ABOUT NUMERICAL ANALYSIS OF ELECTROMAGNETIC AND THERMAL FIELD IN INDUCTION EQUIPMENT WITH MOVING BODIES

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This paper presents a numerical computation method and also an analysis procedure that can be used in order to solve the quasi-stationary electromagnetic and thermal field for induction heating devices with moving parts. The analysis takes into account the relative movement between inductor and the heated part. The proposed method allows to use the same FEM discretization network for all steps of the analysis. Numerical simulation allows determining accurately the thermal regime of the induction heating process and the optimal parameters which offer maximum efficiency. Therefore the experiments’ number in designing process can be decreased and a better knowledge of the process can be obtained. The obtained results offer important information during the ferromagnetic hardening process, and also for the processes optimization and equipment design.¹

1. INTRODUCTION

In the last century, ones with the technological revolution from industry, the old industrial equipment from metallurgical power plants was replaced with the new units which use the electromagnetic field in order to process different ferrous or non-ferrous bodies. These industrial processes are now based on the efficient use of coupling between electromagnetic, thermal and mechanical phenomena because of its important advantages reported to the classical methods. A main purpose in order to compute the coupled electromagnetic and thermal field and motion is

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constituted by the elaboration of the numerical methods and procedures. The main purpose is optimal design of the electrotechnic equipment for all these devices that use eddy currents to accomplish the desired temperature for moving parts.

The determination of the eddy currents by using electromagnetic induction phenomena is an efficient method to generate heat sources in volume for the conducting media. An issue of great interest is the computational problem of the power losses through eddy currents. These losses through the caloric effect are used to accomplish the induction heating of conducting domain in the desired area. The determination of power losses through eddy currents requires to solve the complex cvasistationary state problem coupled the thermal diffusion problem. In most of the cases which imply hardening, the considerate part is ferromagnetic, where the B-H relationship is strong non-linear. The coupling between the eddy currents problem and the thermal diffusion problem has a main interest because the ferromagnetic part is heated over the Curie point, where the B-H relationship becomes the one of the vacuum, therefore the magnetization characteristic is strongly dependent to temperature. Some difficulties might occur in the numerical computation of the coupled electromagnetic and thermal problem (EM-T): the nonlinearity B-H relationship when the temperature decrease under the Curie point in the solid phase, strong nonlinearity of the thermal equation in the phase changing area, powerful dependence with temperature of the electromagnetic parameters. The thermal diffusion problem is also nonlinear and the material’s thermal constants depend on temperature.

Specialists from the electrical engineering domain have already obtained important results regarding the numerical analysis of eddy currents problems [1],[2], [3] thermal diffusion problems and also for the coupled EM-T for steady mediums and mediums in motion [5]. The software market already offers professional software for the numerical computation of these problems. In this matter, in contrast with other papers [4], the main purpose of this paper is to develop methods and procedures for the numeric solutions of EM-T problem for mediums in motion.

2. FIELD PROBLEM FORMULATION

The sinusoidal state is studied. This is valid even for the non-linear media if the cvasilinar approximation is considerate, where the permeability is corrected for each iteration in accordance with the magnetic induction. It is the most efficient procedure for analysis the coupled electromagnetic and thermal problem. In order to solve the electromagnetic field problem associated to each considerate case to be studied is necessary to impose the computational domains where the field problems need to be solved. The electromagnetic field is described by the Maxwell’s law, and its fundamental equations accrue [2].
rot \ \nu \ \text{rot} \ \mathbf{A} + \sigma(j \omega \mathbf{A} + \text{grad} \ T) = 0 \ \text{in} \ \Omega_c, \ \ (1)

\text{rot} \ \nu \ \text{rot} \ \mathbf{A} = \mathbf{J}_0 \ \text{in} \ \Omega_0, \ \ (2)

where \ \Omega_c \ \text{represent the conducting domain surrounded by an unbounded non-conducting domain} \ \Omega_0 \ \text{where the current sources are situated, and} \ \nu = 1/\mu, \ \text{and} \ \mu \ \text{represents the magnetic permeability.}

From equation (1) accrue:

\text{div} \ \sigma(j \omega \mathbf{A} + \text{grad} \ T) = 0. \ \ (3)

Many commercial software for the numerical solution of the electromagnetic field problem use the reduced magnetic scalar potential for the insulated domains (with air).

