



Dr. **Valery Rudnev**, known as “Professor Induction”, discusses in the heat processing different aspects of induction heating, novel theoretical and practical knowledge related to different heat treating technologies accumulated in the North America and around the globe.

## Induction heating of steel billets: causes of billet sticking/fusing problem and its prevention

Steel components by far represent the majority of hot worked billets and bars for which electromagnetic induction is used as a source of heat generation (**Fig. 1**). At the same time, Ni-base superalloys, Ti, Cu, Mg, Al as well as many other non-ferrous metals and alloys are also inductively heated for a number of commercial applications producing various shapes, properties and microstructures.

Temperature greatly affects the formability of metals. Heating of a workpiece through its cross section to temperatures of the plastic deformation range creates a favorable condition for metal to be subsequently forced by various means into a wanted shape. The versatility of induction heating (IH) is associated with its ability to heat the workpiece entirely or its specific areas uniformly or, if preferred, creating appropriate thermal profiles.

The most popular metal hot working processes for which IH is applied are as follows [1]:

- **Forging:** Billets, rods, bars, and the like are heated either in cut lengths or continuously, and are forged in presses, hammers, upsetters, etc.
- **Forming:** Hot forming includes a variety of metal-working operations generally encompassing bending, expanding, spinning, and some others.
- **Extrusion:** This process relies on forcing or squeezing heated materials through a die, as it takes place in direct and indirect extrusion.
- **Rolling:** Bars, rods, rings, plates, etc. are rolled into the desired sizes and shapes.

In addition to obtaining desirable shapes, metallic components produced by warm and hot working often exhibit enhanced structural integrity, superior mechanical properties, and desirable grain structure compared to cast materials. Fibrous grain structures developed after forging can be very beneficial. For example, if grain flow is oriented perpendicular to the most likely direction of crack development during service, such structures can impede crack initiation and growth, improving engineering properties.

There is a wide range of workpiece sizes that are induction heated. Some components are made from ingots or continuous cast metals and their alloys; others use wrought or powder metallurgy materials. Though specific applications may call for achieving certain desirable thermal gradients, in the great majority of IH, it is necessary to provide the metallic workpiece at a target temperature with the desired heat uniformity across its diameter/thickness as well as along its length and circumference.

### BILLET OVERHEATING PROBLEM IN STEEL FORGING

In an attempt to increase metal plasticity and life of dies, some forgers have a tendency to increase the forging temperatures above the suggested maximum levels. This could potentially lead to steel overheating. “Overheating” is a generic term representing a number of undesirable metallurgical phenomena and has been discussed in numerous publications.

Overheating worsens all critical properties of steel, including its ductility, impact strength, tensile strength, and others. Metallurgical “burning” is the severest form of steel overheating that results in a permanent irreversible damage of the product. It causes intergranular liquation (also called incipient melting or grain boundary liquation), internal oxidation, and degradation of grain boundaries and could promote radial and/or longitudinal cracking (**Fig. 2**, left two images).

Overheating is largely correlated to the melting point of a particular steel grade, the presence of alloying elements, low-melting phases and residuals (e. g. Cu, P, S, etc.), temperature and the time steel is exposed to high temperatures. If burning occurs, steel properties cannot be restored by heat treating or subsequent mechanical working requiring removing affected areas or scrapping the metal.

The formation of oxides beneath the surface of the heated steel (an internal oxidation), severe decarburization and scaling (**Fig. 2**, right image) as well as disproportionate grain coarsening are other highly undesirable phenomena associated with reaching excessive temperatures.



**Fig. 1:** Steel components by far represent the majority of warm and hot worked parts for which electromagnetic induction is used as a source of heat generation



**Fig. 2:** In the presence of oxygen at elevated temperatures, the steel's surface is oxidized, generating excessive scaling (right image). Development of transverse and longitudinal cracks (left and middle images) may be a concern when heating high-carbon steels, cast irons, and steel castings as well as other materials that exhibit low toughness [1]

Severely scaled, decarburized, and internally oxidized steels can produce a number of undesirable consequences. For example, those layers or their traces might be seen in the products as bands of decarburized materials containing oxide particles, islands, or clusters and may be entrapped into a product during its hot working.

