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THE PRINCIPLE POSSIBILITIES OF THE FAST-CHANGING MAGNETIC FIELD FOR THE SOLID PLASTIC DIELECTRICS DEFORMING

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Abstract. *The paper is dedicated to theoretical study of pulsed electromagnetic force action on dielectrics based upon the polarization phenomena. For the real dielectrics the necessary working frequencies for force deforming are fixed and the acting electrical fields are calculated. The real possibility of usage of the electrical field energy for dielectrics processing is illustrated.*

Key words: *pulsed electromagnetic action, dielectric, polarization phenomena.*

ПРИНЦИПИАЛЬНЫЕ ВОЗМОЖНОСТИ БЫСТРОИЗМЕНЯЮЩИХСЯ МАГНИТНЫХ ПОЛЕЙ ДЛЯ ОБРАБОТКИ ТВЕРДЫХ ПЛАСТИЧНЫХ ДИЭЛЕКТРИКОВ

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Аннотация. *Статья посвящена теоретическому исследованию импульсного электромагнитного силового воздействия на диэлектрики, основанного на поляризационных эффектов. Для реальных диэлектриков фиксируются необходимые рабочие частоты для силы деформирования, и рассчитываются действующие электрические поля. Иллюстрируется реальная возможность использования электрической энергии для обработки диэлектриков.*

Ключевые слова: *импульсное электромагнитное воздействие, диэлектрик, поляризационные эффекты.*

ПРИНЦИПОВІ МОЖЛИВОСТІ ШВИДКОЗМІНЮВАНИХ МАГНІТНИХ ПОЛІВ ДЛЯ ОБРОБКИ ТВЕРДИХ ПЛАСТИЧНИХ ДІЕЛЕКТРИКІВ

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Анотація. *Стаття присвячена теоретичному дослідженню імпульсного електромагнітного силового впливу на діелектрики, заснованого на поляризаційних ефектах. Для реальних діелектриків фіксуються необхідні робочі частоти для сили деформування, і розраховуються діючі електричні поля. Ілюструється реальна можливість використання електричної енергії для обробки діелектриків.*

Ключові слова: *імпульсний електромагнітний вплив, діелектрик, поляризаційні ефекти.*

Introduction

The ecology and power engineering are the main problems of modernity. There is no sense to determine, what it is the first and what it is the second one. The different points of view may arrange the importance of these problems as they like. On principle, the business consists in answer on questions, where can the energy be taken and how can the environment be kept for next generations? The solving of these problems determines the humanity future. In this connection the so named progressive technologies acquire great importance. At the first turn we mean the manufacture methods with usage of the electromagnetic fields energy. Such technologies must satisfy to requirements of ecological purity, high productivity and low energy consumption. Two last facts are closely connected, because the productivity level defines the level of energy consumption and vice versa. The justice of this statement is obvious. In fact, if the productivity increases at the expense of the articles quantity growth at each production operation, but not its velocity, then, ultimately, the energy expenditures for production of one article can be the corresponding times less [1].

Literature review and problem formulation

The practice employment of the pulse electromagnetic fields energy opens the exclusive perspectives for the development of the new progressive technologies by processing any raw materials of any physical nature including dielectrics. The plastic deformation and failure of the dielectric specimens under the power electric fields influence have been marked in the experiments on the investigation of the insulation puncture in the high-voltage installations at the beginning of the 1960's [2].

But it should be marked that some information about practical usage of any field technologies by dielectrics processing is absolutely absent in the modern science literature. In this connection a research work directed to elaborating the new methods of dielectrics processing are very actual and interesting. The aim of the present paper is to give some first theoretical estimates of possibilities of the electromagnetic field technology for dielectrics processing.

Theoretical analysis

The main physical statements for the next consideration are based on and taken from the well known classical science literature sources [3,4]. Mathematical transformation are fulfilled according to recommends and rules developed in the handbook [5].

Supposing that the energy value is the same for the dielectric specimen and the metal workpiece deformation we can get some approximate imagination about the acting fields amplitudes. The connection between the fields intensities can be find from the equality: $0,5\cdot\mu\cdot\mu_0\cdot H^2 = 0,5\cdot\varepsilon\cdot\varepsilon_0\cdot E^2$ where μ and ε – are the relative magnetic and electric permeability.

$$E = \sqrt{\frac{\mu}{\varepsilon}}\cdot Z_0\cdot H. \quad (1)$$

where Z_0 is the vacuum wave resistance, $Z_0 = 120\pi$ Ohm.

