Kirk-Othmer Encyclopedia of Chemical Technology.

FURNACES, ELECTRIC, INDUCTION FURNACES

Induction furnaces utilize the phenomena of electromagnetic induction to produce an electric current in the load or workpiece. This current is a result of a varying magnetic field created by an alternating current in a coil that typically surrounds the workpiece. Power to heat the load results from the passage of the electric current through the resistance of the load. Physical contact between the electric system and the material to be heated is not essential and is usually avoided. Nonconducting materials cannot be heated directly by induction fields.

Utility power distribution grids normally operate at a fixed frequency of 50 or 60 Hz. These frequencies can be utilized directly for the induction process if the load characteristics are appropriate. If they are not, specific applications can be optimized by the use of variable and higher frequencies produced by solid-state frequency power converters connected between the supply and the load.

The efficiency of an induction furnace installation is determined by the ratio of the load useful power, P_{n}, to the input power P_{o}, drawn from the utility. Losses that must be considered include those in the power converter (transformer, capacitors, frequency converter, etc), transmission lines, coil electrical losses, and thermal loss from the furnace. Figure 1 illustrates the relationships for an induction furnace operating at a constant load temperature with variable input power. Thermal losses are constant, coil losses are a constant percentage of the coil input power, and the useful out power varies linearly once the fixed losses are satisfied.

1. Induction Heating

1.1. Design

The coil of an induction heater typically encircles the load, as shown in Figure 2. The current intensity within the load is greatest at the surface and diminishes to zero at the center (Fig. 2**a**) (1). This crowding of the current close to the surface is known as skin effect. The rate at which the current intensity decreases from its maximum value at the surface is a function of the applied frequency, the resistive and magnetic properties of the load, and the load diameter. A useful term in induction design is reference depth, which is defined as the thickness of a shell that with a constant value of current equal to the current at the surface of the load results in developing the same power as the actual load (Fig. 2**b**). The electrical efficiency of an optimized induction heating coil and load combination as a function of reference depth is shown in Figure 3. The curve suggests that a minimum load diameter of four times the reference depth is desirable for reasonable efficiency.

1.2. Power Supplies and Controls

Induction heating furnace loads rarely can be connected directly to the user's electric power distribution system. If the load is to operate at the supply frequency, a transformer is used to provide the proper load voltage as well as isolation from the supply system. Adjustment of the load voltage can be achieved by means of a tapped transformer or by use of a solid-state switch. The low power factor of an induction load can be corrected by installing a capacitor bank in the primary or secondary circuit.

