MAXIMIZING FLEXIBILITY, CONTROLABILITY AND EFFECTIVENESS OF INDUCTION HEATING SYSTEMS

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Introduction

Temperature greatly affects the formability of metals. Heating of billets, bars, slabs, plates and rods through its entire body to temperatures that correspond to the plastic deformation range creates a favorable condition for metal to be subsequently forced by various means into a desired shape. Within this article, the term billet will be used representing a number of similar workpiece shapes, including bars, rods, wires, heavy-wall tubes, etc. There are many ways to heat metals prior to warm and 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.

In recent decades, induction heating has become an increasingly preferable choice for heating metals. This tendency continue to grow at an increasing pace due to an ability of induction heating to create high heat intensity quickly and not just at the surface of the workpiece but within its internal areas as well. This creates favorable condition to quickly achieve required temperature uniformity and lead to low process cycle time (high productivity) with repeatable high quality while using minimum floor space. Practically immediate readiness of induction systems to start production without a necessity of having prolonged warm-up (idle) times is other appreciable advantage of induction heaters compared to alternative processes (e.g., gas furnaces).

Induction heating is more energy efficient and inherently environmentally friendlier than most other heat sources. A considerable reduction of heat exposure also contributes to the environmental friendliness.

Today’s forge shops must quickly adjust to a rapidly changing business environment, maximizing process flexibility, and electrical efficiency, yet still satisfy continuously increasing demands for higher-quality products and induction heating addresses these challenges in the most effective way.

Induction heating offers additional attractive features such as

- A measurable reduction of scale and surface decarburization.
- Ability for in-line heating and processing.
- Short start-up and shutdown times. Energy is used when workpiece is being heated. No energy is required to build or maintain furnace temperature. Heating begins when an inductor is energized.
• Readiness for an automatization with lower labor cost.
• Ability to heat in a protective atmosphere, if required.

Billets and bars are heated either fully (Figure 1) or partially either in cut lengths or continuously and are forged in presses, hammers or upsetters.

![Figure 1 - Examples of in-line multi-coil induction heating systems (Courtesy of Inductoheat Inc.)](image1)

The forging industry’s drive to more accurate net shaped high quality parts and a necessity in providing more value to the forger’s customer is inherently related to the needs of further improving quality of forged parts which relates to developing superior design concepts of induction heaters and process control strategies that optimize all stages involved in the warm or hot forming operation. Modern approach for designing forging processes requires considering induction heating not as a standalone process, but as a part of an integrated system including its all-important elements: the process of induction heating, the change in the billet temperature profile during its transportation from the heater to the metal forming machine and process of plastic deformation itself.

The selection of principal process parameters, such as power, frequency, number of coils and their length is a complex function of the process specifics. Steel billets (including plain carbon, microalloyed and alloy steels), by far, represent the majority of hot-formed billets, although other materials including titanium, superalloys, aluminum, copper, brass, bronze, magnesium, nickel and others are also induction heated for forming.

![Figure 2 - Non-uniformity of initial heat distribution prior to induction reheating](image2)

Usually, the initial temperature of the workpiece prior to induction heating is uniform and corresponds to an ambient temperature. However, there are cases, when an initial temperature is not uniform and poorly defined. Induction heaters installed between continuous casting operation and rolling operation or induction reheating after piercing and prior to extrusion can serve as typical examples of non-uniform initial thermal conditions. Due to the nature of the previous technological operation (including uneven cooling of different areas), the outside surface layers and particularly the workpiece’s end and edge areas could become appreciably cooler than the central and internal regions. As an example, Figure 2 shows temperature non-uniformity of pierced stainless steel hollow billet prior to its reheating in induction heater for a subsequent direct extrusion.
Aspects of mathematical modeling

In the last decade, when discussing subjects related to a mathematical modeling and optimization of induction heating, the word “usefulness” has been replaced by a word “necessity”. Modern computer modeling is capable to effectively simulate electromagnetic and thermal phenomena. Simulation provides the ability to predict how different, interrelated and non-linear factors may impact the transitional and final thermal conditions and what must be accomplished to improve the effectiveness of the process, determine the most appropriate recipes to optimize a process and serve as a comfort factor when designing new systems.

In recent years finite element method became a dominant numerical simulation tool for a variety of engineering applications. Though finite element method is very effective modeling technique, it cannot be considered as an ultimate computational tool for all induction heating applications. In some cases a combination of different numerical methods (finite-differences, edge elements, boundary elements and others) is more effective, in others FEA is a preferred choice.

