INNOVATIVE INDUCTION HEAT TREATING TECHNOLOGIES

Abstract.

Presentation focuses on:

1. Novel approaches to induction heat treating of critical automotive components, including but not limiting to induction contour hardening of spiral, hypoid and bevel gears with diameters from 6” to 8” (patent pending) and sprockets. Patented CrankPro Technology for non-rotational hardening and tempering of crankshafts (V-4, V-6 and V-8) and camshafts with non-convention journals and lobes.
2. Specifics of induction hardening of hand tools (i.e., wrench jaws, hammers), fasteners, etc.
3. Induction heating of large-diameter (8 to 12 in. and larger) billets made from carbon steels, stainless steels and Inconel, including a comparative assessment of progressive multi-stage horizontal induction heating approach vs. static heating using vertical inductors (frequency selection, electrical efficiency, system flexibility, cost, etc.).
5. Developing compact and highly-efficient induction tempering and stress relieving systems.

1. Novel approaches to induction heat treating of critical automotive components.

Non-rotational hardening and tempering of crankshafts and camshafts.

Induction heat treatment is traditionally popular choice for hardening and tempering of quality crankshafts. Crankshafts are widely used in internal combustion engines, pumps, compressors, etc. and belong to the group of the most critical auto components typically weighing between 30 to 85lbs depending upon the engine. At the same time, weight of some crankshafts exceeds 2000 lbs. (i.e. crankshafts for ship industry or stationary engines of power generators).

Figure 1. V-6 and V-8 crankshafts
A crankshaft, typically cast or forged, comprises a series of crankpins (pins) and main journals (mains) interconnected by webs/counterweights (Figure 1). Steel forgings, nodular iron castings, micro-alloy forgings and austempered ductile iron castings are among the materials most frequently used for crankshafts [1]. High strength and elasticity, good wear resistance, light weight, and small torsion vibration, geometrical accuracy, short length and low cost are some of the most important crankshaft requirements.

Figure 2. CrankPro® machine utilizing non-rotational SHarP-C Technology for induction hardening and tempering crankshafts and camshafts (Courtesy to Inductoheat, Inc.).

The Stationary Hardening Process for Crankshafts (SHarP-C Technology) has been considered by many heat treat experts as a revolutionary induction heat treating system (Figure 2). This patented technology eliminates the need to rotate or move either the inductor or the crankshaft during heating and quenching cycles while at the same time eliminating high current contacts when using encircling clamp-type coils (no flexible cables to wear out as well).

According to a stationary hardening process, an inductor consists of two coils (Figure 3): a top (passive) coil and a bottom (active) coil. The bottom coil, being active, is connected to a medium or high frequency power supply, while the top coil (passive) represents a short circuit (a
loop). The bottom coil is a stationary coil, while a top coil can be opened and closed. Each coil has two semi-circular areas where the crankshaft’s features will be located.

After loading a crankshaft into the heating position the top coil moves into a “closed” position and the power is applied from the power supply to the bottom (active) coil. The current starts to flow in the top coil. Being electro-magnetically coupled to a top coil, a current flowing in the bottom coil will induce the eddy currents that start to flow in the top coil. Those induced currents will be oriented in the opposite direction compared to a source current. If design parameters have been chosen correctly, the difference between the source current flowing in the bottom coil and the current induced in the passive coil will be negligible (less than 3%).

Any heated feature of the crankshaft (main, pin, oil seal) “sees” the SHarP-C inductor as a classical encircling cylindrical coil with induced eddy current flow along the circumference of the heat treated feature.

Figure 2 shows a CrankPro machine, which implements a SHarP-C Technology. In general, this novel patented induction technology provides several principle benefits compared to conventional approach requiring crankshaft rotation:

