

Article

State of the Art and Future Trends in Monitoring for Industrial Induction Heating Applications

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Abstract: Induction surface hardening (ISH) processes are widely used in the heat treatment of numerous industrial components, especially in the automotive industry. Since this industry operates under very demanding quality standards, it is crucial for these heat treatment processes to meet rigorous specifications to ensure the safety and reliability of the produced components. This implies the precise and repeatable control of certain parameters throughout the manufacturing process of each of the parts treated, through precise and reliable instrumentation in electromagnetically harsh environments. The main objective of this work is to define the monitoring process for an industrial IHS application, determining the control needs and the methods of measurement, recording, and verification of the parameters that ensure the quality of the process. This paper describes the monitoring process of induction surface hardening, emphasizing the use of sensors and modern measurement and control systems. A comprehensive monitoring system supported by a programmable logic controller (PLC) and mixed acquisition and instrumentation systems (analog and digital) implemented with a high-performance Field Programmable Gate Array (FPGA) will be presented.

Keywords: index terms; monitoring; sensors; instrumentation; induction heating; industrial application; energy conversion



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1. Introduction

Induction heating is a heat treatment method widely employed in various industrial applications [1]. In this process, the workpiece, which is the part to be heated, is positioned within a magnetic field generated by a coil known as the heating inductor. An induction heating converter supplies this coil with a high-amplitude and high-frequency current [2]. The heat is generated in the workpiece through Foucault or eddy currents induced on its surface, resulting in Joule and hysteresis losses. The depth of the heated zone, referred to as the penetration depth δ , is contingent upon the frequency of the current, primarily due to the skin effect, as well as the heat conduction properties. Higher operating frequencies result in a shallow skin depth, whereas lower frequencies lead to a greater penetration depth [3].

The load of induction heating converters comprises the heating inductor and its equivalent loss resistance, which can be connected in series or parallel depending on the model. To compensate for the reactive energy of the load, a capacitor is added, creating a resonant load. The capacitor may be connected in series, as seen in series resonant inverters (SRI) [4–6], or in parallel, as observed in parallel resonant inverters (PRI) [7–9]. Both types of inverters are utilized in applications such as forging, welding, melting, hardening, and various other metal heat treatment processes.

ISH is a specific type of induction heating treatment in which a metal part is heated using induction and subsequently quenched. During the quenching process, the metal undergoes a martensitic transformation, resulting in the increased hardness of the part.

Induction hardening is particularly useful for selectively hardening specific areas of a part or assembly without impacting the overall properties of the part. This method allows for precise control over the hardening process, making it a preferred choice in various industrial applications where localized strengthening is required. Many mechanical parts, such as shafts, gears, and springs, are subjected to induction surface hardening.

The design of an induction heating system for induction surface hardening must take into account the specific requirements, including the characteristics of the part to be heated, the desired penetration depth, and the geometry of the inductor. These factors play a crucial role in determining the optimal parameters for the power converter design, ensuring effective and efficient heat treatment processes. By carefully considering these factors, engineers can tailor the induction heating system to meet the precise needs of the application, resulting in consistent and reliable surface hardening outcomes.

The integral control of an induction surface hardening process is more complex compared to most other industrial thermal processes. The primary variable to control precisely is the energy delivered to the workpiece reliably and repeatedly, ensuring it reaches a specific location within the workpiece to meet heat treatment specifications. The challenge in this application is that time intervals are measured in seconds and fractions of seconds, and power densities can reach hundreds of kilowatts per square centimeter. In some cases, this raises the workpiece surface temperature with gradients up to 2200 K/s or more, with a typical temperature accuracy better than 2%. These rapid temperature variations occur in high-speed sweep heating operations, such as sweep speeds of 10 cm/s with a coil length of 2.5 cm, or with small parts in static heating operations (single shot), where heating times can be 0.5 s or less [2,10].

Precise control of the cooling fluid will also be critical to cool the workpiece at the required rate and achieve the desired metallurgical structure. Furthermore, this process control must be implemented in a noisy electromagnetic environment, usually in conjunction with functions to control complex and fast machines and with a separate system to monitor the process and the workpiece to ensure product quality. All this makes the control of the induction hardening process one of the most complex industrial heat treatment applications.

Therefore, process monitoring is a necessary quality requirement. If data are recorded and stored for each cycle, they become a powerful tool for diagnosing variations in the process or for reviewing the cause when parts are found out of specification after the induction surface hardening process.

A review of the existing literature reveals a lack of comprehensive works covering all aspects related to monitoring in industrial ISH applications. This underscores the novelty of this article, which specifies the main parameters that define the application and details how they are monitored and controlled. The paper is structured as follows: Section 2 focuses on the different control process modes and the analysis of monitoring parameters. In addition, various modern methods of metallographic testing for verification is conducted. Section 3 develops the study of the verification and recording methods and presents the validation of results using an experimental setup. Finally, in Section 4, the conclusions are drawn.

2. Methods and Materials

Surface induction hardening systems typically employ either scanning or static heating methods, often incorporating rotating components within the inductor. During the process, the entire area is heated uniformly for a predetermined duration.

Scanner systems are widely used for induction heating. Scanners allow the piece to be thermally treated progressively in the direction of the axis of the workpiece. The piece remains rotating supported on two points while the induction coil or the piece moves at a controlled speed. Scanners are very versatile and can be used for both vertical and horizontal applications. Typical scanners are controlled by computer numerical control (CNC), which allows for precise positioning, speed, power, rotation, and quenching control.