Power ratings, frequency range and temperature requirements

The power ratings of induction heating machines range from less than 10kW up to dozens megawatts typically utilizing low and medium frequency (50Hz to 30 kHz). In cases when it is required heating high electrically resistive materials (e.g., Ni-based super alloys, titanium) having relatively small diameters (less than 6mm dia.), applied frequencies are higher being in 70 kHz to 400 kHz range.

The choice of frequency is always a reasonable compromise in induction heating. Too low frequency might result in undesirably large penetration depth that, in turn, might lead to poor coil efficiency due to an eddy current cancellation and have greater impact on presence of sub-surface overheating. When the frequency is too high, an induced current concentrates within a fine surface layer compared to the diameter of the billet requiring long heat times that in progressive induction heating call for longer heating line. Optimal frequency is a complex function of several process features [1, 2].

It is typically required to raise the billet’s temperature to a specified level and degree of heat uniformity. The uniformity requirement may include maximum tolerable temperature differentials — “surface-to-core,” “end-to-end,” and “side-to-side.”

Instead of uniform temperature requirements, some applications require developing certain thermal gradients. A longitudinal thermal gradient along the billet’s length (profile heating) is often desired when heating billets fabricated from certain metals (for example, pure aluminum and aluminum alloys) prior to direct or continuous extrusion, for example [1]. Taper heated billets having a hot nose and cooler tail compensate for the heat generated during direct extrusion resulting in a desirable condition of an isothermal extrusion.

It is important that the maximum temperature anywhere within the billet does not exceed certain level ensuring that none of the billet’s areas are overheated and “hot shortness” as well as steel “burning” does not appear. Taking into consideration that pyrometers can only reliably measure billet’s surface temperature at certain spots, there is always a danger to “miss” an overheating of the local or/and sub-surface areas. Therefore, precise temperature control based on a reliable prediction of temperature distribution within the billet using an advanced modeling capability is essential.

A common incorrect assumption

Some practitioners incorrectly assume that with induction billet heating the coldest temperature is always located at the core of the billet and the maximum temperature is always located at its surface. It is also often assumed that overheating does not occur if surface temperature measured by a pyrometer or thermocouple does not exceed the maximum permissible level. Besides that, process
control systems that predict rise of an average temperature and temperatures of surface and core of
the billet often assumed to be sufficient to guarantee proper heating providing a comfortable factor
for some practitioners. Example of such typically predicted “surface-to-core” temperature profile is
shown on Figure 3. However, it is imperative to recognize that under certain but very realistic condi-
tions, the presence of heat losses from billet’s surface may shift the temperature maximum further
away from the surface marking its location somewhere beneath the billet’s surface.

Study shows [2, 5] that positioning and magnitude of the subsur-
face temperature surplus and potential steel overheating is a complex
function of four major factors: frequency, refractory, final tempera-
ture, and power distribution along the heating line.

Lower frequencies increase the
current penetration depth resulting
in more “in-depth” heating and lead-
ing to a faster temperature raise at
billet’s core. This shortens the in-
duction line, but on another hand,
under some conditions, it can also
increase the subsurface overheating
by making it more pronounced and
shifting the location of the maxi-
mum temperature further away from
the surface.

The use of an appreciably thick refractory with improved thermal insulation properties does just
the opposite, reducing subsurface over-heating and shifting billet’s maximum temperature towards its
surface. Increase of the forging temperatures lead to an effect similar to an effect of lowering
frequency in regards to a location of maximum temperature and severity of the subsurface heat
surplus. An effect of power distribution along the heating line on billet’s temperature distribution is
more complex. In most publications devoted to progressive induction heating of billets, it is strongly
suggested to have a graded (profiled) power distribution along induction line by putting more power
at the beginning of the line. 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, allowing more time to soak
into the core and shortening the length of the line. This approach typically utilizes a single inverter
that powers several coils with graded number of copper turns or/and series/parallel coil circuit
connections.