The typical intensity value for the magnetic pulse metal working constitutes about $H = 10^7$ A/m. Supposing $\frac{\mu}{\varepsilon} = 1$ with the help of the correlation (1) we may get the upper value of the electric field intensity which is necessary for the dielectric specimen deformation $E = 1,2\cdot\pi\cdot 10^9$ V/m.

Besides this estimation, the formula (1) permits to trace the dependence of the mechanical processes in dielectrics from their inner properties.

As it is known, the polarization phenomena lies in the base of the electrical influence forces, to be more exact - the electrical pressure. The property to be polarized is being characterized by the relative electric permeability – ε. The more ε the higher inner field amplitude and the external electric field pressure becomes more intensive.

Really, as it follows from the qualitative dependence (1), the deformation of the dielectric specimens with high value of the relative electric permeability occurs under the lower intensities of the external electric field.

The force influence efficiency on dielectric is being defined by duration of the electric pulse too. The time parameters of acting fields have to provide the specimens deformation before the electrical puncture occurrence.

The main conclusion from the conducted qualitative consideration is the statement: on principle, the methods of the dielectric deformation with help of the electromagnetic pressure forces have to be based on the power fields application with the enough small duration. The action time does not have to exceed the discharge and puncture evolution time of the dielectric specimen.

The more concrete remarks consist in the following:
- the electric intensity value must be by two orders greater than the magnetic field intensity in the time of the metal working;
- the pulse influence duration must not exceed of the characteristic time value 10^{-7}s.

Now we will transit from the qualitative analysis to the quantitative one. We will calculate the main parameters of the high-speed force influence processes on dielectric workpieces in the of concrete construction inductor system with the according electromagnetic fields sources.

At the beginning we will determine the pressure on a dielectric in the non-homogeneous electric field. We want to get the common formula which is analogous one to the well known dependence for the magnetic pulse metal working.

Let a dielectric plate (infinitely long and wide) with the thickness L and the relative electric permeability ε is situated in the electric field $\vec{E}(x)$, which changes through the dielectric thickness only (the according coordinate is X). The intensity vector direction is arbitrarily.

In the non-homogeneous electric field each elementary volume of the linear-polarized dielectric experiences the action of the force which equals to the sum of all forces applying to each its molecule. The separate dielectric molecule can be considered as the electric dipole polarized by the external field $\vec{E}(x)$. The acting on an elementary volume force may be described by the known correlation:

$$\mathrm{d}F_X = grad\left(\frac{\vec{P}\cdot\vec{E}}{2}\right)\cdot \mathrm{d}V \qquad (2)$$

where $\vec{P}$ - is the polarization vector.

The field pressure on the dielectric is directed with the inner normal vector to its surface (in the OX-axis). The pressure value will equal:

$$F_X = \left.\frac{\vec{P}\cdot\vec{E}}{2}\right|_0^L \qquad (3)$$

In the linear approach we may suppose that $\vec{P}(x) = \varepsilon_0\cdot(\varepsilon-1)\cdot\vec{E}(x)$. If to take onto account it the formula (3) is being transformed to the view:

$$F_X = \frac{\varepsilon_0\cdot(\varepsilon-1)}{2}\cdot(E^2(L) - E^2(0)). \qquad (4)$$

where $E(L)$ and $E(0)-$ are the electric field intensities on the boundary surfaces of the dielectric plate.

As it is seen from formula (4), the acting on the linear dielectric in the non-homogeneous electric field force is directed to the side of the intensity magnitude increase. Quantitatively, the pressure on the specimen is being defined by the difference between the electric intensities squares on its boundary surfaces.

It is obvious, this difference has maximum, if the field equals to zero on some one surface of the plate. Besides, the else one conclusion follows from formula (4): the influence force on the dielectric does not equal to zero, if $\varepsilon \neq 1$ only. Speaking by other words the electric field acts on the substances which can be polarized.
We have said the pressure would be maximum one if the electric field intensity equaled to zero on the one of the specimen surfaces. In this connection the natural suggestion appears after the constructive execution of one of the main elements of the inductor system for the electromagnetic dielectric articles stamping: it is necessary to place the worked billet on the metal surface where the tangent component of the electric field intensity vector will equal to zero.
The processes analysis in the suggested construction can be conducted with the simplified model help. In this case we may consider the fast-changing magnetic field action on the plane dielectric layer situated on the ideal conducting metal surface.

The problem of the field excitement will not be considered. It will be the separate investigation subject.

