Induction heating of cylindrical billets by rotation in uniform magnetic field solved as mechanical transient

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1. Introduction

Induction heating of nonmagnetic billets is a widely spread industrial technology used for their softening before hot forming. The conventional static heaters exhibit, however, rather low electrical efficiency (about 60%). That is why a new innovative technique has recently been introduced consisting in heating of a billet by its rotation in uniform magnetic field produced by static coils carrying direct current. In several existing references this process was analyzed (in the steady state) by the finite element method [1], [2].

The paper offers integrodifferential modeling of the process. This novel approach developed by the authors directly provides the temporal and spatial distribution of eddy currents in the heated cylinder, without any need to calculate the distribution of the field quantities (like magnetic vector potential), which substantially reduces the time of computation and numerical errors. There is also no need to care for the boundary conditions because they are implemented directly in the kernel function of the corresponding integrals. The problem of temperature rise is solved in the quasi-coupled formulation. Respected is also the mechanical transient characterized by the increase of revolutions up to their nominal value.

Key words: Induction heating, integrodifferential method, finite element method, numerical analysis, electromagnetic field, temperature field.

2. Formulation of the problem and its mathematical model

A nonmagnetic cylindrical billet rotates in uniform magnetic field produced by a static field coil carrying DC current I, see Fig. 1. The driving unit is represented by an asynchronous motor of given torque characteristic $M(\omega)$ where ω denotes the angular frequency.

We will assume that the arrangement is very long in the axial direction, so that it can be considered 2D. Now the solution can be performed in the polar coordinate system. The complete mathematical model of the problem consists of three equations. The first one describes the rotation of the billet in the form

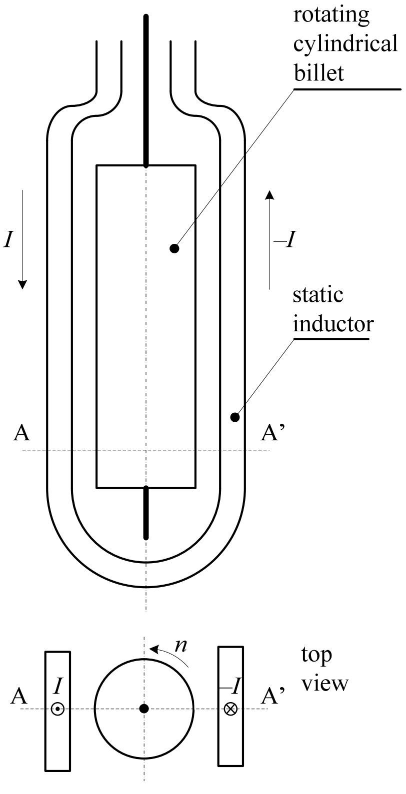

Fig. 1. Induction heating of rotating cylinder by static inductor carrying direct current I

$$J\frac{\mathrm{d}\omega}{\mathrm{d}t}+D\omega=M(\omega)-M_{\mathrm{d}}(\omega),\ \ \omega(0)=0 \qquad (1)$$

where J denotes the moment of inertia of the billet, D the coefficient of damping and $M_{\mathrm{d}}(\omega)$ the strongly nonlinear drag torque due to Lorentz forces acting in the billet.

In order to determine the specific Lorentz forces and losses in the billet, we have to know the spatial and temporal distribution of eddy current densities in it. Distribution of this quantity was derived in [3] or [4] and for the considered case it is given by equation

$$\begin{aligned} J_{1z}(r,\varphi) = {} & \frac{\mu_0 \omega \gamma_1}{2\pi} \cdot \frac{\mathrm{d}}{\mathrm{d}\varphi} \int_{\Omega_1} J_{1z}(P_1) \ln\left(s_{QP_1}\right) \mathrm{d}S + \\ & + \frac{\mu_0 \omega \gamma_1 J_{2z}}{2\pi} \cdot \frac{\mathrm{d}}{\mathrm{d}\varphi} \int_{\Omega_2} \ln\left(s_{QP_2}\right) \mathrm{d}S + \\ & + \frac{\mu_0 \omega \gamma_1 J_{3z}}{2\pi} \cdot \frac{\mathrm{d}}{\mathrm{d}\varphi} \int_{\Omega_3} \ln\left(s_{QP_3}\right) \mathrm{d}S \end{aligned} \tag{2}$$

