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An Approach for Designing a Complex Inductor –Workpiece system for Induction Heating

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Abstract **– The current paper presents an approach for designing a complex electromagnetic system consisting of an inductor and a workpiece. The approach is based on known methodologies and includes numerical methods for modelling. Using this approach, a methodology for designing the geometry of the inductor, based on the geometry of the workpiece, is suggested. The methodology can be used to develop designs with uniform temperature field, improved quality of the heating process and increased energy efficiency. Experimental study that verifies the advantages of the methodology is presented.**

Keywords **– design methodology, induction heating, numerical methods**

1. Introduction

Induction heating devices used for thermal processing of steel are required to provide specific electrical and temperature parameters during the heating process. Those characteristics include: field distribution – boththermaland electromagnetic, temperature values, heating rate, power, etc... [1], [2]. The correct values of those parameters define the quality of the processed product and energy efficiency of the process.

The most common methods for designing induction heating devices with specific characteristics can be summarized as [1], [2]:

- Chart analysis methodology – time-tested approach used for both research and design [1],[2]. This methodology is based on analytical relationships and experimental data – presented through tables or charts. A main disadvantage of this approach is its lack of flexibility – the approach is mainly applicable in systems that include a cylindrical or flat inductor and aworkpiece with the same shape. The chart analysis methodology is difficult to apply where other geometrical shapes are involved.
- Numerical methods. The most common numerical method applied to the designing induction heating devices and their behavior under different workpieces [6] is the Finite Element Methodology (FEM)[7], [8]. The numerical approach uses computational procedures that can define the distribution of the electromagnetic and thermal fields[9], [12]. Advantage of the numerical method is that it takes into account the functional relations between the thermal properties of the materials, the temperature and the intensity of the electromagnetic field [10] during the transient heating process [11].

The aim of the current paper is to suggest a modified methodology based on FEM for designing a system of inductor and a workpiece for induction heating. The main aspects of the suggested methodology are:

- Application of FEM for modeling a system of inductor and a workpiece for induction heating
- Determining the geometry of the system inductor and a workpiece, through process simulation – in order to increase processing efficiency

2. Design methodology

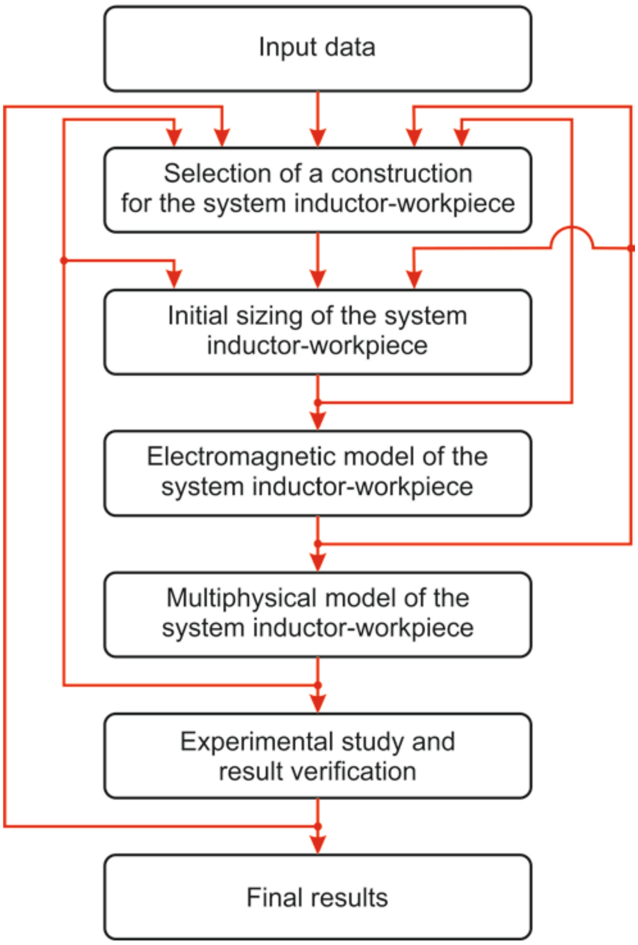

Figure 1.Algorithm for design of a system inductor-workpiece

The flow of the suggested design methodology is presented graphically and structurally in figure 1. Its steps can be summarized as follows:

Step 1 – input data

The input data that has to be defined and is required to initiate the algorithm is as follows: geometrical size of the workpiece; the type of the material; temperature; time and rate of the heating process; electrical characteristics of the power supply for the induction heating device – output current, voltage and frequency.

Step 2 –selection of the construction of the system inductor-workpiece.

