INFLUENTIAL PARAMETERS ON THE INDUCTIVE QUENCHING TECHNOLOGY FOR LARGE BEARING RINGS

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Abstract

Induction quenching can be used for hardening the outer surface of large parts, achieving superior mechanical properties, with the advantage that heating is not required to the whole part. Induction heating is a complex combination of electromagnetic, heat transfer, and metallurgical phenomena involving factors such as: current, voltage, frequency, applied power, scanning speed, heating period, and many more. The influence of some of these factors on the material properties will be shown for an induction-quenched steel large bearing ring (50CrMo4). It was observed that increasing the induction heating working frequency results in a decrease in the quenched depth in the sample, but also in an increase in sample surface temperature. It was possible to obtain the same desired thickness of the hardened layer using different combinations of power and frequency density. For example, when it would be necessary to obtain a hardened shallow superficial layer, the same result could be obtained with a lower frequency than the optimum in combination with a higher power density applied for a shorter time. On the other hand, if a thicker layer is desired, with an existing system using a higher frequency than the optimum value, the use of a lower power density in combination with a higher heating time would be beneficial. Choosing the optimal parameters is critical, in terms of lower number of defects, such as cracks and uneven depths for the hardened material.

Keywords: Induction quenching, steel, bearings

1. INTRODUCTION

Induction quenching technology, used for superficial hardening of bearing rings, amongst other industrial applications, involves induction heating of the surface to be quenched. In terms of induction quenching, the process involves two phases, the first one being the superficial heating by induction of the part using an inductor coil (usually a water-cooled copper coil), followed by the actual quenching in water or other cooling medium [1]. Induction quenching is a heat treatment process widely used in industry to improve the mechanical properties of metallic parts, including hardness and fatigue strength. The main advantage of the method is that it can only be applied to a particular zone of the hardened part (superficial layers, pins, gears) without affecting the properties of the core material, which remains ductile and resists well to dynamic stresses. Other advantages of the induction quenching process compared to classical thermal treatments are: significant shortening of the heat treatment cycle duration, decreased energy consumption, and the grain growth phenomenon is very limited [2]. It has applicability in the case of large pieces, with various shapes, with a significant advantage in terms of reduced deformation, especially for large parts, due to short-term partial heating. Moreover, the internal thermal and structural stresses usually do not lead to cracks as in the case of classic hardening [3]. During induction quenching a medium or high frequency alternating current is passed through the copper coil generating a magnetic field which in turn creates eddy currents in the conductive section which heat the piece to the desired temperature. The current depth of penetration into the piece is directly dependent on the operating frequency of the generator [4].

Power and frequency are two of the most important factors affecting the penetration depth of the electromagnetic field. In surface hardening applications, the frequency may vary from very high values, such as 4000 kHz (used for special applications such as surface hardening of thin wires) down to the 50 Hz [5]. It is possible to obtain the same desired thickness of the hardened layer using different combinations of power and frequency density. For example, when it is necessary to obtain a thin superficial layer, the same result could be obtained with a lower frequency than the optimum, in combination with a higher power density applied for a shorter time. On the other hand, if a thicker layer is desired, it can be obtained using a higher frequency than the optimum, and the use of a lower power density in combination with a higher heating time. In the case of bearing rings, the ultimate end-use of this technology is to obtain a hardened layer with a preset thickness on the active surface of the bearing ring, which should be uniform both on the circumference of the ring, as well as in cross-section [6].

Hereinafter, some of the results concerning the influence of the induction quenching technological parameters on the characteristics of the 50CrMo4 steel are presented.

2. EXPERIMENTAL DETAILS

The steel grade studied in this work was 50CrMo4, which is currently used in the production of large-sized bearing rings by a few manufacturers. This is steel practically intended for a secondary tempering heat treatment followed by a high temperature annealing, in order to obtain a final sorbit structure. This grade of steel has a C content (in wt. %) of 0.46-0.54, Mn 0.5-0.8, Cr between 0.9-1.2, Mo between 0.15-0.30, P max. 0.025, Si max. 0.4 and the balanced is Fe. The presence of molybdenum in the composition of this steel is particularly important in reducing the tendency of fragility after annealing, a tendency which is specific to high-quality steels subjected to this type of heat treatment. Moreover, molybdenum contributes to increased fatigue resistance, and contributes to structural refinement.

The 50CrMo4 steel samples were cylindrical: 30 mm diameter and an average length of 77 mm. The main objective to be pursued is to obtain a uniformly hardened layer with a thickness dependent on the parameters applied to the induction generator: frequency, power, current intensity, heating duration, displacement rate in relation to the inductor coil, etc. In addition to the parameters applied to the induction generator, the distance between the sample and the inductor can be modified by reducing the diameter of the sample or by eccentrically positioning it in the inductor. Considering the percentage of carbon for this type of steel, the heating temperature is required to be in the range of 870-900 °C, necessary to reach the γ solid solution range, following a rapid cooling in a quenching medium. The samples were heated using an inductor coil with an inner diameter of 50 mm. The inductor coil and the steel sample placement can be seen in **Figure 1**.

