Numerical Simulation of Continuous Induction Steel Bar End Heating with Material Properties depending on Temperature and Magnetic Field

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Abstract - **The continuous induction steel bar end heating is investigated by means of numerical calculations. A numerical model is used for the calculation of the three-dimensional eddy current and the heating process. The differential equations describing the electromagnetic field are integrated as an A-φ formulation. For the calculation of the temperature fields the Fourier's heat-conduction equation is used. On principle for the numerical solution the finite element method is used. The effect of material properties depending on temperature and magnetic field are taken into consideration in an iterative manner. The results of simulation correspond well to experimental data and give good transparent of the process. The computing time, however, is too long for an effective realization of optimization processes.**

I. Introduction

The continuous induction steel bar end heating is used to heat up the bar ends for forging or hardening. The bars are moving from the left to the right (see fig. 1). The heating process should be as fast as possible. The bars leaving the inductor should have a special temperature distribution depending on the following process. For optimum inductor design the electric losses (heat sources) in the steel bars are important. The heat sources and the velocity of the bars determine the temperature of the last bar.

Therefore only a three-dimensional numerical model for the whole inductor is very useful to obtain the eddy current distribution in the steel bars and the resulting temperature distribution.

II. Mathematical Model

Assuming that all field quantities are sinusoidal with time we can work in the complex domain. Using the magnetic vector potential $\underline{\vec{A}}$ and the scalar potential $\underline{\varphi}$ for the magnetic field we have to solve following well known differential equations [3], [4], [5]:

$$\mathrm{rot}\frac{1}{\mu}\mathrm{rot}\underline{\vec{A}} - \mathrm{grad}\frac{1}{\mu}\mathrm{div}\underline{\vec{A}} + j\omega\kappa\left(\underline{\vec{A}} + \mathrm{grad}\,\underline{\varphi}\right) = \kappa\underline{\vec{E}}_0 \quad (1)$$

$$\mathrm{div}\,\mathrm{grad}\,\underline{\varphi} + \mathrm{div}\,\underline{\vec{A}} = 0 \quad (2)$$

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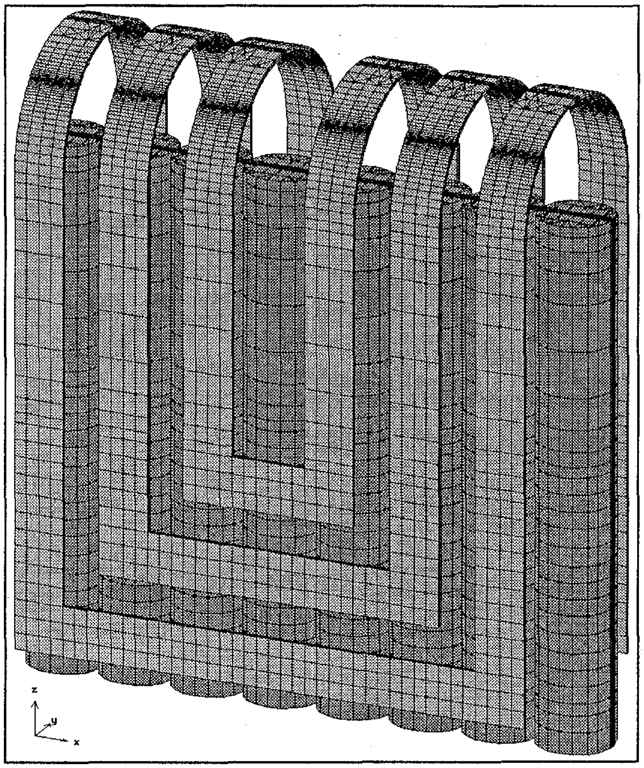

Fig. 1. Finite element mesh of the inductor with steel bars (without air).

Where μ is the permeability, κ is the electrical conductivity of the material and ω is the angular frequency of the generator.

The calculation of the temperature field is effected on the basis of Fourier's heat-conduction equation [1]:

$$\frac{\partial(c\rho\vartheta)}{\partial t} = \mathrm{div}(\lambda\,\mathrm{grad}\,\vartheta) + p_v - \vec{v}\,\mathrm{grad}(c\rho\vartheta) \quad (3)$$

Where λ is the thermal conductivity, c is the specific heat and ρ is the density. The temperature ϑ depends on both the location (x, y, z) and the time t.

The velocity vector field $\vec{v}$ makes it possible to consider continuous feed processes. Because the velocity of the moving bars is constant the problem becomes steady-state.

