



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.

## Implications of induction hardening

One of the most common applications of induction heat treatment is the hardening of steels, cast irons, and powder metal-lurgy materials. Among other workpieces, such components as camshafts, crankshafts, gears, transmission shafts, ball studs, pins, working surfaces of tools, and many others are commonly hardened using electromagnetic induction developing an attractive blend of engineering properties.

A typical induction hardening (IH) procedure involves heating the alloy to the austenitizing temperature range, holding it (if necessary) at a temperature for a period long enough for the completion of the formation of a fully or predominantly austenitic structure and then rapidly cooling/quenching it below the  $M_s$  critical temperature. Rapid cooling allows replacement of the diffusion-dependent transformation of austenite by diffusion-less shear-type transformation, producing a much harder constituent called martensite.

It should be mentioned that there are much less frequent cases of hardening when instead of forming martensitic structures; it might be desirable to form predominately bainitic or even fine pearlitic structures. For example, when hardening high carbon steel rails for railways, owing to the specifics of the process requirements and safety concerns, formation of any martensite in the as-hardened structure is not permitted. Nevertheless, it is more the exception than the rule, and for the great majority of induction hardening applications, the goal is developing fully or predominantly martensitic structures.

In some applications, it may be desirable to obtain a certain combination of hardness, wear resistance, and contact fatigue strength at the surface or near-the-surface areas without affecting the core microstructure as it is in case of hardening of gears and shafts. Other applications might require an increase of hardness and strength of the entire cross section of the part.

Factors traditionally used by commercial heat treaters to evaluate induction equipment include technical capability, quality, price, delivery, and longevity. However, in light of recent industrial trends, an equally important factor is equipment flexibility [1]. In the past, parts suppliers would often have a particular part contract for many years. Today, contracts can move from supplier to supplier much more frequently, so winning a contract over

the competition could require a supplier to assess new induction equipment that can perform the job, purchase and setup the equipment, and complete a production part approval process (PPAP) to be in production in a short period of time. Modern, high quality and reliable equipment must be readily available and must allow easy retooling and reprogramming to process different parts.

Even a decade ago, in discussing induction shaft hardening, it was not uncommon to assume part geometry similar to that shown in **Fig. 1** (bottom-left). Today, in order to accommodate light-weighting initiatives and minimize weight in shaft-like components, designers must drill holes, reduce cross sections, make grooves, and use custom shapes and alloys to accomplish these goals.

Geometrical irregularities of parts (Fig. 1) can distort the electromagnetic field generated by an inductor, potentially causing temperature variations and excessive shape distortion. For example, scan hardening shafts with large diameter changes, multiple holes, and sharp shoulders can produce unwanted deviations in hardness patterns and metallurgically undesirable structures.

Significantly different hardness case depths along the length of a component are often specified for multifunctional, complex geometry components (e. g., components having both solid sections and hollow sections with variable wall thickness).



**Fig. 1:** An array of a variety of geometries of modern shaft-like components that are routinely hardened using electromagnetic induction (Courtesy of Inductoheat, an Inductotherm Group)

All these require a capability to control an intensity and depth of heat generation during scan hardening. Unfortunately, the majority of commercially available medium- and high-frequency power sources are designed to deliver a certain frequency, which cannot be instantly and deliberately changed during scan hardening.

Because of that, in many cases, the available frequency may be considerably higher or lower than the optimal value for a particular portion of the workpiece. If available frequency is significantly higher than desirable, it produces a smaller than ideal depth of heat generation, which might not be sufficient for proper austenitization of the subsurface region at the required hardness depth. Thus, additional time is required for thermal conduction to provide heat flow from the workpiece surface toward the required depth. This is commonly accomplished by reducing both scan rate and power density (otherwise, the surface can be overheated). This adds unnecessary cycle time and can still lead to undesirable metallurgical issues related to excessive peak temperatures and unwanted distribution of residual stresses.

In contrast, a frequency lower than optimal produces an exceedingly deep austenitized layer resulting in a deeper than needed hardness pattern and potentially excessive distortion. Scan rate and power density are increased as an attempt to suppress thermal conduction and reducing the negative impact of using a lower than desirable frequency.

A single, optimal frequency rarely exists to accommodate the wide variety of geometries (Fig. 1), which is why conventional scan hardening with fixed frequency must always compromise between achieving the desired metallurgical quality, production rate, and process capability. While process modifications to suppress or promote thermal conduction can help reduce the negative impact of using non-optimal frequencies, they often cannot eliminate it and can also negatively affect the metallurgical quality of heat treated components, magnitude and distribution transient and residual stress, as well as distortion characteristics.

