INTRICACIES FOR THE SUCCESSFUL INDUCTION HEATING OF STEELS IN MODERN FORGE SHOPS

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ABSTRACT

Over the past three decades, induction heating has become an increasingly popular in forge shops. Among other subjects, this paper discusses:

- Trends in forging steels. Selection of forging temperatures.
- Intricacies of process requirements associated with recent knowledge related to theory and practice of induction heating.
- Novel induction billet heater design concept.
- Temperature uniformity requirements. Common misassumption.
- “Stand-by” and “Rapid start” features of modern induction heaters.

INTRODUCTION

There are many ways to heat billets prior to hot forming (i.e., forging, upsetting, rolling, extrusion, etc.) including the use of induction heaters, gas-fired furnaces, infra-red heaters, electric and fuel-fired furnaces, etc. Over the past three decades, induction heating has become an increasingly popular choice due to its ability to create high heat intensity quickly and within the billet, leading to low process cycle time (high productivity) with repeatable high quality while using a minimum of shop floor space. Induction heating is more energy efficient and inherently more environmentally friendly than most other heat sources[1]. A considerable reduction of heat exposure contributes to the environmental friendliness.

Induction heating offers other attractive features such as 1) a noticeable reduction of scale, 2) short start-up and shut-down times, 3) readiness for automatization with lower labor cost, and 4) ability to heat in a protective atmosphere if required.

In order to take full advantage of the benefits from induction heating, the modern forge shop needs to understand a few of the intricacies associated with this type of heating based on recently obtained knowledge related to theory and practice of induction billet heating.

INDUCTION BILLET HEATING APPROACHES

There are two basic induction billet heating approaches: progressive and static heating: [1] In *progressive multistage horizontal heating*, two or more billets are moved (via pusher or indexing mechanism, for example) through a single coil or multi-coil *horizontal* induction heater (Fig. 1). As a result, the billet is sequentially (progressively) heated at predetermined positions inside of the induction heater.

Figure 1. Four module InductoForge™ progressive horizontal billet heater

In *static heating*, a billet is placed into an induction coil having a *vertical* or *horizontal* arrangement for a given period of time while a set amount of power is applied until it reaches the desired heating conditions. The four photos in Fig. 2 show a billet being discharged after being statically heated in a vertical inductor[1,2]. When the heating cycle is completed, the control system checks whether the press is ready to accept the billet. If it is not, the inductor changes its mode from heating to holding.

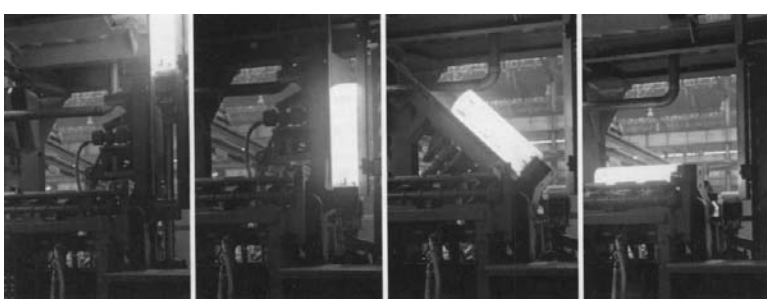

Figure 2. Discharge sequence for large steel billet after being statically heated in a vertical inductor.

Progressive multistage horizontal heating is a popular approach for small- and medium-size billets (usually less than 7in. [178mm] in diameter). When heating large-diameter steel or titanium billets (8in. [200mm] and larger), it is often advantageous to use static heating with a vertical coil arrangement or a combination of the progressive multistage horizontal method for preheating and the static vertical method for final heating[1]. The pros and cons of the progressive multistage horizontal versus static vertical billet heating approaches are given in Ref.2. This paper focuses on a progressive multistage horizontal heating.

The selection of power, frequency and coil length in induction billet heating applications is highly subjective, depending upon the type of heated metal, required temperature uniformity, billet size, etc. Depending upon the application, powers from hundreds to thousands of kilowatts and frequencies from 60Hz to 10 kHz are commonly used for induction billet heating [1].