The selected construction depends highly on the geometrical properties of the workpiece or the casting – when melting is involved. The most common constructions that can be applied are presented in [1].

Step 3 – Initial sizing of the system inductor-workpiece.

The initial sizing uses chart analysis. The analytical description of the processes is based on the equations presented bellow [1].

First the power density on the surface of the workpiece p_{02} is determined as:

$$p_{02} = P_2 / S_2,\ W/m^2 \tag{1}$$

Where S_2 [m^2] is the surface of the workpiece; P_2 *[W]*-the sum of the power dissipated in the workpiece and the heat losses (this parameter is related to the temperature and rate of the heating process).

Afterwards the permeability μof the workpiece is determined as a function of the specific power density on its surface - p_{02}.

The magnetic field intensity H_{02m} on the surface of the workpiece can be then determined based on the specific power density on the surface of the workpiece - p_{02}:

$$H_{02m} = \sqrt{\frac{p_{02}.10^9}{\sqrt{\rho_2 \cdot \mu \cdot f \cdot F}}},\ \text{A/m} \tag{2}$$

Where ρ_2 *[Ω.m]*is the specific resistance of the workpiece; *f[Hz]*- the frequency; *F* – correction function.

Using a chart, the coefficient of electromagnetic connection k is determined [1].

Following the magnetic field intensity H_{01m} on the surface of the inductor based on its geometrical properties can then be determined as:

$$H_{01m} = H_{02m} / k,\ A/m \tag{3}$$

After accounting for the losses in the inductor and the full power *S* the current *I* can be determined as:

$$I = \frac{S}{U},\ A \tag{4}$$

The number of turnsw_1 of an inductor with height h_1, magnetic intensity H_{01m} and current *I* can be determined as:

$$w_1 = \frac{H_{01}h_1}{\sqrt{2}I} \tag{5}$$

The winding step is given as:

$$b_1 = \frac{h_1}{w_1} \tag{6}$$

Step 4 – Development of an electromagnetic model of the system inductor- workpiece

The development of an electromagnetic model allows the study of the magnetic and thermal field distribution in the workpiece.

This step allows précising the model. The data can later be used for the thermal model [3], [4], [5]. If model results are unacceptable where the distribution of the magnetic field is uneven or high leakage of the inductor is present, the design can be altered. Correction can be made beginning from step two or three.

During step 4 it is required to develop a geometrical model of the system inductor-workpiece. The parameters of the model are taken from the previous step. An example model is presented in figure 2.

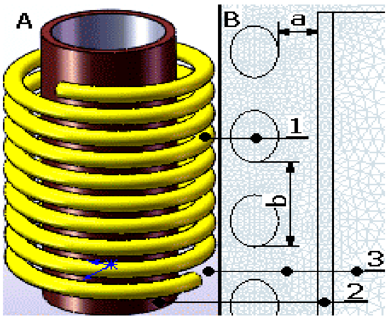

Figure 2.Geometrical model of the designed system inductor- workpiece: A – three dimensional model; B – two dimensional model; 1- inductor; 2- workpiece; 3- outside environment; a – distance between the workpiece and the inductor; b – winding step

Electromagnetic model

System modeling at this stage allows reduction of the numerical procedures – results can be used for realization of the multiphysics model. For development of the model, a specialized software tool for FEM analysis is used – ComsolMultiphysics.

The development of the model requires the definition of the electrical and magnetic properties of each area – given by the geometry of the model and defined border conditions.

The mathematical model that defines the electromagnetic filed can be given by the following equation:

$$\nabla\times\left(\frac{1}{\mu(H)}\cdot\nabla\times\dot{\mathbf{A}}\right)+j\cdot\omega\cdot\gamma\cdot\dot{\mathbf{A}}=\dot{\mathbf{J}}_c+\frac{\gamma\cdot\dot{U}_c}{L}\cdot\mathbf{e}_\varphi \tag{7}$$

Where γ[S/m] is the specific electrical conductivity; μ[H/m] – absolute permeability; ω [rad/s] – angular velocity – defined by the frequency of the induction heating power supply; J_c [A/m2] – current density;U_c[V] – voltage on the inductor; L [m] – length of the induction wire; A [Wb/m] – vector of the magnetic potential.

The following border conditions are used:

- Magnetic insulation – given for the outer borders of the model. If the system is symmetrical the magnetic insulation is defined on the axis of symmetry as well. Where magnetic insulation is specified:

$$A=0 \tag{8}$$

- Continuity – defined at the borders of the workpiece and the inductor:

$$n\times(H_1-H_2)=0 \tag{9}$$

<u>*Step 5 – Multiphysic model of the system inductor-workpiece*</u>

Here results from the geometrical models in the previous step are used to develop the multiphysical model. The multiphysic model encompasses both the temperature and electromagnetic fields.