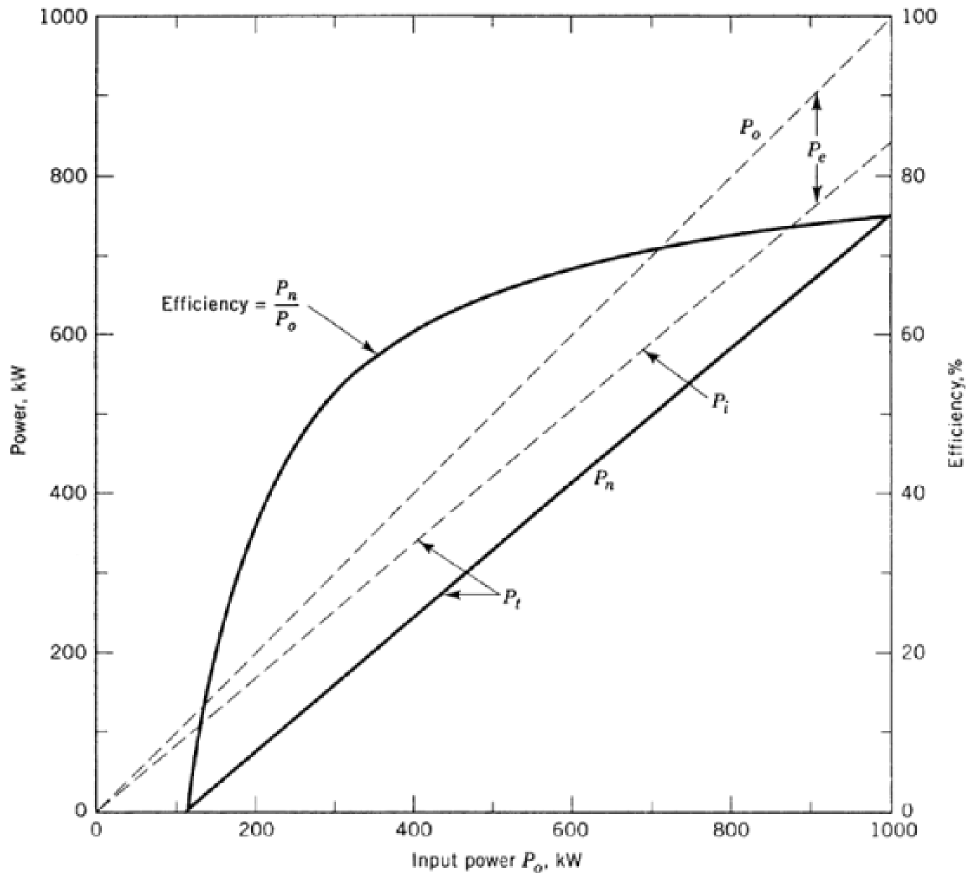

Fig. 1. Induction furnace efficiency. Typical characteristics of a 1000 kW furnace. Example: P_e=15% of P_o and P_t=100 kW. P_n=useful power; P_o=power input; P_e=electrical loss; P_i=induced power; and P_t=thermal loss.

Some induction heating furnaces must operate at frequencies higher than the supply frequency. Formerly, rotating motor alternator frequency converters were used. Now the availability of high speed, high power silicon controlled rectifiers for use in frequency converters has made rotary converters obsolete. Modern units operate at higher efficiency, cost less, require less factory space, and coordinate readily with process controls (2).

2. Economics

Induction heating equipment installations can require significant investment in electric power components as well as the work handling equipment made necessary by the process. These costs can be offset by savings in plant space, reduction in metal loss, precise control of product temperature, and reduced in-process inventory. A typical continuous induction heating line consumes about 360 kW·h/t heating carbon steel bars to 1230°C.

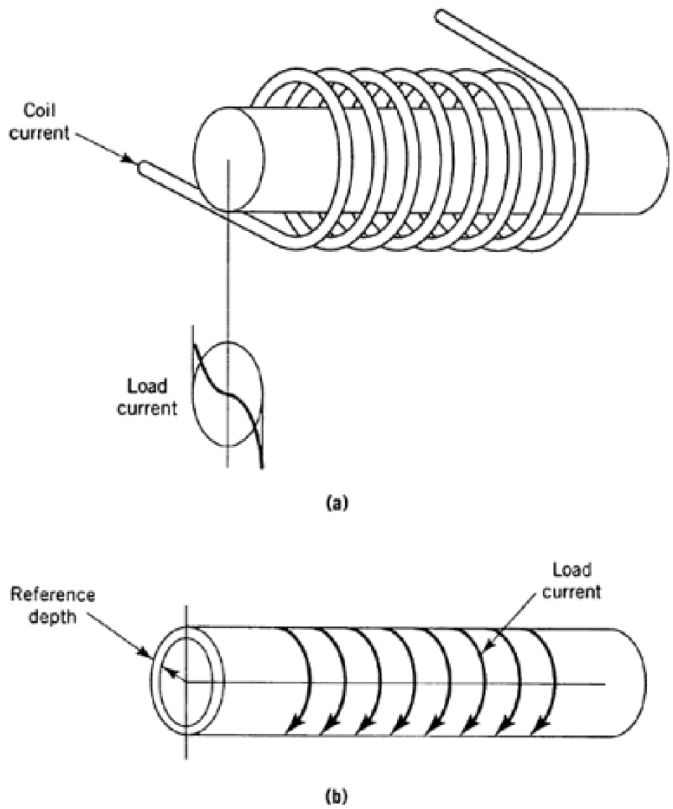

Fig. 2. Induction heating coil and load showing (**a**), current distribution in load, and (**b**), reference depth.