Piece loading and rotation systems can vary from simple manually operated mechanisms to fully robotic ones.

Machines that enable static heating do not provide movement of the workpiece, only rotation. The workpiece is placed inside or in proximity to an induction coil and it is heated and cooled in place. Obviously, this is the least versatile system and requires a specially designed inductor that fits perfectly to the desired heating profile on the workpiece, but it can be very cost-effective for the right application [11].

Figure 1 shows two images that illustrate the main features of the scanning (left) and static (right) heating methods.

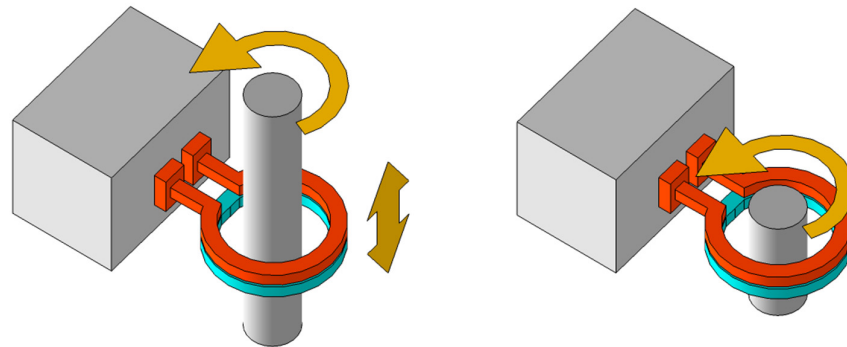


Figure 1. Scanning (left) (with vertical movement) and static (right) (only rotation) heating methods.

The control modes for the heat treatment of discrete parts are typically in open-loop mode (without a feedback loop), configuring the position of the part and inductor, the converter power, and the heating and quenching time. Open-loop control then fundamentally depends on the power converter, which can be controlled in closed-loop mode (feedback to a set point) to ensure that the requested power level is the power level supplied [2,10]. Some of the main control design elements in ISH are safety, process control and machine operation, productivity, repeatability, and ease of configuration and operation. Methods of controlling the various variables that govern the surface hardening process are discussed in the following section.

Figure 2 shows the diagram of an induction surface hardening installation where the basic elements that compose it can be found. The system is basically composed of the heating subsystem, the quenching subsystem, the parts manipulator subsystem, and the control subsystem.

The heating subsystem is constituted by the induction converter, which is connected to the electrical power supply and generates and regulates the power applied to the workpiece through the heating inductor. After induction heating, the workpiece is rapidly cooled by the quenching system, which includes valves and flow control elements, as well as pressure control devices and a heat exchanger to maintain a constant temperature of the cooling fluid. The installation included a system of specific manipulators that positioned the parts in the inductors with high precision. This subsystem also performs the rotational movements of the workpiece and the displacements of the inductor and the quench. The control subsystem is based on a PLC equipped with all the necessary sensors and actuators to monitor and control the system parameters.

Process monitoring is widespread in various applications, especially in the automotive industry. Ideally, the control system should obtain information that is as accurate as possible. For example, feedback on the voltage and current of the heating coil terminals should be made as close as possible and with good accuracy and noise immunity. In this way, monitoring during induction heating eliminates variables from the power circuit, such as loose bolts and components prone to deterioration such as capacitors and transformers. All elements of the control design are critical, from focusing on the ladder logic necessary to properly, reliably, and safely control the process to wiring the machine with proper grounding and separation of power conductors from control conductors, low-level signal

wiring from higher signal levels, and the isolation of servo controls from all other signals. Although the requirements of the monitoring system vary with the application, below is a list of parameters that are typically controlled.

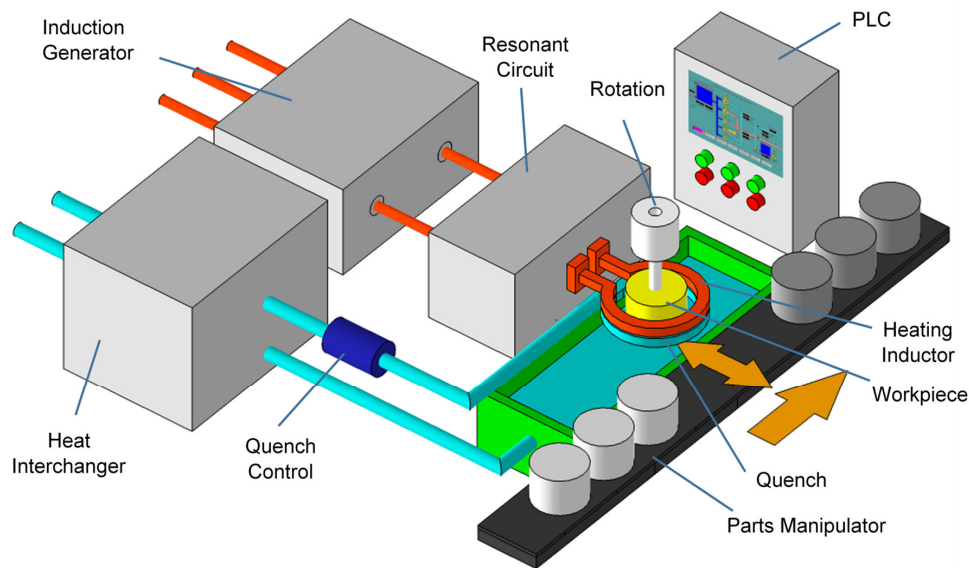
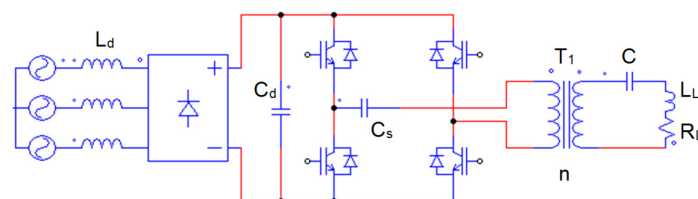


Figure 2. Diagram of an induction surface hardening installation.

