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TECHNOLOGY REVOLUTION ADVANCES INDUCTION HEATING

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REVOLUTION–NOT EVOLUTION–NECESSARY TO ADVANCE INDUCTION HEAT TREATING

Modern, high quality equipment must be readily available and flexible enough to allow for easy retooling and reprogramming to process a variety of parts.

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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 even more important factor is flexibility[1-3]. 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.

In discussing induction shaft hardening even a decade ago, it was not uncommon to assume a part geometry similar to that shown in Fig.1. Today, however, lightweighting initiatives are common in automotive, off road, and agricultural vehicle designs, as well as aerospace and other industries. To minimize weight and optimize industrial properties and residual stress distribution in shaft-like metallic components, designers must drill holes, reduce cross sections, make grooves, undercuts, and shoulders, and use custom shapes and alloys to accomplish these goals.

This article focuses on the technical revolution taking place in induction heating, which for the first time enables preprogramming of induction equipment to change frequency and power during the heating cycle in the same manner as machinists have been programming CNC machines for years. This is illustrated through a case study of induction hardening a shaft-like component such as that shown in Fig. 1, representative of a wide variety of other shaft-like parts that are now routinely induction hardened (Fig. 2)[1].

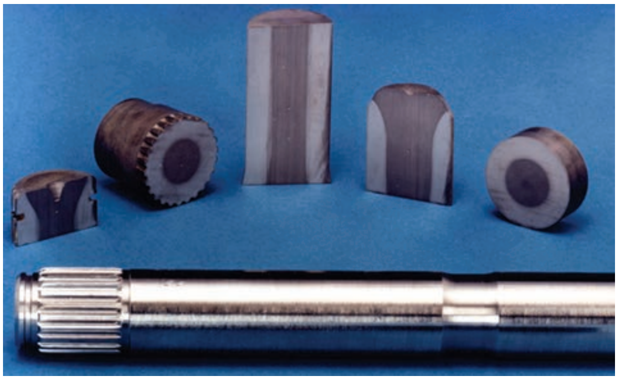

Fig. 1 — Representative shaft-like component induction hardened a decade ago.

THE CASE FOR SCAN HARDENING

Many steel shafts are strengthened using induction scan hardening. Scan-hardening systems are commonly associated with lower capital cost compared with static, or single shot, hardening and also offer process flexibility with respect to workpiece length and, to some extent, variations in shaft diameter. In scan hardening, the inductor or workpiece (or both) can move linearly relative to each other during the hardening cycle. Depending on workflow orientation, the system can be built vertical, horizontal, and at an angle, though vertical scan hardening is the most popular

Fig. 2 — Examples of the variety of part geometries in modern shaft-like components.

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design for a number of reasons such as a reduced equipment footprint.

A small portion of a component's full hardened length is heated at a given instant in time, enabling the hardening of elongated parts using relatively small (and generally less expansive) power supplies. Scanning systems offer the ability to vary scanning speed and power during the process, which controls the amount of heat applied to different areas of the shaft. Induction scanners incorporate a number of different elements, with inductor design and power supply having the most significant impact on hardening results[2, 3].

SCAN HARDENING DRAWBACKS

Common geometrical irregularities and discontinuities of parts can distort the magnetic 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. In addition, 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). This requires a corresponding variation of localized heat generation depth during scanning. 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.

In many cases, the available frequency may be considerably higher or lower (in folds) than the optimal value for a particular portion of the shaft. If it is significantly higher than desirable (Fig. 3, center), it produces a smaller than ideal depth of heat generation (current penetration depth), which might not be sufficient for proper austenitization of the subsurface region at the required hardness depth. Therefore, 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 lead to undesirable metallurgical and mechanical issues related to excessive peak temperatures and unwanted distribution of residual stresses.

In contrast, a frequency lower than optimal (Fig. 3, right) produces an exceedingly deep austenitized layer resulting in a deeper than needed hardness pattern and excessive distortion. Scan rate and power density are increased to suppress thermal conduction, reducing the negative impact of using a lower than desirable frequency.

A single, optimal frequency rarely exists to accommodate the wide variety of part geometries, 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, transient and residual stress distribution, and distortion characteristics[2, 3].

