Numerical Modeling of Induction Heating Process using Inductors with Circular Shape Turns

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Abstract: **This paper is focused on the problem of numerical modeling of electromagnetic field coupled with the thermal one in the heating process of the steel billets, using inductors with circular shape turns. As results we have: electromagnetic field lines evolution and map temperatures in piece at the ending of heating process.**

Keywords: ***Numerical modeling, heating process, electromagnetic field.***

I. INTRODUCTION

The optimal design and the development of complex electromagnetic systems, such as the induction heating installations, are very expensive. The interaction between electromagnetic and thermal fields, time and space variation of quantities which characterize the induction heating process make impossibile to determine the optimal parameters of these equipments (number of turns, inductor lenght, frequency, air-gap between inductor and piece) by usual analytical methods. The final variant is usually obtained after a lot of experiments that suppose supplementary expenses and delay of project assimilation.

By numerical modelling we make an association between an inductive heating instalation (inductor – heating piece) and a mathematical model with the help of Maxwell equations and the boundary conditions necessary to solve the problem of the electromagnetic field coupled with the thermic one. In this purpose, a numerical simulation had been used, which allows to analyse the induction heating process of cylindrical surfaces. The [8] analysis was made by simulating of the heating process, with a specific FEM package for this coupled problem, the FLUX 2D software.

II. MATHEMATICAL MODEL

The mathematical models of electromagnetic and thermal fields, based on the specific laws of this phenomenon are described by partial differential equation.

In this paper, for the coupled electromagnetic and thermal field, the general equations used are, [4]:

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla \times H = J \tag{2}$$

The material equations are:

$$H = \nu B \tag{3}$$

$$J = \sigma E \tag{4}$$

The magnetic flux density B, using the magnetic vector potential A, is:

$$B = \nabla \times A \tag{5}$$

where ϕ is the electric scalar potential. So we obtain:

$$E = -\frac{\partial A}{\partial t} - \nabla \Phi \tag{6}$$

$$\nabla \times (\nu \nabla \times A) = J \tag{7}$$

The current density is given by the relation

$$J = -\sigma \frac{\partial A}{\partial t} - \sigma \nabla \Phi \tag{8}$$

It satisfied the continuity equation

$$\nabla \cdot J = 0 \tag{9}$$

By substituting equation (8) in relation (7) and (9), the equations for the vector and scalar potentials become:

$$\nabla \times (\nu \nabla \times A) + \sigma \frac{\partial A}{\partial t} + \sigma \nabla \Phi = 0 \tag{10}$$

After transformations the equation (9) takes the following form:

$$\nabla \times (\nu \nabla \times A) + j\omega\sigma A = \underline{J}s \tag{11}$$

where:

$$A = A(P,t) = A(P)e^{j\omega t h}$$

In the solution of the field equations, the boundary and initial values of the vector potential must be known.

The thermal field is modeled by:

$$\gamma\, C\frac{\partial T}{\partial t} - \nabla\lambda\nabla T - \lambda\nabla^2 T = J^2\varphi(T) \qquad (12)$$

In the heat transfer process there are three kinds of boundary conditions commonly used.
The first boundary condition (Dirichlet boundary condition), corresponds to a surface at a fixed temperature T_S, [5],

$$T(t) = T_S \qquad (13)$$

The second condition (Neumann boundary condition), corresponds to the existence of a fixed or constant heat flux at the surface. This heat flux is related to the temperature gradient at the surface by Fourier's law:

$$g'' = \lambda_h\frac{\partial T}{\partial n} \qquad (14)$$

The third boundary condition corresponds to the thermal convection at the surface:

$$-\lambda_h\frac{\partial T}{\partial n} = \alpha_s(T_s - T_a) \qquad (15)$$

Thus the complete third boundary condition is:

$$-\lambda_h\frac{\partial T}{\partial n} = \alpha_s(T_s - T_a) + C_s\left(T_s^4 - T_a^4\right) \qquad (16)$$

where C_S is the radiation coefficient and α_S represent the convections. For a surface I the radiation coefficient C_S is given by:

$$C_{s,i} = \sigma_h \cdot \varepsilon_i \cdot F_{ij} \cdot A_i \qquad (17)$$

where A_i is the area of surface i, F_{ij} is the view factor form surface I to surface j, ε is the emissivity and σ_h is the Stefan-Boltzman constant.

