Milliseconds pulse induction hardening

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Abstract: This paper presents a technology that allows a fast surface induction hardening of workpiece of relative small dimension by means of a single current shot. This technology was proposed already in 50's but at that time the availability of power converters limited its industrial application to the hardening of very small surfaces. Nowadays, the process can be applied in automotive industrial applications thanks to the availability of power converters in the megawatt range. Pulse induction hardening process is characterised by high power densities, heating times in the range of tens to hundreds of milliseconds and cooling rates attained by self-quenching without the use of external quenching means. In the paper, authors give some practical diagrams for the preliminary definition of the heating parameters that could help the design of this type of process.

Keywords: induction hardening; numerical methods; pulse discharge.

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1 Introduction

Many studies, developed in the seventies, have demostrated the feasibilty of induction hardening processes carried out in millisecond range by applying very high power densities and its applicability in industrial production (Ettenreich, 1968; Orlich, 1971; Früngel and Ettenreich, 1972; Früngel, 1972; Früngel et al., 1974; Weinek, 1975; Hassan, 1980).

However, for the high specific power required and the consequent high power rating of the supply frequency converters, up to now it has found application only in cases in which the surface to be hardened was relatively small. In fact, for hardening some tens of cm^2 wide, the corresponding input power from the supply network to the high-frequency generator can reach peak values up to several hundreds or more than a thousand of kW.

A way to overcome this limitation was proposed in the eighties by the use of capacitors-discharge high-frequency generators (Crepaz et al., 1981, 1982; Lupi et al., 1982, 1983, 1984, 1986).

In recent years, in particular for the development of the double-frequency induction hardening of gears, very high power frequency converters have been developed and used, which allow to accomplish the heating of relatively large surfaces with high specific power in times of the order of milliseconds (Biasutti and Krause, 2010). This makes currently interesting the study of induction hardening processes in extremely short heating times, such as to ensure the self-quenching of the body and to avoid the use of external quenching media. In fact, this process can nowadays be applied to a range of workpieces of interest for automotive industry.

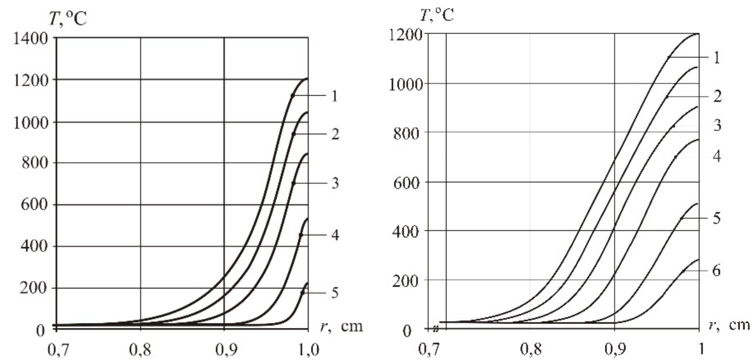
2 Characteristics of very fast induction heating transients

The preliminary analysis of the heating parameters for hardening processes in the milliseconds range has been made with reference to a cylindrical workpiece of annealed steel C45 of 20 mm diameter and to the austenitisation temperature of 800°C. In order to obtain first guidance values, the simple 1D numerical program ELTA has been used. It allowed to obtain the temperature profiles along the workpiece radius at the end of the heating process and from it to evaluate the corresponding austenitisation thickness Δ_{800}. The analysis of the same distributions during a subsequent natural cooling transient has also shown

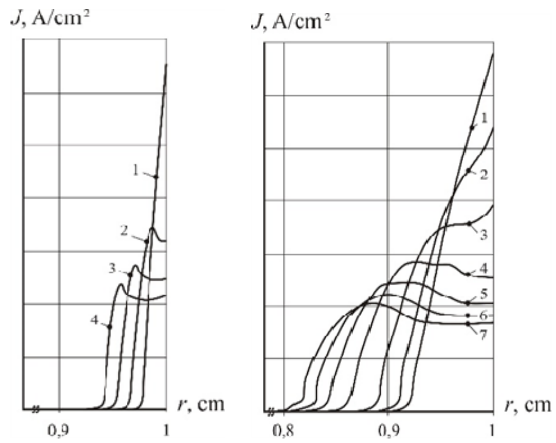
- that the cooling speed is always high enough for assuring the self-quenching of the workpiece without the need of any external quenching medium
- that the hardened layer will correspond to the thickness of austenitisation thickness at the end of the heating period.

