Numeric Modeling of the Electromagnetic Induction Heating Process for Thermal Treatments

Claudiu Mich-Vancea*, Mariana TĂMAŞ**
*University of Oradea, Faculty of Electrical Engineering and Information Science,
1 Universitatii st., Oradea, Romania; cmich@uoradea.ro

**Technical College "Mihai Viteazul" Oradea,
25 Poieniței Str., Oradea, Romania,Tel/fax:+40 259 431426, mariana.tamas@yahoo.com

***Abstract* – One of the current technologies of electromagnetic processing of materials proposed for study in this work is hardening through inductive heating. During the past years, there have been developed modeling methods of the hardening processes in which the numeric analysis of the electromagnetic field is joined with the analysis of thermal diffusion. The hardening solutions of a screw with ball are analyzed with the help of the FLUX program package, resulting the hardening time and the distributions corresponding to the electromagnetic and thermal fields.**
***Keywords:* finite element method, electromagnetic induction, electromagnetic field, thermal field.**

I. INTRODUCTION

The results known in material engineering show that the hardness of certain metallic elements can be increased by hardening, heating up the element over a certain temperature and then cooling the element. Unfortunately, after hardening the entire element, it becomes breakable, sometimes impossible to be used for the purpose it has been designed. For this reason, the hardening of an element will be executed only on the area where increased hardness is required. Surface hardening provides metallic elements the characteristic to resist to abrasion, maintaining, in the same time, its overall elasticity and mechanical resistance. A modern and efficient way of superficial heating can be obtained by using an electromagnetic field variable in time. In the volume of the metallic element, eddy currents are induced, their distribution depending on the geometry of the element, on the material properties and on the frequency of the electromagnetic field. If the frequency is higher, the Joule losses, due to the eddy currents, are more distributed in a narrower area situated close to the element surface. The distribution is superficial and the depth of the area with important Joule losses is the penetration depth. The accurate determination of eddy currents distribution implies solving a complicated problem of electromagnetic field in quasistationary regime. The heating time must be low enough not to diffuse too much in the volume of the element. The evolution of the thermal field depends on the losses through eddy currents and requires the solving of a complicated problem of thermal diffusion. The material properties depend on temperature, so the two problems, electromagnetic and thermal, are connected. The surface hardening through electromagnetic induction has significant advantages, compared to other methods of hardening, such as: regulation of thickness of the hardening layer, inexistent pollution, relatively easy automatization. During the past years, methods of modeling the hardening processes have been developed, in which the numeric analysis of the electromagnetic field has been connected with the analysis of thermal diffusion. Presently, the methods are applicable to any type of geometry and can take into consideration the modification both of the electromagnetic parameters and of the thermal ones, according to temperature. The most evolved programs use the pseudo linear model in which the B-H relation is a linear one, magnetic permeability being corrected according to the actual or maximum value of the magnetic induction. This work follows the direction of establishing new, efficient hardening procedures which should lead to high productivity in the case of typo-dimensions of screws with ball. The solutions are analyzed with the help of the FLUX2D program package, resulting the hardening time and the distributions corresponding to the electromagnetic and thermal fields.

II. NUMERIC MODELING OF THE ELECTROMAGNETIC FIELD COUPLED WITH THE THERMAL ONE

The patterns used in order to simulate the functioning of the electro-technical devices are described by equations with partial derivatives in domains with, often, a very complex geometry. The numeric methods, the only ones available in such situations, resort to the discretization techniques of the calculus domain. In literature [1] and [2], there is information regarding these approximation methods, especially regarding the methods using finite differences and finite elements.

The most used method in modeling the electromagnetic field coupled with the thermal one is the finite element method [5].

The quasi-stationary electromagnetic field solves the following equation system:

$$\begin{aligned}&\mathrm{div}D = \rho \qquad \mathrm{div}B = 0\\ &\mathrm{rot}\bar{E} = -\frac{\partial \bar{B}}{\partial t} \qquad \mathrm{rot}\bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t}\\ &\bar{D} = \varepsilon\bar{E} \quad \bar{B} = \mu\bar{H} \ \text{ and } \ \bar{J} = \sigma\bar{E}\end{aligned} \tag{1}$$

For simplicity, there are considered μ (magnetic permeability), respectively σ (electric conductivity) as constants.