We will conduct calculations in the Decart rectangular coordinates system. We will combine the plane ZOY with the ideal conducting metal surface. The dielectric thickness (in the OX-axis) equal to L. The model for calculation on Fig.1 is being supposed as the infinite long in the dimensions X and Y. The relative electric permeability of the layer equals to ε.

In the area where $x \geq L$ the homogeneous external magnetic field exists with the only intensity tangent component $H_{Y0}(t)$.

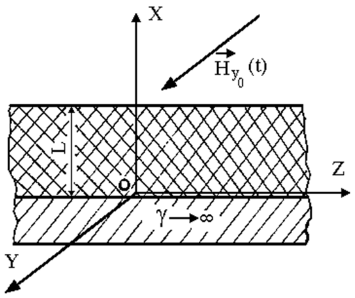

Fig. 1. The calculation model of the inductor system element for the electromagnetic dielectric stamping: the plane dielectric work-piece on the ideal conducting metal surface

For the problem solving we will use the integral Fourier transform. We will look for the non-zero field components into the dielectric in the following form:

$$\begin{cases} H_Y(t,.x) = \int\limits_{-\infty}^{\infty} H_Y(\omega,x)\cdot\exp(i\omega t)\mathrm{d}\omega; \\ E_Z(t,.x) = \int\limits_{-\infty}^{\infty} E_Z(\omega,x)\cdot\exp(i\omega t)\mathrm{d}\omega; \end{cases} \quad (5)$$

where ω – is the angular frequency.

Now we will execute the Fourier transform in the Maxwell equations. After substitution of the formulas (5) and some simple transforming we may get:

$$\begin{cases} \dfrac{\partial^2 H_Y(\omega,x)}{\partial x^2} + \varepsilon\cdot k^2(\omega)H_Y(\omega,x) = 0; \\ E_X(\omega,x) = -\dfrac{i}{\omega\cdot\varepsilon\cdot\varepsilon_0}\cdot\dfrac{H_Y(\omega,x)}{x}; \end{cases} \quad (6)$$

where $k(\omega)$ is the wave factor, $k(\omega) = \dfrac{\omega}{c}$; c – is the velocity of the light into vacuum.

The functions satisfying to the system of the differential equations are the following:

$$\begin{cases} H_Y(\omega,x) = A(\omega)\cdot\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot x) + \\ +B(\omega)\cdot\sin(\sqrt{\varepsilon}\cdot k(\omega)\cdot x); \\ E_Z(\omega,x) = \dfrac{i\cdot Z_0}{\sqrt{\varepsilon}}\cdot[A(\omega)\cdot\sin(\sqrt{\varepsilon}\cdot k(\omega)\cdot x) - \\ -B(\omega)\cdot\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot x)], \end{cases} \quad (7)$$

where $A(\omega)$ and $B(\omega)$ are the unknown constants of integration; Z_0 - is the wave resistance of vacuum.

The unknown constants in the formula (7) can be defined with help of the boundary conditions:

$$H_Y(\omega, x = L) = H_{Y0}(\omega); E_Z(\omega, x = 0) = 0,$$

where $H_{Y0}(\omega)$ is the Fourier transform of the external magnetic field intensity.

Without the intermediate transformations we are writing:

$$\begin{cases} H_Y(\omega,x) = H_{Y0}(\omega)\cdot\dfrac{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot x)}{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot L)}; \\ E_Z(\omega,x) = \dfrac{i\cdot Z_0}{\sqrt{\varepsilon}}\cdot H_{Y0}\cdot\dfrac{\sin(\sqrt{\varepsilon}\cdot k(\omega)\cdot x)}{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot L)}; \end{cases} \quad (8)$$

where $H_{Y0}(\omega) = \dfrac{1}{2\pi}\cdot\int\limits_{-\infty}^{\infty} H_{Y0}(t)\cdot\exp(-i\omega t)\mathrm{d}t.$

Now we will find the electromagnetic fields intensities taking in account the formulas (8) and the function $H_{Y0}(\omega)$

$$\begin{cases} H_Y(t,x) = \dfrac{1}{2\pi}\int\limits_{-\infty}^{\infty} H_{Y0}(\tau)\int\limits_{-\infty}^{\infty}\dfrac{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot x)}{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot L)} \\ \times\exp(i\omega(t-\tau))\mathrm{d}\omega\cdot\mathrm{d}\tau; \\ E_Z(t,x) = \dfrac{i\cdot Z_0}{2\pi\sqrt{\varepsilon}}\cdot\int\limits_{-\infty}^{\infty} H_{Y0}(\tau)\times \\ \times\int\limits_{-\infty}^{\infty}\dfrac{\sin(\sqrt{\varepsilon}\cdot k(\omega)\cdot x)}{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot L)}\cdot\exp(i\omega(t-\tau))\mathrm{d}\omega\cdot\mathrm{d}\tau; \end{cases} \quad (9)$$