FORGING STEELS AND COMPOSITION RANGES

Steel billets, by far, represent the majority of hot-formed billets, although other materials including titanium, aluminum, copper, brass, bronze, and nickel are also induction heated for hot forming.

Steel alloy grades are not necessarily always of the same precise composition. For example, most plain carbon and low alloy steels can have a carbon content range of about 0.05%. This variation in carbon content can produce a 90^{o}C (160^{o}F) variation in the solidus temperature for the steel. Hence, the optimal forging temperature within a single grade can vary depending on the precise chemical composition of the steel.

Steelmaking operations have improved over the years and the steel that is obtained from a reputable supplier will often have a very consistent chemical composition. Possible variations in the chemistry of a given steel calls for a more precise control of temperature. It is important for the forger to understand the variations that can occur within steel chemistries and understand how to tune their induction heating process in order to obtain the best temperature for forging.

Trends in forging steels with emphasis on microalloyed steels

Microalloying additions of typically 1000 parts per million or less are currently used in a variety of forged steel products to enhance properties and/or reduce production costs. Titanium, niobium, and vanadium microalloying additions have been utilized in medium carbon steels to improve mechanical properties in the as-forged condition. As a result, these microalloyed-forging steels can be economically advantageous as compared to traditional quenched and tempered (QT) grades for a variety of forged components by reducing alloying additions (such as Cr, Ni and Mo) and post-forging processing operations, especially heat treatments. Although these microalloyed steels can exhibit hardness and fatigue properties comparable to QT grades, they often have lower impact strengths than QT forgings. The lower impact properties reduce their comparative feasibility for some applications.

Microalloying additions in steels modify mechanical properties predominantly through the precipitation of carbonitrides during thermal or thermomechanical processing. These carbonitrides can be used to increase strength (i.e., dispersive strengthening) and/or improve toughness (through microstructural refinement). Table 1 provides a summary of the austenite solubility and precipitate effects of the three major microalloying elements -- vanadium, niobium, and titanium.

Because of the high solubility in austenite and the ability to precipitate upon cooling vanadium microalloyed forging steels seem to be preferred over niobium. The temperature range for forging niobium microalloyed steels in a consistent fashion is much tighter than for the vanadium steels. In both cases, control of the cooling rate after forging is critical to insure optimum properties.

Table 1. Austenite Solubility and Precipitate Effects for Major Microalloying Elements

<table>
<tr><th>Microalloying Element</th><th>Solubility in Austenite</th><th>Carbonitride Precipitate Effects</th><th>Solute Effects</th></tr>
<tr><td>V</td><td>High</td><td>• Dispersion Strengthening
• Intragranular Ferrite Nucleation</td><td rowspan="3">• Solid Solution Strengthening
• Inhibition of Austenite Grain Growth (Solute Drag)
• Recrystallization Inhibition (Solute Drag)</td></tr>
<tr><td>Nb</td><td>Temperature Sensitive</td><td>• Dispersion Strengthening
• Austenite Grain Boundary Pinning
• Recrystallization Inhibition</td></tr>
<tr><td>Ti</td><td>Low</td><td>• Austenite Grain Boundary Pinning</td></tr>
</table>

Residual in Steels. Oxidation (Scaling).

With the increased use of electric furnace steel, which is made from recycled scrap, residual elements can be found in forging steels. Over the last several decades, the amount of copper residual has increased in most common forging grades. Copper, as a residual element is not eliminated in the steelmaking process. Additionally, the characteristics of the Cu-Fe system produce some issues for copper-iron alloys such as the lower melting point of copper (1085 ºC) and the low solubility of copper in iron at low temperatures.

The solubility of copper in iron oxide FeO is very low. At high temperatures (above 1100^{o}C), where the oxidation rate of iron is quite high, there is rejection of the copper from the oxide into the metal creating a copper-enrichment zone at the metal oxide interface. At high temperatures, the copper is liquid and can penetrate along grain boundaries with ease. This penetration debilitates the grain boundaries, which, in the presence of a tensile stress, causes them to break resulting in a defect that is known as hot shortness.