Results for a typical heating transient are shown in Figure 1.

Figure 1 Temperature distributions (a,b), current density (c,d) and power (e) along radius at different time instants of the heating transient

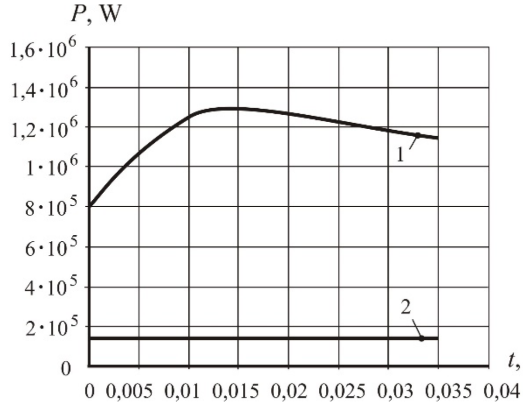


(a) *t = 35-25-15-5-1 ms* (b) *t=35-28-21-14-7-3 ms*



(c) *t=5-15-25-35 ms* (d) *t = 1-3-7-14-21-28-35 ms*

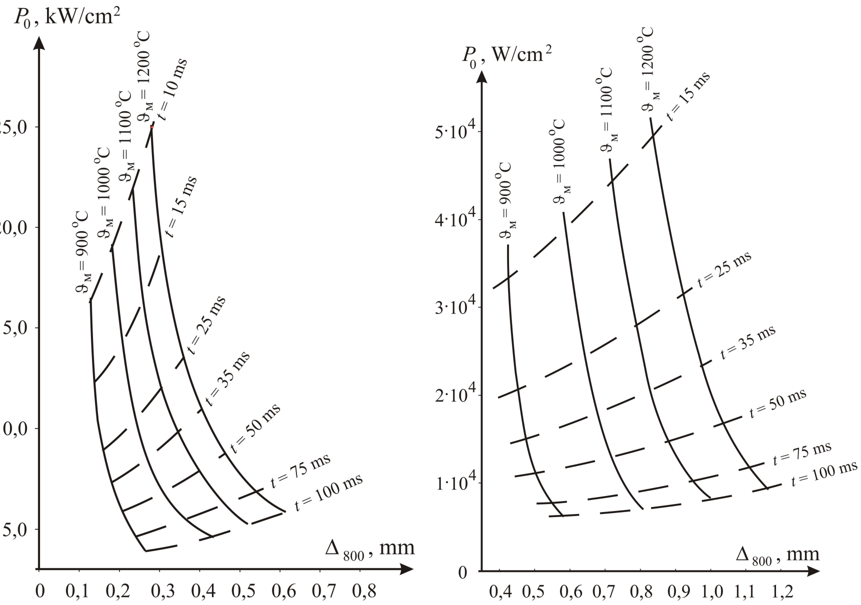
Figure 1 Temperature distributions (a,b), current density (c,d) and power (e) along radius at different time instants of the heating transient (continued)