CASE STUDY: CONVENTIONAL SCAN HARDENING

Induction scanning is often used to harden components containing multiple diameter changes and variable case pattern requirements along the length of the shaft. To illustrate, consider induction scan hardening of a 25-mm (1-in.) SAE 4140 steel stepped shaft with several geometric variations along its length, the most significant being a 5 mm (0.2 in.) diameter reduction. Figure 4 shows the required case

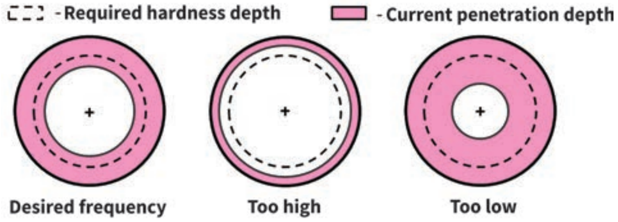

Fig. 3 — Effect of non-optimal selected frequencies on depth of current penetration (heat generation) in induction surface hardening of a solid shaft; (left) desired frequency, (center) frequency too high results in shallower depth of heat generation, and (right) frequency too low results in excessively deep heat generation.

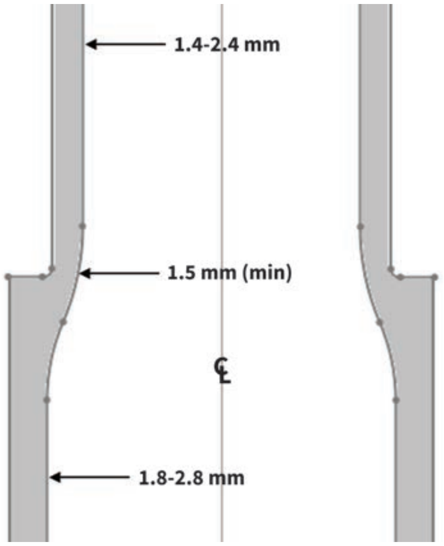

Fig. 4 — Example of hardness specification for a multi-diameter shaft.

pattern in the diameter transition area. A single-turn profiled inductor is used due to the sharp case pattern run-out specification at the end of the shaft.

Hardening using a conventional (fixed frequency) scan hardening system requires selecting a single frequency for the entire hardening process. Required case depths along the length of the shaft on the order of 2 mm (0.08 in.) necessitate using a nominal frequency of 30 kHz to achieve near-optimal hardening results in the straight regions of the shaft. Figure 5 shows an instantaneous temperature distribution during the initial stage of scan hardening[3].

The fixed frequency recipe used in scan hardening this portion of the shaft is shown in Fig. 6. As the part is translated downward and the diameter transition approaches the top of the coil, the scan rate is increased to address the inherent tendency to overheat the external corner of the diameter transition. The scan rate is then reduced to zero for a short dwell time with the bottom face of the coil positioned just above the diameter transition. This helps improve heating of the internal corner of the diameter transition and compensates for the heat sinking and electromagnetic decoupling occurring in this area. After a 2-sec dwell, the scan rate returns to a steady 8 mm/s (0.3 in./s), with the exception of a very brief period where a faster scan rate is used to mitigate the risk of overheating in the area directly above the diameter transition.

Figure 7 shows the case pattern in this region of the shaft. While case depths above and below the diameter transition meet customer specifications, the case depth in the internal corner of the diameter transition is only 0.9 mm (0.035 in.), failing to meet the required 1.5 mm (0.06 in.) minimum.

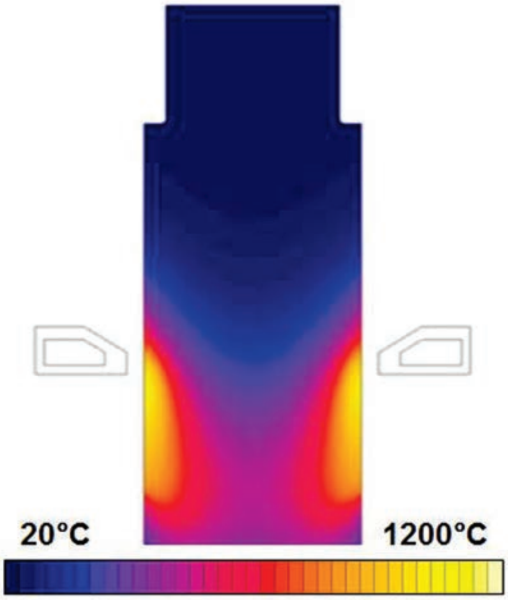

Fig. 5 — Temperature pattern during initial stage of scan hardening a stepped shaft.

