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Computation of induced current density in a cylindrical workpiece heated by induction with an internal inductor using FLUX3D software package

Abstract. *The paper presents a model of induction heating implemented in FLUX 3D program. Multi-variant calculations of current density distributions were performed. The paper deals with the distribution of current density only for the power source frequency of 9835 Hz. Knowledge of current density distribution is the key to designate the input impedance of the heater, which is strongly influenced by the parameters of the power source.*

Streszczenie. *W pracy przedstawiono model nagrzewnicy indukcyjnej zaimplementowany w programie FLUX 3D. Wykonano obliczenia rozkładu gęstości prądu w programie FLUX 3D metodą elementów skończonych. Zaprezentowano układ nagrzewnicy indukcyjnej wsadu cylindrycznego ze wzbudnikiem wewnętrznym. Źródło zasilania o częstotliwości 9.835 Hz i o prądzie o wartości skutecznej 2kA.* ***(Zastosowanie programu FLUX 3D do obliczenia rozkładu gęstości prądu indukowanego we wsadzie cylindrycznym nagrzewanym indukcyjnie z wzbudnikiem wewnętrznym)***

Keywords: Induction heating, induction hardening, electromagnetic fields.
Słowa kluczowe: Nagrzewanie indukcyjne, hartowanie indukcyjne, pole elektromagnetyczne.

Introduction

Induction heating is the process of heating an electrically conducting object (usually metal) by electromagnetic induction. Eddy currents (also called Foucault currents) are generated within the metal and resistance leads to Joule heating of the metal. High frequency alternating current (AC) passes through a coil. This coil is known as the work coil or the inductor. The frequency of AC used depends on the object size, material type, coupling (between the work coil and the object to be heated) and the penetration depth. It varies from a few Hz to tens of MHz. The passage of current through this coil generates a very intense and rapidly changing magnetic field in the space within the work coil. The workpiece to be heated is placed within this intense alternating magnetic field. The alternating magnetic field induces eddy currents flow in the conductive workpiece. In addition, high frequency used in induction heating applications gives rise to a phenomenon called skin effect. Skin effect forces the alternating current to flow in a thin layer towards the surface of the workpiece. Skin effect increases the effective resistance of the metal to the passage of the large current. Therefore it considerably increases the heating effect caused by the current induced in the workpiece.

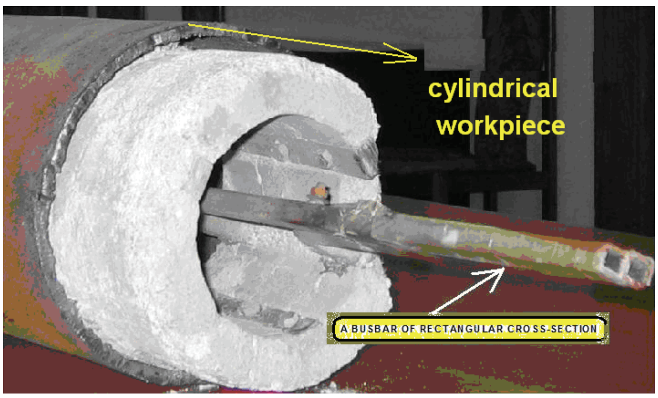

Fig.1. Real system consisting of a cylindrical workpiece with an internal inductor

In theory only 3 things are essential to implement induction heating: a source of high frequency electrical power, a work coil to generate the alternating magnetic field and an electrically conductive workpiece to be heated. However, practical induction heating systems are usually a little more complex. Depending on the heating processes the workpieces and the inductors can have any shape [1, 2]. In this paper we will consider electromagnetic phenomena in a cylindrical workpiece with a coaxial coil placed inside the heating tube – Fig. 1.

Mathematical model

The workpiece processed by induction heating has a cylindrical shape. The studied device shown in the figure below comprises the following components:

- an inductor that generates the source field: the inductor is a cylindrical coil supplied by a sinusoidal current source,
- a workpiece, which corresponds to the thermal treated component: the steel bridle

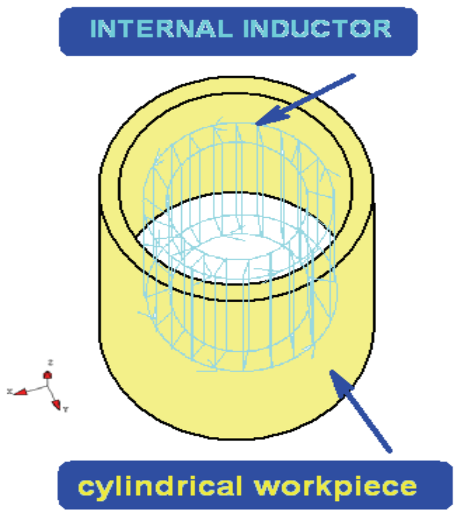

Fig.2. Model of a cylindrical workpiece with an internal inductor

The objective of modeling is to obtain a mathematical representation of the induction heating process by first determining the induced current distribution in the component. Ultimately, one would like to achieve a predictive capability that could be of assistance throughout the process of optimization and new process design. The formulation of the problem requires the statement of the electromagnetic field (Maxwell's) equations in the time-harmonic form neglecting displacement fields. Next, since the magnetic field density can be represented in terms of a magnetic potential $\underline{A}$ by $\underline{B} = \mathrm{curl}\underline{A}$ one has [3]:

- for the workpiece

(1) $$\nabla^2 \underline{A} - \mathrm{j}\omega\mu\gamma\underline{A} = 0$$

- for the internal inductor

(2) $$\nabla^2 \underline{A} - \mathrm{j}\omega\mu\gamma\underline{A} = -\mu\underline{J}$$

The current density is described by the formula:

(3) $$\underline{J} = -\mathrm{j}\omega\mu\gamma\underline{A}$$

The electromagnetic field in the cylindrical workpiece can be given by the analytical formulae if we assume that the tube is long enough and the magnetic field inside, generated by the work coil, is uniform [4, 5].

Numerical model

If the heating tube and the inductor have finite lengths the electromagnetic field in a heating system cylindrical workpiece – internal inductor can be solved by numerical methods only [6-8].

The present paper deals with numerical investigation of an induction heating system. It consists of a cylindrical workpiece and a cylindrical inductor inside it – Fig. 3.

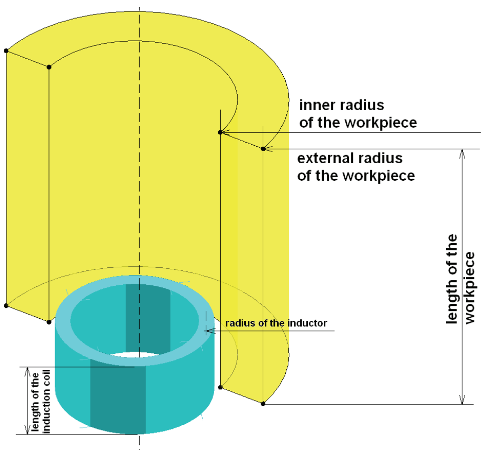

Fig.3. Geometrical model of a cylindrical workpiece with an internal inductor

The geometrical dimensions of the internal inductor are:

- internal radius 0.0705 m,
- external radius 0.0825 m,
- number of turns 5,
- height 0.08 m,
- current 2000 A,
- frequency9835 kHz.

The geometrical dimensions of the steel pipe are:

- inner radius of 0.0925 m,
- external radius 0.1015 m,
- length 2.0 m.

This induction heating system with pieces of cylindrical shapes is axisymmetric therefore we can consider 1 / 8 of it only – Fig. 4.

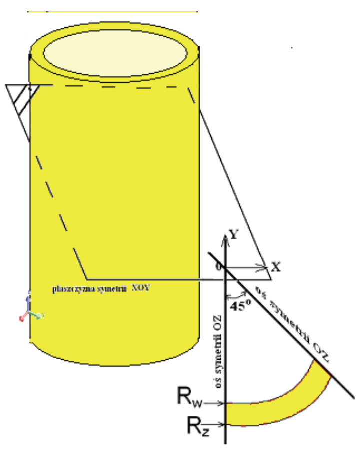

Fig.4. 1/8 of the cylindrical workpiece model

Nowadays, most standard problems in low-frequency are modelled via Maxwell's equations and solved by finite methods (FEMs) [9, 10]. For example several magneto-harmonic models are available in FLUX3D software [11-13]. In this case we build the mesh shown in Figure 5 with the parameters listed in Table I.

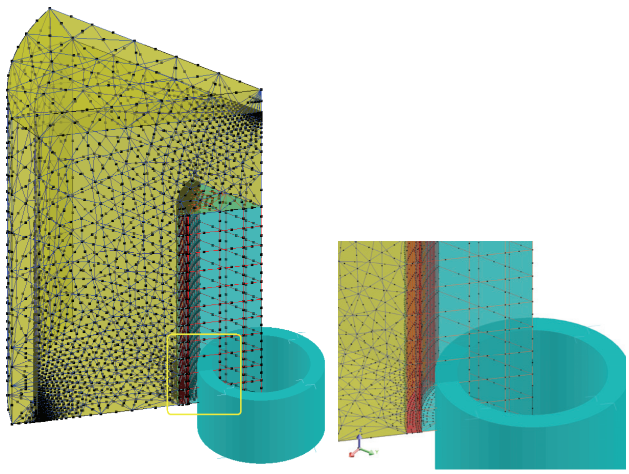

Fig.5. The mesh on selected faces of the computation domain.