- Since there is no rotation of a crankshaft involved during heating/quenching process, it is not necessary to move heavy structures often weighing over 2,000lbs through the orbital path during heating. No high current electrical contacts or flexible cables to wear out. There is “open-close” action only with far less moving parts.
- Induction coils are much more robust and rigid, being CNC machined from solid copper without any brazed parts. This eliminates inductor distortion and hardness pattern drift. There are far fewer components involved in the novel coil design, meaning higher reliability because of the smaller numbers of parts that can go wrong. The SHarP-C coil-to-journal air gap is noticeably larger compared to air gaps required by rotational crankshaft hardening process. This creates a favorable condition to reduce stress-corrosion and stress fatigue induction coil failures. SHarP-C technology allows tooling life to be increased by at least four times.
- No wearing of the locators/guides involved. SHarP-C process utilizes inductors, which do not require contact guides, or complex and expensive non-contact coil positioning tracking systems of any kind. The coils are much less sensitive to coil-journal air gaps and to variation of adjacent masses as compared to existing technology.
- Accurate CNC coil shaping and utilization of “quick change” pallet approach guarantee that coils are automatically aligned with respect to the crankshaft after coil replacement. No time consuming process adjustments are required to “tweak” each coil after replacement. Unitized construction allows quick, error free, “production ready” factory installation and start-up.
- Crankshaft pins and mains have superior microstructural properties as compared to conventional crankshaft induction hardening processes utilizing “U”-shaped coils. These include the noticeable reduction of grain growth, decarburization and oxidation of the pin/main surface. The hardened zone is clearly defined and “crisp” (Figure 4) without the “fuzzy transition zone” that is present when longer heat times are employed. The case depth consists of fine grain martensitic microstructure with a negligible amount of retained austenite and without any traces of free ferrites. Essential surface compressive stresses obtained when applying SHarP-C technology are imperative for prevention of the surface crack development.

Although, the stationary hardening process is a cost-effective and space-saving technology, it has a limited utilization for hardening of the crankshafts with split-pins. This novel crankshaft hardening/tempering process is designed with ergonomics in mind, including a compact design with significantly reduced floor space requirements and can be used not only for crankshafts but
camshafts as well. There is easy access to all parts of the machine. CrankPro machines are easier to operate and maintain with significant reduction of industrial noise and a major improvement in coil life.

![Camshaft Image]

Figure 4. Induction hardening patterns according SHarP-C Technology

2. Induction hardening of gear and critical components.

In recent years, gear manufacturers have gained additional knowledge about how technology can be used to produce quality parts. The application of this knowledge has resulted in gears that are quieter, lighter, and lower cost, and have an increased load-carrying capacity to handle higher speeds and torques while generating a minimum amount of heat.

Gear performance characteristics (including load condition and operating environment) dictate the required surface hardness, core hardness, hardness profile, residual stress distribution, grade of steel, and the prior microstructure of the steel.

In contrast to carburizing and nitriding, induction hardening does not require heating the whole gear (Figure 5). With induction, heating can be localized to only those areas in which metallurgical changes are required. For example, the flanks, roots, and tips of gear teeth can be selectively hardened.

![Gear Image]

Figure 5. Induction hardened gears

A major goal of induction gear hardening is to provide a fine-grain martensitic layer on specific areas of the part. The remainder of the part is unaffected by the induction process. Hardness, wear resistance, and contact fatigue strength increase.

Another goal of induction gear hardening is to produce significant compressive residual stresses at the surface and in a subsurface region. Compressive stresses help inhibit crack
development and resist tensile bending fatigue. Depending upon the required hardness pattern and tooth geometry, gears are induction hardened by encircling the part with a coil (so-called “spin hardening”) or, for larger gears, heating them “tooth-by-tooth” (“tip-by-tip” or “gap-by-gap”).

"Gap-by-Gap” induction hardening of gears

Figure 6. “Gap-by-Gap” gear hardening principle and typical inductor designs

“Gap-by-Gap” technique requires the coil to be symmetrically located between two flanks of two adjacent teeth (Figure 6). Hardening inductor can be designed to heat only the root and/or flange of the tooth, leaving the tip and tooth core soft, tough and ductile (Figure 7).

Figure 7. “Gap-by-Gap” pattern profile

There are many variations of coil designs applying these principles. Probably two of the most popular inductor designs are shown on Figure 6. Applying a single-shot or scanning heating mode can realize “gap-by-gap” gear hardening technique. Scanning rates can be quite high, reaching 15” per minute and even higher. Coil geometry depends upon the shape of the teeth and the required hardness pattern. Both “tooth-by-tooth” and “gap-by-gap” techniques are typically not very suitable for small and fine pitch gears (modules smaller than 6).

Gear spin hardening

Spin hardening: Spin hardening is particularly appropriate for gears having fine- and medium-size teeth (Figure 8). Gears are rotated during heating to ensure an even distribution of energy and quenchant. When applying encircling coils, there are five parameters that play
important roles in obtaining the required hardness pattern: frequency, power, cycle time, coil geometry, and quenching conditions.

Figure 8. Examples of gears that use induction spin hardening techniques

Different patterns can be produced by properly controlling these parameters. Figure 9 shows a variety of induction-hardened patterns. They were produced by varying heating time, frequency, and power.