2.1. Heating Position

The parts and the inductor itself must be accurately positioned. Sensors may be needed to ensure that these elements are correctly located. However, it is also possible to use novel methods based on measuring the characteristic parameters of the resonant circuit [12,13]. An incorrect position of the inductor or the workpiece leads to significant changes in the fundamental parameters of the resonant circuit, which are the resonance frequency and its equivalent resistance. By measuring these parameters before the hardening process, these positions can be verified, and it is also possible to detect deformations of the inductor or even changes in the dimensions or material of the workpiece. In order to find a method to measure these parameters of the resonant circuit, we must first conduct a preliminary study of the power converter.

Figure 3 shows the typical system configuration of a series converter for induction heating. The output power stage consists of a single-phase voltage-source full bridge inverter using four IGBT modules. The output of the inverter is connected to a series resonant circuit, composed by C_L , L_L , and R_L , through the matching transformer T_1 . C_d is the dc-link capacitor and C_s is an AC coupling capacitor. The DC power supply for the inverter is a three-phase diode bridge rectifier connected to the 400 V, 50 Hz power line through the inductance L_d . An example of a typical design for medium-power applications would be characterized by a working frequency of 50 kHz and an output power of 100 kW. The values of the main components of the power converter for this example are shown at the bottom of Figure 3.



$$L_d = 100\mu\text{H}; C_d = C_s = 100\mu\text{F}; n = 7:1; C = 6.7\mu\text{F}; L_L = 1.5\mu\text{H}; R_L = 47\text{m}\Omega$$

Figure 3. Typical configuration of the induction power converter.

Since the frequency selectivity of a resonant circuit is large for induction heating application, if the frequency f of the square wave voltage at the output of the inverter is very close to the resonant frequency f_o , only its first harmonic must be considered for power calculations. Under these conditions, the following equation is obtained [14].

$$\frac{4V_d}{n^2\pi} \sin \omega_o t = L_L \frac{di_o}{dt} + \frac{1}{C} \int i_o dt + R_L i_o \quad (1)$$

where V_d is the DC voltage, i_o is the current of the resonant circuit, $\omega_o = 2\pi f_o = 1/\sqrt{L_L C}$, and n is the transformer turn ratio of T1. Assuming that the quality factor of the series resonant circuit $Q = L_L \omega_o / R_L \gg 1$, the output current of the inverter i_o is given by

$$i_o = \frac{4V_d}{n^2\pi R_L} \left(1 - e^{-\frac{R_L}{2L_L}t}\right) \sin \omega_o t \quad (2)$$

Considering that the converter generates a short power pulse of a few switching cycles with a duration of T_{on} , the envelope of the resonant current i_E exhibits the first-order response shown by the black solid shape in Figure 4 that is given by

$$i_E = \begin{cases} I_{\max}(1 - e^{-t/\tau}) & (0 \leq t \leq T_{on}) \\ i_E(T_{on})e^{-(t-T_{on})/\tau} & (T_{on} \leq t) \end{cases} \quad (3)$$

where $I_{\max}$ is the maximum current in the case of a large value of T_{on} , and the time constant is

$$\tau = \frac{2L_L}{R_L} = \frac{2Q}{\omega_o} \quad (4)$$

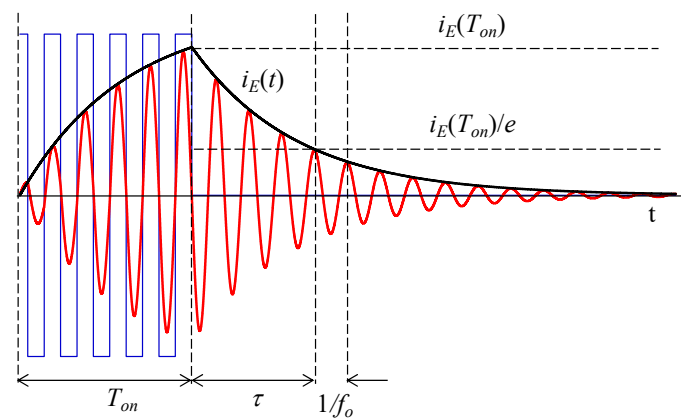


Figure 4. Induction converter waveforms for short power pulse. The blue trace is the converter output voltage and the red trace is the resonant current i_o . The black trace is the envelope of the resonant current.

Setting $t = T_{on} + \tau$ in the second equation of (3) results in $i_E(T_{on} + \tau) = i_E(T_{on})/e$, which allows us to measure the value of the time constants of the envelope τ . Also, it is possible to measure the period of the free oscillation of the resonant current whose inverse value is the resonant frequency f_o . With this measurement made by the FPGA's fast acquisition platform of the converter electronic control, it is possible to determine the characteristic values of the resonant load.

This procedure can be performed each time just before the heating process without altering the process, since the time required is a few milliseconds and the energy utilized is completely negligible.

