RECENT INVENTIONS AND INNOVATIONS IN INDUCTION HEATING TECHNOLOGY

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Temperature greatly affects the formability of metals. Heating of a component 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.

Over the past three decades, induction heating has become an increasingly preferable choice for heating metals prior to warm and hot working. This tendency continues 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, 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 environmentally friendlier than most other heat sources (it is free from CO_2 emission). 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.

Induction heating offers additional attractive features such as:

- A measurable reduction of scale.
- Ability for in-line heating and processing.
- Short start-up and shutdown times.
- Readiness for automatization with lower labor cost, and
- Ability to heat in a protective atmosphere if required, etc.

Billets, rods or bars are heated either fully (Fig.01) or partially; either in cut lengths or continuously and are forged in presses, hammers (repeated blows) or upsetters (which gather and form the metal).

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 and innovative process control strategies that optimize all stages involved in the forging process.

Modern approach for designing forging processes requires considering induction heating not as a stand-alone process, but as a part of an integrated system including its all-important elements.

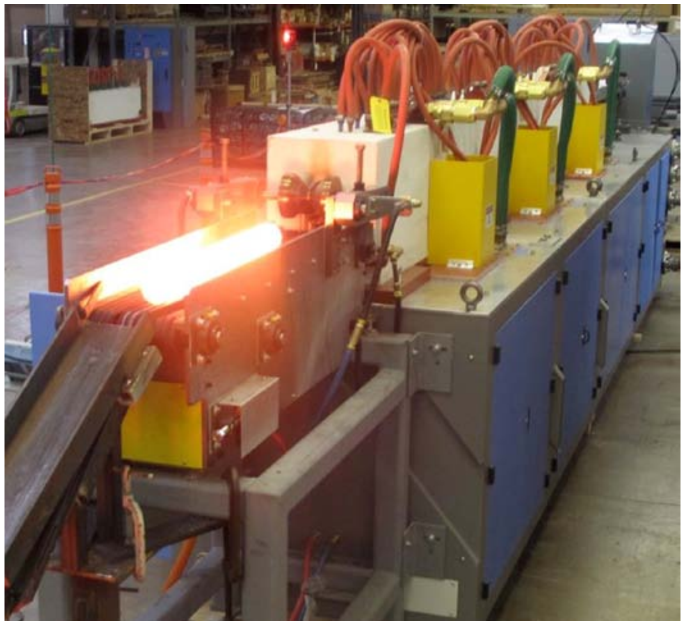

Figure 1. InductoForge^{TM} system for heating billets or bars.

Steel components (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, zirconium, nickel and others are also induction heated for warm and hot forming.

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. Induction heaters installed between continuous casting operation and rolling operation or induction reheating after piercing and prior to extrusion can serve as a typical example.

Due to the physical nature of the previous technological operation (including uneven cooling of different areas of the processed workpieces), the surface layers and particularly the end and edge areas could become appreciably cooler than the central and internal regions. As an example, Fig.02 shows significant temperature non-uniformity of pierced stainless steel hollow billet prior to its reheating in induction heater prior to direct extrusion.

Measures should be taken to design induction re-heating systems flexible enough that would be able to compensate incoming appreciably non-uniform temperature profiles and provide the billet with sufficiently uniform temperature distribution. The uniformity requirement includes maximum tolerable temperature differentials — “surface-to-core,” “end-to-end,” and “side-to-side.”

A longitudinal thermal gradient along the billet’s length (profile heating) is sometimes desired when heating billets fabricated from certain metals (e.g. aluminum) prior to direct or continuous extrusion, for example.

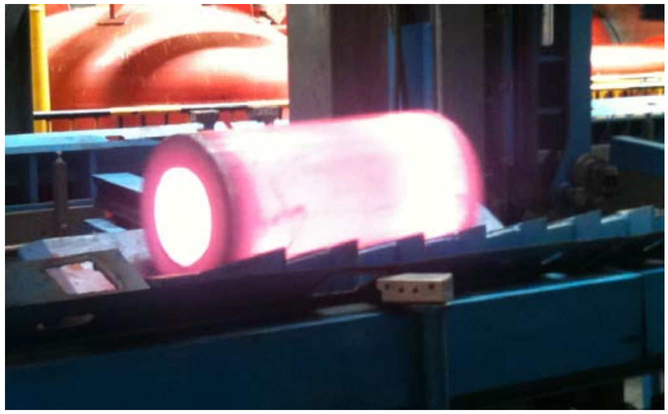

Figure 2. In some cases, the initial temperature of the workpiece prior to induction heating is considerably non-uniform.

