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INDUCTION HEATING OF NON-MAGNETIC SHEET METALS IN THE FIELD OF A FLAT CIRCULAR MULTITURN SOLENOID

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Abstract. *The theoretical analysis of electromagnetic processes in the system for induction heating presented by a flat circular multiturn solenoid positioned above a plane of thin sheet non-magnetic metal has been conducted. The calculated dependences for the current induced in a metal sheet blank and ratio of transformation determined have been obtained. The maximal value of the transformation ratio with regard to spreading the eddy-currents over the whole area of the sheet metal has been determined.*

Key words: *induction heating, the induction system, the induced current, eddy current, heating of metal.*

ИНДУКЦИОННЫЙ НАГРЕВ НЕМАГНИТНЫХ ЛИСТОВЫХ МЕТАЛЛОВ В ОБЛАСТИ ПЛОСКОГО ЦИЛИНДРИЧЕСКОГО МНОГОВИТКОВОГО СОЛЕНОИДА

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Аннотация. *Проведен теоретический анализ электромагнитных процессов в системе индукционного нагрева, представленного плоским круговым многовитковым соленоидом, расположенным над плоскостью тонколистового немагнитного металла. Получены расчетные зависимости для тока, индуцированного в листовом металле, коэффициент трансформации и его максимальное значение.*

Ключевые слова: *индукционный нагрев, индукторная система, индуцированный ток, вихревые токи, нагрев металла.*

ІНДУКЦІЙНЕ НАГРІВАННЯ НЕМАГНІТНИХ ЛИСТОВИХ МЕТАЛІВ У ОБЛАСТІ ПЛОСКОГО ЦИЛІНДРИЧНОГО БАГАТОВИТКОВОГО СОЛЕНОЇДА

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Анотація. *Проведено теоретичний аналіз електромагнітних процесів у системі індукційного нагрівання, який представлено плоским круговим багатовитковим соленоїдом, розташованим над площиною тонколистового немагнітного металу. Отримано розрахункові залежності для струму, індукованого в листовому металі, коефіцієнт трансформації та його максимальне значення.*

Ключові слова: *індукційне нагрівання, індукторна система, індукований струм, вихрові струми, нагрівання металу.*

Introduction

Statement of the problem. Induction heating (IH) is heating of a metal object called «a blank» by electric currents. The latter are induced by variable magnetic field of an inductor (single-turn or multiple-turn solenoid). Flow of the eddy-currents is accompanied by heat liberation determined by the effect of Joule-Lenz's law, which results in the object heating [1, 2]. This effect has found a wide industrial application in performing a whole number of working operations, for example, quenching the surfaces of metal products, non-contact heating of liquids, levitation melting of metals, etc. [3, 4].

Publications analysis

Among the latest works devoted to IH there should be mentioned those, which in details describe processes in instruments of the method – generators of transverse magnetic field [5] and generalize the results of integrated studies presented in Russian as well as foreign literature, describe the methods of calculating integral characteristics of the heating processes and the results of physical experiments on industrial units [6].

Interest in IH has been observed in vehicle repair technologies. Here production operations on glass removal, cleaning lacquer coatings, disconnecting bolt joints, softening car body metal coatings before planishing dents, etc. [7].

The idea of using the induction pre-heating in magnetic-pulse metal treatment was suggested yet in the eighties of the 20th century [8]. The authors of the proposal developed and created the system initiating the flow of current in the work tool coil till the moment of force impact. The induction pre-heating allowed sufficient increasy in magnetic-pulse deformation efficiency in whole.

Following the logic of the first proposal of the work authors [8] positive results can be expected at using IH in production operations with magnetic-pulse attraction of preselected areas of thin metals particularly in operations on external planishing of car body elements [7, 9].

A single-sided induction heating system based on IGBT is proposed in the article [4]. Authors have a simulation of the single-sided induction heating system in ANSYS. He simulation results are compared with the experimental results. And also authors estimate the temperature distribution model by the least squares theory.

From the above-mentioned, it is clear that IH of nonferromagnetic materials in the field of a flat circular multiturn solenoid presents a quite urgent scientific and technical problem, which solving is required for production operations to repair vehicles.

The objective of the research

The objective of the research is theoretical analysis of electromagnetic processes in the system for induction heating presented as a flat circular multiturn solenoid placed above the plane of thin sheet non-magnetic metal.

Electromagnetic processes

When making calculations analytical dependences for induced currents obtained by the authors of the works [10] can be used. The design model in the cylindrical coordinate system with unit director vectors $\vec{e}_r, \vec{e}_\varphi, \vec{e}_z$ is presented in fig. 1.

