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COMPUTATIONAL MODELING OF ELECTROMAGNETIC FIELD PROPAGATION AND DEFORMATION PROCESS OF ELECTROMAGNETIC FORMING TECHNOLOGICAL SYSTEMS

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Abstract - The article deals with the issues of computer and computational modeling of the technological operations of electromagnetic forming. This is a progressive method of processing conductive materials with electromagnetic field forces. In this case, computational modeling is necessary, on the one hand, to determine the rational values of design and operational parameters that ensure the achievement of the goal of the technological operation, on the other hand, the conditions under which the equipment remains operational are determined. The computational method is presented, which is based on numerical schemes of the finite element method and allows solving the problem of electromagnetic field propagation and the problem of deformation within the framework of one design scheme. The key parameters in relation to which the numerical solution is carried out are the scalar electric potential, the vector magnetic potential and nodal displacements. The deformation process is studied by analyzing the distribution of key characteristics of the stress-strain state of the elements of the technological system. In the analysis of electromagnetic forming operations, the main one is the "strong" force effect of the electromagnetic field on electrically conductive bodies, therefore, the contribution of the electrical component was neglected. Coherence of the processes of propagation of the electromagnetic field and deformation of conditioning by the introduction of electromagnetic forces into consideration. The application of this computational method for modeling the technological processes of electromagnetic forming using a folded single-turn inductor with an assistant screen is presented.

Keywords: Computational modelling, Electromagnetic field, Electromagnetic forming, Stress-strain state, Finite element method, Electromagnetic forces.

1.Introduction

Electromagnetic forming (EMF) is a progressive method of processing a variety of materials, which uses the occurrence of a force interaction of an electromagnetic field (EM-field) with an electrically conductive workpiece in order to achieve an irreversible shape change of the latter. At the moment, EMF is widely used in various industries: automotive, aircraft, electrical engineering, radio engineering and others.

EMF has many advantages over traditional technologies for irreversible deforming of materials. Among the main advantages are, firstly, the non-contact force effect (due to the absence of a punch), which allows us to form blanks with finished surfaces and not damage such surfaces. The second important advantage of EMF is the possibility of varying the magnitude of electromagnetic forces acting on the workpiece within the technological cycle.

The current state of development of technological operations of EMF and trends towards their further development are fully described in review article [1]. It should be noted that at the present time, EMF is used for processing both traditional and powder materials, both small-scale and large-scale [2] workpieces are processed, EMF is also used for processing ready-made complex systems, such as cars or airplanes.

For example, EMF technology is currently widely used for non-contact connection of various structural elements [3,4]. Another of the main advantages of EMF is the ability to easily vary the amount of force impact, which leads to extremely high quality of the treated surface [5-7]. EMF is successfully used in combination with other material processing technologies, for example, with electro-

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hydraulic machining [8], with quasi-static machining [9]. This combination significantly increases the efficiency of technological processes.

Examples of the application of EMF technologies for vehicle repair work by attracting workpieces to the inductor are given in the works of Yu.V. Batygin, S.F. Golovashchenko, A.V. Gnatov and their colleagues [10-12]. These articles substantiate the theoretical foundations of the proposed technologies, present computational models of promising inductor systems, and present the results of analytical computational studies on the distribution of the main quantitative characteristics of the EM-field. These articles consider the possibilities and principles of influence on ferromagnetic and non-ferromagnetic materials, and propose appropriate model options for inductor systems.

Although the main object of force influence under EMF conditions is the workpiece, however as part of the EMF technological operation, the source of the EM-field – the inductor (solenoid) is equally exposed to force and this influence can be so great that it can lead to the loss of performance of the inductor due to its destruction or irreversible deformation of its elements. When developing an EMF technological operation, it is necessary to ensure both the possibility of the necessary irreversible shape change of the workpiece and the operability of the inductor. It is rational to achieve this using appropriate mathematical modeling and computational analysis.

The usage of computational modeling at the stage of creating or improving technological operations of EMF is now a mandatory factor, as evidenced by many scientific articles devoted to this topic. Here, for example, we can note the work [13], which can be considered one of the first to fully outline the issues of computational modeling in EMF systems. The paper [14] examines in detail the plastic shape changes of the workpiece during EMF. The paper [15] expands on the application of the finite element method (FEM) for simulation of EMF technological processes. Moreover, the related problem of EM-field propagation and the deforming process is considered here. Articles [16,17] provide specific examples of numerical calculations and modeling of various technological operations of EMF. Such modeling made it possible to determine the rational values of some operational parameters of EMF technological processes, which allow to achieve the success of the technological operation.