Although many of the workpieces (for example, bars, billets, plates or rods) being manufactured today lend themselves to processes in which entire workpieces are heated and fed into a machine for subsequent operation, in some cases it is required to heat only a certain portion of the workpiece, for example its end. Some examples of these types of parts are “sucker rods” for oil country goods or various structural linkages in which an eye or a thread may be added to one or both ends of the bar.

Tempering, subcritical annealing or stress relieving of threads of shafts represents other applications where selective areas are heated by induction. Re-heating of edges of slabs, transfer bars, plates and strips, as well as heating of middle sections of the pipes or tubes are also belong to the family of applications where selective heating is required.

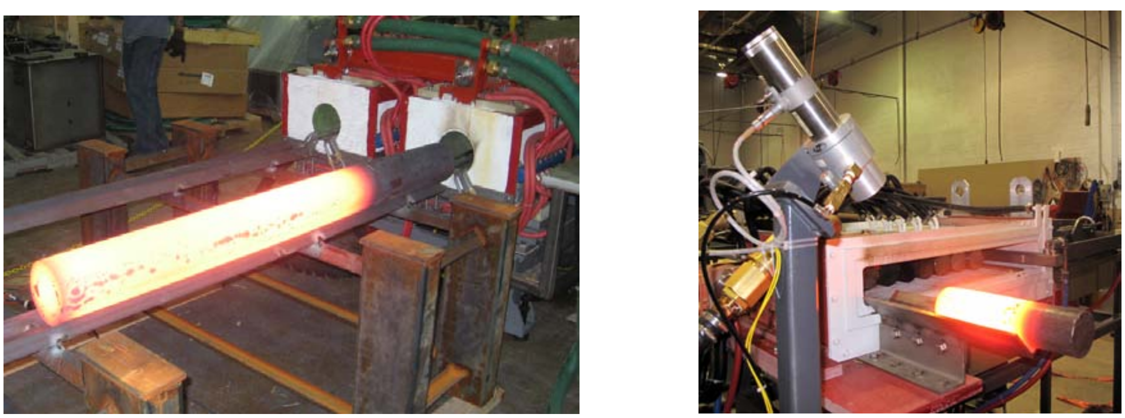

Figure 3. Various coil design can be used to provide selective heating.

Placing the end of the bar into an inductor of appropriate style and heating it for a specified amount of time accomplishes end heating. Multiple bar ends can be heated in a single-turn or multi-turn cylinder (Fig. 3, left), oval or rectangular solenoid coil (Fig. 3, right), as well as in channel-type inductors (also called a slot or skid coils), or in multiple coil arrangements that are configured out of individual conventional solenoid coils. Upon leaving the coil, the bar's ends are at the required temperature, and the workpiece moves to the subsequent technological operation, for example metal forming.

Materials with high values of thermal conductivity conduct the heat faster helping to equalize thermal gradients and improve heat uniformity. Therefore, it is typically easier to provide "surface-to-core" temperature uniformity for metals with high thermal conductivity such as aluminum, silver or copper. Metals with lower thermal conductivities, including stainless steel, Ni-based super alloys, titanium and carbon steel require extra care in order to obtain the desired "surface-to-core" temperature uniformity. This "extra care" includes proper selection of heating mode, design concept, process recipe and other parameters that allow avoiding following undesirable phenomena:

- Having the heat deficit in the billet's core.
- Subsurface overheating.
- Billet sticking.
- Hot shortness.
- Excessive scale formation and oxidation, etc.

In contrast to applications requiring heating of an entire body, in selective heating, a high value of thermal conductivity is quite often a disadvantage because of its tendency to provide an intense heat transfer not only in the radial direction but in axial direction as well. This results in equalization (soaking) of the longitudinal temperature distribution leading to heating not only in the workpiece area that is required to be heated but also in a much greater area due to thermal conduction (the so-called, thermal sink effect). Heat flow that occurs due to the heat sink effect not only leads to a 3-D re-distribution of the temperature profile but also affects the amount of total mass of the metal being heated. This directly affects the regions adjacent to the areas to be heated and giving the rise to power consumption and, in some cases, could lead to some problems related to handling of the heated workpieces.

For high production rates (i.e., 1800 pieces per hour or even higher) both oval and channel type inductors (also called, a slot or skid coils) become virtually the most suitable options and are often employed with fully automated or semi-automated handling. Unfortunately, the majority of all-purpose commercially available software does not take into consideration important features and specifics of the current flow when using both oval and channel inductors.

Some of bar end heating applications require a specific temperature profile along the heated length of the workpiece (so-called profile heating or gradient heating), including sharp or gradual cut-off of the heat pattern and/or certain length of the longitudinal transition zone.