2.2. Heating Time

The heating time is generally controlled accurately using electronic timers provided by programmable controllers, but care must still be taken with very short heating times due to the inaccuracy of controller cycle times. Modern controllers have highly precise and repetitive timers, so time variation is usually not a problem. It is crucial to transfer the electronic signal defining the heating time as directly as possible to the power converter to prevent uncontrolled delays caused by intermediate devices.

2.3. Power Level

The power level of the induction heating generator must be monitored and controlled using accurate measuring systems from the acquisition of the voltage $v(t)$ and the current $i(t)$ in the heating inductor. The instantaneous power is defined by

$$P(t) = v(t)i(t) \quad (5)$$

The average power or active power is the mean value of the instantaneous power:

$$P = \frac{1}{T} \int_0^T v(t)i(t)dt \quad (6)$$

The apparent power is the product of the root mean square (RMS) values of voltage and current:

$$S = V_{RMS}I_{RMS} \quad (7)$$

and the reactive power, which does not have a dissipative character (energy storage), is

$$Q = \sqrt{S^2 - P^2} \quad (8)$$

To conduct the power measurement, electronic wattmeters are typically used which are analog/digital circuits that correspond to what is indicated in the block diagram of Figure 5.

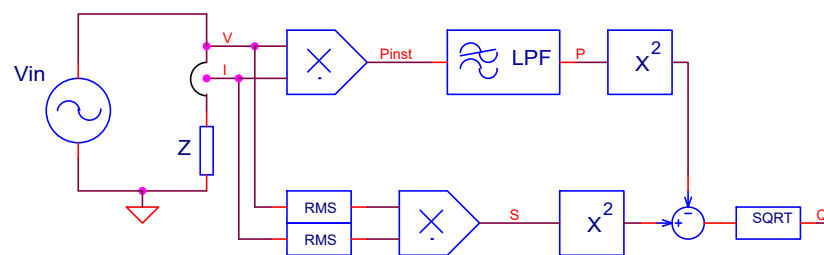


Figure 5. Electronic wattmeter block diagram.

The accuracy of these instruments is very high but other factors may affect the actual power level reaching the workpiece, such as noise affecting the generator regulation accuracy or overheating of components conducting and distributing generator output power, such as contactors, transformers, electrical connections, and other elements.

In certain applications such as dual frequency induction hardening where the total power delivered to the workpiece is the combination of two powers with different frequencies. The circuit in Figure 5 must be duplicated and connected to the power circuits through selective frequency filters, making it possible to split the total power into two components with different frequency.

2.4. Energy

The energy must be monitored. The energy applied to the inductor–workpiece assembly during the process must be measured. The energy is measured in kilowatt-seconds and

is widely used to monitor the heating process quality. The electrical energy is given by the following expression:

$$E = \int_{t_1}^{t_2} P(t) dt \quad (9)$$

where t_1 and t_2 correspond, respectively, to the initial and final instants of the measurement. Therefore, once this measurement interval is defined, the measuring equipment must integrate the power. If it is constant during the measurement period, the energy will simply be the product of the power and the time interval. The electronic systems are circuits that correspond to what is indicated in the following block diagram.

The voltage-controlled oscillator (VCO) circuit obtains a square or rectangular signal whose frequency is proportional to the instantaneous power. The counter implicitly performs the integration (accumulation) of the power, which is subsequently displayed. The 1/N divider block allows the specification of the selected units and the scaling factors incorporated into the measurement for visualization.

Equivalent to what was indicated in the previous section, in dual frequency applications the circuit in Figure 6 should be duplicated to calculate the energy that corresponds to each frequency.

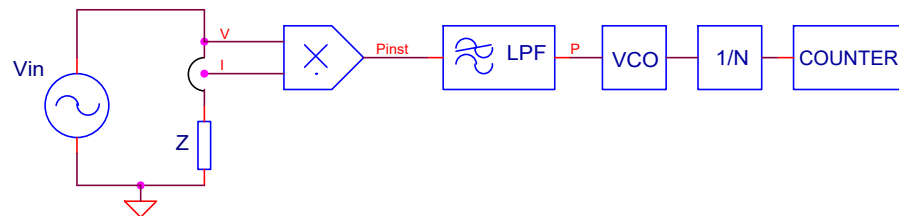


Figure 6. Block diagram of an electronic energy measurement system.

2.5. Temperature Monitoring

Thermocouples or infrared cameras are used to measure and monitor the temperature of the workpiece during heating to ensure it reaches the desired level for the intended heat treatment process. For applications like bright annealing with a consistently clean surface, it can work quite well. However, for most heat treatment applications, there may be visualization or emissivity issues, and the preferred pyrometer may need multiple control ranges. An optical pyrometer can be used as an over-temperature control trip with a limited range, for example, 10% of the desired final temperature. This is generally a reliable approach. Another more accurate method is to measure the surface temperature fields during induction heating using a high-speed infrared camera system. Image analysis tools have been implemented to automatically extract the temporal evolution of isotherms [15].

To increase the accuracy of temperature measurement, modern infrared thermometers consist of a double laser sight. The two laser beams follow the infrared optical path to mark the position of the measuring field at any distance. At the focus point, both lasers intersect, which greatly promotes exact alignment and reduces measurement errors. Figure 7 shows an ISH application where temperature measurement is performed with a dual laser sight infrared thermometer located at some distance from the workpiece.