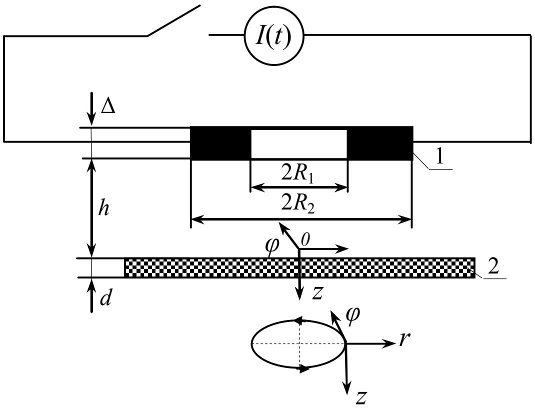

Fig. 1. The design model of the system «inductor–blank»: $I(t)$ – alternating-current source; 1 – multipleturn solenoid; 2 – flat sheet blank

The assumptions accepted.

1. The system has axial symmetry, so that $\frac{\partial}{\partial\varphi} = 0$ (φ – polar angle).
2. The inductor – a flat coil (the number of turns w), which thickness is quite small and its metal is so «transparent» for the existing fields ($\Delta \to 0$) that has no effect on the taking place electromagnetic processes.
3. In the inductor there flows the harmonic current $I(t)$, which time parameters allow using in

calculations a known condition of quasi-stationary electromagnetic processes so that $\frac{\omega}{c}\cdot\ell \ll 1$ (here ω is a circular frequency of the process, *c* – light velocity in the vacuum condition, *l* – the most common geometrical dimensions of the system).

4. The radial length of the sheet blank is quite large, so that $\frac{d}{R_{1,2}} \ll 1$, where *d* – the metal thickness, $R_{1,2}$ – internal and external radius of the field inductor.

The results of the works of reference [9, 10], where electromagnetic processes were studied in the system similar to the considered one but with a single-turn field magnet/inductor we rewrite in a form convenient for numerical estimates.

$$J_{\varphi}(r,t) = 4\cdot j_m \int\limits_0^{\infty} f(x)\cdot x^2 \cdot e^{-x\frac{h}{d}} J_1\left(x\frac{r}{d}\right)\times$$
$$\times\sum_{k=0}^{\infty} a(k)\frac{F_k(x,\beta_k)}{\Phi_k(x)}\frac{dj\,(t)}{dt} * e^{-\frac{\left(\beta_k^2+x^2\right)}{\tau}t}dx \quad , (1)$$

where $j_m = \frac{I_m\cdot w}{\left(R_2 - R_1\right)}$; I_m – amplitude of the excitation current; *w* – number of turns; $R_{1,2}$ – internal and external radius of the inductor; *j*(*t*) – time dependence of the current in the inductor; *t* – time;

$$a(k) = \begin{cases} 0{,}5, & k = 0; \\ 1{,}0, & k \neq 0; \end{cases}$$

$$f(x) = \frac{1}{x^2}\int\limits_{x\cdot\frac{R_1}{d}}^{x\cdot\frac{R_2}{d}} f(y)\cdot y\cdot J_1(y)dy\,;$$

f(*y*) – the function describing radial distribution of the current density in the inductor; β_k – roots of equation

$$\left(1-\left(\frac{\beta_k}{(\lambda\cdot d)}\right)^2\right)\sin(\beta_k) + 2\left(\frac{\beta_k}{(\lambda\cdot d)}\right)\cos(\beta_k) = 0;$$

$$F_k(x) = \left(1-\cos\left(\beta_k\right)\right) + \frac{\beta_k}{x}\cdot\sin\left(\beta_k\right);$$

$$\Phi_k(x) = \cos\left(\beta_k\right)\cdot\left[x^2 + 2x - \beta_k^2\right] -$$
$$-2\cdot\beta_k\cdot\sin\left(\beta_k\right)\cdot\left[1+x\right] \quad .$$

Taking into account the specifics of the present task and in accordance with the accepted assumptions the expression (1) can be rewritten as follows:

$$J_{\varphi}(r,\varphi) = 4 j_m \int\limits_0^{\infty} f(x) x^2 e^{-x\frac{h}{d}} J_1\left(x\frac{r}{d}\right)\times$$
$$\times\sum_{k=0}^{\infty} a(k)\frac{F_k(x,\beta_k)}{\Phi_k(x)}\left(\cos\varphi * e^{-\frac{\left(\beta_k^2+x^2\right)}{\omega\tau}\varphi}\right)dx \quad , (2)$$

where $f(x) = \frac{1}{x^2}\int\limits_{x\cdot\frac{R_1}{d}}^{x\cdot\frac{R_2}{d}} y\cdot J_1(y)\cdot dy$ – corresponds to uniform distribution of the current density in the inductor; $\left(\cos\varphi * e^{-\frac{\left(\beta_k^2+x^2\right)}{\omega\tau}\varphi}\right)$ – convolution function corresponds to harmonical time dependence of the excitation current;

j(*t*)=sin(φ) (φ=ω·*t* – signal phase);

$$\left(\cos\varphi * e^{-\frac{\left(\beta_k^2+x^2\right)}{\omega\tau}\varphi}\right) =$$
$$= \int\limits_0^{\varphi}\cos(\eta)\cdot e^{-\frac{\left(\beta_k^2+x^2\right)}{\omega\tau}\cdot(\varphi-\eta)}d\eta\,;$$