Hot shortness is not a new problem; it has been known since the early 1900s, when it was called red-shortness. The issue arose again in the late 1950s and 1960s, when the amount of copper residuals increased in steels, and the steel industry encountered production problems. Since the late 1990s, the issue once again took on importance, mainly for economic and environmental reasons. Hot shortness is defined as”brittleness in metal in the hot forging range", particularly in some types of steel containing low melting point elements, especially copper[3]. This phenomenon occurs commonly at the surface of these steels because, during the re-heating before or during forming, the content of non-oxidizing elements such as copper increases. For this reason the term "surface hot shortness" is sometimes used. The phenomenon of hot shortness in copper-containing steels is strongly influenced by other residual elements such as antimony, tin, and arsenic. These residuals are more soluble in copper than in iron. Nickel additions can reduce the hot shortness of copper-containing steels, since it forms complete liquid and solid solutions with copper [4]. Precise temperature control during the forging of steels is needed in order to avoid hot shortness problems from appearing due to residuals.

In the presence of oxygen at high temperatures, steels can form an oxide surface coating often referred to as scale. The oxidation process can depend on several mechanisms 1) the transport of oxygen from the bulk gas phase surrounding the steel, 2) the reactions at the gas/scale interface, and 3) the diffusion of iron through the scale to the gas/scale interface. The first two mechanisms result in linear growth kinetics (i.e. the amount of scale varies directly with the amount of time that the steel is at temperature). The third mechanism results in parabolic growth kinetics (i.e. the amount of scale varies with the square root of time at temperature). Above 700^{o}C the oxidation of iron follows the parabolic law with three oxide layers developing on the surface -- hematite Fe_2O_3 (1%), magnetite Fe_3O_4 (4%), and wustite FeO (95%) [5].

Oxidation of steel is not too different from iron, where normally only two oxide forms are present: Fe_3O_4 and FeO. Nevertheless, noble elements such as copper do not oxidize.

The alloy content of the steel and residuals also affect the scale formation. Silicon has been shown to react with the oxide to form a complex iron-silicon oxide on the surface. Stainless steels have been designed to be more scale resistant that plain carbon and low alloy steels. In stainless steels the chromium content will oxidize preferentially to the iron forming a protective layer of chromium oxide on the surface, which prevents or delays the further oxidation of the iron in the steel.

The main advantage of induction heating forging billets is that the billet reaches required temperature more rapidly and remains at that temperature for a shorter period of time. Since the formation of scale increases with the amount of time at high temperature, there is much less scale associated with induction heating.

HEATING TEMPERATURES, CRITERIA AND DESIGN APPROACHES

The required heating temperature depends upon the type of heated metal and specifics of forging. The selection of forging temperatures for plain carbon and alloy steels is based upon four major factors: (1) carbon content, (2) alloy composition, (3) the temperature range for optimum plasticity [maximum forgeability], and (4) the amount of reduction [6]. Based upon these four considerations, forging temperatures are selected such that the material has the lowest possible flow stress (and therefore lowest possible forging pressure).

Burning, intergranular melting, or grain boundary liquations are related to a localized melting at the austenite grain boundaries [7]. During the forging process the metal undergoes deformational and frictional heating, and if this heating in combination with the billets pre-deformation temperature is high enough to allow intergranular liquation, then failure may occur by intergranular cracking. It is critical that the hot forging temperatures are low enough such that none of the billet areas reaches the solidus temperature, while maintaining the maximum temperature possible to minimize the flow stress, thus minimizing the required forging pressure. This maximum forge temperature with a safety factor to account for both differences in chemistry and variations in temperatures within the heated billet is referred to as the maximum possible forging temperature.

When determining the recommended forging temperature, carbon content is the dominant factor. The solidus temperatures for both plain carbon and alloy steels have approximately the same linear behavior (care should be taken with steel high in silicon, which has a significantly lower solidus temperature). Recommended forging temperatures are approximately 165^{o}C (300^{o}F) below the solidus temperature for plain carbon steels and an additional 30-55^{o}C (50-100^{o}F) lower for alloy steels. Above these temperatures the steels are subject to possible damage by incipient melting or overheating [6].