(e) *1-workpiece power; 2-losses*

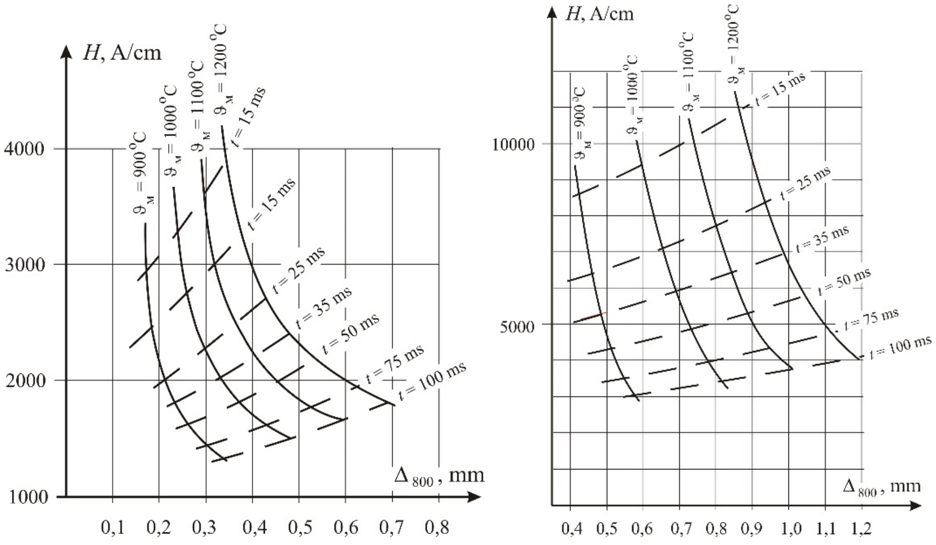
In particular they shown that, due to the very high heating rates, the current density distribution along the workpiece radius is characterised by the well known magnetic wave phenomenon during most of the transient heating stage (Lupi et al., 2015, 2017). In this way the current density is mainly concentrated in the austenitising depth during the whole process.

Figure 2 Austenitising depth Δ_{800} at 500 kHz (left side)) and 50 kHz (right side) with different heating times and various maximum surface temperature (a,b) transients with constant surface power density, (c,d) with constant surface magnetic field intensity; austenitising temperature ϑ_a = 800 °C; steel C45 annealed]



(a) (b)

Figure 2 Austenitising depth Δ_{800} at 500 kHz (left side)) and 50 kHz (right side) with different heating times and various maximum surface temperature (a,b) transients with constant surface power density, (c,d) with constant surface magnetic field intensity; austenitising temperature ϑ_a = 800 °C; steel C45 annealed] (continued)



(c) (d)

The results of the 1D numerical calculations are summarised in the diagrams of Figure 2 which give the process parameters, i.e., surface power density and magnetic field intensity, required for achieving a given austenitising depth Δ_{800} in a process with prefixed maximal surface temperature and given heating time.

Even though calculated for a specific workpiece diameter, in practice the results can be extended to larger diameters due to the negligible influence of the load curvature effect.

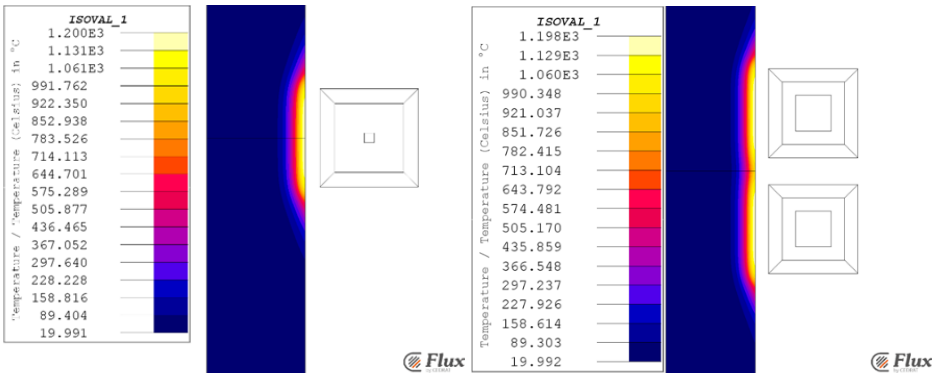
3 Heating parameters

Since in most hardening applications inductors with few turns are used, the results of 1D calculations cannot be used directly. However, they can give useful guidance information for subsequent 2D calculations.