It should be noted that modern computational modeling of EMF processes should be based on appropriate methods and approaches of numerical analysis. The most used currently is the finite element method (FEM), which has a high degree of versatility. It should also be noted that the use of FEM allows analyzing both the processes of EM-field propagation and deforming processes within the framework of one design scheme, and this is carried out with a high degree of approximation to reality.

The purpose of the studies presented below is to create a computational method for analyzing the propagation of the EM-field and the process of deforming in technological systems of EMF and to apply the method to the computational modeling of such technological systems.

Within the framework of the stated purpose of research, the following objectives should be decided by mathematical, computational and computer modeling: the creation of a design scheme, the choice of a numerical method and the conduct of appropriate computational studies.

The scientific novelty lies in the application of in-depth calculation methods of analysis to the modeling of technological processes of a certain class of EMF.

2. Mathematical Framework

Modeling of EMF technological operations should generally be based on the solution of several problems, the most important of which are the problem of EM-field propagation and the problem of deforming of elements of technological system and workpiece. To describe the process of EM-field propagation in EMF technological systems, it is necessary to rely on Maxwell's canonical equations, to describe the deformation process, it is possible to rely on the complete system of equations of the theory of elasticity. In full, the mathematical formulation of these problems is presented in the articles [18,19].

When using FEM to model these processes, it is necessary to consider the variational formulation of the problem. Variational, i.e. "weak" formulation of the initial system of differential equations describing a particular physical process, requires the construction of appropriate functionals. Functionalities can be built in different ways. For example, when solving the problem of thermal conductivity (stationary or transient), we have only one differential equation with respect to one variable, which is most often chosen as temperature. Then the corresponding functional is simply Euler's equation for the differential equation of thermal conductivity.

When we solve the problem of even elastic deforming, we are dealing with a system of 15 differential and algebraic (Hooke's law) equations relative to 15 tensor-vector components of the stress-strain state (SSS). In this case, the construction of one Euler equation by purely mathematical methods is an extremely complex problem.

In this case, the use of the so-called variational principles, which are formulated on the basis of general laws of mechanics, is popular. Specifically, the most commonly used in solving elastic deformation problems are the principle of minimum total deformation energy (Lagrange's principle) and the principle of virtual work. Ultimately, when implementing such principles, solving the initial boundary value problem is reduced to solving a system of algebraic equations with respect to the values of key functions (most often this is a displacement).

When solving problems of EM-field propagation with subsequent analysis of the deformation process, principles similar to energy principles can also be applied. To formulate the total energy of the EM-field, the number of key characteristics should be reduced, which can be done by introducing the concepts of vector magnetic A and scalar electric φ potentials:

$$\vec{B} = \vec{\nabla} \times \vec{A}; \quad \vec{\nabla} \cdot \vec{A} = 0; \quad \vec{E} = -\frac{\partial \vec{A}}{\partial t} - \vec{\nabla}\varphi \tag{1}$$

here $\vec{B}$ is the magnetic induction vector, $\vec{E}$ is the vector of electric field intensity. It is also necessary to reformulate the initial and boundary conditions for these new EM-field quantities:

$$\vec{A}(0) = 0; \varphi(0) = 0. \tag{2}$$

$$\vec{A}\Big|_{\infty} = 0; \ \varphi\big|_{\infty} = 0. \tag{3}$$

$$\left.\frac{\partial \varphi_i}{\partial x_i}\right|_{\Gamma} = -E_{\Gamma i}, \quad i = 1,2,3; \qquad \left.\left(\frac{\partial A_i}{\partial x_j} - \frac{\partial A_j}{\partial x_i}\right)\right|_{\Gamma} = B_{\Gamma k}, \quad i \neq j \neq k = 1,2,3. \tag{4}$$

Here we are talking about considering the EM field in a body surrounded by an air medium (3) and in a body considered without an ambient medium (4). The symbol Γ means that the corresponding quantity belongs to the boundary of the body.

The introduction of the concepts of vector magnetic and scalar electric potentials allows us to respond to two global challenges. Firstly, it allows us to reduce the number of determining variables in relation to the EM-field propagation problem. Secondly, it allows you to easily "separate" problems in relation to the electrical and magnetic components in the future.

And also, this "tool" of analysis allows us to clearly show that the electrical component can be easily rejected when we consider a "strong" force effect on conductive bodies.