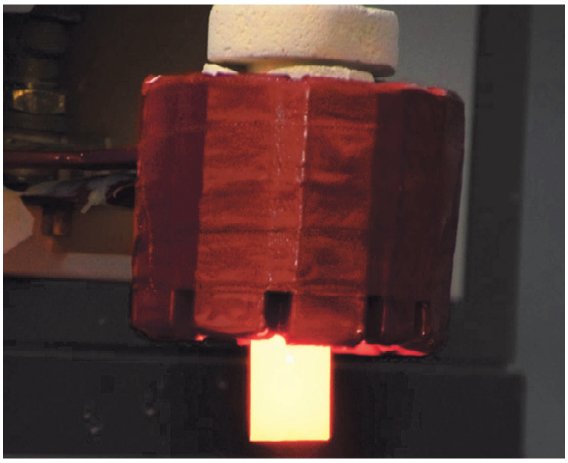
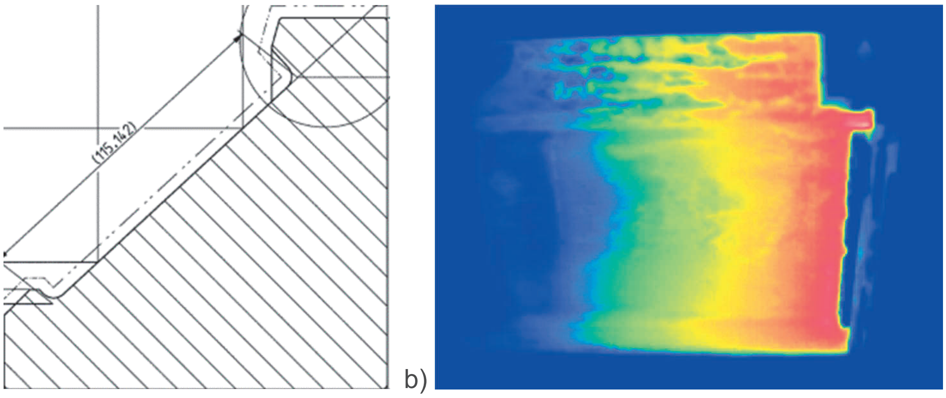


Figure 1 Sample placement in the inductor coil

Moreover, the heating process of large-sized bearing rings was studied on an industrial installation. A bearing ring with the geometry shown in **Figure 2a** was heated by an inductor that follows the geometry of the ring profile. An OPTRIS thermal camera, positioned near the inductor, was used for temperature acquisition. The ring was heated using five power stages: 33 %, 35 %, 37 %, 39 %, 41 %, which translate to the following current intensities: 402 A, 423 A, 447 A, 473 A, 495 A. The rest of the parameters were maintained at identical values: the distance between the inductor and the ring (5 mm), the displacement rate of the inductor in relation to the ring, the working frequency (4 KHz), the inductor configuration (position and number of the concentrating or insulating plates). The variation of the temperatures at the surface of a ring, depending on the inductor movement, is exemplified in **Figure 2b**.



a) b)

Figure 2 Bearing ring cross-section (left), temperature variation at the surface of the ring (right)

3. RESULTS AND DISCUSSIONS

Induction heating is based on the phenomenon of magnetic induction and skin effect, according to which an electric current is induced in the heated piece located in a magnetic field, which is distributed only in the peripheral layers of the piece. The Joule effect, which occurs under the action of induced currents, causes the heating of the part in a relatively short time. The thickness δ of the respective heated layer depends on the resistivity ρ and the magnetic permeability μ of the material and the frequency of the induced current f. This dependence is expressed mathematically by the relation:

$$\delta = 503\times(\rho / \mu_r f)^{½} \qquad (1)$$

According to equation (1), (where ρ - resistivity [Ω m], μ_r - relative magnetic permeability, f - current frequency [Hz]) the magnitude of the penetration depth of the electromagnetic field in the material varies with the square root of the electrical resistivity and inversely proportional to the square root of the relative magnetic permeability and frequency [5]. Mathematically speaking, the depth of penetration of the electromagnetic field in the piece, δ, in equation (1) is the distance from the surface to the core of the piece, the distance at which the current decreases exponentially to "1 / exp". The power density at this distance will drop to "1 / exp2" from its value at the surface. Generally, the optimum frequency will lead to a depth of penetration in the piece that will be 1.2 to 2 times the required depth, keeping this ratio compensates for the softening effect of the cold core of the piece.

