The day after tomorrow – the future of induction heating

by **Valery Rudnev**

Today's metal working and heat treating shops must quickly adjust to a rapidly changing business environment, maximizing process flexibility and energy efficiency, yet still satisfy continuously increasing demands for higher-quality products. This article addresses these and other challenges faced by modern industry when applying induction systems for heating and heat treating. Several recently developed innovative processes and apparatus are reviewed and expectations for future technological developments are provided. This article is based on a keynote lecture presented at XVIII International UIE-Congress "Electrotechnologies for Material Processing" in Hannover, Germany, on June 6–9, 2017.

It is always difficult to try to predict what to expect the day after tomorrow. There have been many people who have tried to predict the future and failed, though there are a few of Nostradamus caliber. A quote from Lord Kelvin, a brilliant scientist, who once said, "Radio has no future," should serve as a precaution for those who are not as gifted as he. Nevertheless, let's imagine what the near future holds for induction heating based on recent technological advancements and what items of an induction "wish list" could reasonably soon become a reality.

Heating by means of electromagnetic induction is a topic of major significance, and the technology continues to grow at an accelerated rate. Thermal applications include hardening, tempering, stress relieving, normalizing, brazing, soldering, coating, drying, as well as preheating ferrous and nonferrous metallic and composite materials prior to warm and hot working and many other processes [1]. Heating inductor and induction coil are terms used interchangeably for the electrical apparatus that provides the electromagnetic heating effect in the workpiece positioned in close proximity. An inductor is often simply called by induction professionals as a "coil", but its geometry does not always resemble the classic circular coil shape. As an example, **Fig. 1** shows an array of a virtually endless variety of geometries of heating inductors needed to accommodate a correspondent endless variety of parts (**Fig. 2**). Certain know-how is associated with almost each application applying differ-

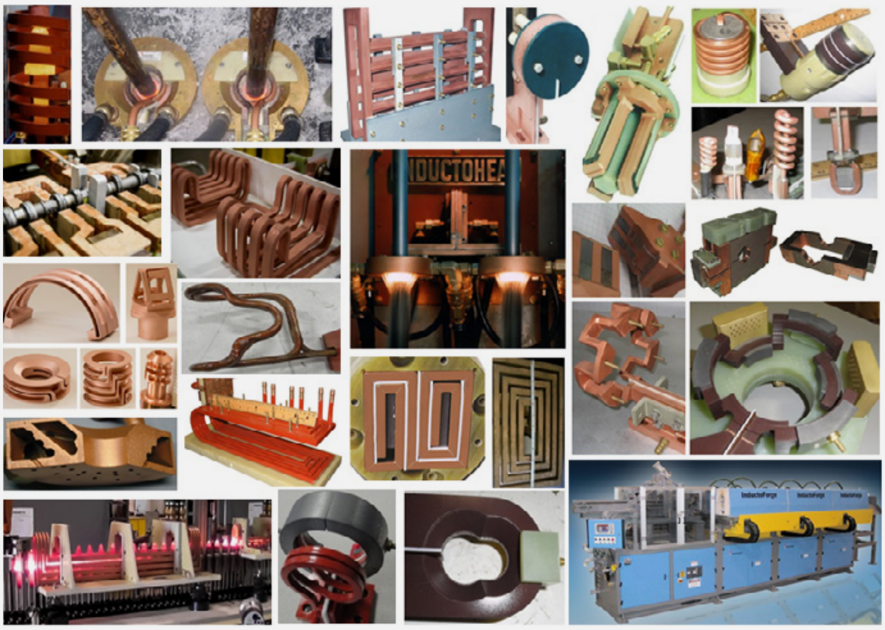

Fig. 1: An array of a virtually endless variety of geometries of heating inductors (Courtesy of Inductoheat Inc.)

Fig. 2: Variety of workpiece geometries that routinely apply induction heating (Courtesy of Inductoheat Inc.)

ent coil/part geometry introducing certain challenges to so called conventional induction designs.