Model of the temperature field

When developing the model of the thermal field only the workpiece is taken into account. The following mathematical description is used:

$$\rho(T)\cdot c(T)\cdot\frac{\partial T}{\partial t}=\nabla\cdot(\lambda(T)\cdot\nabla T)+q_v \tag{10}$$

Where: T [K] is the temperature; t [s] – is the time for the process; ρ[kg/m^3] - material density in function of the workpiece temperature; c [J/kg.K] – specific thermal capacity in function of the temperature; λ [J/kg.K] – coefficient of heat transfer in function of the temperature; q_v [W/m^3] – volumetric density of the power in the workpiece due to induced eddy currents (this parameter is taken as a result from the electromagnetic model):

$$q_v=\frac{1}{2}\cdot\omega^2\cdot\gamma(T)\cdot\dot{\mathbf{A}}^2 \tag{11}$$

During the heating process two approaches can be used:

Where high speed processes (for example when quenching) and sequential heating is involved it can be taken that the heating is adiabatic – on the surface of the workpiece a Neumann boundary condition can be given:

$$\frac{\partial T}{\partial n}=0 \tag{12}$$

For other heating processes on the surface of the workpiece, a border condition of Newton-Rikhmanfor heat transfer for convection and radiation can be used:

$$-\lambda(T)\cdot\left(\frac{\partial T}{\partial n}\right)=\alpha\cdot(T-T_C) \tag{13}$$

$$-\lambda(T)\cdot\left(\frac{\partial T}{\partial n}\right)=\varepsilon\cdot\sigma\cdot\left(T^4-T_C^4\right) \tag{14}$$

Where α [W/m^2.K] – coefficient of convection heat transfer; T_C [K]- temperature of the cooling environment; ε - emissivity; σ [W/m^2.K^4] – constant of Stefan–Boltzmann.

In case of heat transfer through radiation between two objects, it is necessary to provide an angular coefficient of radiation and temperature of the objects in the radiation process [13].

If after completing the simulations with the developed multiphysics model, the results do not satisfy given requirements for the temperature distribution it will be necessary to change the parameters of the inductor, the selected construction or the installed power.

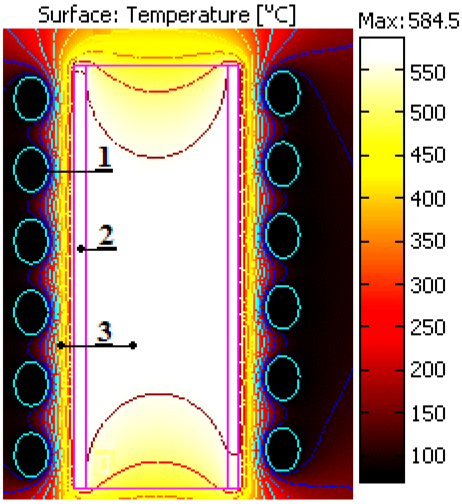

Figure 3.Model of the system inductor-workpiece; 1- inductor; 2 – workpiece; 3- air

An example model developed using the suggested methodology is presented in figure 3. The heated workpiece is a hollow cylindrical object that has to be heated to 580°C with acceptable tolerance of ± 10°C. The inductor is wounded uniformly on a copper tube that allows water cooling.

Based on the presented inductor-workpiece configuration and due to the thermal processes that take place – heat is distributed unevenly on the surface of the workpiece – figure 5.A

