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Industrial Heating System Creating Given Temperature Distribution

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Abstract: The aim of the work is precise coupled electromagnetic-temperature field analysis using the finite element method of an induction heating system and creation of adequate field models at chosen control points. The obtained models have been applied in an optimisation task, concerning special requirements for temperature distribution in the heated detail. The field analysis problem was solved as nonlinear, transient and axisymmetrical. The field models used in the optimisation problem were based on the Response surface method and Design of experiment. The presented example refers to a real induction heating system. Heated details after plastic deformation and hardening are used for producing farm instruments.

Keywords: Coupled field, Induction heating, Response surface method, Optimisation.

1 Introduction

Nowadays, induction heating systems are widely used in industry [1]. Induction heating plays an important role in industrial heating. It can heat very accurately depths and surface areas in clean operating conditions with high power densities and short heating times. That is why they are of permanent interest to researchers in recent years.

The present paper deals with investigation of an induction heating system. It consists of a flat inductor wound of rectangular wires which is posed over a square magnetic core. The system is applied for temperature treatment of stainless steel discs. After heating and plastic deformation, hardened discs are used for producing farm instruments.

Generally, flat inductors have been used for low and medium heating of flat details, usually of regular shape. The temperature field importance is as follows:

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– for temperatures lower than 500°C the temperature field distribution is not significant and the inductor is constructed with a constant winding step;

– for medium temperatures of heating before hardening creation of an electromagnetic field is necessary, which ensures a thermal field with a specified distribution and that is why the inductor should be wound either in sections or with a variable winding step.

A flat inductor with a constant winding step was developed as a prototype for heating up to temperatures of 800-900°C made of stainless steel discs for agricultural tools, having an outer diameter of 600-700 mm and thickness 6 mm before hardening. Having in mind the lack of theoretical analysis of the distribution of electromagnetic and thermal fields the requirement for specific distribution of temperatures has not been fulfilled. This was the motivation for numerical and experimental modelling, for which a laboratory prototype has been created.

The aim of the work is investigation of the electromagnetic and temperature field of the induction heating system and creating adequate field models at some control points. These are used in solving an optimisation problem, concerning special requirements for temperature distribution in the heated detail.

Numerical models of the coupled electromagnetic and temperature fields were based on the finite element method (FEM) and response surface method (RSM). Electromagnetic and temperature distributions were obtained using the COMSOL 3.3 software package. The results were compared to experimental data for a given temperature in a laboratory experimental setup [2].

2 Induction Heating System Description

A general view of the induction heating system is shown in Fig. 1.

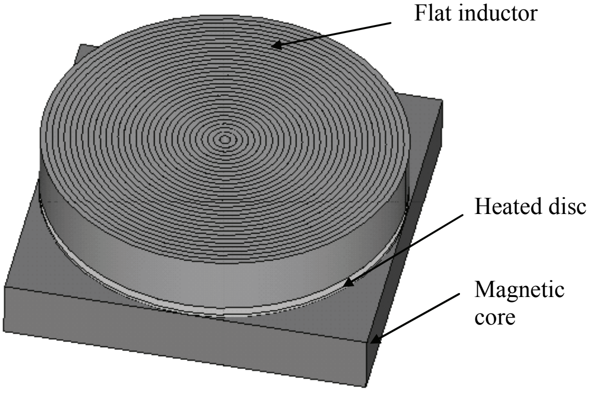

Fig. 1 – *Geometry of the induction heating system.*

The inductor is posed over a 100 mm high square magnetic core. It includes 30 conductor turns with a rectangular cross section of $100 \times 10\,\text{mm}$. The matter between them is insulating. The input voltage and the exciting current are $380\,\text{V}$ and $3300\,\text{A}$ respectively. The current frequency is $f = 50\,\text{Hz}$. The system is applied for temperature treatment of stainless steel discs with $680\,\text{mm}$ diameters and $6\,\text{mm}$ thickness. The distance between inductor and heated disc is from 5 to $15\,\text{mm}$. In 10 minutes the measured temperature in the middle of the disc arises close to 8000°C. The temperature of ambient air and the initial temperature of the heated detail is $T_0 = 20°\text{C}$.

Due to the specific purpose: heating, plastic deformation and then hardening of the details, there are special requirements for temperature distribution in the heated discs. It is necessary to obtain a practically homogeneous temperature field in the heated detail in a short time (during the transient heating process). It can be realised by optimisation of the system's design – changing the distance between inductor and heated disc and making section inductors with different current densities.

