, along with specific audit procedures. The three areas typically involving standards are:

- Fundamentals and vocabulary
- Requirements
- Guidance for performance improvement

The standards define the QS requirements and provide a detailed QS assessment format. Included are advanced production quality planning and control plans. Of particular interest to heat treating is the production part approval process (PPAP) that is required for induction-hardened parts. Instructional manuals with procedures and forms can be obtained from the Automotive Industry Action Group (see Ref 1).

Qualify system assessment is the first step in formalized certification and is used in several different ways according to the needs of the customer and supplier:

- First-party assessment is self-assessment of one's own quality system, with certain minimum requirements and questions to be answered.
- Second-party assessment is assessment by the supplier of its customer's quality system, with certain minimum requirements and questions to be answered. This includes tier 1 suppliers' assessment of all sub-contractors.
- Third-party assessment is an assessment by an independent auditor/registrar. The assessment method is composed of three major phases: Phase I is a review that determines whether the quality manual and supporting documentation, as required, meet all requirements. Phase II is an onsite audit to determine the degree and effectiveness of the implementation of the quality system at the supplier's site. Phase III is an analysis and a report to provide the findings of the first two phases.

Essentially at this point the auditor/customer will present the findings and decide whether the supplier is recommended/not recommended or has what is called a “variable score.” Major nonconformances may be noted, which represent an opinion that a total breakdown in the system will result in the failure of the quality system to assure controlled processes and products and that nonconforming products are likely to be shipped. Minor nonconformances are those that are not likely to result in the probable shipment of nonconforming product. The training of most auditors seems to be that improvement can always be implemented regardless of the merits of the system they are auditing.

The PPAP requires the production run for one shift or less of parts on the induction heat-treating system that are to be used for production. During this production run, considerable documentation and testing must be done. On shipment, a part submission warrant (Fig. 14.1) must be sent with the parts. According to the standards, submission of PPAPs is always required before the first production shipment of product.

The usual requirements for induction-hardened parts at the minimum are a completed copy of a warrant with completed workpieces, inspection results, process capability results, process control plan, gage study as applicable, and a failure mode and effects analysis (FMEA).

Control plans provide a written summary description of the systems used in minimizing process and product variation, and they are an integral part of an overall quality process. The required actions for each phase of the heat-treating process are described to ensure that all process outputs will be in a state of control. Because processes have the expectancy of continuous improvement, a control plan reflects a strategy that is responsive to changing process conditions. Controls plans are updated as measurement systems and control methods are evaluated and updated. Figure 14.2 illustrates an example of a control plan for a specific workpiece that was induction hardened. Current instructional manuals with current forms should be obtained before attempting to complete a control plan or an FMEA.

The FMEA is a systems failure mode and effects analysis. This is a disciplined analytical technique that assesses and assures, to the extent possible, that potential failure modes and their associated causes/mechanisms have been addressed. Through use of the systems, the degree of risk can be determined, along with plans of recommended action for reduction of these risks. Figure 14.3 illustrates an FMEA for a specific induction-hardened part.

The goal is to produce defect-free, induction-hardened parts. The intention is that preventive techniques be used to control the repetitive production processing, with written forms used to present a plan that shows that the process has been designed properly.

Part Submission Warrant

Part Name 1		Part Number 2	
Safety and/or Government Regulation ☐ Yes 3 ☐ No		Engineering Drawing Change Level 4 Dated _____	
Additional Engineering Changes 5		Dated _____	
Shown on Drawing No. 6		Purchase Order No. 7 Weight 8 kg	
Checking Aid No. 9		Engineering Change Level 10 Dated _____	
SUPPLIER MANUFACTURING INFORMATION		SUBMISSION INFORMATION 13	
Supplier Name 11 Supplier Code _____		☐ Dimensional ☐ Materials/Functional ☐ Appearance	
Street Address 12		Customer Name/Division 14	
City/State/Postal Code _____		Buyer/Buyer Code 15	
		Application 16	
REASON FOR SUBMISSION 17			
☐ Initial Submission		☐ Change to Optional Construction or Material	
☐ Engineering Change(s)		☐ Sub-Supplier or Material Source Change	
☐ Tooling: Transfer, Replacement, Refurbishment, or additional		☐ Change in Part Processing	
☐ Correction of Discrepancy		☐ Parts Produced at Additional Location	
☐ Other – please specify _____			
REQUESTED SUBMISSION LEVEL (Check one) 18			
☐ Level 1 – Warrant, Appearance Approval Report (for designated appearance items only).			
☐ Level 2 – Warrant, Parts, Drawings, Inspection Results, Laboratory and Functional Results, Appearance Approval Report			
☐ Level 3 – At Customer Location – Warrant, Parts, Drawings, Inspection Results, Laboratory and Functional Results, Appearance Approval Report, Process Capability Results, Capability Study, Process Control Plan, Gage Study, FMEA.			
☐ Level 4 – Per Level 3, but without parts.			
☐ Level 5 – At Supplier Location – Warrant, Parts, Drawings, Inspection Results, Laboratory and Functional Results, Appearance Approval Report, Process Capability Results, Capability Study, Process Control Plan, Gage Study, FMEA.			
SUBMISSION RESULTS 19			
The results for ☐ dimensional measurements ☐ material and functional tests ☐ appearance criteria ☐ statistical process package			
These results meet all drawing and specification requirements: ☐ Yes 20 ☐ NO (If "NO" – Explanation Required)			
DECLARATION			
I affirm that the samples represented by this warrant are representative of our parts and have been made to the applicable customer drawings and specifications and are made from specified materials on regular production tooling with no operations other than the regular production process. I have noted any deviations from this declaration below:			
EXPLANATION/COMMENTS: 21			
Print Name _____ Title _____ Phone No. _____			
Supplier Authorized Signature 22 _____ Date _____			
FOR CUSTOMER USE ONLY			
☐ Approved ☐ Rejected ☐ Other _____			
Part Disposition Customer Name _____ Customer Signature _____ Date _____			

Fig. 14.1 Part submission warrant. Source: Ref 1

Completion of the Warrant

PART INFORMATION

1. **Part Name** and 2. **Part Number**: Engineering released finished end item part name and number.
3. **Safety/Regulated Item**: "Yes" if so indicated on part drawing, otherwise "No."
4. **Engineering Change Level & Approval Date**: Show change level and date for submission.
5. **Additional Engineering Changes**: List all authorized engineering changes not yet incorporated on the drawing but which are incorporated in the part.
6. **Shown on Drawing Number**: The design record that specifies the part number being submitted.
7. **Purchase Order Number**: Enter this number as found on the purchase order.
8. **Part Weight**: Enter the actual weight in kilograms to three decimal places.
9. **Checking Aid No.** Enter the checking aid number, if one is used for dimensional inspection, and,
10. Its **Engineering Change Level** and **Approval Date**.

SUPPLIER MANUFACTURING INFORMATION

11. **Supplier Name & Supplier Code**: Show the code assigned to the *manufacturing location* on the purchase order.
12. **Supplier Manufacturing Address**: Show the complete address of the location *where the product was manufactured*.

SUBMISSION INFORMATION

13. **Submission type**: Check box(es) to indicate type of submission.
14. **Customer Name**: Show the corporate name and division or operations group.
15. **Buyer Name**: and **Buyer Code**: Enter the buyer's name and code.
16. **Application**: Enter the model year, vehicle name, or engine, transmission, etc.

REASON FOR SUBMISSION

17. Check the appropriate box. Add explanatory details in the "other" section.

REQUESTED SUBMISSION LEVEL

18. Identify the submission level requested by your customer.

SUBMISSION RESULTS

19. Check the appropriate boxes for dimensional, material tests, performance tests, appearance evaluation, and statistical data.
20. Check the appropriate box. If "no," enter explanation in "comments" below.

DECLARATION

21. **Comments**: Provide any explanatory details on the submission results; additional information may be attached as appropriate.
22. The responsible supplier official, after verifying that the results show conformance to all customer requirements and that all required documentation is available will sign the declaration and provide **Title** and **Phone Number**.

FOR CUSTOMER USE ONLY

Leave blank.

Fig. 14.1 (continued)

INDUCTION HEAT TREATING CORPORATION CONTROL PLAN										
Customer: <u>XXX Automotive</u>			Original FEMA Date:							
Part Number: <u>X000000X</u>			Revised IEMA Date:							
IHT Approval:			Revision No.:							
QC contact:			Production contact							
Process	Machine/device	Characteristics		Special char. class	Methods				Control method	Reaction plan
		Product	Process		Product spec. tolerance	Evaluation/measurement technique	Sample size	Frequency		
First Piece Inspection	Setup	Surface hardness	...		HRC 59.5/66.0	Microhardness tester	1	Each setup	Cut parallel slice, polish through 600 paper, check hardness on contact angle at 1.2 mm deep per sketch.	Correct process and repeat inspection
	Setup	Case depth			2.7/3/7 mm tester	Microhardness	1	Each setup	Cut parallel slice, polish through 600 paper, check hardness on contact angle per sketch	Correct process and repeat inspection
	Setup	Run in/run out Pattern	...		6.5/10.5 mm	Digital caliper	1	Each setup	Cut parallel slice, polish through 600 paper, macroetch with nital	Correct process and repeat inspection
	Setup	Microstructure	...		100% martensite	Microscope 400X	1	Each setup	Cut parallel slice, polish through alumina, etch with nital, check per sketch	Correct process and repeat inspection
Hardening	Machine	Surface hardness	...		HRC 59.5/66.0	Microhardness tester	1	Each hour	Cut parallel slice, polish through 600 paper, check hardness on contact angle at 1.2 mm deep per sketch.	Correct process and repeat inspection
	Machine	Case depth	...		2.7/3/7 mm	Microhardness tester	1	Each hour	Cut parallel slice, polish through 600 paper, check hardness on contact angle per sketch	Correct process and repeat inspection
	Machine	Run in/run out pattern	...		6.5/10.5 mm	Digital caliper	1	Each hour	Cut parallel slice, polish through 600 paper, macroetch with nital	Correct process and repeat inspection
Quench	Operator		Quench concentration		8%+/-2%	Refractometer	1	Start up and weekly	Measure concentration & record weekly	Rectify as needed results on inspection log
	Machine		Quench temperature		90 F + 5/ - 15 F	Controller	1	Every 4 h	Read & record on inspection log	Rectify as needed
Temper	Machine	Surface hardness	...		350F +/- 5 F	Microhardness tester	1	Every load	Place slice in separate container in with load	If hardness is high, segregate and call customer to authorize higher tempering temperature.

Fig. 14.2 Control plan. Source: Ref 2

INDUCTION HEAT TREATING CORP.											
Process FEMA											
Customer: XYZ Automotive		Power Supply: 260-1		Original FEMA Date:		Revised FEMA Date:		Revision No.:			
Part Number: Hub XX											
IHT Approval: _____											
Characteristic ID/Name	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Consequences	Potential Cause(s) of Failure	Occurrence	Current Process Controls	Detection	Recommended Action(s)	Responsibility & Target Completion Date	Action Results
Storage											
Oil free hubs	Quench contamination	Reduction of Pattern	2		Too much oil by CNC	2	Wash if necessary	1	4	None	
Load Fixture											
Hand Load Parts on Hub	Load Hub Wrong Way	Improper Case Pattern	6		Operator Error	1	Cause Control: Standard Operator Instruction	1	6	None	
Austenitizing											
Heat Hub to Austenitizing Temp.	Power too High Power too Low Time too Long Time too Short	Case too deep Shallow case, soft Hub Case too deep Case too shallow, soft Hub	6 6 6 6		Wrong Set up Coil Deterioration Wrong Set up Wrong Set up Coil Deterioration	1 1 1 1	Cause Control: Set up Instruction Cause Control: Standard Operator Instructions, Inspection Plans Cause Control: Set up Instruction, Inspection Plan Characteristic Control: PLC Controls, Part Position, Power Supply Regulation, Quench Control Cause Control: Set up Instruction, Inspection Plan Characteristic Control: PLC Controls, Part Position, Power Supply Regulation, Quench Control Cause Control: Standard Operator Instructions, Inspection Plans	1 1 1 1 1 1 1 1	6 6 6 6 6 6 6 6	None None None None None None None None	

Fig. 14.3 Process FEMA. Source: Ref 2

Characteristic ID/Name	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Scalability	Potential Cause(s) of Failure	Occurrence	Current Process Controls	Detection	Recommended Action(s)	Responsibility & Target Completion Date	Action Results Actions Taken	Severity	Occurrence	Detection	Prevention
Quenching															
Concentration of Polymer/Water Mix	Too Lean	Quench Cracks	7		Measuring Error	1	Cause Control: Set up Instructions, Inspection Plan	1	None						
	Too Rich	Shallow Case Depth	6		Measuring Error	1	Cause Control: Set up Instructions, Inspection Plan	1	None						
	Flow Too Low	Shallow case depth, Soft spots	6		Improper Set up	1	Cause Control: Set up Instructions, Inspection Plan	1	None						
	Time too Short	Shallow case depth, Low Hardness	6		Improper Set up	1	Cause Control: Set up Instructions, Inspection Plan	1	None						
	Temperature too High	Shallow case depth, Low Hardness			Improper Set up	1	Cause Control: Set up Instructions, Inspection Plan	1	None						
Tempering															
(batch in furnace)	Not Tempered	Surface too hard	1		Load not put in furnace	1	Cause Control: Instructions, Inspection	1	None						
	Wrong Temperature	Wrong hardness	1		Controller Set Wrong		Cause Control: Instructions, Inspection	1	None						
	Time too short	Surface too hard	1		Controller Set Wrong		Cause Control: Instructions, Inspection	1	None						

Fig. 14.3 (continued)

A Quality Induction Heat-Treating System

The elements of a quality induction heat treating system depend on the application and the system being used. Table 14.1 shows a model of the elements of a quality induction-hardening system that includes machine design, process controls, FMEA and so forth, preventive maintenance, and training. This type of checklist helps in considering all aspects of the potential purchase of an induction heat treating system. Existing systems can also be compared so that possible system improvement can be made.

Table 14.1 Model of quality induction hardening system

Machine design	Process controls	FMEA, DCP, inspection	Preventive maintenance	Training
Specifications may include:	Minimum controls suggested:	1. Complete FMEA 2. DCP, if required 3. Define all inspection responsibility including short- and long-term capability studies 4. Design inspection check sheet 5. Set up production control process sheets 6. Define any containment procedures, such as lock boxes for parts rejected by faults	1. Create malfunction check sheets 2. Verify check sheets are being used 3. Create preventive maintenance program 5. Quality standards 6. System checks	Who to set up what 1. Introduction to metallurgy 2. Process parameters 3. Quality standards 4. System checks Operators 1. Process parameters 2. Coil maintenance 3. Quality standards 4. System checks Maintenance 1. Process parameters 2. Coil maintenance 3. System checks 4. Troubleshooting
1. Define quality requirements 2. Select power supply 3. Define and select cooling water system 4. Define quench system requirements 5. Define heat station requirements 6. Define control system requirements 7. Specify system configuration 8. Specify any specific print and manual 9. Specify initial system startup needs and training 10. Warranty 11. Terms of purchase	1. Quench system a. Pressure b. Low flow c. Low and high temperature d. Filtering e. Quench quality 2. Cooling water system a. Low pressure and flow: power supply, heat station, coil b. High temperature c. Resistivity d. Filtering 3. Control system for quality 4. Induction coil a. Ground fault detector if possible b. Cooling water c. Pressure switch for low pressure if pressure boosting pump is used d. Workpiece position correct in coil 5. Fixture a. Rotation detection b. Means of lubrication c. Machine shutdown on fault and part rejection process d. NDT quality verification if possible Verification 1. Specified and documentation of trip conditions that cause a fault or trip 2. Documentation and follow-up on malfunction check sheets Frequency To be established after review of control plan			

NDT, nondestructive testing. Source: Ref 2

Table 14.2 Malfunction check sheet

Induction Hardener No. _____			Date: _____		
	Required setting	Actual setting	Fault indicator	Cycle stop	Remarks
1. Quench system					
a. Low-pressure fault at manifold					
b. Low quench flow					
c. Quench temperature low					
d. Quench temperature high					
e. Plugged quench holes on inspection					
f. Quench filter pressure low					
g. Quench concentration check					
h. Quench needs changing					
2. Cooling water system					
a. Low-pressure/flow power supply					
b. Low-pressure/flow heat station					
c. Low-pressure/flow coil					
d. High-temperature power supply					
e. High-temperature heat station					
f. High-temperature coil					
g. Water resistivity low					
h. System filter needs change					
3. Power supply energy output					
Solid state					
a. Record actual power output					
b. Record actual voltage output					
c. Record actual current output					
d. Record actual frequency					
e. Record any other system fault					
f. Record any system limit indication					
Radio frequency					
a. Record plate current					
b. Record plate voltage					
c. Record grid current					
d. Record RF overload fault					
All					
a. Record energy monitor fault					
b. Record rotation slow fault					
c. Record any part proximity fault					
d. Record low temperature IR fault					
e. Record any other system fault					
4. Induction coil					
a. Ground fault					
b. Coil overheating					
c. Coil bus, fishtails, quick-connect overheating					
d. Coil alignment off					
e. Defective coil (visual) or inspection					
f. Coil flux concentrator defective					
5. Mechanical malfunctions					
a. Any fault					
b. Any breakdown					
c. Other					
6. Metallurgical quality					
a. Surface hardness					
b. Case depth					
c. Pattern length					
d. Microstructure					
e. Other					
RF: radio frequency. Source: Ref 2					

Process control involves monitoring all important variables that can affect the processing quality. Table 14.2 provides an example of a malfunction check sheet that can be used to record the processing variables with their limits and settings. The fundamental concept of statistical process control is that process adjustment is made on an ongoing basis to keep the process in control. Quality induction hardened parts are produced through intention with thorough planning and documentation in all phases of production.

REFERENCES

1. Automotive Industry Action Group, unpublished data
2. R.E. Haimbaugh, Induction Heat Treating Corp., personal, 2001

CHAPTER 15

Maintenance

MAINTENANCE and preventive maintenance programs are important factors in keeping induction-heating systems in operation. When troubleshooting is required, trained personnel should be used because of the high voltages present inside the power supplies (particularly radio frequency power supplies). Most maintenance for induction heat-treating systems is centered on the cooling water systems, the high-frequency electrical output connections from the heat station, the induction coil, any mechanical fixturing, and the quench system, because the power supplies and heat stations have very few mechanical devices.

Maintenance requirements should be determined with a preventive maintenance program established according to the needs of the system. Table 14.1, presented in Chapter 14, "Quality Control," in this book, provides a model for maintenance requirements. Radio frequency power supplies, for instance, have hour meters so that oscillator tube life can be monitored for warranty purposes. The preventive maintenance schedule should list the items to be monitored and the frequency for monitoring. Critical items that require daily monitoring may need their own check sheets. Periodic items, such as those monitored monthly or semiannually, may need to have work orders generated so that the maintenance can be performed and verified. Individual manufacturers' maintenance programs should be the minimum level to which maintenance programs are followed. This Chapter presents recommendations for general maintenance.

Power Supplies and Heat Stations

Solid state and radio frequency power supplies need little periodic maintenance, assuming that they are in dust-tight enclosures. Experience has shown that a monthly visual inspection of the inside of the power supply is beneficial. The examination should include inspection for water leaks from hose connections and signs of discoloration on copper bus,

tube connections in oscillator sets, and any signs of oil leaks from capacitors. The studs and taps on any heat station component, such as capacitors or transformers, need to have special attention paid to overheating, plus cleaning if dirty or corroded. Care must be given to not overtorque.

Flow and pressure switches should be checked for proper operation on a semiannual basis. Separate heat stations should also be monitored. Every five years protective devices such as water flow, water pressure, and door interlocks should be checked to make certain they activate. Any deteriorated water cooling hoses should be replaced with nonconductive, low-carbon hose. Make certain that the hose lengths replaced duplicate those removed. Always follow the original equipment manufacturer's maintenance recommendations.

