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VALERY RUDNEV, DON LOVELESS, KURT SCHWEIGERT, PETER DICKSON AND MIKE RUGG
INDUCTOHEAT, INC. | MADISON HEIGHTS, MI

Efficiency and Temperature Considerations in Induction Re-Heating of Bar, Rod and Slab

WHEN DESIGNING MODERN IN-LINE INDUCTION HEATING SYSTEMS, A REQUIREMENT FOR TEMPERATURE UNIFORMITY OF THE RE-HEATED PRODUCT IS ONLY ONE OF THE GOALS. ADDITIONAL DESIGN CRITERIA INCLUDE COST, MAXIMUM PRODUCTION RATE, MINIMUM METAL LOSSES (DUE TO SCALE, OXIDATION, BURNS, DECARBURIZATION, ETC.) AND PROVIDING COMPACT SYSTEMS THAT HAVE A HIGH ELECTRICAL EFFICIENCY. OTHER IMPORTANT FACTORS INCLUDE QUALITY ASSURANCE, ENVIRONMENTAL FRIENDLINESS, AUTOMATION CAPABILITY, RELIABILITY AND MAINTAINABILITY OF THE EQUIPMENT, AND COST. THIS ARTICLE DESCRIBES SEVERAL OF THESE CRITERIA.

Modern techniques for producing long products such as cylindrical and rectangular shaped bars and rods integrate three stages of production—casting, re-heating and rolling—into a continuous line. The goal of re-heating is to provide the bar/rod at the rolling stage with the desired temperature profile across its thickness, diameter and length. In some cases, initial temperature of the product prior to re-heating is ambient.

In other cases, the initial temperature is non-uniform due to uneven cooling of the rod/bar as it progresses from the caster.

In the past, gas-fired furnaces were typically used because of the low cost of gas. In recent years, however, bar/rod producers are shifting their preference toward induction heating systems. Gas-fired furnaces require a very long heating tunnel to achieve the desired temperature uniformity. The length presents a great problem in plants due to the limited space between the cast-

er and rolling mill. Also, gas-firing can result in poor bar surface quality (due to scale, decarburization, etc.), and faces environmental restrictions. These factors resulted in heating by induction becoming the popular approach to re-heating bars and rods of both ferrous and nonferrous metals.^[1]

“SURFACE-TO-CORE” TEMPERATURE PROFILES

Depending upon the process parameters, an induction bar/rod heating system may consist of one or several in-

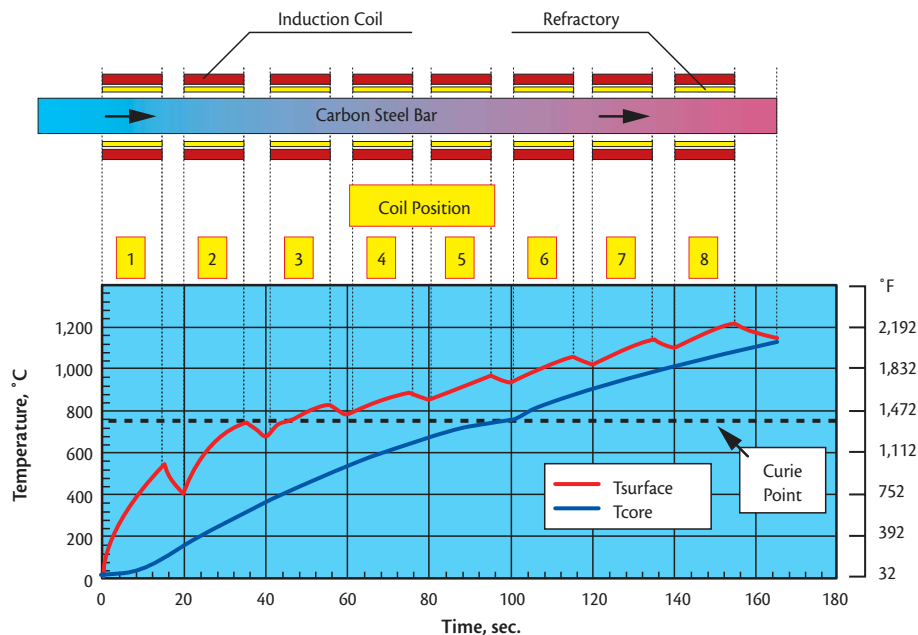


Fig. 1 Thermal profile of a steel bar being as processed through an eight-coil induction line.

line induction coils. The challenge in induction heating arises from the fact that “surface-to-core” temperature profile continues to change as the bar passes through the line of induction coils. Since the core of a bar is heated solely by thermal conductivity, the bar core tends to be heated more slowly than its surface. In addition, leading and trailing ends have a tendency to heat faster than the body of the bar.^[2]

The main reason for heat deficit in the core of the bar is the so called skin effect. This effect deals with current penetration depth (surface layer where 86% of power is induced) and depends upon metal properties and frequency (see Table I). It is typically much easier to provide “surface-to-core” temperature uniformity for metals with high thermal conductivity such as aluminum or copper bars. Metals with poor thermal conductivity, including stainless steel, titanium and carbon steel require extra care in order to obtain required temperature uniformity, including a careful determination of the number of induction coils, their design, distribution of power along the induction line, control features and frequency choice.