Starting from the data of Figure 2 and applying the approximate method for calculation of inductors of the electrical circuit equivalent to the magnetic reluctances (Lupi et al., 2015, 2017), it is possible to evaluate the inductor current giving the same power density developed in the workpiece with a short inductor and in a ‘long’ inductor-load system.

In the following, two examples are given with reference to a short single-turn and double-turn inductors encircling a ‘long’ cylindrical workpiece. The evaluation of the required current for the inductor-load system of Figures 3(a) and (b) gives values in accordance with the diagrams with an accuracy in the range of 10–12 %.

Figure 3 (a) Single-turn inductor and workpiece [coil: copper tube 10 × 9 × 1 mm, internal radius r_i = 10.1 mm; workpiece: external radius r_e = 10 mm, steel C45, annealed; heating parameters: f = 500 kHz; t = 100 ms; I = 3.1 kA; at coil half height: Δ_{800} = 0.75 mm with surface magnetic field intensity H_e = 2730 A/cm] and (b) double-turns inductor and workpiece [same geometrical parameters; heating parameters: f = 500 kHz; t = 100 ms; I = 2.75 kA; Δ_{800} = 0.75 mm; H_e = 2730 A/cm] (see online version for colours)

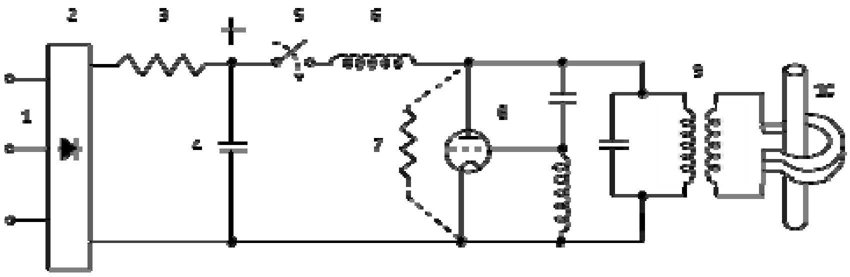


(a) (b)

4 Power pulses from capacitors-discharge high-frequency generators

In the 1980s, several studies have analysed the possibility of carrying out the surface hardening of steel with power pulses obtained by high-frequency generators supplied by the discharge current of a bank of capacitors (Figure 4) (Crepaz et al., 1981, 1982; Lupi et al., 1982, 1983, 1984, 1986).

Figure 4 Scheme of a pulse high-frequency generator [1-network supply; 2-controlled power rectifier circuit for charging the bank of capacitors at a HV voltage V; 3-limiting resistance; 4-bank of capacitors C; 5-thyratron connecting device; 6-inductance L of discharge circuit; 7-equivalent resistance R of high-frequency generator; 8-triode valve; 9-radio frequency transformer; 10-work coil and workpiece]



The advantages of this supply system are the possibility of producing power pulses up to hundred of kW, which are needed for the hardening of many tens of cm^2 surfaces, with input power from the network of some tens of kW only, and the strict control of the energy transferred to the workpiece at each pulse, since it corresponds to the energy stored in the capacitor bank.

Moreover, a convenient choice of the electrical parameters of the discharge circuit, allows to modify the characteristics of the power pulse and therefore the time temperature distribution in the workpiece and the time spent above the transformation temperature. This allows to affect the structure of the hardened layer in order to obtain the best results, even starting from steels with different characteristics before hardening.

In the over-damped case ($R > 2\sqrt{(L/C)}$), the high-frequency magnetic field intensity on the workpiece surface varies during the discharge with the following law:

$$H \cong k \cdot f \cdot C_0 \cdot V \cdot k_i(t) \tag{1}$$

with:

$$k_i(t) = \frac{1}{\gamma}\left[e^{\alpha(1-\gamma)t} - e^{\alpha(1+\gamma)t}\right]$$

$$\alpha = -R/2L; \quad \alpha = -\frac{R}{2L}$$

$$\gamma = \sqrt{1 - \frac{4L}{CR^2}}$$

where

f: frequency

C_0: tank circuit capacitor of the high-frequency generator

$k_i(t)$: coefficient depending on the characteristics of high-frequency generator, work-coil, workpiece, as well as the position in the inductor-workpiece system.