Maintenance and Replacement of Capacitors

Any sign of an oil leak is considered an immediate cause for replacement of a capacitor. Shorted capacitors must be removed. At times faulty capacitors can be difficult to diagnose when the shorts are intermittent, with the capacitor "healing" itself between heat cycles. If one side of a capacitor is not grounded, then the capacitor must be discharged before handling. An insulated wire should be used to avoid drawing the discharge from the threads of the capacitor terminals, which might result in damage to the threads. When removing and installing capacitors, care must be taken so that the studs are not overtorqued. Before disposal of any old capacitors, federal, state, and local regulations should be reviewed to see if there are any that are applicable. Any old capacitors need to be checked for polychlorinated biphenyl (PCB) notations.

Controls, Programmable Logic Controllers (PLCs), and Computers

- Back up all recipes as required; do this every time any changes are made to recipe programs.
- Replace any backup battery as required by the original equipment manufacturer's manual. Be sure to back up all data before changing the battery. Some batteries have one-year maintenance; others, five-year maintenance.
- At least yearly if a computer is being used, defrag the hard drive and empty the wastebasket/recycle bin.

High-Frequency Electrical Output

This is considered to be anything in the high-frequency electrical connections from the terminal of the output transformer in the heat station to

the induction coil. Coils have leads that are used to fasten onto either an output bus connection or the heat station transformer output. Because output bus and coil leads are exposed to the quenchant, there is a tendency for buildup of scale particles from the workpieces and subsequent arcing. Depending on the quenchant, periodic inspection and cleaning should be done. Gummy residue as left from polymer quenchants should be removed. All connections should be examined for signs of discoloration caused by overheating. When coils are changed, the electrical connections should be cleaned. Mild abrasives such as steel wool or Scotch-Brite (or equivalent) should be used to prevent stock removal. If there are any bolt replacements, the bolts must be made of the same nonferrous material as the bolts previously used, or if stainless, the stainless must be nonmagnetic. When fastening the output bus or coil into the transformer, to keep from stripping the holes the bolts must be carefully torqued according to the manufacturer's instructions.

Induction Coil

Many induction coils are low maintenance, particularly the coils that are used on lower power densities and those without magnetic flux concentrators. If any leaks develop, the coils should be removed from production, cleaned, and repaired.

Common coil problems are:

- *Arcing:* Arcing may occur due to the coil coming in contact with the workpiece or it could be the result of foreign debris. Anytime arcing occurs, production should be stopped and the condition remedied. If the workpiece is hitting the coil, the condition could be from vibration due to restriction of the coil to the cooling water, poor position of the workpiece relative to the coil, or eccentric rotation of the workpiece. An overheating coil needs either more cooling water or a better design. Arcing across the turns of the coil or bus support of the coil is usually due to scale or oil contamination in the quench system. Better cleaning of the coil or scale removal from the quench system should be done. Another condition is arcing across the flux concentrator as it degrades. The coil should be repaired or replaced.
- *Overheating:* Overheating can result in coil failure if insufficient cooling water is flowing through the coil. Water flow can be reduced by cooling system problems, or leaks can occur for any reason. Flux concentrators can also have insufficient cooling, resulting in overheating and premature failure. In-line pumps will increase the water flow. Also, changing the design of the coil cooling to increase the cooling passage or reduce sharp turns will help.
- *Fatigue:* Coils with high current concentrations can have flexure, particularly at soldered joints that have abrupt changes in direction of the

cooling water. This can ultimately cause the coil to fatigue and break. Also, some coils can have localized current concentrations, which can cause the coils to overheat and fail. Coils usually fail at a stress point, where there is an abrupt change in direction of the coil, such as a right angle with a brazed joint.

- *Deterioration of electrical contact:* The bolts holding the coil or bus to electrical contact may loosen causing the current to flow through the bolt. This results in overheating and melting of both, with subsequent loss of current to the coil.
- *Degradation of magnetic flux concentrator:* All concentrators degrade with time in service. Even in normal working conditions their capability to concentrate magnetic fields starts to degrade as soon as they are put into service. This is a natural phenomenon; the concentrator material degrades in time due to the intensity of the magnetic flux field and the heat from radiation. This includes degradation of magnetic particles, degradation of the binders used to hold the particles together, and rusting, arcing, spalling, and other problems. The controllers with kilowatt-second monitoring windows may not pick up degradation of coils that are deteriorated enough to cause a difference in the hardened pattern. This is because the kilowatt-seconds shown on the meter is the total of the delivered power required to heat the part and energy losses produced in the induction coil. It is possible for coil losses to increase due to degradation of the coil, which in turn reduces the power into the part. Because the kilowatt-seconds are the total of both sources, the meter may show no change. The inspection frequency of the heat-treated parts may need to be determined and set to find the point at which coil replacement is necessary.

After removal and repair of a coil, the coil should be tested for leaks and flow. Simple testing can be performed by placing a fitting to close one end of the coil and holding the coil in a tank of water with high air pressure applied at the opposite end. If possible, it is advisable to actually run water through the coil at the same pressure as applied to the coil at the induction heater and verify that the water flow is adequate. For critical coils, records should be maintained on the required water flow of each. Testing the water flow can determine whether the flow is adequate and whether any blockage occurred from the repair process.

Cooling Water Systems

Each manufacturer has recommendations for water system purity for their power supplies, generally with conductivity, dissolved minerals, solids, and pH specified. The purity of the cooling water systems must be maintained. If the cooling systems are closed systems, such as deionized systems with automatic control of the water resistivity, a neutral pH of 7

together with recommended biocide levels should be maintained. General operating specifications are discussed in Chapter 3, “Induction Heat Treating Systems,” in this book. A good control range for the water resistivity is 50 to 100 $\mu\text{S}/\text{cm}$, while some feel that a range of 50 to 400 $\mu\text{S}/\text{cm}$ is suitable. If there is not closed-loop control of water purity, the water should be periodically changed according to the instructions of the manufacturer, or every six months at a minimum. Filtering down to 25 μm is advised, and of course, cleaning and/or exchange of filters should be done on a logged basis. Table 15.1 provides troubleshooting for closed water systems with towers. Make certain that, if the system uses ethylene glycol to prevent freezing of the cooling water, automotive antifreeze is not used in any coolant that is circulated in the power supplies. Automotive antifreezes are conductive, and they can cause electrolysis in dc circuits.

Quench System

Quench rings, pads, and integral quench coil outlets are prone to clogging when either unfiltered or polymer-based quenchants are used. Some of the different types of polymer quenchants tend to build up with use, not only coating anything in contact with the quenchant but also tending to close and restrict the outlet holes. When a particular outlet hole clogs, the flow of quenchant will redistribute to the other outlet holes. The result can be incomplete quenching of the workpiece, although the total flow of quenchant is the same. The flow redistributes through the other holes, and flow switches may not indicate the clogged condition. Daily visual inspection is sometimes the only means of finding clogged holes, and inspection should be done with the quenchant flowing. If individual clogged holes cannot be cleaned, the quench ring may need to be removed for cleaning.

Maintenance requirements change according to the type of system and quenchant. Over time all quenching systems need to have the heat exchangers cleaned. Unless otherwise established, this should be done every

Table 15.1 Water system troubleshooting

Fault	Possible problem	Preventive maintenance (PM)
Line water is too hot	Outside temperature is too hot for tower Tower fan has failed	Be able to add city water if necessary
Power supply water too hot	Line water to heat exchanger is too hot	Monitor line water temperature.
	Heat exchanger is fouled	Clean heat exchanger on PM program
	Temperature controls not working	Repair. Have emergency bypass available
	Temperature control valve not working	Repair. Have emergency bypass available
Individual line overheating in power supply or heat station	Clogged water line	Clean. Check for proper filtering and resistivity
Low pressure out of filter	Clogged filter	Clean or replace
High return pressure (reduces flow through power supply)	Return water line clogged	Clean
	Return water line too small	Increase pipe size

Source: Ref 1

year. Oil quenches may have Y-type or screen filters that periodically need to be cleaned. In addition, a sample of the oil should be sent back to the supplier for testing at least once a year to make certain that there has been no deterioration. The five basic causes of contamination in water and polymer quench systems are:

- *Solids contamination*, comprising scale and metal particles that collect in the quench tank, should be removed on a continuous basis.
- *Tramp fluid buildup* can occur from extraneous sources such as machining fluids on the workpieces, hydraulic oil leaks from hydraulic lines in the fixturing, and excess grease/oil that was applied to conveyors, bushings, and other lubrication points. These contaminate the water-polymer quenchant and can change the cooling rate while the refractometer produces readings that make the concentration of water-polymer ratio appear in range. Viscosity is used as a control method to help determine accurate concentrations in these cases and is discussed later in this section.
- *Biological contamination* is likely in any polymer quenchant system. The contamination is most likely to be noticed after a period of inactivity, such as over a weekend. There will be an odor to the quenchant with possibly a “slime” covering the surface. Microbiological treatment can be effective but should be under the guidance of an expert.
- *Dissolved materials* occur in some regions of the country in the makeup water used to mix polymers. Some evaporation of water occurs during quenching, and over time the dissolved salt level increases. The nature and effect of dissolved salts will depend on the makeup water used. Over a period of time the buildup of dissolved salts can affect the cooling rate of the quenchant and, if not recognized, may not be identified by normal refractometer or viscosity tests. The faster cooling rate can produce undesired metallurgical effects for some steels and parts, such as quench cracks or distortion.
- *Breakdown of the polymers* can occur over time of use. The polymers differ in their stability and bonding, and they are subject to thermal/oxidation conditions that can lead to polymer degradation. The effect is that, although the concentration does not change, the quenching rate changes. This problem seems to be application sensitive, and many systems last indefinitely while other systems may suddenly start cracking the workpieces. The degradation cannot be determined by viscosity or through use of a refractometer. If quench cracking becomes a problem, recharge the quenchant to see if the cracking is eliminated. If so, the polymer quenchant should be periodically recharged. One simple way to do this is to determine either a time period or production rate of the number of parts needed to be run before recharging.

Heat Exchangers

Heat exchangers are typically used for cooling the water recirculated through the power supplies, heat stations, and quench tanks. If the cooling water used for heat exchange has much hardness, calcium deposits can form on the plates or tubes of the heat exchangers, which reduce the ability of the heat exchangers to extract heat. It is recommended that, depending upon the hardness of the water being used, the heat exchangers be cleaned. Plate-type heat exchangers are easier to clean than tube-type exchangers. One type of cleaner recommended is dehumidified cleaner.

Rust on Workpieces

Closed-loop, water-based and polymer quench systems need to have the rust inhibitors checked on a weekly basis.

Periodic Maintenance

All filters must be cleaned or changed. In addition, the concentration of the water:polymer ratio needs to be verified at least weekly through a refractometer and/or viscosity. Figure 15.1 illustrates the viscosity/concentration relationship, with the multiple curves reflecting the flexibility in

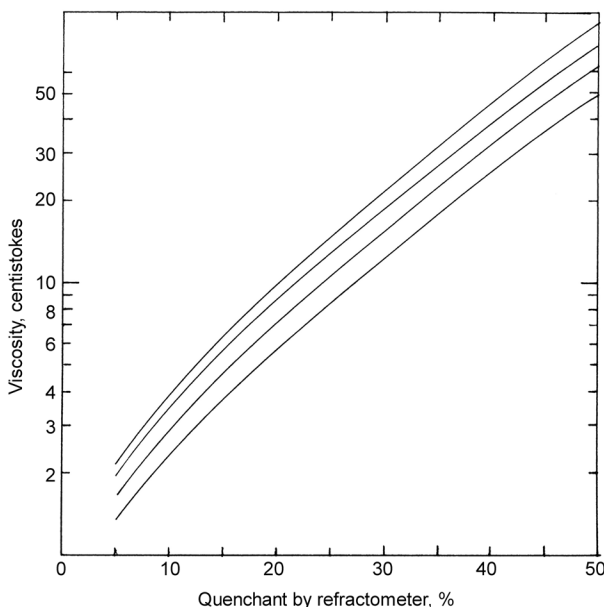


Fig. 15.1 Viscosity/concentration relationship for polyglycol quenchant.
Source: Ref 2

temperature at which the viscosity determination can be made. Because the viscosity of the quenchant solution is largely independent of other factors, such as solids contamination, a viscosity measurement provides a better reading of the effective polymer ratio. Use of viscosity as an online means of concentration verification continues to be developed.

Over-temperature alarms or shutdown controls installed on quench systems should be tested on a six-month basis to make certain that protective devices are operating. In addition, quality control methods should be established to ensure that there is no contamination of the quenchant. Oil quenches can be contaminated by water, with the bath itself appearing coffee colored rather than the dark, black, or bluish appearance of pure quench oil. Polymer-water quench systems that are contaminated by hydraulic fluid tend to have discolored quenchant, and in the morning before the system is started up the hydraulic fluid will be floating on the surface of the quench tank. Air can also be a contaminant in a water-based quenchant, giving it a foamy or milky appearance. Contaminated quenchants of any kind should be replaced with new quenchant.

Mechanical Systems or Fixturing

The mechanical systems or fixturing will have individual needs according to the particular system needs, including lubrication, adjustment, cleaning, and so forth. With the increased use of PLCs, relay operation is not a problem. However, the solenoids and other types of proximity switches and limit switches may need cleaning and maintenance. A backup of all recipes off all PLCs and computer systems is recommended. It is advisable to check the operating manuals to make certain that any batteries present for memory retention are replaced as recommended (they may have a one- to five-year life).

REFERENCES

1. R.E. Haimbaugh, Induction Heat Treating Corp., personal, 2001
2. R. Blackwood and E. Mueller, Installation and Control of Polymer Quenchants, *Heat Treat.*, Oct 1981

1

APPENDIX

Metallurgical Definitions for Induction Heat Treating

A

alternating current (ac). An electric current that reverses its direction many times every second. The current supplied by the utilities in the United States reverses 60 times per second, or 60 hertz (Hz). Power supplies used for induction heat treating change the 60 Hz line power to much higher frequencies, most commonly ranging from 3 kHz (3,000 Hz) to 450 kHz (450,000 Hz).

anneal. To soften.

austenite. The microstructural phase that is formed when steel is heated above the transformation temperature (approximately 760 to 1010 °C, or 1400 to 1850 °F, depending on the type of steel). When steel is held above the transformation temperature long enough, the transformation to austenite will be completed. It is necessary to induction austenitize steel before it can be quenched. The term *induction harden* really means to induction austenitize and quench so that the area that is heated is hardened.

B

bainite. A mixture of iron carbide plates in ferrite that forms when steel is not quenched fast enough. Bainite usually forms during cooling below the 565 to 275 °C (1050 to 530 °F) temperature range. Bainite is not a desirable product in induction-hardened parts that specify the microstructure be 100% martensite.

BHN. Brinell hardness number. See *Brinell*.

boiling stage. The second stage of cooling when quenching a part. (The first stage is the vapor stage.) The quenchant that is in contact with the part boils until the temperature of the surface of the part passes below the boiling temperature of the quenchant being used.

Brinell. A hardness tester that uses balls to make an impression. A measurement of the diameter of the indent is made. A table is used to convert the diameter of the indent in millimeters to the Brinell hardness number (BHN). The test is often used by heat treaters to measure the hardness of annealed and normalized steels as produced by conventional heat-treating furnaces. The Brinell numbers can be correlated to Rockwell numbers, with BHN numbers of 230/400 correlating to HRC 20/43.

C

capacitor. An electrical device that stores a charge of electricity. Capacitors with taps are used to change the frequency for tuning power supplies.

carbide. A compound of carbon and a metal such as iron. Carbon in steel is normally found as iron carbide. The objective in heat treating is to dissolve the carbides during austenitization. Because of this, it is recommended that the carbides be dispersed in the steel in small particle sizes.

carbon. Carbon is an element. This means that it cannot be broken down into any other form. It can exist in the three different microstructures: carbon, graphite, or diamond.

carbonitriding. A process in which heat-treating furnaces produce a thin layer of iron carbide and nitrides on the surface of a steel part. When quenched, the layer is very hard. The case depth may be 0.0762 to 0.3048 mm (0.003 to 0.012 in.). Nitrides make the parts resistant to induction tempering. Therefore, parts that have been carbonitrided may be difficult to induction temper or anneal below 50 HRC.

carbon restore. The process of restoring a decarburized surface to the core carbon content. This is a batch process and is done in an atmosphere heat-treating furnace with special atmosphere control.

carbon steel. Steel that contains up to 2% carbon with no other alloying elements.

carburizing. A process in which a heat-treating furnace is used to produce a layer of iron carbide on the surface of a steel part. When quenched the layer is very hard. The case depth may be from 0.127 to 2.54 mm (0.005 to 0.100 in.). Steel parts can be first carburized and then either quenched and tempered or slow cooled before being induction hardened.

cast iron. Iron that contains carbon content higher than 2%. The excess carbon will be found in the form of iron carbide or graphite. The types

of cast iron most likely to be processed with induction are gray cast iron, nodular cast iron, and modular cast iron.

cementite. See *iron carbide*.

Charpy impact test. An impact test in which a V-notched, keyhole-notched, or U-notched specimen, supported at both ends, is struck behind the notch by a striker mounted at the lower end of a bar that can swing as a pendulum.

cold-drawn bars. Most bars less than 38.1 mm (1.5 in.) in diameter are cold drawn. The bars are first hot rolled and wound into coils. Then the bars are straightened and are pulled through dies that reduce the diameter of the bar.

compound. A compound is formed when two or more elements combine. An example is iron carbide. A common example of another compound is the antacid calcium carbonate (such as Tums or Roloids), which is taken for stomach acid.

compression. The force that occurs when an object is pushed together from both sides. Some induction-hardened parts form compressive cases that actually add to the strength of the part.

conductor. An object that transfers heat or electricity. Heat flows through, or is conducted by, metal. Electricity flows through a copper wire conductor. A part being heated by induction is conducting electricity poorly (there are high heat losses due to the resistance to the flow of the high frequency electric current).

continuous cooling diagram. The diagram that shows the microstructures that are produced by different rates on continuous cooling for a type of steel.

convection. The transfer of heat by conduction in a fluid, such as air, water, or oil.

convection stage. The last stage of cooling when quenching, in which heat is transmitted from the surface of a part by convection through the quenchant. This is the slowest portion of quenching a part. This is also where most, if not all, of the transformation to martensite occurs.

core hardness. The hardness found near the center of a bar.

critical temperature range. The range in temperature at which austenite starts to form and completes forming.

cryogenic treatment. The cooling of steel parts in freezers ranging from -129 to -185 °C (-200 to -300 °F).

crystal (grain). Small units of atoms that are aligned alike. When viewed under the microscope the crystal looks the same. Crystal surfaces can be seen when parts are broken.

Curie temperature. The temperature 766 °C (1413 °F), at which steel becomes nonmagnetic. Radio frequency induction heaters will have the plate current drop. Solid-state induction heaters will have an automatic frequency shift to regulate for constant output.

current density. The amount of current in an area (amps/square inch). The higher the current density, the faster the rate of heating.

cutoff wheel burn. The localized tempering effect that can be produced by a cutoff wheel. This can be due to such factors as improper cooling, not positioning the part correctly, or using too hard of a cutoff wheel material for the hardness of the part being cut.

D

decarburization (decarb). A surface condition on steel parts for which the surface has lower carbon content. The carbon has burned out during the original making or subsequent heat treating of the steel. A heat-treated part with this condition will have lower hardness on the surface. This condition is normally fixed by either restoring the carbon in a furnace or machining off the lower-carbon surface.

ductility. The property of a metal that allows it to be permanently deformed before rupturing.

E

effective case depth. The depth of the hardened case is defined by a hardness value. HRC 50 is a commonly used value; however, other values, such as HR15N and microhardness scales, may be used. Because there is no agreed standard for induction-hardened case depths, many manufacturers define their own standard.

electromagnetic. The invisible energy field that surrounds an induction coil.

etch. Solutions of water or alcohol with a small amount of nitric or hydrochloric acid that attach to the surface of metal to show grain boundaries and compounds such as iron carbide (pearlite).

eutectic. The chemical composition of 0.8% carbon where austenite, on slow cooling, forms ferrite and carbide simultaneously. Note that this is the lowest temperature for transformation to austenite on heating. The transformation occurs at one temperature, and there is no transformation range.

