Improvement of the Induction Heating Process by Numerical Simulation for the Semi-finished Products

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Abstract ***– In the paper we present the numerical simulation of the electromagnetic phenomena coupled with the thermal ones when processing the semi-finished products made up of non-ferrous alloy, through electromagnetic induction with the purpose to obtain a homogenous heating of the pieces in the shortest time. Maxwell's equations that describe the heating process through induction, show that the important quantity, basically important to determine the eddy currents induced in the piece, is the intensity of the magnetic field, resulting the electromagnetic losses, due to their transformation in thermal energy. Determining these losses and verifying the quantity of heat emerged in the piece is also possible by means of mathematical calculus with the help the numerical modeling by methods of approximation such as the method of the finite differences or the finite element method. So far the results of the experiments have show that the intensity of the magnetic field for a long inductor is more intense in the center of the inductor and weaker at its extremes. The purpose of the numerical modeling is to render solution to homogenize the intensity of the magnetic field according to the geometry of the inductor.***

Keywords: ***electromagnetic field, thermal field, inductor.***

I. INTRODUCTION

The numerical simulation has become an important tool to reduce the manufacture cost of a product and to improve the heating quality through induction. The numerical simulation of the heating process through induction implies the calculus of the eddy currents, which are basically the cause of the electromagnetic losses due to the development of heat in the semi-finished piece, [2].

The designing of the heating installation is briefly realized by means of analytical calculus that leads to some errors, which are reduced later by adopting the installation to that point to fulfill the technological process's demand. The presented methods imply expensive cost for the installation. Later there has been noticed a generalization of the designing of the electromagnetic heating installation of induction with the help of the numerical simulation. The company which produces, electromagnetic heating installation through induction is specialized in designing those installations with the help of the numerical simulation providing best solutions at the best prices.

The numerical simulation of the electromagnetic processes coupled with the thermal once is realized with the help of some well knows methods in the field of the specialists, such as: the finite elements method and differences finite method, statement based on methods of approximation, [1].

II. MATHEMATICAL MODELS

The geometrical forms, and the position of the piece that needs processing towards the inductor, have a large influence upon the transmission of the electromagnetic energy from the inductor to the piece responsible for the development of heat. The present tendency when processing the hot pieces is to obtain an homogenous heating of the piece.

By numerical simulation on association has been made, between on inductive heating installation (inductor – heated piece) and a mathematical model with the help of Maxwell's equations and the boundary conditions, necessary to resolve the problem of the electromagnetic coupled with the thermal.

For this case it results:

$$\begin{aligned} &\nabla \times \mathbf{H} = \mathbf{J} \\ &\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ &\mathbf{B} = \mu \mathbf{H} \qquad \textit{or} \qquad \mathbf{B} = f(\mathbf{H}) \\ &\mathbf{J} = \sigma \mathbf{E} \end{aligned} \tag{1}$$

from which it results the equation to resolve the electromagnetic field:

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{E} + \sigma \frac{\partial \mathbf{E}}{\partial t} = 0 \tag{2}$$

The analysis of the distribution of the thermal field can be determined from Fourier's equation:

$$-\nabla \cdot \mathrm{k}(\nabla \cdot \mathrm{T}) + \mathrm{c}\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \mathrm{p} \tag{3}$$

where: T - temperature;
c - specific heat;
k - thermal conductibility;
p - thermal energy.

To obtain unique solution for the equations (2) and (3) are necessary imposed the boundary conditions Dirichlet and Newman, [2].

The solution for the differential equations (2) and (3) will be found with the help of Galerkin technique of the nodal finite elements method:

$$E \approx \sum_k E_k \cdot \varphi_k$$

$$T \approx \sum_k T_k \cdot \varphi_k$$

where φ_k is form function associated to the point k.

The Galerkin method is used to resolve the following nodal equations resulted from Maxwell's equations:

$$\int_\Omega \nabla \times \frac{1}{\mu} \varphi_k \nabla \times \mathbf{E} \, d\Omega + \int_\Omega \varphi_k \sigma \frac{\partial \mathbf{E}}{\partial t} \, d\Omega = 0$$

respective

$$\int_\Omega \nabla \cdot \lambda \varphi_k (\nabla \cdot T) \, d\Omega + \int_{S_c} \varphi_k \alpha (T - T_{ext}) \, dS = p$$

The numerical simulation is primarily focused in solving the problem of the electromagnetic field and then based on the results it is intended to solve the problem of the thermal field.

