INDUCTION HEATING: EVERYTHING YOU WANTED TO KNOW, BUT WERE AFRAID TO ASK

As a regular contributor to the *HTPro* eNewsletter, Professor Induction answers a wide variety of questions regarding induction heating and heat treating. Included here are three recent challenges and solutions.

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Fig. 1 — Induction heating applications across a variety of industries.

Induction heating is a multifaceted phenomenon composed of complex interactions involving electromagnetics, heat transfer, materials science, metallurgy, and circuit analysis—with applications across multiple industries. Figure 1 shows a small portion of a virtually endless variety of workpieces where electromagnetic induction heating is used to develop an attractive blend of microstructures and properties at a competitive cost.

We use an induction process where we need to include physical barriers and/or a safety warning for people with medical devices such as metallic implants and cardiac pacemakers to stay a certain distance away. What is the required distance for people with such devices to stay away from induction heating coils? Thank you for any help you can provide on stand-off distances.

Answer: Many studies have been conducted to evaluate the direct and indirect effects of electromagnetic field (EMF) exposure on health, passive and active medical implants, and hypersensitivity. Several national and international organizations including the Institute of Electrical and Electronic Engineers (IEEE), International Radio Protection Association (IRPA), World Health Organization (WHO), Occupational Safety & Health Administration (OSHA), and others have developed awareness programs regarding non-ionizing radiation and evaluation of the health risks associated with external field exposure when using any electromagnetic device (such as cell phones, household electrical appliances, computer monitors, transmitting antennas, microwave ovens, induction coils, and others). A large body of scientific research exists and a number of international standards, guidelines, and regulations have been put into effect. For example, in the U.S. these include the following standards:

- IEEE: C95.6 Safety levels with respect to human exposure to electromagnetic fields, 0 to 3 kHz.
- IEEE: C95.1 Safety levels with respect to human exposure to electromagnetic fields, 3 kHz to 300 GHz.

All manufacturers of electromagnetic devices (including induction heating manufacturers) are supposed to comply with international/national standards and regulations related to controlling external exposure to EMF in the workplace.

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Fig. 2 — Holaday 3-axis VLF Magnetic Field Meter HI-3637.

There is no universal guideline for so-called "safe stand-off distances" for employees with medical devices or people without them, because such distances are application-specific and greatly depend on coil design details, applied power and frequency, presence of other electromagnetic devices in coil surroundings, and other factors. The magnitude of an external magnetic field can be either computer modeled or measured. For example, at Inductoheat we use both techniques.

In some cases, the induction coil is not the main source of EMF exposure and other electromagnetic sources (e.g., transformers, bus bar networking, electromagnetic lifting devices) might contribute to an even greater degree to the magnitude of EMF at the workplace.

A number of devices are available to measure EMF exposure in the workplace, ranging in applied frequencies and designs. Based on our experience, three-axis measuring devices provide acceptable accuracy if properly used and calibrated. For example, for a number of years Inductoheat has been using the Holaday 3-axis VLF Magnetic Field Meter HI-3637 (Fig. 2). This device is capable of providing isotropic measurements of a magnetic field's magnitude. The instrument is designed to conform to the requirements issued in the IEEE protocols and guidelines for suitable frequencies

Following are some general guidelines for monitoring and supervision of EMF exposure:

- *Running conditions of the induction system:* The machine should be running with the maximum running parameters for output KW or the maximum allowable running current/voltage to the coil.
- *Measurement specifics:* The induction machine envelope should be drawn and measurements should be taken at the operator station (or where other people may be present) and at a number of points around the perimeter of the machine at distances from the machine of 0.25, 0.5, 1, 1.5 meters, and more (whatever is most appropriate) and different heights from the floor. Data should be reviewed and a report issued to indicate whether the measured values comply with safety requirements. All readings should be taken and properly documented including setup parameters for capacitor and output transformer settings. If necessary, measurements should be made to calculate the coil running current for the specified meter readings.

Over the years, manufacturers of induction machinery have developed a number of ways to minimize external magnetic field exposure in cases where it exceeds maximum permissible levels. This includes a number of patented designs and proprietary techniques including passive and active magnetic shields, magnetic shunts, and Faraday rings, to name a few.