F

ferrite. Ferrite is thought of as pure iron, and it is one of the two crystalline forms assumed by iron.

ferrite banding. Parallel bands of ferrite that run in the long direction of a bar of steel. The ferrite bands are between bands of pearlite.

flashpoint. The point at which an oil quench will catch fire and stay on fire. Below this temperature a flame caused by a part being quenched will self-extinguish.

flux field. Refers to the invisible lines of electromagnetic energy surrounding an induction coil.

frequency. Same as *hertz*. It is how many times an electric current reverses its direction in a second. Frequency was the term used in the United States before hertz was adopted. Older literature will refer to 60 cycles rather than 60 hertz or 450 kilocycles (Kc) rather than 450 kHz.

G

grains. Same as *crystal*. Metals are crystalline in nature. In order to see grains under a microscope, the parts are polished to eliminate scratches and then etched. Etching shows the grain boundaries.

grain size. The number of grains in a given area. Grain size numbers range from 1 to 15, with 1 being the largest grain size.

graphite. Graphite is one of the forms of carbon that is found in ductile cast irons. It is very soft. Cast irons with graphite will produce lower Rockwell test readings than the hardness of the iron itself because of the graphite's effect in lowering average hardness. Microhardness is used to measure the hardness of iron in the matrix.

grinding crack or burn. The pressure of a grinding wheel on a hardened part can produce intense heat at the point of contact. This heat not only can locally temper the part but also can produce small cracks. The cracks often form networks that look like chicken wire. Tempering parts above 121 °C (250 °F) before cutting or grinding reduces the tendency toward production of grinding cracks. Grinding or cutoff wheel burns can be detected by double-etching techniques.

H

hardenability. The term for how deep below the surface a part will harden. Hardenability is important for the selection of steels that are capable of quenching cases deep enough to meet specific case depth requirements.

hardenability bands. The minimum and maximum hardness that is expected from commercially available heats of steel from end-quench testing procedures. The end-quench test is commonly called the *Jominy hardenability test*. The hardness is measured starting from the end of the bar at 1.59 mm ($1/16$ in.) intervals. The distance of interest for induction hardening is the first 1.59 mm ($1/16$ in.) because it represents the range of surface hardness that can be expected. The other distance of interest is the depth at which HRC 50 can be produced because it represents the effective case depth that can be expected.

heat of steel. Refers to steel that is made in one batch. The chemistry and microstructure steel should be the same.

heat station. The name given to the enclosure placed between the induction heater (power supply) and the induction coil. The heat station con-

tains any necessary transformers and capacitors for load matching and tuning. Some power supplies have the heat station built in, and others require external heat stations. The induction coil is attached at the output side of the heat station.

hertz (Hz). Same as *frequency*. The line frequency furnished in the United States is 60 cycles, or 60 Hz.

high frequency. When discussing power supply frequencies, frequencies greater than 100 kHz.

homogeneous. Uniform. A homogeneous microstructure is desired in parts for induction hardening.

hot-rolled steel. Hot rolling first reduces all steel bars in cross-section size.

HRA, HRB, HR15N, and so forth. Rockwell hardness test scale indicating which particular test scale is to be used. See also *RA, RC, and so forth*.

I

induce. When one conductor of electricity causes an electric current to flow in another conductor. An induction coil induces current into the part being heated.

induction coil or inductor (work coil). Water-cooled copper windings that circulate the electric current for induction heating.

induction heater or power supply. The name given to the electrical box that changes the 60 Hz line frequency to higher frequency.

iron. Pure iron is one of the elements. See also *ferrite*.

iron carbide (cementite). A compound of iron and carbon that is very hard and brittle.

isothermal transformation diagram. Shows the microstructures produced by rapid quenching to specific temperatures and then holding at that temperature until transformation from austenite is complete. This diagram does not give much information for the purposes of induction quenching.

Izod impact test. A type of impact test in which a V-notched specimen, mounted vertically, is subjected to a sudden blow delivered by the weight at the end of a pendulum arm.

L

low frequency. Refers to frequencies between 1 kHz and 10 kHz.

M

macrostructure. The metal structure that is seen with no magnification. The part may be polished and etched. Sometimes flow lines from forg-

ing and some grain and phase structures can be seen without magnification.

Magnaflux. An inspection process that uses ultraviolet light to detect cracks in a part.

manganese. An element that is present in concentrations from 0.6 to 1.5% in steels that are normally induction hardened. This element helps steel to harden better.

martensite. The microstructure that is desired when quenching a part. The normal objective is to produce a fully martensitic microstructure if possible.

martensite transformation range. Depends upon the type of steel. During quenching, transformation to martensite generally starts at or below 265 °C (530 °F) and completes at room temperature or slightly below.

medium frequency. Frequencies between 10 kHz and 100 kHz.

melting. Caused when parts are overheated. After cooling the surface will appear to have flowed.

microhardness. A hardness indent is made with a microhardness testing machine and is measured at 400× magnification.

microstructure. The crystalline structure and phases that are seen on a polished and etched part when viewed by a microscope. Common magnifications used are from 100× to 1000×.

N

normalize. The process of heating a part over the critical temperature and cooling at a specified controlled rate.

O

oil quench. Special oils that are made to controlled chemistry and that have a high flashpoint (do not catch fire easily). There are several manufacturers, and the oils can be purchased to different quenching speeds.

output transformer. Common name used for the potted transformer to which the coil leads are attached on radio frequency induction heaters. Most medium-frequency and low-frequency induction heaters used for heat treating also use output transformers for voltage change and tuning.

P

pearlite. Produced when steel that has first been austenitized is then cooled slowly through 760/482 °C (1400/900 °F). The austenitic microstructure transforms in iron carbide platelets (cementite) in a matrix of iron (ferrite). Fine pearlitic microstructures are desirable for parts before

being induction hardened. Pearlite is not normally found in the martensite in induction-hardened areas.

phase. Grain or crystal with the chemical composition and atomic alignment the same. Metallic crystals are solid and do not have the transparency of such crystals as diamonds.

phase diagram. The iron-carbon phase diagram is the diagram used to define what phases are present in steel for all carbon concentrations at different temperatures.

pitting. Caused by overheating. As steels are heated in air greater than 760 °C (1400 °F), the scale on the surface becomes thicker. As the temperature of the heated part increases, scale formation increases to the point that the scale will start flaking. With temperatures greater than 980 °C (1800 °F), the scale can be thick enough that on a finished part there is deterioration of the surface finish. Small pits or holes are formed that can be seen after the parts are quenched.

polymer quench. Mixture a polymer (when concentrated it pours from its container like glue) put into water in a small percentage to reduce the quenching speed. The higher the concentration or temperature, the slower the quenching speed. With higher polymer concentrations there is more dragout, to the point that the surface of the part quenched will feel slimy. All polymer quench residue should be removed before further processing of a part.

power supply. See *induction heater*.

precipitate. When a substance that is dissolved in a liquid comes out of solution in the liquid. Polymer quenches have dissolved polymer. When parts are first quenched and in the vapor stage of quenching, a thin film of the polymer precipitates (forms) on the surface of the part. This film produces uniform, fast quenching. When the part cools so that the quenchant is in the boiling phase, the polymer redissolves into the quenchant.

Q

quench. To cool a part. Common quenchant are air, oil, water, and various polymers. There are three stages of quenching: vapor, boiling, and convection.

R

RA, RC, and so forth. Rockwell hardness test scale indicating which particular test scale is to be used. See also *HRA, HRB, HR15N, and so forth*.

resistance. Refers to how much a conductor resists the flow of an electric current. All metals are conductors. Copper has low resistance and is a

good conductor. Steel has much higher resistance and is a poor conductor.

resulfurized steel. Steels such as AISI 1141 and 1144 contain a high sulfur content purposely added during the making of the steel. Sulfur combines with manganese to create a soft compound that makes the steel more machinable.

retained austenite. Caused by overheating some steels such as AISI 52100 and some of the tool steels, when not all of the austenite turns into martensite during quenching. Retained austenite has a hardness of about 40 HRC and is not generally desirable in parts that are induction hardened. Retained austenite can be transformed to martensite through combinations of tempering and cryogenic treatment.

Rockwell. A hardness testing machine that indicates hardness by the depth to which a small diamond penetrator will penetrate with a given load.

S

scale. Black iron oxide formed on steel parts when heated in air. Above approximately 818 °C (1500 °F), scale starts to flake. When quenched the scale looks like a black, flaky material on the part.

scan. The power supply is continuously on, while parts are moved past the coil with continuous application of quench or the part is stationary while the coil moves.

seam. A shallow crack that is formed when steel bars are made. Seams will tend to be 0.05 to 7.62 mm (0.002 to 0.300 in.) depth. They run along the length of a bar. Seams may fade in and fade out. There may be more than one seam. Seams are considered material defects. Bar stock that has seams must have the seams machined or ground off. Seams can open up more during quenching and give the initial impression that the part has a quench crack.

secondary quench. Refers to a second quench that is applied at a fixed time after a part is taken out of the primary or first quench. In scanning operations a second quench ring may be used.

segregation. Nonuniform distribution of an element, phase, or impurity. Ferrite banding is an example of segregation.

single shot (static heat cycle). Refers to the act of heating the entire part on a timed basis. The induction coil may enclose the entire part or a section of the part. If possible the parts are usually rotated when enclosed and must be rotated or moved when partially enclosed.

spheroidal. Round, such as small round carbides (sometimes referred to as globular) that are desirable in the microstructure for AISI 52100 steel prior to induction hardening.

spotty hardness. Islands of low hardness, which can occur when quenching with water. Steam pockets can occur during quenching in small

spots. This causes the steel to cool more slowly in these regions, producing incomplete transformation to martensite.

stainless steel. Steel that has chromium added to increase resistance to rusting. The types of stainless steel are ferritic, austenitic, and martensitic. Martensitic stainless is the only stainless that is magnetic and is the series of stainless steels that are induction hardened (such as 416, 430, and 440 stainless steels).

static heat cycle. See *single shot*.

stress. A surface or internal force of compression or tension in a part. A part can be in tension at one place and in compression in another.

stress relieve. Heat in a draw furnace at temperatures between 121 to 593 °C (250 to 1100 °F) to reduce or homogenize internal stresses.

T

temper. Heat in a draw furnace at a temperature between 121 to 593 °C (250 to 1100 °F) to reduce the hardness of a quenched part.

tempered martensite. Martensite that is tempered from anywhere between 121 and 593 °C (250 and 1100 °F). The higher the tempering temperature, the softer and more ductile the part.

tension. The act of pulling apart. Parts crack when a tensile force exceeds the tensile strength of a part.

tool steel. Elements such as chromium, nickel, molybdenum, titanium, tungsten, and vanadium are added to the steel to make the steel harden better and to give special wear and strength properties.

torsion. The act of twisting a part.

total case depth. The case depth as defined by etching. Glass bead and nital etching are the two most common methods used.

transformation product. Usually refers to products other than martensite that are formed when a part is not quenched fast enough to produce a completely martensitic microstructure.

transformation range. The range of temperature within which austenite forms either on heating or on cooling. This range is different (higher) for heating than the range for cooling. On phase diagrams the starting point for transformation on heating is referred to as the Ar_1 point, and the point for completion is Ar_2 . On cooling the starting point is referred to as the Ac_1 point, and the point for completion is Ac_2 . Note that these points are defined by cooling very slowly and establishing the points at which the transformations occur.

transformation temperature. The temperature at which a phase change occurs, commonly referring to the temperature at which ferrite starts to transform to austenite. Note that at the eutectic point of 0.8% the transformation starts and completes. At other chemical compositions there is a transformation range.

transformer. An electrical device with input current and voltage that are changed into a different current and voltage. (If the voltage rises, the current decreases and visa versa.) Transformers with taps are used for tuning.

transition product. Undesirable products that form when parts are not quenched fast enough. Examples are pearlite and bainite.

V

vapor phase. The first phase of quenching a hot part. The quenchant next to the part forms a vapor.

Vickers. The type of microhardness indent that is diamond shaped.

W

work coil. See *induction coil*.

APPENDIX 2

Scan Hardening

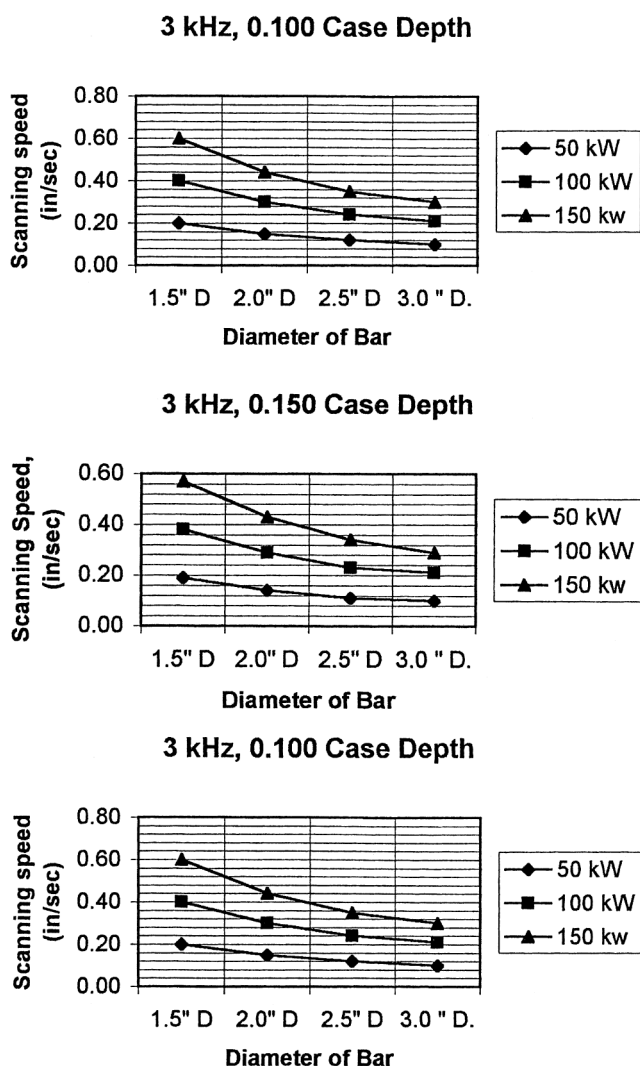


Fig. A2.1 Scan hardening for 3 kHz. Source: Ref 1

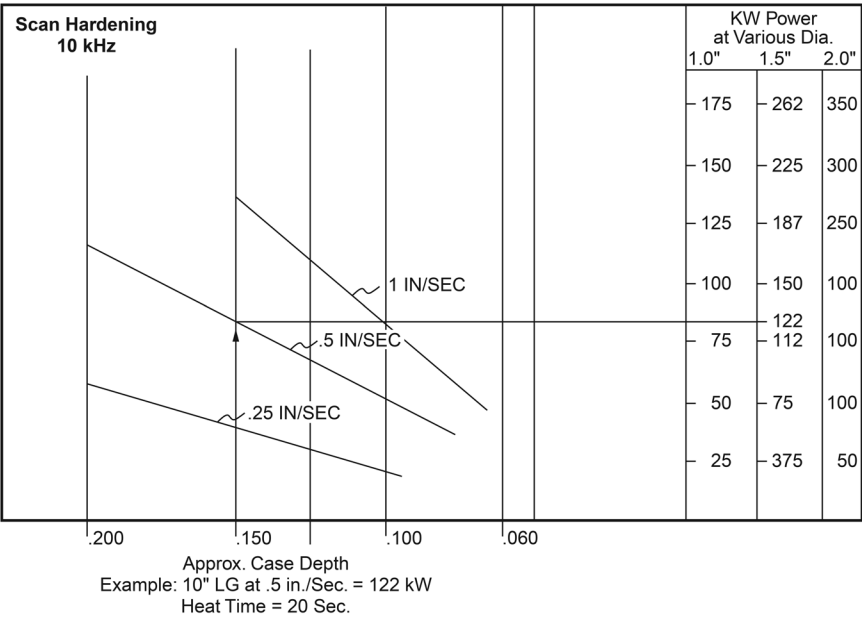


Fig. A2.2 Scan hardening for 10 kHz. Source: Ref 2

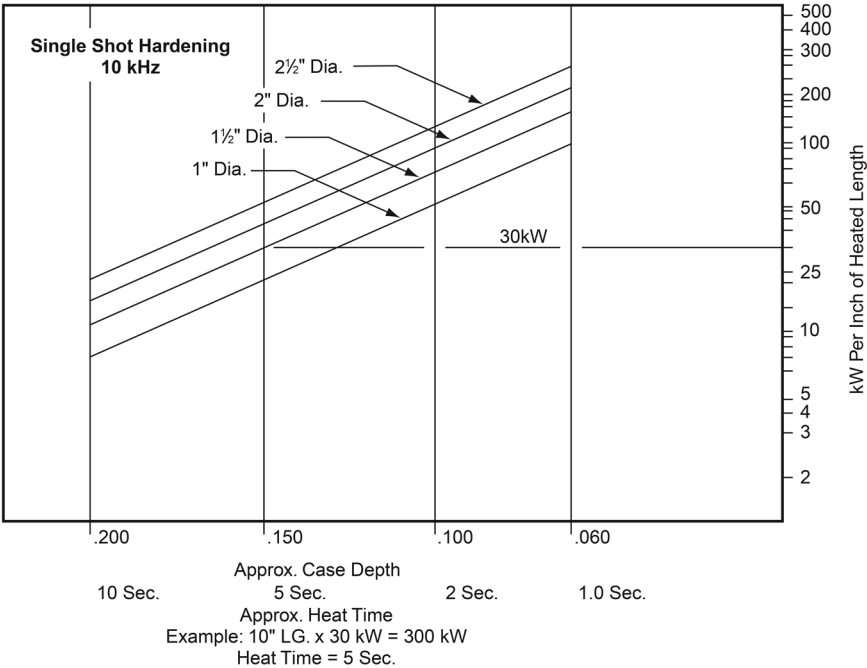


Fig. A2.3 Single-shot hardening for 10 kHz. Source: Ref 2

Table A2.1 Typical operating conditions for progressive through hardening of steel parts by induction

Section size		Work temperature										Inductor input(e)			
		Frequency(a), Hz		Power(b), kW	Total heating time, s	Scan time		Entering coil		Leaving coil			Production rate		
cm	in.	Material					s/cm	s/in.	°C	°F	°C	°F		kg/h	lb/h
Rounds															
1.27	½	4130	180	20	38	0.39	1	75	165	510	950	92	202	0.067	0.43
			9600	21	17	0.39	1	510	950	925	1700	92	202	0.122	0.79
1.91	¾	1035 mod	180	28.5	68.4	0.71	1.8	75	165	620	1150	113	250	0.062	0.40
			9600	20.6	28.8	0.71	1.8	620	1150	955	1750	113	250	0.085	0.55
2.54	1	1041	180	33	98.8	1.02	2.6	70	160	620	1150	141	311	0.054	0.35
			9600	19.5	44.2	1.02	2.6	620	1150	955	1750	141	311	0.057	0.37
2.86	1⅞	1041	180	36	114	1.18	3.0	75	165	620	1150	153	338	0.053	0.34
			9600	19.1	51	1.18	3.0	620	1150	955	1750	153	338	0.050	0.32
4.92	1⅝	14B35H	180	35	260	2.76	7.0	75	165	635	1175	195	429	0.029	0.19
			9600	32	119	2.76	7.0	635	1175	955	1750	195	429	0.048	0.31
Flats															
1.59	⅝	1038	3000	300	11.3	0.59	1.5	20	70	870	1600	1449	3194	0.361	2.33
1.91	¾	1038	3000	332	15	0.79	2.0	20	70	870	1600	1576	3474	0.319	2.06
2.22	⅞	1043	3000	336	28.5	1.50	3.8	20	70	870	1600	1609	3548	0.206	1.33
2.54	1	1036	3000	304	26.3	1.38	3.5	20	70	870	1600	1595	3517	0.225	1.45
2.86	1⅞	1036	3000	344	36.0	1.89	4.8	20	70	870	1600	1678	3701	0.208	1.34
Irregular shapes															
1.75 to 3.33	⅜ to 1⅝	1037 mod	3000	580	254	0.94	2.4	20	70	885	1625	2211	4875	0.040	0.26

(a) Note use of dual frequencies for round sections. (b) Power transmitted by the inductor at the operating frequency indicated. This power is approximately 25% less than the power input to the machine, because of losses within the machine. (c) At the operating frequency of the inductor. Source: Ref 3

(a) Note use of dual frequencies for round sections. (b) Power transmitted by the inductor at the operating frequency indicated. This power is approximately 25% less than the power input to the machine, because of losses within the machine. (c) At the operating frequency of the inductor. Source: Ref 3

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APPENDIX 3

Induction Coil Design and Fabrication

EXAMPLES of the types of induction coils that are typically used are given in Chapter 4, “Induction Coils,” in this book. While some of the simple coils are easy to make and use, other coils such as machined coils need to have development programs with testing before the final coil design is produced. This appendix discusses materials used in coil building, coil design, and coil construction techniques. The electromagnetic flux fields and their influence on coil design are presented. In addition, magnetic flux concentrators and their uses with induction coils and computer-aided design for induction coils are also covered.