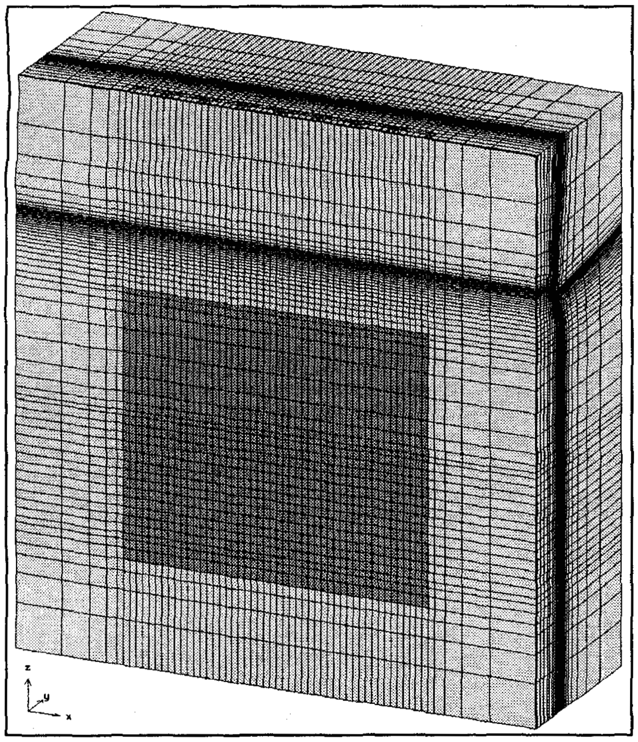

Fig. 2. Finite element mesh of the inductor with steel bars.

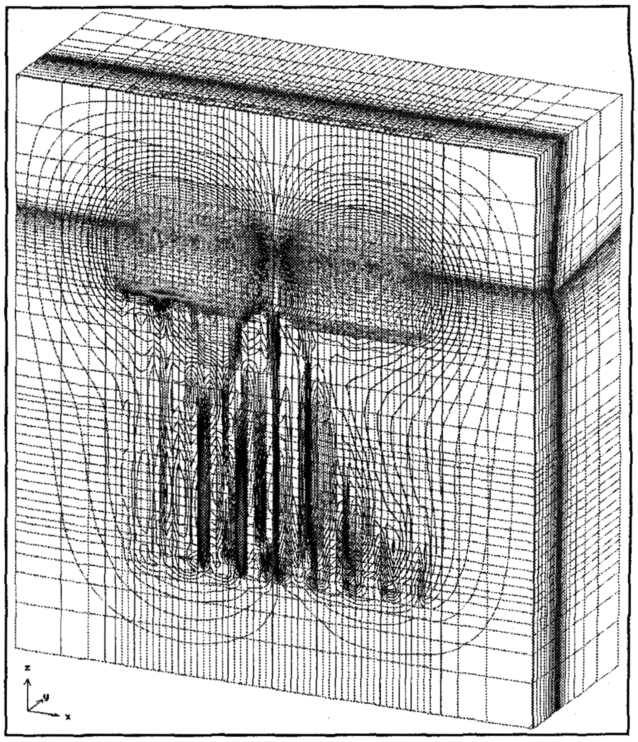

Fig. 3. Isolines of magnetic vector-potential in the plane of symmetry.

It shall be possible to use material properties depending on temperature and magnetic field in the following way:

$$\begin{aligned} \mu &= f(|H|,\vartheta) \\ \kappa &= f(\vartheta) \\ c &= f(\vartheta) \\ \rho &= f(\vartheta) \\ \lambda &= f(\vartheta). \end{aligned} \tag{4}$$

III. Numerical Solution

The numerical calculation of the electromagnetic field and the temperature field are possible by the finite-element method using the Galerkin procedure for solution of differential equations (1), (2) and (3). The necessary boundary, symmetrical and interface conditions are taken into account.

An exhaustive description of the procedure for the A-φ formulation is contained in [3] and [5].

The finite-element method requires the volume element discretization of the bounded three-dimensional solution domain. At the nodes thus produced, the discrete values of the vector potential $\underline{\vec{A}}$ and in the electrically-conductive zones, additionally the scalar potential $\underline{\varphi}$ are sought as unknown field quantities. The problem of the three-dimensional magnetic field is thus reduced to the solution of a system of linear algebraic equations. The matrix is symmetrical, and sparsely occupied. A discretization adapted to the specific problem leads to grid networks containing up to 100,000 nodes or elements. A large matrix is produced, requiring storage forms that need small storage space. For the solution of the system of equations, the incomplete Cholesky decomposition conjugate gradient method is used as an iterative process to reach the solution.

The calculation of the temperature field is also carried out with the help of the finite element method (Galerkin procedure) on the basis of differential equation (3). Only the grid network inside the bars is required. On the outer surface area, heat losses due to convection and radiation are taken into consideration. The calculation of the temperature field of the moving bars is effected on a fixed grid network.

Because of the continuous movement of the bars from the entrance the geometry of the magnetic field problem is changing permanently. So for every time step it would be necessary to generate a new grid network and to compute the electromagnetic field again. Because of a long duration of this procedure an assumption was made that the bars are moving forward in steps. In this way the following bar occupies the place of the one going ahead.