The variational formulation of the problems of EM-field propagation and the resulting deformation of systems of conductive bodies is covered in detail, from a mathematical point of view, in paper [20]. In this work, we will focus on some of the cornerstones that are necessary for a clearer understanding of the problem.

So, in the future, we will consider the case of a linear relationship between the main quantitative characteristics of the EM-field. We will consider exclusively the elastic deformation of the elements of the EMF technological systems.

Note that in the above studies we will not touch on the issues of heat transfer during the flow of electric current and, accordingly, the related issues of the influence of a non-stationary temperature field on the deformation process.

Thus, we consider the problem in a linear isothermal formulation. This allows us to assert that the solution of the problems regarding the propagation of the EM-field and the deformation of the system of conductive bodies corresponds to the condition of the minimum total energy E_{TOT}, consisting of the energy of elastic deformation U and the energy of the EM-field W:

$$\delta E_{TOT} = 0, \quad E_{TOT} = U + W \tag{5}$$

The energy of elastic deformation is determined as follows:

$$\begin{gathered} U = \frac{1}{2}\int_V \hat{\varepsilon} \cdot\cdot {}^{(4)}\hat{C} \cdot\cdot \hat{\varepsilon} dV - \int_S \vec{p} \cdot \vec{u} dS; \\ {}^{(4)}\hat{C} = -\frac{\nu E}{(1+\nu)(1-2\nu)} \hat{I} \otimes \hat{I} + \\ + \frac{E}{2(1+\nu)}\left(e_k \otimes \hat{I} \otimes e^k + e_i \otimes e_k \otimes e^i \otimes e^k\right), \end{gathered} \tag{6}$$

here $\hat{\varepsilon}$ is the tensor of deformations, $\vec{p}$ is the vector of surface mechanical loads, $\vec{u}$ is the vector of displacements, ν is the Poisson's ratio, E is the Young's modulus, $\hat{I}$ is the unit tensor, V is the body volume, S is the body surface on which mechanical loads and displacements are known.

In the case when we consider the problem of analyzing the propagation of the EM-field in the assumption of a linear relationship between its main quantitative characteristics, then the energy of the EM-field in terms of potentials can be written as follows:

$$\begin{gathered} W = \int_V \left(\frac{1}{2\mu_c}\left|\vec{\nabla} \times \vec{A}\right|^2 - \vec{j} \times \vec{A}\right) dV + \\ + \int_V \left(\frac{\varepsilon_c}{2}\left|\vec{\nabla}\varphi\right|^2 - \rho_e \varphi\right) dV. \end{gathered} \tag{7}$$

Here, currents $\vec{j}$ and electric charges ρ_e can be considered as sources of the EM-field, μ_c and ε_c are the magnetic and electrical permeability of the material.

To find a solution, it is necessary to apply the first condition from (5). Since we have chosen displacement, vector magnetic and scalar electric potentials as independent variables, we can talk about a general system of three equations:

$$\delta E_{TOT} = 0 \Rightarrow \begin{cases} \dfrac{\partial E_{TOT}}{\partial \varphi} = 0; \\ \dfrac{\partial E_{TOT}}{\partial \vec{A}} = 0; \\ \dfrac{\partial E_{TOT}}{\partial \vec{u}} = 0. \end{cases} \quad (8)$$

Next, when reformulating the problem from a general mathematical form to numerical schemes corresponding to the FEM, it is necessary to go through several steps. First, it is necessary to represent the energy expressions (6) and (7) in vector-matrix form. Second, apply formula (8) to these new expressions. In the end, we will get a system of algebraic equations, which can be broadly divided into three groups: describing the propagation of scalar electric potential, vector magnetic potential, and displacements:

$$\begin{cases} [\Sigma]\{\varphi\} + [\Sigma_m]\{A\} + [\Sigma_k]\{u\} = \{\rho_e\}; \\ [M]\{A\} + [M_e]\{\varphi\} + [M_k]\{u\} = \{J\}; \\ [K]\{u\} + [K_\varphi]\{\varphi\} + [K_m]\{A\} = \{p\}, \end{cases} \quad (9)$$

In formula (9), the following notations are adopted: $[K]$ is the stiffness matrix, $[M]$ is the "magnetic" matrix, $[\Sigma]$is the "dielectric" matrix, $\{u\}$, $\{p\}$, $\{A\}$, $\{\varphi\}$, $\{J\}$, $\{\rho_e\}$ are the column vectors of displacements, surface distributed forces, vector magnetic potential, electric potential, specified current densities and electric charge. Additionally appeared as a result of the variation operation: the matrices $[\Sigma_m]$, $[M_e]$ characterizes the changes in the magnetic field due to the presence of an electric one, and vice versa, the matrices $[\Sigma_k]$, $[M_k]$characterizes the changes in the electric and magnetic fields due to deformation (i.e, piezo effects). The article [20] describes in detail how these matrices are calculated. In fact, these matrices are a computational way to take into account the possible coherence of the processes of EM field propagation and deformation for a wide range of materials. As for the second and third components from the third equation (9), the paper [20] shows that these are nothing more than electromagnetic forces.