Induction Coils

Coil Construction. The construction of coils requires skill and expertise. Whether the coils are made from tubing, machined components, or a combination of both, silver solder is most commonly used to fasten the copper sections together. While there is some use of soft solder, it is not as good structurally and electrically because components are glued together. A heating source that is good to use for soldering is an oxygen-acetylene torch with proper head size.

Copper will work harden when bent or formed. Too much work hardening can cause collapse of tubing. If the copper gets hard to work, it can be annealed by heating it red hot with a torch and then water quenching. Remember that copper is “hot short” and will break if bent or stretched when red hot. When machining copper blanks, proper techniques must be used because copper can be “gummy.”

Before silver soldering, the copper surface needs to be clean and free of contamination. Silver solder flux is used to prevent oxidation during the

soldering process. Adjoining parts should be brought to soldering temperature at the same time, and excessive silver solder should not be used. If the inside-diameter (ID) cooling passages are small, care needs to be taken that the silver does not close or clog the cooling passages. Small globules of flux will remain in the body of the silver joint after soldering. Any surface flux is hard to mechanically remove after cooling. Soaking and flushing the area with hot water (as close to boiling as possible) will remove the flux. After the flux is removed, the coils should be checked for leaks. Finally, light glass bead cleaning will remove any oxides from surface of the coil and will leave the surface with a bright finish.

Coil Materials. Coils are made from copper because of its low resistance to the flow of the high-frequency current and its relatively low price. Coils made from tubing and many of the low- and medium-power coils are made from commercial copper, while oxygen-free high-conductivity (OFHC) copper is favored for the high-power, machined coils. When high power is sent through these coils, it is important that coil losses are minimized. All induction coils usually require water cooling to absorb the power losses and to prevent overheating of the coils.

One of the design limitations of coils is the inability of the water passages to carry enough water for proper cooling. Tube ID limits minimum copper tubing size that can be used. Tubing is made as small as 2.6 mm (³/₃₂ in.) in diameter, while the maximum size is limited more by the ability to shape and form the tubing rather than by size. Tubing sizes commonly used are shown in Table A3.1, with other sizes available. Tubing should be purchased in the annealed state if possible.

Materials for Coil Support and Fixtures. The materials used around coils should be either nonconductive or nonferrous. Small brass screws, with their heads removed, can be brazed onto the copper turns, with the threaded ends inserted into fiberglass supports secured with nuts. Aluminum channels are easy to use for support guides. Trays and wheels for holding workpieces often use transite, a nonasbestos insulating material. While steel is used for holding nests if sufficiently far from the flux field, brass and nonmagnetic stainless steel are often used when the flux fields heat the nests. Some setups even provide a quench outlet for fixture or nest

Table A3.1 Copper tubing commonly used for induction coils

Tubing type			
Round		Square/rectangular	
mm	in.	mm	in.
3.125	¹ / ₈	3.125 × 3.125	¹ / ₈ × ¹ / ₈
4.688	³ / ₁₆	4.688 × 4.688	³ / ₁₆ × ³ / ₁₆
6.250	¹ / ₄	6.250 × 6.250	¹ / ₄ × ¹ / ₄
9.375	³ / ₈	6.250 × 12.50	¹ / ₄ × ¹ / ₂
9.375		12.50 × 25.00	¹ / ₂ × 1
9.375		12.50 × 37.50	¹ / ₂ × 1 ¹ / ₂

Source: Ref 1

cooling during the heat cycle. Table A3.2 shows several of the materials that have been used over the years.

Water Flow in Coils. Coils with inadequate water flow will melt or will have soldered or brazed joints fail. Care must be taken in the fabrication of the coils to minimize restrictions. As with all piping used to carry water, the water passages should be clean, free of burrs, and able to avoid reduction in cross section, such as at brazed joints. The cooling water, if free of dissolved solids, can have the temperature rise to over 80 °C (175 °F). Therefore, compared to the cooling water requirements of the power supply, which may permit only an 80 °C (20 °F) temperature rise, the amount of water in gallons per minute is reduced.

The amount of cooling water needed for a coil is linear to the temperature rise and can be calculated as $kW = gpm \times \Delta^{\circ}F \times 500 \times 3414$. If the coil loss is 50% of a 100 kW system and a temperature rise of 45 °C (85 °F) is permitted, the coil water flow required is approximately 4 gpm. When the coil cooling water, even if aided by a booster pump, cannot provide this flow, the coil will overheat and fail. Steam pockets, which occur when water is heated to the melting point, produce coil overheating and eventually a melting failure.

Figure A3.1 shows water flow versus tubing ID. Tube cross-sectional area, length, and restrictions such as right-angle turns affect the amount of flow through a given coil. One technique that is used to increase the water

Table A3.2 Structural materials for induction heating fixtures

Material	Characteristics and comments
Nonmetals	
Diamonite(a)	Aluminum oxide; very hard, dimensionally stable; standard and special shapes; resists high temperatures
Epoxy Fibre Glass FF91(b)	Coil-mounting supports; good electrically; also useful for soft soldering to about 230 °C (450 °F)
Transite II(c)	Worktable tops; heat resistant; avoid for coil supports (electrically poor)
Mycalex, Supramica(d)	Various grades; useful for high-temperature coil supports; special shapes available
Silicone rubber (RTV)(e)	Molds accurately; flexible; useful for soft soldering to 315 °C (600 °F)
Fired Lava(f)	Easily machinable before firing; good heat resistance; less strength than Diamonite
Nonmagnetic metals(g)	
Aluminum alloys	Fixture base plates, worktables; useful for soft soldering (does not bond)
Brass (free machining)	Supporting screws, locators adjacent to coils, sinks, etc.; corrosion-resistant pins; quench and recirculating tanks
Titanium	Useful for positioning of parts to be silver brazed; does not stick
Nichrome	Excellent high-temperature strength; oxidation resistant; used for locating and holding of parts
Inconel alloys	Useful for locating parts, radiant (susceptor) heating of thin materials
Magnetic metals(g)	
Low-carbon steel	Structural members; cabinets; worktables
Alloy steel (hardenable)	Moving parts of fixtures subject to wear
Stainless steel (hardenable)	Moving parts of fixtures subject to wear and corrosion

(a) Diamonite Products Div., U.S. Ceramic Tile Co. (b) Formica Div., American Cyanamid Co. (c) John-Manville Co. (d) Mycalex Corp. of America. (e) Dow-Corning Co. (f) American Lava Corp. (g) Materials listed are available from a number of manufacturers. Source: Ref 2

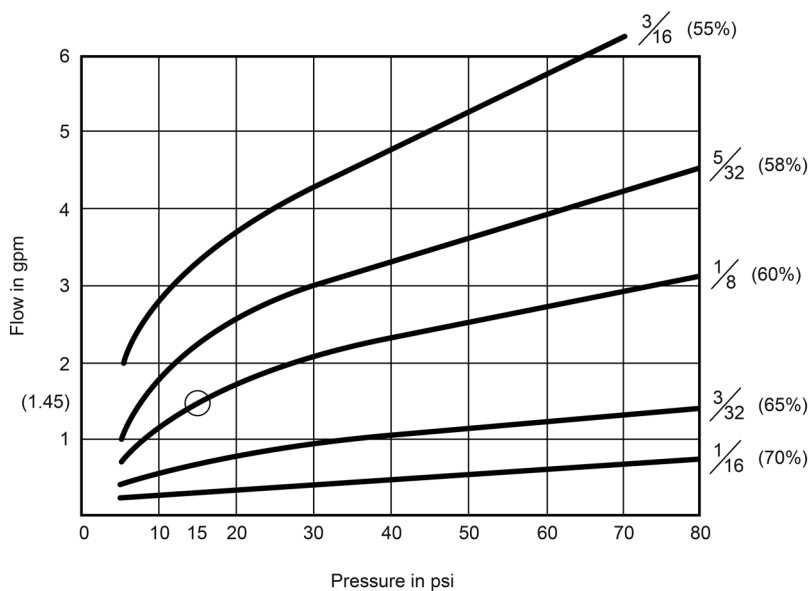


Fig. A3.1 Water flow through tubing. Source: Ref 3

flow to higher than that provided by round tubing is to use rectangular or square tubing. Rectangular tubing is more difficult to wind around small diameters without collapsing and to wind multiturn coils with the turns characterized for either different-diameter spacing or offset between the turns. Techniques such as pouring sand or even a low-melting-point eutectic alloy in the coils have been used to help prevent collapse. (The eutectic has a melting point below 100 °C, or 212 °F, and can be blown out when submerged in boiling water.)

Coil Wall Thickness Adjacent to the Workpiece. The current in a coil is concentrated mainly on the face of the coil that is adjacent to the workpiece. Therefore, the amount of copper in this part of the coil will dictate how much the copper heats due to the resistance of the high-frequency current. Reference depth and the depth of heating are discussed in Chapter 2, “Theory of Heating by Induction,” in this Volume. Because the reference depth increases as frequency decreases, the most efficient ideal coil will have wall thickness as shown in Table A3.3.

All of this having been said about tubing cross section, much of the time the coil design prevents the uses of a wall thickness that is less than ideal. Thinner wall thickness is sometimes needed on high-power-density coils because the copper itself cannot conduct heat fast enough to the cooling water to prevent overheating. When this occurs, the wall thickness must be reduced.

Coil Efficiency Design. The coupling or air gap between the coil and the workpiece has a large overall effect on coil efficiency. With higher

Table A3.3 Copper coil wall thickness selection for frequency

Frequency	Minimum wall thickness	
	mm	in.
450 kHz	0.8 to 1.0	0.032 to 0.040
10 to 50 kHz	1.0 to 2.1	0.048 to 0.090
3 kHz to 10 kHz	3.0 to 4.0	0.125 to 0.156

Source: Ref 1

frequencies, the gap is more important because the coil's magnetic flux field is coupled more tightly to the coil. Therefore, the closer any coil is coupled to the workpiece, the higher the coil efficiency. Thus, while tight gaps are important, in practice the process itself determines the coupling as a result of the spacing needed to keep the workpiece from hitting the coil. Coupling distances can vary from as close as 0.75 mm (0.030 in.) to 25 mm (1 in.). Loose coupling during austenitizing is used only when necessary for the process. An example is a workpiece that is scanned and has two different diameters to be heated. The coil is coupled as tightly as possible to the largest diameter. The coupling then increases when scanned onto the smaller diameter. Another requirement for using larger coil coupling is the warping of scanned parts during heating and the subsequent need for larger coil coupling to keep the coil from arcing to the part. Finally, when the workpiece being heated has areas such as fillets that need to be hardened, the coil coupling may be changed to promote uniform heating of the shaft diameter and the fillet area. Typically the coupling needs to be close to the fillet and adjacent shoulder.

Coil Design. The statement used to be made that coil design is 50% theory and 50% practice. Experienced fabricators of induction coils can make most of the common coils without any difficulty. If a new application is involved, design of the induction coil starts with the analysis of the workpiece and production requirements, as discussed in Chapter 11, "Induction Heat Treating Process Analysis," in this Volume, with a suitable frequency and output power selected.

After frequency selection and power, quenching and fixturing are built around the coil design. Sometimes more than one coil design can produce the desired result. An example of this occurs when an encircling coil is used to scan a part or where a longitudinal, single-shot coil is used to statically heat the same workpiece. When high production rates are needed, the choice may be multiple heating positions or the single-shot heating. Single-shot heating has limits in not being able to heat long parts because the energy requirements are too high. Long parts, such as axle shafts, are scanned. As mentioned, mechanical handling equipment can require a larger air gap that can influence frequency and even power choices. The high frequencies, such as 450 kHz, are most efficient with tight coupling to the coil. The lower frequencies are more tolerant to

wider coupling to the coils. Table A3.4 shows recommended coil coupling for efficiency.

When heating the ID of parts, unless a hairpin coil is used (which can be very inefficient), the return leg of the coil goes down the center of the coil. Thus, the minimum part ID is restricted to three times the diameter of the tubing plus two times the gap between the return leg and the surrounding outside turns. If 1/8 in. tubing is used with a 1/32 in. coupling between the return leg of the coil and the coil coupling to the part is 1/32 in., the minimum ID of the part would be 1/2 in. Since 1/32 in. is very tight coupling, 5/8 in. and larger are normally considered better IDs to try to harden. ID coils need more cooling water than a normal helical coil because the return lead is being heated inductively. Also, there can be some shrinking of the heated part's ID because of shrinking due to thermal expansion.

Figure A3.2 shows the design of two different types of contact used to fasten coils or bus extensions to the power supply. Figure A3.2(a) shows what is called the fishtail type. It is machined and designed so that the bolts holding the leads to the power supply are offset and do not carry current. The current transfer occurs through the flat machined surfaces on each side of the bolt slots. Figure A3.2(b) shows a flat plate that is designed to fit onto a quick connector. The current flows through the flat plates, and the cooling water is introduced through the holes with O-rings in the center of the block. The opposite end of the plates shown could have fishtails for connection to the bus or the power outlet of the power supply. The flat plates connecting to the work coil are clamped onto the face of the plates seen (Ref 4).

Coil Turns. The relationship of coil type and coil efficiency is important. For instance, where optimal efficiency is desired, a two-turn helical coil is preferred over a single-turn helical coil. Multiturn coils are even more efficient, and helical coils are more efficient than hairpin or channel coils. Finally, internal coils tend to be the most inefficient, particularly on small bores. This makes bores less than 12.5 mm (0.5 in.) hard to heat by radio frequency (RF), and bores less than 25 mm (1 in.) hard to heat with 10 kHz.

Multiturn coils are the most efficient. The number of turns on a coil is dictated by the ability of the heat station to either match the coil voltage directly or to have an output transformer that will match the turns. The

**Table A3.4 Coil coupling to workpiece
versus frequency**

Frequency	Coil coupling to workpiece	
	mm	in.
50 to 450 kHz	1.5 to 2.0	0.060 to 0.080
3 to 50 kHz	2.0 to 3.0	0.080 to 0.120
1 kHz to 3 kHz	3.0 to 6.0	0.120 to 0.230

Source: Ref 1

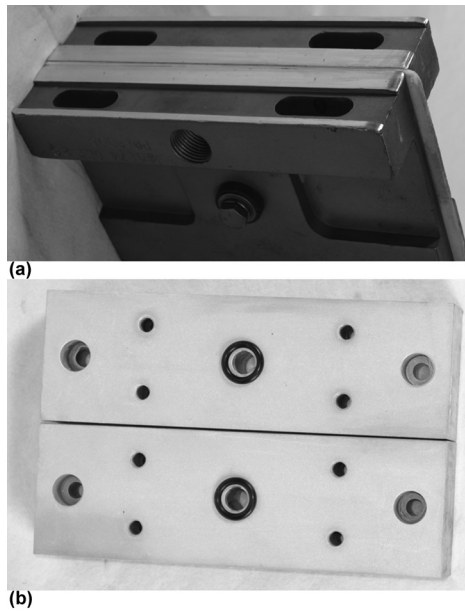


Fig. A3.2 (a) Fishtail-type and (b) flat plate machined coil contact types.
Ref 4

higher voltages and low current of RF permits more frequent use of multiturn coils. In the same respect, 3 through 25 kHz coils are more likely to be low-turn, heavier-current carrying coils. Single-turn coils can be machined to make them more rigid. Machined coils also have the ability to use integral quenches, and this can make them useful in some systems.

Radio frequency single-turn encircling coils have an electromagnetic dead spot at the rear of the coil where the coil leads attach to the coil. Workpieces must be rotated to provide uniform heating because of this dead spot. As the frequency of the power supply lowers, this dead spot becomes less pronounced. At 10 kHz, encircling-type coils built to the contour of the cam will heat the cam without a dead spot.

Different workpiece shapes also dictate frequency selection. For instance, rounded-square-shaped power transmission shafts will uniformly heat with a helical encircling coil on 10 kHz, while the same coil design will heat only the corners on 450 kHz. At 10 kHz, the coil can be a helical coil with the shaft rotating, rather than contoured to a square shape.

Tube or Machining. The first basic decision in material selection for a coil is whether to use tubing or to machine the coil. Tubing is generally much more economical to use, and it is often used for higher-frequency and multiturn coils. Round, square, and rectangular tubing is used. Copper tubing is wound and is contoured to the desired shape. When winding, any time work hardening becomes excessive the tubing must be annealed by heating it red hot and quenching in water. Copper is “hot short,” so it will

break when winding red hot unless special forming techniques are used. Where coil efficiency is important, square and rectangular tubing is more efficient. However, they are more difficult to form without collapsing. Copper tubing is silver brazed to the coil leads. If the leads cannot provide sufficient coil rigidity, brass studs can be brazed onto the coil turns and fastened into insulated blocks.

Liners can be brazed into copper tubing when heating the workpiece. These liners serve to make the coil act as if it were a square or rectangular coil. The liners also absorb mild arcs, preventing water leaks that would have originated from a tubing coil. An example is a 1.5 by 122.5 mm ($1/16$ by 0.5 in.) copper insert that is brazed into the 75 mm (3 in.) ID of a 6.25 mm (0.25 in.) round copper encircling coil. The coil induces current into the workpiece as if the coil was 12.7 mm (0.5 in.) wide.

Machined coils make use of copper bus bar or plate that has cooling passages drilled or milled. The machined cooling passages then have precisely made copper inserts brazed over the passages. Machined coils can use both machined sections and tube sections brazed together.

Connection to Leads. All coils need to have leads that connect to the output power section of the heat stations. Where the distance to the coil is small, the coil either bolts directly onto the terminal output of the heat station or slides into a quick-connect mechanism that is already attached. When the distance is extended, bus transmission leads are generally needed. All fasteners used must be nonmagnetic. Brass, silicon bronze, and, where higher strength is necessary, nonmagnetic stainless steel bolts are used for the connection of the coil or bus leads. Hose clamps, if used, need nonmagnetic screws. There are a number of different types of bolt and hole configurations, depending upon the power supply and manufacturer. Before ordering any coil, the design is being used must be known.

The coils as connected to the output transformer or its extension must have good contact for passing the current and the connection must not overheat. When coils are replaced for maintenance or replacement, it is desirable that the coils are the same to avoid adjustment of the fixturing.

Bus and Lead Design. The design of the coil leads and extension bus is important for most power supplies in order to deliver full power to the coil, except for some power supplies that need additional resistance in the coil circuit in order to make full power. As the output power and distance increase, the bus leads are made wider with a narrow gap in between. Many bus leads have a 1.5 mm (0.060 in.) air gap with a Teflon insert between the leads. Illustrations of some bus extensions are shown in Chapter 4, "Induction Coils," in this Volume under the discussion of "Bus Bars for Power Transmission."

