About numerical analysis of electromagnetic field induce in gear wheels during hardening process

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Abstract ***The paper presents the results of a numerical simulation using finite element analysis for a coupled magneto-thermal problem, specific for induction hardening processes. The analysis takes into account the relative movement between inductor and the heated part. Numerical simulation allows to determine 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.***

Keywords: ***finite element method, electromagnetic induction, hardening.***

I. INTRODUCTION

Numerical analysis of the coupled electromagnetic and thermal fields in the eddy currents problem became an actual theme with important results in various fields [1, 3, 4, 8]. To solve this problem there are in the literature [2, 5, 7] several formulae based on approximation methods both using finite differences and finite element. In [3, 6, 8] there are some numerical applications for the coupled thermal and electromagnetic fields. There, the space distribution and time variation of the fields and other specific quantities are computed.

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 make impossibile to determine the optimal parameters of these equipments by usual analytical methods.

The result obtained by this methods often doesn't satisfies the requirements of an industrial use regarding energetical criteria or imposed thermal constraints. The final variant is usually obtained after a lot of experiments that suppose supplementary expenses and delay of project assimilation.

A possible solution for these problems is the numerical modelling that allows to analyse the phenomena which characterize the process in its evolution. In this purpose, a numerical simulation had been used, which allows to analyse the induction hardening process.

This paper presents certain results obtained by finite element analysis of a non-linear model of electromagnetic field expressed in vector potential coupled with a transient thermal field. The analysis was made by simulating of the heating phenomenon, with a specific FEM package for this coupled problem.

II. 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 modeling for induction heated moving parts and to determine optimal solutions for a 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 magnetodynamic model expressed versus vector magnetic potential becomes:

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

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 transitory thermal field is modeled by:

$$\gamma\, c \frac{\partial T}{\partial t} + div\left(-\lambda \cdot grad\ T\right) = p$$

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:

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

The modeling 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.

III. THERMAL DIFFUSION PROBLEM

The diffusion of thermal field is describe by equation:

$$-\operatorname{div} \lambda \operatorname{grad} T + c\frac{\partial T}{\partial t} = p$$

where c is volume thermal capacity, λ is thermal conductibility and p volume power density who transform himself from electromagnetic form in heat. To equation we add the boundary condition:

$$-\lambda\ \frac{\partial T}{\partial n} = \alpha\left(T - T_e\right)$$

And, initial condition for temperature: $T(0) = T_{in}$.

Time discretisation of equation (10) its doing through Crank-Nicholson technique, and space discretisation through finite element method.

IV. THE COUPLED OF THERMAL DIFFUSION PROBLEMS WITH EDDY CURRENTS

Material parameters from eddy currents problem (B-H characteristic and resistivity) depend from temperature, in time material parameters from thermal problem depend from the result of eddy currents problem (power density) and temperature (thermal capacity and thermal conductibility). From that reason, each adopt time steps for thermal problem, it return to eddy currents problem and diffusion problem, material parameter proofs. If the correction is not significant, we go to the next time step. If its signalize instability in time, then the time step must reduce.

V. NUMERICAL SIMULATION AND RESULTS

Numerical simulation allows to determine accurately the relationship between the frequencies used, the power density and the desired treatment depth.
The optimal frequency can be estimated by the penetration depth of induced currents.
The process consists in performing a single hardening at 8 kHz using an inductor as shown in figure 1.
The inductor is dimensioned in order to assure a distribution of the currents in the piece which implies the optimal heat treatment.
Distribution of isovalues echiflux is shown in figure 2 for circular conductor. Figure 3 presents the variation of magnetic field and flux density in different phase.