In the computational and numerical modeling of technological EMFs, the most important thing is to take into account the force effect of the EM-field on the conductive materials from which the inductor (solenoid) is made and from which the workpiece is made. Thus, the determining system of algebraic equations (9) will be simplified to the form:

$$\begin{cases} [M]\{A\} = \{J\}; \\ [K]\{u\} = \{p\} + \{f_{em}\}, \end{cases} \\ \{f_{em}\} = -\frac{1}{2}\{A\}^{\mathrm{T}} \frac{\partial [M]}{\partial u}\{A\}. \quad (10)$$

In the case of using FEM, the solution of the system (10) occurs relative to the nodal values of the vector magnetic potential and the nodal values of the displacement vector.

The presented scheme of numerical solution can also be applied in cases of nonlinear problems. Nonlinearity in the analysis and modeling of EMF technological processes can occur due to a specific material relationship between the main characteristics of the EM-field, due to inelastic deformation of the workpiece (possibly inductor elements) and due to the manifestation of contact interaction effects between the elements of the technological system. Then the considered computational method can also be used in combination with a number of iterative processes, where a corresponding linear problem is solved at each step.

3. Example of the Computer Simulation

Consider a computational simulation of EM-field propagation and deformation process for a technological system containing a single-turn inductor with an assistant screen and a thin workpiece. The principle of using inductors of this type is presented in the work [10-12]. When solving the tasks, we will follow the recommendations given in the article [21].

Operating conditions, design features and fixing conditions allow us to consider the problem in an axisymmetric formulation. Figure 1 shows the design scheme of the problem. The design scheme contains a folded single-turn inductor, a workpiece (thin round plate) and an ambient medium (air). The inductor consists of a steel housing (it simultaneously plays the role of an assistant screen), a rectangular cross-sectional current conductor and insulation separating the current conductor from the housing.

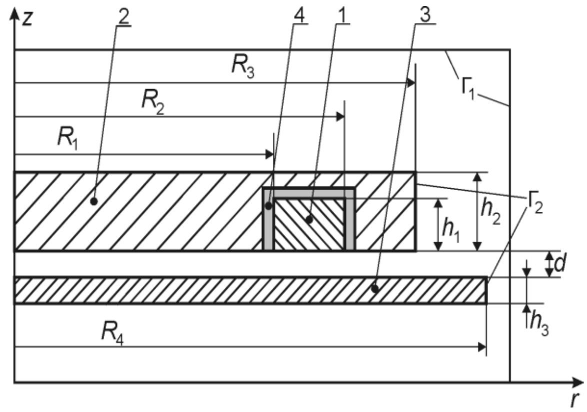

Figure 1: Design diagram of the inductor together with the workpiece: 1 - current conductor; 2 – assistant screen; 3 – workpiece; 4 - insulation of the current conductor

Table 1 shows the physical and mechanical characteristics of the material of the components of the inductor and the workpiece.

Table 1. Physic-mechanical parameters of system elements

	CC	Wp	AS	In
μ_r	1	1	1	1
$\gamma, (\Omega m)^{-1}$	$7{\cdot}10^7$	$0.2{\cdot}10^7$	$0.2{\cdot}10^7$	0
E, GPa	120	200	215	2.5
ν	0.33	0.29	0.27	0,3
σ_y, MPa	380	220	270	–
σ_B^+, MPa	–	–	–	70
σ_B^-, MPa	–	–	–	90

In Table 1, the following notations are used: μ_r is the relative magnetic permeability of the material, γ is the electrical conductivity of the material, *E* is Young's modulus, ν is the Poisson's coefficient, σ_y is the yield strength of the material, σ_B^+ is the tensile strength of the material, σ_B^- is the compressive strength of the material. The following abbreviations are introduced in the table 1: CC is a current conductor (the material is copper), Wp is a workpiece (the material is non-magnetic steel), AS is an asistant screen (the material is non-magnetic steel), **In** is insulation (the material is caprolon).