USE OF COMPUTER MODELING

By combining the use of advanced computer modeling software with sophisticated engineering background, modern induction heating specialists may analyze in a few hours, complex technological problems that could take days

or even weeks to solve using other methods. Computer models can predict how different factors impact the transitional and final heating conditions of the bar, and what must be accomplished in the design of the induction heating system to maximize the effectiveness of the process and guarantee

the desired thermal conditions. Fig. 1 shows the results of the transitional and final heating conditions of a 3 inch diameter carbon steel bar and its “surface-to-core” temperature profile along the induction line. The line consists of eight 6 inch diameter induction coils measuring 40 inches in length

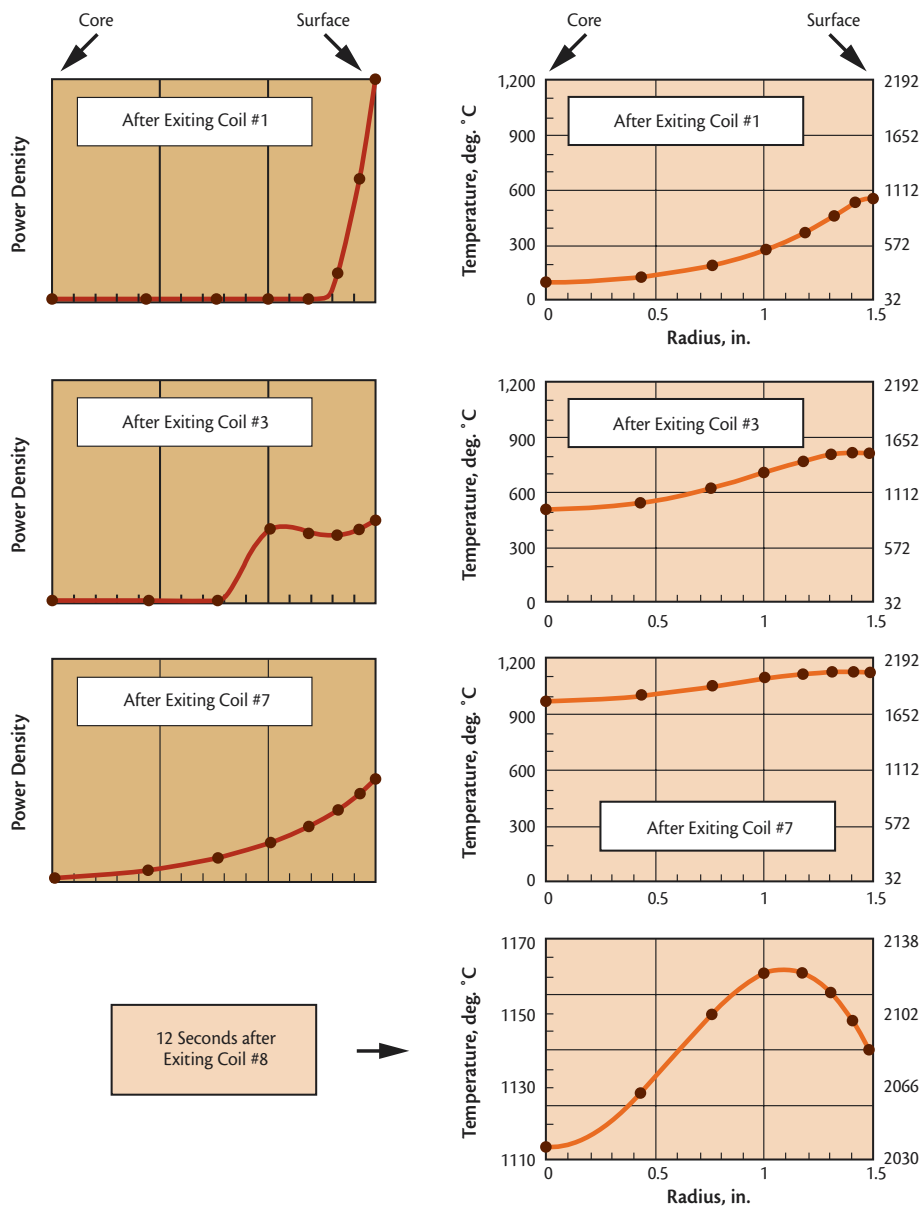


Fig. 2 Power density and temperature profiles of a bar at different positions in an in-line induction heater.

