Induction Heating Theory-Principle

INDUCTION HEATING was first noted when it was found that heat was produced in transformer and motor windings, as mentioned in the Chapter "Heat Treating of Metal" in this book. Accordingly, the theory of induction heating was studied so that motors and transformers could be built for maximum efficiency by minimizing heating losses. 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. Throughout the years the understanding of the basic principles has been expanded, extending currently into computer modeling of heating applications and processes. Knowledge of these basic theories of induction heating helps to understand the application of induction heating as applied to induction heat treating. Induction heating occurs due to electromagnetic force fields producing an electrical current in a part. The parts heat due to the resistance to the flow of this electric current.

Resistance

All metals conduct electricity, while offering resistance to the flow of this electricity. The resistance to this flow of current causes losses in power that show up in the form of heat. This is because, according to the law of conservation of energy, energy is transformed from one form to another—not lost. The losses produced by resistance are based upon the basic electrical 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 losses (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 there were some induction heaters built in World War II that had silver wiring because of the copper shortage). Copper wires are used to carry electricity through power lines because of the low heat losses during transmission. Other metals, such as steel, have high resistance to an electric current, so that 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 household, 60 Hz 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 (elec-

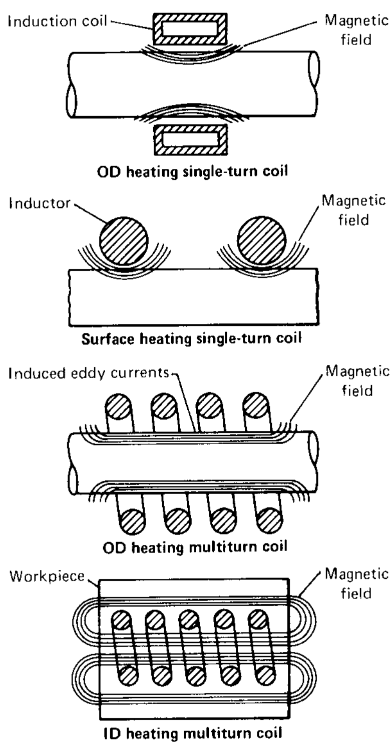

Fig. 2.1 Induction coil with electromagnetic field. OD, outside diameter; ID, inside diameter. Source: Ref 1

tromagnetic, 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 is dependent 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 upon the physical properties of the workpieces as they are being heated. These properties are temperature dependent, and the specific heat, magnetic permeability, and resistivity of metals change with temperature. Figure 2.2 shows the change in specific heat (ability to absorb heat) with temperature

