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Three-dimensional magneto-thermal model of induction heating process of moving bars

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Abstract: This paper presents a three-dimensional model of the magnetothermal phenomena of induction heater. The development of these models is based on the finite volume method. The heater is designed to treat aluminum bars prior deformation of the moving case. Therefore, the purpose of this work has physical and mathematical aspects. The first aspect copes with the various physical phenomena: electromagnetic, thermal and moving as well as their coupling. The second aspect is to look for a way to solve such multi-physics mathematical problem, strongly nonlinear with complex boundary conditions not previously well defined.

Keywords: Induction heater, 3D magnetothermal modeling, moving load, finite volume method, prior deformation.

1. Introduction

The study of induction heating means the simultaneity to study the electromagnetic and thermal phenomena. In the case of the treatment of a moving load, as in our case, we added a related movement term to the preceding phenomena [1, 2, 3].
From physics perspective, the problem is multiple and complex due to the interdependence of three phenomena intimately related. Mathematically speaking, these phenomena are described by a complex system of strongly nonlinear partial differential equations.
Our aim in this research is to develop mathematical and numerical models that are able to study the system with different configurations and applications, as well as in the three-dimensional structure.
The software tool to be developed is based on the finite volume method. This method is very consistent to solving the thermal problems, and will be extended to that of the electromagnetic problem [4].
In the past years, several works have been devoted to the development of mathematical and numerical models for magnetothermal coupling. Several references have presented models in two dimensions fed by current or/and voltage, among which, we may cite [5, 6, 7, 8].
Thereafter, other works in 3D, based on the finite element method, were published [9, 10, 11, 12]. But, this numerical method is still a time consuming calculation despite its use in most commercial software [13].
Our elaborate final coupled model is based on the finite volume method which is now considered as the most convenient method when the systems are strongly non-linear [14].
The following assumptions were made:
- We neglected the displacement currents
- We neglected the volume density of space charge
- The effect of velocity is neglected in the electromagnetic equation.

2. Model Formulation

The governing equations are [10], [11], [15], [16]:

2.1. Electromagnetic Equation

On a modified magnetic vector potential formulation is given by the following electromagnetic equation:

$$Rot(\frac{1}{\mu}rot\vec{A})+\sigma\frac{\partial\vec{A}}{\partial t}=\vec{J}_s \tag{1}$$

And,
The Coulomb gauge for to have a unique solution:

$$div\vec{A} \tag{2}$$

Or, we use a single equation, that the Coulomb gauge is enforced in the system by introducing a penalty term to the equation (1). Hence we obtain [11]:

$$Rot(\frac{1}{\mu}rot\vec{A})-gr\vec{a}d\left(\frac{1}{\mu}div\vec{A}\right)+\sigma\frac{\partial\vec{A}}{\partial t}=\vec{J} \tag{3}$$

In harmonic analysis, the general magnetodynamic equations in Cartesian coordinates (x,y,z), without the gauge, is given in three-dimensional by:

$$\begin{aligned}
&\frac{\partial^2 A_x}{\partial y^2}+\frac{\partial^2 A_x}{\partial z^2}-\frac{\partial^2 A_y}{\partial x\partial y}-\frac{\partial^2 A_z}{\partial x\partial z}-j\sigma_\alpha\mu_\alpha\omega A_x=\mu_\alpha J_{sx}\\
&\frac{\partial^2 A_y}{\partial x^2}+\frac{\partial^2 A_y}{\partial z^2}-\frac{\partial^2 A_x}{\partial x\partial y}-\frac{\partial^2 A_z}{\partial y\partial z}-j\sigma_\alpha\mu_\alpha\omega A_y=\mu_\alpha J_{sy}\\
&\frac{\partial^2 A_z}{\partial x^2}+\frac{\partial^2 A_z}{\partial y^2}-\frac{\partial^2 A_x}{\partial x\partial z}-\frac{\partial^2 A_y}{\partial y\partial z}-j\sigma_\alpha\mu_\alpha\omega A_z=\mu_\alpha J_{sz}
\end{aligned} \tag{4}$$

The index α indicates the different regions of the domain (inductor, air, load).
$\sigma=\sigma(T)$ – electrical conductivity, $\mu=\mu(T)$ – magnetic permeability, J_S – coil current density.