COMMONLY OVERLOOKED METALLURGICAL SUBTLETY OF INDUCTION HARDENING

Induction hardening is commonly described as a process that involves the heating of the entire component or its portion to the austenitizing temperature, holding it, if necessary, for a period long enough to obtain required degree of austenite homogenization and then rapidly cooling it to below the M_S temperature where the martensitic transformation begins. At the same time, there are less frequent cases where instead of forming martensitic structures it might be desirable to form predominately bainitic or pearlitic structures or mixed structures.

In the case of hardening steels, the critical temperatures are often determined by mathematical correlations that indicate an effect of certain additional chemical elements on positioning of critical temperatures. Unfortunately, some practitioners are unaware that those correlations might be misleading in the majority of induction hardening applications because they are valid only for the equilibrium heating conditions. Equilibrium condition simply does not exist in induction heating and we are always dealing with a degree of non-equilibrate. **Table 1** shows an example of typical heat intensities for selected induction applications.

Metallurgically inclined professionals are aware that rapid heating affects the kinetics of austenite formation, shifting it toward higher temperatures in order to create conditions conducive to the required diffusion-based processes and producing an austenitic structure with a sufficiently uniform distribution of carbon.

If an austenite has appreciably non-uniform distribution of carbon then, upon quenching, a decomposition of heterogeneous austenite begins in lower carbon regions. This shifts the CCT curves to the "left" with greater probability of forming upper transformation products. The CCT curves for regions having excessive amounts of carbon will be shifted in the opposite direction with a corresponding reduction of the M_S temperatures. Thus, heterogeneous nature of austenite might result in an unacceptable heterogeneous as-quenched microstructure. Observation of "ghost pearlite" and/or other upper transformation products during a metallographic evaluation of as-hardened specimens can be associated with the presence of severely heterogeneous austenite.

Table 1: Typical heat intensities in selected induction heating applications [1]

Application	Heat intensities, °C/s
From room temperature to A_{c3} temperature range	
Contour hardening of small and medium-size gears	300–1,800
Surface hardening of shaft-like components	150–800
Through hardening or deep case surface hardening	50–500
Normalizing of thin wires, ropes, rods, strips, etc.	250–400
Through heating prior to warm and hot working	2.0–60
From room temperature to temperatures below A_{c1} critical temperature	
Subcritical annealing of "thin" workpieces	50–350
Stress-relieving and high temperature (650 °C) tempering	20–60
Low-temperature tempering (300 °C) of medium size components	4.0–10

Presence of significant microstructural and chemical segregations in the prior (parent) microstructure could have a measurable impact on a degree of heterogeneity of formed austenite after rapid heating. A number of studies were conduct-

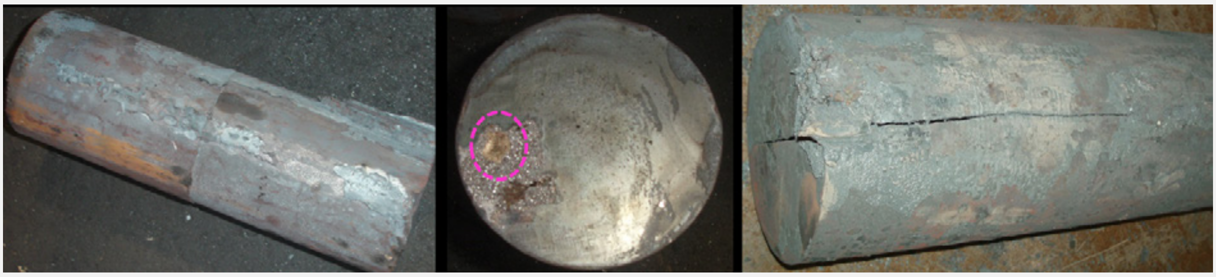

Fig. 3: An appearance of billet-sticking (left) and cracking (right) are often associated with subsurface overheating (middle) [1]

ed to quantify the impact of heat intensity rates and prior microstructure on a shift of critical temperatures producing continuous heating phase (CHT) transformation diagrams.

