DYNAMIC TEMPERATURE FIELD IN THE FERROMAGNETIC PLATE INDUCED BY MOVING HIGH FREQUENCY INDUCTOR

by

Vesna MILOSEVIC-MITIC[a*], Tasko MANESKI[a], Nina ANDJELIC[a], Ljubica MILOVIC[b], Ana PETROVIC[a], Branka GACESA[a]

[a]University of Belgrade, Faculty of Mechanical Engineering, KraljiceMarije 16
[b]University of Belgrade, Faculty of Technology and Metallurgy, Karnegijeva 4
Republic of Serbia

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The subject of the paper is the temperature distribution in the thin metallic ferromagnetic plate influenced by moving linear high frequency induction heater. As a result of high frequency electromagnetic field, conducting currents appear in the part of the plate. Distribution of the eddy-current power across the plate thickness is obtained by use of complex analysis. The influences of the heater frequency, magnetic field intensity and plate thickness on the heat power density were discussed. By treating this power as a moving heat source, differential equations governing distribution of the temperature field are formulated. Temperature across the plate thickness is assumed to be in linear form. Differential equations are analytically solved by using integral-transform technique, Fourier finite-sine and finite-cosine transform and Laplace transform. The influence of the heater velocity to the plate temperature is presented on numerical examples based on theoretically obtained results.

Keywords: *electromagnetic field, temperature, high frequency inductor, ferromagnetic plate, moving heat source*

Introduction

The rigorous phenomenological magneto-elastic theory for ferromagnetic materials based on the large deformation theory and the classical theory of ferromagnetism has developed at the end of sixties. Since the general nonlinear theory was complicated, Y.W. Pao and C.S. Yeh[1] derived a set of linear equations and boundary conditions for soft ferromagnetic elastic materials. They applied linear theory to investigate magneto-elastic buckling of an isotropic plate. General information about the theory of magneto-thermo elasticity were presented in monograph by H. Parkusv [2].A great contribution of a research in this scientific field was given by W. Nowacki. He discussed various dynamic problems of thermo-elasticity induced by moving heat sources [3]. Thermo-elastic vibrations of thin plate subjected to one moving heater was theoretically obtained and presented in [4].

The influence of the magnetic fields in a rotating media was considered in [5]. Sharma and Pal investigated the propagation of a magnetic-thermo-elastic plane wave in

* Corresponding author; e-mail: vmilosevic@mas.bg.ac.rs

homogeneous isotropic conducting plate subjected to uniform static magnetic field [6]. The influence of the impulsive electro-magnetic radiation on the temperature, strain and stress fields in thin metallic plate was discussed in [7] based on the linear temperature distribution across the plate thickness. The similar theory for thick plates with appropriate nonlinear distribution was presented in [8].

Because of some disagreement in analytical and experimental results, the methods of numerical analyses were involved in consideration of the magneto-elastic problems [9]. A coupled thermo-mechanical finite element model of friction stir welding was developed using program Abaqus and presented in [10]. A mathematical model for the temperature field developed during high frequency induction heating together with the experimentally obtained results were established by Shen, Yao, Shi and Hu [11]. Temperature distribution in a thinmetallicplate subjected to law-frequencyelectromagneticfield was solved in analytical form as the interior Dirichlet boundary problem and presented in [12].In the numerical study of the three-dimension heat conducting problem with a moving heat source, Douglas-Gunn alternating implicit method was applied in [13].

Basic equations

The problem considered in the paper shows one type of interaction between electromagnetic and temperature field in a solid ferromagnetic plate. It is assumed that the plate material is elastic, isotropic, soft ferromagnetic, possessing a good electric conductivity. Many nickel-iron alloys used for building the magnetic circuits of motors, generators, inductors, transformers have these features.

As a result of time changing electromagnetic field conducting currents appear in electric conductors. This problem is mathematically described by the system of Maxwell's equations [1,2]

$$rot\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t},\ rot\vec{K} = -\frac{\partial \vec{B}}{\partial t},\ div\vec{D} = 0,\ div\vec{B} = 0, \tag{1}$$

with the relations for slowly moving media and modified Ohm's low[2]

$$\vec{D} = \varepsilon_0\left(\vec{K} + \dot{\vec{u}} \times \vec{B}\right),\ \ \vec{B} = \mu\left(\vec{H} - \dot{\vec{u}} \times \vec{D}\right), \vec{J} = \sigma\left(\vec{K} + \dot{\vec{u}} \times \vec{B}\right) \tag{2}$$

The following notation is applied: H – intensity of magnetic field, K – intensity of electric field, B – magnetic induction, D – electric induction, J – current density, u – deflection, μ – magnetic permeability,σ- electric conductivity, ε_0 – dielectric constant of vacuum, t –time.