It is typically required not only to raise the billet's temperature to a specified level but also to provide a certain degree of heat uniformity. The uniformity requirement may include maximum tolerable thermal gradients: "surface-to-core," "end-to-end," and "side-to-side." A billet that is heated with appreciable non-uniformly can cause problems with premature die wear on hammers and presses and may cause problems by requiring excessive force to form the metal. At the same time, there are cases when obtaining certain temperature gradients within the billet is desirable. For example, when heating certain metals prior to direct or continuous extrusion, "leading" thermal gradients along the billet's length are often preferable.

In some cases, the initial billet temperature is the ambient temperature. In other cases, the initial temperature prior to induction heating is non-uniform (for example, after billet's piercing).

"Surface-to-core" temperature uniformity

One of challenges in induction heating arises from the necessity to provide the required "surface-to-core" temperature uniformity. Due to the physics of the induction process, the billet's core tends to be heated slower than its surface. Figure 3 shows the "time - temperature" profile of conventional three-coil system. Conventional induction heating design for forging uses a single power supply and several coils

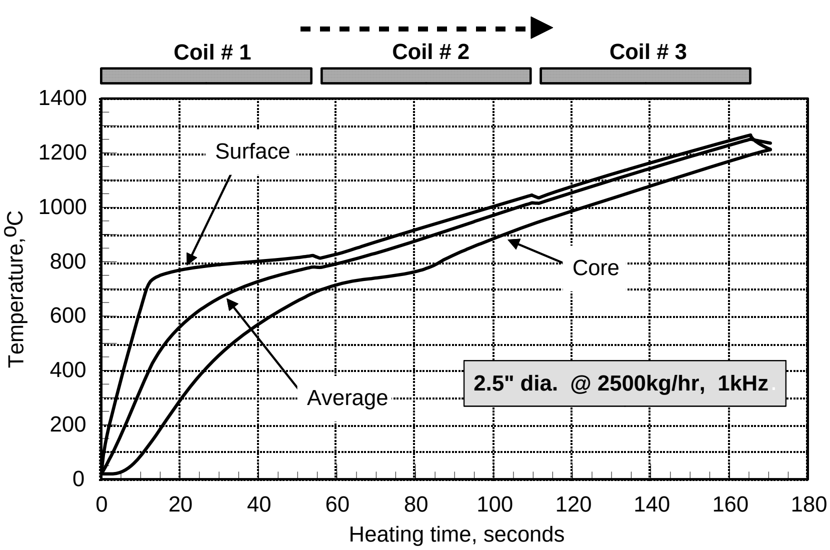

Figure 3. Conventional "time-temperature" profile

having a series/parallel connection. The main reason for the heat deficit in the core of the billet is the "skin" effect [1].

The "skin" effect depends upon the metal's electro-magnetic properties and frequency. Due to this effect, 86% of the power is induced within the surface layer ("skin" layer), which is called the current penetration depth [1]. According to "skin" effect, the induced current decreases from the surface towards the billet's internal area. The core heats due to thermal conductivity.

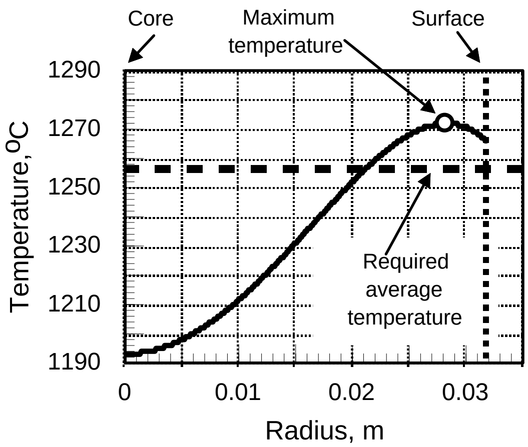

Figure 4. "Surface-to-core" profile at exit of coil # 3 (see Fig.3)

If frequency is too low, then an eddy current cancellation within the billet can occur, resulting in poor coil efficiency. When the frequency is too high, the "skin" effect will be highly pronounced, leading to a current concentration in a fine surface layer compared to the diameter of the billet. In this case, a long heating time will be required in order to provide sufficient heating of the billet's core. Prolonged heat time corresponds to a longer heating line, which in turn, increases surface heat losses due to thermal radiation and convection. The choice of frequency is always a reasonable compromise.