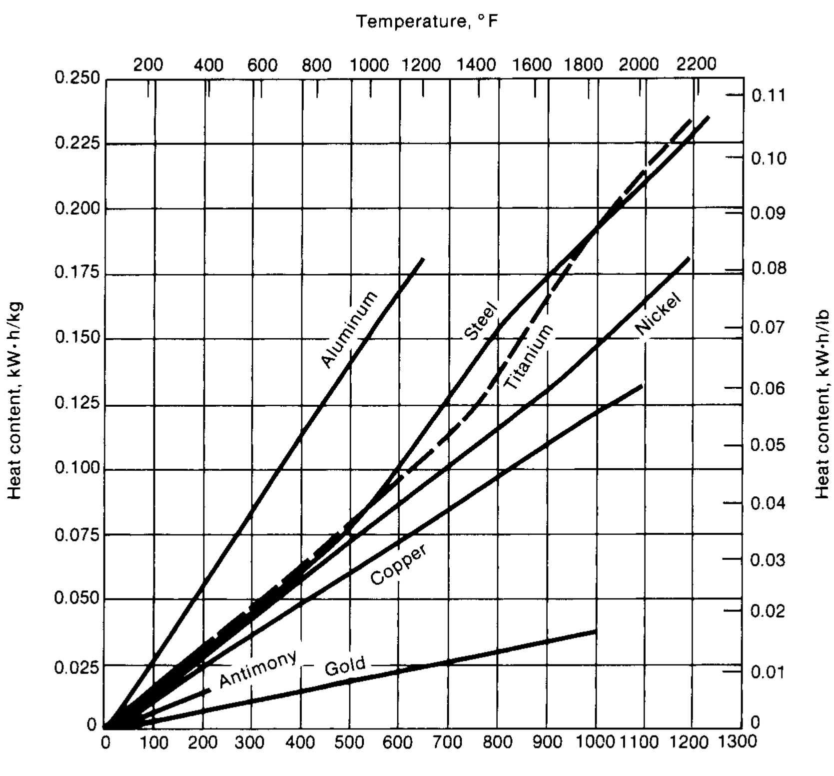

Fig. 2.2 Change in specific heat with temperature for materials. Source: Ref 2

for various materials. Steel has the ability to absorb more heat as temperature increases. This means that more energy is required to heat steel when it is hot than when it is cold. Table 2.1 shows the difference in resistivity at room temperature between copper and steel with steel showing about ten times higher resistance than copper. At 760 °C (1400 °F) steel exhibits an increase in resistivity of about ten times larger than when 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 the 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 are being heated, such as those made from carbon steels, 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

Table 2.1 Resistivity of different metals

	Approximate electrical resistivity, μK · cm (μK · in.), at temperature, °C (°F), of:							
Material	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

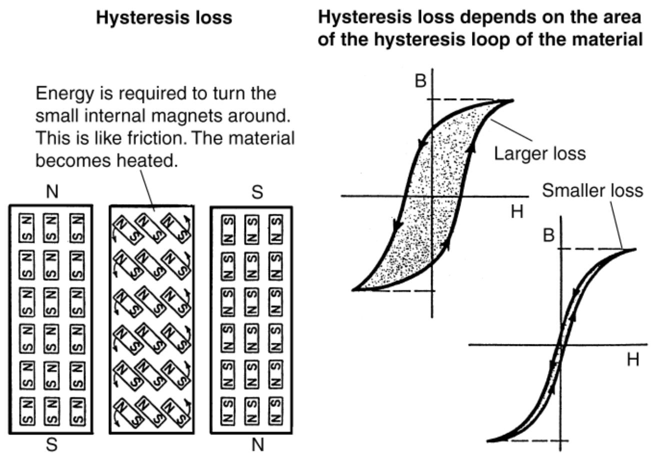

Fig. 2.3 Effect of hysteresis on heating rate. N, north; S, south; B, flux density in a ferromagnetic material; H, corresponding magnetic intensity. Source: Ref 4

occur. Figure 2.3 shows an illustration of hysteresis and the effect on the magnetic flux field strength. Figure 2.4, as represented by the line "ABCD," shows the Curie temperature for carbon steels.

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 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 heating that a given frequency will produce at a given power and workpiece temperature. The cross-sectional size of the workpiece being heated must be at four times the reference depth, or what appears to be current cancella-