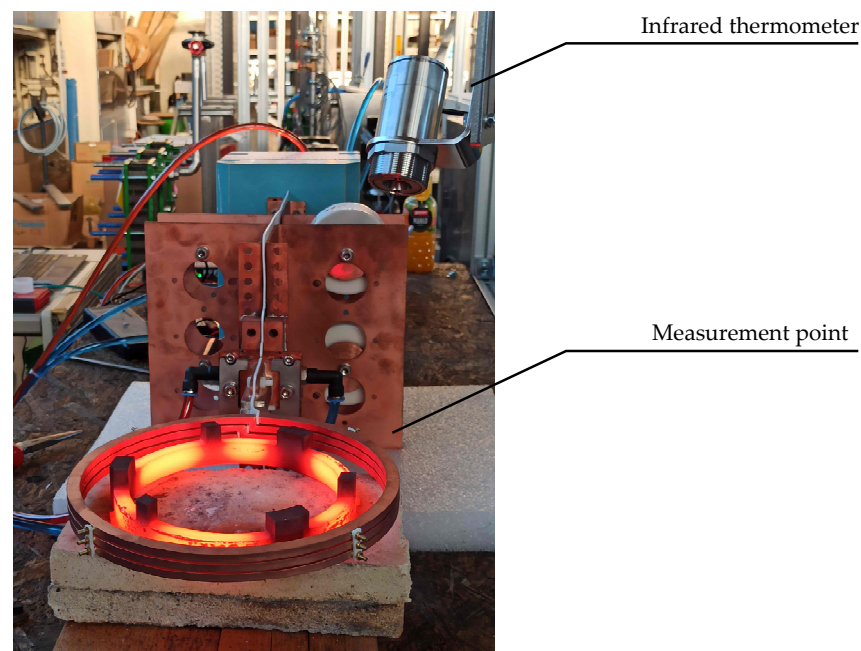


Figure 7. Temperature monitoring using a dual laser sight infrared thermometer (Optris, Berlin, Germany).

2.6. Rotation Speed

Many applications have fixed rotation speeds, and speed is not critical. However, in high-power and short-time heating cycles, it may be important to verify that the rotation speed is correct. The majority of speed sensors detect the motion of ferromagnetic structures, such as gearwheels or shafts, based on the variation in magnetic flux. When the sensor passes over a tooth or gap, the impact on the magnetic field changes accordingly. These changes in the magnetic field can be converted into electrical variables and subsequently conditioned. In other words, the variation in the magnetic field reflects the electrical output signal of the sensor. The measuring principles are based on Hall-effect sensors or inductive sensors. From these data, a PLC calculates and displays the rotation speed.

2.7. Quench Position

The quench position is typically controlled by the cooling fixture, which is usually installed on the inductor or internally machined within the inductor itself. Therefore, the position of the shower is determined by the heating position.

2.8. Quench Delay

Quench delay is an important part of the process. It is the time from the end of heating to the start of quench and sometimes needs to be designed taking into account the quench valve operation time.

2.9. Quench Time

This time must be controlled and monitored during static heating cycles. Scanning cycles may have cooling initiated at the beginning of heating or controlled at a later time. Usually, the accuracy in monitoring this time is not critical.

The delay and duration of the quench are programmed and monitored with the timers included in the PLC.

2.10. Quench Flow and Pressure

Quench flow and pressure must be controlled and monitored. Manually adjusted valves are typically used to produce a fixed flow. They can also be controlled by the

programmable controller using electro-hydraulic servo actuators if the process requires variation in flow and pressure during the process. Typically, cooling flow and pressure are monitored to ensure they are above a certain minimum value.

2.11. Quench Temperature

This temperature must be controlled and monitored. The workpiece quench rate and thus the related metallographic processes are highly dependent on the quench liquid temperature that is typically controlled using a feedback analog system that controls a solenoid valve on the cold water side of the heat exchanger, maintaining the cooling liquid temperature as constant.

IHS facilities have modern pressure, flow, and temperature measurement systems such as those shown in Figure 8.



Figure 8. Pressure, flow, and temperature sensors.

2.12. Quench Liquid Composition

The concentration of dissolved quench agents must be controlled, generally by manual checking with a refractometer at regular intervals. Digital refractometers increase results reliability in comparison with analog refractometers, eliminating operator dependency and assisting with error detection.

2.13. Metallurgical Analysis

In any case, the best way to determine if a process is functioning correctly is through a metallurgical analysis. The laboratory typically assesses the quality-related material properties of ferrous materials. Here, several measuring techniques are available, allowing for the microstructure to be directly analyzed, for example, by x-ray diffraction and optical or electron microscopy. Traditionally, destructive testing methods are used to measure the mechanical properties, such as hardness and tensile strength, of metallic materials. However, modern industrial production is highly automated, necessitating automated quality inspection. The quality characteristics of raw materials, semi-finished, and final products should be assessed not only in material laboratories but also concurrently with or integrated into production processes. This objective can only be achieved by the application of appropriate nondestructive testing (NDT) methods.

The available systems for NDT quality inspections utilize optical, thermal, mechanical, electromagnetic, or acoustic methods. Today, the most popular are the backscattering and 3MA methods.

2.13.1. Backscattering Method

Ultrasonic waves traveling through polycrystalline materials, such as steel, are scattered at interfaces within the material where there are changes in density and/or elastic properties. Typically, ultrasonic waves scatter in all directions, including back towards the ultrasonic transducer that generated the initial pulse. The amount of backscattered ultrasound received by the transducer depends on the ratio of the size of the scattering geometry to the wavelength of the ultrasound, as well as the degree of material property difference at the interface, which is referred to as acoustic impedance change [16].