Coil Characterization. When designing a coil, it is important to visualize the distribution of the eddy currents that cause the workpiece to heat. The objective is to induce current in the area required to be heated. The specifications of the workpiece will show the desired heat-treated pattern. In effect, the coil needs to be designed to produce the high heat in the pat-

tern area. Single-turn coils produce eddy-current distribution dependent on the coupling to the workpiece. Figure A3.3 shows the temperature profile resulting from the electromagnetic flux in a simple, single-turn coil. Current concentrations are less intense at the ends and provide taper in the profile. The right-hand figure shows the profile from a conditioned coil that was machined to produce offset in the center of the coil. By changing the coil coupling, the temperature profile is less intense in the center and more intense on the edge, producing a more uniform and wider profile. Another way to characterize a coil is to add turns. Figure A3.4 illustrates four examples of coil characterization on a multiturn coil. Figure A3.4(a) shows the uneven heating produced in the original coil. Figure A3.4(b) spreads the middle turns, decreasing the coil efficiency in the center. Figure A3.4(c) changes the coil coupling by making the center turns tighter and the outside turns looser, and Figure A3.4(d) simply makes the coil longer by adding a turn. The other type of coil modification is to add a flux concentrator to the coil. This is discussed later in this Chapter.

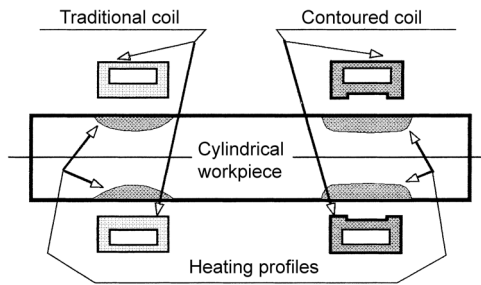


Fig. A3.3 Induction heat treatment: temperature profiles with traditional and contoured single-turn induction coils. Source: Ref 5

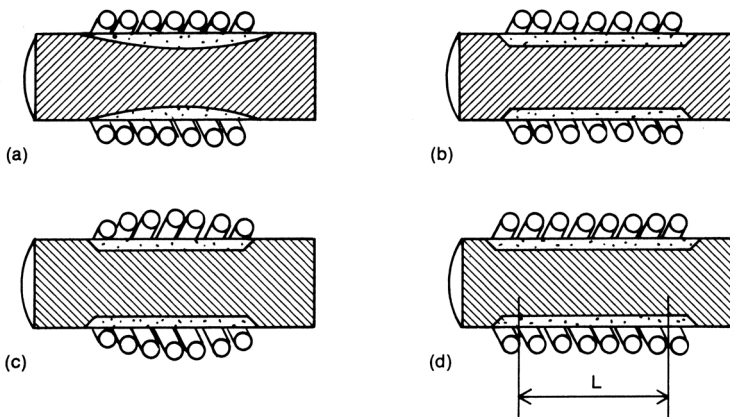


Fig. A3.4 Characterization of multiturn coils: (a) uneven heating pattern in a round bar obtained by a coil with an even pitch, a problem that can be corrected by (b) increasing the pitch of the central turns of the coil, (c) varying the coupling, or (d) using a longer coil. L: length to be heated. Source: Ref 6

Quenchant Effect on Coil Design. The type of quenchant and how it is to be applied need to be known before coil design can be completed. As discussed in Chapter 6, “Quenching,” in this Volume, the three basic types of quenchant application are:

- Integral, from within the coil
- Spray, separate from the coil
- Submerged or dunk, separate from the coil

The type of quenchant is dictated by the workpiece and process requirements. Once the quenchant has been selected, the method of application can be decided. The only real effect on the coil occurs when a spray quenchant is to be applied from the coil itself. Figure A3.5 shows a coil with integral quench and a coil with a separate quench. In this case, the coil is most likely to be a machined coil, because either the quenchant itself can be used to cool the coil, or a two-chamber coil can be made, with one cooling passage for the coil and one for the quenchant.

The design of the quench inlets and outlets are discussed in Appendix 4, “Quench System Design,” in this Volume. Integral quench coils have the quench holes drilled through the heating face. These quench holes should not take up more than 10% of the heating face. In order to control the direction of the quenchant stream, the wall thickness of the copper must be at least 1.5 times the orifice diameter. Table A3.5 shows rule-of-thumb quenchant hole sizes for different shaft diameters.

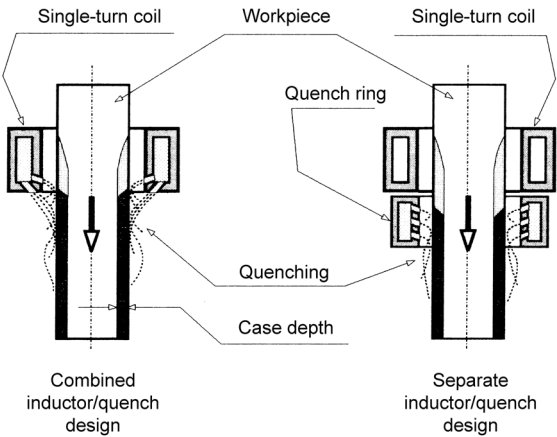


Fig. A3.5 Combined and separate coil/quench design. Source: Ref 5

Table A3.5 Workpiece diameter versus quench-hole size

Workpiece diameter		Quench hole size	
mm	in.	mm	in.
6.25 to 12.5	0.25 to 0.50	1.15 to 1.58	0.046 to 0.063
12.5 to 37.5	0.50 to 1.50	1.58 to 2.35	0.063 to 0.094
>37.5	>1.50	3.13 to 3.9	0.125 to 0.156

Source: Ref 1

Design for Use of Flux Concentrators

Flux concentrators are used to shape the flux field so that more intense flux concentrations are produced in a workpiece in the areas where heat is required, while reducing flux leakage into areas in which heat is not desired. Flux concentrators improve overall process efficiency, but some heat loss is produced in the concentrator material and must be removed. The coil cooling water or the quenchant must remove this heat. In addition, the electromagnetic forces of the concentrators that tend to loosen the concentrator from the coil. Due to the copper work hardening because of mechanical stresses caused by the coil flexing, if the original coil is susceptible to stress cracking, the use of any of the nonlaminated concentrators enhances early coil failure.

Installation depends upon the type of concentrating material that is used. Laminates of various shapes and thicknesses can be purchased to various sizes and shapes (Ref 7). Laminates must be securely fastened to the coil in such a manner that there is no electrical path between the laminates. One method of installation is to wedge packets of laminates between copper wedges that are brazed to the coil. The concentrating materials, such as Ferrotron or Fluxtrol, can be screwed or epoxy glued to the coils after being machined to the correct contour (Ref 8). The moldable concentrator material can be purchased from Alpha 1 and is molded and baked to the coil.

Cooling must occur from conduction of the heat into the work coil, the quenchant from drilled holes through the concentrators where the concentrator is used for quench outlets, or from application of quenchant at the end of the heating cycle. Some of the concentrating materials have better resistance to deterioration from the quenchant if they are painted with glyptol.

The cooling method selected will first be determined by the material used for the flux concentrator and the process environment. Most heat is removed via heat conduction from the water-cooled copper coil. Adhesive layer thickness, the consistency of gap filling, and the adhesive thermal conductivity play a role. Direct water cooling has been used in some applications using supplemental water drizzles and quench heads. The suppliers of the materials have instructions for the application and use of their materials.

Selection of material depends upon frequency, power density, and application. The concentrator suppliers have their concentrating materials rated by the intended frequency of use. Laminations are best used under 10 kHz, where they tend to be the most efficient. However, laminates do not work well around bends in the coil because of the problem of being able to stack them tightly. Also, laminates do not wear well in areas where they are the subject of flux fields that are produced where the coil has two different orientations, such as some single-shot coils, which heat both longitudinally and around diameters at the ends of the coils. The machin-

able concentrators are suited for the types of coils in which they can be machined for good contact and for use with medium frequencies. The efficiency of these concentrators increases with frequencies from 10 to 50 kHz. The ferrite concentrators work best with RFs. Care needs to be taken when using concentrating material in the RF regions where the dielectric properties of the concentrating materials are not high enough to prevent arcing.

The moldable concentrating materials work well with many coils in which it is more difficult to machine the material. As of the date this Volume was written the claims regarding operating efficiency in general application of the different types of materials, such as the machinable versus moldable, are hard to resolve. Furthermore, the expectation is that continued improvements will be made in material for higher frequency use in the future. Table A3.6 lists factors of selected magnetic flux concentrators that affect their longevity (Ref 9). The suppliers of concentrator materials have detailed online help regarding the selection, application, and fabrication of their materials.

Design. The concentrators are used to shape the flux field into specific areas. Figure A3.6 shows the shaping effect for a single-turn coil. The pattern produced by the coil with concentrating material is more uniform and shaped to the width of the coil than the pattern produced by the bare coil. Figure A3.7 illustrates the shaping of the flux field on a two-turn coil. The two-turn coil with concentrator produces more heat in the center area de-

Table A3.6 Comparison of selected features of magnetic flux concentrators that affect their longevity

Property or characteristic	Laminations	Iron- or ferrite-base powder materials
Homogeneous properties	Fair (pronounced heterogeneous properties)	High (still heterogeneous)
Magnetic properties (magnetic permeability, magnetic saturation, etc.)	High	Fair (particularly in strong fields)
Curie temperature	High	Fair
Electrical resistivity	High (if installed properly with respect to the field orientation and frequency)	High
Thermal conductivity and capability to be cooled	Good to fair (depending on orientation of stack to magnetic field)	Fair
Maximum long-term use temperature	Good (depends on thermal insulation between sheets of laminations, typically above 500 °C, or 930 °F)	Fair (less than 250 °C, or 480 °F, because of low working temperature of binders)
Machinability	Fair	Good
Resistance to corrosion	Fair	Good
Typical working frequency range	50 Hz to 50 kHz	50 Hz to 800+ kHz
Localized overheating	Fair	Fair
Capability to withstand high-temperature radiation and heat convection	Good	Fair
Impact strength	Good to fair (depending on orientation of stack to impact)	Fair
Capability to be applied to complex-shaped coils	Fair	Good

Source: Ref 9

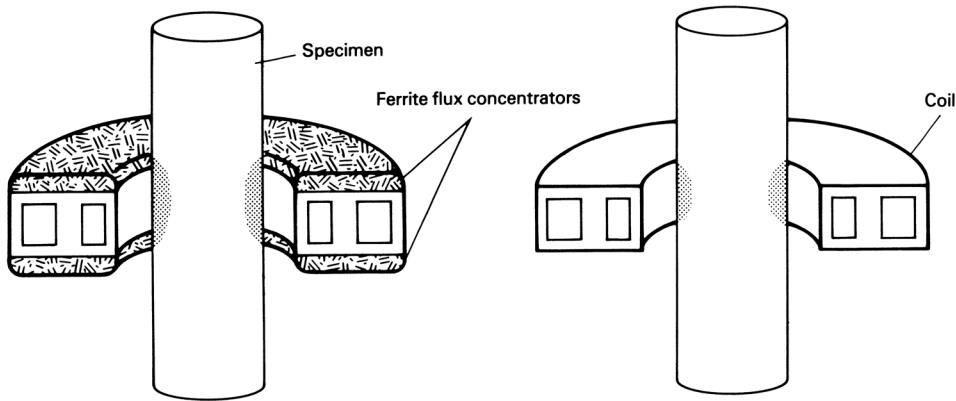


Fig. A3.6 The effect of using a flux concentrator on the heating of a shaft. Source: Ref 10

sired, with less stray flux. Figure A3.8 shows the flux field in an application such as a crankshaft journal. Use of concentrating material forces all coil current into the bottom of the coil, inducing the current into the main diameter without heating the side.

Levitation of Workpiece. The magnetic flux field produced by high power densities can levitate the workpiece during heating. The levitation effect is more pronounced with frequencies below 10 kHz, but it has been observed even at RFs. Depending on the application, the workpieces may need to be held on both the top and bottom, or somehow otherwise clamped.

Computer-Aided Coil Design (CAD)

Computer simulation of induction hardening requires special software and considerations to achieve accurate results. Induction hardening involves several different phenomena that depend upon one another. With today's computer software and hardware, it is impossible to simulate all of these phenomena simultaneously. Hence, decisions must be made regarding what part of the problem is most important for simulation and what part must be done empirically or based on experience. The best approach at the time this Volume was written involves electromagnetic and thermal field simulation, and if desired, the thermal field can be exported to a structural transformation program.

The programs available for induction hardening simulation include:

- One-dimensional (1D) electromagnetic and thermal (coupled)
- Two-dimensional (2D) electromagnetic or thermal, 2D coupled
- Three-dimensional (3D) electromagnetic or thermal
- For some specific cases, 3D coupled

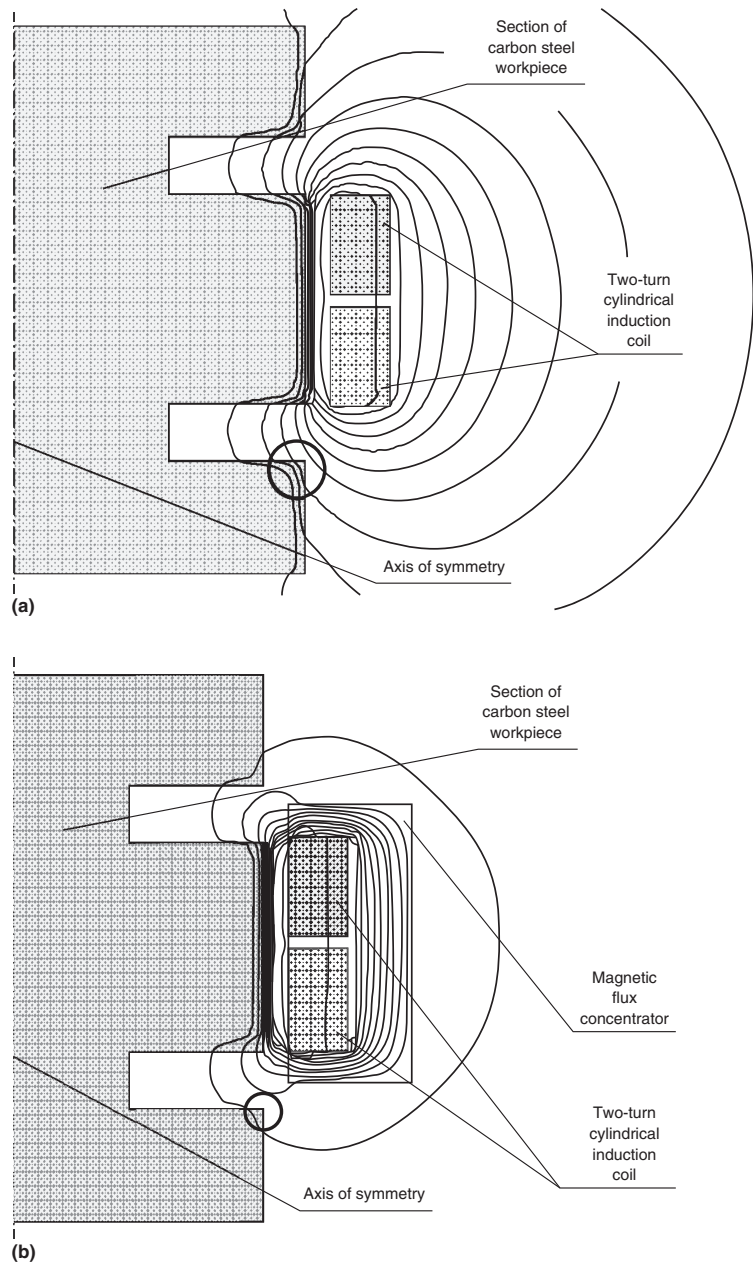


Fig. A3.7 Electromagnetic field distribution in two-turn coil (a) without and (b) with a magnetic flux concentrator. Source: Ref 5

Due to the complexity of the electromagnetic field problem, no commercial computer simulation program exists for 3D coupled simulation of all induction system configurations. Also, the time that is required for direct 3D optimization of an induction-hardening system would take from weeks to months, even with today's fastest computers.

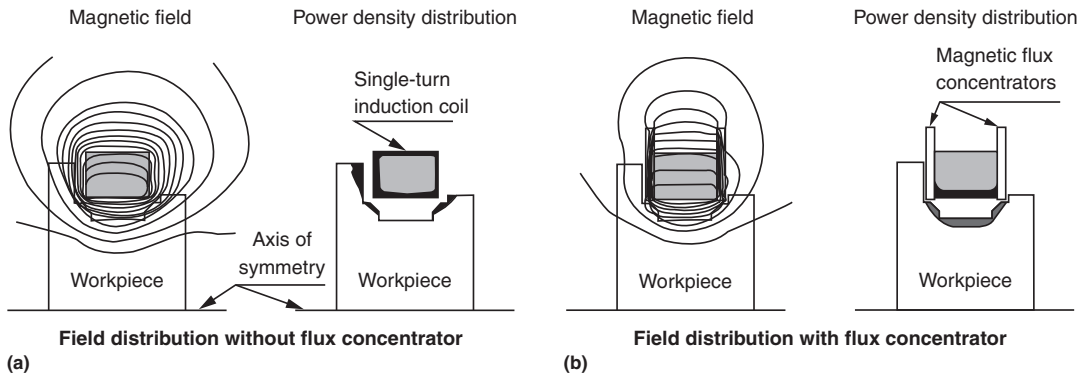


Fig. A3.8 Field distribution (a) without and (b) with a flux concentrator. Source: Ref 11

Because of this, a hierarchical approach is currently taken to induction-hardening process design through computer simulation. The “rule of pyramid” for computer simulation of induction heating states that more simple programs should be used, limiting the number of cases to be simulated with the more complicated software. It is believed that this approach, which begins with 1D coupled simulation, greatly reduces the time required for simulation of the induction-hardening process. For most cases, 1D coupled simulation alone or 1D coupled plus some 2D simulation is enough for induction coil optimization.

ELTA simulation software was used to make a good approximation with the 2D system. Figure A3.9(a) and (b) shows the temperature distribution in an induction-scanning application. Figure A3.9(a) represents the temperature distribution, with the lightest shade corresponding to the full austenitization temperature required for complete martensite formation. In this process, induction was used to harden a 45.8 mm (1.8 in.) outside-diameter shaft for the automotive industry. The frequency for this application was 3 kHz, and the scanning speed was 7.5 mm (0.3 in.) per second.

The results of induction hardening simulation can be almost exact. The accuracy of simulation depends mainly on the correct material property description, especially for magnetic steels. The software selection is critical also. Currently, there is a great deal of information available on the mechanical properties of steels at room temperature. However, there is a lack of information on material properties at elevated temperatures critical for induction heating simulation, such as permeability, electrical resistivity, and thermal conductivity. It is in the intermediate temperature ranges where the material database must be improved. Fortunately, above the Curie temperature, most steel alloys have close to the same electrical resistivity and thermal conductivity. Given accurate material properties, computer simulation can provide almost exact results for prediction and optimization of the induction-hardening processes.

