NUMERICAL MODELING OF THE ELECTROMAGNETIC FIELD WITHIN THE INDUCTION HARDENING OF INNER CYLINDRICAL SURFACES

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***Abstract* – The paper presents the numerical modeling of electromagnetic field within the induction hardening of inner cylindrical surface. The numerical computation has been done by means of finite element method in order to solve the coupled electromagnetic and thermal field question. The obtained results provide information regarding the heating process taking into account the relative movement between the inductor and workpiece, the over heating of thin layers, the geometrical configuration of the inductor as well the technological requirements correlated with electrical parameters and represents an active tool to setup the induction heating equipment in order to get best results during hardening process .**

***Keywords:* eddy current, finite element method, hardening**

I. INTRODUCTION

Heat treatment is one of the most important stages of metal processing because it determines the final properties that enable components to perform under such demanding service conditions as high load, high temperature, and adverse environment. Induction heat treatment is applicable to hardening, tempering, normalizing, and annealing a wide range of parts, particularly in ferrous alloys, medium- and high-carbon steels, alloy and stainless steels, and tool steels. It is also finding increasing application in the nonferrous metals industry.

Numerical analysis of the coupled electromagnetic and thermal fields in the eddy currents problem is an important theme with important results in various fields. The induced eddy currents question require to solve complicated cvasitationary questions coupled with thermic difusion. The surface hardening is usualy used for the ferromagnetic bodies, where the contitutive *B-H* relationship is strongly nonlinear. The coupling betwen eddy current question and thernic difussion is very impotant because the part has to be heated over the Curie point, where *B-H* relationship becomes the vacum one, therefore the magnetization characteristic depend by temperature. The maximum differential relative permeability can get values betwen 1 to 5000 for differnt values of the temperature. Also the thermic difussion question is nonlinear also, the material constants depends on temperature as well.

Different calculation methods [1], [2] computer programs and experimental equipment used for mathematical and physical analyses of the complex process in induction heating, are discussed in the technical literature. Contribution on optimal design, of induction heating equipment, electric equipment choice in technological installations and computation of the energetic parameters are discussed in [3]-[5].

We intent to establish a complex system to simulate the whole process of induction hardening of inner cylindrical surfaces by using industrial equipment with moving parts in order to use it as an active aid for the equipment settings during processes and design optimization.

II. FIELD PROBLEM FORMULATION

We study the sinusoidal state, and. this is valid even for the non-linear media if the quasiliniar 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 question. In order to solve the electromagnetic field question 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]:

$$rot\,\nu rot\,\underline{A} + \sigma(j\omega\underline{A} + grad\,\underline{V}) = 0 \quad in\ \Omega_C \qquad (1)$$

$$rot\,\nu rot\,\underline{A} = \underline{J_0} \quad in\ \Omega_0 \qquad (2)$$

From equation (1) accrue:

$$div\,\sigma(j\omega\underline{A} + grad\,\underline{V}) = 0 \qquad (3)$$

The scalar electric potential $\underline{V}$ has to be defined only for the conducting domains Ω_C, and on the edge of the conducting domain Ω_C the normal component to the surface of the current density needs to be zero:

$$\sigma(j\omega\underline{A} + grad\,\underline{V})n = 0 \quad on\ \partial\Omega_C \qquad (4)$$

In order to insure the uniqueness for the (A,V) formulae we have to impose an additional condition for the magnetic vector potential $\underline{\boldsymbol{A}}$ and this can be described by the Coulomb gauge:

$$div\,\underline{A} = 0 \tag{5}$$

The following boundary conditions are given:

$$n \times \nu\, rot\,\underline{A} = g \qquad \text{on } S' \tag{6}$$

$$A_n = 0 \qquad \text{on } S' \tag{7}$$

$$A_t = f \qquad \text{on } S'' \tag{8}$$

If S" is formed for n disjunctive surfaces S_k, then on n-1 surfaces the null fluxes for $\underline{A}$ are given through Coulomb gauge (5), which for the discontinuous surfaces preserve the normal component. Arise $\underline{A}$ unique determinate because $\underline{B}$ is unique determinate and the boundary conditions for $\partial\Omega_C$ accrue:

$$-\frac{\partial V}{\partial n} = j\omega \underline{A} \tag{9}$$

The value for $div\sigma grad\underline{V}$ can be obtained and for one point from Ω_C the $\underline{V}$ value can be given, and as result $\underline{V}$ is unique determinate in Ω_C.

