Model of induction heating of rotating nonmagnetic billets and its experimental verification

F. Mach[1], P. Karban[1], I. Doležel[1], P. Šíma[2], Z. Jelínek[2]
[1]University of West Bohemia, Faculty of Electrical Engineering, Univerzitní 26, 306 14 Pilsen, Czech Republic
[2]ETD Transformátory, a.s., Plzeň - Doudlevce, Zborovská 22/54, Pilsen, Czech Republic
fmach@kte.zcu.cz, karban@kte.zcu.cz, idolezel@kte.zcu.cz, petr.sima@etd-bez.cz, zdenek.jelinek@etd-bez.cz

***Abstract*—Induction heating of nonmagnetic cylindrical billets is modeled. The billet rotates in static magnetic field generated by appropriately distributed permanent magnets. The mathematical model of the process consists of two second-order partial differential equations describing the distributions of magnetic and temperature fields. Its solution is solved numerically in the quasi-coupled formulation respecting all important nonlinearities. The computations are carried out by own code Agros2D based on a fully adaptive higher-order finite element method. The most important results are verified experimentally on an industrial prototype of the device.**

***Index Terms*—Induction heating, magnetic field, temperature field, finite element method, numerical simulation, temperature measurement, power measurement**

I. Introduction

Induction heating of cylindrical billets of nonmagnetic metals (mostly aluminum) before their hot forming is a multipurpose widely spread technology. Nowadays, it is often realized by rotation of the billet in static magnetic field generated by direct current-carrying coils ([1], [2]). The main issue is here to obtain a sufficiently high magnetic field (and, consequently, eddy currents and Joule losses in the billet for producing required amount of heat). The only solution is using very high field currents, which is conditioned by the presence of superconducting field coils with the necessary cooling infrastructure (which leads to higher investment and operation costs). Presently, systems based on this way of heating successfully work in few industrial plants and their efficiency is reported to reach about 70 %.

The paper analyzes another version of this method suitable for billets of lower diameters (about 0.1 m). Here, the static magnetic field is generated by appropriately arranged high-parameter permanent magnets. This version is characterized by the total absence of the field coils (and corresponding Joule losses) and the only losses in the system are those of the mechanical origin. The driving engine must provide a torque higher than the drag torque caused by the interaction between the static magnetic field and currents induced in the rotating billet. In this case, the efficiency can reach even 85 %. The first study of the system was published in [3], and certain results were validated (with a very good agreement) experimentally on a physical model.

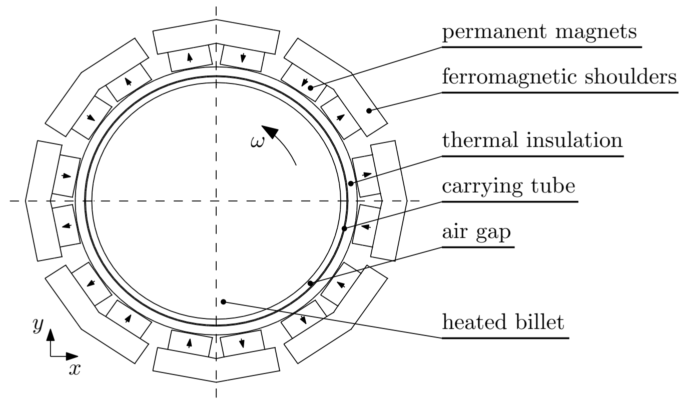

Figure 1: Arrangement of discussed device (arrows in permanent magnets show angle of remanent magnetization)

II. Description of the technical problem

The investigated arrangement is depicted in Fig. 1. It is sufficiently long in the axial direction, so that the distributions of magnetic and temperature fields in the system may be considered 2D. The aluminum billet of diameter 120 mm rotates (at angular velocity $n = 1000$ rev/min) in the static part of the system consisting of permanent magnets fixed on ferromagnetic shoulders. The permanent magnets are placed behind good thermal insulation that prevents them from excessive heating due to convection and radiation of heat from the billet. The shoulders with permanent magnets are normally parallel with the longitudinal axis of the billet, but when a specific temperature profile of the billet is required, they can be slightly shifted at one end of the billet. The dimensions of the air gap, shoulders and permanent magnets may vary in smaller intervals.

The principal task is to model the time evolution of the heating process and determine its overall efficiency. The results are compared with measurements on the industrial prototype of the device (see Fig. 2).