3. Applications

A unique capability of induction heating is apparent in its ability to heat the surface of a part to a high temperature while the interior remains at room temperature. Proper selection of material, high frequency, and high power density can produce a thin surface hardness with a heat unaffected core (3). Figure 4 shows the cross section of a typical automotive shaft heated with 10 kHz at various power densities. The required hardness depth is selected to satisfy the product requirements. The ability to precisely control the power and length of the induction heating cycle allows it to be integrated into complex work handling equipment.

Induction heating using low frequency and low power density when applied to a stationary or moving bar can produce a uniformly heated part suitable for introduction to a rolling mill (4). A coil line capable of producing 32 t/h of 17.8 cm (7 in.) diameter alloy steel bars heated to 1177°C is shown in Figure 5.

Induction heating is used to heat steel reactor vessels in the chemical process industry (5). The heat produced in the walls is conducted to the material within. Multisectioned coils are used to provide controlled heat input to the process material as it passes through the reactor. Figure 6 illustrates a cross section of such a typical installation.

High process temperatures generally not achievable by other means are possible when induction heating of a graphite susceptor is combined with the use of low conductivity high temperature insulation such as flake carbon interposed between the coil and the susceptor. Temperatures of 3000°C are routine for both batch or continuous production. Processes include purification, graphitization, chemical vapor deposition, or carbon

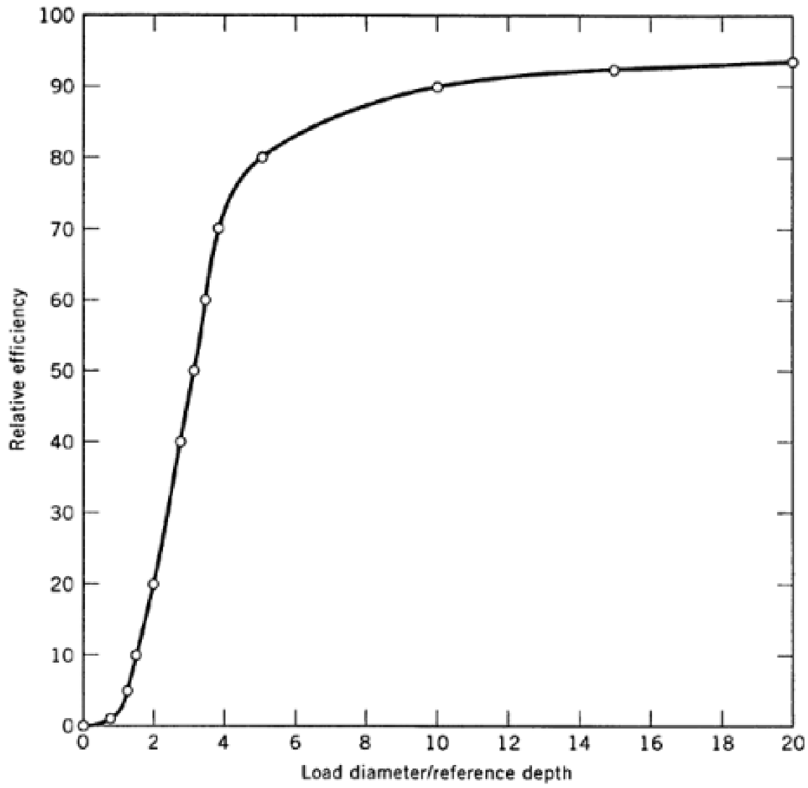

Fig. 3. Relative coil efficiency vs ratio of load diameter to reference depth.

vapor deposition to produce components for the aircraft and defense industry. Figure 7 illustrates a furnace suitable for the production of aerospace brake components in a batch operation.