<u>A common misassumption</u>

Some practitioners incorrectly assume that with induction heating the maximum temperature is always located at the billet's surface. If surface temperature measured by a pyrometer does not exceed the maximum permissible level then it is assumed that overheating does not occur. Figure 4 shows "surface-to-core" temperature of 2.5" (63.5mm) diameter billets immediately after exiting the last coil, using a traditional three-coil design approach shown on Fig.3. The presence of surface heat losses shifts the temperature maximum further away from the billet's surface marking its location at about 3/16" (5mm) beneath the surface. Positioning and magnitude of the maximum temperature within the heated billet is a complex function of four factors: *frequency*, *refractory*, *final temperature,* and the *power distribution along the heating line*.

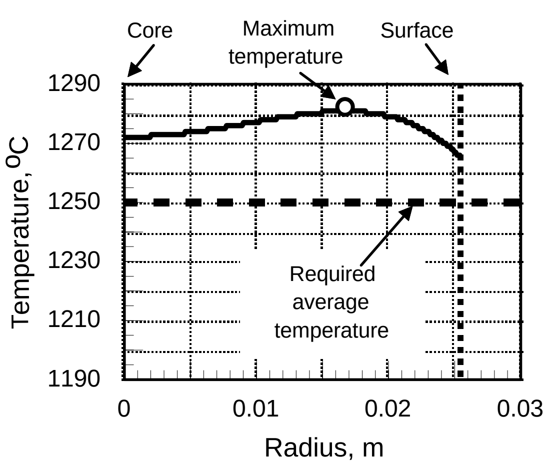

Figure 5. "Surface-to-core" profile at coil exit when heating 2" (50.8mm) billets

Lower *frequency* results in more "in-depth" heating leading to a faster heating of billet's internal areas and its core. This shortens the induction line, but it can also increase the maximum of the subsurface temperature and shifts its position further away from the surface.

The use of an appreciably thick *refractory* with lower thermal conductivity does just the opposite, reducing subsurface over-heating and shifting it towards the billet's surface.

Requiring higher *final temperatures* results in an effect similar to lowering frequency on positioning and magnitude of the maximum temperature.

An effect of *power distribution along the heating line* on billet's temperature distribution is a controversial factor that is seldom discussed in the literature. In most publications devoted to in-line induction heating of billets and bars, it is strongly suggested to have a graded heating pattern by putting more power into the coils at the beginning of the line. This approach typically utilizes a single power supply that powers several coils with graded number of turns or/and series/parallel coil circuit connection. Putting more power up-front might sound as a universal "rule of thumb" since it forces more energy into the billet at the front of the heating line, giving it more time to soak into the core of the billet. The temperature in the center of billet can reach the forging temperature in a shorter period of time, reducing the length of the coil line.

The problem with this type of design, however is that the power distribution along the heating line cannot be easily modified if the production rate changes. For example, if the production rate is reduced, a subsurface overheating problem worsens and could negatively affect the billet's subsurface microstructure. It is also very common to find an appearance of billet-sticking problems with graded coils. This occurs when the system runs at a rate slower than the maximum for which it is designed. Since the system puts more energy into the billet in the first coils, too much energy soaks down into billet's subsurface area when the line runs slow. The presence of surface heat losses can reverse an expected radial temperature profile shown on Fig.4. When the pyrometer measures the desired forging temperature on the surface of the billet, the temperature inside the billet can actually be much higher. In many cases, it may be hot enough to cause the billets to fuse together. The effect of subsurface overheating is particularly pronounced when heating smaller size billets at a lower rate using an induction line designed for heating larger billets at a nominal rate. As an example, Fig. 5 shows "surface-to-core" profiles when heating 2"(50.8mm) diameter billets at a slower rate utilizing an induction line designed for processing 2.5"(63.5mm) billets at a nominal rate. Note the billet's surface temperature in both cases is the same (compare surface temperatures on Fig.4 and Fig.5).

