Want Your Bar at Uniform Temperature?

In-line induction heating, used correctly, will do just that.

In the forging process, the goal of heating cylindrical and rectangular shaped bars is to provide the bar with the desired—typically uniform—temperature across its diameter/thickness as well as along its length.

Typically, in the past gas-fired furnaces were used because of the low cost of gas. However, in recent years, forgers are shifting their preference toward induction-heating systems.

First, gas-fired furnaces require a very long heating tunnel to achieve the desired temperature uniformity, impractical in many forging-plant layouts. Also, gas-firing can result in poor bar-surface quality due to scale, decarburization, oxidation, coarse grains, etc. Finally, gas heating faces environmental restrictions.

These factors resulted in in-line heating by induction becoming the popular approach to heating bars of both ferrous and nonferrous metals. Power ratings of these machines vary from less than 100 kW to 10 MW. Their success is based on in-depth understanding of the process features, sophisticated design concepts, and precise engineering, which allow one to achieve a reasonable commercial acceptable compromise among often contradictory process requirements and design criteria.

When designing modern in-line induction heating systems, a requirement for temperature uniformity of the heated product is only one of the goals. Additional design criteria include maximum production rate; retention of metal quality by limiting 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. The last criterion, but not the least, is the competitive cost of an induction-heating system. Following are ways to optimize criteria.

Surface-to-core Temp. Profiles

Depending upon the process parameters, an induction-bar-heating system may consist of one or several in-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. The bar core tends to be heated slower than its surface. At the same time, leading and trailing ends have a tendency to heat faster than the body of the bar.

The main reason for heat deficit in the core of the bar is the so-called skin effect. This effect depends upon metal properties and frequency of the induction heating power. Due to skin effect, 86% of the power is induced within the surface layer, which is called the current-penetration depth. Induced current decreases from the bar surface toward its internal area. A bar core heats due to thermal conductivity. 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, frequency choice, and control features.

Of great use in the manufacture of induction-heating systems are computational methods that allow manufacturers to determine comprehensive details of that process.

As an example of such computational methods, Figs. 1 and 2 show the results of the transitional and final heating conditions of a 3-in. diameter carbon steel bar and its surface-to-core temperature profile along the induction line. Coil parameters are:

ID—6 in.
Refractory thickness—0.5 in.
Coil length—40 in.
Number of coils—8.
Gap between coils—12 in.
Frequency—1 kHz.
Production rate—2.56 in./sec.

Induction heating of magnetic material such as carbon steels presents several unique aspects as compared to nonmagnetic metals.

Typically, three stages comprise the heating cycle for magnetic materials. At the first stage the entire workpiece is magnetic and the skin effect is pronounced. All power induced in the bar appears in the fine surface layer, which typically doesn't exceed 0.25 in. for frequencies 500 Hz and above. Due to the relatively low temperature in this stage, the radiation losses from the bar surface are relatively low. This leads to a rapid increase in temperature at the surface with no change at the core. Intensive surface heating results in a significant surface-to-core temperature gradient. Fig. 2 shows a typical temperature profile and power density (heat source) distribution along the radius of the bar after exiting Coil No. 1—scales of power density profiles are different for various coil positions. As shown in Fig. 2, the temperature profile does not match the heat-source profile because of thermal conductivity, which spreads the heat from the surface toward the core.

During the first stage, the coil efficiency is quite high—typically 80% or higher—and continues to improve due to an increase in steel electrical resistivity with the raising of temperature. Since surface temperature is still well be-

An in-line induction bar heater. (Photo courtesy of Inductoheat Inc.)
In-line Induction Bar Heating

Fig. 1. In-line induction bar heating represented graphically.

low the Curie point, the magnetic permeability remains high and its slight reduction does not affect the climb in electrical efficiency. After a short time, coil efficiency reaches its maximum value and then efficiency starts to decline.

The second stage takes place when the surface temperature passes the Curie point—i.e. after exiting Coil No. 3 (Fig. 2). After that, the intensity of heating will noticeably decrease. This will occur primarily due to the following:

- Steel surface loses its magnetic properties and the relative magnetic permeability drops to 1. As a result, the power density induced within the bar will also decrease.
- Specific heat has its maximum value—a peak—near the Curie point. The value of the specific heat denotes the amount of energy that must be absorbed by the metal to achieve the required temperature.

At this stage, the electrical resistivity of the carbon steel increases approximately two or three times compared to its value in the initial stage. At the same time, the decrease in magnetic permeability is much more pronounced—30 times or more. Both factors cause an increase of current penetration depth by six to 12 times. A significant portion of the power is now induced in the internal layers of the bar. The bar surface becomes nonmagnetic while internal layers retain magnetic properties.