A special coil configuration is used to heat thin strips of metal that cannot be heated efficiently with a coil that encircles the load, as the strip thickness is small compared to the depth of penetration. The transverse flux induction coil is positioned on either side of a strip to produce a uniformly heated strip with good efficiency in a much smaller space than conventional radiant or convective strip heating furnaces (6).

4. Induction Melting

Induction melting applications almost always contain the liquid metal charge within a hearth formed by a suitable refractory material. It is possible to design the hearth to satisfy a wide variety of application requirements ranging from a few kilograms to hundreds of tons of metal and for operation in normal or hostile environments. As the heat is developed within the charge, the metal and the furnace refractory are not exposed to excessive temperatures that may be present in either electric arc or fuel-fired furnaces (7, 8). Operation is practical in vacuum or inert atmospheres for the production of critical materials that require protection from oxygen or other gases. The environmental impact of an induction furnace is generally less than that of an equivalent fuel-fired furnace.

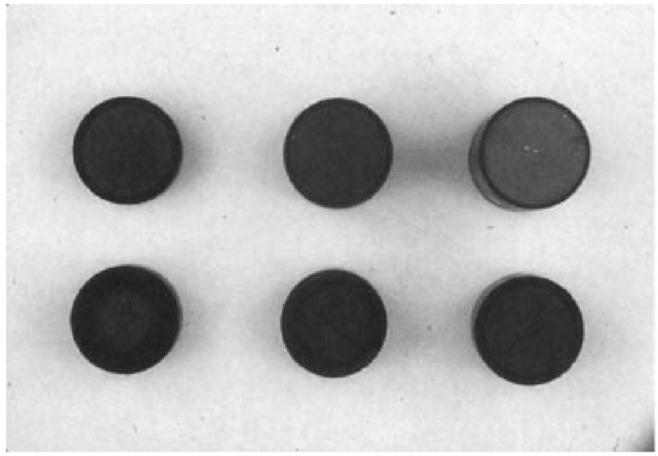

Fig. 4. Automotive shaft cross sections showing the effect of power density vs hardened depth.Courtesy of Ajax Magnethermic Corp.

5. Coreless Induction Furnaces

Coreless furnaces derive their name from the fact that the coil encircles the metal charge but, in contrast to the channel inductor described later, the coil does not encircle a magnetic core. Figure 8 shows a cross section of a typical medium sized furnace. The coil provides support for the refractory that contains the metal being heated and, therefore, it must be designed to accept the mechanical loads as well as the conducted thermal power from the load. In small coreless furnaces the coil itself may possess sufficient strength to allow satisfactory operation. Larger furnaces provide support to the coil from surrounding structures.

5.1. Frequency Selection

When establishing the specifications for a coreless induction furnace, the material to be melted, the quantity of metal to be poured for each batch, and the quantity to be produced per hour must be considered simultaneously. Graphs have been developed that combine these factors with practical experience to indicate possible solutions for a specific requirement.

Skin effect is utilized in the design of coreless furnaces. It is particularly evident when the furnace is full of molten metal. Current and power are distributed within the volume of metal just as they are in an induction heating load. In both cases power density at the center of the coil is greater than at the ends of the coil, and in the coreless furnace this results in a circulation of metal. This circulation assists in the melting process by carrying the charge below the surface of the melt and assures a uniform bath temperature and metallurgical homogeneity. The use of lower frequencies produces stronger circulation in the same furnace at the same power level.