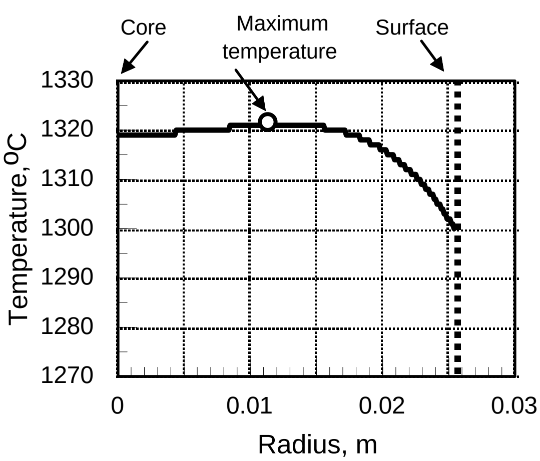

Figure 6. Effect of higher temperatures on positioning of subsurface maximum

Figure 6 shows the effect of higher *final temperatures* on positioning and magnitude of maximum temperature when heating 2"(50.8mm) billets at a slower rate (compare Fig.5 vs. Fig.6). The necessity to increase the surface temperature can dangerously aggravate subsurface overheating.

Therefore, in order to optimize induction heating performance, improve product quality, and avoid unpleasant surprises related to subsurface overheating, it is imperative that an induction system be capable of redistributing power along the line while heating billets of different sizes and production rates. When heating large billets at nominal rates, more power should be shifted towards the beginning of induction line. At slower rates however, when heating smaller than nominal size billets power should be shifted towards the end of the induction line.

Longitudinal and transverse cracks

Longitudinal and transverse cracks may be a concern when heating brittle and low ductility metals (i.e., high carbon steels). These cracks appear due to excessive thermal stresses (thermal shocks) that take place when thermal gradients exceed the permissible levels. These levels vary depending upon the metal chemical composition, microstructure, billet size and temperature.

Most of these cracks could appear during the initial heating stage, when the internal areas of the billet have a non-plastic condition. A "soft" start is required to avoid cracking [1].

INDUCTOFORGE™: A NOVEL INDUCTION BILLET HEATING TECHNOLOGY

Today's forge shop must often adjust to a rapidly changing business environment. InductoForge™ Modular Billet Heater is Inductoheat's novel technology that was specifically developed for the forging industry to meet modern requirements. The billet heater's basic component is a fairly simply, time-proven induction power supply with a heavy-duty induction coil mounted on top. These power and coil modules can be combined in-line to form a heater that provides the required production rate. It is easy to add or remove modules to the heating line to match changes in production.

While the coil and power module are the basic components of the system, there are several others that complete it. On the in-feed end, a cabinet houses the PLC and other controls. The HMI (Human Machine Interface) is mounted on a pendulum so that the operator can position the screen for easy viewing. A tractor or pinch-roll drive system is mounted on top of this cabinet for pushing the billets through the induction coils.

Many of the benefits of the modular construction result from the ability to control each coil individually, including but not limiting to [8]:

- Optimized power distribution along the heating line
- Superior temperature control minimizes probability of subsurface overheating
- Increased efficiency of induction system
- Unique Standby and Rapid Start Capabilities

The iHAZ Temperature Profile Computer Modeling system utilizes the powerful proprietary software[8] that is specifically developed for optimizing performance of induction heating systems based on a set of operating parameters specified by the user. The resulting operating parameters needed to run the system as calculated can be downloaded to a recipe in the heating systems PLC.

InductoForge™ billet heater features superior flexibility and can be 20% more efficient than older, conventionally designed induction systems, particularly when the billet heater is run at reduced production rates. While most induction heating systems can only achieve an energy consumption of 2.5-2.7 kg/kW-hr, the InductoForge™ billet heater has been measured to exceed 3 kg/kW-hr.

There are virtually no transmission losses between the coil and power supply, because the induction coil sits on top of the power supply. This alone can increase efficiency by more than 5% over conventional induction units in which the power supply is separate from the coil stand.