It is NOT widely known even among metallurgists that when heat intensities exceed about 20–30 °C/s, instead of the normal order of critical temperatures: A_{c1}, A_{c2}, A_{c3}, rapid heating can switch an order to A_{c2}, A_{c1}, A_{c3}. On the basis of the information provided by Orlich et al. [2–3], there are many steels that exhibit such a behavior [2–3]. This change might be critical in some induction heating applications (including hardening, as well as subcritical and intercritical processing) leading to unexpected occurrence of severe eddy current cancellation and drastic efficiency reduction, which could shift a relatively easy job to an almost impossible one [1].

In contrast to thermal or mechanical properties, electromagnetic properties of metallic alloys are not readily available in the literature and it is our hope that "the day after tomorrow" will improve our knowledge in regards to those physical properties critical for an electromagnetic induction.

REAL-LIFE CHALLENGES ASSOCIATED WITH TEMPERATURE MEASUREMENT AND SYSTEM FLEXIBILITY

J. W. N. Sullivan, Science Writer (1886–1937), once said: "It is much easier to make measurements than to know exactly what are you measuring." Some practitioners involved in induction heating prior to hot working (e. g. forging) incorrectly assume that with induction bar/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 that is measured by a pyrometer does not exceed the maximum permissible level. It is imperative to recognize that under certain but very realistic conditions, the presence of heat losses from the workpiece's surface in combination with in-depth heat generation typical for induction heating may shift the temperature maximum further away from the surface marking its location somewhere beneath it.

An appearance of billet-sticking (**Fig. 3**, left) and cracking (right) are often associated with subsurface overheating. Fig. 3, middle reveals that severe overheating (localized melting) occurred below the surface. A billet-sticking/fusion problem is more likely to occur with conventional power distribution along the 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 workpiece in the beginning of the heating line, too much energy soaks down into the subsurface area in cases when the line runs slowly. The presence of surface heat losses can reverse a commonly expected radial heat profile.

Case study [4]: An induction system for heating 0.064 m diameter carbon steel billets at a production rate of 2,500 kg/h is made up of three inline coils connected electrically in series and fed from a 1 kHz inverter (**Fig. 4**). **Fig. 5** shows surface-to-core profiles at an exit of the last coil when heating 0.051 m diameter carbon steel billets: Fig.

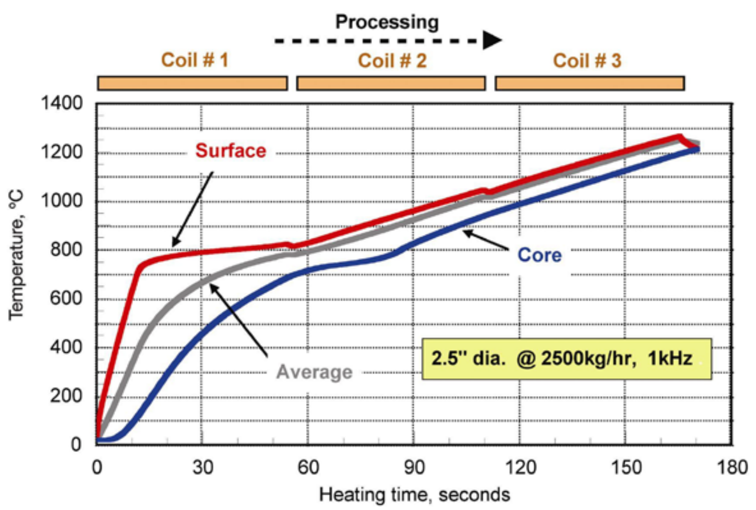

Fig. 4: Results of computer modeling of an induction system for heating 0.064-m-diametercarbon steel billets comprising three in-line coils. Frequency is 1 kHz [4]

