# Modeling of Electromagnetic and Thermal Processes of High-frequency Induction Heating of Internal Cylindrical Surfaces of Ferromagnetic Details

Bohos Aprahamian[1] and Maik Streblau[2]

*Abstract* - **Currently increasingly widespread the application of the induction hardening of ferromagnetic details, due to the high efficiency and universality of this kind of heat treatment.**

**For the most part, the companies which realize this method have limited power capacities and limitations in the frequency range. For these reasons, certain difficulties arise in the induction hardening of cylindrical internal surfaces and achievement of even hardened layer along the detail providing concrete depth.**

**Optimization of the technological regimes can be effectively done using computer models.**

**For this purpose two-dimensional model was developed, simultaneously analyzing the electromagnetic and thermal processes, having taken into account their influence on the properties of the detail and with his help we have optimized the parameters of the inducers.**

*Keywords* - **Induction hardening, Hardened layer, Inducer, Computer model, Optimization**

## I. INTRODUCTION

The annealing of the internal cylindrical surfaces of ferromagnetic details require the achievement of appropriate speed of heating providing uniform hardened layer depth [1].

Since induction heating machines with lamp generators (440kHz) are still used, often problems related to a shortage of capacity for implementation of the technological regime arise, especially in hardening of internal cylindrical surfaces, due to the ring and proximity effects [2], leading to dissipation of the electromagnetic field around the treated surface of the workpiece.

In regard to the reasons maintioned above interesting is the optimization process for maximum utilization of the power entering the generator through reduction of the electromagnetic dissipation. This paper presents a model of inductor-workpiece system to solve the defined problem.

The Figure 1 presents the inductor-workpiece system configuration. The workpiece is made of structural steel grade C45 [1], [2].

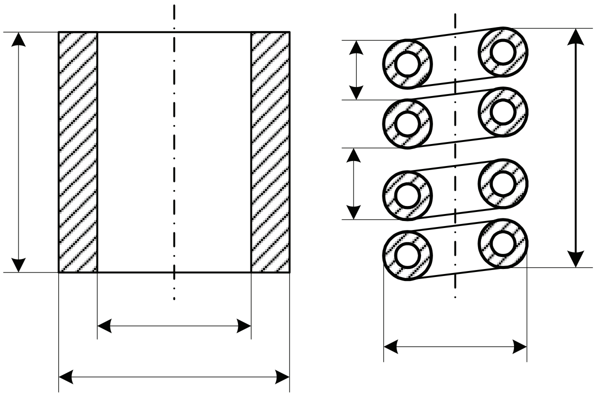

Fig. 1. Dimensions of the workpiece and the inductor

The variety of configurations of the processed details define as uneconomic the process of experimental investigation. Currently the large opportunities of process modeling are widely used [3], [4].

## II. THEORETICAL MODEL

To carry out the theoretical investigation two-dimensional axial symmetric model is used, analyzing both the electromagnetic and thermal problem [5].

The simulation of the electromagnetic processes is done by harmonic electromagnetic analysis, described by the following differential equation and boundary condition - zero magnetic potential within the model.

$$\nabla \times \left( \frac{1}{\mu(B,T)} \times \nabla \times \dot{A} \right) + j \cdot \omega \cdot \gamma(T) \cdot \dot{A} = \frac{\gamma \cdot \dot{V}_{coil}}{2 \cdot \pi \cdot r} \tag{1}$$

As a source is set the voltage, determinant the current density inside the inductor.

The thermal problem is simulated by transient thermal analysis, described by the following differential equation:

$$\rho \cdot c \cdot \frac{\partial T}{\partial t} = \nabla\left(\lambda(T) \cdot \nabla T\right) + q_V \tag{2}$$

where:

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[1] Bohos Aprahamian is with the Faculty of Electrical Engineering, Technical University – Varna, 1 Studentska str., Varna, Bulgaria, e-mail: bohos@abv.bg.

[2] Maik Streblau is with the Faculty of Electrical Engineering, Technical University – Varna, 1 Studentska str., Varna, Bulgaria, e-mail: streblau@yahoo.com.

$$q_V = \frac{1}{2} \cdot \frac{\dot{J}^2}{\gamma(T)} = \frac{1}{2} \cdot \omega^2 \cdot \gamma(T) \cdot \dot{A}^2 \qquad (3)$$

The boundary condition, ensuring coherence of equation (2) is the requirement of Dirichlet, specified on the boundary of the model. On the bordering surface of the inducer to the environment a natural convective heat transfer as a function of the temperature and radiant heat transfer are set [6].

In the description of the model the perceived assumptions are as follows:

- the power supply of the inductor-workpiece system is via sinusoidal voltage with constant frequency - 440kHz;
- the inductor is with water cooling and therefore the changes of the electrical conductivity during the heating process are not taken into account;
- the changes in the density and specific heat capacity of the workpiece, depending on the temperature changes do not account in the model building.

## III. THEORETICAL INVESTIGATION

With the above model theoretical invstigations were conducted at constant voltage and frequency. The time to realize the heating process was set to 4.5 seconds.