Typical distributions of the function $K_i(t)$ are shown in Figure 5.

Figure 5 Function $K_i(t)$ for different values of discharge circuit parameters [C = 260 μF; (a) ——R = 500 ohm; L = 1 H; (b) -·-·-R = 500 ohm; L = 10 H; (c) ----130 μF; R = 550 ohm; L = 0.5 H]

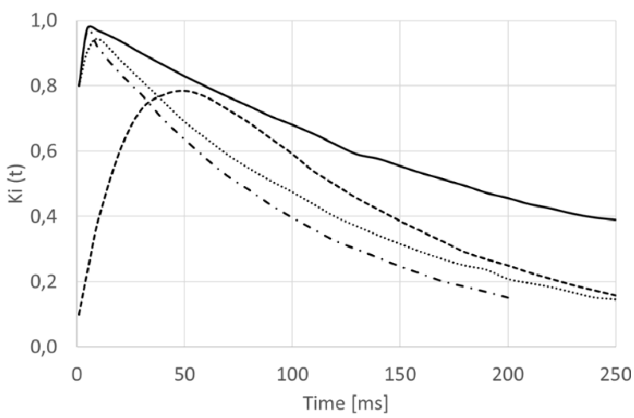
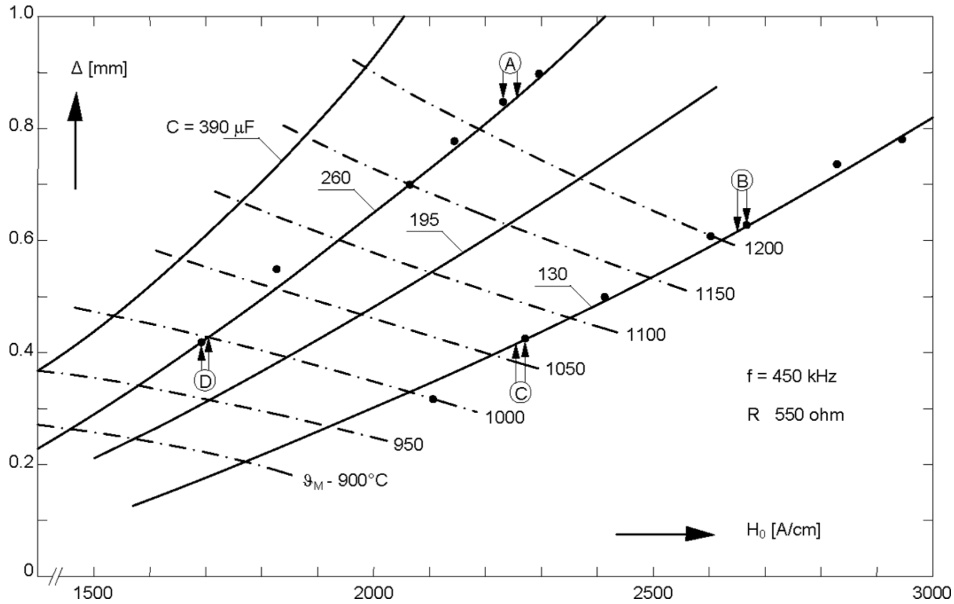
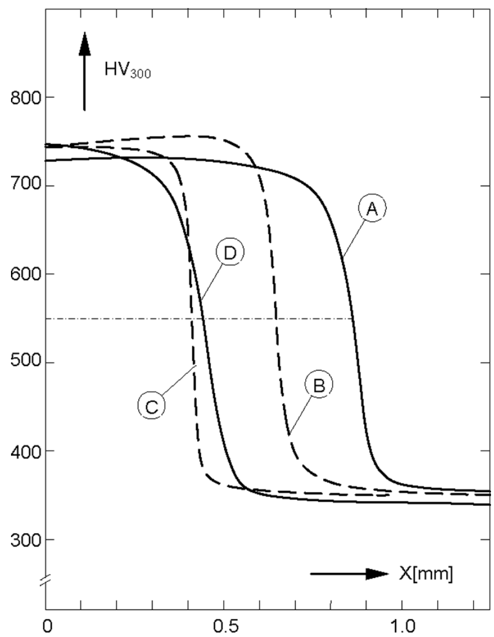


