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Numerical modelling of induction hardening of steel bodies

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Abstract

The paper deals with some example of numerical modeling of 3D continual induction surface hardening of steel bodies. Mathematical and computer models of the process that are solved numerically by combination of professional software and own procedures are presented in the paper. Special emphasis is put on taking into radiation phenomena often omitted by other authors. The elaborated algorithms are demonstrated on an illustrative example. The results are discussed and final conclusions are formulated.

Introduction

Surface hardening of steel bodies based on rapid induction heating belongs to modern, energy-efficient and environment-friendly technologies. The paper is aimed at the numerical simulation of continual induction hardening of working surfaces of various steel tools like used in plastic working technologies The elements made from typical carbon steels have various shapes and dimensions. They can be heated by a non-moving or moving inductors of the shape adjusted to the geometry of the 3D workpiece and then immediately cooled in a quenchant or by a properly designed sprayer. The solution of the problem starts from constitution of the mathematical model describing distribution of harmonic electromagnetic and non-stationary temperature fields. The task is formulated typically as a weakly-coupled problem. The result is the knowledge of evolution of temperature and consequently hardness distribution in the hardened layer of the body. The calculations are realized mainly by the 3D professional FEM-based codes in cooperation with some own numerical procedures. The methodology is illustrated on solution of a particular technical problem, discussion of its results and formulation of final conclusions.

1. General Information

The basic exemplary arrangement of the inductor - steel body system is depicted in Fig. 1

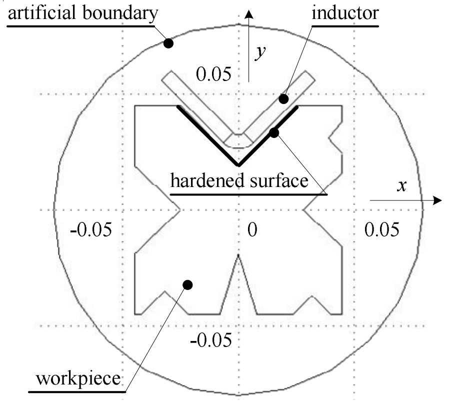

Fig. 1. Basic arrangement of the inductor-hardened body system

The task is to harden the indicated surface of the steel body. The inductor formed by a massive conductor moves at a slow velocity from the front part to the rear part of the workpiece. Then the heated surface is intensively cooled by the sprayer. The aim of the paper is to map the temperature evolution and resultant hardness in the domain of the hardened surface.

2. Mathematical model

The mathematical model of the problem is given by two partial differential equations describing distribution of non-stationary electromagnetic and temperature fields

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

where $\boldsymbol{A}$ denotes the magnetic vector potential, μ the magnetic permeability. γ the electrical conductivity, $\boldsymbol{v}$ – velocity of workpiece movement and $\boldsymbol{J}_{\mathrm{z}}$ - external current density.

For coreless inductor and also in every case when for any reasons magnetic permeability could be considered as constant electromagnetic field is described in a simplified way as a quasi-stationary field by the Helmholtz equation for phasors of magnetic vector potential $\underline{\boldsymbol{A}}$ and external current density $\underline{\boldsymbol{J}}_{\mathrm{Z}}$ [1]

$$\operatorname{curl}\operatorname{curl}\underline{\boldsymbol{A}}+\mathrm{j}\cdot\omega\gamma\mu\underline{\boldsymbol{A}}-\gamma\mu\left(\boldsymbol{v}\times\operatorname{curl}\underline{\boldsymbol{A}}\right)=\mu\underline{\boldsymbol{J}}_{\mathrm{Z}} \tag{2}$$

where: j denotes– imaginary unit, ω - angular frequency.

Each sub-domain of the system (workpiece, inductor, sprayer, surroundings etc.) is characterized by specific values of γ and μ The Dirichlet condition along the artificial boundary sufficiently distant from the inductor-workpiece system reads

$$\underline{\boldsymbol{A}}=0 \tag{3}$$

Definition area of non-stationary temperature field is represented by the workpiece and its distribution is given by the Fourier-Kirchhoff equation [2]

$$\operatorname{div}\left(\lambda\cdot\operatorname{grad}T\right)-\rho c\left(\boldsymbol{v}\operatorname{grad}T\right)=\rho c\cdot\frac{\partial T}{\partial t}-p_{\mathrm{V}} \tag{4}$$

where λ denotes the specific heat conduction of the material, ρ its specific mass, c its specific heat and p_{V} the specific average Joule losses given as

$$p_{\mathrm{V}}=\gamma\omega^{2}\left|\underline{\boldsymbol{A}}\right|^{2}. \tag{5}$$

The boundary conditions are set up according to the physical nature of the task. In analyzed case of induction heating being the first step of the hardening process as well as for the short second step natural cooling it is necessary to take into consideration both convection and radiation phenomena. In case of the third step – intensive cooling of the workpiece more often it is enough to take into consideration convection only. At the external surfaces of the workpiece the following boundary condition is valid:

$$-\lambda\frac{\partial T}{\partial n}=\alpha_{\mathrm{k}}\left(T-T_{\mathrm{k}}\right)+\sigma_{\mathrm{o}}\cdot\varepsilon\cdot\left(T^4-T_{\mathrm{r}}^4\right) \tag{6}$$

where n – outward normal to the surface, α_{k} - convection heat transfer coefficient, T_{k} - ambient temperature, σ_{o} - Boltzmann constant, ε - total emissivity, T_{r} - temperature of surrounding surface