In the figures below are represented graphically the distribution of the magnetic vector potential and magnetic induction in the starting and ending point of time, and the distribution of temperature field in the section and on the surface of the workpiece.

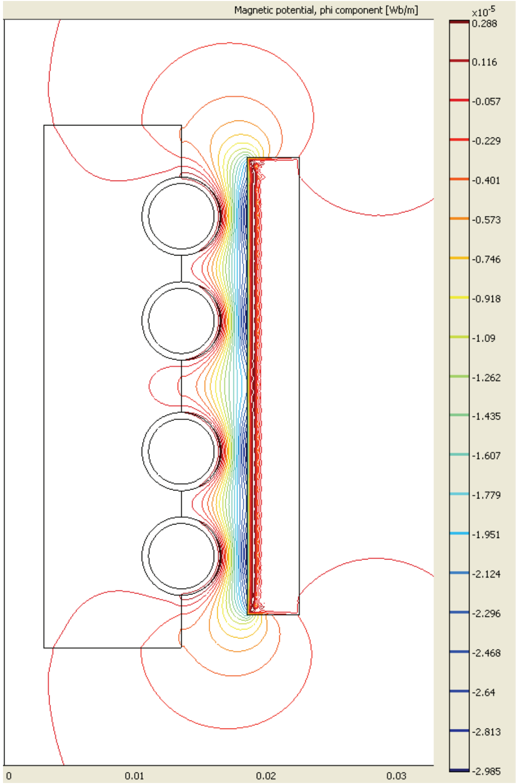

Fig. 2. Distribution of the magnetic vector potential in the beginning of the process

