Figure 1. Four-module InductoForge progressive, horizontal induction billet heater

Ensuring the Quality of Inductively Heated Billets

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In-line induction heating has become a popular method of heating billets in forging applications. There are many parameters to be considered in designing an induction heating system to meet the needs of modern forge shops. Application experience and computer modeling capability are important tools in developing effective induction billet-heating systems and avoiding unpleasant surprises related to common incorrect assumptions.

Today's successful forge shops must quickly adjust to a rapidly changing business environment, yet still satisfy demands for higher-quality products. During the past three decades, the induction heating of billets has become increasingly popular because of its ability to induce heat sources not just at surface but within the heated billet. Induction heating is more energy efficient and environmentally friendlier than other heating methods. Additionally, induction offers a noticeable reduction of scale, short start-up and shutdown times, easy automation integration and the ability to heat in a protective atmosphere. Steel billets (including plain carbon, microalloyed and alloy steels) represent the majority of hot-formed billets, although other materials such as titanium, aluminum, copper, brass, bronze and nickel are also induction heated.

Progressive Induction Heating

Progressive or continuous induction is a popular method of heating small- and medium-size billets when billets are moved through a single or multi-coil horizontal induction heater (Figure 1). As a result, the billet is sequentially (progressively) heated at predetermined positions within the induction heating line.

The selection of principal process parameters, such as power, frequency and coil length, is a function of the metal to be heated, the required temperature uniformity, billet size and other parameters. Depending on the application, power ratings from hundreds to thousands of kilowatts and frequencies from 60Hz to 10kHz are commonly used.

Forging Steels and Heating Temperatures

The selection of forging temperatures for steels is based on carbon content, alloy composition and forging specifics, including the temperature range for optimum plasticity and the amount of reduction. Based on these considerations, optimum forging temperatures that result in the material's lowest flow stress (lowest forging pressure) are selected.

Carbon content is the primary determinant of the forging temperature. Generally, recommended forging temperatures are approximately 165˚C below the solidus temperature for plain carbon steels and 30-55˚C lower for alloy steels. If forging occurs above these temperatures, the quality of forged parts can be compromised. On a cautionary note, steel alloy grades are not always of the same precise composition, which can lead to variations in the solidus temperatures. Hence, the optimal forging temperature, even within a single grade, can vary.

Microalloying elements are used to modify steel's mechanical properties. Typical microalloying (using metals such as titanium, niobium and vanadium) of 1,000 parts per million or less are currently used in many forged-steel products to enhance their properties and/or reduce their production costs. These microalloyed forging steels can be less expensive than traditional quenched-and-tempered (QT) grades by reducing alloying additions and post-forging operations.

Residuals in Steel and Hot Shortness

All commercial steels contain residual (trace) elements. In common forging steels, the amount of copper has increased over time because residual copper is not eliminated in the steelmaking process. The resultant copper-iron system causes some issues such as the lower melting point of copper and the low solubility of copper in iron at low temperatures.

The solubility of copper in iron oxide (FeO) is low. At temperatures above 1100°C, where the oxidation rate of iron is high, there is rejection of the copper from the oxide into the metal. This creates a copper-rich zone at the metal-oxide interface. At high temperatures, the copper is liquid and can penetrate along grain boundaries with ease, weakening them and causing a defect known as hot shortness in the presence of a tensile stress.

During forging, metal undergoes deformational and frictional heating. If this heating, in combination with the billet's pre-deformation temperature, is high enough to allow intergranular liquification and steel burning, then failure may occur by intergranular cracking. To prevent this, the hot-forging temperature needs to be kept low enough so that no region of the billet becomes sufficiently overheated to negatively affect the steel's microstructure.

Heat Uniformity Requirements

In billet heating, it is necessary to not only heat the workpiece to the desired level but also to provide a certain degree of heat uniformity. Uniformity requirements include maximum tolerable thermal gradients: surface-to-core, end-to-end and side-to-side. Without some thermal uniformity, a heated billet can cause problems (such as premature die wear) by requiring excessive force to form the metal.

The maximum suggested forging temperature is that which includes a safety factor to account for potential variations in steel chemistry and thermal variations within the heated billet. It is important that the maximum temperature anywhere within the billet does not exceed this critical temperature. Considering that pyrometers can only reliably measure a billet's surface temperature, there is always the risk of "missing" regions of local and/or subsurface overheating. Therefore, it is imperative that process temperature control is assisted with advanced computer-modeling capability helping to predict internal thermal conditions of heated billets.

Effect of Frequency

One of the challenges of induction heating arises from the necessity of achieving the required surface-to-core temperature uniformity. Due to the physics of the induction process, a billet's core heats more slowly than its surface. This "skin" effect is responsible for 86% of all heating power induced within the surface layer, which is called current penetration depth (δ).

The choice of frequency is always a reasonable compromise in induction heating. Too low a frequency might result in undesirably large δ, which could lead to poor coil electrical efficiency. Too high a frequency could lead to long heating times that, in progressive induction heating, would require a longer heating line. Obviously, there is an optimal frequency that is a complex function of process features.

