A glowing billet comes off the induction line.

North American Forging *is* Advanced Manufacturing

(Part 3: Advanced Billet Heating Operations)

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In a modern forge, billet heating is critical and often controlled to tight specifications by various methods, including gas-fired furnaces, electric heaters, infrared heaters and induction heaters. This article will focus on induction heating and its place as an advanced and controlled thermal process enabled by a host of modular and modern heating units tailored for specific forged parts.

Today's modern induction forge heaters are designed to apply sophisticated process monitoring and quality-assurance strategies that may include elements of artificial intelligence. Temperature greatly affects the formability of metals. The heating of billets and bars through their entire cross sections to temperatures within their plastic deformation range creates a favorable condition for metal to be subsequently forced into a desired shape.

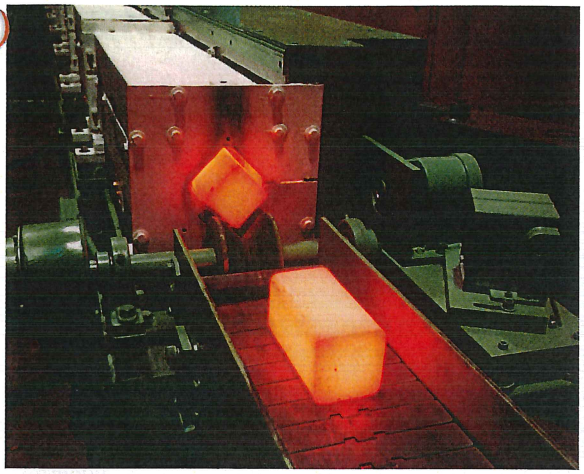
In the past, workpieces were placed into sizeable fuel-fired furnaces for prolonged periods. It was expected that thermal conductivity would have sufficient time to convey the heat from the workpiece surface to its core. Unfortunately, there are several undesirable metallurgical phenomena associated with steel being exposed to high temperatures for lengthy periods, including metal loss due to scale generation, severe decarburization, intergranular oxidation, severe grain coarsening and more.

Electromagnetic induction heating addresses these phenomena and is becoming a preferred choice for heating metals. This is based on its ability to create high heat intensities from the surface through the core of the workpiece, resulting in reduced time to heat the workpiece, high production rates and maximized energy efficiency.

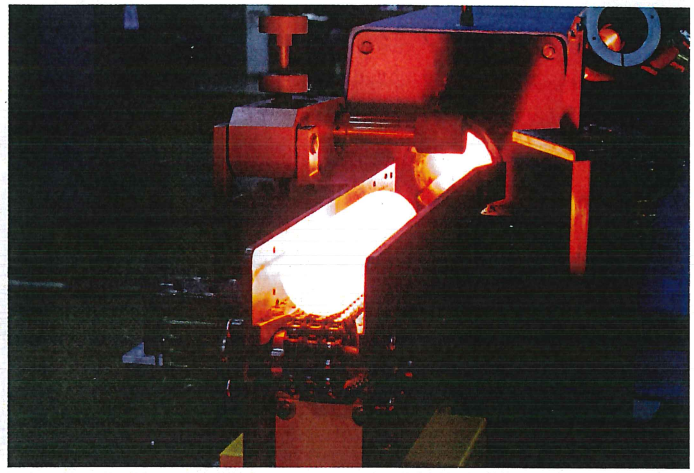
Temperature Measurement Issues

Coupling advanced mathematical models with induction heating enables tighter process control in billet and bar heating operations. Pyrometers can only measure the temperature at certain spots of a workpiece's surface. In actuality, the surface temperature uniformity of a billet may be within the typical range for forging operation, but its internal heat distribution might be far outside that range. Local subsurface overheating or underheating may occur. In practice, no part of the workpiece should become overheated (or underheated) or the steel and processing can be adversely affected.

Since internal temperatures cannot be measured or seen, they can only be simulated mathematically. Therefore, precise temperature monitoring based on a reliable prediction of temperature distribution within the workpiece is imperative in designing modern induction bar and billet heating systems.



Internal billet temperatures can only be modeled, not measured directly.



Billet surface temperature may not be the hottest of the entire cross section.

The induction heating industry has developed application-oriented software to optimize modern induction heaters. Highly technical and specialized software utilizing numerical simulation techniques is an essential part of a modern induction heating package. The results of simulations can be loaded into a PLC to operate the billet heater.

Software output is not just a significant part of the process control of an induction heater. It can also be effectively used in optimizing the entire forging line, including the computation of energy usage and utility costs.

Multi-Objective Optimization

When designing an induction heating system, there is always some uncertainty associated with the need for different production runs and changing market needs. Therefore, it is necessary to react quickly to develop a process-control strategy utilizing versatile computational intelligence to ensure the attainment of production goals. Induction heating is a dynamically controlled system with 3-D temperature distribution defined as an output-controlled function. The technology has evolved to the point where it has provided much of the heavy lifting for challenging process situations.

The mathematical modeling of induction heating can be divided into a number of interrelated and nonlinear sub-phenomena. Yet, machine learning capability is the subject of future R&D projects that will allow computerized control algorithms to provide self-teaching through the analysis of process inputs. Development of temperature-profile modeling software included into an equipment package represents a measurable step in optimizing the entire forging process and ensuring the quality of heated billets.

Subsurface Overheating

Some users of induction systems incorrectly assume that the coldest temperature is always located at the core of the billet and the maximum temperature is always located at the surface. It is also often assumed that overheating does not occur if the pyrometer-measured surface temperature does not exceed the maximum permissible level. Furthermore, process-control systems that predict workpiece temperature profiles are sufficient to guarantee proper heating.