Cartesian coordinate system is sustained so that x_1 and x_2 are the axes in the middle plate surface and x_3 is perpendicular one.

The power of the conducting currents represents one type of volume heat source in the plate. So, system of equations describing temperature field in a plate is [14]

$$\left(\nabla^2 - \frac{1}{\kappa}\partial_t\right)\theta - \eta\ \dot{u}_{j,j} = -\frac{W}{\lambda_0},\ W = W_E + W_H + \frac{J^2}{\sigma}, \qquad (j = 1,2,3) \tag{3}$$

where κ is the coefficient of thermal intensity, η is the coupling between the temperature and the deformation fields, λ_0 is heat conduction coefficient, ∇^2 is Laplace operator and ∂_t is the time derivative. Temperature field is presented as θ [℃, *K*] = T-T_0 where T_0 is the temperature of the plate in its natural state.

The heat generates in unite volume and unit time (heat source intensity) $W(x_1, x_2, x_3, t)$ consists of three parts: intensity of external heat source W_E, hysterisis losses W_H and Joule's heat. If one assumes that the temperature changes linearly across the thickness of the plate, temperature field $\theta(x_1, x_2, x_3, t)$ can be described using two values, τ_0 and τ_1 as

$$\theta(x_1, x_2, x_3, t) = \tau_0(x_1, x_2, t) + x_3 \tau_1(x_1, x_2, t) \tag{4}$$

If equation (3) is multiplied with $x_k^3 (k = 0.1)$ and integral of it is made through the plate thickness, the results are two partial differential equations describing temperature field in a plate as [14]

$$\left(\nabla_1^2 - \frac{1}{\kappa}\partial_t\right)(\tau_0) + \frac{1}{h}\left[\frac{\partial\theta}{\partial x_3}\right]_{-\frac{h}{2}}^{\frac{h}{2}} = -\frac{W_0}{h\ \lambda_0}, \quad \left(\nabla_1^2 - \frac{12}{h^2} - \frac{1}{\kappa}\partial_t\right)\tau_1 + \frac{12}{h^3}\left[x_3 \frac{\partial\theta}{\partial x_3}\right]_{-\frac{h}{2}}^{\frac{h}{2}} = -\frac{12 W_1}{h^3 \lambda_0}$$

$$W_k(x_1, x_2, t) = \int_{-\frac{h}{2}}^{\frac{h}{2}} W(x_1, x_2, x_3, t) \cdot x_3^k \cdot \mathrm{d}x_3, \qquad (k=0,\ 1), \tag{5}$$

where h is the plate thickness and ∇_1^2 is two-dimension Laplace operator defined as

$$\nabla_1^2 = \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial x_2^2}.$$

Presented differential equations have to be completed with the appropriate set of boundary and initial conditions.

The power of the linear frequency electromagnetic heater

In the part of a plate size d×c×h the magnetic field occlusions and time changing induction prompts conducting currents and Joule's heat losses. In order to calculate heat power next approximations are involved and applied (fig. 1):

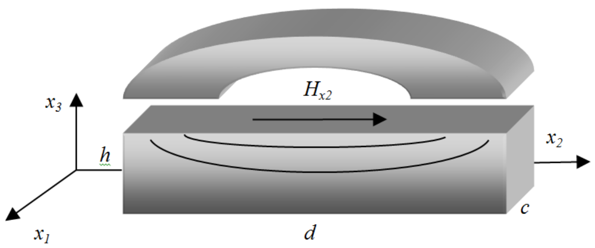


Figure 1. Linear frequency inducting heater in Cartesian coordinate system

- the component of magnetic induction $\boldsymbol{B}_{x1}$ can be neglected compared to $\boldsymbol{B}_{x2}$,
- because of the skin-effect, the component $\boldsymbol{B}_{x3}$ is small compared to $\boldsymbol{B}_{x2}$.