Further it is necessary to find the integrals in the correlations (9). These integrals

$$\begin{cases} I_1 = \int\limits_{-\infty}^{\infty}\dfrac{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot x)}{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot L)}\cdot\exp(i\omega(t-\tau))\mathrm{d}\omega; \\ I_2 = \int\limits_{-\infty}^{\infty}\dfrac{\sin(\sqrt{\varepsilon}\cdot k(\omega)\cdot x)}{\cos(\sqrt{\varepsilon}\cdot k(\omega)\cdot L)}\cdot\exp(i\omega(t-\tau))\mathrm{d}\omega; \end{cases} \quad (10)$$

can be calculated with the residues theory methods.

From the analysis of the functions in the integrals (10) we see they have the infinite number of the simple poles on the real axis (naturally, $x \neq L$):

$$\omega_n = \pm \frac{2n+1}{4}\omega_0; \qquad (11)$$

where $\omega_0 = \frac{2\pi \cdot c}{\sqrt{\varepsilon} \cdot L}$ and $n \in Z$.

As it is known, the integrals of such view can be calculated if to suppose the small field attention existence in the real physical system. It means the appearance of the positive imaginary part in the resolved spectrum frequencies (11). The presence of the positive imaginary parts permits to regard that the functions poles will be situated not on the real axis, they will lie in the upper half-plane of the complex variables, where $\operatorname{Im}\omega > 0$.

In accordance with the Jordan lemma from the complex variable functions theory the integration circuit can be closed in the lower half-plane for $(t\text{-}\tau) < 0$ where the poles are absent. If $(t\text{-}\tau) > 0$, the integration circuit is being closed in the upper half-plane where the infinite number of the simple poles is situated.

If to take in account the integrals (10), we can get:

$$I_1 = \begin{cases} 0, t < \tau, x \in [0, L]; \\ 2 \cdot \omega_0 \sum_{n=0}^{\infty} (-1)^n \cdot \cos\left(\frac{2n+1}{2} \cdot \pi \cdot \frac{x}{L}\right) \times \\ \times \sin(\omega_n (t - \tau)), t > \tau, x \in [0, L]; \\ 2\pi \cdot \delta(t - \tau), x = L; \end{cases} \qquad (12)$$

where $\delta(t\text{-}\tau)$ – is the Dirac function.

$$I_2 = \begin{cases} 0, t < \tau, x \in [0, L]; \\ 2 \cdot \omega_0 \sum_{n=0}^{\infty} (-1)^n \cdot \sin\left(\frac{2n+1}{2} \cdot \pi \cdot \frac{x}{L}\right) \times \\ \times \cos(\omega_n (t - \tau)), t > \tau, x \in [0, L]; \end{cases} \qquad (13)$$

Now we will find the space-time dependences for the field vectors excited in the dielectric layer for the zero initial conditions.

Using the formulas (12) and (13) we are writing:

$$H_Y(\mathrm{t}, \mathrm{x}) = \begin{cases} \frac{\omega_0}{\pi} \sum_{n=0}^{\infty} (-1)^n \cos\left(\frac{2n+1}{2} \pi \frac{x}{L}\right) \times \\ \times \int_0^t H_{Y0}(\tau) \sin(\omega_\mathrm{n} (t - \tau))\, \mathrm{d}\,\tau, \\ x \in [\mathrm{x}, \mathrm{L}); \\ H_{Y0}(\mathrm{t}), x = L. \end{cases} \qquad (14)$$

$$E_Z(\mathrm{t}, \mathrm{x}) = \frac{\omega_0 \cdot Z_0}{\pi \cdot \sqrt{\varepsilon}} \cdot \sum_{n=0}^{\infty} (-1)^\mathrm{n} \times \\ \times \sin\left(\frac{2n+1}{2} \pi \frac{x}{L}\right) \int_0^t H_{Y0}(\tau) \cos(\omega_\mathrm{n} (t - \tau))\, \mathrm{d}\,\tau. \qquad (15)$$

For the further analysis we will define the electric field intensity on the dielectric boundary surface.