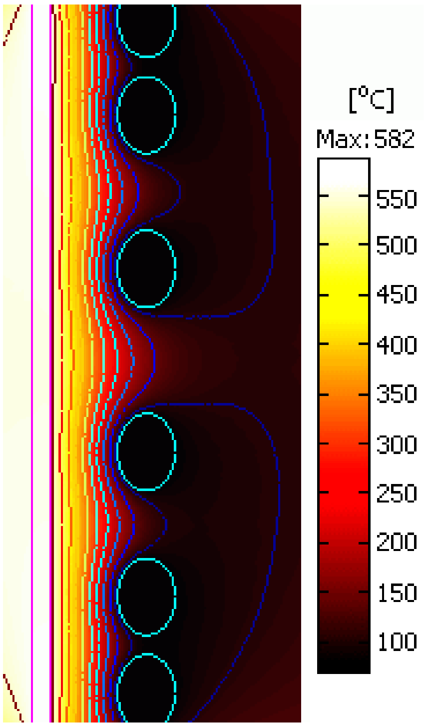

Figure 4.Model with uneven distribution of the windings of the inductor

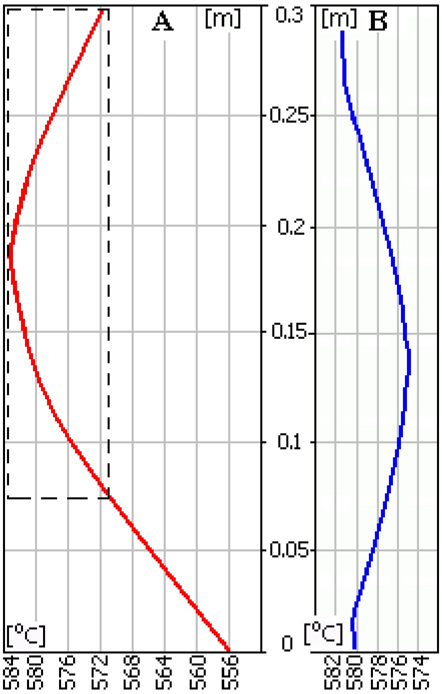

Figure 5.Distribution of the thermal field over the surface of the workpiece where A corresponds to the model from figure 3 and B to the model from figure 4

The data from the model shows that only a partial area satisfies the given temperature condition. In figure5.A this is the hatched area.

A uniform temperature distribution can be obtained where longer heating time is applied – if the process and workpiece specifics allow it. This however will use up more energy. Another approach will be to change the winding step of the inductor.

Figure 4 shows a model where unevenly distributed winding step is used. The thermal field distribution for this model is shown in figure 5.B. Heat deviation satisfies the required temperature condition.

In this way the model included in the suggested methodology can be applied to determine the parameters of the construction. This leads to a higher quality production and better energy efficiency of the device.

The model allows determining other system parameters as well. Those parameters can be related to the energy efficiency and can include: the cooling process of the inductor and the volume of water that needs to circulate; speed of movement of the workpiecethrough the inductor at continuous serial heating process.

Step 6 – verification of the obtained results and experimental studies.

Experimental studies are integral part of any design. The presented modified methodology was applied for various constructions and different technological heating processes.

Experimental results are obtained using two sets of inductors – presented in figure 6, where an evenly winded inductor is shown at figure 6.A. and an unevenly wounded one in figure 6.B. The inductors are developed using the models presented in figures 3 and 4.

Figure 6. Experimental inductors developed through models presented at figures 3 and 4.

Two sets of experiments are carried out. The first one involves quenching; the second one melting. For both cases natural and forced cooling through water is examined in order to determine the characteristics of the cooling system. Figure 7 shows the results from those experiments where measurement has been taken down using a thermographic camera.

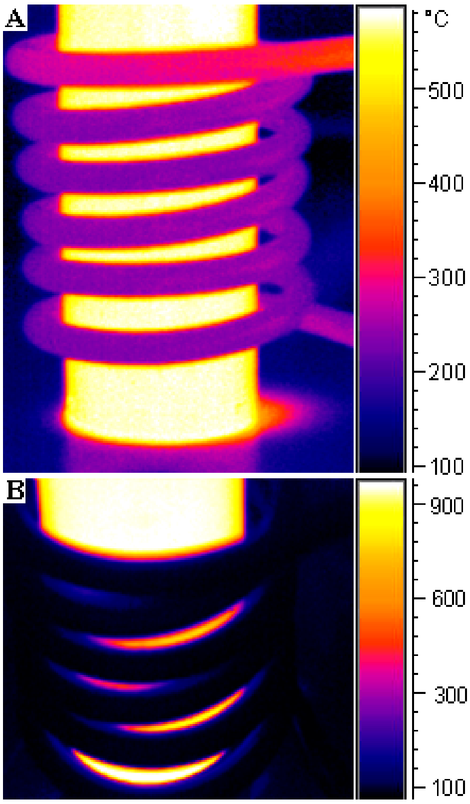

Figure 7.Photos taken with thermographic camera A - inductor without water cooling; B – inductor with water cooling.