5.2. Operation

Small and medium sized *coreless induction furnaces* powered from high frequency power supplies can be started with a charge of metal pieces at room temperature, usually scrap material of appropriate alloy. The charge material is selected to allow a reasonable power to be drawn from the power supply. As the metal charge begins to melt, a molten pool is established and the charge compacts, allowing additional charge to be added. Alloy additions and temperature adjustments complete the melting cycle (9). Higher operating efficiency is achieved if the next cycle is initiated promptly after the charge is poured off so that the stored energy in

Fig. 5. Continuous bar heating line.Courtesy of Ajax Magnethermic Corp.

the hearth refractory is not lost to the coil cooling water. Large coreless furnaces operating at line frequency are often started with a molten initial charge, although it is possible to start with a charge of solid material. Typical operation of these furnaces involves dispensing 20 to 30% of the furnace capacity and immediately recharging dry or preheated material into the bath as power is applied. These furnaces are usually held full during off shifts to maximize refractory life. An alternative is to empty the furnace and maintain the refractory continuously warm with supplemental heat. Furnaces with capacities of 4.5 to 13.6 t with input power ratings of 825 to 1100 kW/t produce liquid iron at a consumption rate of 550 to 600 kW·h/t.

5.3. Hearth

The induction melting coil is almost always round and in the form of a right cylinder. It is highly desirable that the refractory lining within the coil be uniform in thickness, so most hearths are cylindrical whether they hold a few kg or 59 t. There are a few instances of a smaller coil being attached to the bottom of a larger hearth, so the hearth could be modified to suit a particular requirement (10). Oval coils have been built and operated satisfactorily, but they are rare.

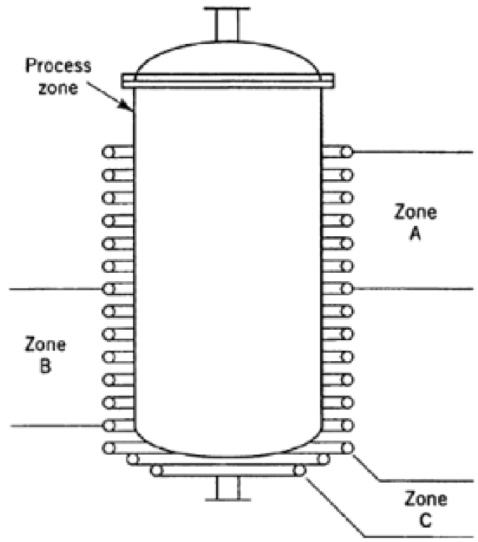

Fig. 6. Process reactor.

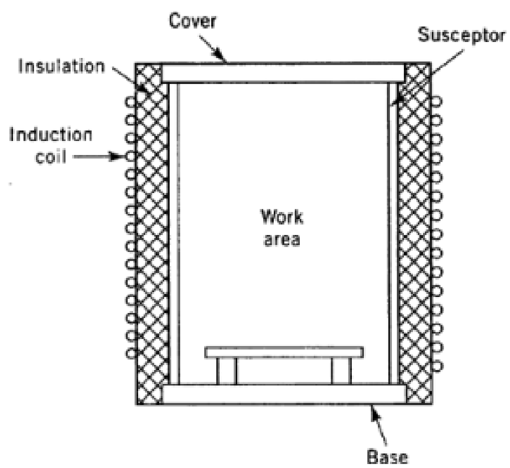

Fig. 7. High temperature processor.

6. Channel Induction Furnaces

The term *channel induction furnace* is applied to those in which the energy for the process is produced in a channel of molten metal that forms the secondary circuit of an iron core transformer. The primary circuit consists of a copper coil which also encircles the core. This arrangement is quite similar to that used in a utility transformer. Metal is heated within the loop by the passage of electric current and circulates to the hearth above to overcome the thermal losses of the furnace and provide power to melt additional metal as it is added. Figure 9 illustrates the simplest configuration of a single-channel induction melting furnace. Multiple inductors are also used for applications where additional power is required or increased reliability is necessary for continuous operation (11).