An accurate prediction of an electromagnetic field and temperature distribution in bar end heating applications, as well as required coil design parameters (including power and optimal frequency) and accurate assessment of the process subtleties can be obtained using numerical simulations.

Recognizing the importance of computer modeling in predicting how different, interrelated and non-linear factors may impact the transitional and final thermal conditions of billets and bars and what must be accomplished to improve process effectiveness and determine the most appropriate process recipes, several innovative subject-oriented numerical computational codes have been developed.

The fact that, the bar is only partially inserted into the heating coil does not permit using analytical or equivalent circuit calculation methods to accurately simulate this process, because those methods are based on the assumptions of an infinitely long ideal cylinder coil with a symmetrically located workpiece.

On the other hand, a great majority of numerical commercial software used for modeling of induction heating processes are all-purpose programs that were developed for other applications (such as transformers, NDT, magnetic recording, etc.) and were later adapted for induction heating. Regardless of well-recognized capabilities of generalized programs they often experience difficulties in taking into consideration certain features of induction bar end heating. This includes:

- Multiple workpieces progressively move side-by-side through an inductor.
- Different orientation of eddy current flow within the workpiece at various heat stages.
- The presence of thermal refractory and the necessity of taking into consideration radiation view factors.
- Initial temperature distribution might be appreciably non-uniform.
- Presence of end plates, profiled coil turns, water-cooled support rails, guides, fixtures, liners, etc.

It is important to be aware that some critical features of induction heaters could be limiting factors for all-purpose software dramatically affecting an accuracy of simulations. This leads to the necessity of developing various proprietary application-oriented programs allowing selection of the most appropriate modeling technique and taking into consideration specifics of a particular induction process and its subtleties.

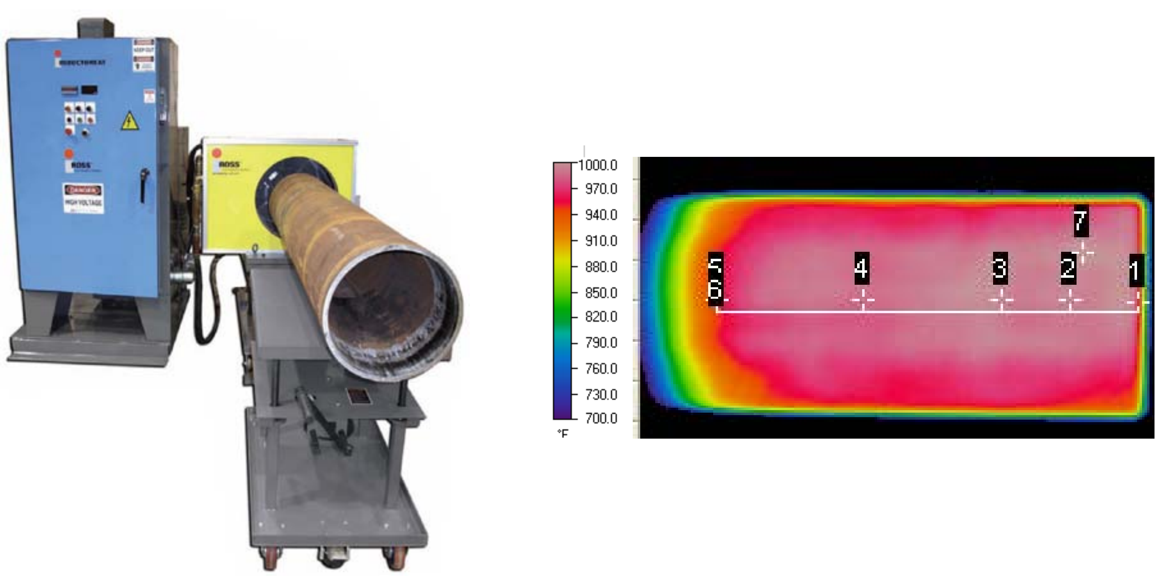

Figure 4. FluxManager™ Technology (*US Patent No. 7,317,177*) to stress relieving of steel tube/pipe ends.

Several innovative technologies will be discussed in this presentation. This includes but limiting to

- Development of FluxExtender Technology (patent pending world-wide) to assure temperature uniformity when heating large billets with appreciably non-uniform initial temperatures.

- Development of FluxManager^{TM} Technology (*US Patent No. 7,317,177*) to stress relieving of steel tube/pipe ends (Fig.4).

- Induction heating of irregular shape workpieces, including non-cylinder workpieces and telescope-type elongated workpieces.

- Specifics of induction heating of magnesium alloys.

- Induction oscillating technology.

- Advanced inverters with independently controlled power and frequency during operation.

- Novel computer modeling technologies to simulate inter-related induction heating processes.