Figure 6 (a) Relationship between austenitising depth, high-frequency magnetic field intensity and maximum surface temperature, for various values of capacity C and (b) hardness profiles at different heating conditions [f = 450 kHz; $R \approx 550\ \Omega$; $L \approx 0.2$ H; • experimental points (steel UNI C43); A: C = 260 μF, H_0 = 2250 A/cm; B: C = 130 μF, H_0 = 2650 A/cm; C: C = 130 μF, H_0 = 2250 A/cm; D: C = 260 μF, H_0 = 1700 A/cm]



(a)

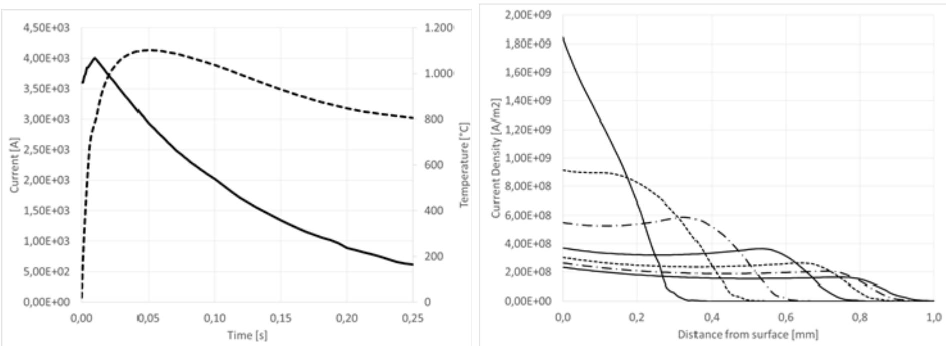


(b)

Since the induced power depends on the high-frequency magnetic field intensity at the workpiece surface, it follows that a convenient choice of the voltage *V* and the circuit parameters *R*, *L*, *C* allows us to select the convenient peak value and time distribution of the induced power, and therefore the transient temperature distribution in the workpiece.

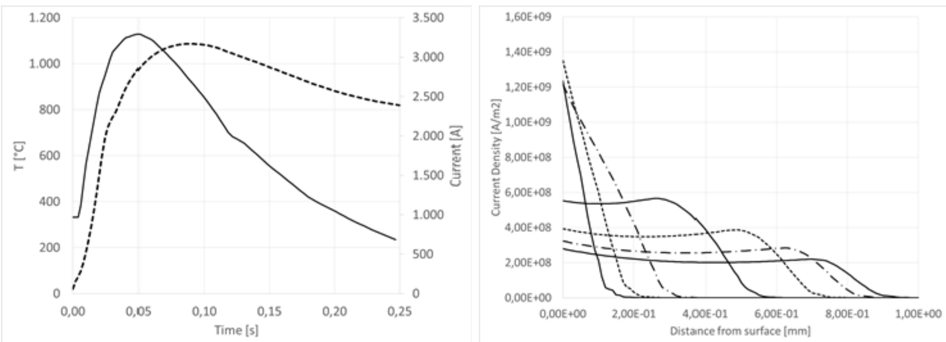
Figure 6(a) shows how the circuit parameters affect the austenitising depth Δ_{800}. Figure 6(b) shows the hardness profile obtained with the different heating conditions highlighted in Figure 6(a). Several experimental tests were carried out with different types of steel, e.g., 40CrMoPb4, quenched and tempered, and UNI C43 normalised.