III. Mathematical model and its numerical solution

The mathematical model of the problem consists of two PDEs describing the distribution of magnetic and temperature fields in the system. Magnetic field is described in terms of magnetic vector potential **A**. Its distribution is given by the

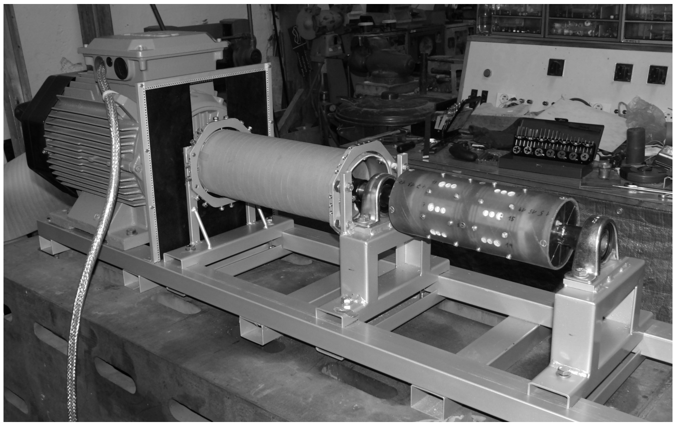

Figure 2: Industrial prototype of the device

equation

$$\mathrm{curl}\left(\mu^{-1}(\mathrm{curl}\mathbf{A}-\mathbf{B}_{\mathrm{r}})\right)-\gamma\mathbf{v}\times\mathrm{curl}\mathbf{A}=\mathbf{0}\,,$$

Here, μ denotes the magnetic permeability, γ is the electrical conductivity, and $\mathbf{v}$ stands for the vector of the local velocity of rotation. Finally, the symbol $\mathbf{B}_{\mathrm{r}}$ represents the remanent magnetic flux density, which is only considered in the domain of the permanent magnets and vanishes elsewhere. The Dirichlet condition $\mathbf{A}=\mathbf{0}$ is prescribed along the artificial boundary in a sufficient distance from the device.

The distribution of temperature field is described by the heat transfer equation in the form

$$\mathrm{div}\,(\lambda\,\mathrm{grad}T)=\rho c\left(\frac{\partial T}{\partial t}+\mathbf{v}\cdot\mathrm{grad}T\right)-w_{\mathrm{J}}\,,$$

where λ denotes the thermal conductivity, ρ is the specific mass, and c represents the specific heat. The equation is considered time-dependent. The source term w_{J} stands for the volumetric heat generated in the material by the Joule losses. Its value is given by the formula

$$w_{\mathrm{J}}=\frac{||\mathbf{J}_{\mathrm{ind}}||^2}{\gamma}\,,$$

where $\mathbf{J}_{\mathrm{ind}}$ denotes the current density induced in the rotating billet, given by the expression $\mathbf{J}_{\mathrm{ind}}=\gamma\mathbf{v}\times\nabla\times\mathbf{A}$. The boundary condition respects the heat convection.

The numerical solution of the problem is realized by a fully adaptive higher-order finite element method whose algorithms are implemented into the codes Agros2D [4] and Hermes [5]. Both codes have been developed in our group for a couple of years. The codes are intended for monolithic numerical solution of systems of generally nonlinear and nonstationary second-order partial differential equations and their principal purpose is to model complex physical problems in the hard-coupled formulations. Both codes are freely distributable under the GNU General Public License.

IV. Results and their discussion

Figure 3 shows the calculated distribution of magnetic field in the system (together with the distribution of the volumetric

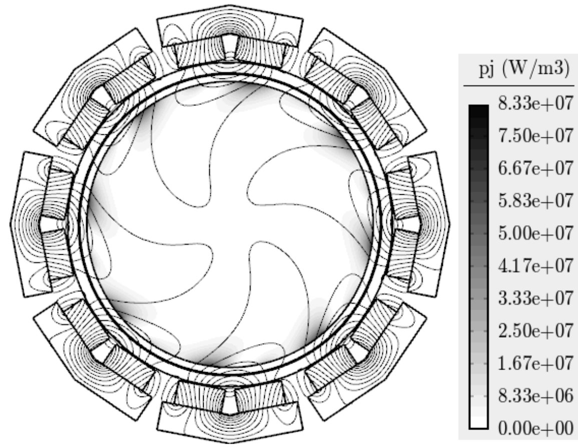

Figure 3: Distribution of power losses in system and line of force in the system

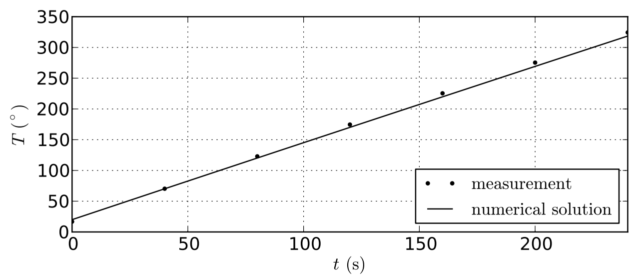

Figure 4: Evolution of surface temperature of billet: full line–numerical solutin, doted–measured

Joule losses in the billet) at the beginning of the heating process (at T = 40 °C). Fig. 4 shows the time evolution of the surface temperature of the billet (full line – calculated, crosses – measured). The overall efficiency of the device is about 80 %.

V. Acknowledgment

This work was supported by the European Regional Development Fund and Ministry of Education, Youth and Sports of the Czech Republic (project No. CZ.1.05/2. 1.00/03.0094: Regional Innovation Centre for Electrical Engineering - RICE), by the Grant project GAR P102/10/0216 and project SGS-2012-039.

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