3 Coupled Field Analysis

Due to the axial symmetry of the geometry and cylindrical coordinates, the problem is considered as a two-dimensional one. Numerical simulation of the heating process consists of analysis of a two-dimensional electromagnetic problem coupled with a transient thermal problem, taking into consideration system nonlinearities (change of physical properties during heating).

The electromagnetic problem is quasistationary and the field model with respect to the magnetic vector potential *A* is based on the following equation:

$$j\omega\sigma \boldsymbol{A} + \operatorname{rot}\left(\frac{1}{\mu}\operatorname{rot}\boldsymbol{A}\right) = \boldsymbol{J}\,. \tag{1}$$

where ω is the angular frequency, σ is the electric conductivity, μ is the magnetic permeability and *J* is the current density.

The transient thermal field is modelled by:

$$\gamma c \frac{\partial T}{\partial t} + \operatorname{div}(-\lambda \operatorname{grad} T) = q \tag{2}$$

where λ is the thermal conductivity, *T* is the temperature, γ is the density, *c* is the specific heat. Eddy currents induced in an electrically conductive heated body produce specific Joule losses *q*:

$$q = \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t}\right)^2 \tag{3}$$

Equation (2) is solved under convection and radiation conditions.

The coupled problem is solved using coupling of the quasistationary electromagnetic and transient thermal problem in a domain consisting of the whole system and a wide buffer zone around it.

4 FEM Simulations

Numerical simulation of the coupled fields was carried out using FEM and the COMSOL 3.3 software package.

The results were obtained for a time period of 1500 seconds. The electromagnetic problem was solved at every 10 seconds taking into account the temperature dependence of material properties. As a result of electromagnetic field analysis, the heat generated in the heated detail was obtained and used as the heat source during the next 10 seconds. The thermal problem was solved as nonlinear and the temperature dependence of thermal coefficients was taken into account.

A finite element mesh consisting of 45517 elements is shown in Fig. 2.

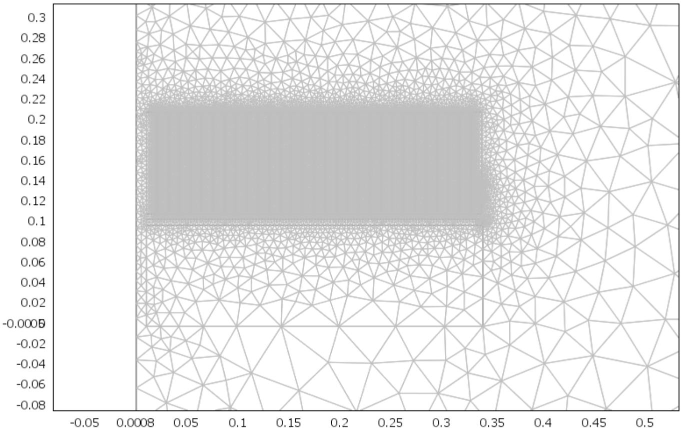

Fig. 2 – FE *mesh for problem solving.*

The result of electromagnetic field analysis – total current density distribution is shown in Fig. 3.

For the time period of $t = 600\,\text{s}$ the point with the maximal temperature was determined. It is the point with a radius of $r = 0.21\,\text{m}$ and the temperature is 883°C. This time was considered because this was the time in which the experiment was carried out. The transient heating process in this point is shown in Fig. 4.