TABLE I CURRENT PENETRATION FOR HOT STEEL AS FUNCTION OF FREQUENCY

Frequency, kHz	Depth, mm	Depth, in.
0.06	72	2.83
0.5	25.1	0.99
1	17.7	0.7
10	5.6	0.22
30	3.2	0.13
200	1.25	0.05

with a gap of 12 inches between the coils. The coils are operating at 1 kHz at a production rate of 2.56"/sec. Refractory thickness is 0.5 inch.

In Fig. 2, typical "surface-to-core" temperature profiles and power density (heat source) distributions are shown along the radius of a bar after exiting Coils 1, 3, and 7 and after 12 sec. of bar transportation on free air (scales of power density profiles are different for various coil positions). The temperature profile does not match the heat source profile because of thermal conductivity of metal.^[1]

"NOSE-TO-TAIL" TEMPERATURE PROFILES

"Surface-to-core" is only one component of the thermal conditions specified by the customer. Another component is "nose-to-tail" temperature profile. When bars travel "end-to-end" through an induction heating line the "nose-to-tail" temperature uniformity is not a problem. However, in most cases, there is a 5 inch to 10 inch or more air gap between leading and following bars. Existence of these air gaps could create unacceptable temperature non-uniformity along the length of the bar.

An electromagnetic field distortion results in a variation of induced power in areas of the bar ends. This distortion is referred to as the electromagnetic end effect. In the case of non-magnetic metals (i.e., certain stainless steels, aluminum, titanium or carbon steel heated above Curie point), there is typically a surplus of induced power in the bar end area compared to its body.^[1]

For ferromagnetic bars, even inside a long inductor, the ends may be either overheated or underheated^[3] and the task of obtaining "nose-to-tail" temperature uniformity is typically a more difficult one compared to minimizing "surface-to-core" temperature gradient. Studies show that the power deficit causing underheating of the end area will be pronounced for steels with high magnetic permeability heated with relatively low or moderate power density. In some cases, it can have a unique "wave-shaped" power distribution along the bar length. In this case, there will be a local surplus of power in the end of a bar, however in the region adjacent to the end there will be a power deficit compared to the power induced in the body of the bar.

INDUCTION HEATING MANUFACTURERS ARE PAYING SPECIAL ATTENTION TO MAXIMIZING THE ENERGY EFFICIENCY AND MINIMIZING THE COST OF EQUIPMENT.

ENERGY EFFICIENCY AND COST

Induction heating manufacturers are paying special attention to maximizing the energy efficiency and minimizing the cost of equipment. Highly efficient solid state power supplies, tapered low-loss coils, sophisticated refractory and short bus bars are some of the factors which can minimize energy demand.

Deciding what cross-section range of bars should be processed in a given set of induction coils requires consid-

eration of a number of factors. Coil heating efficiency is largely a matter of the fill factor (area of the workpiece to be heated compared to the inside diameter of the coil windings). As the fill factor decreases, the efficiency decreases and energy costs rise. On the other hand, if one invests in a second set of coils, the savings in energy cost are diminished by the capital cost of the second coil set. There is also a production loss due to the time required to change coil lines, although advanced "quick change" design features can minimize this downtime.

An analysis of the product mix is necessary to determine how often the bar size may change and what the duration of each product run will be. These answers will help the



Fig. 3 An induction bar heating line.

bar retains its magnetic properties, and then uses a higher frequency in the next stage when the bar becomes non-magnetic. The dual frequency concept may also be effectively applied for avoiding undesirable temperature non-uniformity within transverse cross sections of non-cylindrical shaped bars/rods.

Fig. 3 shows an in-line induction heater of carbon steel bars. Bars are 20 ft. long and of various diameters (1.5" and 2"). Production rate is 16,500 lbs./hour. The system consists of 9 coils. Frequency of 1 kHz is used on the initial heating stages. Final heating is provided by two 750 kW, 3 kHz solid state power supplies (model SP5). Bars are unloaded from railroad tracks outside, placed on a bar bundle table and then fed end-to-end through the building wall to a bar feeder rack. Bars escape one at a time and feed through the induction heating line. The bar handling system also

user determine the value of the second coil set. Note that below Curie point the heating efficiency is not as greatly effected by bar size range, thus it may be worthwhile to change only the "above Curie temperature" coils.

Another consideration that has been employed quite effectively for improving the efficiency of an induction system is the application of a dual-frequency design concept. This concept utilizes a low frequency during the initial stage of heating when the



Fig. 4 Rectangular bar exiting and in-line induction bar heater.