Electromagnetic field in the plate material has only H_{x2}andK_{x1}components so Maxwell equations are

$$\begin{aligned} \operatorname{rot}\vec{H}_{x_2} &= \vec{K}_{x_1}, \\ \operatorname{rot}\vec{K}_{x_1} &= -\partial_t \vec{B}_{x_2} \end{aligned} . \tag{6}$$

It is assumed that all field components vary in time t as exp$(j\omega t)$, where ω is the appropriate angular frequency. Using symbolic-complex method ($\vec{H} = \underline{H}e^{j\omega t}$) the following equation is

$$\frac{\partial^2 \underline{H}_{x2}}{\partial x_3^2} + \gamma \cdot \partial_t \cdot \underline{H}_{x2} = 0$$

$$\gamma^2 = j\sigma \cdot \mu \cdot \omega, \qquad \gamma = (1+j) \cdot \sqrt{\sigma \cdot \mu \cdot \pi \cdot f} = (1+j)k\,, \tag{7}$$

where f [Hz] is appropriate frequency. The solution of equation (7) has the form

$$\frac{\partial^2 \underline{H}_{x2}}{\partial x_3^2} + \gamma \cdot \partial_t \cdot \underline{H}_{x2} = \underline{C}_1 e^{\gamma \cdot (h/2 - x_3)} + \underline{C}_2 e^{-\gamma \cdot (h/2 - x_3)} \tag{8}$$

Coefficients $\underline{C}_1, \underline{C}_2$ can be obtained based on boundary conditions

$$\underline{H}_x = \begin{cases} \underline{H}_0, & (x_3 = h/2) \\ 0, & (x_3 = -h/2) \end{cases}, \tag{9}$$

$$\underline{C}_1 = -\frac{H_0 \cdot e^{-\gamma h}}{2S \cdot h \cdot \gamma \cdot h}, \qquad \underline{C}_2 = \frac{H_0 \cdot e^{\gamma h}}{2S \cdot h \cdot \gamma \cdot h}. \tag{10}$$

The solution for the magnetic field intensity is

$$\underline{H} = \underline{H}_0 \cdot \frac{Sh \cdot \gamma \cdot (h/2 - x_3)}{Sh \cdot \gamma \cdot h} \tag{11}$$

Conducting currents and Joule`s heat power $W(x_3)$ are defined with the relations

$$\underline{J}_{x2} = \frac{\partial \underline{H}_{x2}}{\partial x_3} = -\underline{H}_0 \frac{Ch \cdot \gamma \cdot (h/2 - x_3)}{Sh \cdot \gamma \cdot h} \tag{12}$$

$$W(x_3) = \frac{1}{2} \cdot \frac{\left|\underline{J}_{x2}^2\right|}{\sigma} = \frac{k^2 \cdot H_0^2}{\sigma} \cdot \frac{Ch \cdot 2k \cdot (h/2 + x_3) + \cos 2k \cdot (h/2 + x_3)}{2Ch \cdot 2k \cdot h - \cos 2k \cdot h} \tag{13}$$

Based on relation $(5)_3$ appropriate power $W_0^*\left[W/m^2\right]$ can be presented in the final form

$$W_0^* = \int_{-h/2}^{h/2} W(x_3)dx_3 = \frac{kH_0^2}{2\sigma} \frac{Sh2kh + \sin 2kh}{Ch2kh - \cos 2kh} = \frac{kH_0^2}{2\sigma} f_k$$

$$W_0^* = \int_{-h/2}^{h/2} W(x_3)\cdot \mathrm{d}x = \frac{k\cdot H_0^2}{2\sigma}\cdot\frac{Sh\cdot 2kh+\sin 2kh}{2Ch\cdot 2k\cdot h-\cos 2k\cdot h} = \frac{k\cdot H_0^2}{2\sigma}\cdot f_k \tag{14}$$

Heat power intensity depends on magnetic permeability, electric conductivity, magnetic field intensity, plate thickness and frequency. Diagram in fig. 2 presents heat power in soft ferromagnetic material conductivity 7.7 10^6 S/m and relative magnetic permeability 500. The thickness of a plate is sustained to be 5 mm on the square of 100 mm^2.