A Common Incorrect Assumption

Some users of induction heating incorrectly assume that a billet's lowest temperature is always at its core and that its maximum temperature is always located at its surface. Also, it is often assumed that overheating does not occur if the surface temperature does not exceed the maximum permissible level. Additionally, process-control systems that predict surface-to-core thermal gradients in the billet are often assumed to guarantee proper heating. However, it is imperative to note that heat losses from a billet's surface (due to thermal radiation and convection) shift the temperature maximum further beneath the surface. Our research shows that monitoring temperatures only at a billet's surface and core (Figure 2) is insufficient, because a temperature maximum may occur at a subsurface region and be easily missed.

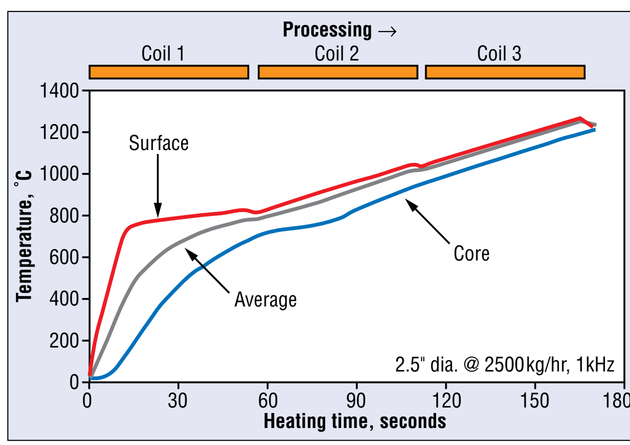

Figure 2. Conventional "surface-to-core" time-temperature profiles

The location and magnitude of subsurface temperature surplus is a complex function of four major factors: frequency, refractory, final temperature and power distribution along the heating line. Lower frequencies result in more "in-depth" heating that assists thermal conduction and leads to a faster temperature rise at the billet's core. This shortens the induction line, but under certain conditions it may increase the risk of subsurface overheating.

The use of a thick refractory does just the opposite, reducing subsurface overheating and shifting the billet's maximum temperature toward its surface. Increasing the final forging temperature has an effect similar to that of lowering frequency.

The effect of power distribution along the heating line is the most complex one. Most often it is suggested that more power be applied to the coils at the beginning of the line. The problem with this approach, however, is that with conventional induction heating design, the power distribution along the heating line cannot be easily modified if the production rate, metal or billet size changes. For example, if the production rate is reduced in this configuration, subsurface overheating could worsen, negatively affecting the billet's subsurface microstructure.

In many cases, the subsurface temperature might be high enough to cause the billets to fuse together. The effect of subsurface overheating is particularly pronounced when heating smaller billets at a lower rate using an induction line designed for heating larger billets. Figure 3 shows "surface-to-core" profiles when heating 2-inch-diameter billets (left) at a slower rate utilizing a conventional induction heating line designed for processing 2.5-inch billets (bottom).

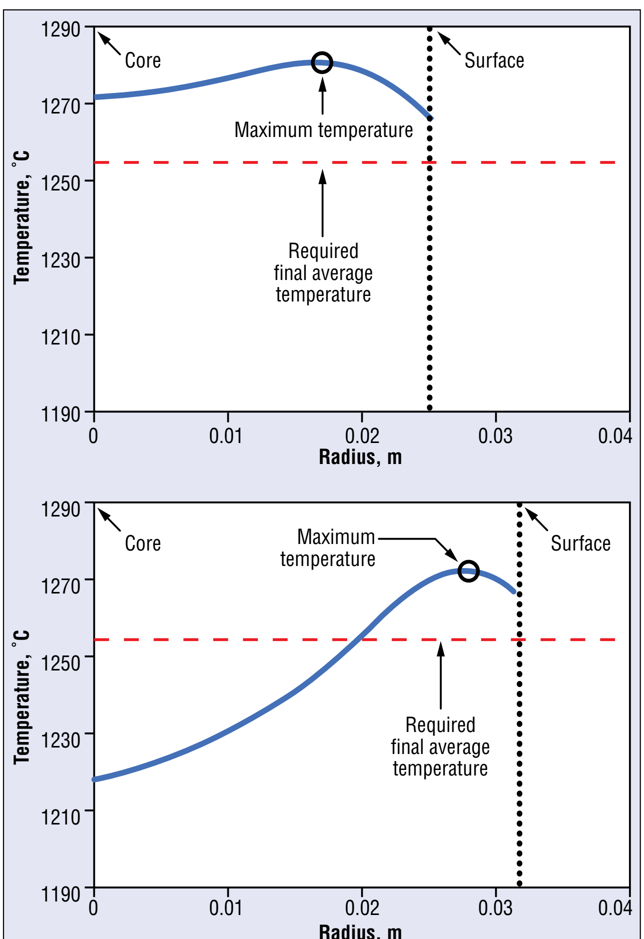

Figure 3. Final "surface-to-core" temperature profiles when heating 2-inch-diameter billets at a slower rate (top) utilizing a conventional induction line designed for processing 2.5-inch billets at a nominal rate (bottom).

