

Numerical analysis method for solving the coupled electromagnetic and thermal field questions for induction heating systems with moving parts

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The paper proposes an analysis method for solving the coupled question of electromagnetic with thermal field and motion into ferromagnetic materials during the induction heating process. The proposed method has a large applicability and can be used during numerical analysis using commercial software and allow to solve the triple coupled question electromagnetic field – thermal field and motion during induction heating. The paper has an applicative research character and the obtained results have practical utility, with the main purpose of optimising the functioning of some devices for induction heating process with moving parts.

(Received March 13, 2008; accepted May 5, 2008)

Keywords: Induction heating, Finite element method, Ferromagnetic materials, Computation procedures for moving parts

1. Introduction

Modern technologies based on induction heating through eddy currents had a fast development in the last decade mostly through its important advantage offered in stand of the classic methods. As full of main objective for the optimal design of electrotechnic equipment dedicated to this installation, a main problem is constituted by the development of new computational methods for coupled electromagnetic and thermal field in conducting media heated by eddy currents.

Numerical analysis of the coupled electromagnetic and thermal fields in the eddy currents problem is an important theme with important results in various fields. To solve this problem there are in the literature [1, 2, 3] several formulae based on approximation methods both using finite differences and finite element. In [4, 5] there are some numerical applications for the coupled thermal and electromagnetic fields and also the optimisation of this process.

The specialists from electrical engineering domain already obtained very important results regarding the solution of eddy currents, thermal diffusion and coupled EM-T questions for steady state, and poor results for the motion state and most of them are referred to 2D structures where the velocity is known. Also the CAD software market already offers professional software which allows solving with good results the steady state questions. As result, the main purpose of the paper is to elaborate methods and develops computational procedure for EM-T questions for moving parts.

2. Numerical modeling of the induction hardening process

The paper presents the possibilities of computer simulation for the induction hardening process of cylindrical parts involving the relative movement between

the inductor and the heated part, using a CAD package for finite element analysis of the magnetic and thermal fields.

Simulations aim to study the possibilities of numerical modelling for induction heated moving parts and to determine optimal solutions for heating equipment.

Due to the axial symmetry of the geometry and to the cylindrical coordinates, the initial 3D problem reduces to a 2D one.

Using the complex representation, the non-linear magneto dynamic model expressed versus vector magnetic potential becomes:

$$j\omega \mu_0 \sigma \mathbf{A} + \text{rot} \left(\frac{1}{\mu_r} \text{rot}(\mathbf{A}) \right) = \mu_0 \mathbf{J} \quad (1)$$

The uniqueness of the solution is assured by knowing the sources of the electromagnetic field, of the material properties, of the initial conditions and of boundary conditions.

To define the material properties, the program allows the creation of a material database offering a wide range of models and properties.

The analytical model $\mathbf{B}(\mathbf{H})$ is characterised by equation:

$$\mathbf{B}(\mathbf{H}) = \mu_0 \cdot \mathbf{H} + 2 \cdot \frac{\mathbf{B}_{sat}}{\pi} \cdot \arctg \left(\frac{\pi(\mu_{ri} - 1) \cdot \mu_0 \cdot \mathbf{H}}{2 \cdot \mathbf{B}_{sat}} \right) \quad (2)$$

The transitory thermal field is modelled by:

$$\gamma c \frac{\partial T}{\partial t} + \text{div}(-\lambda \cdot \text{grad } T) = p \quad (3)$$

The conditions on the computing boundary for the thermal problem extracted from the electromagnetic problem domain are homogenous Neumann conditions

$dT/dn = 0$ and non-homogenous Neumann conditions for the convection and radiation thermal transfer boundaries:

$$\lambda \frac{\partial T}{\partial n} = -P_t - \alpha_c (T - T_a) - \varepsilon_{rad} (T^4 - T_a^4) \quad (4)$$

The modelling of the coupled electromagnetic and thermal fields implies the following steps:

- description of the problem: geometry definition, computing domain splitting and physical properties association;
- developing of the numerical method of simulation;
- checking, viewing and interpreting the simulation results.

3. Induction heating of moving parts

Industrial applications for induction heating with moving parts start to be used more often because of its advantages. Most of the induction heating equipments with moving parts has as characteristic that one element is moving related to the fixed part. If the inductor is fixed, the heated parts is in motion related to inductor, or other applications will consider the heated part as fixed and the inductor will be in motion related to the part. Related to the constructed variant of the inductor and number of the free motion grades for the movement the induced electromagnetic field and thermal field in the half finished product will get a more homogenous distribution. As result will have a uniform heating of the considerate half finished product and to the end of hardening process a high quality product.