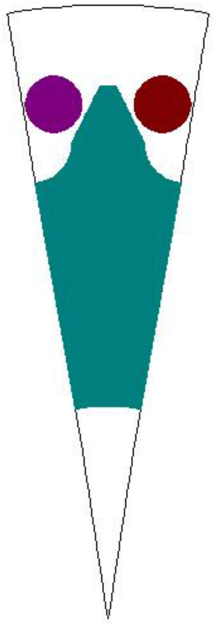


Figure1. Computational domain

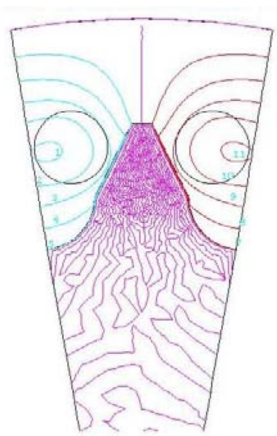
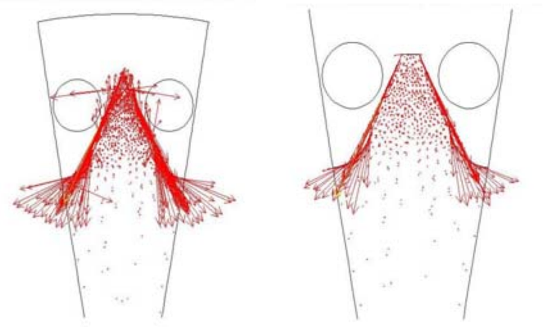
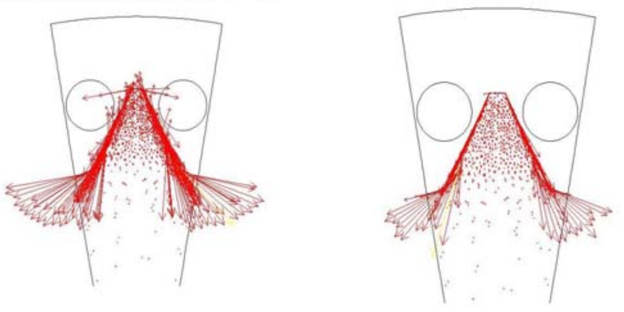


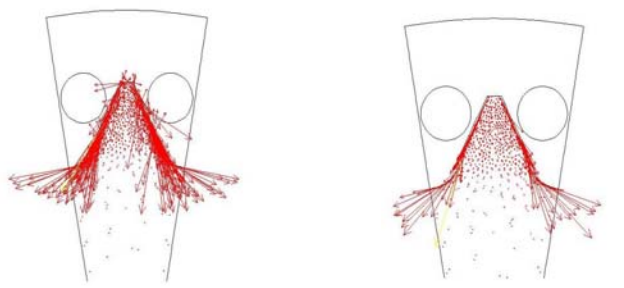
Figure 2. Distribution of echiflux isovalues



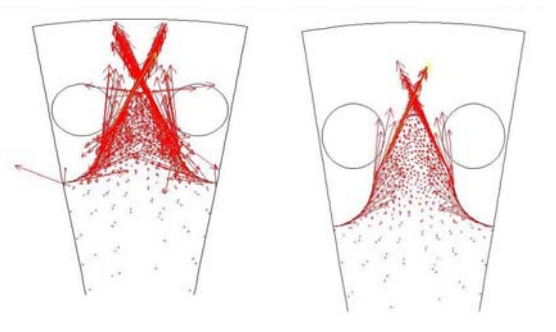
Phase 0



Phase 45



Phase 90



Phase 180
Figure 3. Magnetic field and flux density

The magnetic induction of steel is dependent by magnetic and temperature field and is shown in figures 4.
The thermal field variation in point A and B are shown in figures 5, 6, 7. The B-H curve are shown in figures 8.

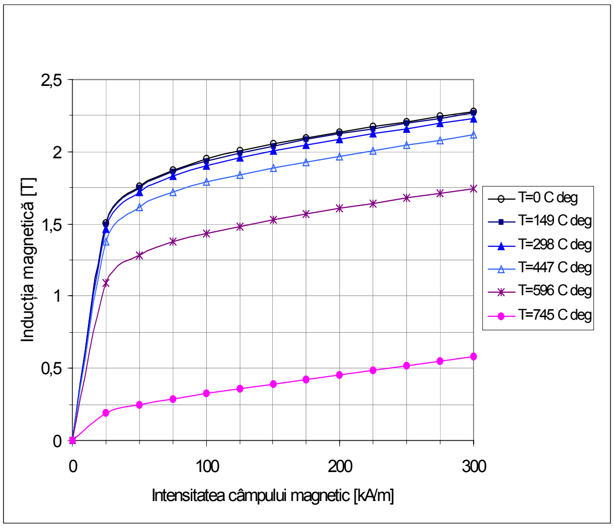


Figure 4. The magnetic induction of steel dependence by magnetic field and temperature