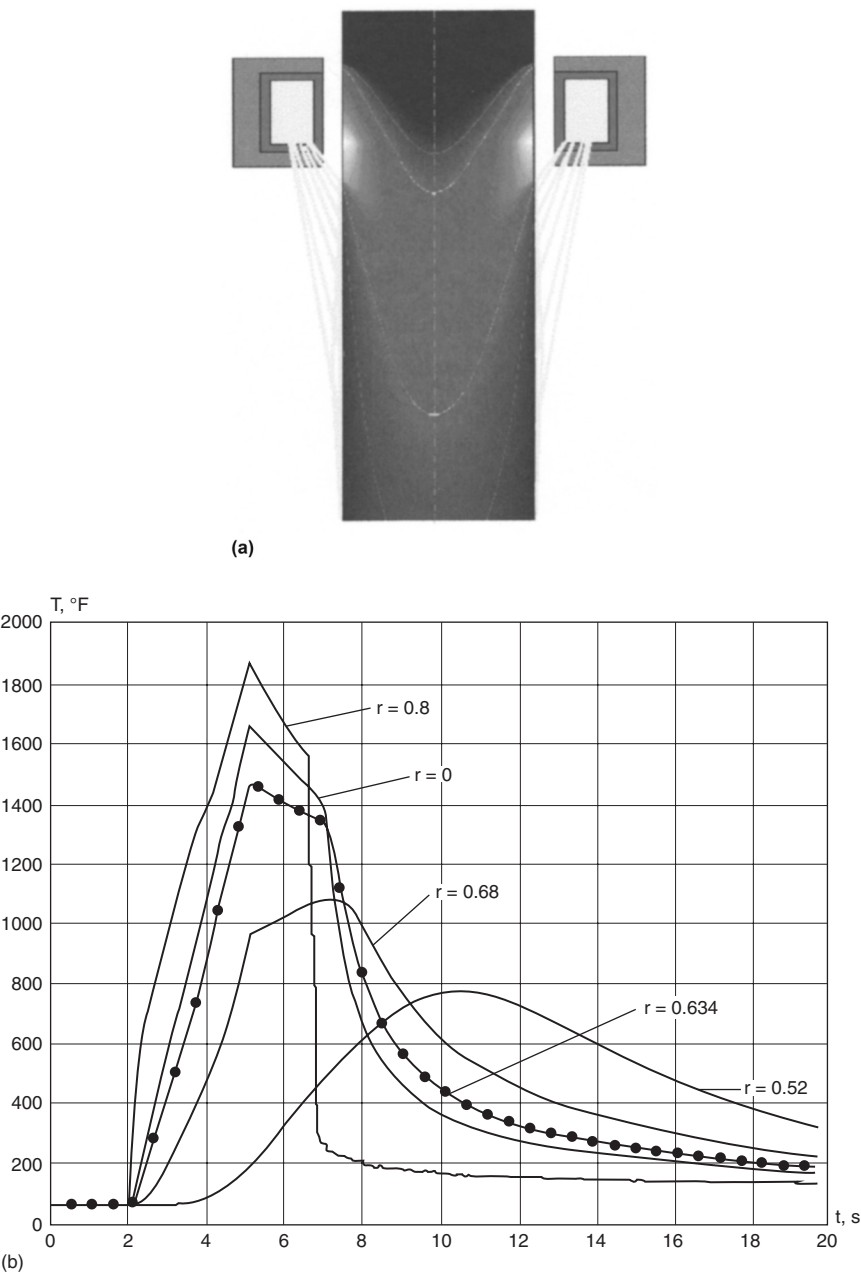


Fig. A3.9 ELTA software: (a) simulation of induction scanning, and (b) temperature graphs at different radii versus time for the induction scanning process. See text for details. Source: Ref 12

There is research progressing on the use of 3D printers for making induction coils. When perfected this should produce distinctly better design and operating characteristics over machined and assembled induction coils (Ref 13).

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APPENDIX 4

Quench System Design

THIS APPENDIX DISCUSSES the design of the actual quench devices or outlets and the design of cooling systems. Chapter 6, “Quenching,” in this book covers the basics of quenching theory, including the selection of quenchant, their temperature control, and applications. Quench outlets include spray-type quench fixtures, including various types of integral quenches in coils, quench rings, quench jets, and quench pads. The term *quench ring* is used to describe the quenching fixture for the balance of this appendix. The quenching system contains the controls, heat exchanger, temperature regulators, filters, and pumps necessary to provide cooling for the quenchant.

The Quench Cooling System

The design of the quench cooling system sets the basic limit on how much steel can be quenched. Other factors that influence the flow of quenchant on the workpiece are the hose inside diameter (ID) from the manifold to the quench ring, the number of hoses, the quench ring inlet size, and number of holes and hole size at the outlet of the quench ring.

The amount of quenchant required can be reasonably calculated from the theoretical viewpoint of assuming that the quenchant needs to extract all of the heat content needed to heat the workpiece. Other heat losses, such as residual heat left in the workpiece, are not significant. For example, if a workpiece requires an effective heat input of 40 kW, then the heat content for the quenchant can be derived by the method used to calculate the heat loss: gallons per minute (gpm) = $(40 \times 3413)/(500 \times 30)$, or 9.2 gal/min (from $\text{gal/min} = (\text{kW} \times 3414)/(500 \times \text{temperature rise } ^\circ\text{F})$). For this 40 kW heat absorption the quench system must be capable of supplying 9.2 gal/min through the quench ring assuming a 22 °C (40 °F) temperature rise. Cutting the temperature rise in half would double the water flow requirement.

Most quench systems use centrifugal pumps, which are sized by pressure drop and fluid flow requirements. The sizing of the pump versus the operating pressure is important not only for maximizing flow but also for producing long motor life. A given centrifugal pump supplying quenchant into a manifold at a given pressure determines the maximum amount of quenchant flow that can be produced.

With a given outlet pressure, the amount of quenchant that can be sprayed on a workpiece for cooling depends first on the design from the manifold outlets to the quench ring outlet holes, and then on the quench ring design. As with any hydraulic system, system pressure drops reduce quenchant flow. Restrictions, sharp turns, corners, and smaller-ID piping all reduce pressure and flow. To maximize flow, ideal changes in ID of piping outlets and piping size or hose should not be more than one to one. Thus, starting with the quench manifold outlets, the area of the total ID of the outlets from the manifold should not exceed the area of the ID of the manifold itself. For example, if the outlet from the quench manifold (inlet to the quench ring or integral quench coil) has four 12.7 mm (0.5 in.) hose connections, the manifold needs to have a minimum of 25 mm (1 in.) ID. Table A4.1 shows the number of inlets that can be put into a quench ring from a given manifold size. There must be enough inlet lines of adequate size to the quench ring to furnish the needed quenchant flow. Figure A4.1

Table A4.1 Quench manifold size required for inlets to quench ring

Inlet diam. (in.)	Number of inlets versus manifold size (in.)				
	1	2	3	4	5
1/4	1/4	3/8	1/2	3/4	3/4
3/8	3/8	3/4	3/4	1	1 1/4
1/2	1/2	3/4	1	1	1
3/4	3/4	1 1/4	1 1/4	1 1/2	2
1	1	1 1/4	2	2	2 1/2

Source: Ref 1

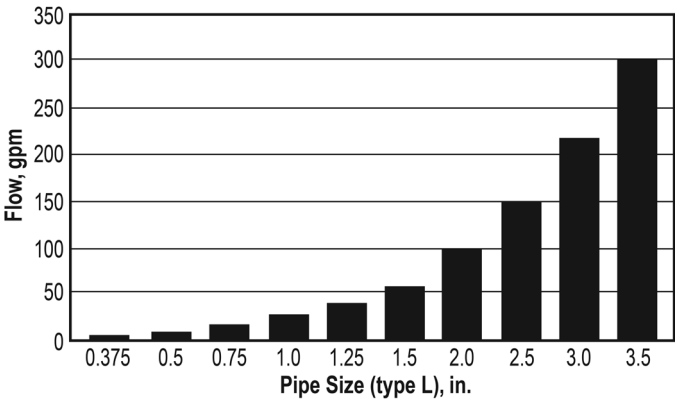


Fig. A4.1 Quench flow vs. pipe size (velocity, 3 m/s, or 10 ft/s). Source: Ref 2

shows quench flow versus pipe size. Four 12.7 mm (0.5 in.) pipes would have a flow capability of 40 gpm, while four 19 mm (0.75 in.) pipes would carry about 72 gpm as shown.

The ability of a quenchant to absorb heat from a workpiece depends on the heat absorption characteristics of the quenchant itself, the effective flow of quenchant that is applied to a workpiece, the quenchant temperature, and the nature of the impingement (such as spacing and size of jets). The heat must be absorbed quickly so that spotty hardness and distortion do not occur. If sufficient quenchant is furnished from the manifold to the quench ring, then the size and number of quench holes at the outlet, along with the effective pressure at the coil, determine the amount of quenchant that can be applied. In order to assume that a workpiece will quench, a general recommendation is that the quench hole area should be a minimum of 5 to 10% of the area being quenched. As case depth and part diameter increase, the area of coverage needs to be increased. Rule of thumb for the basic minimum area is shown in Figure A4.2, which indicates the amount of flow that can be applied depending on hole size and pressure. The rate of increase is roughly proportional to the pressure, in that doubling the pressure doubles the flow, while doubling the hole size such as from 1.59 to 3.18 mm ($1/16$ to $1/8$ in.) quadruples the flow. As mentioned in Appendix 3, Induction Coil Design and Fabrication, the number of quench holes in an integral quench inductor is limited to 10 to 15% of the coil width so that there is sufficient copper to carry the current. The quench angle impingement commonly used is at 30° (60° impingement on the part). When separate quench rings and pads are used, this angle is sometimes changed to a straight 90° impingement. Table A4.2 shows an increase in quench hole size versus diameter.

From the determination of the amount of quenchant that can be produced at the inlet, the number of outlet holes can be calculated from the hole area and number of holes. Ideally, the ratio of the inlet area to the

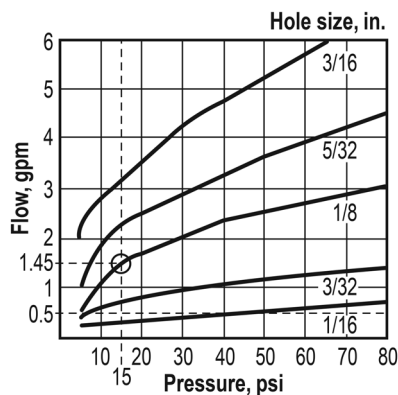


Fig. A4.2 Effect of hole size on quench flow vs. pressure. Source: Ref 2

total area of the outlet holes should be one to one. In practice, the ratio should never exceed one to two. Figure A4.3 shows the effect of inlet-to-outlet ratio on quenchant flow versus pressure.

The hole-to-hole spacing is around two diameters, but the rows of holes may be staggered with offsets so that this can be increased. When the number of holes has been calculated, the design for drilling the holes can be planned. The previous example of 40 kW of heat put into the part required 9.2 gpm of quenchant. Assuming that 5 mm (1/8 in.) holes are desired and spaced 5 mm (0.25 in.) apart in a 40 mm (2 in.) ID quench ring, there is a total of 25 holes per row for a flow at 20 psi of 44 gpm. This is obviously more flow than is needed from a heat extraction viewpoint. The design might call for four to six rows of holes to provide the impingement and coverage needed, and to keep the part in the quench long enough. Obviously this raises the flow requirements greatly. However, sometimes the lower rows of holes can be spaced wider, such as at 10 mm (0.50 in.).

The impingement of quenchant is most important in the stage of quenching that involves cooling below the “knee” of the time/temperature transformation diagram. Actual quenchant impingement on the workpiece is a function of the distance of the quench ring to the workpiece versus the spacing in the quench ring. With tight coupling, integral quench coils have impingement on the workpiece close to the spacing of the drilled holes in the coil. However, a separate quench ring, with loose coupling to the

Table A4.2 Workpiece diameter versus quench hole size

Workpiece diameter		Quench hole size	
mm	in.	mm	in.
2	1/2	1 1/2	1/16
4	1	3	1/8

Source: Ref 1

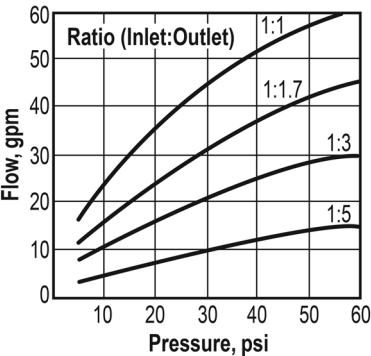


Fig. A4.3 Effect of inlet:outlet ratio on quench flow vs. pressure. Source: Ref 2

workpiece, will have the impingement spray converge. In this case, the drilled hole spacing around the ID can be increased.

A second factor that seriously impacts the number of rows of holes needed is the time the workpiece needs to remain in the quenchant. The workpiece needs to be in the quenchant long enough for the entire case or area to transform to martensite without any tempering or drawback from residual heat in the core. As a rule of thumb, the minimum time for quenching on static heats is the same as the time required for heating. Parts that are being scanned need immediate quenching for two to three times the scanning time. In some cases additional quenching needs to be done through use of a secondary quench application below the first. With secondary quenches, often fixed lines or nozzles can be used because the workpiece is in or below the boiling stage of quenching.

Materials for Quench Rings. Any quench ring that is separate from the coil will heat if metallic and within the area of the induction coil's magnetic flux field. Therefore, the use of nonmagnetic materials is required for quench rings. Surprisingly, if the quench ring is distant from the coil, such as 25 to 50 mm (1 to 2 in.), and the quench is kept on whenever there is a hot workpiece, plastics, fiberglass, and other synthetic materials work. The designs can be made either to fasten together so that any non-ferrous screws are outside of the flux field, or to be glued together. Quench pads or blocks are made from copper or brass and placed outside the coil where the flux field intensity is low. Hose clamps (including the screw) and quick connects should be made from nonmagnetic materials if they heat from the coil's magnetic flux field.

Quench Cooling System Design

The quenchant must be selected for the characteristics desired. This includes the quenchant speed, desired operating temperature range, and additives. Some biocide additives contain chlorine, which can combine with alkaline glycol to form cholorethyl. End users can also specify nitrate- or non-nitrate-based polymer quenchants to avoid the formation of nitrosamine (if nitrosamine is prohibited). Venting of the quench tank may be needed in cases where there is considerable vaporization and where the smell of the quenchant becomes obnoxious.

The quench cooling system must be sized correctly. A source of line water of the required flow and maximum inlet temperature is needed for cooling in the quench system heat exchanger. The quenchant must have the capacity to absorb the heat that is removed from the workpiece. Sizing of the system is a function of the fluid flows on both sides of the heat exchangers, temperature differentials of both fluids, and the size and heat-removal capacity of the heat exchanger. Cooling towers, chillers, and city or well water systems can be used for the line water. Cooling towers are discussed in Chapter 3, "Induction Heat Treating Systems," in this Vol-

ume and are most commonly used in many places when substantial line cooling water is needed due to cost. Cooling towers have the limitation of not being able to cool the recirculated water enough with high outside temperatures and high humidity. As with the quenchant system, closed systems involving chillers or cooling towers may need to have biocides added, and they may also need filtration to remove debris.

Plate-style heat exchangers, although more expensive than cartridge, are recommended. They are easy to clean, and extra plates can be added if additional capacity is needed.

Temperature-controlled valves are used to regulate the cooling of the quenchant by the line water in the heat exchanger. Inverse temperature control valves that operate proportionally by allowing only as much water as needed to provide very close temperature control can be used. Other systems use valves that open and close, as needed, to control the quenchant with a temperature range.

Quench systems must be able to provide the amount of quenchant needed. The holding tank size, as previously mentioned, is recommended to be at least three to four times the quench flow in gallons per minute. A larger tank provides the ability to control the temperature rise better but needs more quenchant when recharging. The system must be capable of maintaining the quenchant within the specified control range, which should normally not exceed 7 °C (10 °F) for a system. A normal control range might be from 35 to 38 °C (90 to 100 °F) or 38 to 443 °C (100 to 110 °F). When operating in controlled temperature ranges above room temperature, heaters are recommended to bring the tank up to temperature, with an overtemperature alarm or cutoff used to prevent high-temperature operation.

The quench tank and piping must not react with the quenchant. Polymers are very hard on painted tanks. In steel tanks with epoxy-coated linings on the interior surfaces, the epoxy breaks down between the fifth and tenth years of use. The epoxy comes loose and will collect in strainers or in the quench spray holes of the coils or quench rings (Ref 3). To prevent galvanic corrosion, the piping should not be made of dissimilar materials. Tank storage capacity of three to four times the quenchant flow per minute is recommended. The quench system piping, solenoids, and manifold must be designed so that the full volume of quenchant is supplied to the quenching position on command. Care must be taken so that the quenchant itself does not drain out of the quench ring. Full flow onto the workpiece should occur immediately after the quench solenoid opens, with no necessity to fill the quench ring first. The quench tank must have suitable filtration to keep the quenchant free of foreign material and scale. Y-type basket strainers are widely used and are the lowest cost. They trap only the larger particles and are suitable for quench tanks. In applications that use spray quenching, a higher degree of filtration is recommended to help keep the holes in the quench rings from clogging. In this case, cartridge-

and bag-type filtration units can be specified to filter from 5 up to 100 μm . A differential pressure switch across the inlet and outlet sides will detect a clogged condition. If the filters are placed in a bypass configuration (similar to the oil filter in a car), a separate flow is run through the cartridge continuously. When the filters are placed in series with the quench ring, a flow switch in series on the outlet side of the cartridge will indicate low flow. A wide variety of controls and systems are available to help “fool-proof” these systems.

Continuous automatic indexing-media-style filters work well if manual replacement of filter media is a problem. These are sometimes called dragout-style filters because the filter paper is dragged across a perforated plate. When the pressure differential is too high, the filter is automatically indexed into a hopper. These filters are good for applications that are high in scale and chips because their large volume and automatic indexing assure good filtration. Positive pressure is used for filtration, and a clean tank is required on applications that cannot afford to have the quenchant flow disrupted in order to clean the filter.

Some of the power supplies, such as radio frequency oscillator supplies, have higher voltage at the terminal connection to the coil. Almost invisible layers of very fine magnetic scale from the quenchant can build up on these terminals, leading to arcing. Magnets or magnetic separators will remove these particles.