The following is achieved:

$$\mathrm{rot}\frac{1}{\mu}\mathrm{rot}\bar{E} = -\sigma\frac{\partial E}{\partial t} \tag{2}$$

The solution of equation (2) can be achieved with the help of the finite element method. This method implies the determination of a global function, which represents the studied phenomenon from the point of view of the studied domain. Because this calculus domain is divided into multiple adjacent sub-domains, named finite elements, the global function is an aggregate of functions associated to each of these elements.

$$\int_\Omega \varphi_k \cdot \mathrm{rot}\frac{1}{\mu}\mathrm{rot}\bar{E}d\Omega + \int_\Omega \varphi_k \cdot \sigma\frac{\partial \bar{E}}{\partial t}d\Omega = 0 \tag{3}$$

where $\varphi_k = 0$ on boundary.

The penultimate term of (3), is integrated and the following is obtained:

$$\begin{aligned}&\int_\Omega \varphi_k\left(\nabla\times\left(\frac{1}{\mu}\mathrm{rot}\,\bar{E}\right)\right)d\Omega = -\int_\Omega \nabla\left(\varphi_k\times\left(\frac{1}{\mu}\mathrm{rot}\,\bar{E}\right)\right)d\Omega =\\ &= -\oint_{\partial\Omega} n\left(\varphi_k\times\frac{1}{\mu}\mathrm{rot}\,\bar{E}\right)dS + \int_\Omega \nabla\left(\varphi_k\times\frac{1}{\mu}\mathrm{rot}\,\bar{E}\right)d\Omega =\\ &= -\oint_{\partial\Omega}(n\times\varphi_k)\frac{1}{\mu}\mathrm{rot}\,\bar{E}\,dS + \int_\Omega(\nabla\times\varphi_k)\frac{1}{\mu}\mathrm{rot}\,\bar{E}\,d\Omega\end{aligned} \tag{4}$$

$$E = E_0 + \sum_{i=1}^{N}\alpha_i\varphi_i \tag{5}$$

and

$$\begin{aligned}&\bar{E} = \bar{E}_t + E_n\cdot\bar{n}\\ &\bar{n}\times\bar{E} = \bar{n}\times\bar{E}_t + n\times E_n\cdot\bar{n}\end{aligned} \tag{6}$$

where $\bar{n}\times E_n\cdot\bar{n} = 0$

The discretization of the calculus domain is the transition from continuous environment to the discrete one, being closely connected to the method used to approximate the equations with partial derivatives. Thus, the calculus domain is cut out of a sub-domains – elements – aggregate, respecting the boundaries and the transition surfaces of the initial sub-domain, obtaining a certain number of knots.

Because φ_i and φ_k are scalar functions, on domain Ω it is chosen a network of finite elements, usually triangular and having equation (6) in which we replace (5), resulting the equation which will be written for each knot of the network, resulting a number N of linear equations, equal with the number of P_i knots, excepting the knots on the Dirichlet boundary where:

$$\begin{aligned}&\int_\Omega\frac{1}{\mu}\mathrm{rot}\varphi_k\left(E_0 + \sum_{i=1}^{N}\alpha_i\varphi_i\right)d\Omega\\ &+\sigma\int_\Omega\varphi_k\frac{\partial}{\partial t}\left(E_0 + \sum_{i=1}^{N}\alpha_i\varphi_i\right)d\Omega = 0\end{aligned} \tag{7}$$

This relation is valid both for bi-dimensional domains and for tri-dimensional ones.

In order to obtain the best possible discretization of the considered pattern, the density of elements must be as high as possible in the areas where the phenomenon is more intense and the elements must be regular enough.

The equation of thermal field diffusion is:

$$\mathrm{div}k\cdot\mathrm{grad}T + c\frac{\partial T}{\partial t} = p \tag{8}$$

with the boundary conditions:

$$-k\frac{\partial T}{\partial t} = \alpha(T - T_{ex}) \tag{9}$$

where: the caloric capacity c depends on the temperature T, with significant variation when the phase shift occurs [3].

The modeling of fields electromagnetically and thermally coupled has been achieved by treating a process of superficial hardening through induction, using the 2D program package. The studied equipment is made up of an inductor and the cylindrical component. Due to the cylindrical symmetry of the physical pattern, the electromagnetic and thermal fields are axis-symmetrical.