The content of this paper is focused on the uniformly heating of the piece by electromagnetic induction, that needs to be processed through numerical simulation, using one of the method presented in the literature of specialization and that is the method of using the variable wrapping step of the inductor.

Simplified system inductor – the heated piece is present in fig. 1, where the following notations have been used: 1) – inductor (the inductor's parameters have the index 1); 2) – the heated pieces (the pieces parameters have the index 2). Characteristic for the modification of the installation output is the depth penetration of the electromagnetic field „δ" in the piece which is according to the properties of the material and the work frequency, [4].

The determination of the inductors step is made from the law of the magnetic circuit with the help of the effective value of the intensity of the magnetic field:

$$H_0 = \frac{N \cdot I_1}{h_1}$$

where: H_0 - the intensity of the magnetic filed;
N - the number turns of the inductor;
I_1 - current in the inductor;
h_1 - the high of the inductor which can be expressed with the number turn of coil and the isolation from these:

$$h_1 = (N-1) \cdot p + b$$

p - wrapping step of the inductor;
b - the high of the turn of inductor.

From this result:

$$H_0 = \frac{N \cdot I_1}{(N-1) \cdot p + b} \tag{4}$$

From the above mentioned equation it results the fact that modifying the inductor wrapping step a modification of the intensity of the magnetic field on the length of the piece, occurs and that being the case of the thermal field also. So by modifying the inductor wrapping step emerges the possibility to modify the field temperature of the piece along its length.

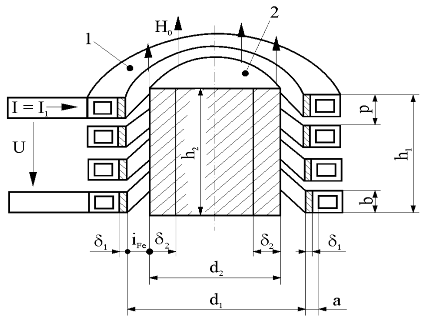

Fig. 1 – Induction heating system.

Considering the literature of specialty, [3], it result that the case of a long inductor with constant wrapping step, the intensity of the magnetic field is higher in the center and lower at its extremes. To uniforms the intensity of the magnetic field and also the heating of the piece on all her length it is necessary to use a variable wrapping step of the inductor, so that the intensity of the magnetic field of the extremes of the inductor to be emphasis and to homogenize along the length of the piece, so in the end it is expected a more powerful heating at the ends of the piece, respectively a homogeneous heating of the piece with the inductor.

III. RESULTS

So far, a series of soft to simulate the electromagnetic processes that use the numerical modeling with the purpose to resolve the field problems has been developed. The soft for the numerical modeling of an imposed problem is specialized to resolve the electromagnetic phenomena with nodal finite elements method. This soft is capable to separately solve problems of electromagnetic and thermal field, but also it can resolve coupled problems.

The numerical simulation was made for an installation designed for the induction heating in volume of the piece up to the temperature of 500 – 650 ^oC of a circular bar made of a non-ferrous material, with a radius of 20 mm, and a length of 800 mm. The inductor is made up of the copper bar with rectangular section are with the high „*b*" wrapped with the step „*p*". The inductor is supplied with a sinusoidal tension of *U* = 500 V and frequency *f* = 1500 Hz.

According to the technological specification imposed after the design calculus, on inductor with 62 turns has resulted, turns made up of cooper bar with rectangular section having the dimension 10x20x2 mm and constant wrapping step *p* = 14 mm.

Due to symmetrical reasons to solve as easily as possible the problem of the volume heating, it has been used the symmetry to the OX axis and OY axis of the system, and so the problem is more easy solved due to these constructive symmetries.

The numerical simulation is started with on length h_l of inductor with constant wrapping step, but after that the wrapping step is modified, up to an inductor of the same length but variable step. The modification to the inductor steps has first been made decreasing from the center to the extremity. The result in this case could not solve the problem of the homogenous heating. The next step of the modification of the wrapping step in order to obtain a homogenous electromagnetic field has been made by decreasing the wrapping step from the center towards the extremes randomly.

The results of the numerical simulation using a constant wrapping step of the inductor are presented in figure 2 and 2A and respectively 3, and 3A. In fig. 2 and 2A it is presented the distributions of the intensity of the magnetic field along the piece (2), and at the extremities of the piece (2A). When analyzing all those figure it can be noticed a non-homogenous distribution of the intensity of the magnetic field noticing an emphasized diminution at the inductors extremes. The numerical simulation confirms the experiments that have been performed so far, that can be found in the literature of specialization, [3].