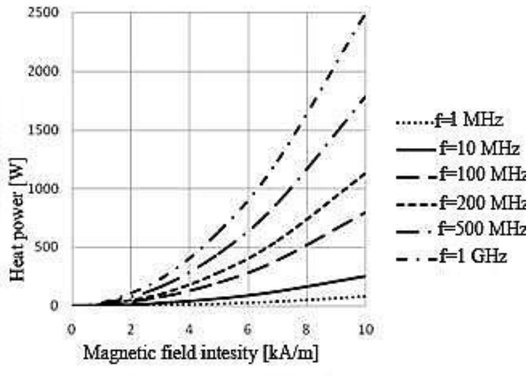


Figure 2. Heat power as a function of magnetic field and frequency

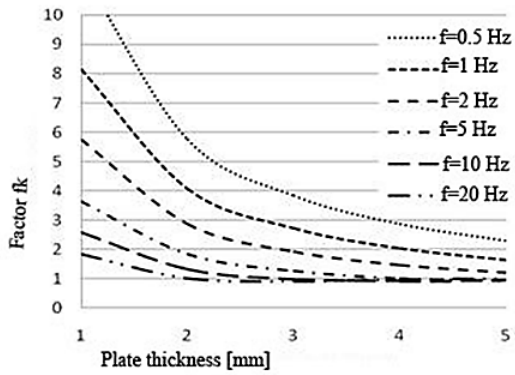


Figure 3. Factor f_k as a function of thickness and frequency

The influence of the plate thickness is represented in factor f_k from the relation (14). As it is shown in fig. 3, for high frequencies the value of f_k is 1, because of the skin-effect.

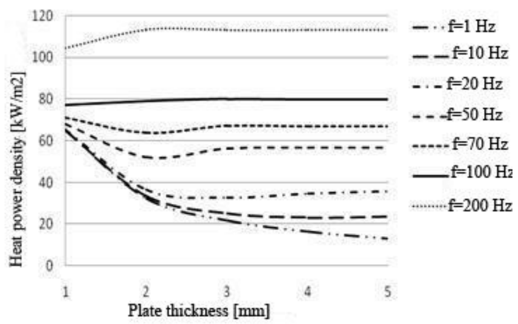


Figure 4. Heat power density as a function of thickness and frequency

For the electro-magnetic frequencies higher than 1 kHz heat power density doesn't depend on material thickness and skin-effect is dominant. It is presented in fig. 4 for magnetic field intensity of H_0=5 kA/m. Based on previous discussion, heat power W_1^* defined in $(5)_3$ can be calculated using Dirac δ-function as

$$W_1^* = \int_{-h/2}^{h/2} W(x_3)x_3\cdot dx_3 = \int_{-h/2}^{h/2}\frac{k\cdot H_0^2}{2\sigma}\delta\left(x_3-\frac{h}{2}\right)dx_3 = \frac{h\cdot k\cdot H_0^2}{4\sigma} \tag{15}$$

Temperature field in the plate induced by moving high frequency heater

Let the thin steel plate be under the influence of the temperature field caused by the high frequency heater moving at a constant velocity v along the edge x_1=0 shown in fig. 5. Let the thermal initial and boundary conditions be assumed in the form

$$\theta\big|_{t=0} = 0, \quad \theta\big|_{x_2=0,a} = 0, \ \frac{\partial\theta}{\partial x_1}\bigg|_{x_1=0,b} = 0, \qquad \frac{\partial\theta}{\partial x_3}\bigg|_{x_3=\pm\frac{h}{2}} = 0. \tag{16}$$

The position of the heater is shown in fig. 5. The equations (5) can be written in the form

$$\left(\nabla_1^2 - \beta_k - \frac{1}{\kappa}\partial_t\right)\tau_k = -\frac{\beta_k^k \cdot c}{\lambda_0 \cdot h}\cdot W_k^* \cdot \delta(x_1)\Pi\left(\frac{x_2 - vt}{d}\right)\left[H(t) - H(t - a/v)\right] \tag{17}$$

$$\beta_k = \begin{cases} 0, & k = 0 \\ \dfrac{12}{h^2}, & k = 1 \end{cases}, \qquad k = 0.1$$