Since pyrometers can only reliably measure a billet's surface temperature, there is always a danger of missing subsurface overheating. Therefore, precise temperature control and an ability to predict a location and magnitude of subsurface overheating are imperative in order to avoid hot shortness and billet sticking problems. Practice shows that when heating large billets at nominal rates, more power should be shifted toward the beginning of the induction line. When heating smaller-than-nominal-size billets at slower rates, it is advisable to shift power toward the end of the induction line. Therefore, the ability of an induction system to dynamically redistribute power along a multi-coil induction heating line is very important.

"Nose-to-Tail" Temperature Distribution

One of the imperative issues related to proper billet heating is providing the required "nose-to-tail" temperature uniformity, which is increasingly critical when heating longer billets. Nose-to-tail temperature distribution is associated with several interrelated phenomena, including electromagnetic end effect, transient end effect and thermal end effect. The impact of each phenomenon is a function of process specifics. Figure 4, for example, shows the appearance of transient electromagnetic end effect while the billet exits the induction coil. Application experience and precise computer modeling are both essential in taking those phenomena into consideration and developing the appropriate process recipe and coil-design features to assure nose-to-tail heat uniformity.

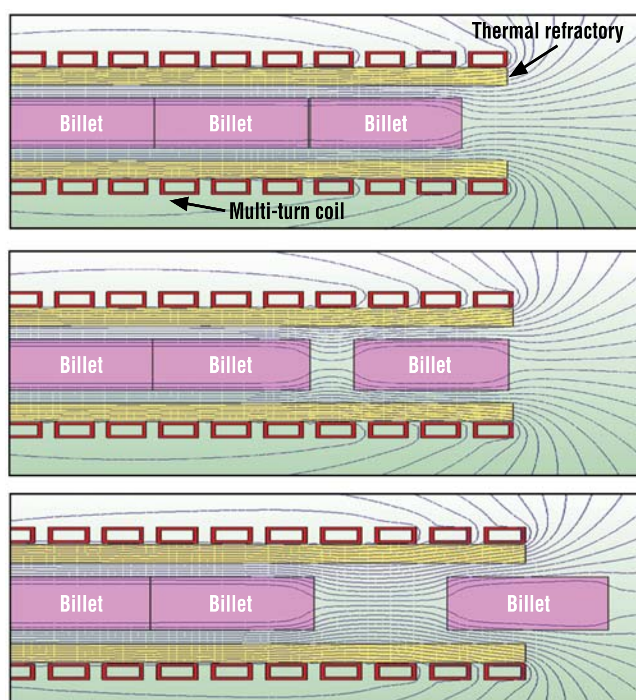

Figure 4. Computer-modeled electromagnetic-field distribution at the exit end of an induction coil (transient end effect).

Heating Brittle Metals

When heating brittle and low-ductility alloys (high-carbon steels, tool steels, etc.), longitudinal and transverse cracks may be a concern. These appear due to excessive thermal stresses (thermal shocks) that occur when thermal gradients exceed permissible levels, which vary with metal chemical composition, microstructure, billet size, temperature, and the presence of internal cavities and severe casting defects. These cracks mostly appear during the initial heating stage, when the internal areas of the billet are in a non-plastic condition. Thus, a system's "soft" start is required to avoid cracking, meaning that lower-than-normal power densities are used during the initial heating stage.

A sophisticated computer-modeling capability is required to optimize an induction heater's performance, assure the quality of forged products and avoid costly surprises related to subsurface overheating and excessive thermal gradients. It is also important that the induction system be sufficiently flexible to redistribute power and frequency along the line while heating billets of different metals and sizes at differing production rates.

InductoForge Billet Heating Technology

The InductoForge billet heater (shown in Figure 1) is Inductoheat's modular technology developed specifically to optimize induction heating for the forging industry. Each module is comprised of a rigid power supply with a heavy-duty induction coil mounted on top. There are virtually no transmission losses between the coil and power supply. These power and coil modules can be arranged in-line to form a system that provides billet heating at the required production rate, yet still offer the flexibility to accommodate changes in the production schedule. Each module allows the control of both the power and frequency of each coil along the induction heating line.

There are several components that complete the system. The PLC, HMI (Human Machine Interface) and other controls are mounted on a pendulum so the operator can position them for easy viewing. A tractor or pinch-roll drive system is used to push billets through the induction coils.

The benefits of modular construction include:

- System flexibility, with optimized power and frequency distribution along the heating line related to the specifics of a particular run; the frequency of each module can be modified (from 500Hz to 6kHz) to process the majority of forged-billet sizes at maximizing efficiency.
- Proprietary computer modeling and advanced temperature-control capabilities to substantially improve the quality of heated parts, assuring enhanced metallurgical structures and a process recipe that minimizes the probability of subsurface overheating and optimizes the performance of induction heating systems based on operating parameters specified by the user.
- Static and dynamic standby and rapid-start capabilities that improve start-up, holding and shutdown process stages.

InductoForge systems can be 15-20% more energy efficient than conventionally designed induction systems, particularly at reduced production rates. Whereas most induction heating systems consume 2.5-2.7 kg/kWh, this system has been measured to exceed 3 kg/kWh.

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