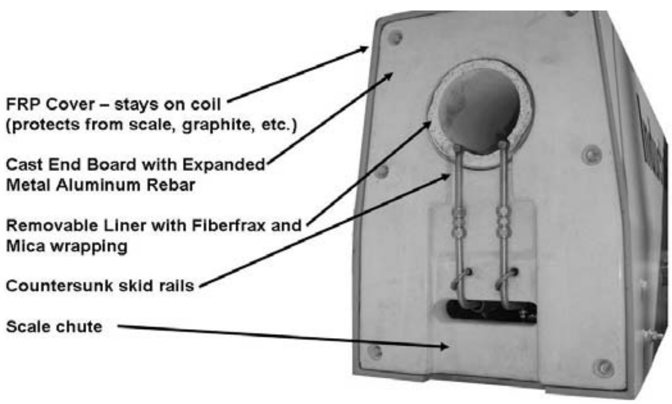

Figure 7. Energy-efficient InductoForge coil

The InductoForge™ coil (Fig.7) utilizes a removable liner with a backing of low thermal-conductivity material to reduce the thermal losses. This gains an additional 3-5% in efficiency. The advanced mechanical coil design adds an additional 7-10% in electrical efficiency.

The frequency of each module can be easily modified to match changes in billet sizes or heated metals avoiding eddy current cancellation and maximizing coil efficiency.

Standby and Rapid Start

The InductoForge™ billet heater controls the power of each coil along the induction heating line. Therefore, it is possible to control the temperature at each coil when production is stopped during an interruption caused by the press or due to other reasons related to an operation of the forging machinery providing optimal re-distribution of power to each coil.

Conventional systems adapted a process control concept that allows only a short holding. Total power of the whole line is reduced or completely turned off. After a short period of time that typically does not exceed 15 minutes, the whole line is emptied. After getting a signal that the forging line is ready to operate, new billets would be loaded and the start-up cycle begins again. Some conventional induction heating machines use "dummy" billets for start-up to achieve the desired thermal conditions. Drawbacks of the conventional design approaches are obvious.

A flexibility of coil power re-distribution along the heating line can be considered an appreciable advantage of the InductoForge™ system particularly during Standby stage. This results, but is not limited to, the following benefits:

a) An additional energy savings, since it is not necessary to re-heat billets and materials savings due to fewer rejects.
b) Production increase and downtime reduction by eliminating wait time for the billets to get back to forging temperature. More billets will be produced since the heater has billets ready for forging immediately after the press is fixed or adjusted.

In order to facilitate the full range of forging operations, two types of standby systems have been developed: *Static* and *Dynamic*.

Static Standby. The billets remain stopped for the entire period of the interruption using Static Standby process control mode. In conventional induction systems, this control mode has well-known limitations related to the distortion of the electromagnetic field between induction coils. It is very difficult to provide a sufficient heating of billet areas located at inductor end regions. Depending upon the standby time, those "cold" spots can be significant requiring the corresponding billets to be rejected when the line starts up. This is often unacceptable for many automatic forging lines and a majority of manual forging lines. Since InductoForge™ coils are butted to each other; the field reduction between coils is minimized allowing Static Standby control mode to produce the least number of rejected billets.