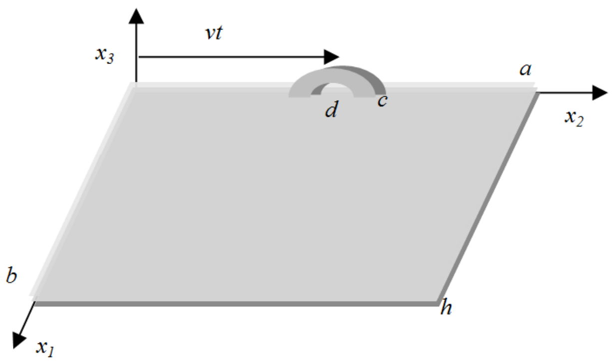


Figure 5. The plate under the moving inducting heater

H(∗) denotes the Heaviside function and Π(∗) is a pulsation function. To solve equations (17) subjected to the initial and boundary conditions (16) is used finite cosine Fourier transform in $x_1$direction and finite sine Fourier transform in direction x_2. Note the transformed function as $\tau_{k,nm}$ $k = 0.1$ and apply in calculation the next integrals

$$\int_0^b \delta(x_1)\cdot\cos(\alpha_n \cdot x_1)\mathrm{d}x_1 = 1, \tag{18a}$$

$$\int_0^a \Pi\left(\frac{x_2 - v\cdot t}{d}\right)\sin(\alpha_m \cdot x_2)dx_2 = \mathrm{d}\sin(\alpha_m \cdot v \cdot t)\frac{\sin(\alpha_m \cdot d/2)}{\alpha_m \cdot d/2}. \tag{18b}$$

Differential equations (17) become

$$\left(\Delta_{nm} + \beta_k^k + \frac{1}{\kappa}\partial_t\right)\tau_{k,nm} = -\frac{\beta_k^k \cdot c \cdot d}{\lambda_0 \cdot h}\cdot W_k^* \sin(\alpha_m \cdot v \cdot t)\cdot\frac{\sin(\alpha_m \cdot d/2)}{\alpha_m \cdot d/2}\cdot\left[H(t) - H(t - a/v)\right]$$

$$\Delta_{mn} = \alpha_n^2 + \alpha_m^2 = \left(\frac{n\pi}{b}\right)^2 + \left(\frac{m\pi}{a}\right)^2 \quad k = 0.1 \tag{19}$$

,

Using Laplace transform defined by integral

$$L\cdot\left[f(t)\right] = f^*(p) = \int_0^\infty f(t)\cdot e^{-pt}\cdot \mathrm{d}t \tag{20}$$

and applying partial integration, we have

$$L\left[\sin(\alpha_m\cdot vt)\cdot H\cdot\left(t-\frac{a}{v}\right)\right] = (-1)^m e^{-p\frac{a}{v}}\frac{\alpha_m\cdot v}{p^2+(\alpha_m\cdot v)^2}. \tag{21}$$

Boundary conditions give transformed forms of the temperature functions τ_0 and τ_1

$$\tau_{k,nm}^* = C_k\cdot\frac{\alpha_m v}{\left[p^2+(\alpha_m\cdot v)^2\right]\left[p+\kappa(\Delta_{nm}+\beta_k)\right]}\left[1-(-1)^m e^{-p\frac{a}{v}}\right]\cdot\frac{\sin(\alpha_m\cdot d/2)}{\alpha_m\cdot d/2},$$

$$C_k = \frac{\kappa\cdot\beta_k^k\cdot c\cdot d}{\lambda_0\cdot h}\cdot W_k^*, \qquad k = 0.1 \tag{22}$$

Based on the inverse Laplace transform denotes as L^{-1}, next function is given as

$$L^{-1}\cdot\left\{\frac{\alpha_m\cdot v}{\left[p^2+(\alpha_m\cdot v)^2\right]\cdot\left[p+\kappa\cdot(\Delta_{nm}+\beta_k)\right]}\right\} = l_k(n,m,t)\cdot H(t),$$

$$l_k(n,m,t) = \frac{\kappa(\Delta_{nm}+\beta_k)\cdot\sin(\alpha_m\cdot vt)-\alpha_m\cdot v\cdot\cos(\alpha_m\cdot vt)+\alpha_m\cdot ve^{-t\kappa(\Delta_{nm}+\beta_k)}}{(\alpha_m v)^2+\kappa^2(\Delta_{nm}+\beta_k)^2} \tag{23}$$