In this case, the source of EM-field was considered to be an electric current, which was uniformly distributed over the cross-section of the turn of the current conductor, in time the non-zero (circumferential) component of the current density changed according to the law $j(t) = j_m e^{-\delta\omega t}\sin(2\pi\nu t)$, where the pulse parameters were chosen as follows: amplitude of current strength is j_m = 40 kA, frequency is ν = 2 kHz, attenuation coefficient is $\delta = 0{,}3$. The solution was carried out for zero initial conditions for one current pulse, in the time range from 0 to 0.003 s, which guaranteed complete attenuation of the current in the pulse.

The geometric parameters of the system were considered as follows: $R_1 = 150$ mm, $R_2 = 1{,}25 \cdot R_1 = 187{,}5$ mm, $R_3 = 225$ mm, $R_4 = 200$ mm, $h_1 = 10$ mm, $h_2 = 15$ mm, $h_3 = 1$ mm, *d* = 1 mm, Conductor insulation thickness is 1 mm. The radial dimensions of the inductor were selected depending on the inner radius of the current conductor turn, the outer radius of the inductor was selected from the condition: $R_3 - R_2 = R_2 - R_1$.

Figure 2 shows the fourth part of the geometric model of the workpiece, inductor and the environment – air.

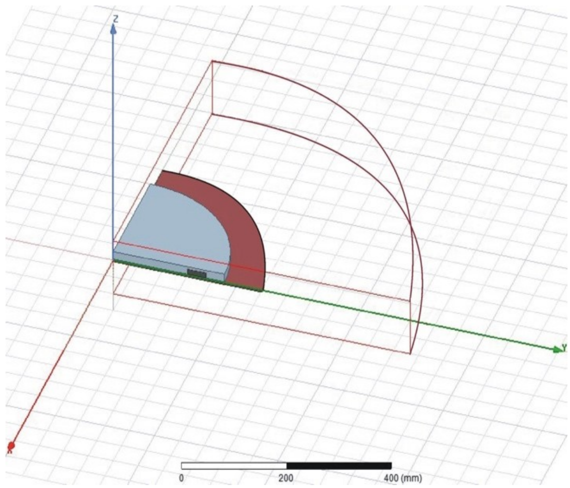

Figure 2: Geometric model of the inductor together with the workpiece and the surrounding environment

The finite-element model was created by means of the ANSYS software using axisymmetric four-nodal finite elements. The finite elemental partitioning was carried out unevenly: the thickening was set in the turn of the current conductor and in the immediate vicinity of it. The inducer presented for analysis is a composite body. In this case, it is extremely important to adequately and correctly take into account the conditions of contact interaction. In this case, the recommendations given in the article [19] are applied for this. Between the components of the inductor, layers of special contact finite elements were introduced. This allows you to take into account the nonlinearity of the initial contact problem by specifying the special material properties of the contact elements.

The reliability and accuracy of the obtained solutions was evaluated by comparing the maximum values of the tangent component of the magnetic field strength with an increase in the number of finite elements of the design scheme. Studies have also been carried out related to the choice of the magnitude of the time step. Three options for the step value were considered: 0.0001 s; 0.00005 s; 0.000025 s. Comparison was made in relation to the maximum values of magnetic field strength. It turned out that a decrease in the time step does not lead to significant changes in the magnitude of the intensity, and all further calculations were carried out for a step of 0.0001 s.

Figures 3 – 5 show some results of calculations regarding the spatial distributions of quantitative characteristics of EMFs, all results are given in accordance with the time maximum. The distribution of lines of a constant level of vector magnetic potential (Figure 3) shows that the greatest magnetic field intensity occurs directly near the turn of the current conductor. The distribution of eddy current over the surface of the workpiece (Figure 4) confirms this conclusion and generally corresponds to the data of analytical studies on the considered type of inductor, given in [11,12].

ANSYS software tools allow us to consider the distribution of electromagnetic force vectors that arise in the elements of the system in such problems. The study of the distribution of electromagnetic forces is extremely important, since in this case they serve as a link that connects the problem of EM-field propagation with the problem of deformation. Figure 5 shows the distribution of electromagnetic force vectors intensity ("electromagnetic pressure") along the surface of the workpiece. It can be seen that the maximum values of the electromagnetic force are observed near the turn of the current conductor, along the entire surface of the workpiece, the effects of attraction to the inductor are realized.