III. FINITE ELEMENT METHOD

The numerical solution of the problem is done by using the Galerkin technique. We project equations (1), (2), (5) on a set of functions $\boldsymbol{N}_k$, ϕ_k, V_k. The $\boldsymbol{N}_k$ function has the boundary condition (8) as null and $rot\boldsymbol{N}_k$ are linear independents. The ϕ_k functions has constant values arbitrariness on S_i, i=1,2,...,n-1 and null values on S_n. The $\boldsymbol{N}_k$ and ϕ_k function are defined on Ω, and V_k on Ω_C.

$$\underline{A} = N_0(t) + \sum_{k=1}^{n_N} \alpha_k(t) N_k + \sum_{k=1}^{n_\phi} \gamma_k(t)\, grad\, \phi_k\,, \tag{10}$$

$$\underline{V} = \sum_{k=1}^{n_v} \beta_k(t) V_k \tag{11}$$

where $\mathbf{N}_0$ carry out the boundary condition (8).

IV. THERMAL FIELD FORMULATION

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

$$-\,div\,\lambda gradT + c\frac{\partial T}{\partial t} = p \tag{12}$$

where λ represents the thermal conductibility and p is the volume density of the power that's transformed from the electromagnetic form to heat and c is the volume thermal capacity. The boundary condition associated to equation (12) is:

$$-\lambda\frac{\partial T}{\partial n} = \alpha\left(T - T_e\right) \tag{13}$$

where α represents the convective thermal coefficient and T_e represents the temperature outside of the Ω_C domain and the initial condition for the temperature is considerate: $T(0) = T_{in}$.

For the time discretization of equation (12) will use a Crank-Nicholson technique, and for the

III. NUMERICAL SIMULATION OF THE INDUCTION HARDENING

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.

To avoid the excessive heating of the thin edge between the two interior cylindrical surfaces, a 3-dimensional model was chosen, which allows to study the induced currents in this part of the cylindrical segment and the proper shape for the inductor. Simulations were done using the *AV-A* model. The 3-dimensional simulation allows visualising the distribution of the eddy currents, induced power and magnetic field coresponding to the required hardness profile.

In figure 1 is presented the cylindrical segment and the shape of the interior surfaces required to be hardened. The process consists in performing a single continuous movement hardening at 8 kHz using an inductor as shown in figure 2.

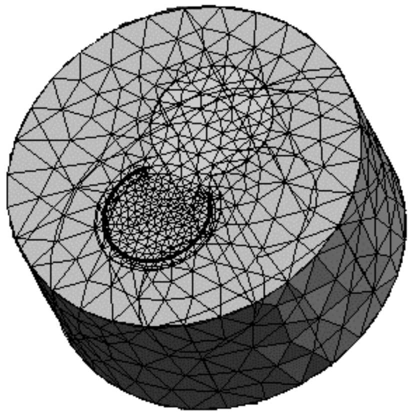

Fig.1. Geometry

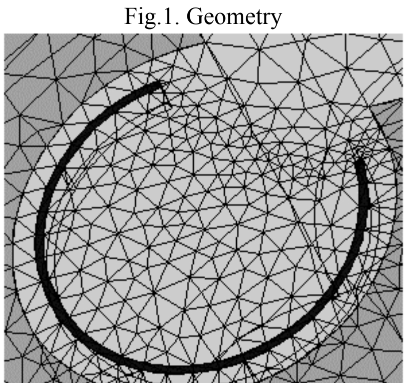

Fig.2. Displacement of the inductor

The inductor is dimensioned in order to assure a distribution of the currents in the piece which implies the optimal heat treatment. Distribution of the induced currents is shown in fig. 3.

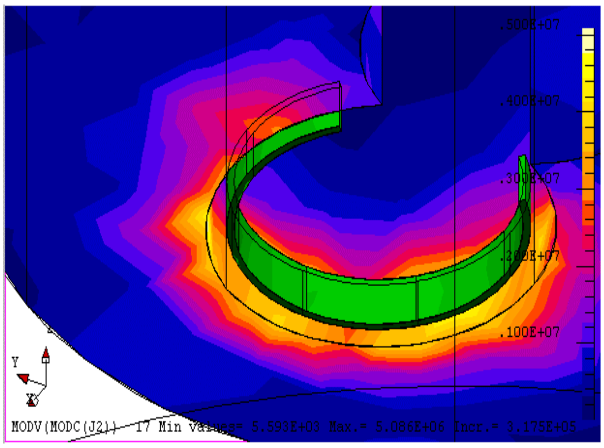

Fig.3. Eddy current distribution over the surface

For thermal field computation we choose a two-dimensional approach considering a half of the interior surface being cylindrical and using a dedicated computer program which computes the thermal field taking into account the relative movement between the inductor, the part and the cooling of the heated surface.

