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Application of the FLUX 3D temperature field analysis of cylindrical workpiece in the process of induction heating

Streszczenie. *W pracy przedstawiono wyniki obliczeń pola temperatury w procesie nagrzewania indukcyjnego wsadów cylindrycznych od wewnątrz. Wykonano obliczenia w programie FLUX 3D metodą elementów skończonych. Obliczenia parametrów pola temperatury wykonano dla trzech różnych czasów nagrzewania. Rozkład temperatury wyznaczony został dla prądu o wartości skutecznej 2kA i częstotliwości 10 kHz.* ***(Zastosowanie programu FLUX 3D do analizy pola temperatury wsadów cylindrycznych w procesie nagrzewania indukcyjnego.)***

Abstract*. The paper encloses the results of the numerical analysis of temperature in the induction heating device for cylindrical workpieces. Numerical simulation was made for three different value of the times. Temperature in the workpiece was calculated for current I=2 kA and frequency f=10 kHz. The heating process was simulated and analyzed in the FLUX 3D program by using of finite element method.*

Słowa kluczowe: Pole temperatury, nagrzewanie indukcyjne, hartowanie indukcyjne, pola sprzężone.
Keywords: Temperature field, induction heating, induction hardening, coupled fields.

Introduction

Induction heating is often used in many production processes such as the automotive industry. A process of heating of current-conducting materials (metals usually) due to electromagnetic induction, which produces eddy currents leading to heating of materials. High speed of heating, high power densities, small heating time, easy automatization and control, clean and safe operating conditions are the main benefits of this type of heating. inductor and heating object called loading [1, 3-5]. An example application of an induction heater may be hardening various types of pipes. For the individual needs the chosen process parameters of inductors and power sources to achieve the proper temperature on the surface of the load. Figure 1 shows a cross section of the pipe-hardened from the inside. Inside the pipe is five turns inductor.

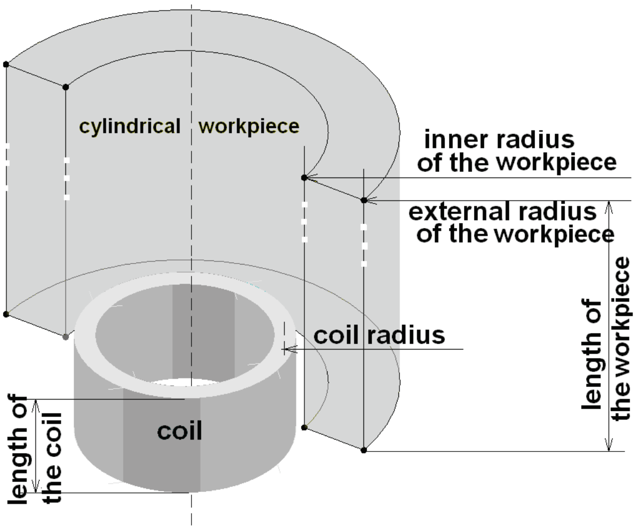


Fig.1. Cross-section of the workpiece of internal inductors.

Construction of mathematical model

In magneto-thermal problems the resistivity ρ and the magnetic permeability μ depend on the temperature $\boldsymbol{\theta}$. When computing eddy currents in ferrous pieces, the non-linear dependence of the magnetic permeability on the magnetic field strength must also be taken into account, because the corresponding regions are often highly saturated. The eddy current density has the expression $\underline{\boldsymbol{J}} = div\boldsymbol{T}$ and the volume density of the induced power is

(1) $$p = \rho \cdot \left|\underline{\boldsymbol{J}}\right|^2$$

The evaluation of the transient temperature field $\boldsymbol{\theta}(\boldsymbol{r},t)$. in the thermal conductive volume regions, characterized by thermal conductivity k and specific heat $\rho \cdot C_p$, where the heat sources are expressed by the volume density p, supposes the integration of the **Fourier equation** [6-8]:

(2) $$\rho C_p \left(\frac{\partial \boldsymbol{\theta}}{\partial t}\right) = div\left(k \cdot grad\boldsymbol{\theta}\right) + p$$

The associated boundary condition of the general form [10-13]:

(3) $$k \cdot \boldsymbol{n} grad\boldsymbol{\theta} = h\left(\boldsymbol{\theta} - \boldsymbol{\theta}_a\right) + \varepsilon \cdot C_n\left(\boldsymbol{\theta}^4 - \boldsymbol{\theta}_a^4\right) + p_s$$

expresses the thermal exchange by convection (coefficient h) and by radiation (coefficient ε) on the surface of the thermal conductive region to the environment having the temperature $\boldsymbol{\theta}_a$. The existence of a thermal flux of surface density p_s can be considered by the boundary condition.

The initial condition related to the thermal field, $\boldsymbol{\theta}(\boldsymbol{r},0)$, must be known.