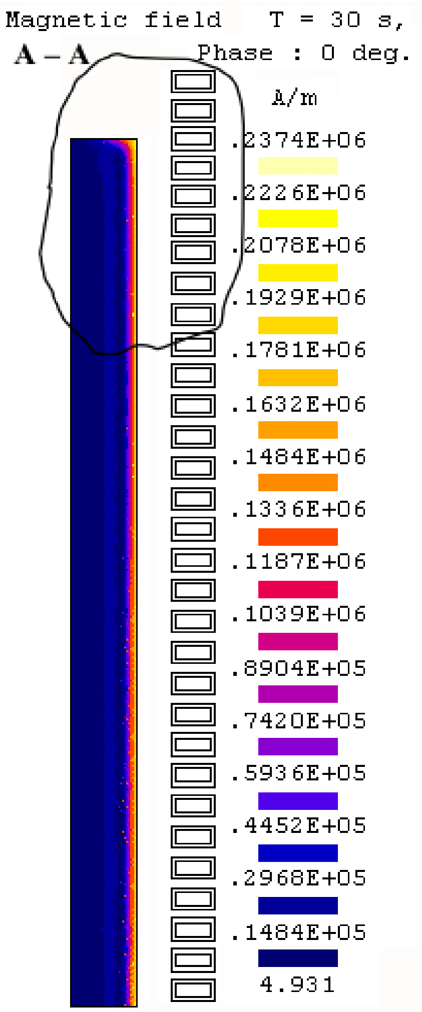

Fig. 2 – The distribution of the intensity of the magnetic field in the piece.

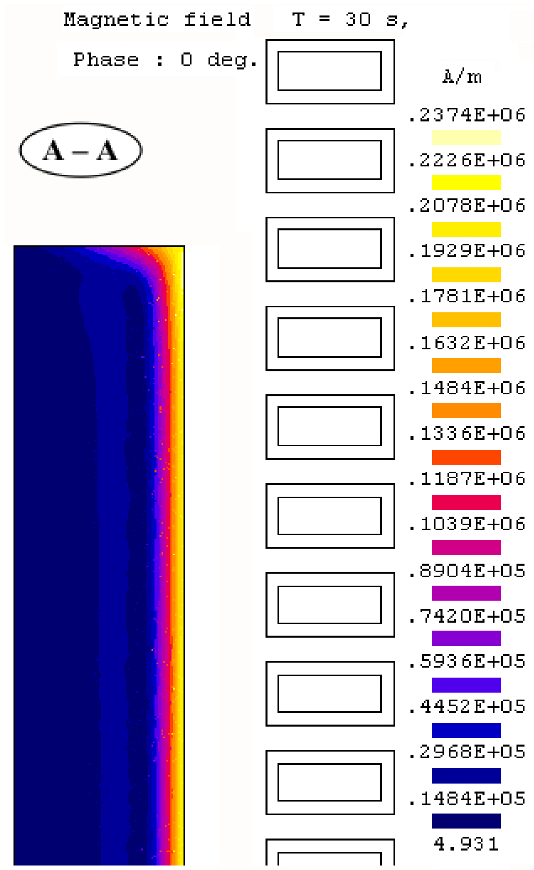

Fig. 2.A – The distribution of the intensity of the magnetic field at the end of the piece.

Solving the thermal problem on the basis with obtained results when solving the problem of the electric field, has emphasized according to figure 3 and 3A, a distribution of the heat developed in the piece resembling the distribution of the intensity of the magnetic field, therefore resulting a more evident heating in the center of the inductor and a less notable heating at the extremes of the inductor.

Through numerical simulation it is supported to realize a more homogenous heating of the non-ferrous piece all along its length. The designing demand is the heating of the piece up to the temperature of 550 – 650 ^{o}C, but without the possibility to melt. The temperature gradient must be at his most 5% of the final temperature value. Analyzing figure 2 and 3A, it is observed that on inductor with constant wrapping step leads to a non homogenous heating of the bar, ant the temperature gradient is of 134.96 ^{o}C there is approximately 32% from the final temperature value.

The results obtained in the first step of the numerical simulation are unsatisfactory and therefore the calculus are retaken modifying the inductor wrapping step so to obtain the inductor wrapping step in such a way that the distribution of the induced field to be homogenous as possible. Following the installations numerical simulation with on inductor having a decreasing randomly wrapping step from the center to the end, the results presented in figure 4 and 4A for the intensity of magnetic field, respectively 5 and 5A for the thermal field distribution, have been obtained.