The two-dimensional computational domain with the finite element mesh is shown in figure 4.

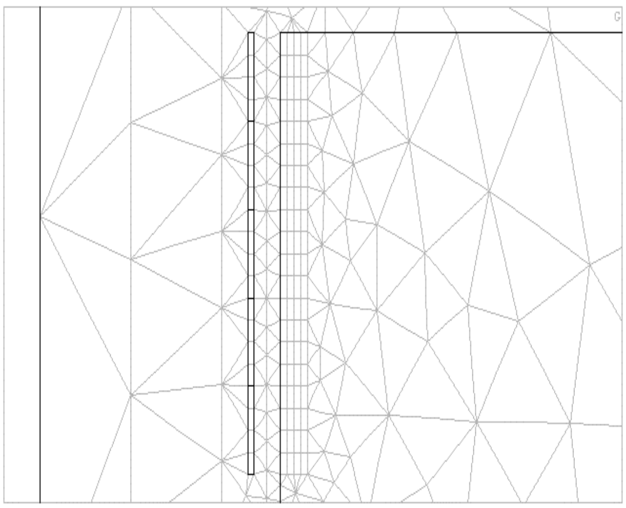

Fig.4. Computational domain for the 2D model

In the following figures are presented the results obtained by using the numerical analysis. Figures 5 show the power density distribution after the first step of the simulation.

Thermal field distribution and space variation of the temperature for the first step are shown in figures 6 and 7.

Induced power variation and temperature after the inductor movement is shown for the next steps. The corresponding power density distribution and thermal field distribution are shown in figures 8, 9, 10 and 11.