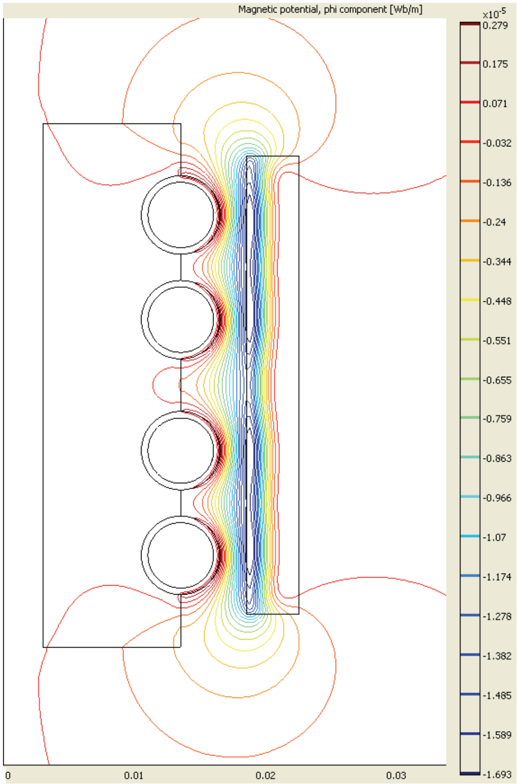

Fig. 3. Distribution of the magnetic vector potential at the end of the process

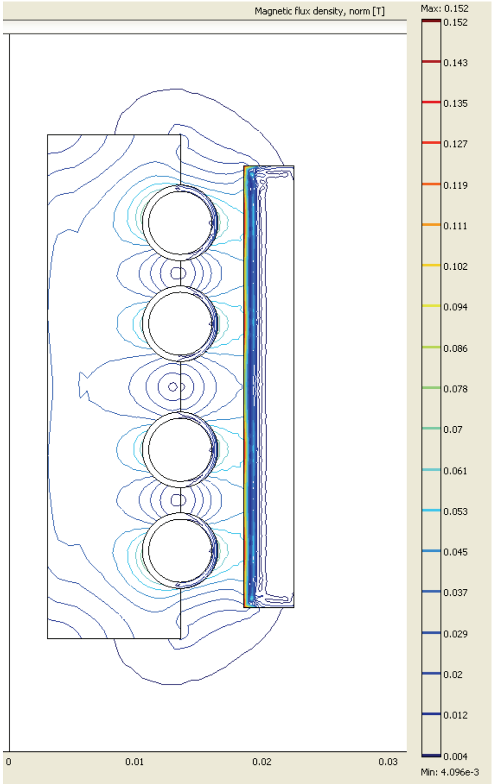

Fig. 4. Distribution of the magnetic induction at the beginning of the process

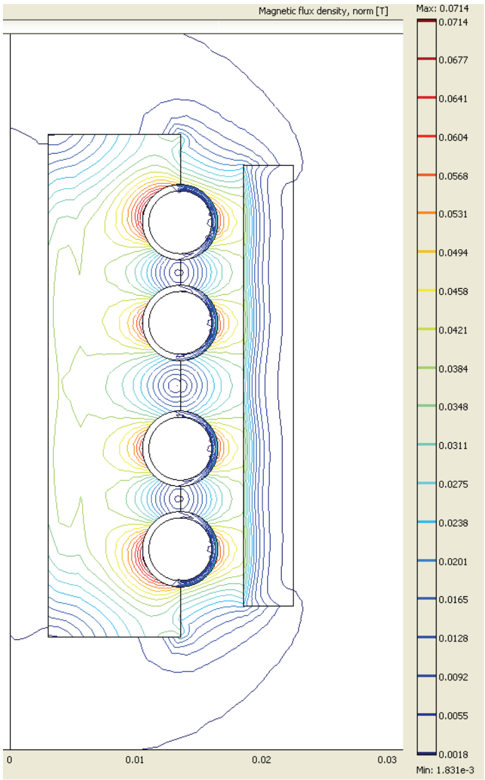

Fig. 5. Distribution of the magnetic induction at the end of the process

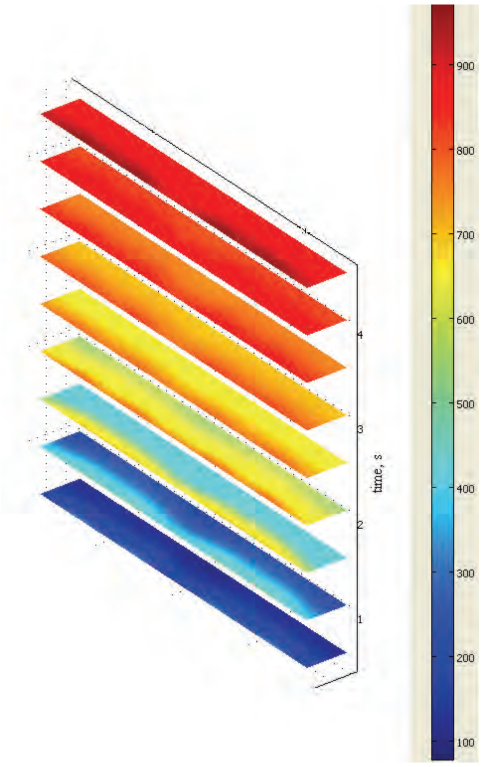

Fig. 6. Temperature distribution along the detail section during the work time

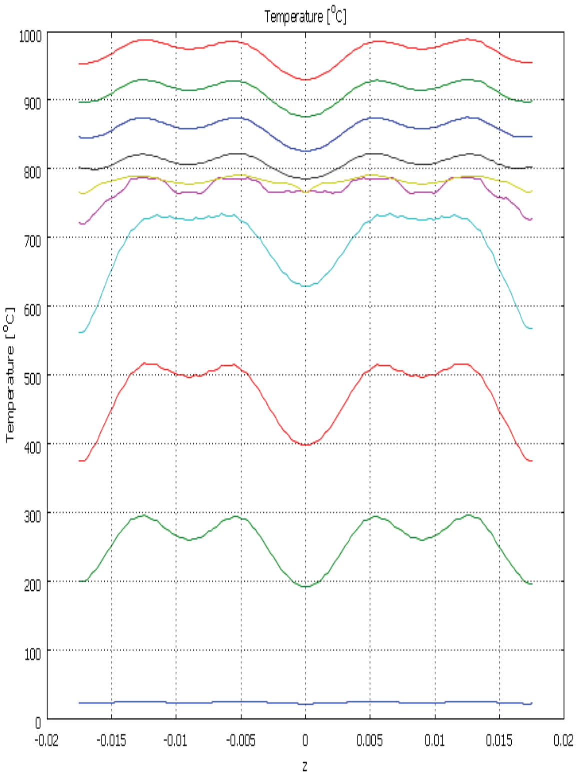

Fig. 7. Distribution of the temperature field on the surface of the workpiece

## IV. CONCLUSIONS OF THE THEORETICAL INVESTIGATION

The distribution of the vector magnetic potential and magnetic induction shown in Figures 2 to 5 demonstrates the existence of double layer (with two highly different permeability zones) heat penetration medium under section of the workpiece until in the end of the process the temperature of the workpiece has passed the Curie point and the distribution of the electromagnetic field cover greater layer then the layer of the heat penetration.

Another important point is the achievement of uniform heating of the workpiece at a depth of the set hardening layer - Figures 6 and 7. The temperature difference is less than 50°C throughout the volume of the heated layer.

To ensure high efficiency it is necessary to use ferromagnetic cores in the system inducer - detail.

The ferromagnetic core shape must follow the configuration of the inducer. For this purpose, a better option is the preparation of magnetic core by molding rather than applying standard core configurations.

The used approach makes possible to develop adequate theoretical models for studying the process of induction heating for different configurations of the details and the inductors.

## V. APPLICATIONS

The investigated technological process has been applied in the production of steel sleeves of train carriage braking systems. In Bulgaria the main manufacturer of such sleeves is Pomorie PLC, furnishing with annealed steel sleeves the railway companies of Germany, Bulgaria and other countries of the European Union.

In Figure 8 a typical system inductor-detail used in Pomorie PLC is presented and in Figure 9 an inductor used for sleeves hardening is shown.

In our research we aim to optimize this production process.

Fig. 8. A typical system inductor-detail used in Pomorie PLC

Fig. 9. An inductor used for hardening of internal cylindrical surfaces of steel sleeves

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