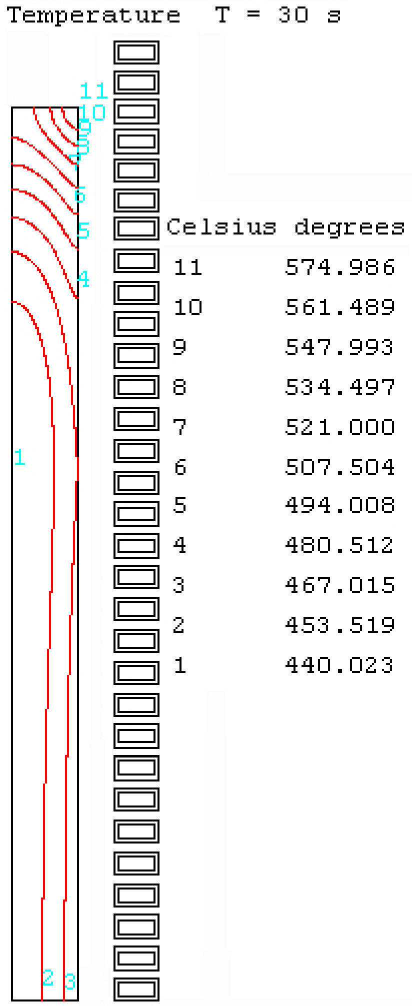

Fig. 3 – The distribution of temperature in the heated piece.

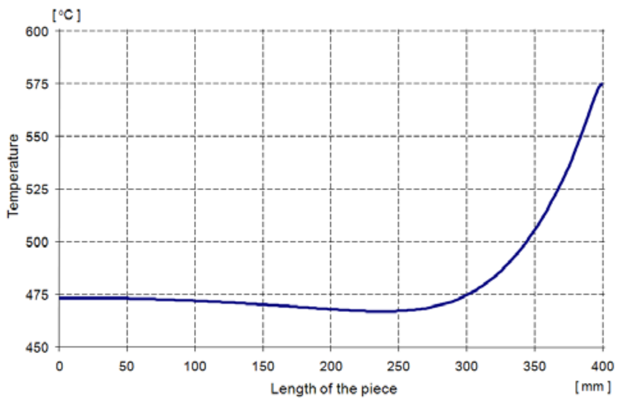

Fig. 3.A – The variation of temperature along the piece with a constant wrapping step.

Determining the wrapping step, which leads to uniform heating of the piece, was done using a parametric solving. By comparison of quantities determined by numerical modeling with of the ideal result we could change the wrapping step until we obtain the difference temperature along the length piece below 5% of the final heating temperature.

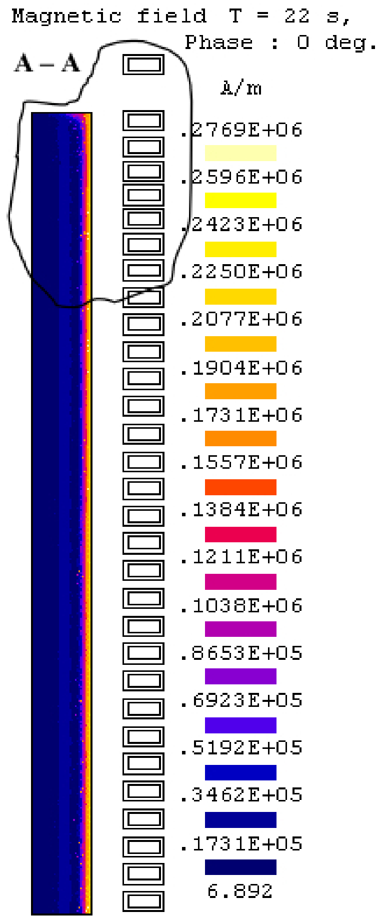

Fig. 4 – The distribution of the intensity of the magnetic field in the piece.