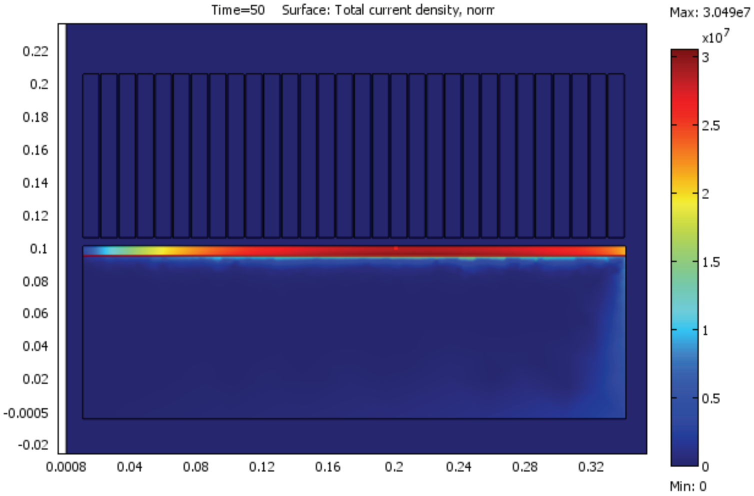

Fig. 3 – *Total current density in the investigated region.*

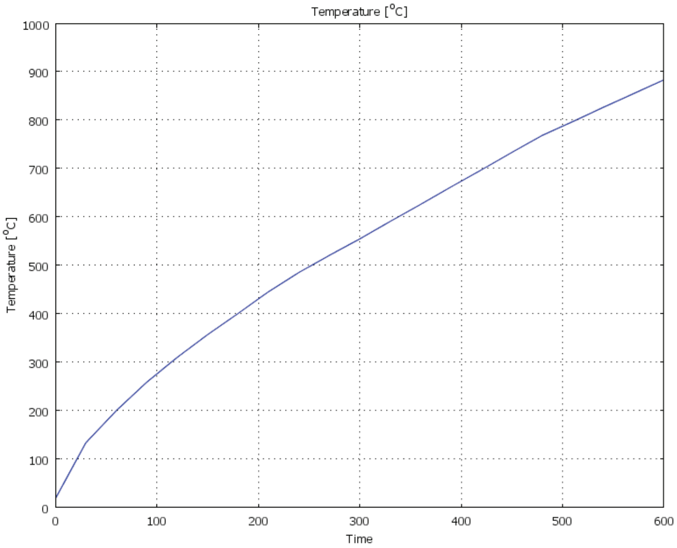

Fig. 4 – *Maximal temperature* (*point of radius* $r = 0.21\,\mathrm{m}$) – *transient process.*

The temperature distribution in the heated disc in the radial direction for time $t = 600\,\mathrm{s}$ is shown in Fig. 5.

The heating process during the observed period is shown in Fig. 6. The temperature distribution in the heated disc in the radial direction at different moments of the heating process (time $t_1 = 100\,\mathrm{s}$, $t_2 = 200\,\mathrm{s}$, $t_3 = 300\,\mathrm{s}$, $t_4 = 400\,\mathrm{s}$, $t_5 = 500\,\mathrm{s}$, $t_6 = 600\,\mathrm{s}$) is shown in Fig. 7.

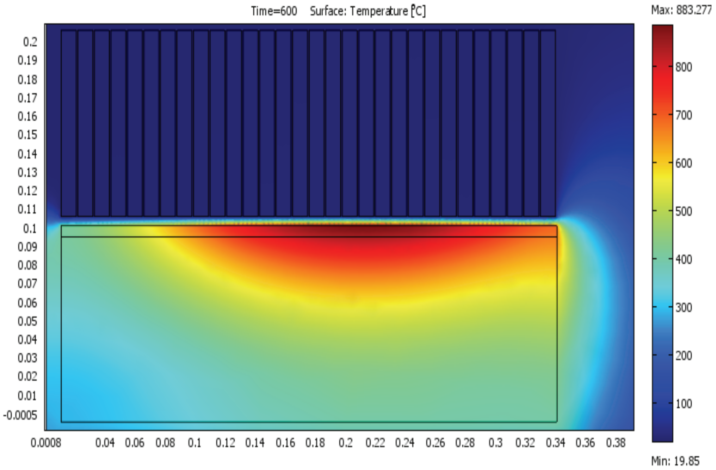

Fig. 5 – *Temperature distribution in the heated disk in the radial direction for time t* = 600sec.

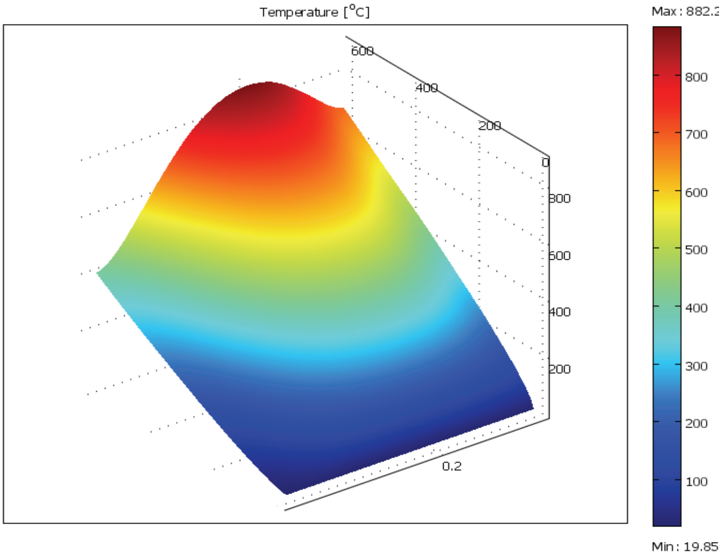

Fig. 6 – *Temperature distribution in the heated disc in the radial direction during the heating process.*