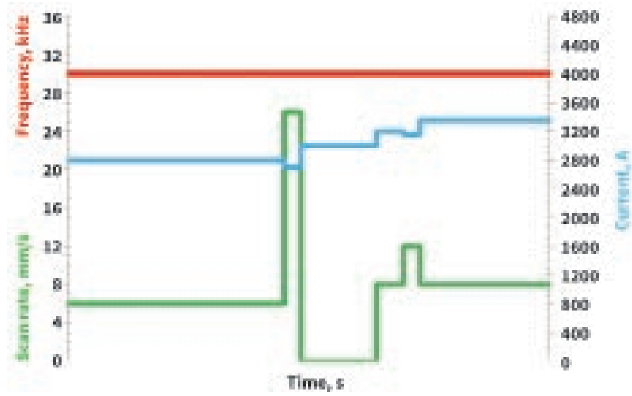

Fig. 6 — Typical process recipe for scan hardening using a constant frequency.

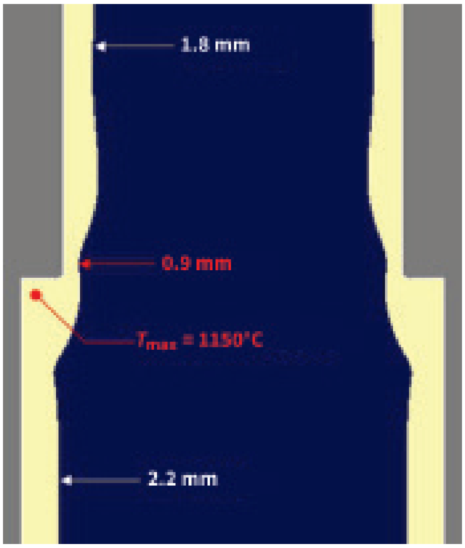

Fig. 7 — Hardness pattern obtained in multi-diameter shaft using constant frequency.

In contrast, a severe heat surplus at the neighboring external corner produces a peak temperature of 1150°C (2100°F), which is troublesome. Such surface overheating is associated with severe grain coarsening, ultimately resulting in poor mechanical properties. Further, overheating is one of the most common causes of crack initiation and propagation, as it weakens the grain structure and increases steel brittleness and sensitivity to developing intergranular cracking[2]. Grain boundary liquation/insipient melting are associated with liquation of low-melting phases and impurities concentrated at grain boundaries, leading to their degradation. A network (chains) of liquated areas at grain boundaries is shown in Fig. 8. Grain boundary liquation is magnified by segregation of Mn, S, Cu, and some other elements to austenite grain boundaries.

Overcoming insufficient case depth in the internal corner of a diameter transition and excessive heating of the neighboring external corner can be difficult or impossible to overcome using conventional fixed frequency hardening systems.

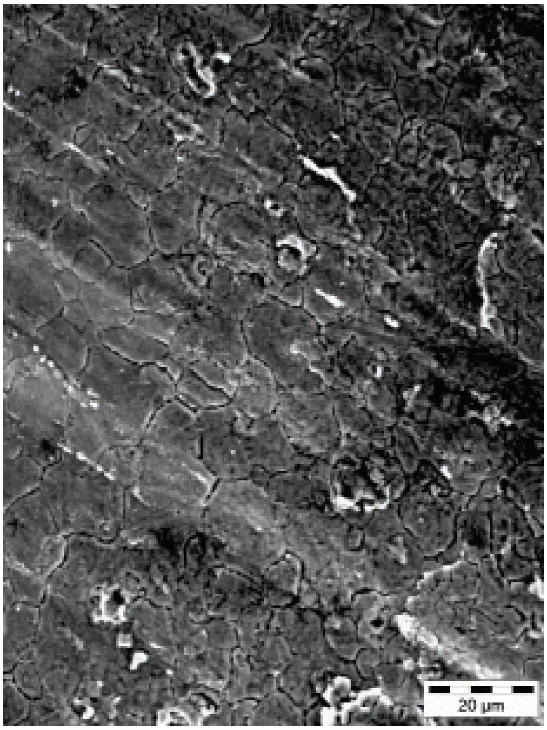

Fig. 8 — Grain boundary liquation caused by overheating.