The electromagnetic and thermal analysis of the aggregate implies the study of the component in four different configurations. This study has been achieved using the following applications from FLUX 2D: magneto-dynamics, case in which there are computed the electromagnetic field and the power induced in the heated component; transient thermal – fast cooling of the component in order to harden the surface and both coupled – magneto-thermal application. The equations solved by FLUX 2D [4] for each application are:

Magneto-dynamics:

Variable is $\bar{A} = \begin{pmatrix}0\\0\\A_z\end{pmatrix}$, complex vector potential in Wb/m

The source is the complex flux density: $\bar{J}\begin{pmatrix}0\\0\\A_z\end{pmatrix}$

Theoretical equation:

$$(j)\omega\sigma\bar{A} + \overline{rot}\left(\frac{1}{\mu} \cdot \overline{rot}\left(\bar{A}\right)\right) = \bar{J} \qquad (10)$$

Normalization constant: $\frac{1}{\mu_0}$

Normalized equation:

$$(j)\omega\mu_0\sigma\bar{A} + \overline{rot}\left(\frac{1}{\mu_r} \cdot \overline{rot}\left(\bar{A}\right)\right) = \mu_0 \cdot \bar{J} \qquad (11)$$

A flux density line is normal to the boundary if Neumann conditions apply and parallel to the boundary if Dirichlet conditions are used.

Boundary conditions:

Dirichlet: $A_z = \text{constant}$

Neumann (default condition):

$$d(A_z)/dn = 0 \qquad (12)$$

Cyclic:

$$A_z j(j = 1, n) = A_z i(i = 1, n) \qquad (13)$$

Anticyclic:

$$A_z j(j = 1, n) = -A_z i(i = 1, n) \qquad (14)$$

Translation:

$$A_z j(j = 1, n) = A_z i(i = 1, n) + C \qquad (15)$$

C = constant equal with flux in the entire domain

Transient thermal:

Variable is temperature T in Kelvin. Theoretical equation:

$$\rho_c \, dT/dt + \mathrm{div}\left(-k \cdot \overrightarrow{\mathrm{grad}}(T)\right) = Q_H \qquad (16)$$

Boundary conditions:

Dirichlet: T = constant

Neumann homogenous (default condition):

$$dT/dn = 0 \qquad (17)$$

Neumann non homogeneous:

$$k \cdot dT/dn = -F_H - h(T - T_0) - \xi\sigma\left(T^4 - Ta^4\right) \qquad (18)$$

The beginning of component heating and the evaluation of heating duration, as well as the computation of the electromagnetic and thermal fields during process of heating the component has been studied using the magneto-thermal application. This application combines the process of a constant magnetic state problem with the process of a transitory thermal problem. The constant magnetic state gives dissipated power due to eddy currents. This dissipated power is used as source for the transitory thermal problem. The eddy electric currents determined by induced electromotive tensions lead to its heating by Joule effect [4] [6] [7].

III. RESULTS

We have taken into study a screw with ball of 25 mm diameter and 446 mm length. In order to obtain a hardness of 58 – 62 HRC, the element must be superficially hardened at 2 – 2.5 mm depth. To achieve this, the element will be heated through induction at a temperature of 900 – 980º C, the advance speed being of 260 mm/min. The element heating in depth depends on the heating time, on the energy transmitted through the element during this time and on the frequency of the induced current. The cooling way is through inductor, using water, the pressure of the cooling environment being of 2 – 4 atmospheres.

In the following figures there are presented some of the results obtained after simulation such as: the line of magnetic flux of the inductor in the system and the distribution of temperature in the piece.

Step 1. Starting of the hardening.

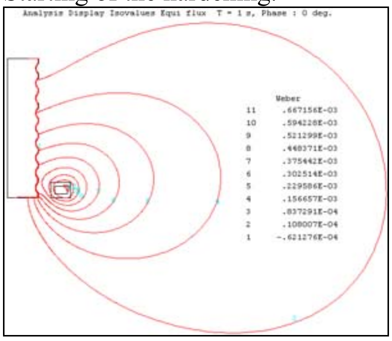

Figure 1. Distributions of the equiflux.

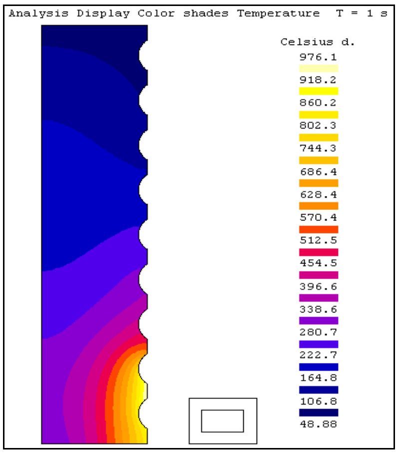

Figure 2. Temperature map at initial moment of hardening.

Step 3

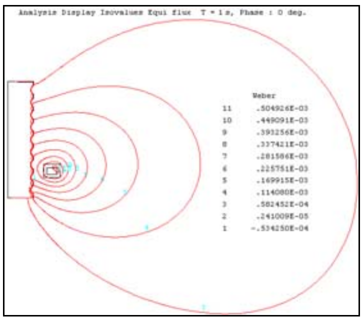

Figure 3. Distributions of the equiflux.