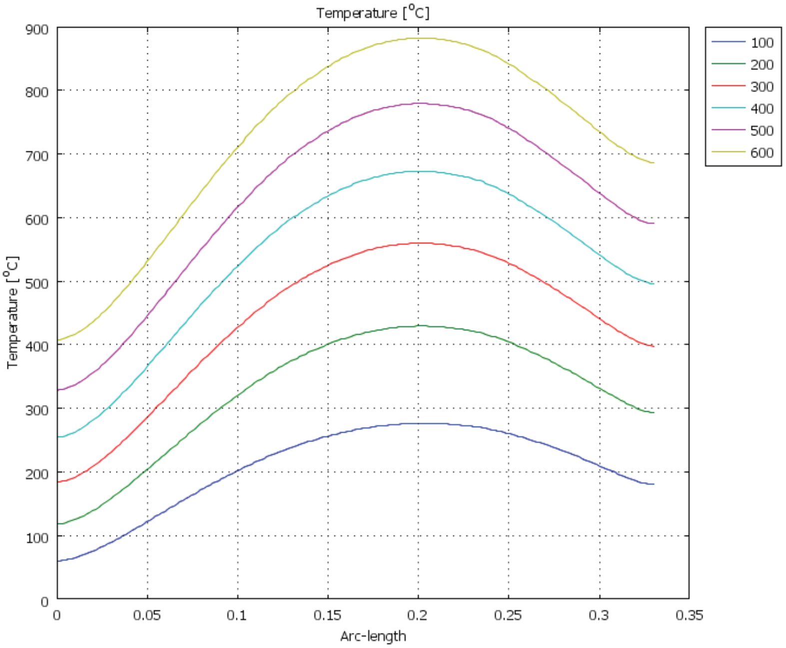

Fig. 7 – *Temperature distribution in the heated disc in the radial direction at different moments of the heating process* (*time* $t_1 = 100\,\text{s}$, $t_2 = 200\,\text{s}$, $t_3 = 300\,\text{s}$, $t_4 = 400\,\text{s}$, $t_5 = 500\,\text{s}$, $t_6 = 600\,\text{s}$).

5 Inverse Problem Solution

Analysis of the temperature distribution shows that the temperature field in the heated disc is rather non-uniform. The temperature in the radial direction at the moment $t = 600\,\text{s}$ varied from 400ºC to 800ºC (Fig. 6 and Fig. 7). Due to the necessity of obtaining a uniform temperature field, an inverse problem was solved – determination of the system's design. It included obtaining of the design parameters providing a practically homogeneous temperature distribution in the radial direction during heating. The chosen design parameters (Fig. 8) are the distance d between the inductor and heated disc and different current densities ($J_1, J_2, \ldots, J_5$) of different sections of the inductor.

Models of temperature values at 8 control points were obtained using a combination of RSM and design of experiments (DOE) [3]. Each experiment was a numerical FEM analysis of the electromagnetic and temperature field. The models significantly depended on the design variables. Thus the temperature at j-th control point $\hat{T}^j$ was approximated as a second order polynomial expression of the following type:

$$\hat{T}^j = b_0^j + \sum_{k=1}^{p} b_k^j h_k + \sum_{k=1}^{p} b_{kk}^j h_k^2 + \sum_{\substack{k=1 \\ r=k+1}}^{p} b_{kr}^j h_k h_r \,. \tag{4}$$

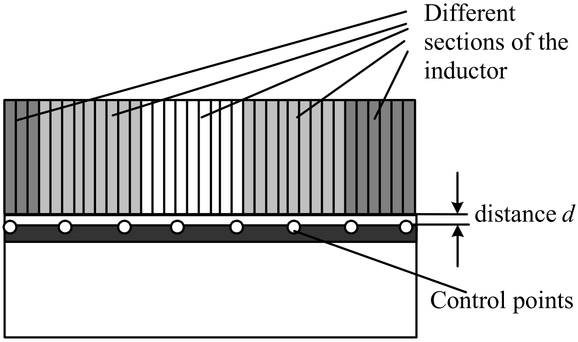

Fig. 8 – *Design parameters.*

In (4), p is the number of design variables h_k, $k = 1 \div p$. The design variables are used in normalized units and correspond to different current densities in inductor sections. The distance d is chosen to be a constant $d = 5\,\text{mm}$ and the densities $J_1 = J_5$, $J_2 = J_4$. Thus the number of FEM experiments using Central Composite Design (CCD) with $p = 3$ design parameters was:

$$M = 2^p + 2p + 1 = 15\,.$$

The inverse problem was solved as an optimization one. The optimization criterion used was the quadratic sum of the differences between the computed and desired constant temperature data:

$$F_{\min}(\vec{h}) = \left\{ \sum_{j=1}^{p} \left(\hat{T}^j - T_{desired} \right)^2 \right\}_{\min} . \tag{5}$$

The obtained design parameters were applied in FEM analysis. The results for the temperature distribution in an optimized induction heating system showed that the special requirements for temperature distribution in the heated detail were satisfied. The temperature distribution in the heated disc in the radial direction in time $t = 600\,\text{s}$ is shown in Fig. 9.