Scale formation is a major concern to the industry since it has a multidimensional negative impact on overall cost-effectiveness, product quality and equipment life [1–5]. Measurable reduction of scale formation/oxidation is imperative to steel processing companies because scale detracts from a value-added product and is associated with at least four additional undesirable factors:

- Metal loss, dimensional inaccuracies and unnecessary metal allowances are associated with excessive scaling.
- Scale adhesion issues may negatively affect not only product quality but a life expectancy of operating machinery accelerating the tool wear. In some cases, scale adheres to the workpiece surface, making its removal via descaling difficult. In other instances, abrasive scaling may adhere to parts of the forming or handling machinery, worsening tool wear, causing high friction conditions, shortening the life of dies and rolls, and producing scale pit marks. Various oxides have different descaling characteristics complicating their removal.
- Scale affects the working conditions of induction heaters: Capital-extensive maintenance programs and necessity of frequent scale removal and disposal are also directly related to a scale formation. The life of refractory linings, skid rails, and copper turns is greatly affected by a scale generation. For example, one of the most frequent causes of forging coil failure is related to loose scale particle and scale dust penetration through micro-cracks and porosities of refractory developing large cracks and eventually leading to arcing between coil turns and melting. Scale accumulation causes production interruptions of not only heating equipment but also downstream operations, requiring time-consuming, intense, and costly maintenance/repair programs, which are associated with unproductive downtime.
- Waste of energy: This obvious factor has a multi-dimensional impact. Amount of energy used to produce the scale is only one factor. Scale can cause premature failures of the hot working

equipment including forging dies and mill rolls, thus, it is associated with energy consumption for repair work. Scale-related failures of hot working equipment are also linked to prolonged stoppages of the processing machinery, including induction systems, leading to the waste of energy associated with a standby (holding) operation as well as with shutting an induction line down, scale clean-up and starting it up again.

In induction forging applications, there are several ways to suppress the scale formation for a given steel grade [1]. Besides the minimizing temperature level being an obvious factor, shortening the time for the workpiece's surface to be exposed to high temperatures in oxidizing atmosphere is another dominant factor. The capability of induction heaters allowing dynamic power redistribution along the heating line for different production runs and thus minimizing the time a metal is exposed to high temperatures is also essential for a scale reduction.

### BILLET FUSING/STICKING PROBLEM, ITS CAUSES AND PREVENTION

Forgers sometimes experienced situations when under seemingly normal heating runs with temperatures registered by pyrometer(s) within a permissible range, two neighboring billets might unexpectedly fused/ welded/ stuck together (**Fig. 3**, above). In some cases, the weld joint of fused billets is located at the billet's surface but in other cases its location might be mysteriously below the surface. For example, Fig. 3, below reveals positioning of billet's fusion mark (where two billets have been welded/stuck together) being located in the subsurface area and not at the surface. Intuitively, billet's sticking/welding problem should be somehow associated with reaching excessive temperatures, however, why billet's fusion mark is sometime located below the surface? Forgers might have a hard time in their attempt to explain this phenomenon, its cause(s) and ways to prevent its occurrence.

There is a common mispostulation that in billet heating, the coldest temperature is always located at the core and that the maximum temperature is always located at the surface. Therefore, it is sometimes improperly assumed that overheating does not

occur if the surface temperature measured by a pyrometer does not exceed the maximum permissible level.

It is important to recognize that, under certain but very realistic conditions, the heat losses from the billet's surface can shift the temperature maximum further away from the surface, marking its location somewhere beneath it. The location and magnitude of subsurface temperature surplus is a complex function of four major factors: electrical frequency, refractory, target temperature, and power distribution along the heating line.

Conventionally designed induction systems for heating small- and medium-sized billets may comprise a single large inverter or few large inverters powering an entire multi-coil line. The coils could be connected electrically in a series or parallel or in a combination of both, depending on the type of a particular power supply and load matching characteristics [1]. Unfortunately, such a design approach when a single-power source feeds a number of coils is inevitably associated with restricted process controllability and flexibility, because power cannot be easily re-distributed to a specific coil but rather to a number of inductors that comprise a particular circuit [1, 6].

The specifics of power distribution along the induction line have a vital impact on the heat profile within the billet. The industry uses different concepts for designing induction forging lines. According to one of such concepts, the intense heating is intended to occur in the first half of the line, developing a correspondent intense surface-to-core heat flow. Energy supplied to the second half of the heating line is substantially lower resulting in only modest rise of the surface temperature further promoting heat soaking towards the billet's core. Electrical power generated within the billet at this stage is primarily compensate for a heat transfer toward the colder core and balances the thermal surface losses. Since typically, an IH system is supposed to process billets of different sizes, a power distribution along a conventionally designed line is commonly selected based on the most power-consuming production run assuming that its performance will be ok for processing other billet sizes.

Applying more power upfront may appear to be a universal remedy since it generates more energy into the billet at the front of the induction line, permitting more time for heat transfer into the billet's center and shortening of the line. However, in other cases, it could exhibit certain drawbacks related to cracking of brittle materials, subsurface overheating, excessing scaling and billet sticking problem, just to name a few.

The use of a single inverter that powers several coils does not permit easily modify the power along the heating line when the production rate, alloy grade, or billet size changes occur. This might negatively impact temperature distribution within the billet.