3. FINITE ELEMENT METHOD

The numerical solution of the problem is done by using the Galerkin technique.

\[ \mathbf{A} = \mathbf{N}_0(t) + \sum_{k=1}^{n_\mathbf{N}} \alpha_k(t) \mathbf{N}_k + \sum_{k=1}^{n_\phi} \gamma_k(t) \text{grad} \ \phi_k, \] \ (4)

\[ V = \sum_{k=1}^{n_v} \beta_k(t) V_k. \] \ (5)

4. THERMAL FIELD FORMULATION

The solutions for the thermal field require solving the thermal diffusion equation:

\[- \text{div} \ \lambda \ \text{grad} \ T + c \frac{\partial T}{\partial t} = p, \] \ (6)

where \ \lambda \ \text{represents the thermal conductibility and} \ p \ \text{is the volume density of the power that’s transformed from the electromagnetic form to heat and} \ c \ \text{is the volume thermal capacity. The boundary condition associated to equation (6) is:} \]
\[-\lambda \frac{\partial T}{\partial n} = \alpha (T - T_e), \quad (7)\]

where \(\alpha\) represents the thermal convection coefficient and \(T_e\) represents the temperature outside of the \(\Omega_c\) domain and the initial condition for the temperature is considerate: \(T(0) = T_\infty\).

For the time discretization of equation (6) will use a Crank-Nicholson technique, and for the space discretization the finite element method.

**5. THE COUPLING BETWEEN THE EDDY CURRENTS PROBLEM WITH THE THERMAL DIFFUZION AND MOTION**

The numerical analysis problem of coupled electromagnetic and thermal field and motion is a complex problem 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 done because of all complications that may appear 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 problems, assume that the mesh is realized so it won’t suffer further changes during the analysis process (Fig 1). The numerical analysis solution for the eddy currents problem suppose to take into account the material parameters (resistivity and the \(B-H\) relationship) which are straight dependents by the temperature, in contrast with the numerical solution of the thermal field, where the material parameters depends only by the results obtained after the computation of the eddy currents problem. That suppose for each time step adopted for the thermal problem, will impose the returning to the eddy currents problem and to the diffusion problem, correcting the material parameters. When the correction in not significant the next time step is studied. If instability in time is detected, then the time step will be decreased automatic. The coupling between the electromagnetic and thermal field and motion represents a complex problem. In this matter has been developed the mathematic model and the numerical analysis procedure which further allows us to modify the material parameters, the boundary conditions or source parameters without modifying the discretization network.

The considerate reference system is the one of the part that will be heated (Fig 1). Because of the low speeds of motion the component induced by the motion for the induced voltage in the part is neglected. An fixed imaginary inductor with its shape that will include all the real inductor trajectory during the motion reported to the reference system will be defined in the reference domain of the part. That
means the shape of the imaginary inductor arise from the reunion of all positions occupied by the real inductor. For each position the coupled electromagnetic and thermal diffusion problem is solved. The solution for the electromagnetic field is done by considering the sinusoidal regime, therefore are used the complex imaginary solutions for the field components. The non-linear $B-H$ relationship is treated iterative, through the pseudo-linear model, correcting the magnetic permeability in accordance with the effective value for the magnetic induction. The thermal diffusion from each position implies also a new time step to be defined. That means 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 problem. All the values resulted from the external step of analysis will constitute initial value for solving the coupled electromagnetic and thermal problem on the current “external” step of analysis.