In regions where the ultrasonic wavelength is large compared to the size of the scattering geometry, higher ultrasound frequencies (or shorter wavelengths) lead to an increased intensity of ultrasonic backscattering. Additionally, the intensity of backscattering rises with the average effective size of the scattering geometry, such as the grain size of the polycrystalline steel. By using an appropriate frequency of around 20 MHz, the microstructural change between the hardened case (typically fine-grained martensite) and the core material with a coarse-grained microstructure results in a distinct increase in backscattering intensity. This phenomenon is observed when the ultrasonic pulse encounters the interface, and standard time-of-flight evaluation determines the depth position of the interface, corresponding to the surface hardening depth (SHD). The thickness of the hardened zone can be calculated by measuring the time it takes for the sound pulse to travel from the surface of the part to the location where scattering occurs, using the known sound velocity of the material.

2.13.2. 3MA Method

The name 3MA stands for Micromagnetic Multiparameter Microstructure and Stress Analysis. It is a systematic and technical combination of four micromagnetic methods: Barkhausen noise (BN), harmonic analysis of the tangential magnetic field strength (HA), multi-frequency eddy current analysis (EC), and incremental permeability (IP) [17].

This micromagnetic method is highly versatile, as evidenced by its wide range of applications, including the quantitative determination of hardness, hardening depth, residual stress, and other material parameters. Today, specialized 3MA systems are available for both manual and automated testing of various materials, semi-finished goods, and final products made of steel, cast iron, or other ferromagnetic materials.

Both methods are valuable for verifying the quality of ISH. Specifically, they allow for the determination of penetration depth and hardness, while also enabling the detection of surface crack failures [18].

3. Results Analysis and Discussion

Some of the verification and recording methods have been briefly discussed. These and others are further explained in this section [19].

3.1. Profiling

Profiling techniques have been successfully implemented in various industrial heat treatment applications, as well as in the manufacturing and maintenance of electronic products and circuit boards, clearly demonstrating their contribution to improving process quality [20]. Profiling is the most accurate method for measuring processes when rapid changes are anticipated and need to be tracked. This allows for the detection of variations in high or low amplitudes, as well as early and late starts. Profiles compare the actual value with both a high and low limit simultaneously during the process to reject the treated part if any of the limits are exceeded and can be saved for later viewing and exported for

analysis in spreadsheet software. Limit modifications can be adjusted for better control and then imported back into the system.

It is crucial to determine which parameters are the most suitable for being controlled through profiling. Figure 9 shows an example of power and energy recording during a 3 s heating process. Although the limits have been applied equally for both parameters, it is evident that power profiling provides more information than energy profiling. This capability enables the detection of specific anomalies that may not directly impact the measurement of the final energy but could indicate potential faults affecting the quality of the heat treatment. Table 1 shows the data acquired for the preparation of the profile.

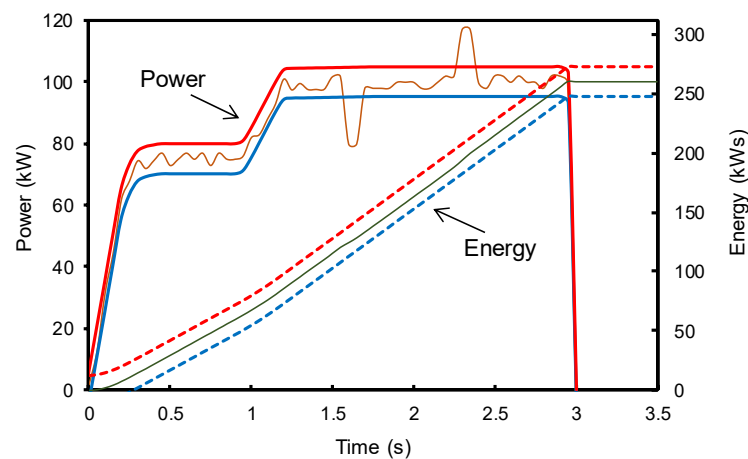


Figure 9. Profiling of power and energy is depicted in the figure. The orange trace represents the power, while the green trace represents the energy. The red and blue lines (solid and dashed) indicate the maximum and minimum allowed values, respectively.

Table 1. Results obtained for an experimental ISH process of 3 s of heating time.

Time (s)	Power (kW)	Energy (kW·s)
0.0	0.0	0.0
0.5	75.0	29.5
1.0	80.0	67.3
1.5	99.8	115.6
2.0	100.0	165.6
2.5	100.0	215.6
3.0	0.0	260.5

3.2. System Faults

Faults are typically monitored using a programmable logic controller (PLC) or other controller type. Historically, faults in the PLC are monitoring high and low limits during the process. If the level of the monitored signal should not vary during the cycle, for example, the cooling temperature, this is an acceptable means of monitoring. Monitoring software can track the number of occurrences and be exported for analysis as needed.

3.3. Statistical Process Control (SPC)

Using collected numerical data, SPC monitors processes to ensure compliance with a quality standard. Statistical process control is a good measure of process stability. SPC does not provide immediate feedback for a good or bad part but it is valuable for verifying that the process is not varying over a longer sample.

The proposed procedures have been implemented through a high-speed measurement and recording system designed for monitoring the power delivered by an induction heating converter in an IHS application. This system has been built and tested. The data collected are transmitted to a programmable logic controller (PLC), which serves as the human–

machine interface (HMI) of the installation. The PLC displays the temporal evolution of the power alongside various other operating parameters of the converter. Figure 10 shows an image of the HMI of the system where power profiling is performed.

