3D Modeling of Induction Hardening of Teeth Wheels

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***Abstract*—Induction hardening of teeth wheels is modeled. The model consists of two nonlinear partial differential equations describing the distributions of magnetic and temperature fields in the system. All material parameters are supposed to be functions of the temperature. The model is then solved numerically in the hard-coupled formulation using the professional code FLUX3D. The methodology is illustrated by a typical example whose results are discussed.**

Keywords—induction hardening; teeth wheel; magnetic field; temperature field; numerical analysis; coupled problem.

I. INTRODUCTION

Induction hardening is a metallurgical process whose purpose is to bring about local changes in the crystalline structure of surface layers of steel bodies resulting in their higher hardness [1–2]. The required parts of the body are first heated somewhat above temperature Ac_3 securing their uniform austenite internal structure. Then, after eventual equalization of temperatures, the body is intensively cooled by a suitable quenchant. The result is harder, but brittle martensite structure of the hardened parts. The structure of the rest of the body (its core) remains unchanged. The situation is indicated in Fig. 1.

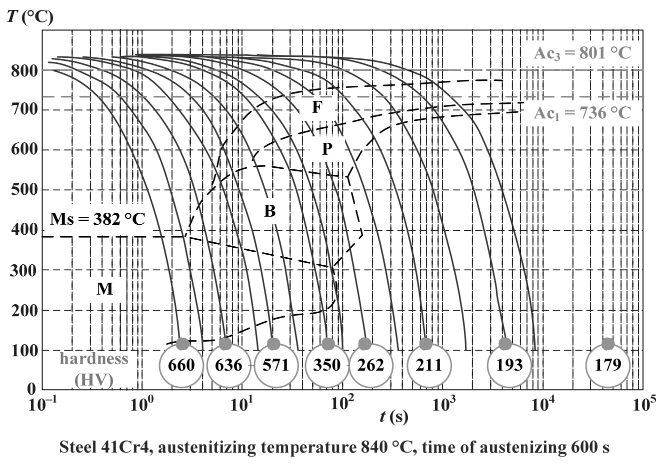

Fig. 1: CCT diagram of typical carbon steel 41Cr4
A – austenite, M – martensite, B – bainite, P – pearlite, F – ferrite
Ac_3 – at this temperature steel exhibits uniform austenite structure
Ms – temperature of the transition to martensite structure

The figure shows several curves of cooling of typical carbon steel (41Cr4) from a starting temperature exceeding Ac_3. Hardness (here in Vickers) HV is a function of the time t of cooling. The higher the velocity of cooling, the harder structure we obtain (see the curves on the left). The other curves (on the right) pass, however, through the area of bainite, pearlite or ferrite.

The paper deals with the computer modeling of induction hardening of a teeth wheel. Its purpose is to harden their surfaces in order to increase their wear resistance. The scheme of the arrangement is in Fig. 2.

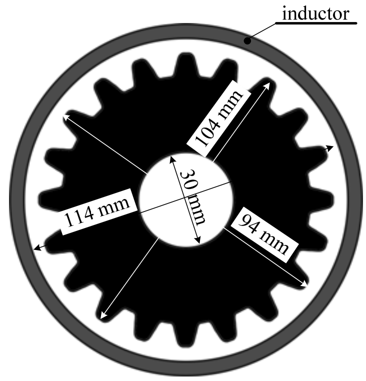

Fig. 2: Induction hardening of a teeth wheel

II. MATHEMATICAL MODEL

The mathematical model of the problem is given by two partial differential equations describing distributions of harmonic electromagnetic field and nonstationary temperature field [3].

$$\operatorname{curl}\left(\frac{1}{\mu}\operatorname{curl}\boldsymbol{A}\right)+\gamma\frac{\partial \boldsymbol{A}}{\partial t}=\boldsymbol{J}_{\mathrm{ext}}\,, \tag{1}$$

where $\boldsymbol{A}$ denotes vector potential, γ the electrical conductivity, μ the magnetic permeability, and $\boldsymbol{J}_{\mathrm{ext}}$ uniform density of the external currents. This equation must be supplemented with a correct boundary condition – in this case of the Dirichlet or Neumann type.

Distribution of nonstationary temperature field in the wheel is given by the heat transfer equation [4]

$$\operatorname{div}\left(\lambda\cdot\operatorname{grad}T\right)=\rho c\cdot\frac{\partial T}{\partial t}-w_{\mathrm{J}} \tag{2}$$

where λ denotes the thermal conductivity of the material, ρ its specific mass, c_{p} its specific heat at a constant pressure (all previous coefficients being functions of temperature) and w_{J} the specific average Joule in the material losses given as

$$w_{\mathrm{J}}=\frac{\boldsymbol{J}\cdot\boldsymbol{J}}{\gamma}\,. \tag{3}$$

where $\boldsymbol{J}$ denotes the density of eddy currents induced in the heated wheel. This is given by the formula

$$\boldsymbol{J} = -\gamma \frac{\partial \boldsymbol{A}}{\partial t} . \quad (4)$$

The boundary conditions have to include convection and radiation.