It is vital to recognize with induction heating that internal heat generation and inevitable heat losses from the surface of the billet can shift the temperature maximum further from the surface, marking its location somewhere beneath. Overheating worsens all the critical properties of steel, including its ductility, impact strength, tensile strength, elongation and reduction of area.

The metallurgical "burning" of steel may result in irreversible damage to the steel structure. It causes intergranular liquation of low-melting phases and the degradation of grain boundaries and their internal oxidation. Grain coarsening is associated with weakened grain-boundary networking, resulting in a reduced total grain-boundary area. In contrast, fine grain structure is associated with greater total grain-boundary area with reduced concentration of impurities, improving the steel's ductility, toughness and impact strength.

If surface or subsurface burning occurs, steel properties cannot be restored by heat treating or mechanical working and may require the scrapping of billets. This emphasizes the importance of computer simulations as a means to reliably predict subsurface thermal conditions.

Metallurgical Specifics of Induction

In the case of heat treating plain-carbon steels, when iron is alloyed with different percentages of carbon, the critical temperatures are often determined by the iron-iron carbide phase-transformation diagram (Fe-Fe_3C diagram) or by correspondent diagrams or mathematical correlations that indicate the effects of certain additional chemical elements on the positioning of critical temperatures in the case of low-alloy steels.

Unfortunately, some practitioners are unaware that those diagrams and correlations might be misleading in the majority of induction heat-treating applications because they are valid *only* for the equilibrium heating conditions. One of the major requirements of an equilibrium condition is very slow heating with sufficient amount of time at temperature to complete phase transformation.

Continuous Heating Transformation (CHT) diagrams are more appropriate for rapid induction heat treating in making a decision regarding the appropriate critical temperatures. Rapid heating has a marked effect on not only the magnitude of critical temperatures but also on their order. As a result of rapid heating, when heat intensities exceed about 20°C/sec (typical in many induction heat-treating applications), instead of the normal order of critical temperatures (A_{c1}, A_{c2}, A_{c3}), rapid heating can switch the order to A_{c2}, A_{c1}, A_{c3} (where A_{c1} is the critical temperature at which austenite starts to form, A_{c2} is the Curie temperature and A_{c3} is the critical temperature at which the material becomes fully austenitic).

Equipment Flexibility

In a modern, highly dynamic and globally competitive marketplace, it is important to build a system with advanced process flexibility that allows adjustment to a rapidly changing business environment. Long-term customers may move their production at a minute's notice. The forger must be able to get new business to cover lost business. Billet size, grade of heated material, production rate and many other factors may change as customer requirements do.

The modular design of induction forge heaters provides the flexibility to meet a wide range of product requirements with minimal equipment change. Modularity allows the easy adjustment of power and frequency within the range of 500 Hz to 6 kHz.

For example, if the production rate is reduced, a subsurface temperature surplus typically worsens with a conventionally designed line, with the potential to negatively affect the subsurface microstructure of the billet. It is also very common to find billet-sticking problems when the subsurface temperature becomes hot enough to cause the billets to fuse together. Modular induction systems maximize process flexibility for the entire induction line and optimize heating parameters for a range of forging applications.

For example, if it is required to heat larger billets (e.g., 4.5 inch diameter), a lower frequency (e.g., 500 Hz) produces more in-depth heating and minimizes heating time. This provides improved radial temperature uniformity. If future market conditions favor smaller billets, then appropriate inverters can be easily reconfigured to produce a higher frequency (e.g., 6 kHz). This results in a more surface-heating effect, avoiding eddy current cancellation and maximizing heating efficiency.

The modular design of induction forge heaters provides the flexibility to meet a wide range of product requirements.

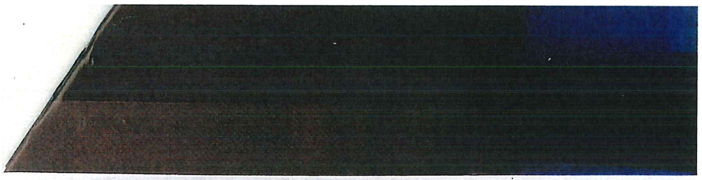
Advanced computer modeling and temperature-control capability of modular systems noticeably improve the quality of heated billets, ensuring enhanced metallurgical structures and selecting a process recipe that eliminates the probability of subsurface overheating. A temperature-profile computer-modeling system optimizes the performance of an induction heating system based on a set of operating parameters specified by the user. Software generates the power setting for each inverter, which can be downloaded into a PLC recipe, and creates a thermal signature for the temperature of the exiting billet, which can be used as input data for modeling subsequent forming operations.

Transient States

Transient processes have a measurable effect on overall performance of an induction heater. The main goal of optimizing transient process stages is to produce as many properly heated billets as possible and minimize the "lost opportunity cost." It would be ideal if a forging line could run continuously with no downtime. Unfortunately, this does not happen in real life. Sometimes plant conditions require an induction line to perform a holding cycle, though its duration is typically unknown in advance.

With conventional billet heaters, if billets were left inside of the coil line overnight it could take as much as two or three lines of billets to get to the proper temperature, negatively affecting energy consumption and productivity. Because of their modular design, each induction coil has its own independently controlled power supply, which allows the induction heater to stop and hold the billets at temperatures for an appreciable amount of time while problems with the press or hammer are fixed.

By establishing and holding a longitudinal thermal profile, it is easier to keep more billets at the correct temperature during a cold or hot start. The rapid-start feature gets the user up and



running quickly in the morning or after holidays. The rapid-start technology of modular systems speeds temperature distribution along the heating line, dramatically reducing the energy wasted in heating two to three lines of billets.

Conclusion

From this short review of induction heating, one appreciates the importance and sophistication of advanced heating for forging operations. This is but one example of process control making forging an advanced-manufacturing technology. We will consider post-forging operations in the next article in this series.

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