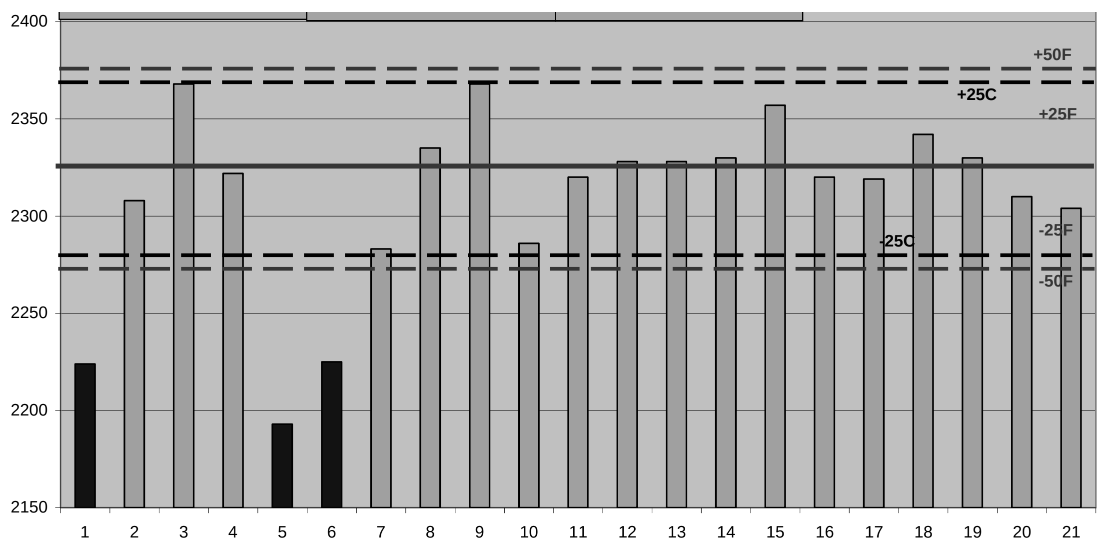

Figure 8. Billet temperatures after restart from Static Standby

Dynamic Standby. – For automatic press lines where all die positions must be filled, the dynamic standby process control concept has been developed. Similar to a Static Standby, the billets are stopped when standby is required. A billet is then pushed out every two minutes. This eliminates the undesirable "cold" spots of billet areas located between the induction coils. When the line is restarted, all of the billets can be forged. Dynamic Standby is different from the old method used by some induction suppliers where the line speed-up and power were reduced. In the case of dynamic standby, the line is actually stopped and a billet gets periodically pushed out of the induction heater. This eliminates the development of any appreciable hot temperature “humps” that is common with the old, conventional style heaters during standby. Figures 8 and 9 show the results of static standby and dynamic standby.

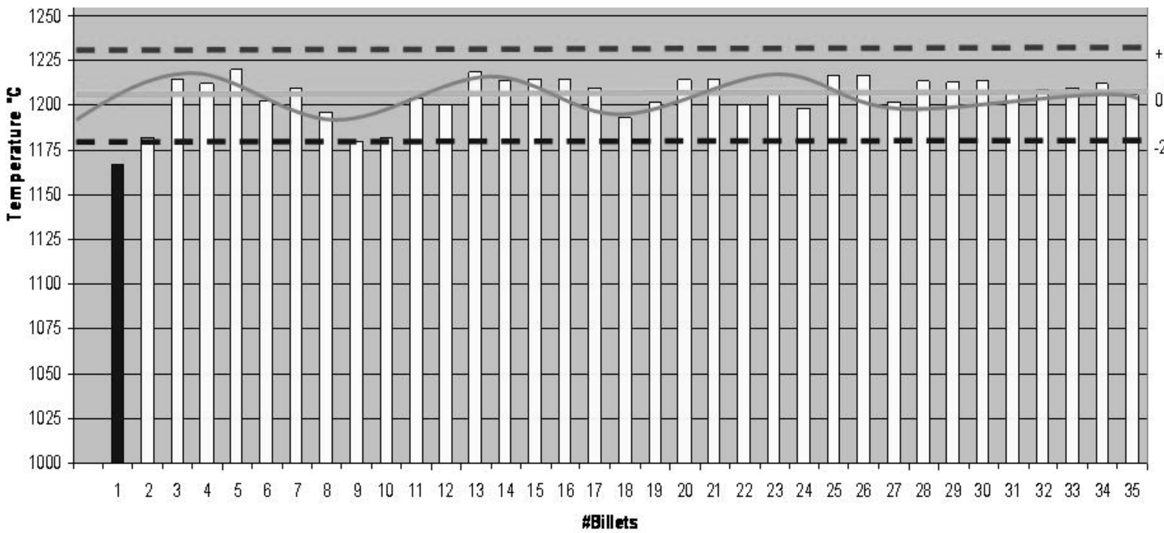

Figure 9. Billet temperature after restart from a Dynamic Standby

<u>Rapid Start</u>. Similar to standby control technology, InductoForge™ systems are equipped with an advanced process control system for rapid start of a line that is full of cold billets. As the heating line gets longer and/or the billet’s O.D. gets larger, it becomes more difficult to push billets out before restarting. One of the challenges with restarting a heater loaded with cold steel billets deals with appreciably different impedances that lead to potential difficulties for conventional inverters during an initial heating stage. Inverters can “hit” certain limits. It commonly takes two or three coil lines of billets to achieve steady-state conditions to get the billets up to forging temperature.

The Rapid Start approach ensures that the billets are heated to a specific level in each coil to simulate the normal (steady-state) temperature profile prior to pushing the billets through the coil line.

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