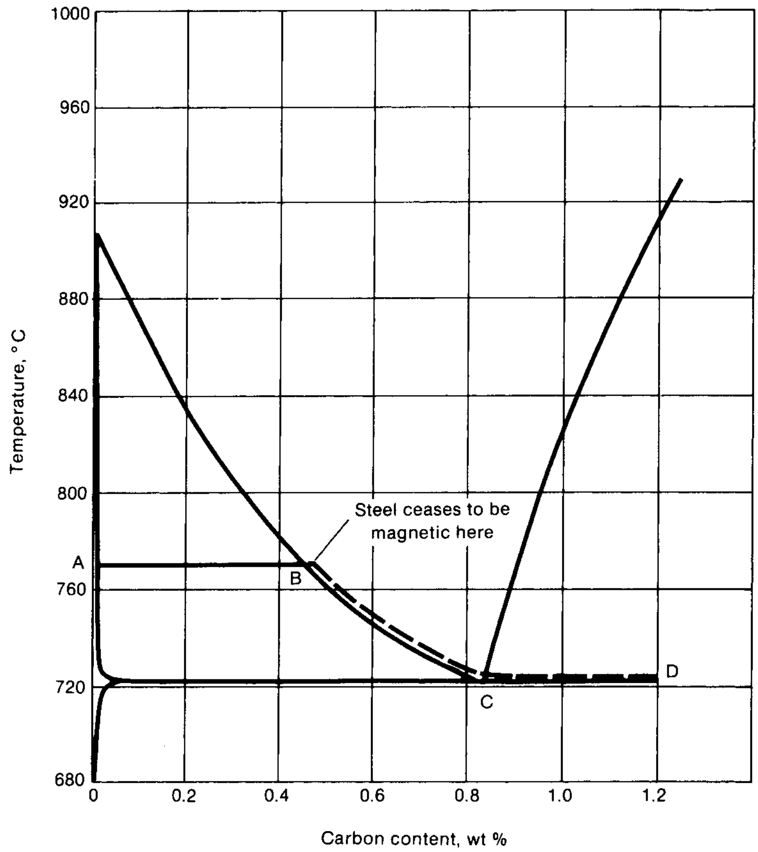

Fig. 2.4 Curie temperature for carbon steels. Source: Ref 2

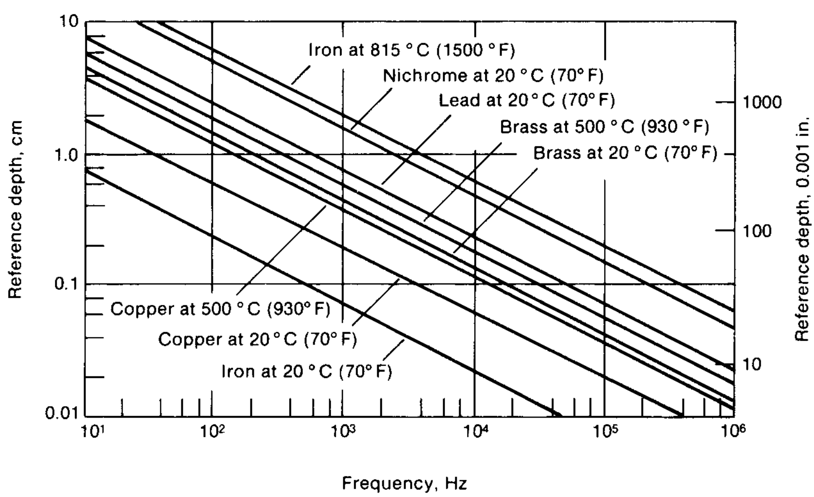

Fig. 2.5 Reference depth for various materials. Source: Ref 2

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

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 one (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, the *a*/*d* ratio of 4 when austenitizing must be based on the reference depth when the steel is at a temperature above the Curie. Figure 2.8 shows an illustration of the deeper depth of current penetration over the Curie. Because of these effects the reference depth of nonmagnetic materials may vary by a factor of two or three 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 as compared to hot steel.