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2. D. Williams, Quench Systems for Induction Hardening, *Met. Heat Treat.*, July/Aug 1995, p 34
3. F. Specht, Maintenance of Induction Heat Treating Equipment, *Induction Heating and Heat Treatment*, Vol 4C, *ASM Handbook*, ASM International, 2014, p 709–713

APPENDIX **5**

Tempering Curves

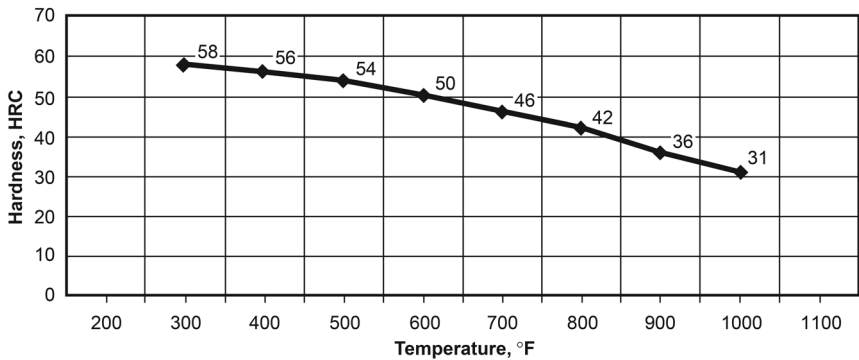


Fig. A5.1 Tempering curve for 1045 steel. Tempered 1 h at heat; as quenched, 60 HRC at 120 °C (250 °F). Source: Ref 1

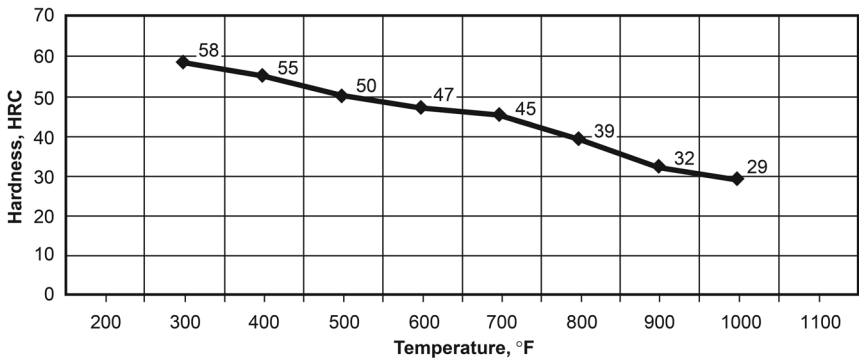


Fig. A5.2 Tempering curve for 1144 steel. Tempered 1 h at heat; as quenched, 60 HRC at 120 °C (250 °F). Source: Ref 1

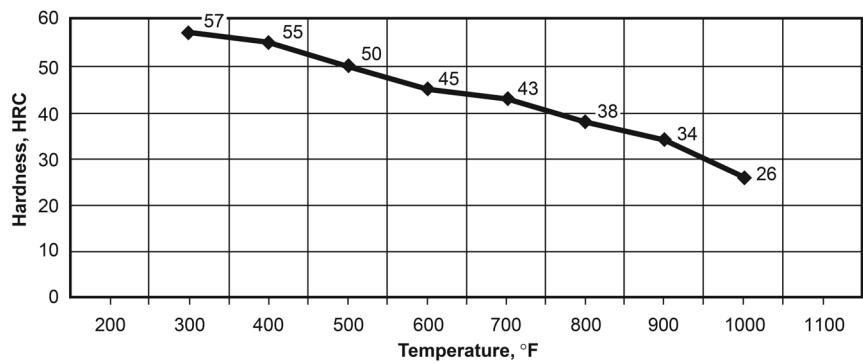


Fig. A5.3 Tempering curve for 4140 steel. Tempered 1 h at heat; as quenched, 60 HRC at 120 °C (250 °F). Source: Ref 1

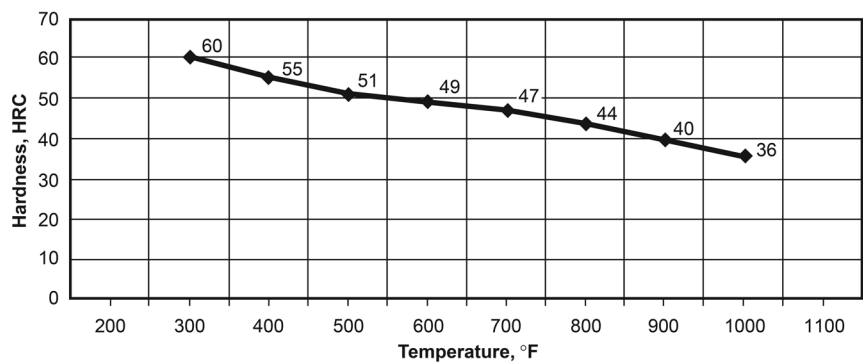


Fig. A5.4 Tempering curve for 4150 steel. Tempered 1 h at heat; as quenched, 62 HRC at 120 °C (250 °F). Source: Ref 1

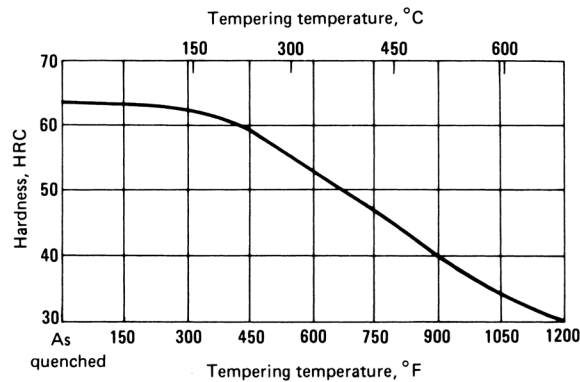


Fig. A5.5 Tempering curve for E52100 steel: average based on a fully quenched structure. Source: Ref 2

REFERENCES

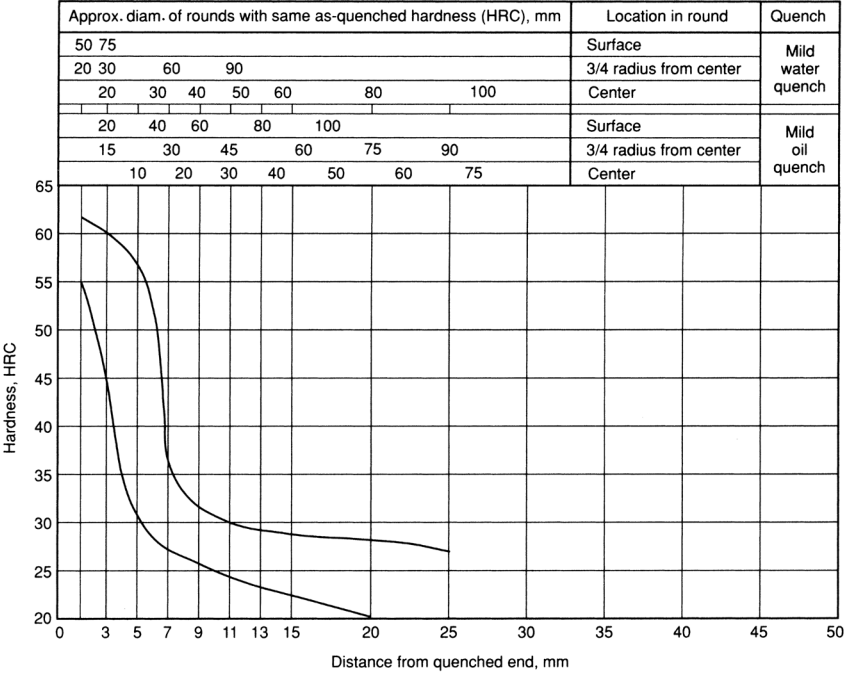
1. R.E. Haimbaugh, Induction Heat Treating Corp., personal research
2. Standard Practices and Procedures for Steel, *Heat Treaters Guide*, American Society for Metals, 1982

APPENDIX 6

Hardenability Curves

SAE/AISI 1045H, UNS H10450

Hardness limits for specification purposes		
J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	62	55
3	60	45
5	53	31
7	36	27
9	32	25
11	31	24
13	30	23
15	29	22
20	28	20
25	27	...
30	...	...



Hardness limits for specification purposes		
J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	62	55
1.5	61	52
2	59	42
2.5	56	34
3	52	31
3.5	46	29
4	38	28
4.5	34	27
5	33	26
5.5	32	26
6	32	25
6.5	31	25
7	31	25
7.5	30	24
8	30	24
9	29	23
10	29	22
12	28	21
14	27	20
16	26	...
18	25	...
20	23	...
22	22	...
24	21	...

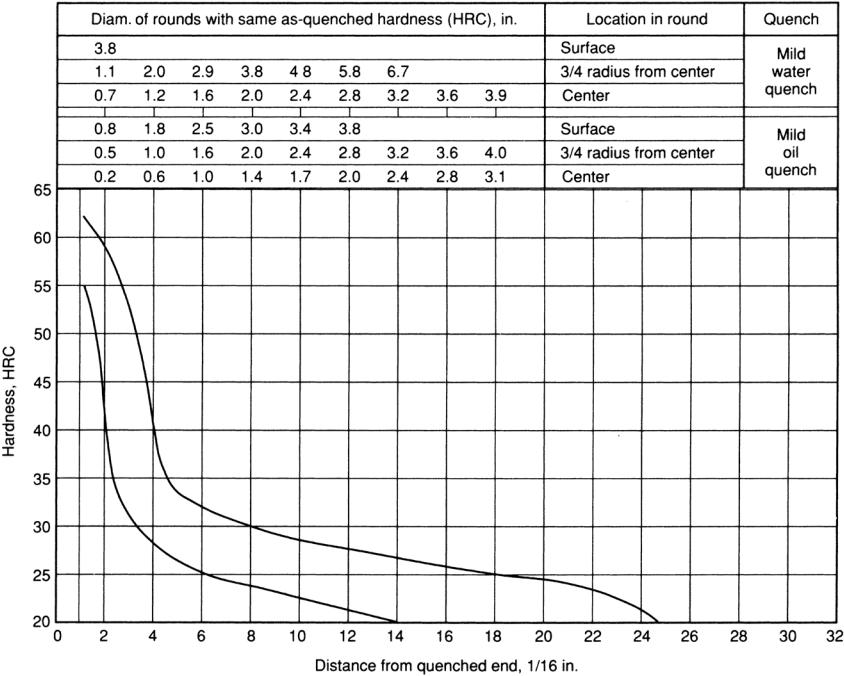


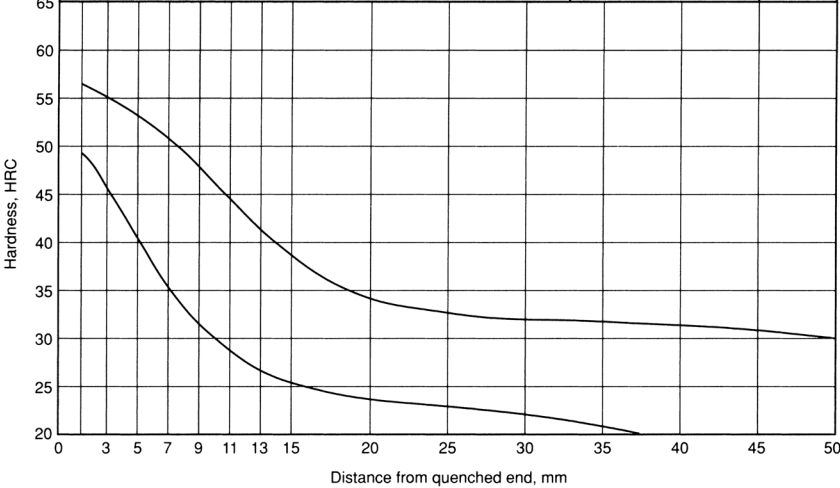
Fig. A6.1 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 870 °C (1600 °F). Austenitize, 845 °C (1550 °F). Source: Ref 1

SAE/AISI 4130H, UNS H41300

Hardness limits for specification purposes

J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	56	49
3	55	46
5	53	40
7	51	36
9	48	32
11	44	28
13	41	26
15	39	25
20	34	24
25	33	23
30	33	22
35	32	20
40	31	...
45	31	...
50	30	...

Approx. diam. of rounds with same as-quenched hardness (HRC), mm										Location in round	Quench
50 75										Surface	Mild water quench
20 30 60 90										3/4 radius from center	
20 30 40 50 60 80 100										Center	
20 40 60 80 100										Surface	Mild oil quench
15 30 45 60 75 90										3/4 radius from center	
10 20 30 40 50 60 75										Center	



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	56	49
2	55	46
3	53	42
4	51	38
5	49	34
6	47	31
7	44	29
8	42	27
9	40	26
10	38	26
11	36	25
12	35	25
13	34	24
14	34	24
15	33	23
16	33	23
18	32	22
20	32	21
22	32	20
24	31	...
26	31	...
28	30	...
30	30	...
32	29	...

Diam. of rounds with same as-quenched hardness (HRC), in.										Location in round	Quench
2 4										Surface	Mild water quench
1 2 3 4										3/4 radius from center	
0.5 1 1.5 2 2.5 3 3.5 4										Center	
1 2 3 4										Surface	Mild oil quench
0.5 1 1.5 2 2.5 3 3.5 4										3/4 radius from center	
0.5 1 1.5 2 2.5 3 3.5										Center	

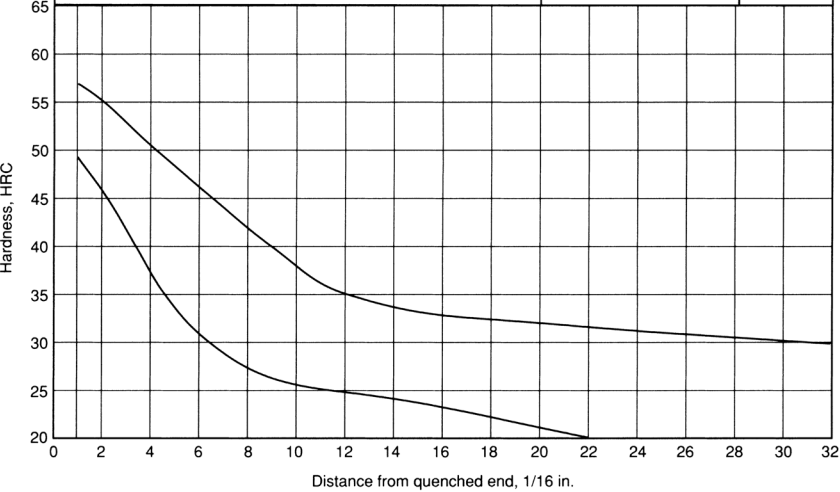
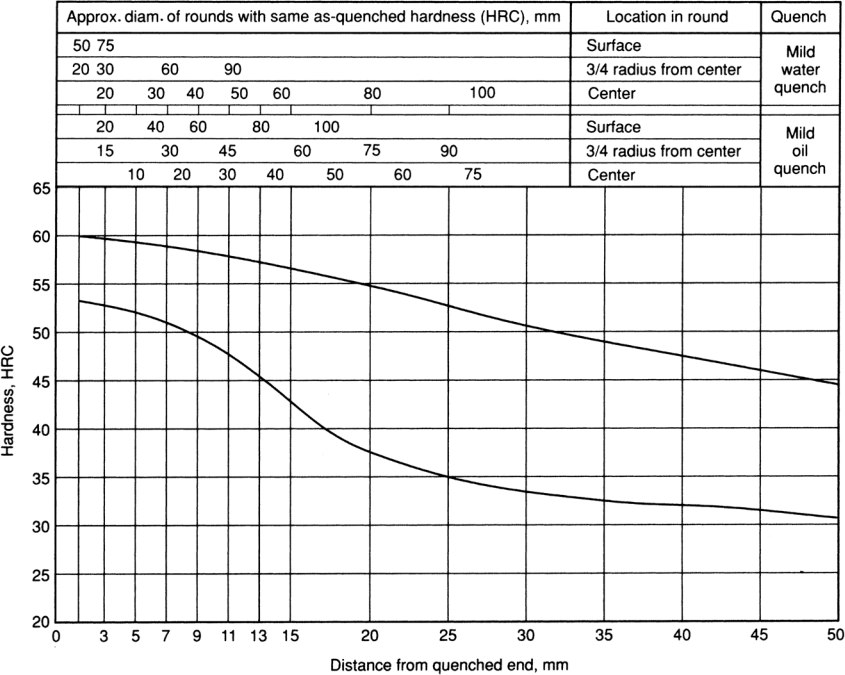


Fig. A6.2 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 900 °C (1650 °F). Austenitize, 870 °C (1600 °F). Source: Ref 1

SAE/AISI 4140H, UNS H41400

Hardness limits for specification purposes		
J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	60	53
3	60	52
5	60	52
7	59	51
9	59	50
11	58	48
13	57	46
15	57	43
20	55	38
25	53	35
30	51	33
35	49	32
40	48	32
45	46	31
50	45	30



Hardness limits for specification purposes		
J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	60	53
2	60	53
3	60	52
4	59	51
5	59	51
6	58	50
7	58	48
8	57	47
9	57	44
10	56	42
11	56	40
12	55	39
13	55	38
14	54	37
15	54	36
16	53	35
18	52	34
20	51	33
22	49	33
24	48	32
26	47	32
28	46	31
30	45	31
32	44	30

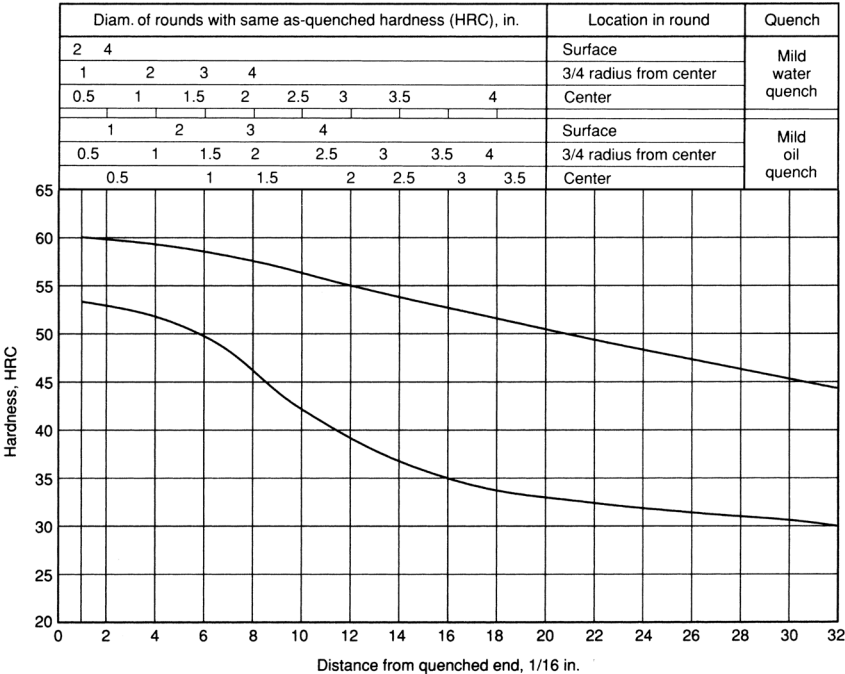


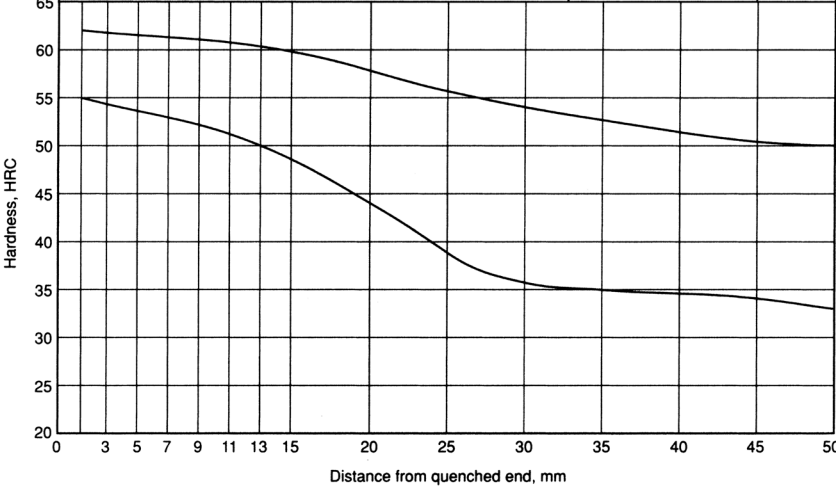
Fig. A6.3 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 870 °C (1600 °F). Austenitize, 845 °C (1550 °F). Source: Ref 1

SAE/AISI 4142H, UNS H41420

Hardness limits for specification purposes

J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	62	55
3	62	54
5	62	54
7	62	53
9	61	52
11	61	51
13	60	49
15	60	48
20	58	43
25	56	39
30	55	36
35	53	35
40	52	34
45	51	33
50	50	33

Approx. diam. of rounds with same as-quenched hardness (HRC), mm		Location in round	Quench
50 75		Surface	Mild water quench
20 30 60 90		3/4 radius from center	
20 30 40 50 60 80 100		Center	
20 40 60 80 100		Surface	Mild oil quench
15 30 45 60 75 90		3/4 radius from center	
10 20 30 40 50 60 75		Center	



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	62	55
2	62	55
3	62	54
4	61	53
5	61	53
6	61	52
7	60	51
8	60	50
9	60	49
10	59	47
11	59	46
12	58	44
13	58	42
14	57	41
15	57	40
16	56	39
18	55	37
20	54	36
22	53	35
24	53	34
26	52	34
28	51	34
30	51	33
32	50	33

Diam. of rounds with same as-quenched hardness (HRC), in.		Location in round	Quench
2 4		Surface	Mild water quench
1 2 3 4		3/4 radius from center	
0.5 1 1.5 2 2.5 3 3.5 4		Center	
1 2 3 4		Surface	Mild oil quench
0.5 1 1.5 2 2.5 3 3.5 4		3/4 radius from center	
0.5 1 1.5 2 2.5 3 3.5		Center	