Applied frequency has the greatest effect on depth of heat generation. Therefore, it is advantageous to apply various combinations of frequency, power, and scan rates at various stages of the scan hardening when addressing the geometrical subtleties of heat treated components. Unfortunately, the majority of current inverters do not have such capability. New generations of IGBT-type inverters (Statipower-IFP and Statitron-IFP) developed by Inductoheat eliminates this limitation and simplifies achieving the required hardness pattern. This inverter technology enables instant, independent adjustment of power and frequency (5–60 kHz) in a preprogrammed manner during the heating cycle greatly expands induction equipment capabilities offering considerable benefits in several induction applications including surface hardening of gears and shafts, through hardening, hardening and tempering, just to name a few [1].

*Through hardening:* When through hardening various diameter bars/rods with multiple diameter changes (e. g., sucker rods), care must be taken to avoid eddy current cancellation, which occurs because eddy currents circulating in opposing sides of the heated

workpiece are oriented in opposite directions and could cancel each other. Certain workpiece's areas might become semitransparent to the electromagnetic field, absorbing a negligible amount of energy and thereby making its heating impossible regardless of the applied coil power. The ability of IFP inverters to instantly change output frequency more than tenfold eliminates this problem. For example, at austenitizing temperatures, 86 % of generated power is concentrated within 2.3 and 7 mm at a frequency of 60 and 5 kHz, respectively. This means that IFP technology maximizes energy efficiency and throughput when through heating 8 and 25 mm dia. parts by applying 60 and 5 kHz, respectively. Metallurgical conditions of the parts can be markedly enhanced by simply reprogramming a process recipe.

*Surface (case) hardening:* Processing 12 mm dia. pins with nominal hardness case depth of 1.8 mm requires a frequency in the 50–60 kHz range. If the product changed to a 30 mm dia. having nominal 5 mm case depth, a lower frequency such as 5–7 kHz is required to ensure more in-depth heat generation. This would optimize the metallurgical quality of the product without compromising the production rate. IFP technology can easily accommodate such required changes.

*Hardening and tempering:* Tempering temperatures are below the Curie point. Thus, steel retains its magnetic properties. This results in shallower heat generation, and can potentially lead to a surface over-tempering and reversal of useful compressive residual stresses at the workpiece surface, particularly when similar frequencies are used for hardening and tempering. Therefore, it is advantageous for induction machines utilized for both hardening and tempering operations to use higher frequencies for hardening and lower frequencies for induction tempering, requirements that are met using IFP technology.

*Tooth-by-tooth scan hardening of gears:* This hardening technique can be applied to external and internal gears and pinions. The inductor is symmetrically located between two flanks of adjacent teeth. Induction-hardened gears can be fairly large, with diameters easily exceeding 3 m, and can weigh several tons. The capability of IFP inverters to instantly change power and frequency during scan hardening is essential for better control of end/edge effects, help to avoid edge overheating and cracking, and it is particularly beneficial when hardening a variety of gears with appreciably different tooth geometry and case depth requirements.

*Spin hardening of gear-like components using encircling inductors:* The ability to independently and instantly change both output power and frequency during the heating cycle allows heat treaters to use a lower frequency for preheating root areas, while higher frequency helps to ensure sufficient heating of tooth flanks and tips when spin hardening moderate size gears, pinions, and sprockets. IFP technology might be a good compromise between simultaneous dual frequency, which has good results but high capital cost, and conventional single frequency systems which are less costly but the quality of hardening of certain types of gears might not always be the best. It does not mean that IFP is the single cure-all solution. There are still plenty of gears that single frequency sys-

tems can already handle just fine. And on the other hand, some gears require a level of metallurgical quality and hardness pattern contouring only achievable with simultaneous dual frequency. There are some limitations associated with IFP technology. For example, at this point, IFP inverters enable instant and independent adjustment of frequency within a 5–60 kHz range. But Inductoheat has positioned IFP as a happy middle ground, giving induction hardening professionals a gradient of options.

This innovative technology effectively addresses industry needs for cost-effectiveness and enhanced process flexibility, greatly expanding induction equipment capabilities and further improving metallurgical quality. If tomorrow one automotive company comes to a processing company and then, a day after tomorrow, another one with a different requirement, suppliers would like to process those parts using the same equipment. Obviously in induction, the coil is commonly dedicated to a particular component's geometry, but the cost of the induction coil is relatively small compared to the cost of the entire system and in particular an inverter. Therefore, if the power supply will provide greater flexibility, that is a big deal in our highly competitive world. The extent of projects that can be undertaken with Inductoheat's IFP technology is widening as the

company works to introduce new models that expand coverage of different ranges of frequencies and maximum powers. More information on this subject can be found in [1–2].

## LITERATURE

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- [2] Rudnev, V.; Loveless, D.; Cook, R.: *Handbook of induction heating*. 2<sup>nd</sup> Edition, CRC press, 2017

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