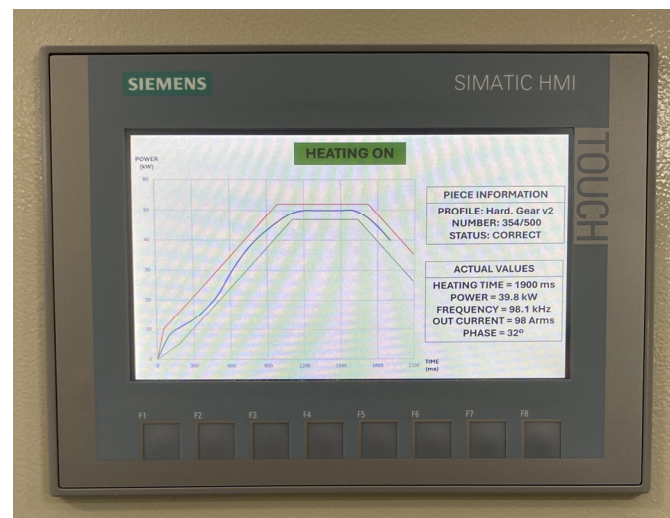


Figure 10. Experimental profiling of power.

The induction heating converter incorporates a System-on-Chip (SoC) from the Zynq 7000 family (XILINX, San Jose, CA, USA), which integrates a microcontroller consisting of a single-core ARM Cortex-A9 responsible for communications between the PLC and the 28 nm Artix 7 FPGA.

The system operates by sampling information from sensors with the FPGA during each switching cycle of the inverter, followed by filtering to mitigate noise from the dv/dt of the MOSFETs switching. Analog sensors measure the direct current bus voltage and current, allowing the instantaneous power applied to the heating workpiece to be derived from their product. This power value is compared to a setpoint for power using a Proportional Integral Derivative (PID) controller to regulate the power setpoint. The control system output is the number of counts equivalent to the switching period of the transistors. The FPGA generates transistor gate signals considering the switching time along with dead time during switching transitions.

Both the filtered sensor and the power value are sent from the FPGA to the microcontroller via the AMBA bus, which enables internal connectivity between these two devices. Similarly, the microcontroller sends the power setpoint value and commands to initiate and stop the heating process to the FPGA.

To communicate between the inverter and the user, a S7 CPU (Siemens AG, Berlin, Germany) is employed, along with a CM 1241 communication module enabling UART communication via an RS485 connection between the PLC and the microcontroller. This setup allows the user to observe heating profiles derived from the applied instantaneous power and adjust power setpoints based on the specific heating requirements of the workpiece.

Figure 11 shows a sequence of experimental images that describes the surface induction hardening process.

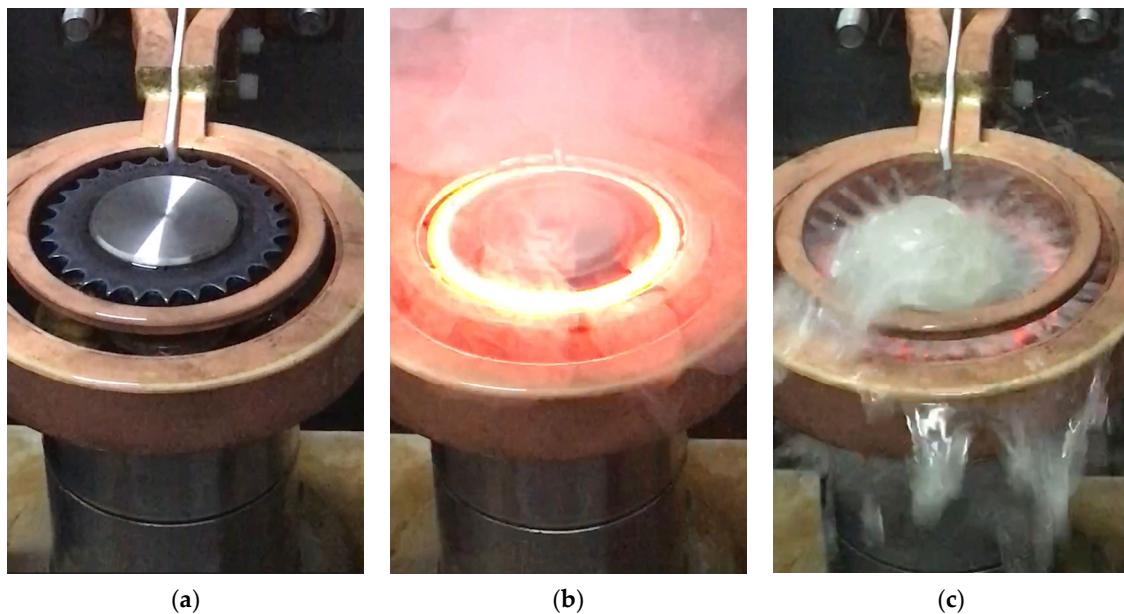


Figure 11. Experimental ISH process: (a) inductor and workpiece placement, (b) rotating and heating, and (c) quenching.

4. Conclusions

This article has outlined the process of monitoring surface hardening through induction, conducting a detailed examination of the fundamental parameters that determine the quality of the heat treatment. It differs from other previous studies because it is presented as a comprehensive work covering all aspects related to monitoring in industrial ISH applications, emphasizing the study of sensors and modern measurement and control systems. Additionally, a quality control system based on profiling essential system parameters has been introduced. Nondestructive testing techniques for controlling metallographic parameters that can be performed online during heat treatment have also been discussed.