At both symmetry planes

$$\frac{\partial T}{\partial n}=0 \tag{7}$$

If we could consider

$$T_{\mathrm{r}}\approx T_{\mathrm{k}} \tag{8}$$

then generalized heat transfer coefficient α_{z} represented both convection and radiation could be introduced. It has a form written below

$$\alpha_{\mathrm{z}}=\alpha_{\mathrm{k}}+\sigma_{\mathrm{o}}\cdot\varepsilon\cdot(T^2+T_{\mathrm{r}}^2)\cdot(T+T_{\mathrm{r}}) \tag{9}$$

Consequently the equation (6) could be written as:

$$-\lambda\frac{\partial T}{\partial n}=\alpha_{\mathrm{z}}\left(T-T_{\mathrm{k}}\right) \tag{10}$$

If condition (8) is not satisfied then (6) could be used in a more general form (11) where radiation heat transfer coefficient α_{r} is clearly represented by a second term of the equation (11)

$$-\lambda\frac{\partial T}{\partial n}=\alpha_{\mathrm{k}}\cdot\left(T-T_{\mathrm{k}}\right)+\alpha_{\mathrm{r}}\cdot\left(T-T_{\mathrm{r}}\right) \tag{11}$$

And if it is not possible to omit multiple reflections phenomena the condition (11) transforms to the form (12) with an additional component p_{r} corresponding to the phenomena of multiple reflections

$$-\lambda\frac{\partial T}{\partial n}=\alpha_{\mathrm{k}}\cdot\left(T-T_{\mathrm{k}}\right)+\alpha_{\mathrm{r}}\cdot\left(T-T_{\mathrm{r}}\right)-p_{\mathrm{r}} \tag{12}$$

Phenomena of multiple reflection phenomena and their role in induction heating are more described for instance in [3, 4].

For cooling the heat transfer condition could be considered in a form (13)

$$-\lambda\frac{\partial T}{\partial n}=\alpha_{\mathrm{k}}\left(T-T_{\mathrm{c}}\right) \tag{13}$$

where T_c denotes temperature of cooling quenchant.

3. Illustrative Example

The investigated workpiece is manufactured from steel 41 Cr4 whose chemical composition is given in table 1

Table 1 Chemical composition of the steel 41Cr4

Type of steel	Component [%].							
	C	Mn	Si	P	S	Cr	Ni	Cu
41Cr4	0,40	0,73	0,24	0,025	0,023	1,05	0,16	0,18

For real conditions of induction hardening diagrams CTA for heating to austenizing temperature and unbalanced diagram $^{*}CTP_C$ were experimentally elaborated [5]. As a result of measurements it could be stated that austenizing temperature Ac3 for rapid induction heating is higher than in case of a classical heat treatment. is shown in Fig. 2.

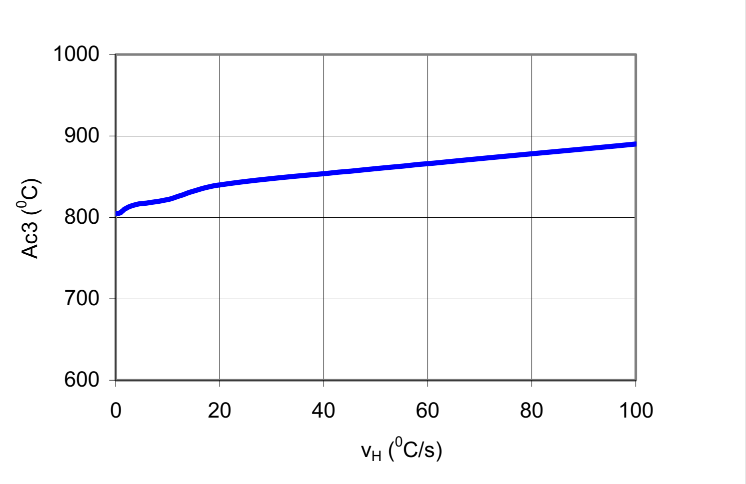

Fig.2 Dependence of Ac3 temperature on velocity of heating

Based upon $^{*}CTP_C$ unbalanced diagram martensite structure of the workpiece could be obtained in case of intensive cooling with velocity more than 100°C/s. Modelling are provided for a few values of inductor current density with a range between 10 – 20 A/mm^2 and frequency $f = 20$ kHz. In order to simplify solving of the equation for electromagnetic field the workpiece is artificially divided into two parts (Fig.3).