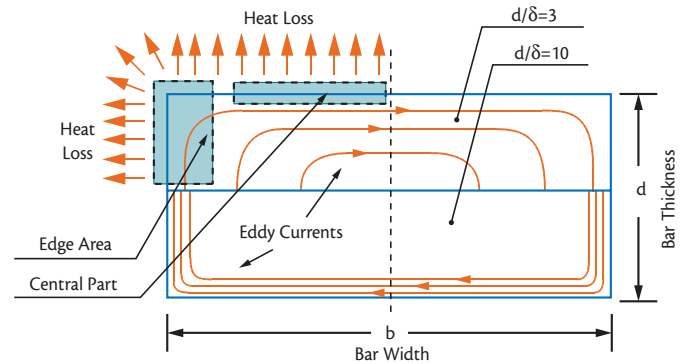


Fig. 5 Eddy current distribution in the transverse cross-section of a rectangular bar (pronounced skin effect at $d/\delta = 10$; unpronounced skin effect at $d/\delta = 3$).

includes a reversing system and an unload table that is used when there is a press stoppage.

RECTANGULAR AND TRAPEZOIDAL CROSS SECTIONS

If a bar/rod has a non-cylindrical shape, there is a distortion of the electromagnetic field in its edge areas.^{13,41} Known as the electromagnetic transverse edge effect, this phenomenon creates a non-uniform temperature profile within the transverse cross section of the rectangular and trapezoidal bar (Fig. 4). This effect also plays a major role in obtaining temperature distribution across the slab, bloom or plate width. Fig. 5 shows the distribution of the induced eddy current within the transverse cross section of the rectangular bar with pronounced skin effect ($d/\delta = 10$, where the bar thickness “ d ” divided by eddy current penetration depth “ δ ” is equal to ten) and when skin effect is not pronounced ($d/\delta = 3$).

If the skin effect is pronounced ($d/\delta > 4$), then the current and power density is approximately the same along

the bar width, except in the edge areas. The edge area, where the distortion of induced power takes place, is usually $[(1.5 - 4.0) \times \delta]$ long. Even though radiation and convection heat losses at the edge are higher than heat losses at the central part (Fig. 5), the edge areas can be overheated in comparison to the central part. This occurs because in the central part the heat sources penetrate from two sides (from two surfaces) and at the edge areas the heat sources penetrate from three sides (two surfaces and butt-edge). Edge overheating usually occurs when relatively high frequency is used and when carbon steel is heated below Curie point or when heating highly electrically conductive metals.

If the skin effect is not pronounced ($d/\delta < 3$), then underheating of the edge areas will occur. In this case, the current’s path in the bar cross section does not match its contour and most of the induced currents will close their loops early, without reaching the edge areas (Fig. 5). As a result, the

power densities and heat sources in the edge areas will be less than corresponding values in the central part of the bar or slab.

CASE STUDY

Recognizing the advantages of in-line induction heating, one of the world largest aluminum producers turned to induction for re-heating con-cast aluminum bars. The cast bars have a trapezoidal cross

section and are processed at a speed of 42 ft./min. The induction re-heater used was a line-frequency unit that required no special power supply (to keep the equipment cost down). However, line-frequency induction heating often falls short of meeting all production requirements due to limited temperature control, industrial noise and an inability to meet thermal uniformity in non-cylindrical shapes.



Fig. 6 A compact, medium frequency bar heater improved efficiency and heating quality for an aluminum bar manufacturer.

After an advanced computer modeling analysis of the efficiency that could be expected, it was found that a medium frequency solid-state power supply with a coil operating at 700Hz/750kW would provide the optimum production/efficiency combination. The net result was a compact re-heating system using a minimum floor space of approximately 60 inches (Fig. 6) with significant efficiency improvements over the line frequency system. Another important benefit was the uniform temperature profiles within the trapezoid-shaped aluminum bar and the ability to control the re-heating process as a function of the alloy, the bar geometry, and

the initial temperature profile before re-heating.

SOLID STATE POWER SUPPLIES

A very important facet of induction heating that is sometimes overlooked in the initial design stages is the ability to successfully deliver to the bar or rod the maximum available power from a given power supply at minimum cost. Quite often, the induction coil is designed to achieve the desired bar/rod thermal condition without regard to the power supply that will be used. This can result in an undesirable situation where the output characteristics of the power supply will not match the input characteristics of the induction

coils. In other words, the power supply will not be able to develop its rated power if the coil requires more voltage or current than the power supply can deliver. Transistorized power supplies are especially cost effective at frequencies of 10kHz and above. At frequencies below 3 kHz, SCRs still dominate the market especially for high power levels.

There are many factors involved in proper matching of the power supply operational characteristics and induction coils. The optimal design of a modern induction heating system must therefore take into consideration not only the features of the physical stand-alone induction heater, but a

combination of the induction coils, load matching components and inverter. **IH**

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