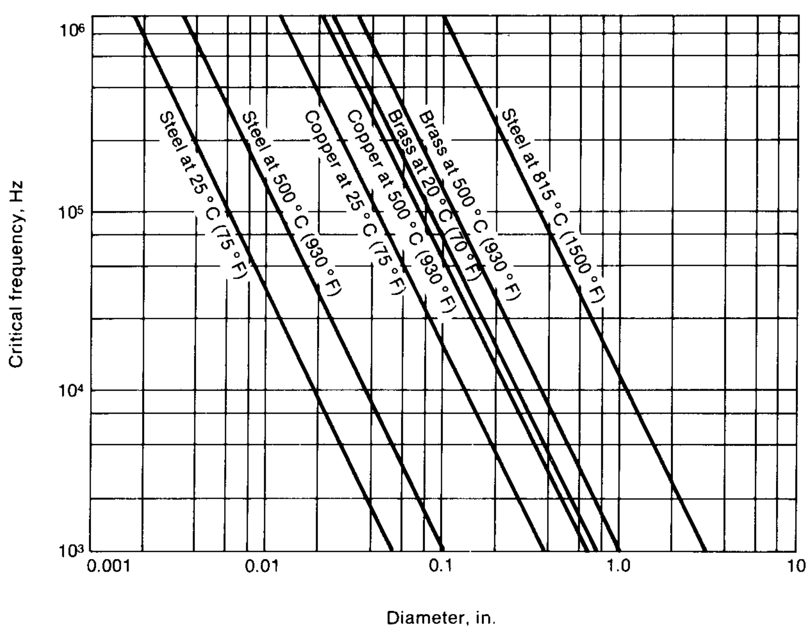

Fig. 2.6 Critical frequency for efficient heating of several materials. Source: Ref 2

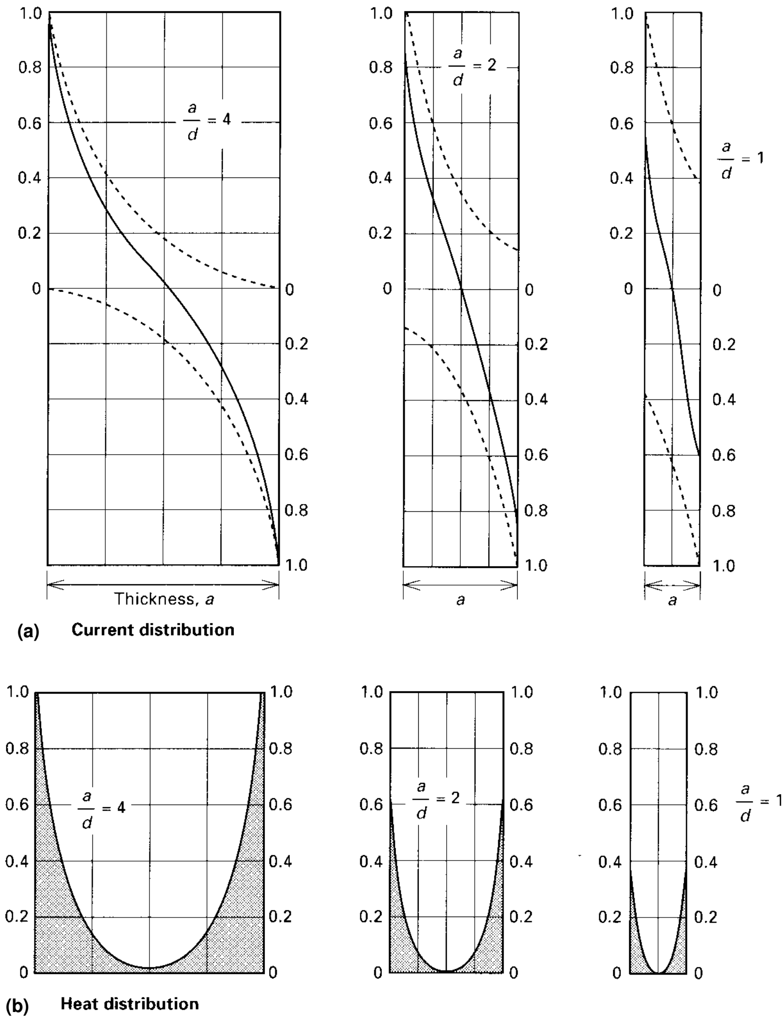

Fig. 2.7 (a) Ratios of object thickness, *a*, and reference depth, *d*. (b) Net heating curves. Source: Ref 5