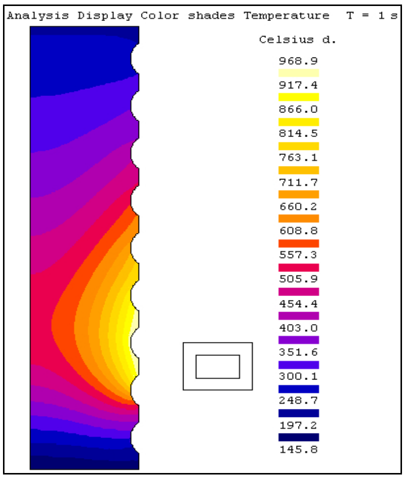

Figure 4. Temperature map.

Step 4.

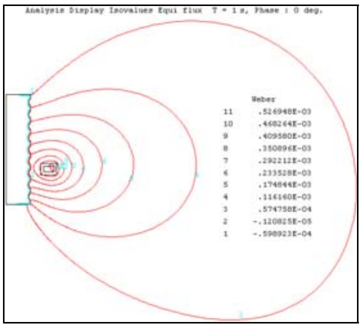

Figure 5. Distributions of the equiflux.

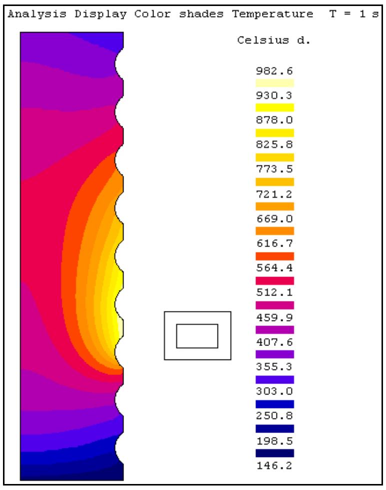

Figure 6. Temperature map.

Step 8

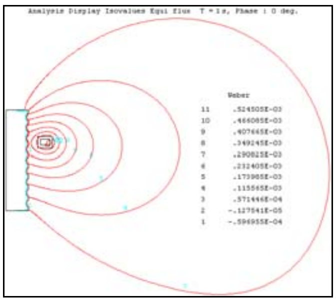

Figure 7. Distributions of the equiflux.

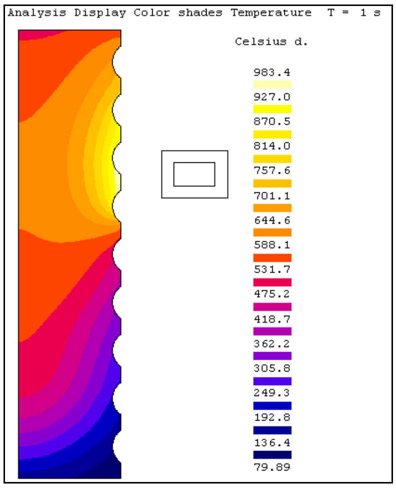

Figure 8. Temperature map.

IV .CONCLUSIONS

The numeric modeling of electromagnetically and thermally coupled fields optimizes the energetic parameters of the superficial hardening installation. These phenomena are simulated numerically in order to obtain a clear image of the structure at the end of the process. Numerical application results emphasize the correlation between magnetic field intensity, induced power density and final thermal field. Numerical modeling allows determining accurately the optimal parameters, witch offer maximum efficiency. There for the experiments number in designing process can be decreased and a better knowledge of the process can be obtained.

REFERENCES

[1] F. Hantila et all, ”The numeric computation of eddy currents” , Ed. ICPE, 2001 (in Romanian).
[2] O.Biro, K.Preiss ,”Finite element analysis of eddy current ”,IEE Trans.on Magn,No.2,1990
[3] T.Leuca,”Câmpul electomagnetic şi termic cuplat-Curenţi turbionari,Ed. Mediamira,Cluj -Napoca, 1996
[4] FLUX2D,version 7.40,User’s Guide, June 1999.
[5] T.Maghiar,T.Leuca,F.I.Hantila,”Numerical analysis of eddy current heating”(in romanian) ,Ed.Universitatii din Oradea, Oradea,2001
[6] Şt.Nay,T.Leuca,T.Maghiar,”Procesarea materialelor în câmp electromagnetic.Aplicaţii utilizând tehnici informatice”, Ed.Universitatii din Oradea, Oradea,2002
[7] T.Leuca, “Numerical modeling energy optimization of the electromagnetic and thermal fields in the induction heating process of the half-finished products, International Symposium on Non/linear Electromagnetic System, Braunschweig,1997.