The magneto-thermal coupling is a weak coupling between electromagnetic and thermal aspects that characterize the induction heating processes.

This coupling supposes the solving of magneto-harmonic and thermal transient equations at each time step. The derivative with respect to the variable time in the Fourier equation is approximated by finite differences and the study time domain (t_0, t_f) is replaced by a series of discrete time step values $(t_0,\ t_1,\ t_2,\ ....\ t_j\ ...\ t_f)$. At each time step t_j, $j = 0,1,2,3,...$ first the electromagnetic aspect is analyzed and then, the thermal one.

The solving of problems with magneto-thermal coupling, require a long computation time. In addition, if problems are magnetic nonlinear, this time can increase considerably.

The algorithm of this method is summarized below [4].

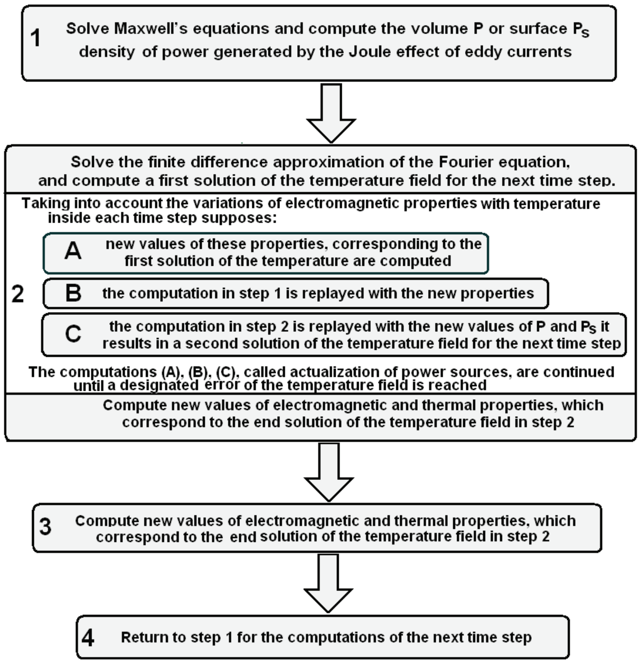


Fig.2 The schematic diagram of the algorithm

Numerical example

Numerical calculations performed for the following parameters of the workpiece and inductor (Fig. 3) [2]:

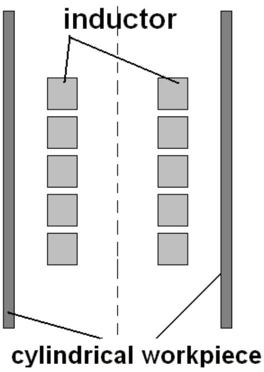


Fig.3. Diagram of inductor heater.

Inductor winding is made of copper with conductivity equal to $\gamma = 5{,}6 \cdot 10^7 [S/m]$ and relative permeability $\mu_r = 1$, through which the current value of the effective I =2kA and frequency f=9835 Hz.

The geometrical dimensions of the internal inductor:

- internal radius 0.0705 m, external radius 0.0825 m
- number of turns 5, height 0.08 m

The geometrical dimensions of cylindrical workpiece:

- inner radius of 0.0925 m, external radius 0.1015 m
- length 2.0 m, conductivity $\gamma = 2 \cdot 10^6 \mathrm{S/m}$
- relative permeability $\mu_r = 300$
- thermal conductivity (workipece) $\lambda = 47 \ \mathrm{W/(m^2 \cdot ^\circ C)}$
- material density $\rho = 7800 \ \mathrm{kg/m^3}$
- specific heat of the charge $c_w = 500 \ \mathrm{J/(kg \cdot ^\circ C)}$,
- convection coefficient $\alpha = 20 \ \mathrm{W/(m^2 \cdot ^\circ C)}$
- radiation coefficient $\varepsilon = 0{,}8$
- ambient temperature $T_0 = 20 \cdot ^\circ C$
- warm-up time t=15 s
- Curie point temperature $T = 760 \ ^\circ C$

The area of computational model is 1/8. XOZ uses a plane of symmetry and two symmetry axis OZ (fig. 4.).

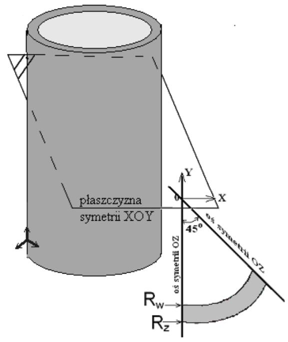


Fig.4 Model of the selected axes and plane of symmetry.