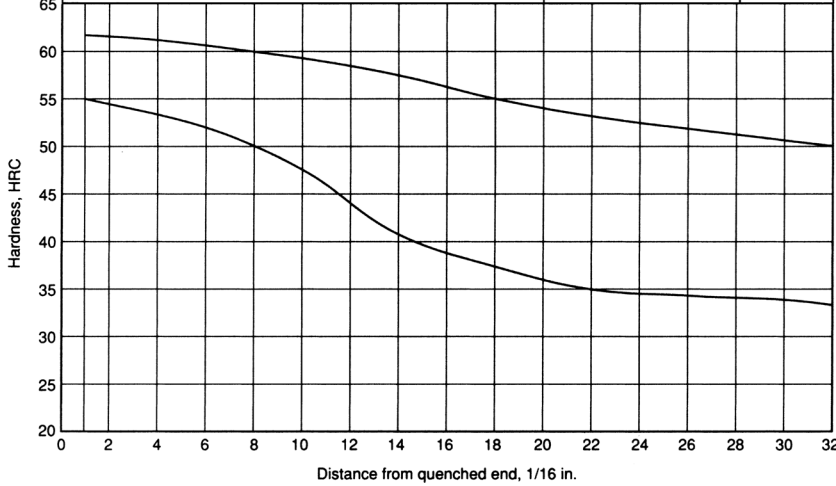
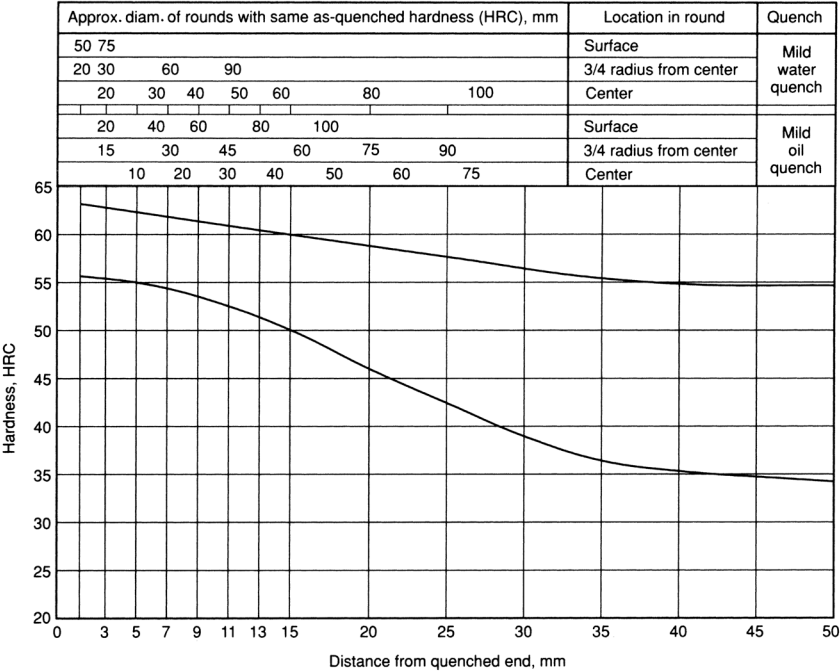


Fig. A6.4 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 870 °C (1600 °F). Austenitize, 845 °C (1550 °F). Source: Ref 1

SAE/AISI 4145H, UNS H41450

Hardness limits for specification purposes		
J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	63	56
3	63	55
5	63	55
7	62	54
9	62	53
11	61	52
13	61	51
15	60	50
20	59	47
25	58	42
30	57	39
35	56	37
40	55	35
45	55	34
50	55	34



Hardness limits for specification purposes		
J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	63	56
2	63	55
3	62	55
4	62	54
5	62	53
6	61	53
7	61	52
8	61	52
9	60	51
10	60	50
11	60	49
12	59	48
13	59	46
14	59	45
15	58	43
16	58	42
18	57	40
20	57	38
22	56	37
24	55	36
26	55	35
28	55	35
30	55	34
32	54	34

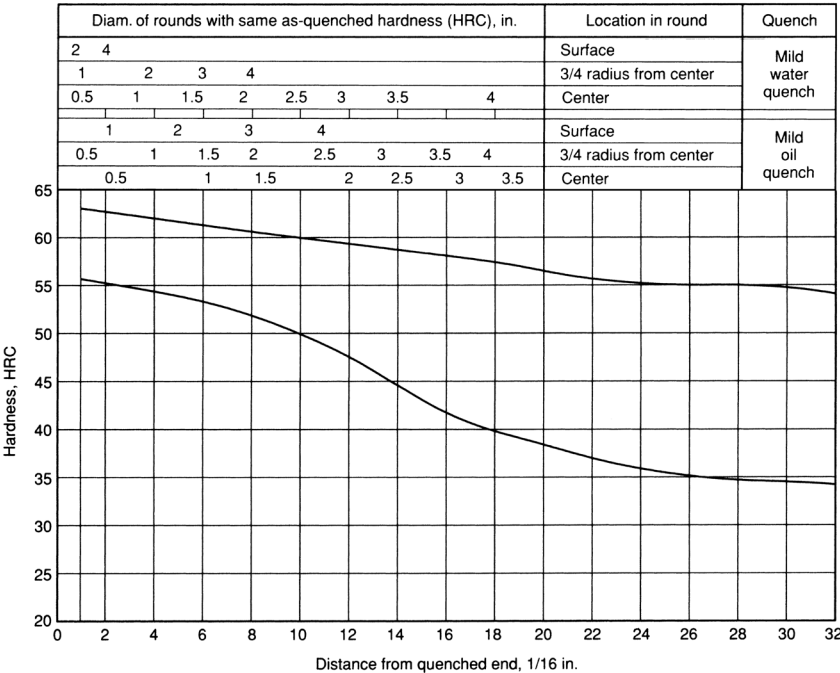
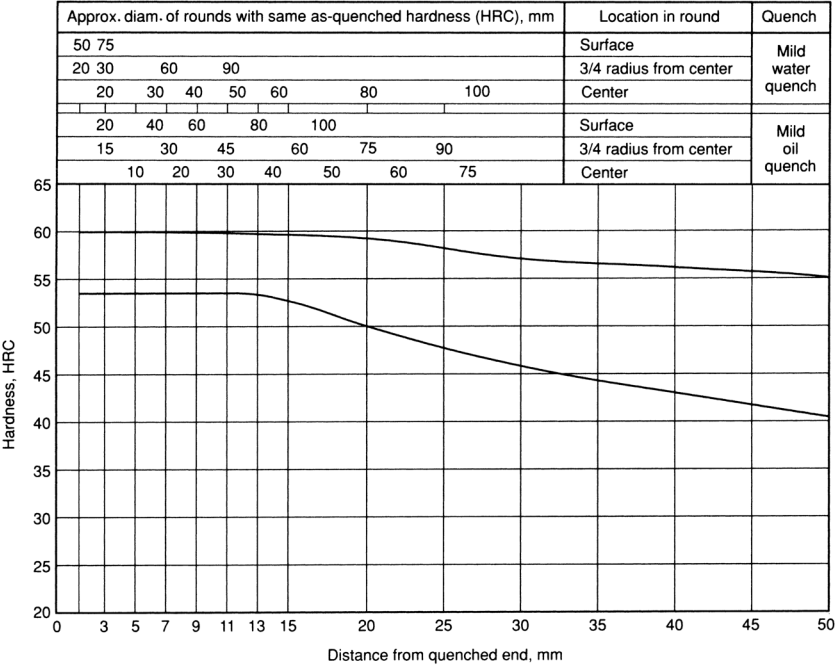


Fig. A6.5 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 870 °C (1600 °F). Austenitize, 845 °C (1550 °F). Source: Ref 1

SAE/AISI 4340H, UNS H43400

Hardness limits for specification purposes		
J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	60	53
3	60	53
5	60	53
7	60	53
9	60	53
11	60	53
13	60	52
15	60	52
20	59	50
25	58	48
30	58	46
35	57	44
40	57	43
45	56	42
50	56	40



Hardness limits for specification purposes		
J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	60	53
2	60	53
3	60	53
4	60	53
5	60	53
6	60	53
7	60	53
8	60	52
9	60	52
10	60	52
11	59	51
12	59	51
13	59	50
14	58	49
15	58	49
16	58	48
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20	57	46
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32	56	40

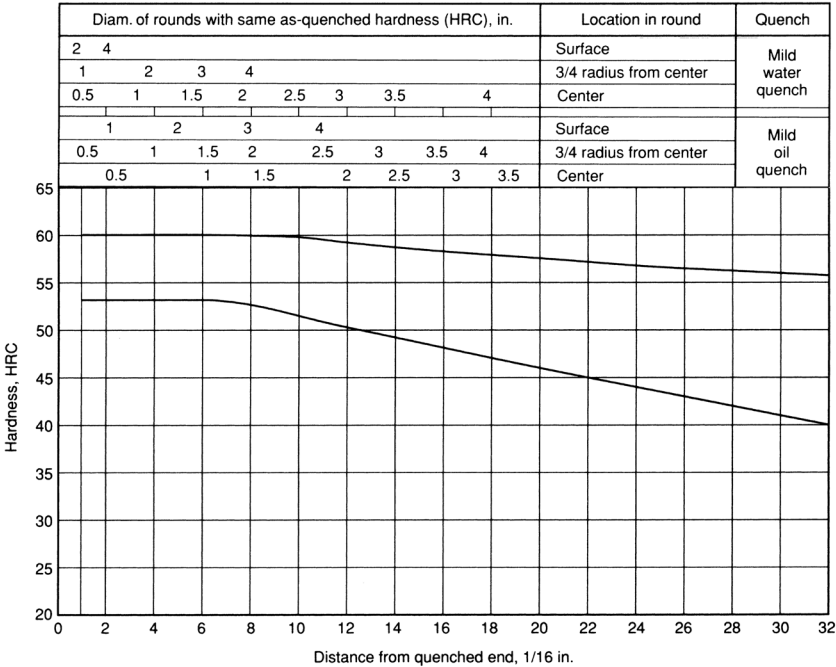
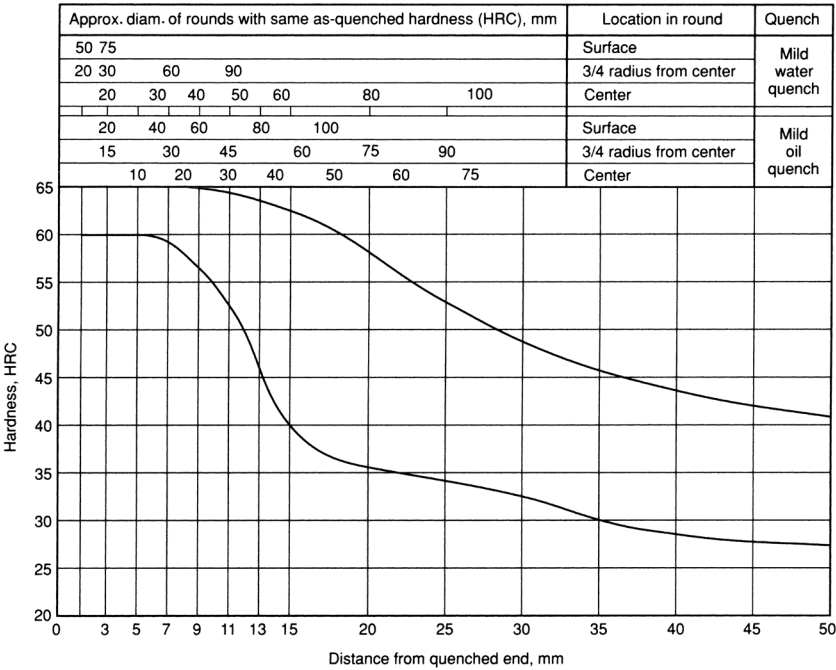


Fig. A6.6 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 870 °C (1600 °F). Austenitize, 845 °C (1550 °F). Source: Ref 1

SAE/AISI 5160H, UNS H51600

Hardness limits for specification purposes		
J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	...	60
3	...	60
5	...	60
7	...	59
9	65	57
11	64	52
13	64	46
15	62	40
20	58	36
25	53	34
30	49	32
35	46	30
40	44	28
45	42	27
50	41	27



Hardness limits for specification purposes		
J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	...	60
2	...	60
3	...	60
4	65	59
5	65	58
6	64	56
7	64	52
8	63	47
9	62	42
10	61	39
11	60	37
12	59	36
13	58	35
14	56	35
15	54	34
16	52	34
18	48	33
20	47	32
22	46	31
24	45	30
26	44	29
28	43	28
30	43	28
32	42	27

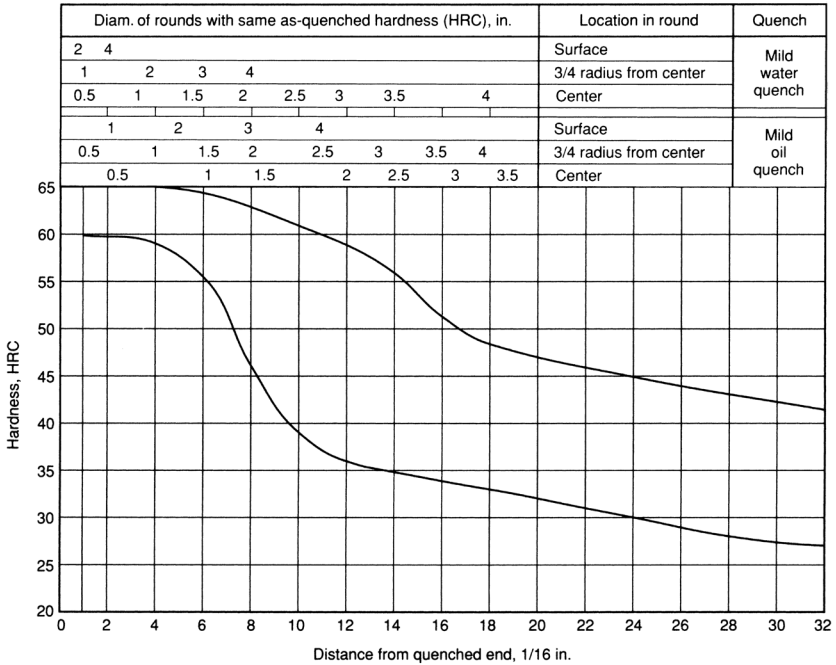
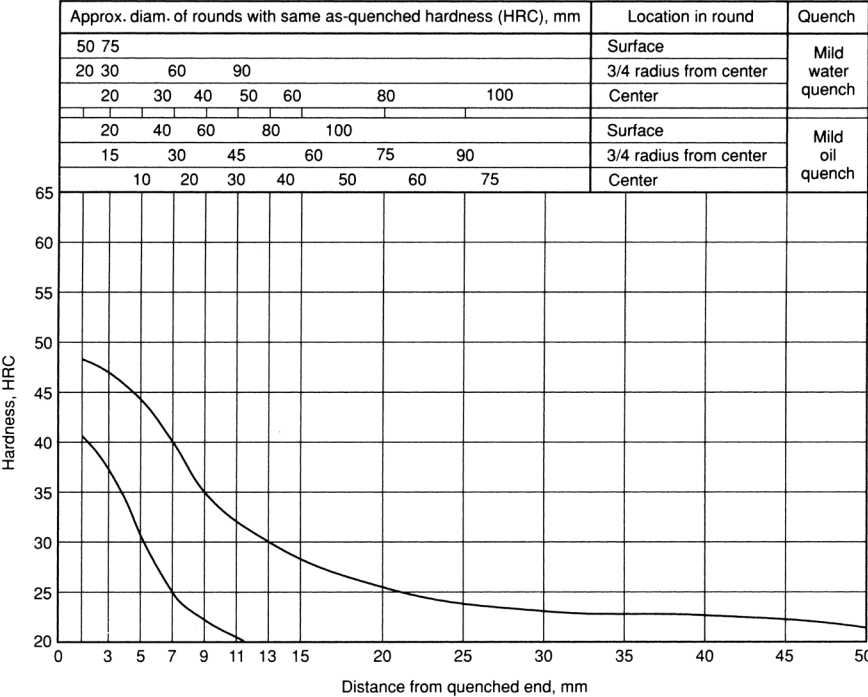


Fig. A6.7 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 870 °C (1600 °F). Austenitize, 845 °C (1550 °F). Source: Ref 1

SAE/AISI 8620H, UNS H86200

Hardness limits for specification purposes

J distance, mm	Hardness, HRC	
	Maximum	Minimum
1.5	48	41
3	47	37
5	44	31
7	40	25
9	35	22
11	33	20
13	30	...
15	29	...
20	26	...
25	24	...
30	23	...
35	23	...
40	23	...
45	22	...
50	22	...



Hardness limits for specification purposes

J distance, 1/16 in.	Hardness, HRC	
	Maximum	Minimum
1	48	41
2	47	37
3	44	32
4	41	27
5	37	23
6	34	21
7	32	...
8	30	...
9	29	...
10	28	...
11	27	...
12	26	...
13	25	...
14	25	...
15	24	...
16	24	...
18	23	...
20	23	...
22	23	...
24	23	...
26	23	...
28	22	...
30	22	...
32	22	...

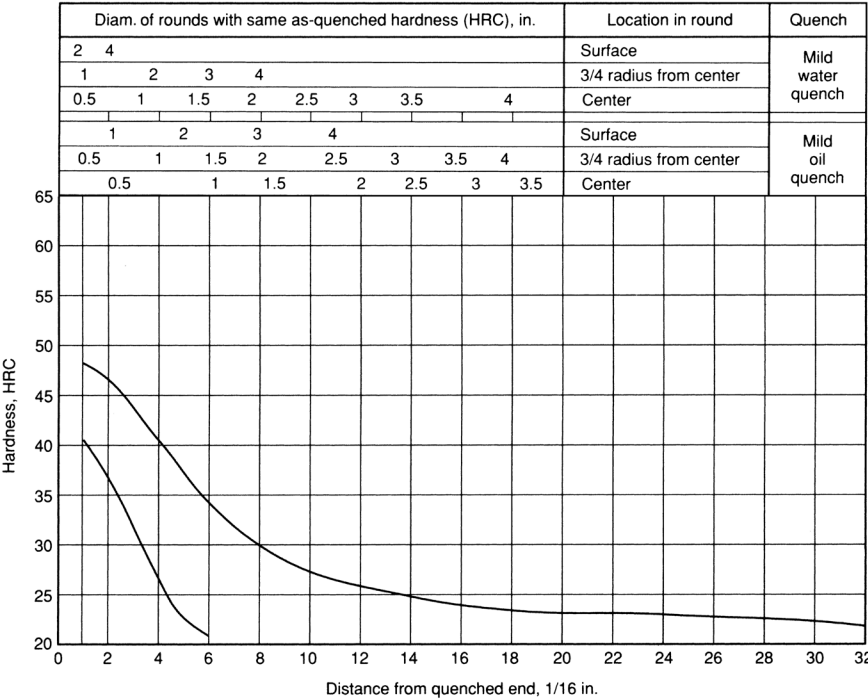


Fig. A6.8 Heat-treating temperatures recommended by SAE. Normalize (for forged or rolled specimens only), 925 °C (1700 °F). Austenitize, 925 °C (1700 °F). Source: Ref 1

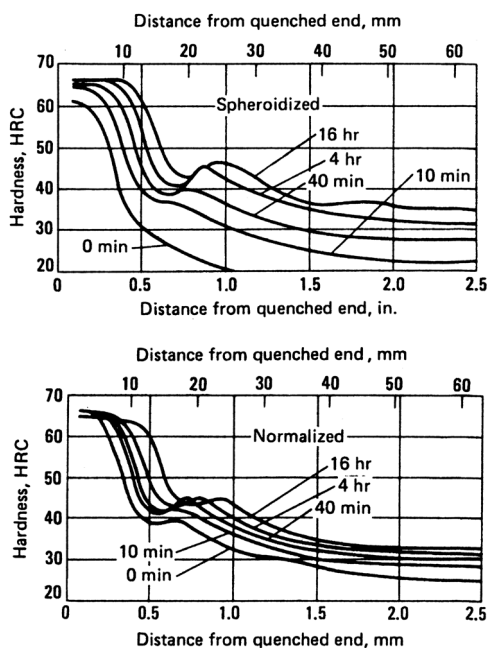


Fig. A6.9 E52100 end-quench hardenability, austenitized at 845 °C (1550 °F). Insufficient time to permit full carbide solubility in austenite.
Source: Ref 2

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