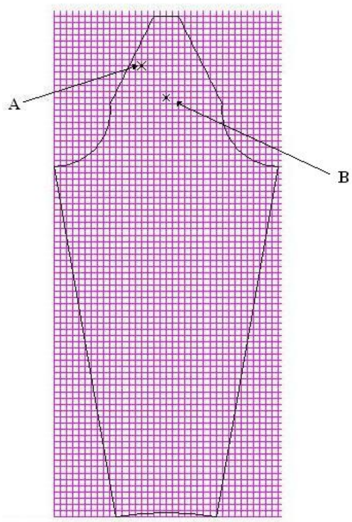


Figure 5. Measure the temperature field in points A and B

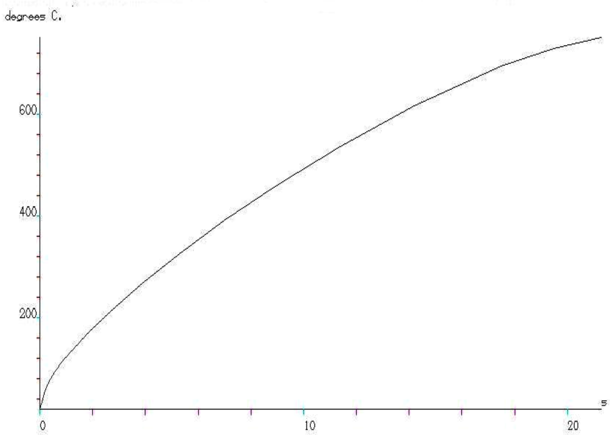


Figure 6. Temperature variation in point A

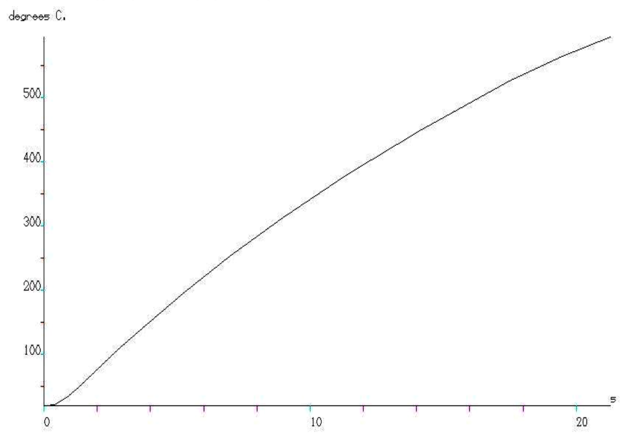


Figure 7. Temperature variation in point B

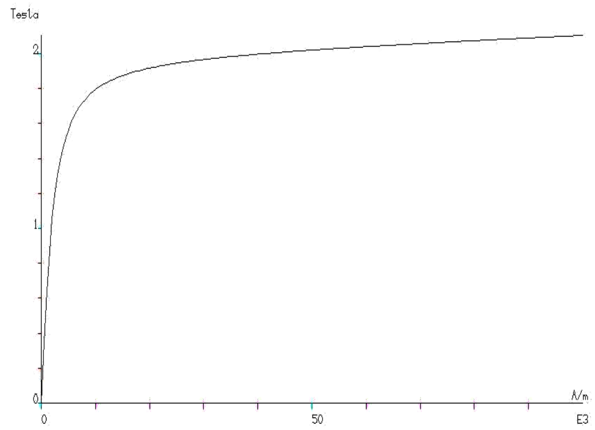


Figure 8. B-H curve

IV. CONCLUSIONS

The numeric simulation of superficial hardening process is a complex problem, where are resolve simultaneous two field non-linear problems one of eddy currents and thermal diffusion. The non-linear problems of eddy currents is provide from non-linear relation of **B-H**, in time the non-linear of thermal problem provide from dependence with temperature of thermal parameters (thermal conductibility, thermal capacity, thermal transfer coefficient on surface).

The coupled of two problems result from strong dependence of relation **B-H** with temperature, in electromagnetic field problem and thermal field source, given by Joule lost, in thermal diffusion problem. The non-linear of **B-H** relation is solve by admit the pseudo-linear model, where $\mathbf{B} = \mu(B)\mathbf{H}$ is, magnetic permeability is iterating accurate in magnetic induction function.

The model great advantage is result from the possibility to adopt the sinusoidal regime and complex image, the numeric form of field equation leading to one algebraic equation system with complex coefficient.

The two coupled field problems is solve with time discretisation procedure, where at each time step, it is make the iterative correction of electromagnetic and thermal parameters.

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