6. NUMERICAL APPLICATION

Let us consider a half finished cylindrical ferromagnetic part placed into an induction heating installation with moving parts. Because the problem presents axial symmetry, the numerical analysis is performed only for half of the computational domain (Fig 1). The half finished product has the dimensions presented in Fig 2 in [mm] and the material is stainless steel AISI-SAE-4135, with the following properties:

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**Fig. 1 – Computational domains.**

air
reserved area for the inductor
inductor
half finished product
The resistivity $\rho[\Omega m]$ variation with the temperature $\rho(\theta)$ is described by the function:

$$\rho[\Omega m] = 8.69779674 \cdot 10^{-13} \cdot \theta^2 + 4.78235404 \cdot 10^{-10} \cdot \theta + 1.56565488 \cdot 10^{-7},$$
for $\theta \in [20 - 800]$ °C

and

$$\rho[\Omega m] = 2.01190476 \cdot 10^{-13} \cdot \theta^2 + 7.12976190 \cdot 10^{-10} \cdot \theta + 6.54785714 \cdot 10^{-7},$$
for $\theta \in [800 - 1400]$ °C.

The $B-H$ relationship variation with temperature is described by the following equation:

$$B(H, \theta) = \mu_0 H + (2/\pi) J_{\eta^0} \cdot \arctg[\pi(\mu_0 - 1) \mu_0 H / (2J_{\eta^0})] \cdot [1 - \exp[\theta - \theta_c] / C].$$

During the electromagnetic field computation, the periodicity condition and the current flow direction constraints the following use for the boundary conditions: the null Dirichlet boundary condition will be used for the vector potential and the axial symmetry boundary condition, as can be seen in Fig. 3. The computational domain for the thermal field is the one of the cylindrical part. On the central side of the cylinder will use the null Neumann boundary condition and for the rest of the boundary will use the mixt boundary condition as can be seen in Fig. 4.
At the beginning we considered the initial time from the start of equipment until the desired temperature indicated by the technician is reached near the inductor. The temperature needs to be kept constant during the whole technological process which involves motion. We proceeded the first phase of the numerical analysis of the coupled electromagnetic and thermal field until the desired temperature, around 800°C, is reached. After this the numerical computation software is stopped and the data are saved. The next phase of the analysis assumes the modification of the inductor position with an exterior step of 10 [mm]. Numerical data accrued at the end of each numerical computation phase will be considerate as initial data for the next step of the analysis and the exterior step for inductors motion is considerate constant and is 10 [mm] for each phase. During the numerical analysis process important results related to the energetic parameters are obtained. In Fig. 5 we present the temperature distributions in side the material during the analysis process in the half finished product considering five steps of analyse for motion according to the Table 1.

Table 1

<table>
<thead>
<tr>
<th>Stages</th>
<th>( t ) [s]</th>
<th>( \Delta t ) [s]</th>
<th>( \Delta s/\Delta t ) [mm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.58</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>25.45</td>
<td>2.87</td>
<td>3.48</td>
</tr>
<tr>
<td>3</td>
<td>29.87</td>
<td>4.42</td>
<td>2.26</td>
</tr>
<tr>
<td>4</td>
<td>34.29</td>
<td>4.42</td>
<td>2.26</td>
</tr>
<tr>
<td>5</td>
<td>39.33</td>
<td>5.04</td>
<td>1.98</td>
</tr>
</tbody>
</table>
7. CONCLUSIONS

The procedure have been developed in order to solve the complex problems that appears during the practical applications from industry related to the induction hardening for half finished products in motion. It allows the farther changes of the material properties, boundary conditions and sources without any changes for the discretization network. The proposed solution can be applied to any motion and it is not restricted to Oz direction.

The developed computation method allows the extension of this coupling to the triple coupled problem: magnetic – thermal – motion. The analysis algorithm of the triple coupled problem can be used in some domains for eddy currents, with large applicability within numerical computation by using professional software. In this matter, the algorithm has been implemented by using the FLUX-2D package which allows us to introduce the nonlinear relationship $B-H$, the dependences of the other thermal parameters: thermal field, magnetic induction and rezitivity.

The method developed in this paper represents a very useful instrument for the hardening in charge technician. By choosing different dimensions for the equipment’s inductor and the mobile device, we can try different solutions in order
to determine the speed of motion for the half finished product and for the time evolution of the current into inductor. In consequence he can determine the optimal evolutions and also the best dimensions for the inductor and the mobile device.

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REFERENCES