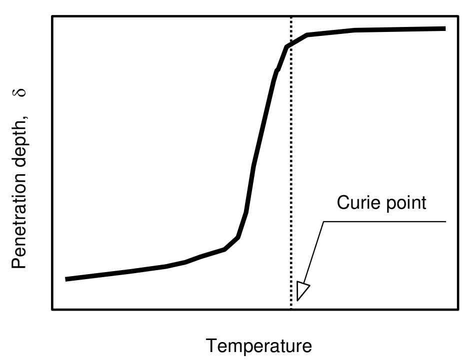

Fig. 2.8 Variation of current penetration depth through Curie. Source: Ref 6

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 to 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 critical frequency as a function of diameter for round bars and Figure 2.10 shows the efficiency of heating as a function of this critical frequency. Higher frequencies are needed to efficiently heat small bars, but as Figure 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 four-to-one ratio will be selected based on a combination of being both higher than the critical frequency and high enough to generate the desired skin effect heating for

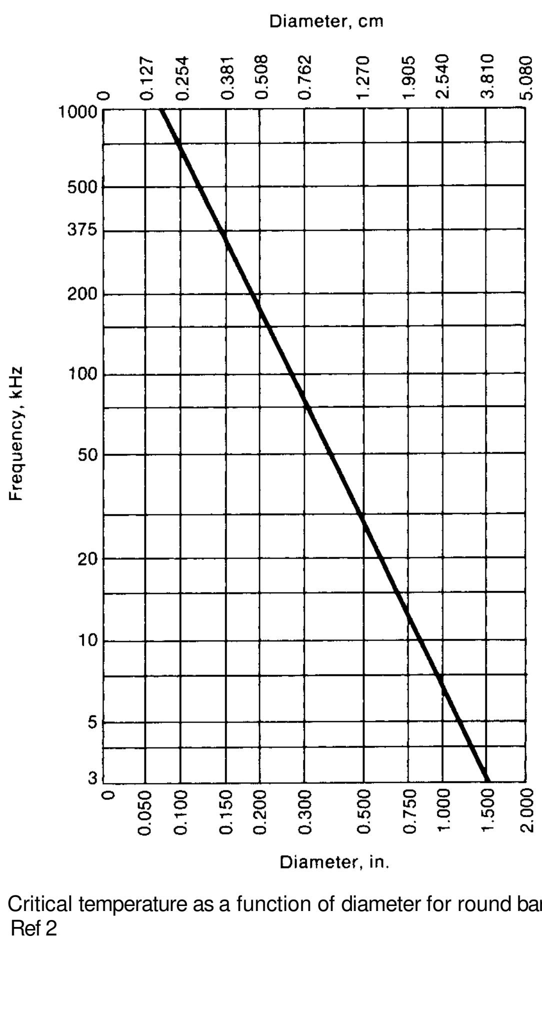

Fig. 2.9 Critical temperature as a function of diameter for round bars. Source: Ref 2