Fig. 9 — Statipower IFP inverter.

SCAN HARDENING BREAKTHROUGH

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 cycle when addressing the geometrical subtleties of induction heat treated components to maximize the production rate and improve the metallurgical quality of heat treated components. Unfortunately, the majority of current inverters do not have such capability.

A new generation IGBT-type inverter (Statipower-IFP) developed by Inductoheat (Fig. 9) eliminates this limitation and simplifies achieving the required hardness pattern. The patented technology is specifically developed for induction heating needs. It enables instant, independent adjustment of frequency (5 to 60 kHz) and power (up to 450 kW) in a preprogrammed manner (Fig. 10) during the heating cycle, optimizing electromagnetic, thermal, and metallurgical conditions[2-4].

CASE STUDY: SCAN HARDENING USING IFP TECHNOLOGY

The capability of IFP inverter technology is illustrated in scan hardening the stepped shaft discussed previously. In the diameter transition area, a frequency reduction promotes deeper heat generation in the internal corner while reducing the risk of overheating the adjacent external corner. The process recipe is shown in Fig. 11. While the variation of scan rate versus time is unchanged from the fixed frequency process, the inverter's output frequency is reduced to 12 kHz when the coil approaches the diameter transition.

The hardness pattern resulting from the variable frequency process is shown in Fig. 12. The hardened case depth in the internal corner of the diameter transition is nearly twice that of the conventional method, increasing to an acceptable value of 1.7 mm (0.066 in.). Further, the peak temperature in the neighboring external corner decreases by

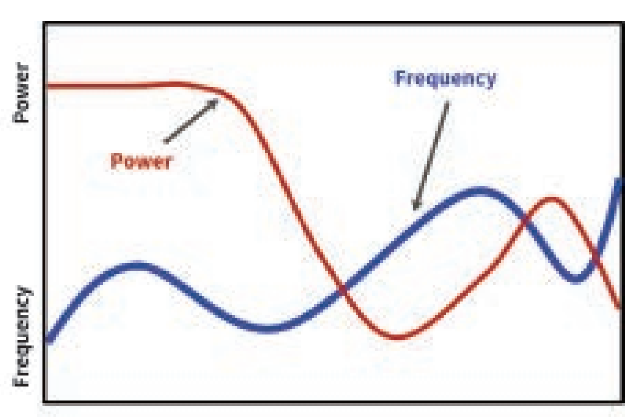

Fig. 10 — Simultaneous variation of frequency and power during modern scan hardening cycle.

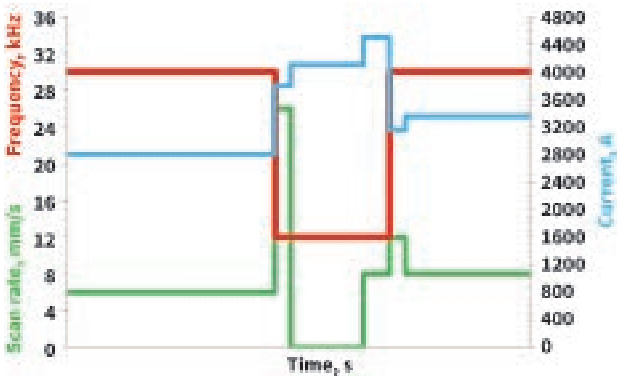

Fig. 11 — Process recipe using Statipower IFP power supply.