Table 1. Data of the using grid

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

For induction heating applications the *TΦ-Φ/Φr* model of the electromagnetic field is frequently used in eddy current problems. This model couples the volume formulations in vector electric potential ***T*** and scalar magnetic potential ***Φ*** in the conductive regions (magnetic or non-magnetic), with the ***Φ*** formulation in magnetic and non-conductive regions, and the ***Φr*** formulation in reduced scalar magnetic potential (non-magnetic and non-conductive regions). The equations solved in eddy current regions are [11]:

(4) $$\mathbf{curl}\left[\frac{1}{\gamma}\mathbf{curl}\underline{\boldsymbol{T}}\right] - \mathbf{grad}\left[\frac{1}{\gamma}\mathrm{div}\underline{\boldsymbol{T}}\right] + \mathrm{j}\omega\mu\left(\underline{\boldsymbol{T}} - \mathbf{grad}\underline{\Phi}\right) = 0$$

and

(5) $$\mathrm{div}\left[\mu\left(\underline{\boldsymbol{T}} - \mathbf{grad}\underline{\Phi}\right)\right] = 0$$

The equation in the non-magnetic and non-conducting region is:

(5) $$\mathrm{div}\left[\mu_0\left(-\mathbf{grad}\underline{\Phi}_r + \underline{\boldsymbol{H}}_0\right)\right] = 0$$

where $\underline{H}_0$ is the magnetic field source generated by the inductor coil in the infinite space in the absence of any material region and is computed by the Biot and Savart formula.

The distribution of current density in a cylindrical workpiece is shown in Figure 6. We also see a coil (with 5 turns) covered by grid computing.

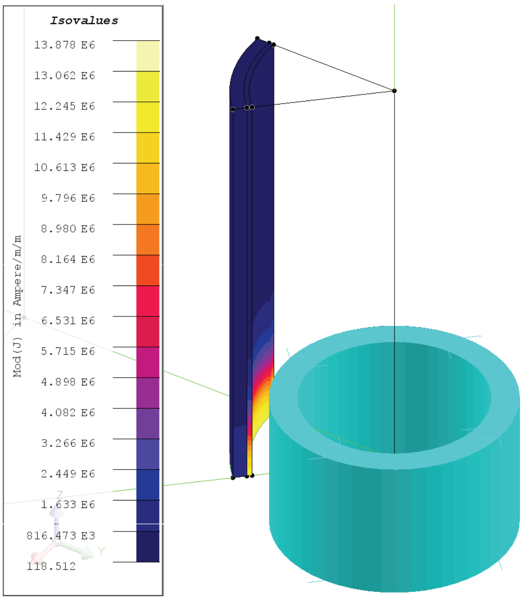

Fig. 6. Current density distribution of a cylindrical workpiece

Figure 7 shows the distribution of the module of current density vector in a selected cross-section of a cylindrical workpiece. The figure also shows the current density vector arrows for the selected phase (180 degrees).

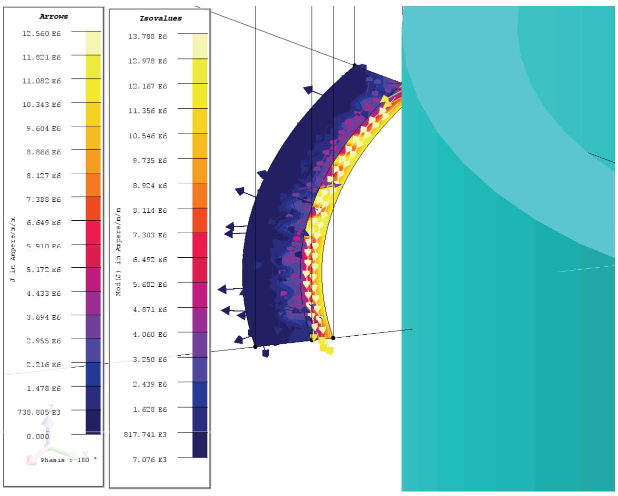

Fig. 7. Distribution of current density in the cross-feed

Conclusions

Performed simulations show that FLUX is a useful tool for preliminary and approximate analysis of the distribution of current density. Using this program multi-variant computer simulation was carried out showing that for high-frequency inductor current over 5kHz clear skin effect and proximity effect take place. The highest current density values of 13.3 MA/m^2 are observed on the internal surface of the workpiece for the frequency of 9835 kHz. Internal inductor is placed in the middle of the tube. Preliminary results of the analysis of this model presented here will be the starting point for further analysis. Further analysis will provide the bulk densities and distributions of surface heating power. The results obtained are useful in predicting the temperature distributions in cylindrical charges and construction of heating systems.

This work was partly financed from the Polish Ministry of Science and Higher Education science 2010-2012 budget as research project N N510 256338.

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