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THE NONLINEAR DEFORMATION OF THE COMPOUND STRUCTURES UNDER ELECTROMAGNETIC FORMING

В роботі обговорюються питання деформування системи електропровідних тіл під дією електромагнітного поля. Проблема нелінійного деформування технологічної системи для електромагнітної обробки розглядається як практичне застосування. Проблема вирішується методом скінчених елементів. Отримано просторово-часові розподіли основних компонент електромагнітного поля. Обгрунтовано можливість розгляду проблеми деформування в квазістаціонарній постановці. Наведено розподіл основних компонент напружено-деформованого стану. Оцінюється вплив величини струму на максимальні напруження.

Ключові слова: електромагнітне поле, пружно-пластичне деформування, пресування порошків, метод скінчених елементів.

В статье обсуждаются вопросы, касающиеся деформирования системы проводящих тел под действием электромагнитного поля. Задача нелинейного деформирования технологической системы для электромагнитного формования рассматривается как практическое применение. Задача решается методом конечных элементов. Получены пространственно-временные распределения основных компонентов электромагнитного поля. Обоснована возможность рассмотрения проблемы деформирования в квазистационарной постановке. Представлено распределение основных компонент напряженно-деформированного состояния. Оценивается влияние величины тока на максимальные напряжения.

Ключевые слова: электромагнитное поле, упругопластическое деформирование, прессование порошков, метод конечных элементов.

The paper discusses issues concerning the deformation of a system of conductive bodies under the action of the electromagnetic field. Problem of nonlinear deformation of technological system for electromagnetic forming is considered as a practical application. The problem is solved by the finite element method. Spatial-temporal distributions of the main components of the electromagnetic field are obtained. The ability to review the problem of deformation in the quasi-stationary formulation is justified. The distribution of the main component of the stress-strain state is presented. The influence of the current magnitude at the maximum stresses is evaluated.

Keywords: Electromagnetic field, nonlinear deformation, finite element method, electromagnetic forming.

Introduction. Electromagnetic field (EM-field) is an integral part of work for many elements of structures and machines. High-intensity EM-fields cause substantial energy levels in electro-conductive bodies, which can lead to failure. Therefore, approaches to determine stress–strain states (SSS) of electro-conductive bodies are required to estimate the strength. Such methods should be based on suitable models of continuum thermo-mechanics. Within the framework of thermo-mechanics, there are two classes of theories: the dynamic theory and the quasi-static one. The latter is used for slowly moving bodies with the speed much less than the speed of light in vacuum. For studies in which the main objective is the analysis of the structural strength the theory of magnetoelasticity can be used. Fundamentals of the theory of magnetoelasticity with coupling EM-field and mechanical stresses and strains in a moving electro-conductive body are given by Knopoff [1] and Chadwick [2]. Dunkin and Eringen [3] formulated the dynamic problems of magneto-elasticity in the case of vibrations of bodies and distribution of magneto-elastic waves. Pidstryhach et al. [4], and Ambarcumyan et al. [5] developed a general theory of magneto-elasticity.

Many production processes of pressure treatment involve the EM-field energy. A review of advances in the technologies of electromagnetic forming (EMF) of materials and the state of the art of the problem of simulation, design and development of manufacturing processes and the equipment for this kind of treatment are presented in [6]. Noteworthy is that a sufficient number of studies are currently known devoted to the simulation of the plastic deformation of workpieces with the EMF based on the analysis of their SSS. The simulation results for the process of the electromagnetic pulse forming of thin-walled workpieces using a continuum thermodynamic model are reported in [7], with the constitutive relations derived for the electromagnetic field components. The workpiece deformation is described using an anisotropic viscoelastoplastic material. The coupling between the EMF and the stress and strain fields is established by the electromagnetic forces in the equations of motion. The results for a numerical simulation of electromagnetic sheet bulging using pulsed electromagnetic fields are given in [8]. The simulation is performed by the finite element method (FEM) and consists of two steps: simulation of the propagation of electromagnetic fields in the workpiece, followed by its elastoplastic deformation. The finite element model includes the workpiece, a flat multi-turn inductor, or coil, and ambient medium (air). The numerical analysis of the distribution of electromagnetic field and electromagnetic force components in the electromagnetic forming of sheet metals is performed in [9]. The problem was solved in the axisymmetrical formulation using the developed FE-model for the flat multi-turn coil, workpiece and ambient medium. The special features of the external EMF are established, implying that the forces of attraction to the coil prevail over those of repulsion.