For the discretization of the area for which the solutions is sought, a semi-automatic process using macro-elements is used [2]. Macro-elements are hexahedral, prisms and

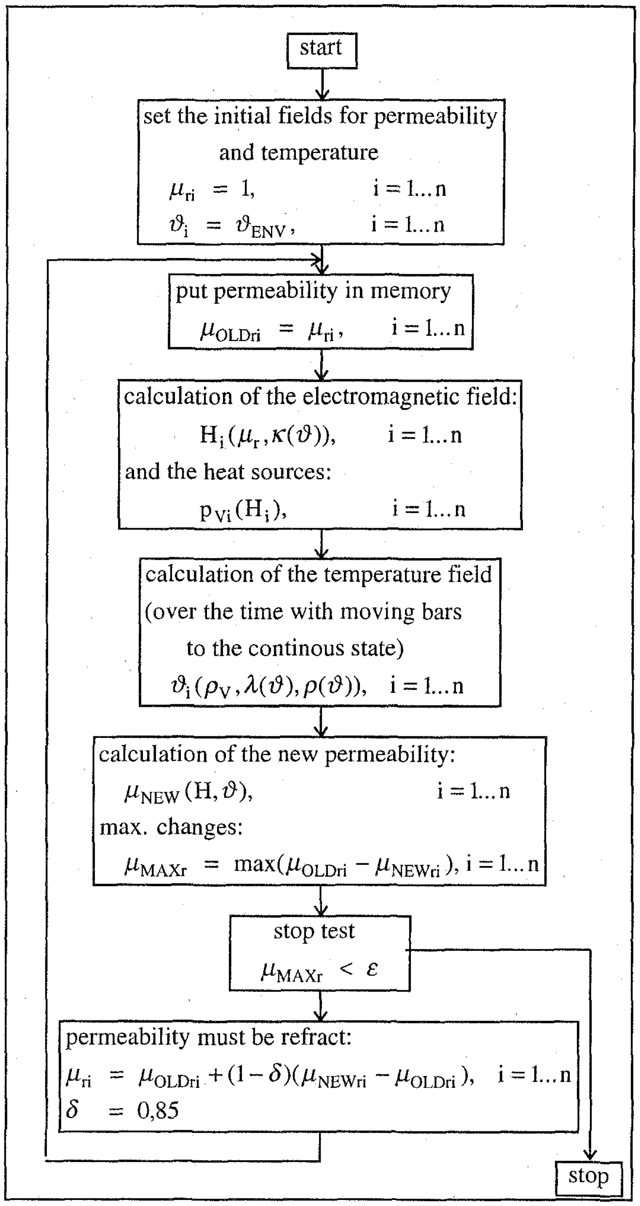

Fig. 4. The iterativ approximation of the material properties depending on temperature and magnetic field.

tetrahedral that are automatically meshed and then put together for the total discretization. The required manual work is limited to the definition of the macro-elements. Grid networks with more then 100,000 elements can, using this process, be constructed without any problem. The macro-element concept does not exclude input faults completely, and for this reason, the resulted discretization is tested for the meshing faults using a special program.
Figure 2 shows the finite element mesh used for calculating the electromagnetic field (112,362 elements and 112,716 nodes). Due to the symmetry of the arrangement, only one half of the computation area is meshed. The calculation is carried out on an efficient HP 9000/750 work station with 256 MB main memory.

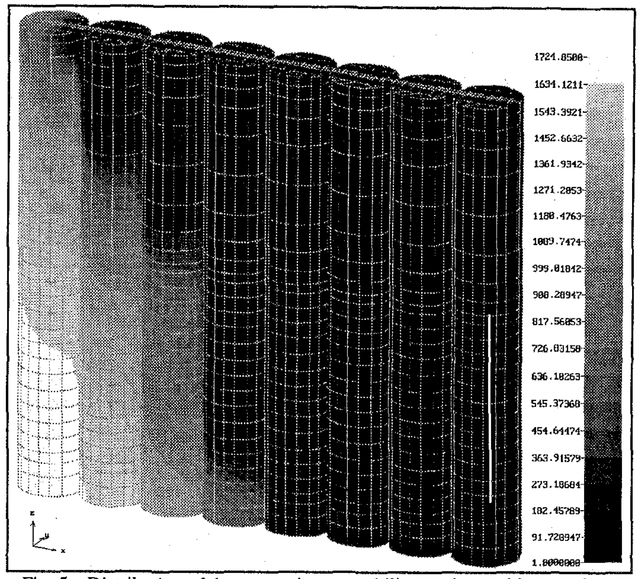

Fig. 5. Distribution of the magnetic permeability on the steel bars surface.