To determine the influence of the heating period, the samples were displaced in relation to the inductor coil at different feed rates, which resulted in a variation in the heating time. **Table 1** shows a selection of experimental conditions for determining the influence of heating time on the final sample surface temperature. The values I (current intensity), U (voltage), f (frequency), P (power) were considered the arithmetic mean of several experiments performed under the same conditions. For 50CrMo4 steel (AISI 4150), the electrical resistivity, ρ, is 24.5×10^{-8} Ω m; the relative magnetic permeability, μr, is 750×10^{-5} and the heating temperature for quenching: 840-870 °C. Surface temperatures were measured with an infrared pyrometer. The temperature variation over time, on selected samples, is shown in **Figure 3** - increasing the heating time results in an increase in the sample surface temperature, as can be seen in **Figure 4**.

Table 1 Induction heating parameters: current, voltage, frequency, power, displacement rate, time, temperature and heated depth

Sample no.	I (A)	U (V)	f (Hz)	P (kW)	v (mm/s)	τ (s)	T_{max} (ºC)	δ_{calc} (mm)
5	507	902	13800	25.2	3.2	24	862.6	24.1
	507	904	13800	23.8				
12	507	891	14000	35	2.2	35	875.7	24.1
	506	892	14000	29.3				
21	506	887	14000	37.3	1.7	45	894	24.1
	507	899	13900	29.1				

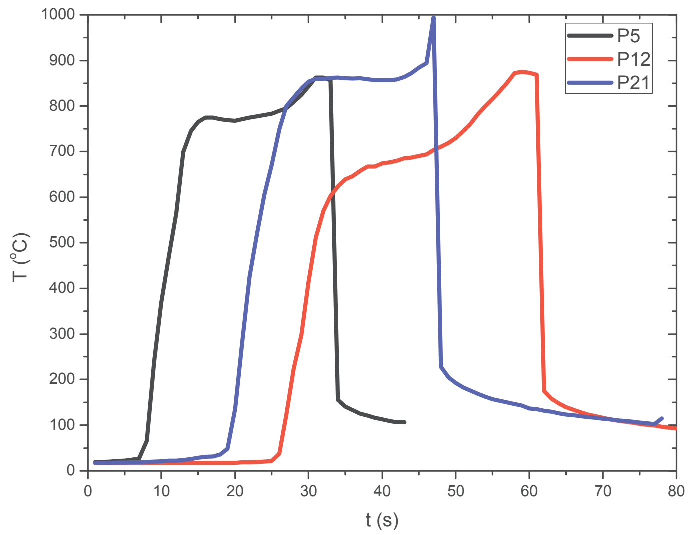


Figure 3 Temperature variation at the sample surface, as function of time

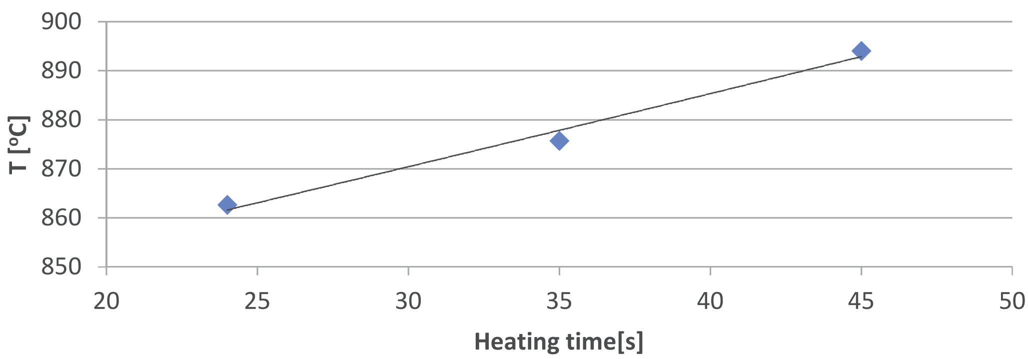


Figure 4 Temperature variation at the sample surface, as function of time

In order to study the influence of frequency on the final result, experiments were performed in which the frequency was varied, maintaining the intensity of the current in the inductor and the heating time at constant values. **Table 2** shows a selection of parameters and results.