The technological process for induction heating into industrial equipments with moving parts requires a covering for the next stages:

- the half finished product is fitted inside the inductor for the start position of the process
- at the beginning of the process the equipment is started with the half finished product in steady position until the desired temperatures indicated by the technician is reached. Once the desired temperature is reached, the displacement of the half finished product inside the inductor starts with variable speed between 2 – 10 [mm/s], speed imposed in order to obtain the desired temperature inside the half finished product will be constant during the whole process without major difference for the temperature rage.
- the half finished product is power washed at the end of the process.

As example we can consider the induction heating equipment with moving parts presented in Fig. 1. The inductor is fixed and the motion of the half finished product is accomplished by the mobile product clamping device.

During the analysis process the equipment parameters will be considered in order to validate the numerical result through experimental values. The equipment is characterised by:

- working frequency 8000 [Hz]
- maximum power 45 [kW], and can be set up in steps
- the displacement can be accomplish after Oz direction

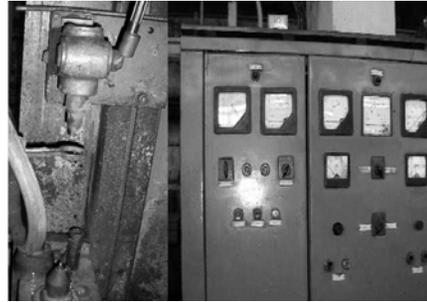


Fig. 1. Inductive heating system with moving parts.

4. Numerical analysis procedure

Numerical analysis question of coupled electromagnetic and thermal field and motion is a complex question because in the most cases of analysis the discretization network is changed once the motion is accomplished. In this case the numerical modelling is difficult to be realised because of all complications that may occur once with the network changes and the material non-linear **B-H** relationship.

The numerical analysis procedure proposed in the paper in order to solve the complex coupled electromagnetic, thermal and motion questions, assume that the mesh is realized so it won't suffer further changes during the analysis process (Figure2). The considerate reference system is the one of the part that will be heated. Because of the low speeds of displacement, the component induced by the motion for the induced voltage in the part is neglected. In the reference domain of the part a fixed imaginary inductor with its shape that will include the entire real inductor trajectory during the motion reported to the reference system will be defined. That mean the shape of the imaginary inductor results from the reunion of all positions occupied by the real inductor. Every single time will be active that part of the imaginary inductor that corresponds to the position of the real inductor. Numerical method of the hardening process presume to establish different time steps for the motion of the part, if we admitted that the part velocity results from the succession of the position that will be occupied by the active region of the imaginary inductor. The thermal diffusion from each position implies also a new time step to be defined. This means that the method uses two different time steps: the "external" step is used to define the successive positions occupied by the active regions from the imaginary inductor and the "internal" step used to solve the thermal diffusion question. All the values resulted from the external step of analysis will constitute initial value for solving the coupled electromagnetic and thermal question on the current "external" step of analysis.

The proposed procedure presents some major advantages: the mesh is generated once for the part and imaginary inductor. The imaginary inductor is divided in cobbles, occupied by the active region during the analysis process, and the mesh will be adapted to all the cobbles without changes. That mean this procedure can be applied with good results to the professional software in order to compute the coupled electromagnetic and thermal question into inductive equipment with moving parts. In order to improve and increase the EM-T results accuracy it is recommended to decrease the "external" step of the analysis. The disadvantage of increasing the number for

the reserved regions of the imaginary inductor will appear. The proposed procedure can be applied to any type of motion and is not restricted by the Oz direction.

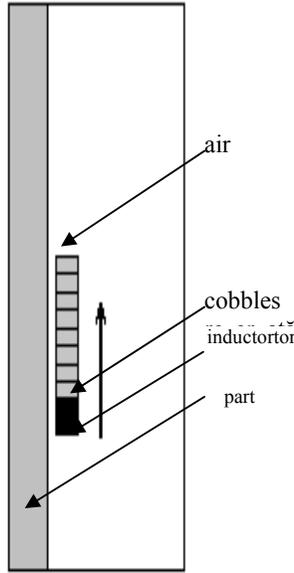


Fig. 2. Reference system for the analysis method.