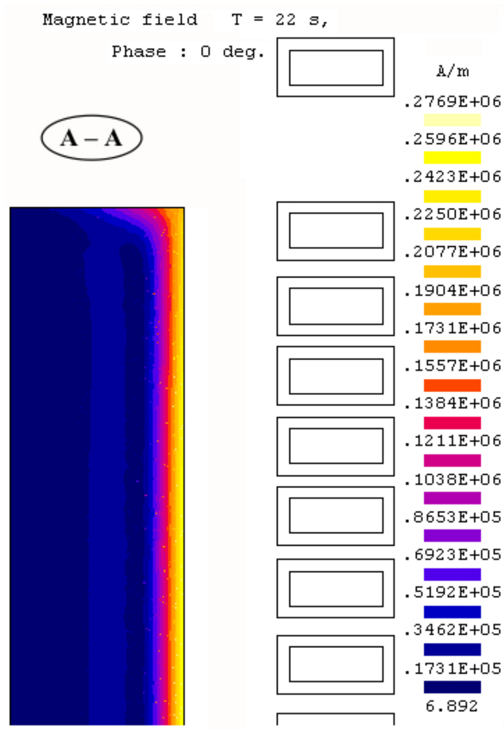

Fig. 4.A – The distribution of the intensity of the magnetic field at the end of the piece.

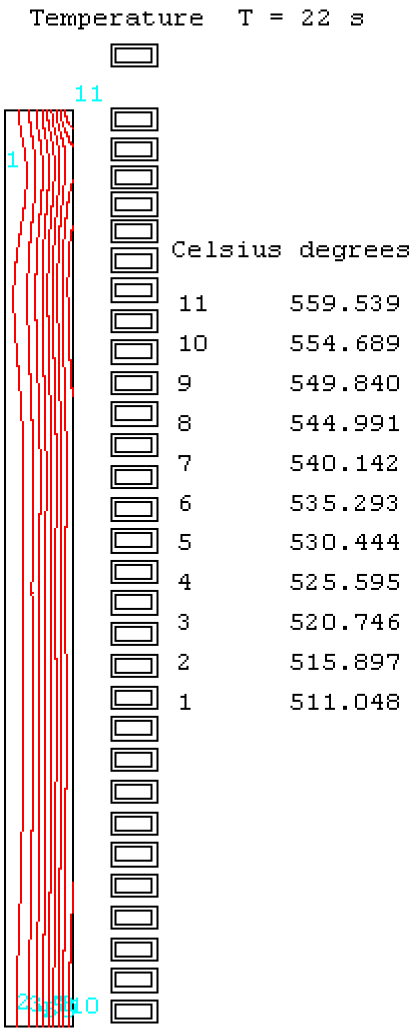

Fig. 5. – The distribution of temperature in the heated piece.

In this case a intensification of the intensity of the magnetic field it can be noticed at the extremity of the piece (fig. 4.A), so all along the piece a homogenous distribution of the intensity of the magnetic field can be noticed. The result of the thermal problem as presented in figure 5, it shows that o homogenous distribution of temperature was performed on the length of the piece.

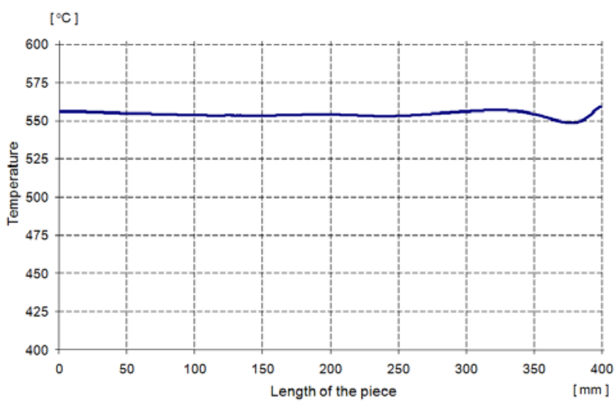

Fig. 5.A – The variation of temperature along the piece with a variable wrapping step.

In this case from figure 5 and 5.A results the temperature gradient, which is 48.49 ^{o}C, between the center and the exterior surface of the piece and the temperature gradient on the length of the piece is 10.72 ^{o}C, gradient which is under the value of 5% from the final temperature value.

III. CONCLUSIONS

The presented homogenous heat in volume is easy to apply, as it doesn't require extra costs of material, it being performed by modifying the wrapping step of the inductor, modifying the geometry of the inductor.

The growth of the intensity of the magnetic field at extremities of the piece, realized with the help of the inductor with variable wrapping step lead to a growth of temperature at the ends of the piece and in the end to a homogenous heating along the piece.

The modification of the wrapping step of the inductor doesn't imply the modification of the installations electric traits, but it raises a problem of accurately construction of the inductor, to realize the necessary wrapping step imposed by the numerical simulation.

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