III. NUMERICAL MODELING RESULTS

We have built a physical model for induction heating in volume of a square cross section piece. In figure 1 we present this inductor - piece device.
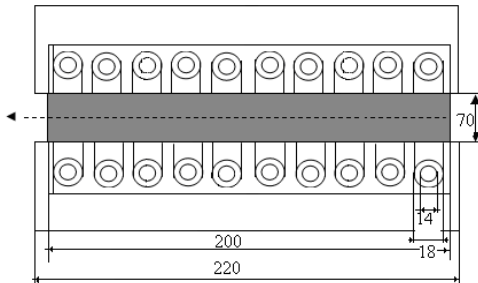

Fig. 1 Inductor-piece device.

The piece that we will heat in inductor is built from steel. The inductor is used to heat the steel billet using the heating in longitudinal field with magnetic core.

The induction device selected for this experiment has the following dimensions: steel billet length a2 = 0.200 m, inductor length L_i = 0.220 m, steel billet width b2 = 0.070 m and steel billet thickness d_2=0.070 m. We will analyse the electromagnetic process in the device formed by inductor and the steel billet, by supposing that magnetic permeability is constant. The billet is heated from the initial temperature T_i=20°C to the mean value of billet temperature at the end of the heating, T_f=1300°C. This piece is heated using a frequency f=1500Hz, and the inductor have a number of 10 circular shape turns.
In this problem, the coupled electromagnetic and thermal fields are studied, with 2D axis symmetric structure in cylindrical coordinates (r,z).
The geometry and the mesh network are created using the preprocessor PREFLU_2D of Flux2D software (Figure 2).
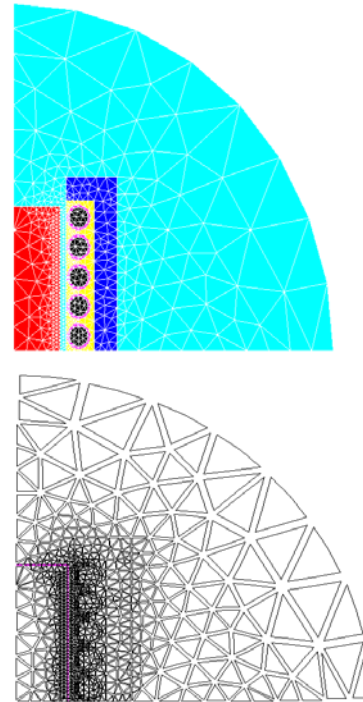

Fig. 2 Geometry and the mesh network

In figure 3 and 4 are presented electromagnetic field lines at the begin, and at the end of induction heating process.
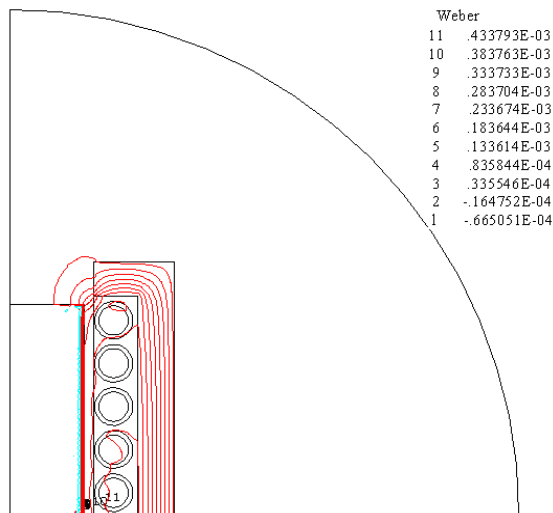
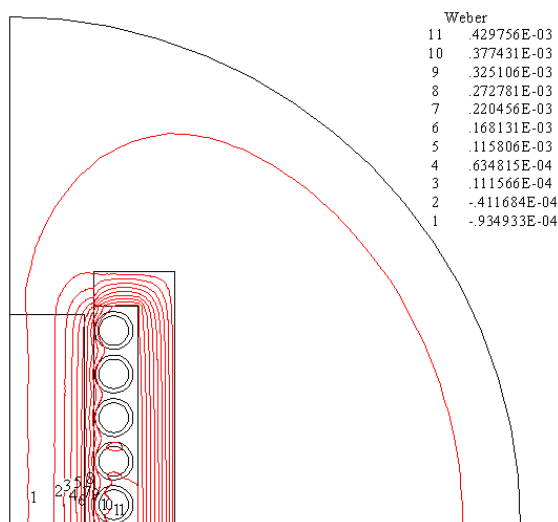Fig. 3 Electromagnetic field lines at the begin of induction heating process