Induced eddy-current and power density distribution along the radius of the bar have a unique wave-shaped form. Fig. 2 shows that after exiting Coil No. 3, the greatest power density is located at the surface. Then the power density decreases toward the core. However, once it reaches a certain distance from the surface, the power density starts to increase again. This takes place due to the remaining magnetic properties of the steel below the surface.

The second stage exists as long as the thickness of the nonmagnetic layer is less than the penetration depth in hot steel. Finally, the thickness of the surface layer with nonmagnetic properties exceeds the penetration depth in hot steel and the wave-shaped distribution of induced power will finally disappear. The power density will then have its classical exponential distribution—i.e. after exiting Coil No. 7 (Fig. 2).

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

Longitudinal and Transverse Cracks

Longitudinal and transverse cracks are concerns when designing induction systems for heating steel bars with high carbon content—AISI 1060 through 1090. These cracks appear due to thermal stresses and poor thermal conductivity of high-carbon-content steels. Thermal stresses are caused by different magnitudes of temperature and temperature gradients.

Most of these cracks occur during the first and second stages of heating, when internal areas of the bar have a nonplastic condition. The ability to accurately predict surface-to-core temperature gradients at different heating stages results in the elimination of dangerous temperature gradients that might result in crack development. At the same time, the ability to predict a temperature profile along the induction line allows one to avoid surface overheating and minimize the duration of high temperature at the bar surface. This leads to the reduction of metal losses due to scale, oxidation, burns, and decarburization.

Nose-to-tail Temperature Profiles

Surface-to-core is only one component of the thermal conditions specified for forgings. 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 an airgap of 5 to 10 in. or more is present between leading and following bars. Existence of these air gaps could create an unacceptable temperature nonuniformity along the length of the bar.

Obtaining the required temperature distribution along bar length requires the ability to manage electromagnetic end effects, effects that are primarily responsible for temperature nonuniformity along bar length and may cause forming process problems.

Fig. 3 shows the power density distribution along a bar length when two bars are located in the middle of the multi-turn inductor. Electromagnetic field distortion and corresponding distribution of induced power within bar end areas are known as electromagnetic end effect.

In the case of nonmagnetic metals—certain stainless steels, titanium, or carbon steel heated above Curie point—there is typically a surplus of induced power in the bar-end area. This power surplus depends upon air gap, frequency, power density, electrical resistivity of the metal, and bar geometry.

The end effect in magnetic bars has several different features compared to the nonmagnetic one. Electromagnetic end effect in ferromagnetic metal is mainly affected by two factors:

1. The demagnetizing effect of eddy currents, which may force the magnetic field out of a bar.
2. The magnetizing effect of the surface and
volumetric currents, which have a tendency to gather a magnetic field within the bar. The first factor causes a power increase at the bar’s end—similar to the end effect of non-magnetic bar. The second causes a power reduction at the bar’s end. Thus, the ends of the ferromagnetic bars, even inside a long inductor, may be overheated or underheated. Studies show that the power deficit causing overheating of the end area will be pronounced for steels with high magnetic permeability heated with relatively low or moderate power density.

As previously mentioned, Fig. 3 shows the power density distribution when two bars are located in the middle of the multi-turn inductor. In reality, this distribution undergoes continuous change as the bar passes through the inductor, and its power density profile becomes more complex. 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, the region adjacent to the end will have a power deficit compared to the power induced in the body of the bar.

Obtaining nose-to-tail temperature uniformity typically is more difficult than minimizing surface-to-core temperature gradient. Understanding the intricacies of the process and applying a control algorithm can minimize nose-to-tail temperature nonuniformity.

Energy Efficiency

Highly effective solid-state power supplies, tapered low-loss coils, sophisticated refractory, and short bus bars are some of the factors that can minimize energy demand.

Application of a dual-frequency design concept is another consideration employed effectively. This incorporates the use of low frequency on the first and second heating stages when a bar retains its magnetic properties. In the third stage, when a bar becomes nonmagnetic, a higher frequency is more efficient.

In some cases, line-frequency induction heating may fall short of meeting all production requirements due to limited temperature control, industrial noise, and an inability to meet thermal uniformity, particularly in the case of bars with rectangular or trapezoidal cross-sections.

If the bar has a noncylindrical shape, a distortion of the electromagnetic field occurs in its edge areas. Known as the electromagnetic transverse edge effect, this phenomenon creates a nonuniform temperature profile within the bar cross-section.

But a high-frequency induction heater with a solid-state power supply can control temperature and provide uniform heating while operating with high electrical efficiency.

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