The problem with this approach, however is that the power distribution along the heating line in
some installations cannot be easily modified if the production rate, kind of metal or billet size
changes. For example, if the production rate is reduced, a subsurface overheating typically worsens
with a conventional induction design potentially negatively affecting the billet’s subsurface micro-
structure. It is also very common to find an appearance of billet-sticking problems to be more pro-
nounced with graded power distribution along induction line when the system runs at a rate slower
than the nominal for which it was designed. Since the system puts more energy into the billet in the
beginning of the heating line, too much energy soaks down into billet’s subsurface area in cases when
the line runs slow. The presence of surface heat losses can reverse a traditionally expected radial
temperature profile leading to the subsurface temperature being greater than at its surface.
In many cases, subsurface temperature might 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, Figures 4 shows “surface-to-core” profiles when heating 2” (50.8mm) diameter billets (Figure 4, left) at a slower rate utilizing a conventional induction heating line designed for processing 2.5” (63.5mm) billets (Figure 4, right) at a nominal rate (see Figure 3). Note that in both cases the billet’s surface temperature that would be recorded by pyrometer is the same. Further reduction in billet’s diameters could worsen a severity of subsurface overheating [5].

Further reduction in the billet’s diameters could worsen the severity of subsurface overheating that can manifest itself in a billet sticking problem (Figure 5), as well as grain boundary liquation (incipient melting) and intergranular cracking (Figure 6).

Besides a potential danger of a premature die wear on hammers and presses, as well as other issues related to altering a quality of forged parts improperly heated billets can raised some safety concerns. Practice shows that 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 it is desirable to use a control strategies that re-distribute power by its shifting towards the end of the induction line.

Figure 4 - Final “surface-to-core” temperature profiles when heating 2” (50.8mm) dia. billets at a slower rate (left) utilizing a conventional induction line designed for processing 2.5” (63.5mm) billets at a nominal rate (right) [5]

Figure 5 - Billet sticking problem occurred due to subsurface overheating

Figure 6 - Grain boundary liquation and intergranular cracking occurred due to poorly controlled subsurface overheating
Taking into consideration that pyrometers can only reliably measure billet’s surface temperature, there is always a danger to “miss” an appearance of the sub-surface overheating. Therefore, precise temperature prediction is imperative in order to avoid localized over-heating that is related to “hot shortness” problems due to low melting point residuals and possible variations in the chemistry of given steel.

**Superior temperature control**

Inductoheat’s IHaz™ temperature profile modeling software represents a measurable step in optimizing an entire forging process. This proprietary PC based subject-oriented software provides more detailed information regarding thermal conditions of inductively heated billets than any pyrometer can.

As an example, Figure 7 shows typical temperature profile generated by IHaz™. It is not only an important part of the process control of induction heater, it also offers detailed knowledge regarding thermal conditions of heated billets that can be effectively used in optimization of forging operation and even during designing dies.

The IHaz™ also provides an estimate of the energy usage that is important in determining utility costs when pricing new parts and what should be accomplished to avoid a probability of sub-surface overheating and steps to further improving a quality of inductively heated parts.

**INDUCTOFORGETM: A novel induction billet heating technology**

The InductoForge™ Billet Heater is Inductoheat’s superior modular technology that was specifically developed for the forging industry to optimize induction heating processes (Figure 8). The heater’s basic concept is a fairly simple including a 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 above-discussed changes in production schedule. Each module allows controlling both; power and frequency of each coil along the induction heating line.

While the coil and power module are the basic components of the system, there are several others that complete it. The PLC, HMI (Human Machine Interface) and other controls are mounted on a pendulum so that the operator can position the screen for easy viewing (Figure 9).

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. Some of those features discussed below:

Superior system flexibility with optimized power and frequency distribution along the heating line related to the specifics of a particular process run. Frequency of each module can be easily modified within 500Hz to 6kHz range to match a demand of the great majority of forged billet sizes maximizing coil electrical efficiency. Superior computer modeling and advanced temperature control of InductoForge™ substantially improves the quality of heated parts assuring enhanced metallurgical structures and selecting a process recipe that minimizes a probability of subsurface overheating.
Unique Static and Dynamic Stand-by and Rapid Start capabilities substantially improve start-up, holding and shutdown process stages. Detailed description of these capabilities can be found at www.inductoheat.com

Temperature Profile Computer Modeling system utilizes the powerful Inductoheat’s proprietary software that was specifically developed to optimize performance of induction heating systems based on a set of operating parameters specified by the user, which can be downloaded to a PLC recipe.

Besides superior flexibility InductoForge™ can be 20% more electrically efficient than older, conventionally designed induction systems, particularly when the billet heater is run at reduced production rates. 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.

The InductoForge™ coil utilizes a removable liner with a thermally enhanced design to reduce the thermal losses. This gains an additional 3-5% in efficiency. The advanced mechanical coil design

References