Substituting $x=L$ in the formula (15) we may get

$$E_Z(t, x = L) = \frac{\omega_0 \cdot Z_0}{\pi \cdot \sqrt{\varepsilon}} \cdot \sum_{n=0}^{\infty} \int_0^t H_{Y0}(\tau) \times \\ \times \cos(\omega_\mathrm{n} (t - \tau))\, \mathrm{d}\,\tau. \qquad (16)$$

If the frequency spectrum has the top limit

$$\omega << \frac{c}{\sqrt{\varepsilon} \cdot L}, \qquad (17)$$

then with help of the formula (8) after the reverse Fourier transform and the substitution $x=L$ we will find

$$E_Z(t, x = L) = \mu_0 \cdot L \cdot \frac{\mathrm{d}H_{Y0}(t)}{\mathrm{d}t}. \qquad (18)$$

The received results should be analyzed.

As it follows from the got formulas, if the spectrum limits are absent, the electromagnetic field is being excited in the dielectric. The intensities will be presented by the infinite sums of the harmonics with the frequencies which are the inversely proportional to the wave trip time through the dielectric layer with the relative electric permeability ε and thickness L.

In the case of the low frequency excitement the electric field intensity on the dielectric boundary surface is proportional to the velocity of the external magnetic field change in the time, to the layer thickness and does not depend on the relative electric permeability (the polarization phenomena).

Let us execute some numerical evaluations.

We will begin from the case, when the external field represents by the only harmonic:

$$H_{Y0}(t) = \mathrm{H}_m \cdot \sin(\omega \cdot t). \quad (19)$$

This harmonic excites on the dielectric surface the electric field. Its intensity can be found after substitution (19) in the formula (16):

$$E_Z(t, x = L) = \frac{2 \cdot \omega_0 \cdot \omega \cdot Z_0}{\pi \cdot \sqrt{\varepsilon}} \cdot H_m \times$$
$$\times \sum_{n=0}^{\infty} \frac{\sin\left(\frac{\omega + \omega_n}{2} \cdot t\right) \cdot \sin\left(\frac{\omega - \omega_n}{2} \cdot t\right)}{\omega^2 - \omega_n^2}. \quad (20)$$

As it follows from the (20), if $\omega = \omega_n$ the resonance phenomena will take place for the electric field $E_Z(t, x = L)$.

So, for $\omega = 0,25 \cdot \omega_0$ we have

$$E_Z(t, x = L) = \frac{2 \cdot Z_0}{\pi \cdot \sqrt{\varepsilon}} \cdot H_m \cdot (\omega t) \cdot \sin(\omega t). \quad (21)$$

In the real conditions the electric field intensity resonance value is limited by the energy dissipation processes in the dielectric substance. It is attributed by the small conductivity presence and being defined quantitatively by the attenuation factor δ. From the physical reasons its value will have to equal $\delta \cong \gamma \cdot (2\varepsilon_0 \varepsilon)^{-1}$.

Numerical estimates

Now we will consider the concrete dielectric, for instance, the plastic material with the relative electric permeability $\varepsilon = 8$ and thickness $L=10^{-2}$ m (from any chemical or physical handbook!).
For $H_m=10^7$ A/m and the resonance frequency $\omega=17{,}8 \cdot 10^9$ Hz with the formula (21) help we is finding for $\omega t=0.5\pi$, that $E_{Zm}=8{,}6 \cdot 10^9$ V/m.

For the low frequency fields, for instance, when $\omega=10^8 << 17{,}8 \cdot 10^9$ Hz, after substitution these dates in (18) we will get, that $E_{Zm}=2{,}5 \cdot 10^7$ V/m.

Having used by the formula (4) we can calculate the according pressure forces. We will take in account, that the tangent component of the electric field intensity will equal to zero on the ideal conducting metal surface.

In the resonance case we will have, $F_{xm}=2{,}6 \cdot 10^9$ N/m^2.

For the low frequency fields the forces amplitudes are less essentially, $F_{xm}=0{,}2 \cdot 10^5$ N/m^2.

The conducted evaluations are being agreed with the preliminary consideration. They show that the essential dynamic forces appear under of the short-time electric fields influence with the dielectrics. These forces can reach the strength limit of the specimens to be worked. In this case it is possible their mechanical deforming and failure even.

Conclusions

For the first time some theoretical consideration of the electromagnetic deforming plastic dielectrics is conducted.
For the real dielectrics some diapason of necessary working frequencies for force deforming is fixed.
The possible amplitudes of acting electrical fields are calculated.
The real possibility of usage of the electrical field energy for some technologies of dielectrics processing is illustrated.

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