III. Numerical Analysis

The 3D computation of the problem was realized by the finite element method, using the code FLUX3D supplemented with a number of own procedures and scripts. A considerable attention was paid to selected numerical aspects of the solution, mainly to the convergence of results in the dependence on the density of discretization meshes for both magnetic and temperature field and also on the position of the artificial boundary in the case of magnetic field.

IV. Illustrative Example

The hardened wheel for automotive industry with 20 teeth is made of steel 41Cr4 (see Fig. 1). Its principal dimensions are given in Fig. 2 and its thickness is 6 mm. The Curie temperature of steel 41Cr4 $T_C = 760\,°C$, the austenitizing temperature $A_{C3} = 801\,°C$. The physical parameters (as functions of the temperature) follow:

$$\rho(T) = \rho_0(1+\alpha T), \quad \lambda(T) = \lambda_0(1+\beta T),$$

$$\rho c(T) = \frac{E}{\sqrt{2\pi}\sigma} e^{-b} + (V_0 - V_i) e^{-\frac{T}{\tau}} + V_i, \quad b = \frac{1}{2}\left(\frac{T - T_C}{\sigma}\right)^2,$$

$$B(H,T) = \mu_0 H + \frac{2J_{S0}}{\pi} \operatorname{arctg}\left(\frac{\pi(\mu_{r0}-1)\mu_0 H}{2J_{S0}}\right) \cdot f(T),$$

$$f(T) = 1 - e^{\frac{T - T_C}{C}} \quad \text{for} \quad T \ll T_C,$$

$$f(T) = 10 e^{\frac{T_2 - T}{C}} \quad \text{for} \quad T \to T_C.$$

Here, $\rho_0 = 0.3 \cdot 10^{-6}\,\Omega\text{m}$, $\alpha = 0.358 \cdot 10^{-2}\,\text{K}^{-1}$, $\beta = 0$, $\lambda_0 = 33\,\text{Wm}^{-1}\text{K}^{-1}$, $E = 6 \cdot 10^8$, $\sigma = 20$, $V_0 = 0.38 \cdot 10^7$, $V_i = 0.57 \cdot 10^7$, $\tau = 550$, $C = 40$, $J_{S0} = 2\,\text{T}$, $\mu_{r0} = 600$, $C_0 = 0.4$, $\alpha_c = 15\,\text{Wm}^{-2}\text{K}^{-1}$, $\varepsilon = 0.7$ (emissivity).

First, the field current in the inductor is set to 4500 A at the frequency $f = 10$ kHz. At the moment when the average temperature of the tooth root reaches 1000 °C, the current source is switched and the final part of heating is realized by the field current 1300 A at the frequency $f = 100$ kHz.

The total time of heating is approximately 10.8 s, the time of cooling is 10 s.

Fig. 3: The solved part of the arrangement

Due to the symmetry, it is sufficient to analyze the part of the wheel according to Fig. 3 (containing one half of the tooth). The thickness of this part is 3 mm (one half of the thickness of the wheel).

The number of DOFs for electromagnetic computations was about 26000, for thermal computations about 5000. The computation of one example took approximately 8 hours.

Fig. 4 shows a detail of the tooth with 22 points A1–A11, B1–B11 at the medium plane of the tooth where we checked the time evolution of the temperature.

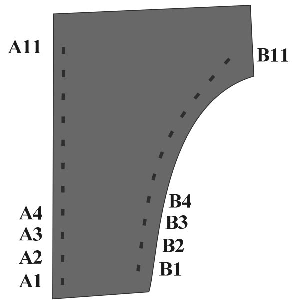

Fig. 4: Selected points of the tooth

Figure 5 shows the profiles of the temperature at points A1–A11 at selected time steps. Its distribution along the particular time levels is fairly homogeneous.

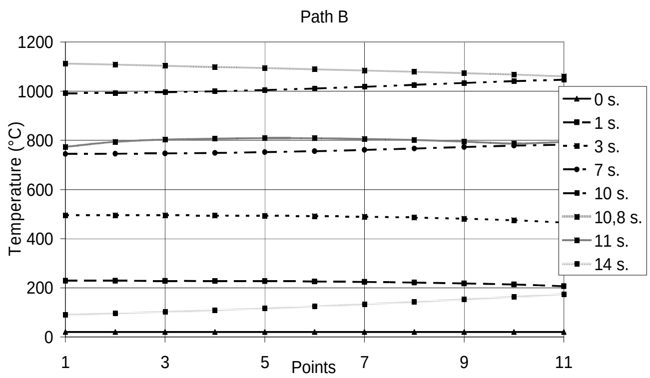

Fig. 5: Time evolution of temperature at points A1–A11

As the time of cooling below the martensite temperature is about 10 s, the resultant hardness of the surface layers of the tooth is about 641 HV (see Fig. 1). This value very well corresponds with the industrial experience.

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