For a few years, we scan hardened relatively straight shafts using a 30 kHz machine. Our new component has a 4.8-mm radial step (sharp shoulder) that overheated when we tried to scan harden. We heard that a single-shot inductor could reduce shoulder overheating and still provide sufficient hardening in the internal corners of the diameter transition, so we asked a local coil builder to make one for us. Corner overheating is reduced, but now we have a 4-6 HRC surface hardness variation around the circumference of the as-quenched component. We didn't have this with scan hardening. How can we fix it?

Answer: An appropriate inductor/quench design and suitable process recipe should not produce such a wide hardness variation along the shaft circumference while using a single-shot inductor. A number of possible causes exist, with two of the most common discussed here:

Heat-related factor. With scan coils, induced eddy current flow is circumferential, producing uniform temperature distribution at any instant of the heat time. Only minor heat variation occurs in a flux fringing region of coil terminals. Part rotation makes this impact negligible, normally providing very uniform temperature distribution (assuming an absence of slots, keyways, holes, and similar geometrical discontinuities). Unlike scanning inductors, the majority of single-shot inductors produce predominately an axial eddy current flow rather than circumferential. Therefore, if the heating time is relatively short (e.g., 2-3 sec), the coil copper heating face is narrow, and rotation speed is insufficient, there might be a noticeable, nonuniform circumferential temperature pattern at the time quenching is applied (Fig. 3). Increasing rotation speed during single-shot heating might solve this problem. The use of a serpentine-type inductor is another option.

Quench-related factor. MIQ coils are often used with scan hardening, normally providing sufficiently uniform circumferential quenching. Quench rings/barrels/followers used in scan hardening also produce reasonably uniform quenching. With a single-shot inductor, there might be ob-

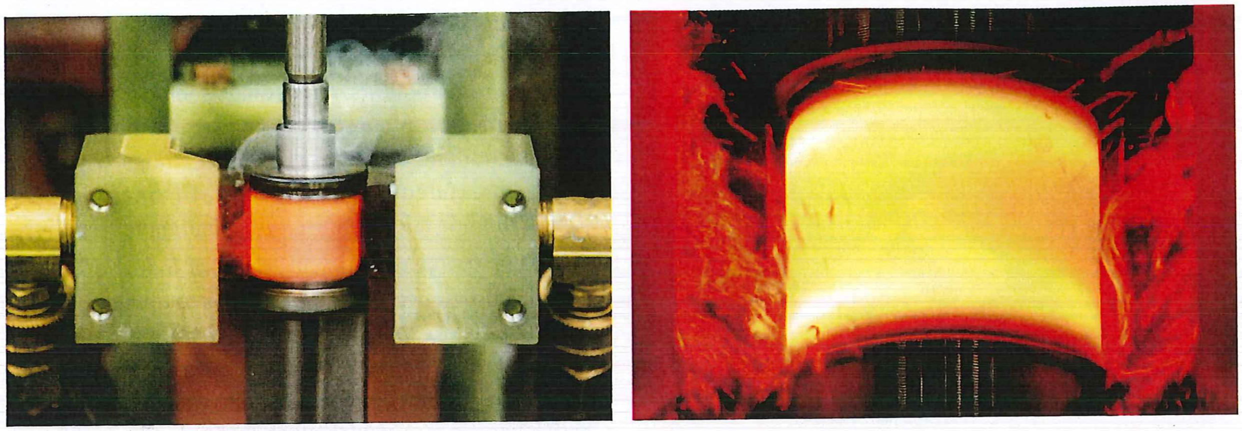

Fig. 3 — A nonuniform circumferential temperature pattern occurring at the time of quenching.

structions for providing 360° access for spray quenching. In some cases, quenching is done from one side, covering only 90°-120° of the austenized surface. This could result in appreciable circumferential spray-quench nonuniformity and correspondent hardness deviation. Solution: Redesign the quenching device, making an attempt to cover as much of the workpiece surface as possible. In addition, try to change the rotation speed during spray quenching (for example, a 25% increase and then a 25% decrease) and compare results. Both insufficient rotation and excessive rotation could result in circumferential quench nonuniformity[1].

We are planning to use induction to heat composite metallic materials prior to diffusion bonding. Is there any concern with respect to excessive noise? Have you found that certain frequencies are noisier than others? If so, do you have a solution for containing the noise level?