Using well-known relation

$$L^{-1}\left[e^{-\alpha p}f^*(p)\right] = f(t-\alpha)\cdot H(t-\alpha) \tag{24}$$

the solution is obtained in the next form

$$\tau_{k,nm} = C_k\cdot\frac{\sin(\alpha_m\cdot d/2)}{\alpha_m\cdot d/2}\cdot\left[l_k(n,m,t)\cdot H(t)-(-1)^m\cdot l_k(n,m,t-a/v)\cdot H(t-a/v)\right]$$

$$k = 0.1 \tag{25}$$

Inverse Fourier transforms give next analytical solution

$$\tau_k = \frac{2}{ab}\cdot\sum_{m=1}^{\infty}\left[\tau_{k,0m}+2\sum_{n=1}^{\infty}\tau_{k,nm}\cdot\cos(\alpha_n x_1)\right]\cdot\sin(\alpha_m x_2), \qquad k = 0.1 \tag{26}$$

or

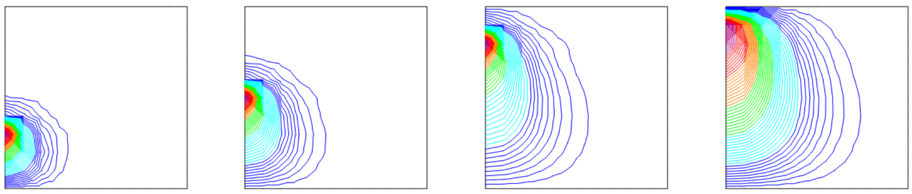
$$\tau_k = \frac{2}{ab}\sum_{m=1}^{\infty} C_k \cdot \frac{\sin(\alpha_m d/2)}{\alpha_m d/2}\cdot\left[I_k(0,m,t)+2\sum_{n=1}^{\infty} I_k(n,m,t)\cdot\cos(\alpha_n x_1)\right]\cdot\sin(\alpha_m x_2)\cdot H(t) -$$

$$-\frac{2}{ab}\sum_{m=1}^{\infty}(-1)^m \cdot C_k \cdot \frac{\sin(\alpha_m d/2)}{\alpha_m d/2}\cdot\left[I_k(0,m,t-\mathrm{a/v})+2\sum_{n=1}^{\infty} I_k(n,m,t)\cdot\cos(\alpha_n x_1)\right]\cdot\sin(\alpha_m x_2)\cdot H(t-\mathrm{a/v}) \quad (27)$$

$$k = 0.1$$

Numerical example

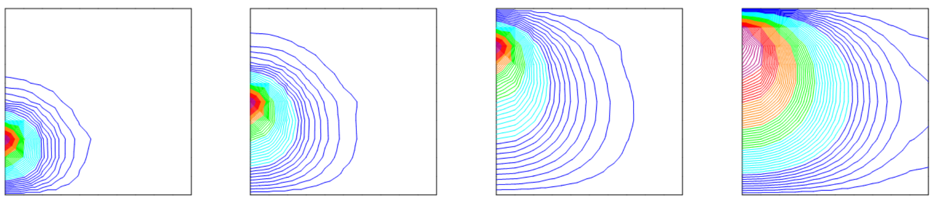
Field amplitudes and current amplitudes decrease on exponential law along the plate thickness. Skin depth decreases with increasing of frequency, conductivity and permeability and for high frequency heaters skin-effect is significant. Numerical example is done for the steel plate dimensions 1000×1000×5 mm. Magnetic and electric material properties are defined in previous examples. The plate is subjected to one linear electromagnetic heater magnetic intensity H_0=5kA/m and dimensions c=10 mm and d=50 mm. Other material properties respected to steel are: heat conduction coefficient λ_o=50 W/mK and coefficient of thermal intensity κ=1.4 10^{-3} m^2/s. In Figures 6 and 7 temperature fields for different times and for two cases of heater velocity are presented.