where γ_1 is the electrical conductivity of the billet, s_{QP_1}, s_{QP_2} and s_{QP_3} are the distances between the reference point Q (φ denoting its angle with respect to axis x), and general integration points P_1, P_2 and P_3 in regions Ω_1 (billet), Ω_2 and Ω_3 (left and right parts of the field coil), respectively (see Fig. 2 showing the top view of the investigated arrangement). Finally $J_{2z} = -J_{3z}$ is the current density in the field coil calculated from the current I and cross-section of the coil.

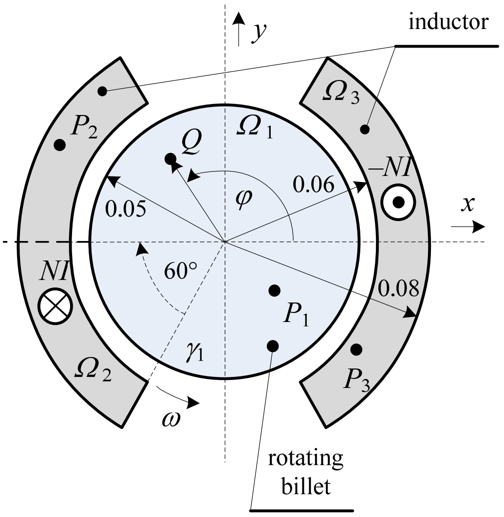

Fig. 2. Detailed view of the solved arrangement

Finally the nonstationary temperature field in the billet is described by the heat transfer equation in the form

$$\operatorname{div}\left(\lambda_1 \cdot \operatorname{grad} T\right) = \rho_1 c_1 \cdot \frac{\partial T}{\partial t} - w \tag{3}$$

where ρ_1 is the specific mass and c_1 the specific heat of the billet. Symbol w stands for the Joule losses due to eddy currents.

3. Selected results

We investigated a lot of examples aimed at heating of mostly aluminum billets. The number of results abounds. For an illustration, we analyzed in details the arrangement whose geometry is shown in Fig. 2. Here the external torque acting on the billet per unit length was $M'(\omega) = 100$ Nm/m and the current density in the field coils $J_{2z} = -J_{3z} = 3 \cdot 10^7$ Am^{-2}. For this case Fig. 3 depicts the time evolution of angular velocity ω of the billet on time t for several different damping coefficients D. All these curves well correspond with the physical reality.

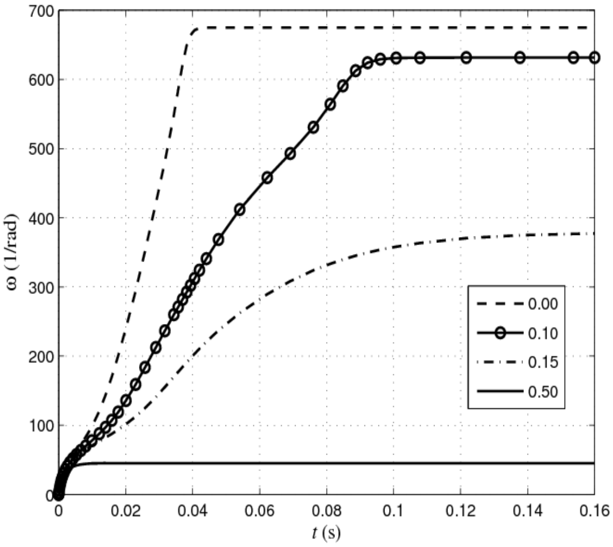

Fig. 3. Time evolution of the angular velocity ω on time for different damping coefficients ($D \in \langle 0, 0.5 \rangle$)

4. Conclusion

The full version of the paper will contain the whole mathematical model with detailed information about its numerical solution and much more result with their discussion.

Some steady-state results were compared with data obtained using professional codes (COMSOL Multiphysics). The accordance was very good (the differences did not exceed about 5%). The future work in the domain will be aimed at the acceleration of the suggested algorithm and evaluation of the inverse possibility of induction heating of an unmoving billet by rotating coils or permanent magnets.

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