2.2. Heat Equation

The thermal equation with moving term is [6]:

$$\rho C_p\vec{V}gr\vec{a}d(T)-div(Kgr\vec{a}d(T))=P \tag{5}$$

With:

$$P=\frac{1}{2}\sigma\omega^2 AA^* \tag{6}$$

T – Temperature, t: – time, ρ – mass density, C_p – specific heat, K – thermal conductivity, P – power density source
In the case of solids, the introduction of the moving term makes sense if we assume that the load is indefinitely along the velocity direction. However, the product to be treated is moving along the axis Z, and therefore:

$$\vec{V}=V\,\vec{k} \tag{7}$$

K – unit vector
V – speed of the load moving
The heat conduction equation in Cartesian coordinates is given by:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-\rho C_p V\frac{\partial T}{\partial z}+P=0 \tag{8}$$

2.3. Geometric model and boundary conditions

The geometric model studied is represented in Fig. 1. The boundary conditions are:

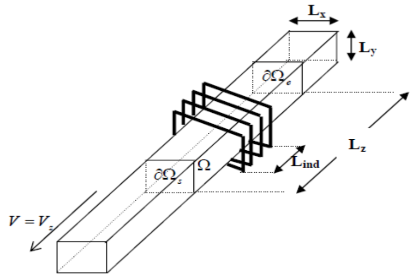

Figure 1: Geometric model

The piece with infinite longitudinal dimension along the zz' movement axis, moves from a infinite time relative to the fixed heat sources. To calculate the temperature, one must therefore limit the study domain of infinite space **Ω∞** to a finite study domain **Ω**. However we must introduce boundary conditions on ∂**Ω**e and ∂**Ω**s of **Ω** being worked on.
We define the study domain **Ω**, length Lz, as the zone of existence of the heat source. ∂**Ω**e its limit to the output of and ∂**Ω**s its limit to the output of the heat source. However, three difficulties are encountered:

- How to define the length Lz of the heat zone;
- The boundary condition at the entrance ∂**Ω**e ;
- The boundary condition at the output ∂**Ω**s.

The existence of the heat source is directly related to the existence of the eddy currents (the magnetic vector potential). Therefore, the thermal analysis domain, in load, is that of the magnetic field. The condition of zero magnetic field (near error) is related to the minimum distance between the inductor and the load (air gap).
According to the Reference [17], as we are as 10 times as distant from the air gap, the margin for error becomes very small. Therefore this distance may ascertain the absence of any electromagnetic phenomenon, and therefore the heat source is zero. At this limit of the input side, the piece is still considered outside the heat zone, and the choice of the condition for this boundary is clear and easy: we fix ambient temperature. At the output, the material has already gone through the important region. In addition, this boundary is sufficiently distant, considering this surface as adiabatic.
By integrating each equation of the model in space, we obtain the statement for the modified magnetic vector potential and temperature at any point inside the study domain. So, each equation is solved separately using the control volume technique of [4]. The resulting system of algebraic equations is solved by an iterative technique.
The convergence of this iterative technique was taken when the computed fields appeared steady in each point within the integration domain.

3. Application

The heating before deformation is an induction heater before forming or assembling. Hot deformation is a fundamental operation of metallurgy. So that the deformation occurs properly, without premature wear of the tools, it is necessary that the product is practically isothermal. The penetration of heat by thermal conduction is an essential phenomenon. The induction, that allows heating the product in depth, has a fundamental advantage over all other processes which heat the product only by conduction from the exterior surface.
In this application, we are particularly interested in the heating of aluminum rectangular bars with the following dimensions [12]: Lx=Ly=80 mm. The inductor has 5 turns in which flows a current I=Is of 500 Hz. The air gap thickness Le=10 mm. However, one delimits the infinite box at Lα=100 mm. At this limit, modified magnetic vector potential A is zero (no electromagnetic phenomena).
The heat conduction equation is associated to the boundary conditions: The phenomena of exchange with the ambient are present for all the 4 exterior surfaces. Numerically, we take: 10 w/(m2.k) and εσ=4.5x108 w/(m2.k4).
The speed movement of the load is 0.4 mm/s (for a passage time of 4 minutes and 10 seconds). These two quantities are within the range of parameters used in practice [11, 3, 18,19].
In order to minimize legends, we note that:
For different curves, the chosen direction is always in the center of the surface, and we are interested only in one half of the load, except for the displacement axis in which we take into consideration the entire length of the load.

3.1. Distribution of the heat source

The power density increases from the center to the outer regions of the load (fig.2). Its intensity increases with the inductor current. Along the axis of movement, the increasing density of power is clear (fig.3). It also presents a number of maximum points relative to the number of inductor turns. These maximum points are shifted from the inductor turns. This is due to the load movement.