$\tau = \mu_0\cdot\gamma\cdot d^2$ – specific time of the field penetration into conducting layer with electric conductivity γ and thickness *d*.

Integrating the expression (2) on $r\in[0;R]$ we find intensity of the current induced in the metal of a sheet blank in the circle of radius *R*.

$$I_{\varphi}(r \le R,\varphi) = \left(I_m\cdot\frac{4\cdot d\cdot w}{(R_2 - R_1)}\right)\times$$
$$\times\int\limits_0^{\infty} f(x)\cdot x\cdot e^{-x\frac{h}{d}}\cdot\left(1 - J_0\left(x\frac{R}{d}\right)\right)\times$$

$$\times\sum_{k=0}^{\infty} a(k)\cdot\frac{F_k(x,\beta_k)}{\Phi_k(x)}\left(\cos\varphi * e^{-\frac{\left(\beta_k^2+x^2\right)}{\omega\tau}\varphi}\right)dx\,. \quad (3)$$

The ratio of transformation is determined as the amplitude ratio of the excitation current and the current induced in a blank in the circle of radius *R* (area: $r \leq \mathrm{R}$).

$$K(R,\varphi)=\frac{J_{\varphi\max}(R)}{I_m}=\left(\frac{4\cdot d\cdot w}{(R_2-R_1)}\right)\times$$

$$\times\int_0^{\infty} f(x)\cdot x\cdot e^{-x\frac{h}{d}}\cdot\left(1-J_0\left(x\frac{R}{d}\right)\right)\times$$

$$\times\sum_{k=0}^{\infty} a(k)\frac{F_k(x,\beta_k)}{\Phi_k(x)}\left(\cos\varphi * e^{-\frac{\left(\beta_k^2+x^2\right)}{\omega\tau}\varphi}\right)\Bigg|_{\max} dx. \quad (4)$$

From the dependence (4) it follows that the ratio of transformation on the current is directly proportional to the number of turns in the primary coil, thickness of the sheet metal and radius of the circular zone where excitement of the eddy-currents is considered.

Varying the mentioned above parameters allows intensifying electromagnetic coupling between the excitation and induced signals thus raising the level of energy transformation in the metal of the sheet blank.

The maximum value of the transformation ratio is observed at $R\to\infty$ taking into account distribution of the edd-currents over the whole sheet metal surface.

From the equation (4) we obtain

$$K_{\max}=\frac{J_{\varphi\max}(R\to\infty)}{I_m}=$$

$$=\left(\frac{4\cdot d\cdot w}{(R_2-R_1)}\right)\int_0^{\infty} f(x)\cdot x\cdot e^{-x\frac{h}{d}}\times$$

$$\times\sum_{k=0}^{\infty} a(k)\frac{F_k(x,\beta_k)}{\Phi_k(x)}\left(\cos\varphi * e^{-\frac{\left(\beta_k^2+x^2\right)}{\omega\tau}\varphi}\right)\Bigg|_{\max} dx. \quad (5)$$

Formulas (2)–(5) are the relations permitting to perform all required numerical evaluation of quality of the processes in the investigated system "inductor – sheet blank" with regard to all peculiarities determined by the prosesses of the field penetration at IH of thin metals.

Conclusions

The main results of the theoretical analysis of parameters of the induction heating process of non-magnetic sheet metals depending on their electric conductivity and the time characteristics of current in the coil of a flat multi-turn inductor come to the following statements.

1. The ratio of transformation in the investigated system is determined by the ratio of effective depth of penetration of the field into the conductor and the thickness of the latter, which, to a certain extent specifies the degree of dispersion of concentration of electromagnetic energy in a certain part of the metal sheet blank.
2. The maximal value of the current transformation corresponds to the current operation frequency in the inductor calculated for the equation

$$f_{\max}\approx\frac{1}{\pi\cdot\left(d^2\cdot\mu_0\cdot\gamma\right)},$$

where *d* – thickness; μ_0 – magnetic conductivity of the vacuum;γ – electric conductivity.

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