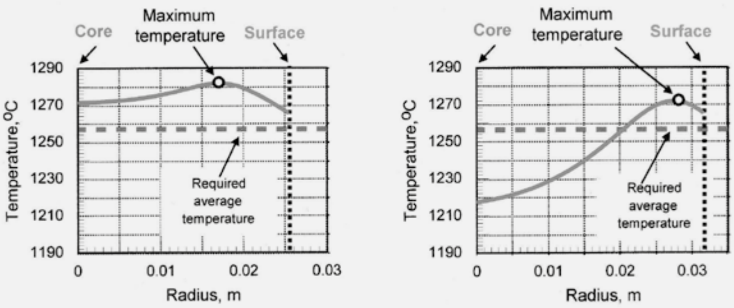

Fig. 5: Surface-to-core profiles at an exit of the last coil when heating 0.051 m diameter carbon steel billets: a – at a slower rate and b – shows heat profiles when processing larger diameter billets at a nominal rate [4]

Fig. 6: Temperature profile modeling software iHaz™ has been included in an equipment package of InductoForge™ systems (Courtesy of Inductoheat Inc.)

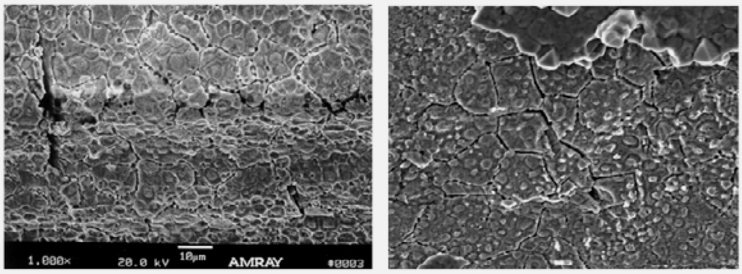

Fig. 7: Examples of grain boundary liquation (incipient melting) phenomenon [5]

5a – at a slower rate and Fig. 5b shows heat profiles when processing larger diameter billets at a nominal rate. Note that in both cases the surface temperature that would be recorded by a pyrometer is the same. Further reduction in the diameter of the billets or production rate could worsen the severity of subsurface overheating that can manifest itself in billets sticking/fusion as well as grain boundary liquation / incipient melting and intergranular cracking. The location and magnitude of the subsurface overheating is a complex function of five major factors: steel grade, frequency, thermal refractory, final temperature, and power distribution along the heating line.

Since in production environment internal temperatures cannot be easily measured nor even seen, they can only be simulated mathematically. Therefore, accurate temperature monitoring based on a reliable projection of temperature distribution is imperative in designing modern induction heaters.

For a number of years, Inductoheat has included temperature profile modeling software iHaz in an equipment package of InductoForge systems (**Fig. 6**). This software does not just simulate electromagnetic-thermal processes, but it also takes into consideration topology of a particular style of power supply, it's load matching capabilities and bus networking. The software helps to generate the power settings for each inverter (in case of in-line systems), which can be downloaded into a PLC recipe and dynamically predicts the internal thermal conditions of heated workpieces.

In a modern, vibrant and globally-competitive market place, it is important not just to build a system that provides accurate heating but a system with superior process flexibility that allows quick adjustment to a rapidly changing business environment. Long-term customers may move their production on a moment's notice. The producers must be able to get new business to cover lost business. One way to maximize the flexibility of induction heaters, ensuring the highest heating quality and minimizing energy consumption is applying modular induction heating technology. There are several variations of the modular design. InductoForge modular induction heating system allows adjusting, not only a power distribution along the heating line but also frequency (500 Hz to 6 kHz range) to optimize heating and allowing intelligent re-distribution of 3-D electromagnetic heat generation and energy consumption of each coil depending upon the production run [4].