At the same time, no sufficient attention is paid to the SSS analysis of the electromagnetic field sources, such as coils. It is known that during the current pulse generation, strong electromagnetic forces, significant in magnitude, act on the coil, which may result in its irreversible deformation. With the variation of the coil shape, the spatial form of the generated pulse is distorted, which adversely affects the production process. The SSS analysis of the coil allows the formulation of recommendations for its design. Therefore, the development of the efficient methods for the SSS analysis of electrically conductive compound bodies and the strength evaluation are urgent from the scientific and practical standpoint.

Formulation of the problem. Papers [10, 11] concern the issues regarding the structural analysis of inductors intended for attraction of ferromagnetic workpieces. For the attraction of non-ferromagnetic workpieces, we can use the inductors with the assistant screen. In this case, there are many issues associated with the structural analysis of the inductor as a whole and its constituent parts. Fig. 1 provides a model variant of composed single-turn inductor with an assistant screen. Such an inductor can be used for straightening dents in thin-walled structural elements [12].

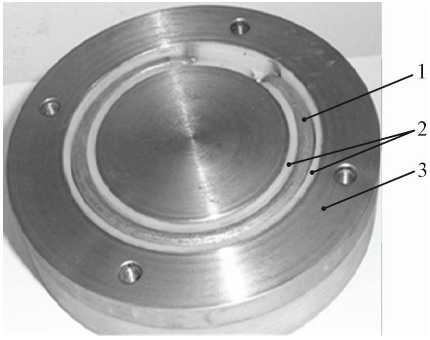

Figure 1 – The single-turn inductor. 1 – wireway of the inductor, 2 – insulation, 3 – assistant screen.

Conditions of loading, fixing and geometry allow us to consider the problem in the axisymmetric formulation. The fig. 2 shows the design scheme of the inductor with the workpiece. The gap introduced between the inductor and the workpiece, simulates a dent in the real case. The system is considered together with environment (air) in order to correctly specify the conditions of attenuation of the electromagnetic field on the distance from the source. Current, uniformly distributed over the cross section of the turn of the inductor, considered as a source of EM-field.

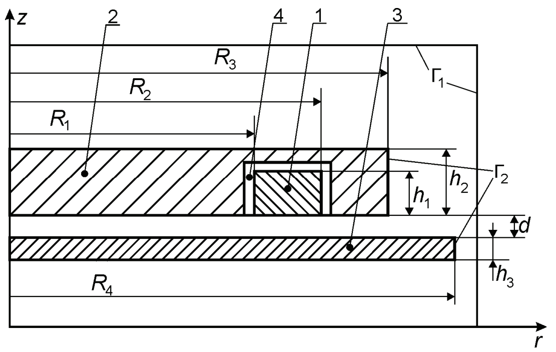

Figure 2 – Inductor – workpiece system (axisymmetrical model). 1 – wireway of the inductor, 2 – assistant screen, 3 – workpiece, 4 – insulation

It is necessary to consider the deformation of the system under given conditions, and then figure out how to change the state of the system with increasing of the current magnitude. For the analysis in this case, we will rely on the problem statement and the solution method proposed in the paper [10].