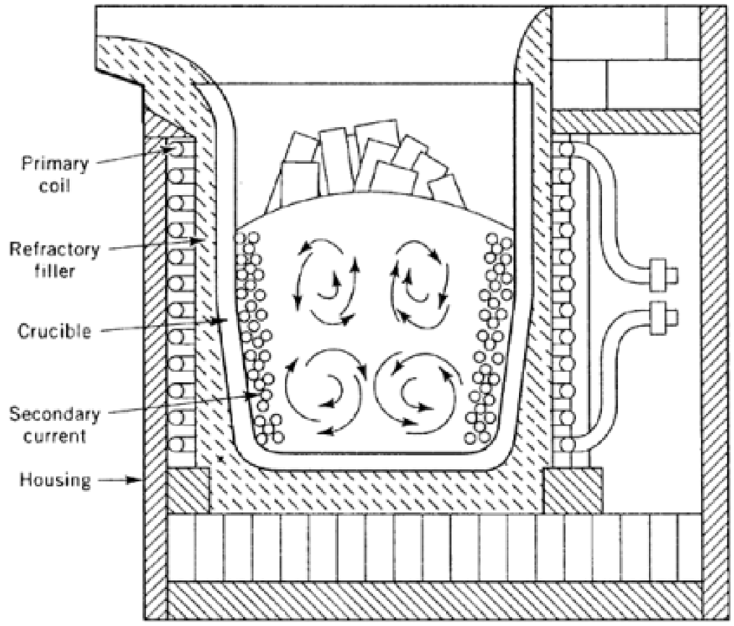

Fig. 8. Small coreless-induction furnace, 500-kg high frequency furnace with insulating board housing and crucible.

6.1. Inductor

The channel inductor assembly consists of a steel box or case that contains the inductor refractory and the inductor core and coil assembly. The channel is formed within the refractory. Inductor power ratings range from 25 kilowatts for low temperature metals to 5000 kilowatts for molten iron. Forced air is used to cool the lower power inductors, and water is generally used to cool inductors rated 500 kilowatts or more.

Metal contained in the channel is subjected to forces that result from the interaction between the electromagnetic field and the electric current in the channel. These inward forces produce a circulation that is generally perpendicular to the length of the channel. It has been found that shaping the channels of a twin coil inductor shown in Figure 10 produces a longitudinal flow within the channel and significantly reduces the temperature difference between the channel and the hearth (12).

6.2. Hearth

The hearth of a channel induction furnace must be designed to satisfy restraints that are imposed by the operating inductor, ie, the inductor channels must be full of metal when power is required, and it is also necessary to provide a sufficient level of metal above the channels to overcome the inward electromagnetic pressure on the metal in the channel when power is applied. Once these requirements are satisfied, the hearth can then be tailored to the specific application (13). Sizes range from stationary furnaces holding a few hundred kilograms of aluminum to rotating drum furnaces with a useful capacity of 1500 t of liquid iron.

The refractory used to construct the hearth can be in the form of bricks, preformed shapes, or monolithic. Often a furnace design utilizes all three. Openings or passageways through the walls are fashioned in the same manner as windows in a brick building.

The steel shell that encloses the refractory is exposed to significant forces from the expansion of the refractory as well as the load from the refractory and the charge within the furnace. Similarly, the structures