In addition, an experimental comprehensive monitoring system supported by a programmable logic controller (PLC) and mixed acquisition and instrumentation systems (analog and digital) implemented with a high-performance Field Programmable Gate Array (FPGA) has been presented. More research is planned to expand the results obtained and apply them in a real industrial application.

Author Contributions: Methodology, V.E.; Software, J.L.B.; validation, J.L.B. and J.J.; investigation, J.J.; writing—original draft, V.E.; writing—review and editing, V.E. and J.L.B.; supervision, V.E. All authors have read and agreed to the published version of the manuscript.

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References

1. Lucia, O.; Maussion, P.; Dede, E.J.; Burdío, J.M. Induction heating technology and its applications: Past developments, current technology, and future challenges. *IEEE Trans. Ind. Electron.* **2014**, *61*, 2509–2520. [[CrossRef](#)]
2. Rudnev, V.; Loveless, D.; Cook, R.; Black, M. *Hand Book of Induction Heating*; CRC Press: Boca Raton, FL, USA, 2017.
3. Brown, G.H.; Hoyler, C.N.; Bierwirth, R.A. *Theory and Application of Radio-Frequency Heating*; Van Nostrand: New York, NY, USA, 1947.
4. Park, N.-J.; Lee, D.-Y.; Hyun, D.-S. A power-control scheme with constant switching frequency in class-d inverter for induction-heating jar application. *IEEE Trans. Ind. Electron.* **2007**, *54*, 1252–1260. [[CrossRef](#)]

5. Faucher, S.; Forest, F.; Gaspard, J.-Y.; Huselstein, J.-J.; Joubert, C.; Montloup, D. Frequency-synchronized resonant converters for the supply of multiwinding coils in induction cooking appliances. *IEEE Trans. Ind. Electron.* **2007**, *54*, 441–452.
6. Lucía, O.; Burdío, J.M.; Millán, I.; Acero, J.; Barragán, L.A. Efficiency oriented design of ZVS half-bridge series resonant inverter with variable frequency duty cycle control. *IEEE Trans. Power Electron.* **2010**, *25*, 1671–1674. [[CrossRef](#)]
7. Dede, E.; Gonzalez, J.; Linares, J.; Jordan, J.; Ramirez, D.; Rueda, P. 25-kW/50-kHz generator for induction heating. *IEEE Trans. Ind. Electron.* **1991**, *38*, 203–209. [[CrossRef](#)]
8. Shenkman, A.; Axelrod, B.; Chudnovsky, V. Assuring continuous input current using a smoothing reactor in a thyristor frequency converter for induction metal melting and heating applications. *IEEE Trans. Ind. Electron.* **2001**, *48*, 1290–1292. [[CrossRef](#)]
9. Zhao, K.B.; Sen, P.C.; Premchandran, G. A thyristor inverter for medium-frequency induction heating. *IEEE Trans. Ind. Electron.* **1984**, *IE-31*, 34–36. [[CrossRef](#)]
10. Davies, J.; Simpson, P. *Induction Heating Handbook*; McGraw-Hill: New York, NY, USA, 1979.
11. Russell, C. Technologies advancing scan and single-shot induction hardening capabilities. *Int. J. Microstruct. Mater. Prop. (IJMMP)* **2018**, *13*, 113–126. [[CrossRef](#)]
12. Sarnago, H.; Lucía, O.; Burdío, J.M. A Versatile Resonant Tank Identification Methodology for Induction Heating Systems. *IEEE Trans. Power Electron.* **2018**, *33*, 1897–1901. [[CrossRef](#)]
13. Lucia, O.; Navarro, D.; Guillén, P.; Sarnago, H.; Lucia, S. Deep Learning-Based Magnetic Coupling Detection for Advanced Induction Heating Appliances. *IEEE Access* **2019**, *7*, 181668–181677. [[CrossRef](#)]
14. Esteve, V.; Sanchis-Kilders, E.; Jordán, J.; Dede, E.J.; Cases, C.; Maset, E.; Ejea, J.B.; Ferreres, A. Improving the Efficiency of IGBT Series-Resonant Inverters Using Pulse Density Modulation. *IEEE Trans. Ind. Electron.* **2011**, *58*, 979–987. [[CrossRef](#)]
15. Larregain, B.; Vanderesse, N.; Bridier, F.; Bocher, P.; Arkinson, P. Method for accurate surface temperature measurements during fast induction heating. *J. Mater. Eng. Perform.* **2013**, *22*, 1907–1913. [[CrossRef](#)]
16. Baqeri, R.; Honarvar, F.; Mehdizad, R. Case depth profile measurement of hardened components using ultrasonic backscattering method. In Proceedings of the 18th World Conference on Nondestructive Testing, Durban, South Africa, 16–20 April 2012.
17. Kennamer, T.; Collins, D. Process Monitoring to Reduce/Eliminate Destructive Testing in Induction Heat Treating. In Proceedings of the 22th Heat Treating Society Conference, Indianapolis, IN, USA, 15–17 September 2003; pp. 112–114.
18. Wolter, B.; Gabi, Y.; Conrad, C. Nondestructive Testing with 3MA—An Overview of Principles and Applications. *Appl. Sci.* **2019**, *9*, 1068. [[CrossRef](#)]
19. Oswald-Tranta, B. Induction Thermography for Surface Crack Detection and Depth Determination. *Appl. Sci.* **2018**, *8*, 257. [[CrossRef](#)]
20. Hsieh, S.-J. Thermal profiling techniques for electronics inspection. *Thermosense XXIX* **2007**, *6541*, 120–128.

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