Answer: In the vast majority of induction applications, noise does not reach an appreciable level. Therefore, there is no reason to be concerned about excessive noise, although there are a few exceptions. Lower frequencies typically result in higher coil current thus increasing electromagnetic forces and coil turn vibration. So, it is reasonable to expect that a system applying line frequency would be associated with a greater magnitude of industrial noise compared to 30 kHz. In addition, systems with a greater amount of kW most likely would also be associated with more noise. Therefore, assuming all other factors are identical, 500 kW can produce greater noise than 100 kW.

When discussing audible noise, we must bear in mind the two main factors that impact how humans are affected by industrial noise—magnitude and unpleasantness/discomfort level. For example, low frequency audible noise (e.g., 60 Hz) could have a higher magnitude, but it might not be as unpleasant to the human ear compared to a lower magnitude noise at an elevated frequency (e.g., 1 kHz).

Following are the four main sources of noise generation during induction heating:

- *Noise generated by the power supply*. Numerous power supplies are available on the market. For induction heating, power and frequency combinations that use single-module inverters vary from line frequency to several hundred kHz and power levels exceeding 1000 kW even for a frequency in the 800 kHz range. Design features of modern power sources based on semi-conductor technology result in nearly silent operation. Therefore, noise stemming from the power supply is not usually a concern.
- *Noise generated from vibration of copper coil turns*. The two main approaches to building induction coils for hot working can be categorized as either open-wound or refractory-encased [Ref. 1]. The open-wound method provides more convenient repair in the event of failure, but coil turns must be secured using studs and proper fixtures to eliminate or minimize vibration and noise. An encased coil using a castable refractory (for example, special grades of cement) offers durability and longer life, eliminating or dramatically reducing the vibration of coil copper turns. Properly designed coils do not exhibit problematic noise levels.
- *Noise generated by workpiece vibration or resonant sound waves (amplifying effect)*. If a workpiece consists of some loose parts, then they may vibrate and produce noise. To assess this possibility, the specific workpiece geometry would need to be reviewed. Pressure can be applied in certain diffusion bonding applications to minimize the possibility of individual component vibrations. When induction heating hollow workpieces (e.g., relatively thin-walled pipes or tubes positioned inside other tubes), certain frequencies in combination with sufficiently high power densities could emit resonant sound waves of an appreciable magnitude, exceeding the audible limit. In cases like this, audible noise can also be a dominant factor that greatly affects the selection of frequency. Each tube has its own structural resonant frequency (SRF), which

depends on the diameter, wall thickness, material, and other factors. When the electrical frequency of the induction coil is sufficiently close to the tube's own resonant frequency, then high amplitude vibration and excessive audible noise may occur. In other words, as a radio receiver transforms electromagnetic waves into an audible sound, somewhat similar mechanisms can occur that cause a tube or pipe to act as an amplifier when dealing with certain frequencies.

- A decision as to whether noise could be reduced by choosing a different (higher or lower) frequency depends on a combination of the structural self-resonant frequency (SRF) of a particular tubular workpiece and the applied electrical frequency. Therefore, in cases like this it is beneficial to measure the workpiece SRF by simply hitting it with a hammer and measuring the resonant audible noise with some kind of audible receiver with the ability to detect the frequency and amplitude of the measured signal. As a result, more intelligent decisions can be made in determining whether a certain frequency would improve the noise level or not compared to a frequency that produces unacceptable noise. For example, if the SRF of a certain workpiece is 300 Hz, then the further away the selected frequency is, the lower the noise that will be produced. In this case, 6 kHz would produce a noticeably lower noise compared to 1 kHz. In contrast, if the SRF is 5 kHz, then the use of 6 kHz will make it worse compared to 500 Hz. Many times, a protective or reducing atmosphere is used while heating metallic materials. Therefore, if your induction system will be located inside a gas-tight chamber/enclosure, this will substantially reduce the noise level.
- *Noise generated by vibration of power cables, buses, and fixtures*. There is a very small probability of using the wrong design of fixtures, power cables, and bus bars. However, any concerns may be addressed by an induction heating expert. ~**HTPro**

Note: More answers to commonly raised questions can be found in Ref. 1.

For more information: All are welcome to send questions to Dr. Rudnev at rudnev@inductoheat.com. Selected questions will be answered in his column without identifying the writer unless specific permission is granted.

Reference

1. V. Rudnev, D. Loveless, and R. Cook, Handbook of Induction Heating, 2nd Edition, CRC Press, 2017.