The general mathematical formulation of problems of non-isothermal elasto-plastic flow of electrically conductive bodies under the influence of an external electromagnetic field is discussed in [10]. To determine characteristics of the electromagnetic field for domains occupied by the body and the environment, the Maxwell equations are formulated. To describe the stress and strain states of the body, constitutive equations for non-isothermal elasto-plastic flow are applied. The influence of electromagnetic fields on the heat transfer and deformation is described by the equations of heat transfer and dependencies for electromagnetic forces. Interactions of electromagnetic and thermal fields, and distributions of electromagnetic forces in the bodies and on the contact surfaces are discussed. The finite element method (FEM) is used as numerical method of analysis. Its specific implementation is based on the principle of minimum of total energy of the system.

The problem was solved with the following geometrical sizes: $R_1 = 150\,\text{mm}$, $R_2 = 167\,\text{mm}$, $R_3 = 175\,\text{mm}$, $R_4 = 200\,\text{mm}$, $h_1 = 10\,\text{mm}$, $h_1 = 15\,\text{mm}$, $h_3 = 1\,\text{mm}$, $d = 1\,\text{mm}$, thickness of the insulation – $1\,\text{mm}$. The size of the environment was varied to meet the conditions of attenuation of the EM-field at a distance from the field source. Material properties: wireway (copper), $\mu_r = 1$, $\gamma = 7\times10^7\,(\Omega\text{m})^{-1}$, $E = 180\,\text{GPa}$, $\nu = 0{,}33$, $\sigma_Y = 180\,\text{GPa}$; assistant screen (steel), $\mu_r = 1$, $\gamma = 0{,}2\times10^7\,(\Omega\text{m})^{-1}$, $E = 215\,\text{GPa}$, $\nu = 0{,}27$, $\sigma_Y = 270\,\text{GPa}$; workpiece (steel), $\mu_r = 1$, $\gamma = 0{,}2\times10^7\,(\Omega\text{m})^{-1}$, $E = 200\,\text{GPa}$, $\nu = 0{,}29$, $\sigma_Y = 220\,\text{GPa}$; insulation (glass fiber), $\mu_r = 1$, $\gamma = 0(\Omega\text{m})^{-1}$, $E = 2{,}5\,\text{GPa}$, $\nu = 0{,}3$, $\sigma_+ = 70\,\text{GPa}$, $\sigma_- = 90\,\text{GPa}$; environment (air), $\mu_r = 1$, $\gamma = 0(\Omega\text{m})^{-1}$. Here: μ_r – relative magnetic permeability, γ – electrical conductivity, E – modulus of elasticity, ν – Poisson's ratio, σ_Y – yield stress, σ_+ – tensile strength, σ_- – compressive strength.

The current density is changed in time according to the law $j(t) = I_m e^{-\delta 2\pi f t}\cdot\sin(2\pi f t)$, where magnitude of current $I_m = 40\,\text{kA}$, frequency $f = 2\,\text{kHz}$, the relative damping coefficient $\delta = 0.3$. A finite element model was created using four-node axisymmetric finite element with bilinear approximation of displacements and circumferential components of the magnetic vector potential. To account the mechanical contact it was introduced the layers of special contact finite elements [13,14]. The boundary conditions, that model the attenuation of EMF on the distance from the source and fixing of the ends of the inductor and workpiece, were considered:

$$A\big|_{\Gamma_1} = 0;\ u_r\big|_{\Gamma_2} = 0;\ u_z\big|_{\Gamma_2} = 0.$$

The spatiotemporal distribution of components of the EM-field was obtained at the first stage of the solution. Also, we performed a series of calculations, which varied the dimensions of the surrounding area. Analysis of the results showed that the components of the EM-field are reduced approximately five times when the distance from the field source to the boundary of the environment is comparable to the double thickness of the assistant screen. Further, the value component of the electromagnetic force acting on the workpiece surface was determined. A comparison with the results presented in [12], which were obtained semi-analytical means showed that the maximum discrepancy does not exceed 12%.