For example, if today's market situation requires heating larger billets (e. g. 115 mm diameter) then lower frequency (e. g. 500 Hz) produces a more in-depth heating effect and minimizes heat time, providing an improved radial temperature uniformity. If tomorrow the market situation changes, demanding heating of smaller size billets (e. g. 30 mm), then appropriate inverters can be reconfigured to be able to produce higher frequency (e. g. 6 kHz). This results in a more surface-like heating effect, avoiding eddy current cancellation, maximizing heating efficiency and minimizing energy consumption. Since each coil can be controlled individually, the power distribution along an entire heating line can be re-balanced and optimized for particular production run based on software recommendations. If the line is running fast, more power can be shifted to the cold end of the heating line. If the line is running slow, the maximum power can be distributed closer to the hot end of the line increasing the efficiency of the heater and improving thermal conditions [1, 4].

It is expected that "the day after tomorrow" highly specialized application-oriented software utilizing advanced numerical simulation techniques will be an essential part of the package of induction machinery and … it does not have to be finite element (FEM) codes. In many cases, a combination of different numerical methods (including finite difference, finite volumes, finite elements, edge elements, boundary elements and others) provides substantial advantages over using a single modelling technique.

INDUCTION HARDENING OF CAMSHAFTS WITH ALMOST UNDETECTABLE DISTORTION

The ability to produce low distortion components is critical necessity of modern technologies, which directly affects process cost-effectiveness and product quality. There are several factors that affect distortion of heat-treated components including workpiece geometry, material grade and its prior microstructure, hardness pattern etc. Camshafts have relatively complex geometry with a lack of symmetry. One of the critical factors affecting distortion is the amount of heat generation and an ability to form a uniform hardness layer regardless of irregular shape of the lobes. The greater the amount of heated metal, the larger and the uneven expansion will be causing greater distortion. Therefore, efforts should be made to minimize the amount of metal being heated while producing sufficient hardness case depth.

With conventional induction hardening, an attempt to provide a sufficient austenization of the heel region of the lobe and needed hardness depth often results in measurable overheating of its nose. This can promote some brittleness and sensitivity to intergranular cracking. An increased use of electric arc furnaces that utilize recycled scrap may produce steels, which may be rich in Cu or other low melting point residuals. Over the last decade, the amount of copper residual has increased in some commercial steel grades.

If during camshaft hardening, the nose of the lobe is overheated then besides other unwanted metallurgical conditions, a phenomenon of grain boundary liquation (incipient melting) may occur (**Fig. 7**) [5]. This is the most common cause of cracking. The phenomenon of grain boundary liquation (GBL) can be amplified by preferential segregation of manganese, sulfur and some other elements at the austenitic grain boundaries. Both phosphorous and sulfur markedly affect the steel overheating. This lowers the melting point in the grain boundary region compared to the nominal solidus temperature of the steel leading to several undesirable phenomena during hardening and potentially promoting a temper embrittlement with locally increased Mn content. Undesirable combinations of impurities, residuals and trace elements used in the steel making, as well as non-metallic and intermetallic constituents could increase brittleness and crack sensitivity. Therefore, it is highly desirable to minimize peak temperatures during austenization.

Patented non-rotational technology developed for hardening of crankshafts (SHarP-C™) has been recently successfully expanded to surface hardening of camshafts. The compound benefits of SHarP-C™ Technology for heat treating camshafts can be summarized as follows:

- Achieving almost undetectable camshaft distortion (about 3–5 microns; based on 1.5 l and 2.0 l diesel or regular fuel engines) and, in many cases, an elimination of an entire straightening operation [6]. This is the combined result of three factors: (1) the ability to form a true uniform hardness pattern (**Fig. 8**) regardless of camshaft's topology, as well as geometry and orientation of the cam lobes, (2) reduction of localized peak temperatures during austenization (60–90 °C reduction on average) and (3) avoidance of applying any pressure/forces during camshaft hardening.
- Experience of using SHarP-C™ camshaft hardening technology reveals producing not only superior straightness but also better metallurgical properties forming fine grain martensitic structures and minimizing a probability of crack development and grain boundary liquation due to a significant improvement in temperature uniformity along the cam lobe perimeter.
- The energy consumption during both heating and cooling is reduced. Depending upon the specifics of the camshaft's geometry and heat treat specifications, combined savings on energy consumption may exceed 12–18 % compared to presently used processes depending upon material, case depth, camshaft shape, size, topology and topography.
- This technology eliminates or measurably minimizes a temper back (undesirable softening) of previously hardened neighboring lobes when heat treating camshafts with closely positioned lobes. This suggests the possibility of using induction tempering in camshaft hardening. Thus, the same system could offer induction hardening and tempering of camshafts as it has been successfully done for a number of years in heat treating of crankshafts.