The heating process for the optimized system during the observed period is shown in Fig. 10.

The comparison between the temperature distribution in control points before and after optimization of the induction heating system is shown in Fig. 11.

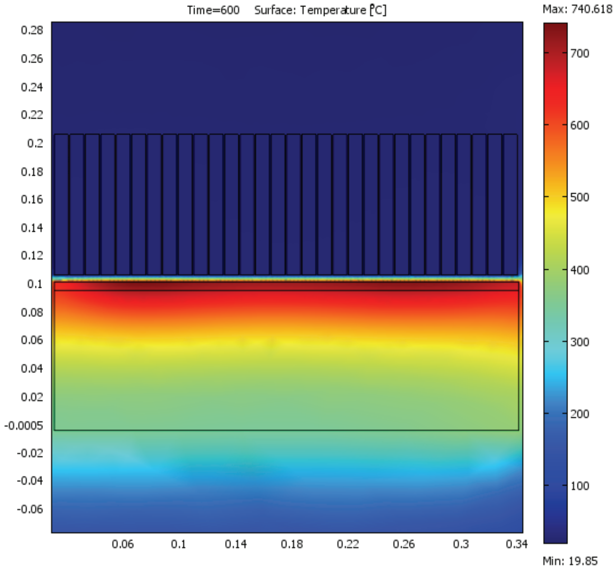

Fig. 9 – *Temperature distribution in the heated disc after optimization in the radial direction for time* $t = 600\,\mathrm{s}$.

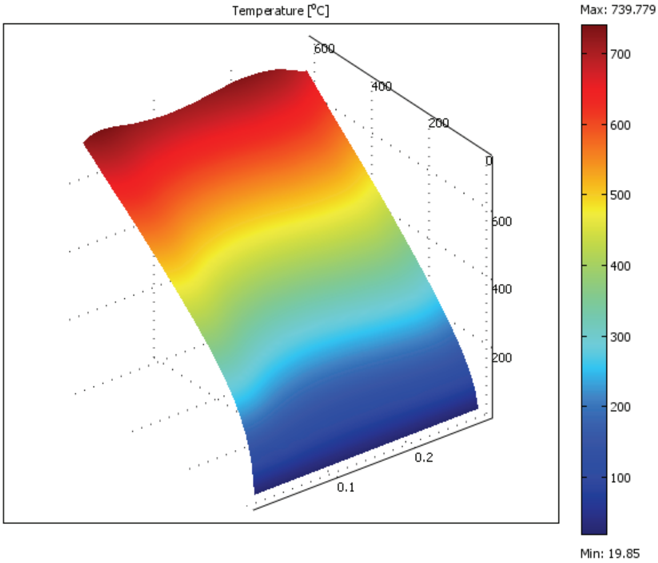

Fig. 10 – *Temperature distribution after optimization in the radial direction during the heating process.*

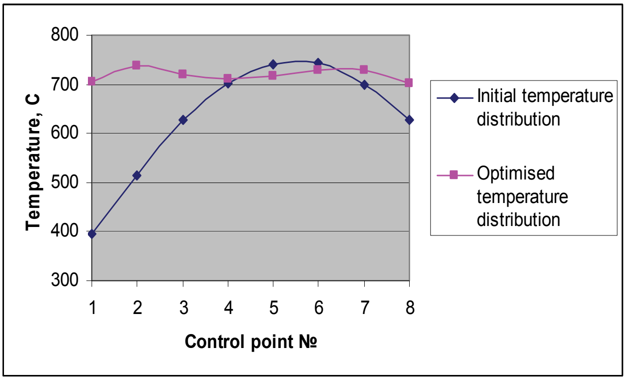

Fig. 11 – *Comparison between the temperature distribution in control points before and after optimization of the induction heating system for* $t = 600\,\mathrm{s}$.

6 Conclusion

A detailed investigation of the electromagnetic and temperature field of an induction heating system was performed using FEM and the COMSOL 3.3 software package. Numerical models of the temperature field in eight control points were obtained based on the finite element method and the response surface method. They were used to solve the optimization problem, taking into account special requirements for temperature distribution in the heated detail. The comparison between the temperature distribution in control points before and after optimization of the induction heating system showed that requirements for temperature distribution in the heated detail were satisfied.

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7 References

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