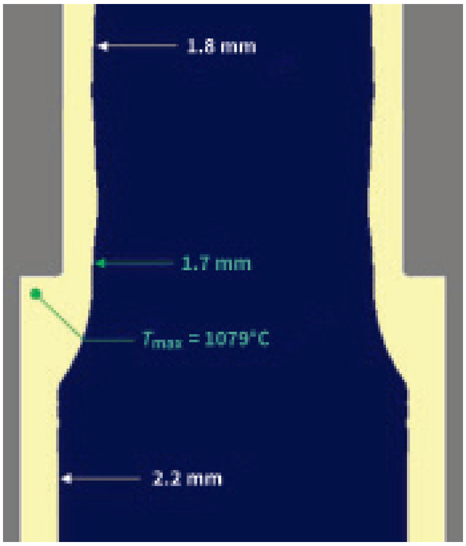

Fig. 12 — Hardness pattern obtained in multi-diameter shaft applying variable frequency, power, and scan rate.

more than 70°C (125°F), substantially reducing the potential for excessive grain coarsening and incipient melting in the external corner.

While reducing the peak temperature from 1150° to 1080°C (2100° to 1975°F) by switching from 30 kHz to a 30 kHz/12 kHz combination is notable, the lower peak temperature still might be of concern to some metallurgists who would like to see it lower. This can easily be achieved using a 30 kHz/5 kHz frequency combination, ensuring improved metallurgical quality and low distortion characteristics of heat treated products.

EXPANDING HORIZONS FOR IFP TECHNOLOGY

The new inverter technology effectively addresses industry needs for cost-effectiveness and enhanced process flexibility, greatly expanding induction equipment capabilities and further improving metallurgical quality of heat treated components. The ability of the technology to instantly change frequency by more than tenfold offers considerable benefits in several induction applications including through hardening, surface (case) hardening, hardening and tempering/stress relieving, spin hardening of gear-like components using circular inductors, and tooth-by-tooth hardening of large gears, just to name a few.

Through hardening. When through heating (i.e., through hardening) various diameter bars and cylindrical shaped parts with multiple diameters, such as 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, dramatically reducing heating efficiency. Under certain conditions, a workpiece can become semitransparent to the electromagnetic field, absorbing a negligible amount of energy and thereby making heating it impossible regardless of the applied coil power. The ability of IFP inverters to vary output frequency more than tenfold compared with conventional power sources eliminates this problem. For example, at austenitizing temperatures, 86% of generated power is concentrated within 2.3 and 7 mm (0.09 and 2.7 in.) 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 (0.312 and 1 in.) diameter parts by applying 60 and 5 kHz, respectively. Energy efficiency is significantly improved and metallurgical conditions of the parts can be markedly enhanced only by reprogramming a process recipe.

Surface (case) hardening. Processing 12 mm (~0.5 in.) diameter pins with nominal hardness case depth of 1.8 mm (0.07 in.) requires a frequency in the 50-60 kHz range. If the product changed to a 30 mm (1.2 in.) diameter part with a nominal 5 mm (0.2 in.) hardness case depth, a lower frequency such as 5 to 7 kHz is required to ensure more in-depth heat generation. This would maximize the metallurgical quality of the product without compromising the production rate. IFP technology can easily accommodate such required changes.

Hardening and tempering/stress relieving. Because tempering temperatures are below the Curie point where steel retains its magnetic properties, a skin effect is always pronounced in induction tempering. This results in shallower heat generation, and potentially can lead to a surface over-tempering effect 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 and stress relieving, requirements that are met using IFP technology.

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.

Tooth-by-tooth hardening 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 (10 ft), and can weigh several tons. Gears used in wind turbines are an example of a product where tooth-by-tooth induction scan hardening is effectively applied. However, this technique presents a challenge of controlling end/edge effects to avoid edge overheating and cracking. The capability of IFP inverters to instantly change power and frequency can help achieve required hardness patterns, particularly in the end zones.

CONCLUSION

Metal parts producers have taken advantage of the benefits of induction heat treating for many years. However, equipment with the technical capability for process flexibility that enables obtaining the desired heating pattern on complex shapes on the first try has been elusive. Inductoheat's revolutionary IFP technology meets this goal. **~HTPro**

Note: Statipower is a registered trademark, and IFP is a trademark of Inductoheat Inc.

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For more information, see our article in the HTPro insert

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