Table 2 Induction heating parameters: current, voltage, frequency, power, displacement rate, time, temperature and heated depth

Sample no.	I (A)	U (V)	f (Hz)	P (kW)	v (mm/s)	T (s)	T_{max} (°C)	δ_{calc} (mm)
8	507	910	8300	20.3	7.7	10	537.3	31.1
14	507	902	11.1	25.1	7.7	10	567.7	27.1
31	507	900	13.9	33.2	7.7	10	574.8	24.1

An increase in induction heating frequency results in a decrease in the penetration depth in the sample but also in an increase in sample surface temperature, as can be seen in **Figure 5**. It is easy to notice that the low heating time has not allowed the temperature values required for the quenching, but the purpose of the measurements was to observe the influence of temperature on the surface of the sample, keeping the rest of the parameters at close range. It is possible to obtain the same desired thickness of the hardened layer using different combinations of power and frequency density. For example, when it is necessary to obtain a thin superficial layer, the same result could be obtained with a lower frequency than the optimum in combination with a higher power density applied for a shorter time. On the other hand, if a thicker layer is desired with an existing system using a higher frequency than the optimum the use of a lower power density in combination with a higher heating time. The literature, which refers to practical data, recommends that the choice of the optimal frequency be made so that the penetration depth, δ, is between 1.2 ÷ 2 times the thickness of the desired layer [5]. It should also be kept in mind that with increasing temperature the electrical resistivity and magnetic permeability of the material change.

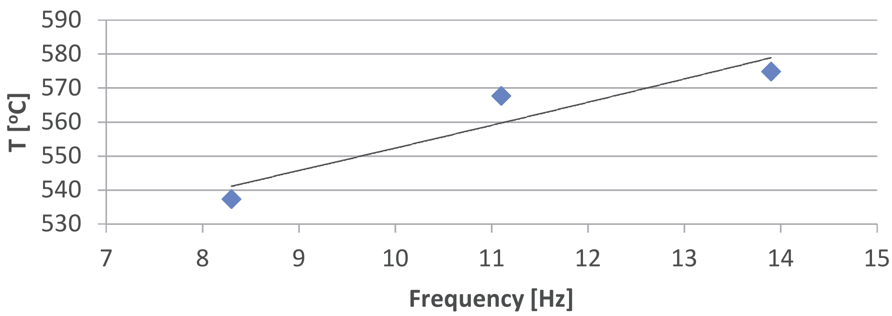


Figure 5 Temperature variations at the sample surface, as function of frequency

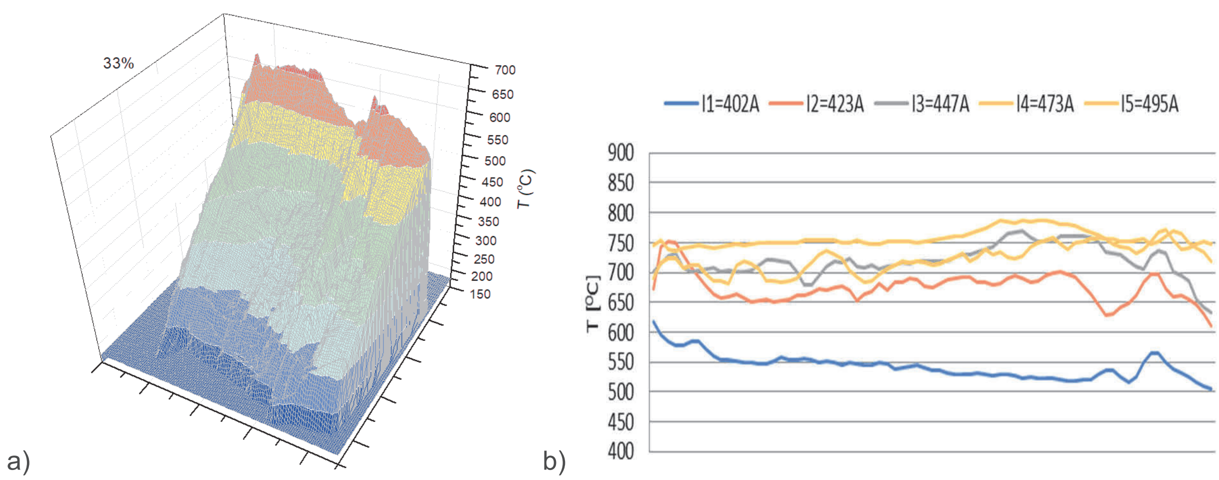


Figure 6 Temperature variation at the sample surface, related to the position on the surface (left); temperature variation for a single line, close to the inductor (right)

The temperature variation on the surface of the bearing ring, measured with a thermal camera, can be observed in **Figure 6a**, for the measurement performed with 33 % power. As can be clearly noticed, the temperature at the surface is not uniform, even if the inductor is positioned at the same distance from the surface of the material. Plotting the variation in temperature for a single line, the closest to the inductor, where the temperature would be the highest, seen in **Figure 6b**, leads to the same observation, that the temperature at the surface is not uniform. The geometry of the bearing ring, in conjunction with that of the inductor, plays an important role concerning the temperature distribution.

4. CONCLUSION

The influence of some of the induction heating process parameters was studied, for a particular application: surface induction quenching, applied to bearing rings. It was observed that increasing the induction heating working frequency results in a decrease in the quenched depth in the sample, but also in an increase in sample surface temperature Moreover, the position and number of insulating/concentrator plates in the inductor stack influences the surface hardening depth on the rolling path.

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