5. Numerical examples

In the following we present a configuration used in induction hardening process of cylindrical half finished products in motion placed into inductive equipment. We intend to simulate all hardening process by using the proposed method. The inductor as can be seen in figure 2 will surround the cylindrical part in order to ensure the heating.

The amplitude of the current density flowing through inductor is $J_0 = 20 \text{ [A/mm}^2\text{]}$, and inductors cross section is $S = 95 \text{ [mm}^2\text{]}$. The cylindrical half finished product is placed into the inductor supplied from an 8 kHz frequency generator for about 22.5 [s], enough time for the product to reach a temperature over 800 Celsius degrees. Once the desired temperature is reached, the displacement of the half finished product related to induct starts with variable velocity. The supposed half finished product has the following features: 35 [mm] wide and 300 [mm] length.

Numerical simulation allows determining accurately the relationship between the frequencies used, the power density and the desired treatment depth. The penetration depth of induced currents can estimate the optimal frequency.

The physical properties of the half finished product are the following: resistivity of $0.25 \times 10^{-6} \text{ [\Omega m]}$ and analytical model $B(H)$ characterised by $B_{sat} = 1.9 \text{ [T]}$ and initial magnetic permeability $\mu_{ri} = 100$. The Curie temperature is $780 \text{ }^\circ\text{C}$ and the material non-linear **B-H** relationship is described by equation (2).

The inductor is dimensioned in order to assure a distribution of the currents in the piece which implies the optimal heat treatment. The movement of the ferromagnetic body is taken into account and the analysis steps are presented in table 1. For each step of the analysis

the displacement step in space is considerate constant - 10 [mm] during the analysis procedure.

Table 1.

| Step | t [s] | Δt [s] | $\Delta s/\Delta t$ [mm/s] |
|------|-------|----------------|----------------------------|
| 1 | 22.58 | 0 | 0 |
| 2 | 25.45 | 2.87 | 3.48 |
| 3 | 29.87 | 4.42 | 2.26 |
| 4 | 34.29 | 4.42 | 2.26 |
| 5 | 39.41 | 5.04 | 1.98 |

In the following figures the induced current distributions and power losses distributions are presented.

Figs. 3, 4, 5, 6 and 7 presents simulation results obtained in order to point out the distribution of the magnetic field for different time steps of analysis and different positions of the inductor.

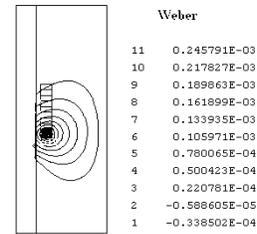


Fig. 3. Magnetic flux distribution in the first step of the analysis.

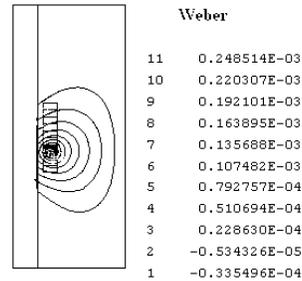


Fig. 4. Magnetic flux distribution in the second step of the analysis.

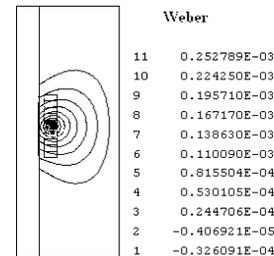


Fig. 5. Magnetic flux distribution in the third step of the analysis

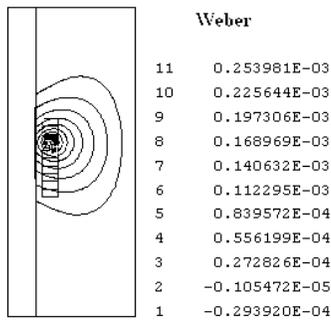


Fig. 6. Magnetic flux distribution in the fourth step of the analysis.

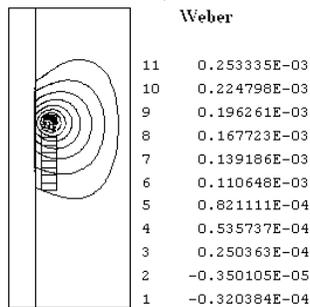


Fig. 7. Magnetic flux distribution in the fifth step of the analysis.