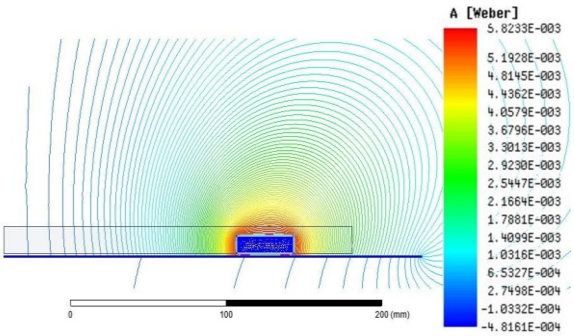

Figure 3: Lines of a constant level of vector magnetic potential

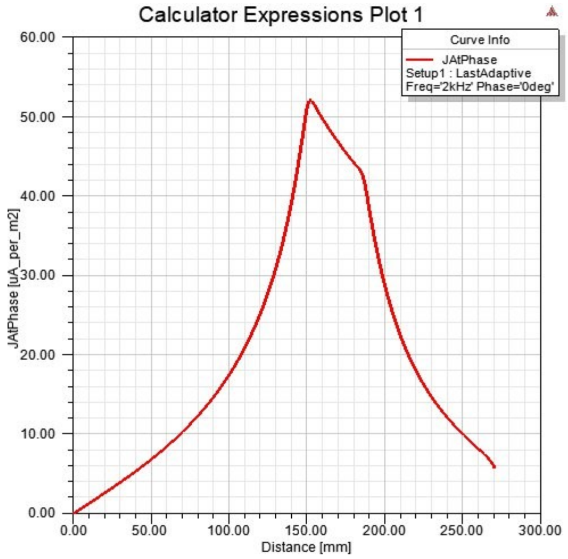

Figure 4: Eddy current distribution along the surface of the workpiece

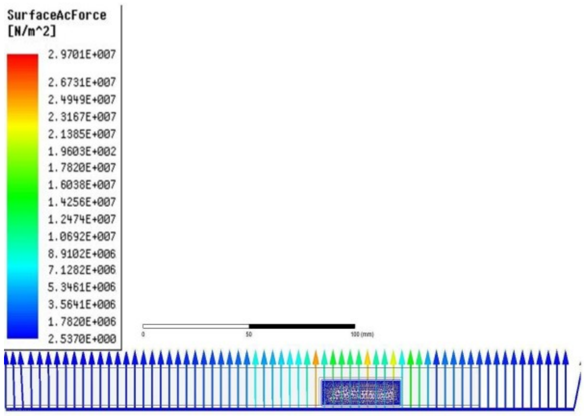

Figure 5: Distribution of electromagnetic pressure over the surface of the workpiece

The presented results of research on the distribution of the main characteristics of the EM field are not only of auxiliary value for further analysis of deformation of elements of the technological system. They also provide a lot of useful information regarding further ways of improving the technological process.

So, from the above data it is clear that the maximum force effect on the workpiece occurs in the immediate vicinity of the current-carrying conductor turn. In a geometric sense, this is a very small area compared to the dimensions of the workpiece. Since the main purpose of the technological operation is to correct defects, it is clear that such a single-turn system will not be effective in the case of affecting large defects on the workpiece.

It may be natural to assume an increase in the number of turns of the current conductor in order to increase the area of effective influence on the workpiece.

In addition, it is known that as the number of turns increases, the intensity of the EM-field increases and, as a result, the magnitude of the electromagnetic forces that will act on the workpiece. This will lead to an increase in the probability of plastic deformations at a given intensity of the EM-field source.

Thus, the development for this class of technological operations is obviously the using of multi-turn inductors.

4. Conclusions

The paper presents an effective method of computational analysis of the processes of EM-field propagation and deformation of technological systems under the conditions of EMF application.

The method is based on the use of numerical schemes of the finite element method. Using the proposed method, a computational simulation was carried out for one class of EMF technological systems, containing a single-turn inductor with an assistant screen and a flat workpiece. Some calculated results are presented regarding the distribution of quantitative characteristics of the EM-field, which allow us to assert that the maximum force action on the workpiece will occur directly in the vicinity of the inductor coil, i.e. in the "working area" of the inductor. This fact allows us to assert that the solidification of inductors of this type requires the alignment of the "working area" with the workpiece place, which is supposed to be processed.

Further development of this work consists, firstly, in a thorough analysis of the plastic shape change of the workpiece using the appropriate theoretical basis, and, secondly, in the simulation of a multi-turn inductor with an assistant screen. Another area of future research is to take into account heat dissipation when repeatedly using an inductor system.

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