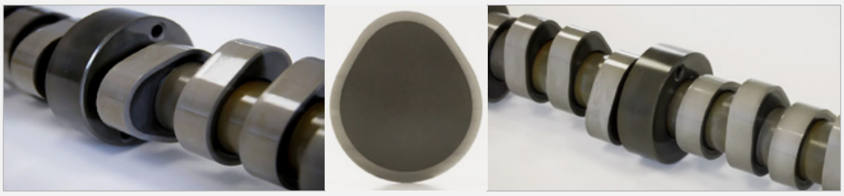

Fig. 8: Examples of true contour hardening patterns of camshaft lobes (Courtesy of Inductoheat Inc.)

A testimonial of one of the users of this advanced process published in [6] could be considered an objective assessment quantifying benefits of this technology based on obtained real-life records: "The SHarP-C hardening machine helped us to reduce the camshaft's distortion down to 3–5 microns and we have been able to eliminate the entire straightening operation. So, our savings on elimination the straightening operation alone is about $ 40,000 per year. On top of that there has been substantial improvement in the quality of the hardened camshafts, and our scrap was reduced about 1.5 %."

MAXIMIZING COST-EFFECTIVENESS OF INDUCTION SURFACE HARDENING

Technical confidence, quality, price, delivery and longevity have traditionally been the five key benchmarks in judging induction hardening equipment by commercial heat treaters [7]. Because of a number of current developments these five are joined by a six one that is equally important – technical flexibility. Under current conditions, heat treat contracts may move from supplier to supplier on an annual basis. Thus, suppliers trying to win these contracts may seek out and source the appropriate equipment to do the processing, purchase the equipment, start the equipment up and complete a Production Part Approval Process (PPAP) to be in production in a short period of time. In addition, the equipment must be high quality, very reliable on hand and easily accessible. Because of these market conditions modern heat treat equipment must allow easy re-tooling and re-programming to process different parts.

Even a decade ago, when discussing the subject of induction shaft hardening, it was not uncommon to assume dealing with predominately straight solid shafts with minor diameter changes. Today, the situation is quite different. The automotive industry is implementing lightweight initiatives in vehicle design to meet more stringent federal Corporate Average Fuel Economy regulations. Similar changes are occurring in off-road, aerospace, agricultural and other industries. Every metallic part in the engine, drivetrain, frame, and safety and exhaust systems is being revised to minimize weight and optimize critical engineering properties as well as residual stress distribution. In case of shaft-like parts, designers drill holes, reduce cross sections, make grooves, shoulders, and use custom shapes and alloys to accomplish these goals [7]. **Fig. 9** shows some representatives of now-days shaft-like components that are needed to be induction hardened. These new challenges push heat treaters to demand innovations from induction equipment suppliers to deliver products that can perform.

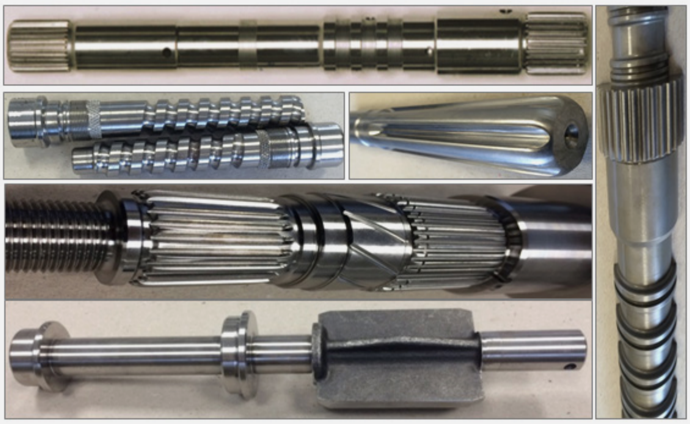

Fig. 9: Representatives of now-days shaft-like components that are needed to be induction hardened