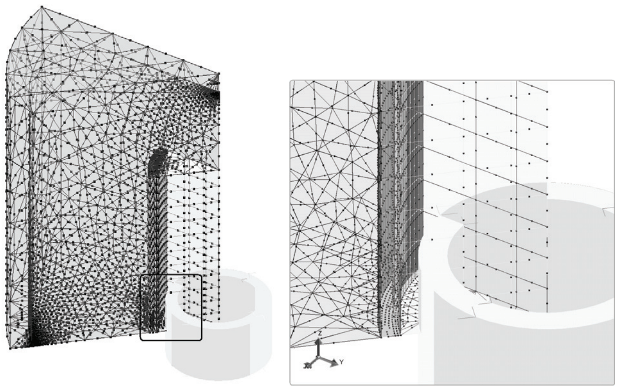


Fig.5 The mesh on selected faces of the computation domain.

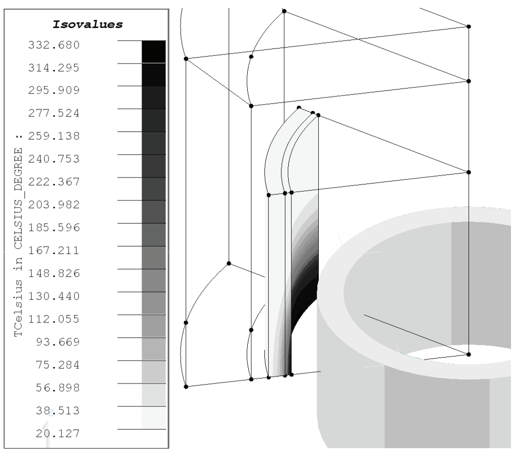
In Table 1 summarizes the number of components using mesh computing.

Table 1. Data of the using mesh

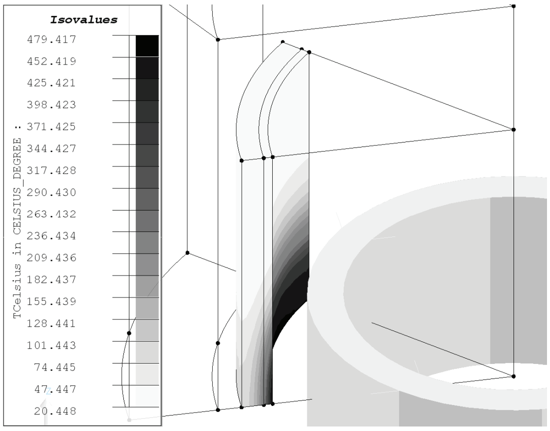
Number of nodes	44181
Number of line elements	512
Number of face elements	5010
Number of volum elements	22683

Figure 6 shows the temperature distribution in the workpiece for the three moments of time.

6 a)



6 b)



6 c)

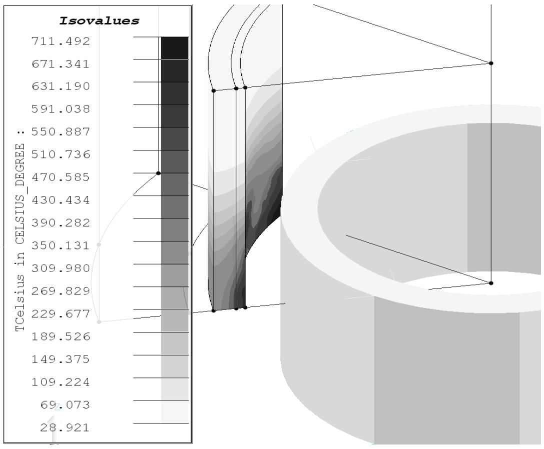


Fig.6 Cylindrical workpiece temperature distribution for a) *t* =0.5 s b) *t* =1,5 s, c) *t* =15 s.

Temperature which is isolated in the charge depends on the physical properties which is characterized by the material from which the workpiece is made [9].

Conclusions

The market provides a wealth of commercial programs that allow 2D or 3D analysis of electromagnetic and thermal phenomena occurring in induction heaters. In the paper the FLUX 3D package, which enables the coupling magnet - thermal and electrical - with the change of thermal physical properties of the charge during the heating process. Field temperatures were determined in the FLUX 3D. The analysis was conducted for three different heating times: 0.5 seconds, 1.5 seconds and 15 seconds. The temperature distribution in the feed cylinder is shown in figures 6 a) – 6 c). Penetration depth for the charge is made of steel type 40 HM depends on the frequency of the power source and the parameters of steel [1-2, 15-16]. In FLUX 3D simulations were performed multi-variant charge heating for different times and different positions heating inductor [17]. The paper presents only the results for the centrally located inside the inductor and cylindrical workpiece for selected heating times. In the drawings can observe the propagation of heat in the feed after a certain period of time. To toughen the feed into the depth of 4mm enough about 3s .

The presented research shows advantages using computer program like FLUX 3D for calculating of distribution of the temperature in the induction heating device for cylindrical worokipece.

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