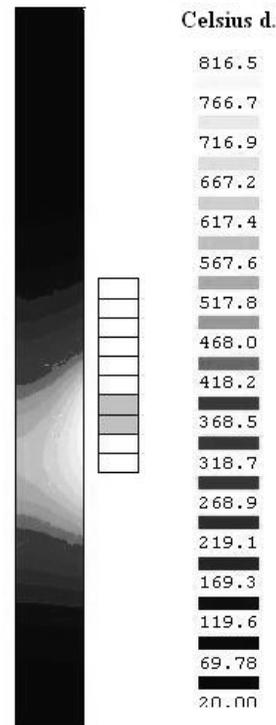


Fig. 9. Temperature distribution inside the half finished product in the second step of the analysis.

The temperature across the half finished product is plotted for the first step of the analysis in figure 8. During the displacement the temperature increases with time, and average temperatures is given in Figs. 9, 10, 11 and 12 for each considerate step of the analysis.

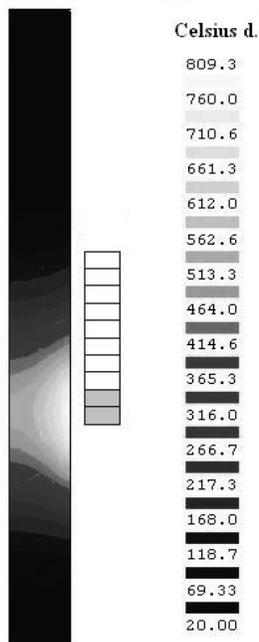


Fig. 8. Temperature distribution inside the part in the first step of the analysis

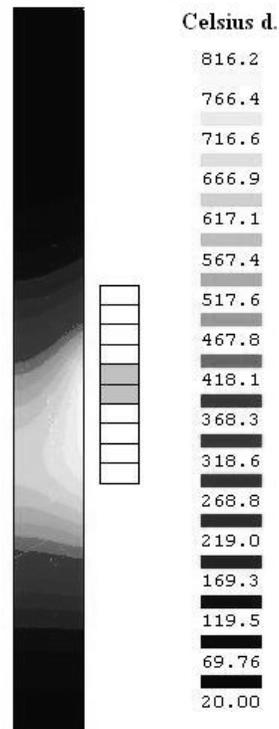


Fig. 10. Temperature distribution inside the half finished product in the third step of the analysis

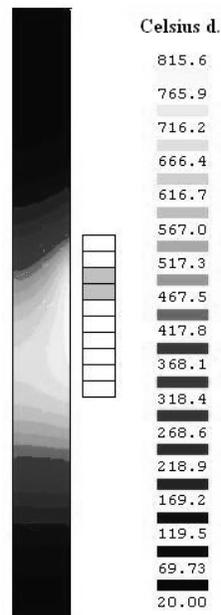


Fig. 11. Temperature distribution inside the half finished product in the fourth step of the analysis.

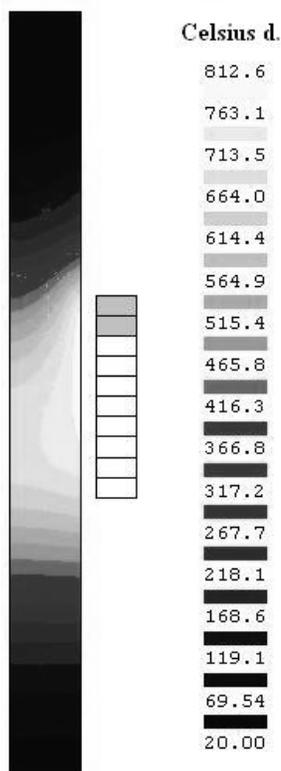


Fig. 11. Temperature distribution inside the half finished product in the fifth step of the analysis.

6. Conclusion

The optimal designing and 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 makes impossible to determine the optimal parameters of these equipments by usual analytical methods.

The proposed method allows us to define the “external” steps as constant, and also if is taken into account that the thermal diffusion has an similar evolution, except the initial time when the part is kept steady to get heated to the desired temperature before the hole process is started. Optimum evolution, the best geometry for the inductor and energetic parameter of the equipment can be obtained as result of the simulation. The proposed method allows us to define any type of steps for both “external” and “internal”.

The obtained results represent for the hardening technician important information regarding the evolution in time of the part velocity and the current through the inductor in order to realise an optimum hardening treatment of the interested surface.

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