Figure 7 (a) Current (–) and temperature (- -) distributions with a pulse of type a) [inductor and workpiece as in Figure 3; *f* = 500 kHz; ϑ_M = 1100°C; Δ_{800} = 0.69 mm (at 80 ms)] and (b) Current density distributions in the workpiece at half inductor height, at the times instants *t* = 2-10-20-40-60-80-100 ms of the heating transient of Figure 7(a)



(a) (b)

Figure 8 (a) Current (—) and temperature (----) distributions with a pulse of type b) [inductor and workpiece as in Figure 3; *f* = 500 kHz; ϑ_M = 1086 °C; Δ_{800} = 0.70 mm (at 130 ms)] and (b) current density distributions in the workpiece at half height of inductor, at the times instants *t* = 2-10-20-40-60-80-100 ms of the heating transient of Figure (8)

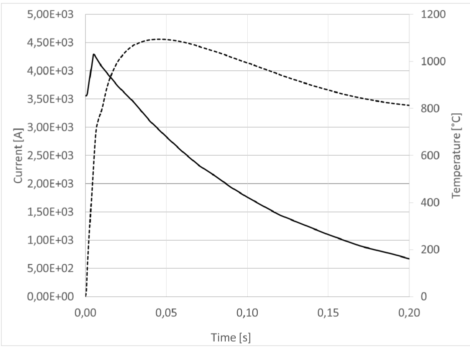


(a) (b)

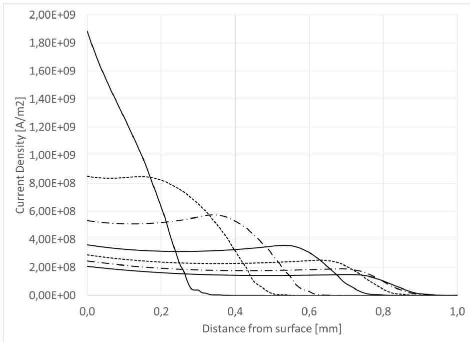
In the diagrams of Figures 7 and 8 are given two examples of heating transients calculated with FLUX with current pulses of type a) and b) respectively. Figure 8 refers to a heating transient with a current pulse of type c) of Figure 5, which reproduces heating conditions practically identical to those of the experimental test of Figure 8(c). The comparison of the calculated and measured values of the austenitising depth Δ_{800} shows a fairly good agreement and the high reliability of the calculated results, as shown in Figure 9. In fact, the experimental austenitisation depth [$\Delta_{800} \approx 0.69$ mm] is in good agreement with the computed one [$\Delta_{800} = 0.64$ mm].

Figure 10 shows a result of a test of pulse hardening of a typical crankshaft for automotive applications.

Figure 9 (a) Calculated current (—) and temperature (----); (b) current density distributions (at times t = 2-10-20-40-60-80-100 ms) with pulse of type c) of Figure 5 [f = 500 kHz; r_i = 8,5 mm; r_e = 7,5 mm; ϑ_M = 1095 °C; Δ_{800} = 0.64 mm (at 70 ms)]; (c) On the right, experimental results of a process carried out with the parameter presented in Figure 9(a) (see online version for colours)



(a)



(b)

(c)

Figure 10 Test of pulse induction hardening of a crankshaft for automotive applications (see online version for colours)

5 Conclusions

In the paper, the induction hardening of steel obtained with very short power pulses of duration of the order of tens of milliseconds has been analysed. The advantage of this type of process is the possibility of obtaining the self-quenching of the body and to avoid the use of external quenching media.

A set of diagrams obtained with a 1D numerical program gives the main parameters of the heating process. Some examples of the use of such diagrams in 2D configurations are presented. As discussed in the paper, the results given in the diagrams are calculated for an infinite long configuration. The equivalent circuit method allows obtaining a preliminary evaluation of the heating parameters for a finite length configuration. Using this preliminary evaluation, the calculated results are within 10% of discrepancies with respect to FEM calculations. This can also explain the difference between experimental and calculated results shown in Figure 9.

The renewed interest in these processes is linked to the today's availability of industrial frequency converters with power ratings up to 3 MW, which thus allow the treatment of surfaces up to or greater than 100 of square centimetres. A comparison with capacitors-discharge high-frequency pulse hardening processes is also presented.

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