Scan hardening

In scan hardening, the inductor or workpiece or both may move linearly relative to each other during the hardening cycle. Depending on the workflow of parts the system can be built as vertical, horizontal, or at an angle, though vertical scan hardening is the most popular design due to a number of reasons including a smaller footprint and specifics of quench flow.

Scan hardening systems offer noticeable process flexibility with respect to the workpiece length and, to some extent, variations in the part diameter. Scanning provides the ability to vary the speed and power during the process, which controls the amount of heat applied to different areas of the shaft.

Geometrical irregularities and discontinuities distort the magnetic field generated by an inductor, potentially causing local temperature variations altering metallurgical quality and may produce excessive distortion. For example, scan hardening shafts with diameter changes of appreciable size, variable wall thickness hollow sections and multiple holes and sharp shoulders can produce unwanted hardness pattern deviations and metallurgically undesirable structures. Additionally, it is often specified for multifunctional complex geometry components to have significantly different hardness case depths along component's length. This would naturally call for a corresponding variation of localized heat generation depth during scanning. Frequency is the most powerful parameter that directly affects the depth of heat generation. Unfortunately, the great majority of commercially available power sources for induction heating are designed to deliver a certain frequency that cannot be instantly and deliberately changed during the scan hardening.

In many cases and depending upon component's topology and hardening requirements, the available frequency may be considerably higher or lower (in folds) than its optimal value for a particular portion of the shaft. If the available frequency is noticeably higher than desirable, it produces a smaller-than-ideal depth of the heat generation that may not be sufficient for proper austenization of the subsurface region at required hardness depth. Therefore, additional time is needed to allow the thermal conduction to provide needed heat flow from the workpiece's surface towards required depth. This is commonly accomplished by a reduction of both scan rate and power density (otherwise the surface can be overheated). Unfortunately, this adds unnecessary cycle time and can lead to undesirable metallurgical and mechanical issues related to excessive peak temperatures and unwanted distribution of residual stresses.

In contrast, if the available frequency is lower than optimal frequency, an exceedingly deep austenized layer and excessive distortion may be produced. In order to reduce the negative impact of using lower than desirable frequency, the majority of induction heat treaters are trying to suppress a thermal conduction by increasing both scan rate and power density [1].

Taking into consideration, a topology of components shown in Fig. 9, a single optimal frequency rarely exists to accommodate a wide variety of part geometries, which is why conventional scan hardening with fixed frequency must always compromise between achieving metallurgical quality, production rate and process capability. While process protocol modifications to suppress or promote thermal conduction can help reduce the negative impact of using other-than-optimal frequencies, they often cannot eliminate it and can also negatively affect the metallurgical quality, stress distribution (both: transient and residual) and distortion characteristics.

Obviously, in order to address geometrical subtleties of heat treated parts in an optimal manner, it would be advantageous to apply various combinations of frequency, power and scan rates at various stages of the scan hardening cycle. Unfortunately, the great majority of available inverters do not have such capability.

A new generation of Statipower IFP inverters developed by Inductoheat (**Fig. 10**) eliminates this limitation and simplifies achieving the required hardness pattern allowing independently and instantly (like a CNC machine) to control frequency and power in a pre-programmed manner during heating cycle optimizing electromagnetic, thermal and metallurgical conditions.

This technology has been on the wish list of commercial heat treaters for some time. Statitron IFP is a true digital microprocessor-based control inverter technology specifically designed for induction heating needs and allowing instant and independent adjustment of frequency (within 5–60 kHz range).