Pyrometers can only reliably measure the temperature at certain spots of the workpiece's surface along the induction lines where a number of billets are progressively processed through. Regardless of the fact that the surface temperature may be within the required range specified for hot working operation ( $\pm 20\text{ }^{\circ}\text{C} - 25\text{ }^{\circ}\text{C}$  or so), the internal heat distribution might grossly exceed that range. Local subsurface heat surplus or deficit may occur. None of the



**Fig. 3:** Example of sticking/fusing of heated steel billets heated in conventionally designed induction systems

workpiece areas should reach too high temperature (permanently damaging steel) or too low temperatures (negatively affecting the process of hot working and equipment life, die wear, etc.). Thus, it is imperative to have a clear understanding regarding internal heat distribution within the billet. Since internal temperatures cannot be easily measured or even seen, they can only be simulated mathematically. Therefore, precise temperature monitoring using advanced computer modeling to obtain a reliable prediction of temperature distribution is imperative in designing modern induction billet heating systems.

The location and magnitude of subsurface temperature surplus and associated with it probability of billets to be fused/welded together is a complex function of several major factors:

- An increase in target temperatures causes a shift in the positioning of the peak temperature further from the surface toward internal regions also increasing probability of a billet sticking in subsurface.
- Lower frequencies produce deeper heat generation that is often associated with more intense temperature rise at the internal regions of the billet exhibiting significant positive effect by shortening the heating line. However, when processing smaller size billets and/or having slower production rates, surface temperatures may reach scale-forming temperatures much faster. At the same time, the peak temperature might be shifted further away from the surface [6]. In this case, the subsurface temperature surplus typically worsens while using conventionally designed lines increasing probability of a billet



**Fig. 4:** InductoForge style modular style billet heaters (Courtesy of an Inductotherm Group)

sticking in subsurface. This can also be accompanied by excessive scaling and potential subsurface steel burning.

- In contrast, the use coil refractories with better thermal insulation properties helps to reduce subsurface heat surplus and shifts the billet's peak temperature toward its surface where it can be monitored by pyrometers.
- In the case of high-production run, it is beneficial to shift more power to the cold end of the heating line. If the line is running slower and/or having billets with smaller diameters, it would be advantageous to re-distribute the maximum power closer to the hot end of the line, increasing the efficiency of the heater, reducing scale, improving microstructural quality of heated billets and reducing a probability of billet's fusion/sticking.
- An increase of an applied force for pushing billets through an IH line can complement one or several above-discussed factors increasing the probability of billet's fusion to occur.

Theoretically speaking, there are some additional factors that might trigger an appearance of billets to be stuck/fused/welded/bonded together (Fig. 3). This includes the pitch of coil turn windings (helix effect) and the size of copper turn tubing. Larger values of these parameters result in greater axial/longitudinal component of eddy current flow, which, in turn, may manifest itself in arc development between neighboring billets and their fusing. However, the impact of these phenomena is seemingly less pronounced compared to the presence of excessively high temperatures and sizable pushing pressure.

### CONCLUSION

One way to minimize a probability of billet's fusion/sticking/welding problem is to apply modular induction billet heating technology, which allows reducing the peak temperature via dynamic re-distribution of the heating power along the multi-coil line. As an example, **Fig. 4** shows one such design – InductoForge style billet heater, which allows adjusting not only the power distribution along the heating line but also the electrical frequency of heating modules within the 500 Hz to 6 kHz range.

Modular design is also beneficial for reducing a probability of crack initiation when a production run includes low-toughness/brittle steels. Transverse and longitudinal cracks may be a legitimate concern when heating those materials due to an extreme sensitivity of those steels to thermal gradients particularly during an initial heating stage.

Modular induction systems allow for intelligent redistribution of electromagnetic heat generation. This maximizes process flexibility for the entire induction line, truly optimizes heating parameters for a wide range of applications, and ensures heating quality.

There is always some degree of uncertainty associated with real-life deviations linked with different production runs. Computer modeling helps to assess particular real-life process disturbances, quickly analyze a specific technological situation, and develop a process control strategy utilizing computational intelligence, statistical methods, and allow truly multi-criteria optimization of induction heating to assure accomplishment of production goals and outperforming conventionally-designed induction forging systems.

Development of temperature profile modeling software included in an equipment package represents a measurable step in providing the metal-working industry with smart induction billet heaters implementing Industry-4.0 strategy. Such application-oriented software assists determining the power settings for each module, which can be downloaded into a PLC recipe and predict the internal thermal conditions of heated workpieces.

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## Induction Thoughts by Dr. Valery Rudnev

In the column entitled "Induction Thoughts" Dr. Valery Rudnev discusses different aspects of induction heating such as implications of induction heating of aluminium or the mysteries in induction heating striping phenomena. Dr. Rudnev has more than 30 years of experience in the field of induction heating. Several of his over 250 publications have been translated into Spanish, Portuguese, German, Russian, Chinese and Japanese. He was elected as a Fellow of the American Society for Materials (FASM) and of the International Federation for Heat Treatment and Surface Engineering (IFHTSE).

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