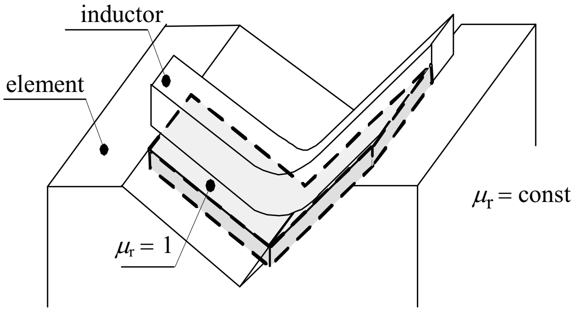

Fig.3 Distribution of relative magnetic permeability in workpiece

Relative magnetic permeability in a thin layer below inductor $\mu_r = 1$, however in all remaining places body do not reach the temperature of the Curie point, so it is assumed that $\mu_r = \text{const}$. Dimensions of thin non-magnetic layer are determined based upon simplified calculations. Below are listed some other parameters of the hardening system:

- length of the body $l = 0.118$ m (see Fig.1),
- velocity of inductor movement $v = 0.002$ m/s
- intensive cooling by sprayed water of temperature $T_c = 10^{\circ}$C,
- convection heat transfer coefficient during heating and natural cooling $\alpha_k = 20 \mathrm{W/(m^2 \cdot K)}$,
- convection heat transfer coefficient during intensive cooling $\alpha_k = 500 \mathrm{W/(m^2 \cdot K)}$,
- ambient temperature $T_k = 30^{\circ}$C,
- total emissivity $\varepsilon = 0.8$ and temperature $T_r = 40^{\circ}$C of the external radiation surface.

The algorithm consists of the following steps:

- the inductor appears above the indicated part. The time of its crossing is 4.5 s calculated as ratio of width of inductor to velocity of inductor movement,
- after crossing the part by the inductor there is a natural cooling (time of that step is 2s).
- now there appears a sprayer with water that provides intensive cooling.

Fig. 4 shows the time evolution of temperature at selected point of the surface.

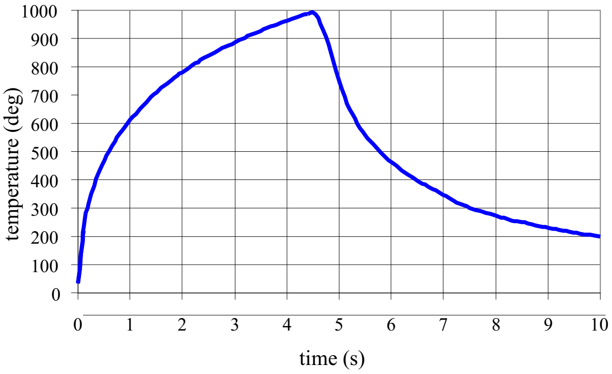

Fig.4 Time evolution of temperature at selected point of the surface (*z* = 0.05)

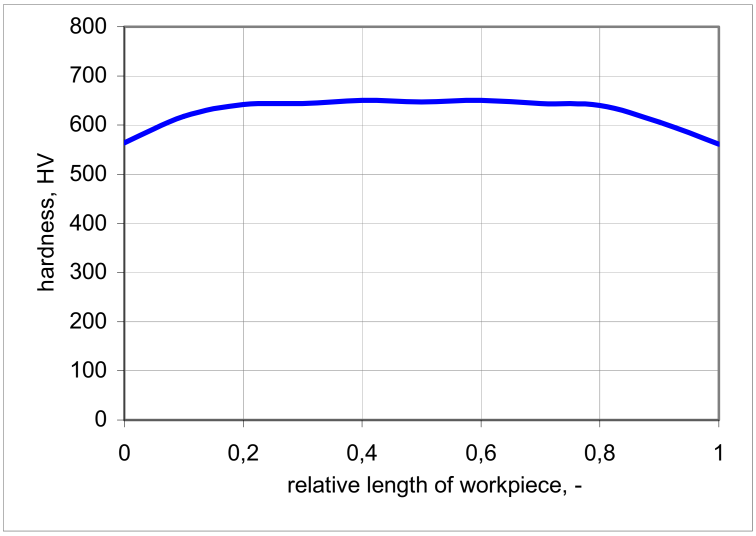

Fig.5 Hardness distribution along working plane of the tool

In order to avoid decreasing of hardness in both end-parts of the workpiece the inductor does not move in these regions for a short period of time.

Based upon known time evolution of temperature for all points of the surface layer and measured $*CTP_C$ unbalanced diagram for investigated steel hardness distribution is determined. Comparison of calculated and measured data for real hardening process is presented in tab. 2

Tab.2 Measured and calculated data of hardness at surface of the workpiece

Relative length	0.05	0.2	0.4	0.6	0.8	0.95
Hardness HV measured	660	664	658	665	657	661
Hardness HV calculated	640	642	640	640	641	642

Conclusions

The paper deals with some example of numerical modeling of 3D continual induction surface hardening of steel bodies. The solution was carried out on a mathematical model in the weakly coupled formulation, but with taking into account radiation phenomena however only in a simplified way. The achieved results qualitatively well correspond with the experimental data. Characteristic is that measured values of hardness are bigger that calculation ones. It is caused by neglecting of multiple reflection phenomena. The next work in the field should be aimed at elaboration of more sophisticated model of the process.

Acknowledgement

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