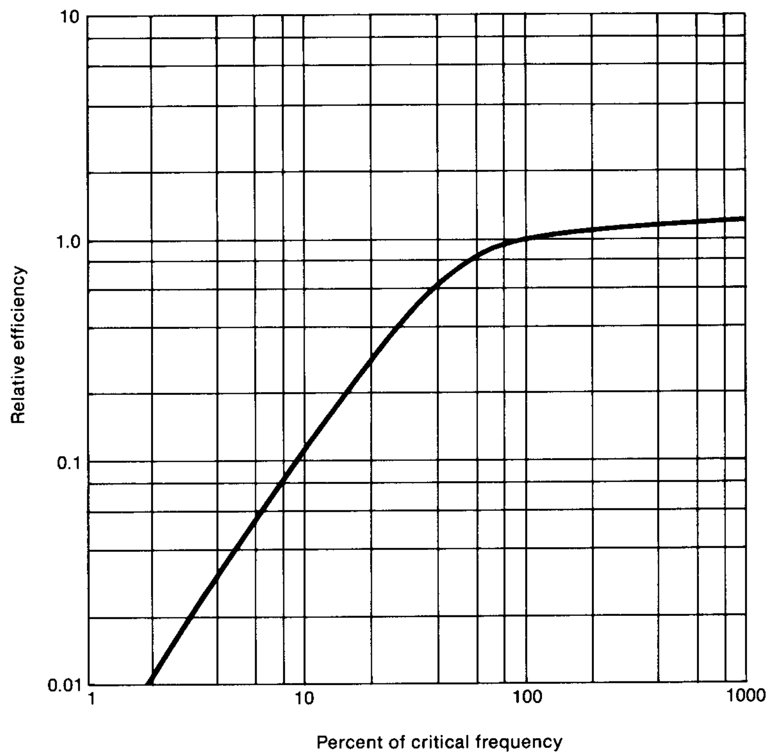

Fig. 2.10 Efficiency of heating as a function of frequency. Source: Ref 2

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. The Chapter "Induction Heat Treating Process Analysis" in this book discusses 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 within the induction coil and is expressed in kW/cm^2 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 kWh is (lbs/hour × specific heat × temperature rise)/ 3413, where the pounds per hour relate to (3,600 seconds × 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 2.2 shows the typical system losses for a typical solid-state power supply system and a radio frequency (RF) vacuum tube system. Through calculation of 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 the Chapter, "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. The Chapter "Induction Heat Treating Process Analysis" in this book 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/cm^2 (10 kW/in.^{2}) is needed and the area to be heated is 5 square inches, 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 workpieces 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

Table 2.2 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 7

the Appendix "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 the Chapter "Induction Heat Treating Systems" in this book. Tables of power densities are listed in that Chapter as well, and tables of scanning speeds are listed in the Appendix "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 minor effect. 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 interreaction 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.

One way to view the heat propagation is as a wave format. 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 2.11 shows the temperature profile of heat for 25 kHz on a 50 mm (2 in.) cylinder. At 0.4 s the surface being heated is being heated under the Curie and is nonmagnetic. At 1.15 s the surface is nonmagnetic, and the surface is heating deeper with minor temperature migration into the core. At 6.5 s 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

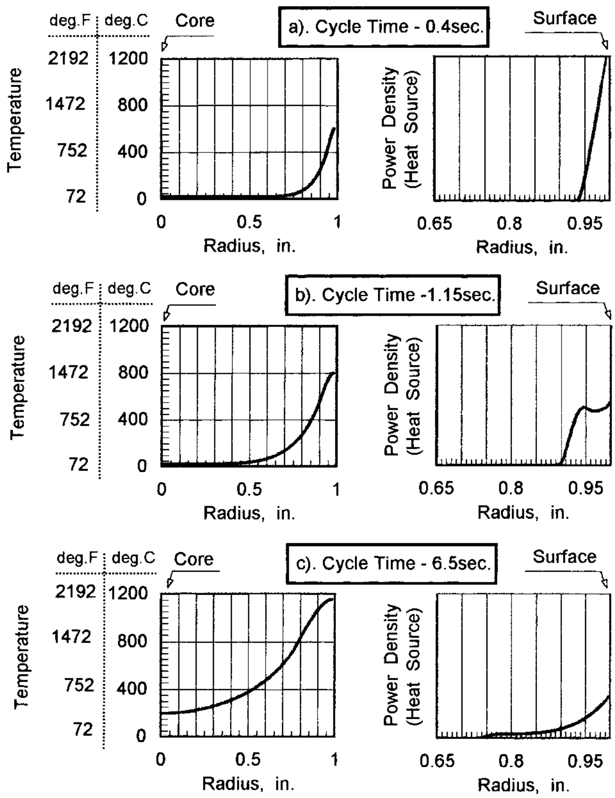

Fig. 2.11 Interrelationship among heating time, power density, and hardened depth. Source: Ref 6

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 in the circumstance of small diameter parts). During case hardening, cooling occurs from both the outer surface on which the quenchant is being applied, and the core towards which the heat is migrating. Holes under the case can affect both the eddy-current distribution and heat transfer. This is discussed in the Chapter "Induction Heat Treating Process Analysis" in this book.

The important thing to remember in frequency selection is 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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