Figure 9. Diversity of hardness patterns obtain with induction spin hardening

As a rule, when it is necessary to harden only the tooth tips, a higher frequency and high power density should be applied. To harden only the tooth roots, use a lower frequency. A high power density generally gives a shallow pattern, while a low power density will produce a deep pattern with wide transition zones. Hardness pattern uniformity and repeatability depend strongly on the relative positions of gear and induction coil, and the ability to maintain the gear concentric to the coil.

There are four popular heating modes used for the induction spin hardening of gears that employ encircling-type coils: the conventional single-frequency, pulsing single-frequency, pulsing dual-frequency concepts and simultaneous dual-frequency. All four can be applied in either a single-shot or scanning heat treating approach. The choice of heating mode depends upon the application and equipment cost. As an example, Figure 10 sows induction hardening of automotive
transmission component. There is a helical gear on the inside diameter and large teeth on the outside diameter for parking brake. Both I.D. and O.D. require hardening. Frequency of 200kHz was used for hardening fine teeth and 10kHz was used for hardening large teeth.

Figure 10. Induction hardening of automotive transmission component

**Induction hardening for hand tools and mining industry**

Complex-shaped parts are typically used for hand tools and in mining industry requiring heat treating specific areas of parts. Due to its ability to selectively heat particular areas, induction heating is often a preferable choice for hardening and tempering of hammers, wrenches, chisels, drill bits, etc. As an example, Figure 11(left) shows induction machine for hardening and tempering the working surface of wrench jaws. Figure 11(right) shows simultaneous induction hardening of mining tool bits and brazing the working tips.

Figure 11. Induction machine for hardening and tempering the working surface of wrench jaws (left) and simultaneous brazing the working tips and induction hardening of mining tool bits (right).
Induction heating of large-diameter billets.

Induction heating is widely used to heat metals prior to hot forming by forging, upsetting, rolling, extrusion, and other methods. Billets are heated either in cut lengths or continuously and are forged in presses, hammers, or upsetters, or are extruded . Steel components by far represent the majority of hot-formed billets, although other materials including titanium, aluminum, copper, brass, bronze, and nickel are also induction heated for hot forming.

The initial temperature of the billet prior to induction heating may be uniform (at ambient temperature) or nonuniform. It is typically required to raise the billet’s temperature to a specified level and degree of heat uniformity. The uniformity requirement may include 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 certain billets prior to direct or continuous extrusion. Depending upon the application, powers from hundreds to thousands of kilowatts and frequencies typically in the line frequency (50 to 60 Hz) to 3 kHz range are the most commonly used for induction heating of large billets.

The most popular billet-heating approaches are progressive multistage horizontal heating and static heating. In progressive multistage horizontal heating, two or more billets are moved (via pusher, indexing mechanism, or walking beam, for example) through a single coil or multi-coil horizontal induction heater (Figure 12). As a result, the billet is sequentially (progressively) heated at predetermined positions inside of the induction heater.

![Figure 12. Progressive multi-stage horizontal heating.](image)

In static heating, a billet is placed into an induction coil having a vertical or horizontal arrangement for a given period of time while a set amount of power is applied until it reaches the desired heating conditions (temperature and degree of uniformity). The heated billet is then extracted from the inductor and delivered to the forming station. Another cold billet is then loaded into the coil and the process repeats. Either approach can use a protective atmosphere if required.

Progressive multistage horizontal heating is popular for small- and medium-size billets (usually less than 6 in. [150 mm] in diameter). When heating large-diameter steel or titanium billets (8 to 12 in. [200 to 300 mm] and larger), it is often advantageous to use static heating with a vertical coil arrangement or a combination of the progressive multistage horizontal method for preheating and the static vertical method for final heating.

The four photos in Figure 13 show how a billet being discharged after being statically heated in a vertical inductor. Billet transfer, tipping, and charging mechanisms are located below the platform and operate as follows:

- Billets to be heated are brought to the vertical cells by a trolley conveyor or roller track.
The billet is then transferred sideways by tipping the trolley platform or by a canted diverting arm inserted into the roller track. The billet rolls off into an intermediate station and then onto a horizontal cradle.

This cradle forms part of a rocking hanger which pivots 90° and sets the billet vertically over a charging jack, which raises the billet vertically into the inductor.

When the heating cycle is completed, the control system checks whether the press is ready to accept the billet. If it isn’t, the inductor changes its mode from heating to holding.

The pros and cons of the progressive multistage horizontal and static vertical billet heating approaches are given in the Table.