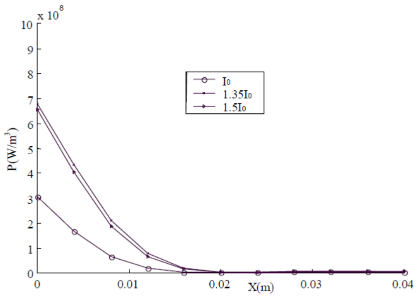

Figure 2: Distribution of the heat source along the x-axis

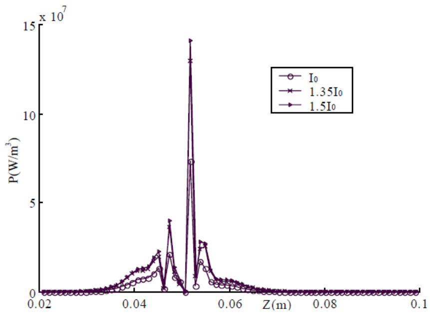

Figure 3: Distribution of the heat source along z-axis

3.2. Temperature distribution

Figures 4 and 5 show the temperature distribution in the load. It was found that:
The value of the inductor current I0 chosen initially at a speed of 0.4mm/s is insufficient to attain a temperature of 500 C. As a result, we increased the current value by 35% then 50%. Especially, when we were only interested in the surface temperature. Otherwise, one can increase the temperature in the center: either by reduction of the speed to allow time for the heat to propagate into the center, or it must proceed to reduce the frequency to have a more uniform heat source, but not below the minimum frequency of risk if not attaining the necessary power.
Another important note is the invariance (almost) of the temperature of the load facing the inductor (with a shift due to the displacement).

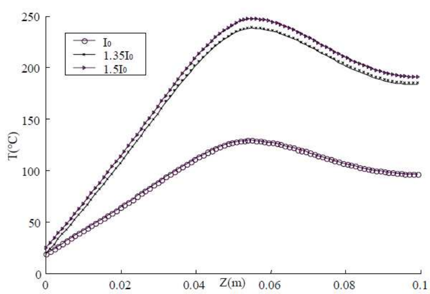

Figure 4: Distribution of the temperature along z-axis

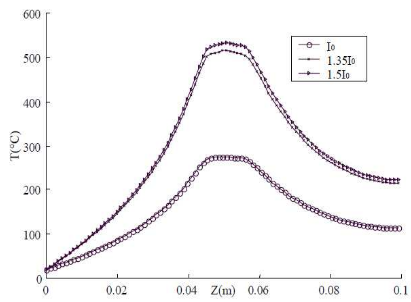

Figure 5: Distribution of the surface temperature along the z-axis

The induction heating in metal processing in the parade has been proposed as an application of the developed models. The heater is intended for induction heating of the aluminum bars for a given transit time of the load [18]. Data from the inductor (current intensity and frequency) are then confirmed valid (the third case cases of our simulation), if we are only interested in an almost uniform surface temperature distribution. However, there is as well as the distribution of the energy source is acceptable. But if we try to find an almost homogeneous distribution of the load is done to reduce the frequency of work to get a more homogeneous distribution of the induced power (source) and also the speed of movement of the load is reduced to allow heat to spread by conduction to the center of the load. A third proposal is related to the length of the inductor: it was found that increasing the length of the inductor increases is also obtained a product with more uniform temperature.
In this work, we are interested rather the physical aspects of the heater than looking for a specific solution.

Conclusion

A magnetodynamic model and a thermal one as well as a methodology of magnetothermal coupling have been developed and tested. The developed computation code has been tested at the sensible model points as well as their coupling. A comparative study has been realized with our axisymetric model and some published papers [6], [11]. Consequentlty, the validity of our software tool has been checked out.
Throughout the various simulations, we were interested in the physical aspects rather than the heater's production capacity. However, following the physico-mathematical mastery of the problem, some solutions have been suggested.

In a continuation of this work, it would be interesting to consider the practicality of models for techno-economic solutions.

Nomenclature

A magnetic vector potential, *T.m*
C_p specific heat, *J/kg.K*
f frequency, *Hz*
I_0 coil current, *A*
K thermal conductivity, *W/m.K*
P power source, *W/m^3*
T temperature, *K*
T_a ambient temperature, *K*
V velocity, *m/s*
μ permeability, *H/m*
ρ mass density, k*g/m^3*
σ electrical conductivity, *S/m*
σ_b Boltzmannconstante, *W/m.K^4*
ε emissivity

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