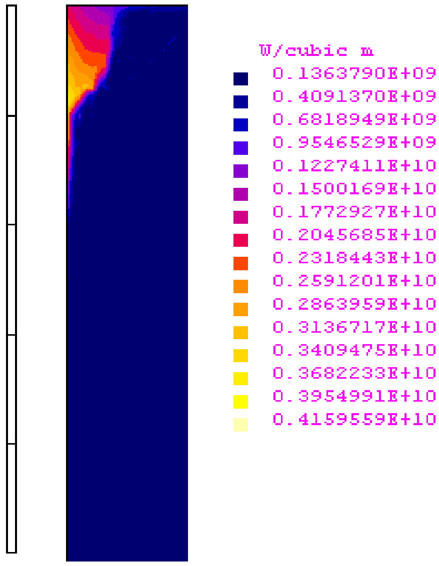

Fig.5. Induced power density after the first step of the analysis

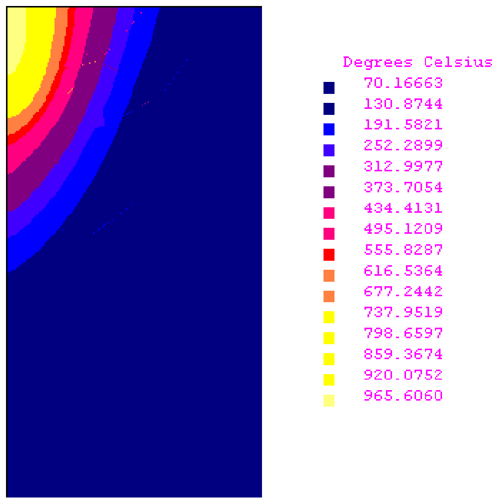

Fig.6 Thermal field distribution after the first step of the analysis

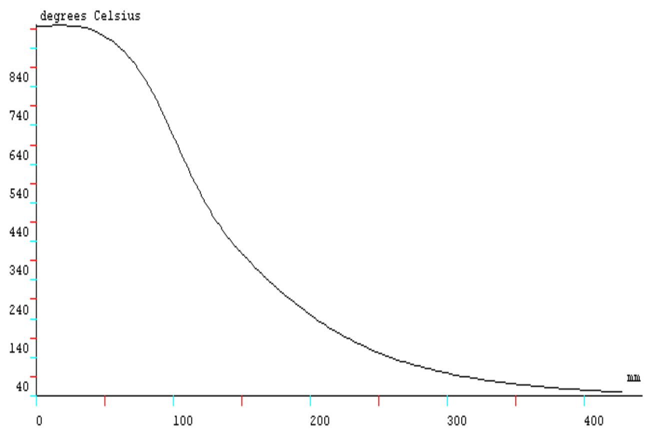

Fig.7 Thermal field variation along the edge

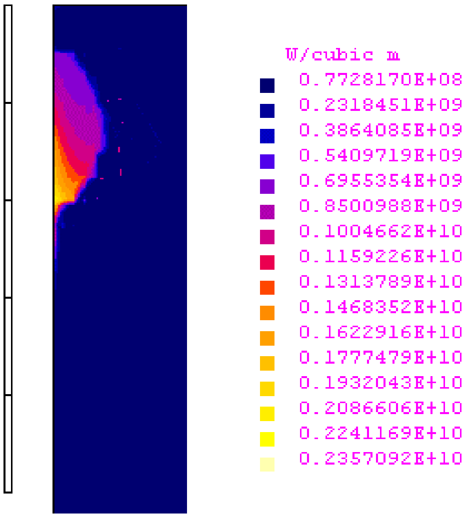

Fig.8 Induced power density after the second step of the analysis

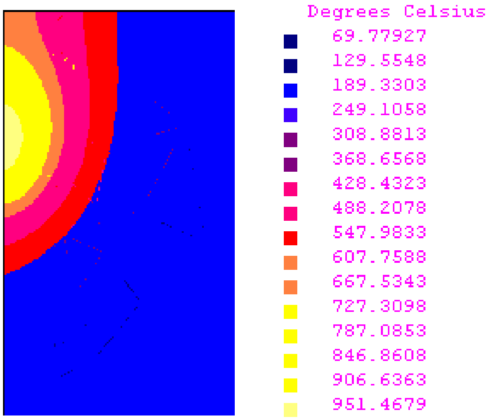

Fig.9 Thermal field distribution after the second step

of the analysis

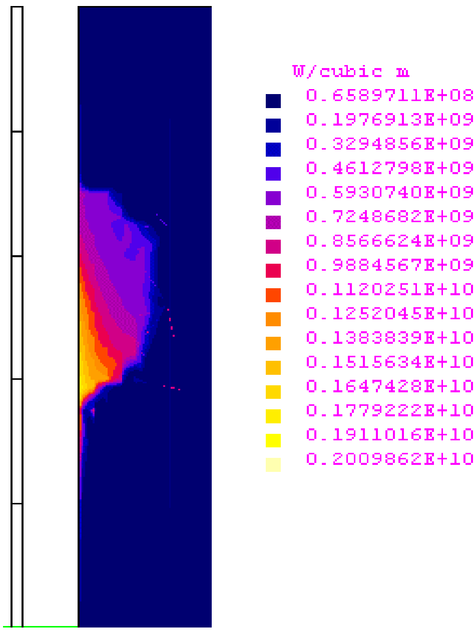

Fig.10 Induced power density after the third step of the analysis

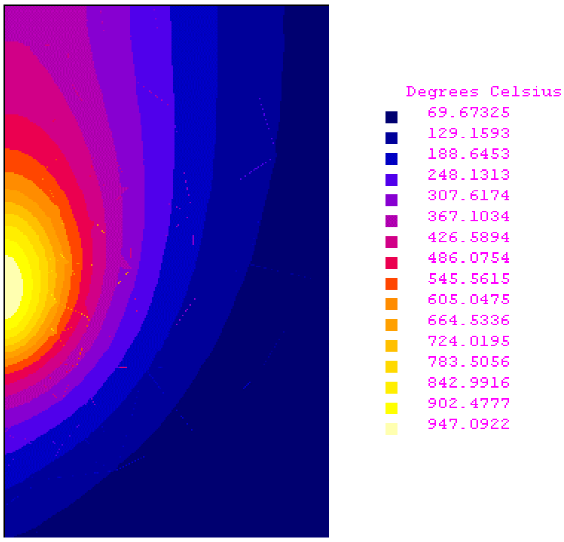

Fig.11 Thermal field distribution after the third step of the analysis

VI. CONCLUSIONS

The optimal designing and development of complex electromagnetic systems, such as the induction heating equipments, are very expensive. The interaction between electromagnetic and thermal fields, time and space variation of quantities which characterize the induction heating process make impossible to determine the optimal parameters of these equipments by usual analytical methods, a lot of experiments which cost time and money being necessary.

A possible solution for these problems is the numerical modelling that allows analysing the phenomena which characterize the process in evolution.

Numerical simulation allows to determine accurately the thermal regime of the induction hardening 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.

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