Temperature θ [ºC, K]

t=15 s	t=25 s	t=40 s	t=50 s
2.19E+02 ... 2.62E+02	2.28E+02 ... 2.74E+02	2.32E+02 ... 2.78E+02	1.04E+02 ... 1.24E+02
1.75E+02 ... 2.19E+02	1.83E+02 ... 2.28E+02	1.85E+02 ... 2.32E+02	8.29E+01 ... 1.04E+02
1.31E+02 ... 1.75E+02	1.37E+02 ... 1.83E+02	1.39E+02 ... 1.85E+02	6.22E+01 ... 8.29E+01
8.75E+01 ... 1.31E+02	9.13E+01 ... 1.37E+02	9.27E+01 ... 1.39E+02	4.15E+01 ... 6.22E+01
4.37E+01 ... 8.75E+01	4.57E+01 ... 9.13E+01	4.63E+01 ... 9.27E+01	2.07E+01 ... 4.15E+01
1.00E-02 ... 4.37E+01	1.00E-02 ... 4.57E+01	1.00E-02 ... 4.63E+01	1.00E-02 ... 2.07E+01

Figure 6. Temperature field for the inducting heater velocity of v=0.02 m/s



Temperature θ [ºC, K]

t=35 s	t=50 s	t=80 s	t=100 s
2.65E+02 ... 3.19E+02	2.85E+02 ... 3.42E+02	2.92E+02 ... 3.50E+02	9.81E+01 ... 1.18E+02
2.12E+02 ... 2.65E+02	2.28E+02 ... 2.85E+02	2.34E+02 ... 2.92E+02	7.84E+01 ... 9.81E+01
1.59E+02 ... 2.12E+02	1.71E+02 ... 2.28E+02	1.75E+02 ... 2.34E+02	5.88E+01 ... 7.84E+01
1.06E+02 ... 1.59E+02	1.14E+02 ... 1.71E+02	1.17E+02 ... 1.75E+02	3.92E+01 ... 5.88E+01
5.31E+01 ... 1.06E+02	5.70E+01 ... 1.14E+02	5.84E+01 ... 1.17E+02	1.96E+01 ... 3.92E+01
1.00E-02 ... 5.31E+01	1.00E-02 ... 5.70E+01	1.00E-02 ... 5.84E+01	1.00E-02 ... 1.96E+01

Figure 7. Temperature field for the inducting heater velocity of v=0.01 m/s

As it can be noted from previous figures, plate temperature depends on heater velocity. Time t_0 is defined as $t_0 = \frac{a}{v}$ and nondimensional time is involved as $\frac{t}{t_0}$.

Temperature intensity for the point in the middle plate surface with coordinates (x_1, x_2) = (300, 500) mm is presented in fig. 8 based on defined nondimensional time and for various heater velocities.

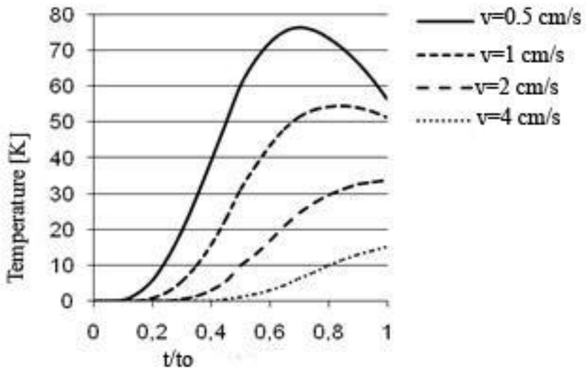


Figure 8. Temperature as a function of non-dimensional time and heater velocity t_o

Conclusion

Magneto-thermoelasticity has received considerable attention because of the possible applications in detection of flaws in ferrous metals, optical acoustics, levitation by superconductors, magnetic fusion and many other electro-mechanical devices.

Temperature field in the thin metallic soft ferromagnetic plate influenced by moving linear high frequency induction heater was analytically obtained and presented in the paper. The problem was described by two systems of differential equations, Maxwell's equations with the relations for slowly moving media and the equations governing temperature field. Temperature field was the result of time varying electro-magnetic field and the appearance of the eddy-current losses in one part of the plate. Distribution of the eddy-current power across the plate thickness was obtained by use of complex analysis. The influences of the heater frequency, magnetic field intensity and plate thickness to heat power density were discussed. Intensity of the losses is exponential function through the thickness of the plate. The inducting heater with high frequency was treated as a surface moving heat source because of the very small skin depth. Temperature across the plate thickness was assumed in linear form and appropriate differential equations governing temperature field were analytically solved by using integral-transform technique (Fourier finite-sine and finite-cosine transform and Laplace transform).The influence of the heater velocity on the plate temperature was presented in a few numerical examples based on theoretically obtained results.

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