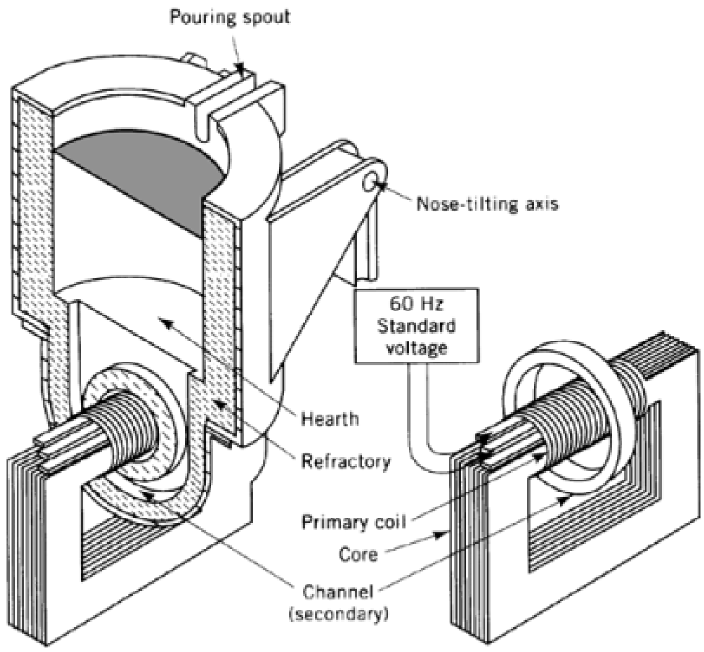

Fig. 9. Basic channel furnace.Courtesy of Ajax Magnethermic Corp.

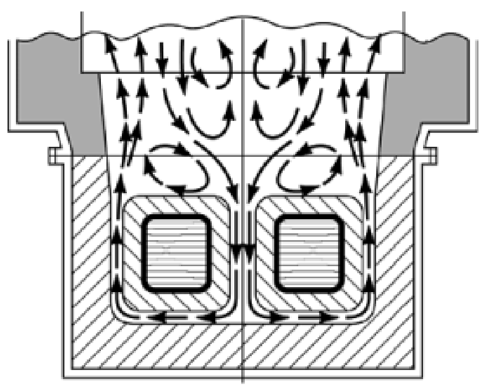

Fig. 10. Twin coil, jet flow inductor.Courtesy of Ajax Magnethermic Corp.

that support the furnace and the foundations must be designed to assure safe operation. A failure of any component can have serious consequences.

6.3. Operation

Channel furnaces can be used for melting or holding metal. In either case, the inductor and the hearth refractory are preheated to avoid thermal shock as the liquid metal is introduced at start up. Once the inductor channel has been flooded, it is rarely emptied until the inductor is taken out of service. Inductor life can vary from six months to a number of years depending on the metal alloy and the size and power rating of the inductor.

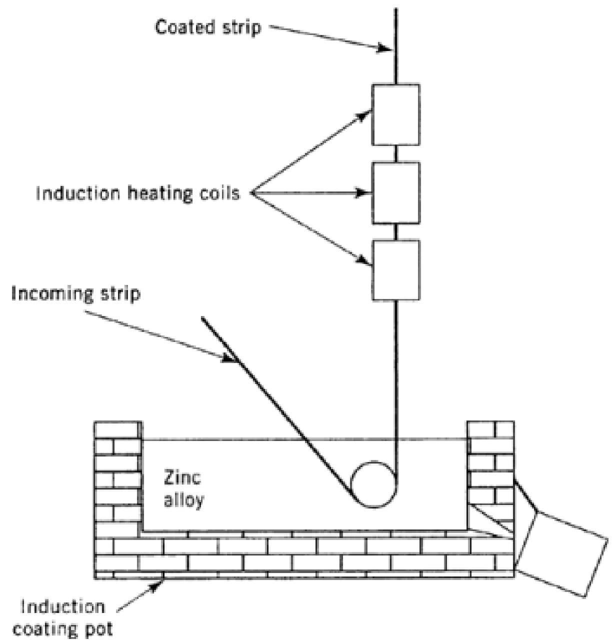

Fig. 11. Galvanize–galvanneal installation.

Channel melting furnaces are often designed so that a large portion of their total capacity can be discharged by tilting or rotating the furnace. Dry or preheated metal is added to the furnace at the melt rate of the furnace.

Holding furnaces usually operate with a relatively constant metal level. Included in this category are furnaces that supply metal to various casting processes and large pots that hold metal for continuous coating lines. Multiple inductor furnaces are designed so that individual inductors can be replaced without emptying the remaining inductors.

6.4. Applications

Small and medium sized foundries producing castings for automotive and other similar applications often utilize iron melting channel melting furnaces. They allow melting off shift at lower power demands and make their total working batch available at the start of the pouring shift. Power consumption under these operation conditions ranges from 600 to 880 kW·h/t. More continuous operation can reduce this figure. Furnaces have been designed to superheat liquid iron delivered in 90 t batches prior to its introduction into a basic oxygen furnace (BOF) for conversion to steel. Similar furnaces are utilized for duplexing in conjunction with cupolas in large foundries.