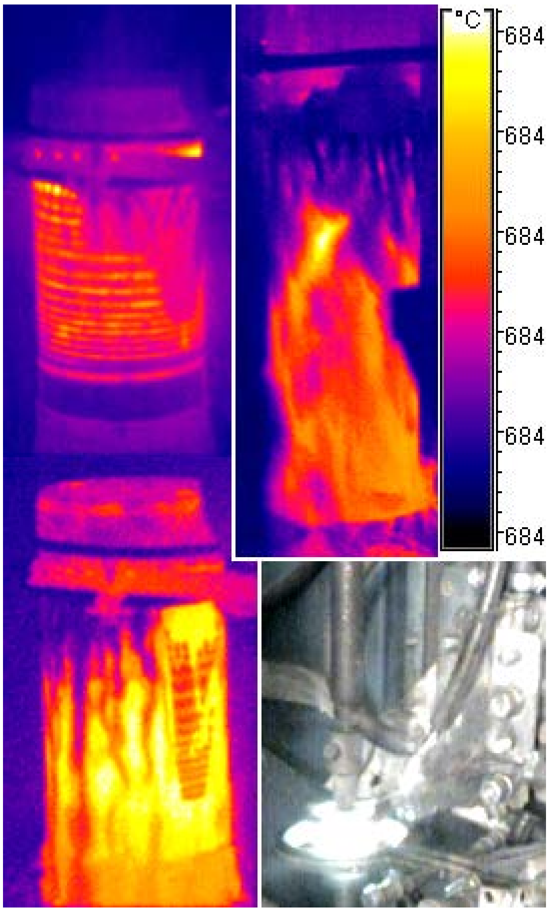

Figure 8. Experimental study of the heating process of quenching with water cooling

For verification purposes the suggested methodology was applied to existing equipment for high frequency induction heating. Experimental results are presented infigure 8. In this specific case, the suggested methodology was used to determine: the movement speed of the workpiece trough inductor; the electrical characteristics of the induction heating power supply; and the volume of water required for the forced cooling of the inductor.

The demonstrated experiments were conducted through an invertor based induction heating power supply working at frequencies of 25kHz÷30kHz.

3. Conclusions

A design methodology for system of inductor-workpiece in devices for induction heating is presented. Based on the conducted studies the following conclusions can be made:

- Using FEM models developed in specialized software, in design work allows some additional possibilities: simulation study of the thermal process; determining the construction inductor-workpiece; specifying the characteristics of the technological process.

- The suggested studies show that the joint usage of analytical and numerical design methods allowsimproving the energy efficiency and securing the quality of the heating as a part of the thermal process.
- The methodology is applicable for design of new equipment and study of existing one when determining the characteristics of the process. This improves energy efficiency and quality of the production.

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References

[1].Kuvaldin, A. B. (1988). Induction Heating of Ferromagnetic Steel. *Moscow, Énergoatomizdat*.

[2].Nemkov, V. S., &Demidovich, V. B. (1998). Theory and Design of Induction Heating Devices. *Leningrad: Energy-atom-print*.

[3].Tahrilov Hr., B. Dimitrov (2010). Effects of the geometrical parameters of a cylindrical inductor on the thermal heating process. *Annual Journal of the Technical University of Varna*

[4].Tahrilov Hr., IlLilqnova (2010). Harmonization of the parameters of a system inductor-workpiece with a given technological process. *Annual Journal of the Technical University of Varna*

[5].Tahrilov Hr., B. Dimitrov (2011). Comparative study between approaches of analytical studies, numerical modeling and experimental based design for induction heating for cylindrical details; Journal “Electronics and electrical engineering – E+E”, Sofia, Bulgaria

[6].Hoemberg D., Induction heat treatments – modeling, analysis and optional design of inductor coils, Habilitationsschrift, TU-Berlin, 2002.

[7].Shokouhmand, H., &Ghaffari, S. (2012). Thermal analysis of moving induction heating of a hollow cylinder with subsequent spray cooling: Effect of velocity, initial position of coil, and geometry. *Applied Mathematical Modelling*, *36*(9), 4304-4323.

[8].Tavakoli, M. H., Karbaschi, H., &Samavat, F. (2011). Influence of workpiece height on the induction heating process. *Mathematical and Computer Modelling*,*54*(1), 50-58.

[9].Karban, P., &Donátová, M. (2010). Continual induction hardening of steel bodies. *Mathematics and Computers in Simulation*, *80*(8), 1771-1782.

[10].Kranjc, M., Zupanic, A., Miklavcic, D., &Jarm, T. (2010). Numerical analysis and thermographic investigation of induction heating. *International Journal of Heat and Mass Transfer*, *53*(17), 3585-3591.

[11].Di Luozzo, N., Fontana, M., &Arcondo, B. (2012). Modelling of induction heating of carbon steel tubes: Mathematical analysis, numerical simulation and validation. *Journal of Alloys and Compounds*, *536*, S564-S568.

[12].http://comsol.com (12.03.2014)

[13].Wong, H. Y. (1977). *Handbook of essential formulae and data on heat transfer for engineers*. London: Longman.

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