Table 1. Comparison of multi-stage in-line horizontal vs. multi-stage vertical approach

<table>
<thead>
<tr>
<th>Pros:</th>
<th>Cons:</th>
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<tbody>
<tr>
<td><strong>Horizontal in-line arrangement</strong></td>
<td><strong>Vertical arrangement</strong></td>
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<tr>
<td>- Lower overall capital cost</td>
<td>- Cost is typically higher</td>
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<tr>
<td>- Bigger inverters can be used because</td>
<td>- Automation and handling are more complex</td>
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<td>coils can have a group connection</td>
<td>- Necessity to compensate a “chimney” effect.</td>
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<tr>
<td>- Easier billet handling and automation</td>
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<td>- Inverters of different frequencies can</td>
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<td>be used to power different inductors (i.e., low frequency at front of the line and higher frequency at its end).</td>
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<td>- Better flexibility and controllability</td>
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<td>since each coil has its own individually-controlled inverter</td>
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<td>- Easy to provide billet holding if press is not ready to accept a billet</td>
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<tr>
<td>- Can relatively easy create longitudinal temperature gradient if required</td>
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<tr>
<td>- Can provide required temperature distribution when geometry or/and initial temperature of billet varies.</td>
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<tr>
<td>- Easy to start-up and compensate for a variation of “cold” refractory.</td>
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<tr>
<td>- Superior heat uniformity around billet’s perimeter.</td>
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<tr>
<td>- Lesser effect on billet’s surface during handling.</td>
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- Difficulty in providing required final thermal conditions (average temperature and uniformity) when initial temperature of billet varies (for example after piercing)
- Difficulty in creating longitudinal temperature gradients (thermal profiling).
- Required “dummy” billets for “start-up” or appreciable number of billets will have to be rejected during start-up.
- Possibility of getting undesirable temperature non-uniformity around billet’s perimeter due to “cold” sink effect and proximity effect (when coil and billet are not concentrical since it is often required to heat a variety of billet diameters using the same coil).
Computer modeling

Experience gained on previous jobs and the ability to computer model induction processes provide a comfort zone when designing new induction billet heating systems. This combination of advanced software and a sophisticated engineering background enables manufacturers of induction heating equipment to quickly determine details of the process that could be costly, time-consuming, and, in some cases, extremely difficult, if not impossible, to determine experimentally.

There are several software program available for modeling progressive multistage horizontal induction heaters. It is more difficult to find software appropriate for computer modeling of static vertical billet heaters. To decide whether a program is suitable for modeling vertical heaters, its capabilities must be thoroughly understood. What follows is a checklist of what users should consider when evaluating potential software for modeling vertical billet heating systems:

- Electromagnetic end effect
- Thermal edge effects (Lambert’s law and view factors, for example)
- Tight coupling of both electromagnetic and thermal processes (“two-step” coupling should be avoided since it does not provide an accuracy required for most applications; “step-by-step” coupling should be used instead)
- Presence of thermal insulation, and the ability to model heat exchange between refractory and heated billet
- Nonlinear interrelated nature of physical properties
- Specifics of coil windings and copper tubing
- Surface losses due to thermal radiation and convection
- Presence of magnetic flux concentrators, diverters, and/or flux extenders
- Heat transfer between heated billet and pedestal
- Transient processes (“cold” and “warm” start-up, and an ability to hold the heated billet inside the induction coil if the forming machine is not ready to accept it)
- Possibility of the billet having a nonuniform initial temperature distribution prior to induction heating (for example, existence of radial and longitudinal temperature gradients after piercing or continuous casting)
- Cooling of the billet in air during its transfer from inductor to forming machine
Figure 14 shows the computer-modeled dynamics of induction heating a Ti-6Al-4V titanium alloy billet in a static vertical inductor using line frequency (60 Hz)\(^3\). Billet dimensions: 7.8 in. (200 mm) in diameter and 26.2 in. (665 mm) long. A “cold” start-up was assumed, where the refractory insulation was initially at ambient temperature. The billet was positioned on a non-electrically-conductive pedestal. The stack of laminations acting as a magnetic flux concentrator was located below the pedestal. A longitudinal temperature gradient (heat profile) was desired, with the top of the billet being cooler. The effect of billet transfer in air after heating is also shown.

By adjusting coil overhangs at top and bottom and the position of the flux concentrator, it is possible to obtain either a uniform axial temperature distribution or a reverse heat pattern having warmer top of the billet, which emphasizes a flexibility as one of advantages of static vertical billet heaters.

Reference.