The effect of material properties depending on temperature and magnetic field is taken into consideration in an iterative manner (see fig. 4).

The permeability as a function of magnetic field strength $|H|$ and temperature ϑ is given by:

$$\mu_r(|H|,\vartheta) = \begin{cases} 1789\left(1-\dfrac{\vartheta^2}{750^2}\right)+1 & |H| < 500\dfrac{A}{m} \\ \left(2{,}41^{14{,}73-ln(|H|)}-1\right)\cdot\left(1-\dfrac{\vartheta^2}{750^2}\right)+1 & |H| \geq 500\dfrac{A}{m} \end{cases} \ \vartheta < 750\,°C; \qquad 1 \quad \vartheta \geq 750\,°C. \tag{5}$$

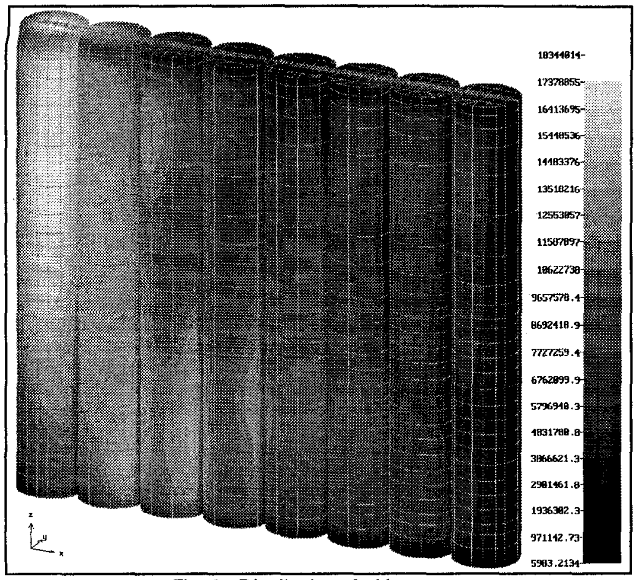

Fig. 6. Distribution of eddy current.

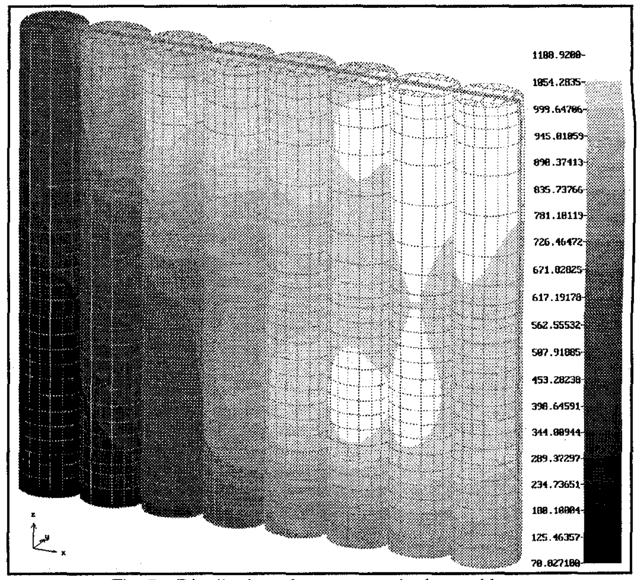

Fig. 7. Distribution of temperature in the steel bars.

IV. Results

The parameters for computed system are the following:

Bar diameter	=	30 mm
Frequency	=	2 kHz
Inductor current	=	2 kA
Inductor voltage	=	59.9 V
Input power	=	34.4 kW
Inductor losses	=	7.6 kW
Inductor efficiency	=	78 %
Reactive power	=	114.8 VAr

Fig. 3 shows a representation of the magnetic vector potential in the plane of symmetry. The areas of high current density are surrounded by the isolines of vector-potential.

The eddy current distribution (real and imaginary part) is illustrated in fig. 6. One can see eddy currents are relatively high in the region of high permeability (fig. 5) and near the coil conductors.

Fig. 7 shows the temperature distribution on the steel bar ends surface. The bars are moving from the left to the right and so the temperature is growing. The bars on the left hand site with temperatures below 750 °C have a high permeability and strong heat sources are produced by the magnetic field. That's why the temperature increases in the first bars very fast.

With the help of the numerical model we get the current of the inductor by given voltage or the voltage by given current.

V. Summary

The above numerical examination shows how it is possible to calculate a special inductor for bar end heating when material properties depend on temperature and magnetic field. Because of the special inductor design only three-dimensional calculation can provide correct results.

The model gives the temperature distribution at the end of the process that is very important for the following processing e.g. hardening or forging. With the help of the numerical simulation are parameter studies very useful. The needed time, however, for meshing and iterative computing of one example is very high (about one week). So for practical aims it is necessary to reduce strongly both the manual work expenditures and computing time.

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