The unique ability to change the frequency instantly by more than tenfold can also be advantageous for machines that need to provide hardening and tempering operations. In this case, higher frequencies can be used for hardening and lower frequencies for induction tempering. It is reasonable to expect that most users of induction machinery will expect from induction capital-equipment manufacturers "the day after tomorrow" providing variable frequency & power sources as a standard platform maximizing flexibility and user's cost effectiveness.

Fig. 10: A new generation of Statipower® IFP™ inverters allows independently and instantly (like a CNC machine) to control frequency and power in a pre-programmed manner during heating cycle (Courtesy of Inductoheat Inc.)

Single-shot hardening

Shaft-like components (e. g. output shafts, flanged shafts, drive shafts, turbine shafts etc.) are among parts that are depending upon design specifics are induction hardened using not only scanning but also single-shot hardening. With the single-shot method, neither the shaft nor inductor move linearly relative to each other; the shaft typically rotates instead. The entire region to be hardened is austenized at the same time.

There are several ways to control heat generation at different regions of a heat treated shaft. This includes a copper profiling resulting in a variation of inductor-to-shaft coupling and/or machining different widths of the current-carrying faces of the inductor. Besides that, a magnetic flux concentrator can be attached to certain areas of the inductor to further enhance localized heat intensity. As a result, certain regions of coil copper might carry extremely high current densities. A combination of intense heat generation within the copper current-carrying face with intense heat radiation from the workpiece's surface (particularly when relatively small coil-to-shaft air gaps are used) may lead to copper overheating. This may promote water vaporization and the formation of a steam vapor barrier in that region.

Regardless of an attempt to position water-cooling pockets as close to the current-carrying face of an inductor as possible and utilization of high-performance pumps, a coil copper might still be overheated, causing accelerated deterioration of the copper surface, which speeds up the onset of inductor copper cracking (due to stress corrosion cracking and stress fatigue) and eventual premature coil failure. As a result, coil life is often shortened to 22,000–24,000 heat cycles (being industry average based on data of one of the world's largest commercial heat treat company) for certain types of shafts and shaft-like components.

Thanks to Inductoheat's inductor design (patented), one of the world's largest suppliers of automotive parts achieved a twenty-fold life increase of some coils based on 2017 data collection, which is verified by the manufacturer's tool-room tag. Other benefits of novel inductor design include measurable improvement in process robustness and coil reliability [8].

Regardless of enormous advantages provided by computer modeling, an "out-of-box" thinking will still be an essential part of the technology innovations "the day after tomorrow".

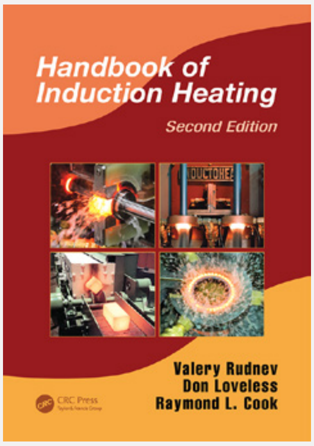

Fig. 11: The 2nd Edition of the Handbook of Induction Heating (Courtesy of CRC Press)

NEW RESOURCE FOR INDUCTION HEATING PROFESSIONALS

Heating by means of electromagnetic induction is a topic of major significance. Recently published (September 2017) the 2nd Edition of the Handbook of Induction Heating [1] is the result of an ambitious undertaking to compile an all-new, comprehensive resource on induction heating and heat treating processes to meet the needs of the induction thermal communities (**Fig. 11**).

This second edition of the Handbook of Induction Heating reflects a number of substantial advances that have taken place over the last decade in the practice and science of induction heating and heat treating, computer modeling, semiconductor power supplies, quality assurance, and process technology. This edition continues to be a synthesis of information, discoveries, and technical insights that have been accumulated in industry and academia. It is expected that "the day after tomorrow" this edition will continue serving an induction community worldwide embarking on the next step in designing cost-effective and energy efficient induction heating and heat treating processes and equipment.

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