Fig. 4 Electromagnetic field lines at the end of induction heating process

In figure 5 and 6 are presented, temperature evolutions of the heating process, in the middle of piece, respectively on the surface of piece, until the piece reach the maximum imposed surface temperature (T=1300ºC).
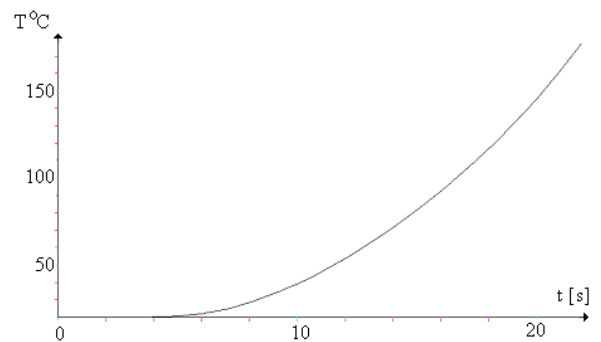

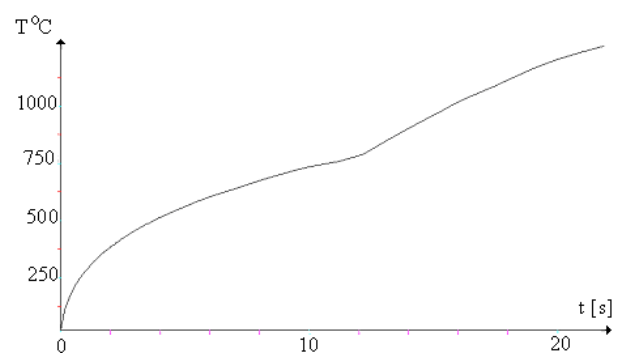Fig. 5 Temperature evolutions of the heating process in the middle of piece

Fig. 6 Temperature evolutions on the surface of piece

Temperature calculation in different points of the piece, temperature at the end of heating in three points.

Table 1

x =35 mm, y = 0 mm	x = 29 mm, y = 0 mm	x = 26,5 mm, y = 0 mm
Temp= 1262,91ºC	Temp = 1250,52ºC	Temp = 1190,11 ºC

The transient heating of the work piece, can be observed on the map temperature at the end of heating process, represented in figure 8.
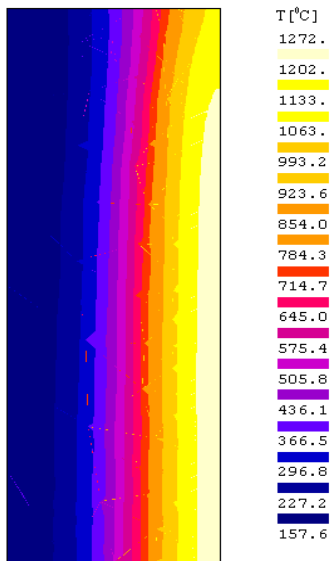
109

Fig.8 Temperature map in the piece at end of heating process

III. CONCLUSIONS

Numerical methods development, for example the development of FEM (Finite Element Method) and of numerical simulation programs, can make possible the simulation of inductor behaviour, before building the prototype and avoiding the designig errors.

This is an remarkable avantage for the designers, because the designer work is realised now using CAD programs, reducing the cost for new developments. The simulation program can give a lot of informations that are experimentaly inaccesible.

The disavantage of circular turns are losses because the circular shape of turn, the time for heating with the sqare turn is lower, and the piece is heated faster.

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