Analysis of the EM-field main components distribution has shown that there is a significant decrease in their value over time. Therefore, the electromagnetic force acting on the workpiece will decrease as fast as the components of the electromagnetic field. Therefore, the deformation problem can be considered in the formulation of the quasi-stationary, with the values of the electromagnetic field components corresponding to the maximum time. Analysis of the displacements shows that the workpiece is deformed to a much greater extent than the inductor. This fact is explained by the peculiarities of the geometry of the objects involved. The inductor is much more massive body than the workpiece. Maximum of workpiece displacements are observed in the vicinity of its center.

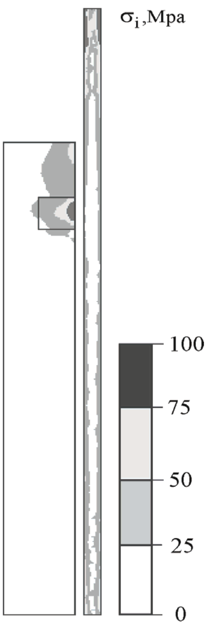

Figure 3 – Distribution of the von Mises equivalent stress

The fig.3 shows the pattern of distribution of intensity of the Von Mises equivalent stress in the elements of the system. Note that the maximum stresses in the inductor are observed directly in the turn and its surroundings. The stresses in the workpiece have two peaks: in the area of fixation and in the vicinity of the center of the workpiece. The stresses in the inductor exceed the stresses levels in the workpiece. Overall, it should be noted that when the magnitude of the current equals 40 kA, neither in the workpiece nor in the inductor stresses does not exceed dangerous values. Although, the stresses in the vicinity of the coil (insulation material) are approaching threat values.

Next, we conducted a series of calculations, which varied the magnitude of the current. Note that the qualitative characteristics of the stress distribution in the elements of the system persist for all values of the magnitude. In the fig.4 are plotted the maximum values of the Von Mises equivalent stress in the inductor and the workpiece versus the amplitude of the current. The maximum stress in the workpiece while all the considered values of the current magnitude do not reach the yield strength, i.e., the workpiece didn't begin to deform plastically. So, when this embodiment of the inductor of the conditions of technological operations will not be achieved. Stresses in the inductor are higher than in the workpiece. The stresses in the insulation material when, the current magnitude equals 60 kA, exceed the limit values. Insulation may deteriorate, which in this case is not valid.

It should also be noted that when current flows, heat generation occurs in the conductor. In our study, issues concerning non-stationary distribution of the temperature field due to heat generation were not considered. It is obvious that the increase in the amplitude of the current will increase the temperature of the system elements that must be considered in the analysis of SSS. Obviously in this case, the method of increasing the number of turns of the inductor is more promising, because, it is known that the generalized magnetic pressure is proportional to the number of turns.

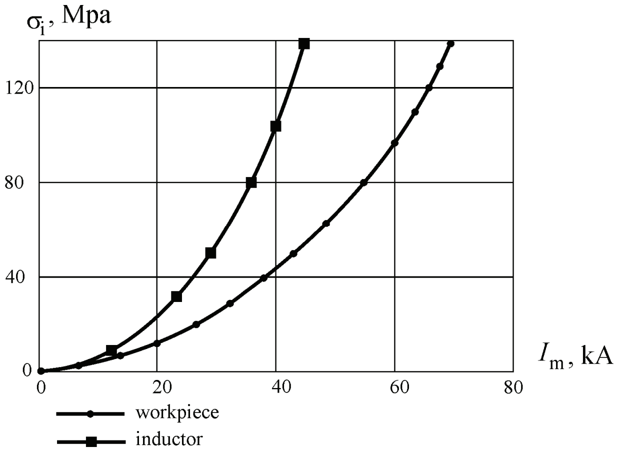

Figure 4 – Maximum von Mises equivalent stress versus magnitude of the current

Conclusions. The paper deals with the issues devoted to the study of elastic-plastic deformation of conductive bodies under the action of the electromagnetic field. The feasibility of using numerical methods of analysis is justified. It is consider the practical task of the analysis of the deformation of the technological system for electromagnetic forming of materials. The distribution of stresses in the elements of the system is obtained. The change in maximum stress with increase in the current magnitude is analyzed.

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