A typical melter installed in a medium sized brass foundry contains 4500 kg of brass and its inductor is rated 500 kilowatts. Brass is an alloy containing copper and zinc. Zinc vaporizes at temperatures well below the melting temperature of the alloy. The channel inductor furnace's low bath temperature and relatively cool melt surface result in low metal loss and reduced environmental concerns. Large drum furnaces have found use in brass and copper continuous casting installations.

A combination of a channel induction holding furnace with an induction heating coil is shown in Figure 11. Steel strip is introduced into a zinc bath in a coating pot. The process is called continuous galvanizing. In this installation further heating of the strip extends the alloying of iron and zinc to produce a "galvannealed" strip for automobile bodies with improved fabrication and corrosion resistance characteristics (14, 15). The control provided by the use of induction furnaces results in a superior product compared to fuel-fired alternatives.

BIBLIOGRAPHY

"Induction Furnaces" under "Furnaces, Electric" in *ECT* 1st ed., Vol. 7, pp. 1–23, by V. Paschkis, Columbia University; in *ECT* 2nd ed., Vol. 10, pp. 252–278, by V. Paschkis, Columbia University; in *ECT* 3rd ed., Vol. 11, pp. 542–550, by M. Tama, Ajax Magnethermic Corp.

Cited Publications

1. J. T. Vaughan and J. W. Williamson, *AIEE Trans.* **65**, 887–892 (1946).
2. G. F. Bobart, *Ind. Heat.*, 22–26 (June 1989).
3. R. F. Kern, *Heat Treat.*, 20–24 (Dec. 1991).
4. S. B. Lasday, *Ind. Heat.*, 42–46 (Feb. 1992).
5. K. G. Webley, "Induction Heating of Steel Reactor Vessels," *Chemical Process Industry Symposium*, AICHE, Philadelphia, Pa., June 5–8, 1978.
6. S. B. Lasday, *Ind. Heat.*, 43–45 (Oct. 1991).
7. S. B. Lasday, *Ind. Heat.*, 31 (Sept. 1991).
8. *Foundry Manage. Technol.*, B3–B13 (Dec. 1990).
9. H. Roth, *ABB Review*, 25–33 (June 1990).
10. H. G. Heine and J. B. Gorss, *Metallurgical Trans. A*, 489–513 (Nov. 1990).
11. M. Tama, *J. Metals*, (Jan. 1974).
12. U.S. Pat. 3,595,979 (July 27, 1971), W. E. Shearman (to Ajax Magnethermic).
13. H. Roth, *ABB Review*, 25–33 (June 1990).
14. U.S. Pat. 4,895,736 (Jan. 23, 1990), R. A. Sommer, G. Havas, and M. Tama.
15. T. J. Logan, *Steel Technol. Int.*, 227 (1992).

General References

16. American Foundrymen's Society, Inc., *Refractories Manual*, 2nd ed., Des Plaines, Ill., 1989.
17. American Society for Metals, *Metals Handbook, Heat Treating*, Vol. **4**, 9th ed., Metals Park, Ohio, 1991.
18. Materials Engineering Institute, *Course 60, Induction Heating*, American Society for Metals, Metals Park, Ohio, 1986.
19. S. L. Semiatin and D. E. Stutz, *Induction Heat Treatment of Steel*, American Society for Metals, Metals Park, Ohio, 1986.
20. W. Trinks, *Industrial Furnaces*, Vol. **1**, 4th ed., John Wiley & Sons, Inc., New York, 1951.
21. C. A. Tudbury, *Basics of Induction Heating*, John Rider, New York, 1960.
22. S. Zinn and S. L. Semiatin, *Elements of Induction Heating*, Electric Power Research Institute, Palo Alto, Calif., 1988.

RICHARD A. SOMMER
Consultant

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