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Computational studies of electromagnetic field propagation and deforming of structural elements for a thin-walled curved workpiece and an inductor

Introduction. *At the present stage of industrial development, the electromagnetic field is widely used in various technological processes. The force effect of an electromagnetic field on conductive materials is used in a class of technological operations called electromagnetic forming.* ***Problem.*** *Under the conditions of electromagnetic forming, the main element of the technological equipment – the inductor – is simultaneously subjected to the force impact with the workpiece. At certain levels of the electromagnetic field, the deformation of the inductor becomes so significant that it can lead to a loss of its efficiency.* ***Goal.*** *Computational analysis of a thin-walled curved workpiece and a two-turn inductor under the conditions of electromagnetic processing of the workpiece corner zone. Determining the distribution of quantitative characteristics of the electromagnetic field and the stress-strain state and conducting assessments based on them regarding the efficiency of the technological operation.* ***Methodology.*** *Computational modeling using the finite element method as a method of numerical analysis. The* ***results*** *on the distribution of quantitative characteristics of the electromagnetic field and components of the stress-strain state for a thin-walled workpiece and an inductor are obtained. It is shown that for the specified characteristics of the technological operation, the inductor remains operational, and plastic deformations occur in the workpiece. A series of calculations were carried out, in which some parameters of the technological system were varied.* ***Originality.*** *For the first time, the results of the calculation analysis of the quantitative characteristics distribution of the electromagnetic field of the deformation process for the «inductor – thin-walled curved workpiece» system are presented.* ***Practical value.*** *The presented design scheme of a curved thin-walled workpiece and a two-turn inductor, the method of calculation analysis and some obtained results can be used in the analysis of electromagnetic processing of thin-walled structures that contain curved elements.* References 16, table 1, figures 6.

Key words: **computational analysis, electromagnetic field, electromagnetic forming, deformation, finite element method.**

Вступ. *Електромагнітне поле на сучасному етапі розвитку промисловості широко використовують у різних технологічних процесах. Силовий вплив електромагнітного поля на провідникові матеріали використовується в класі технологічних операцій, що називається електромагнітним формуванням.* ***Проблема.*** *За умов електромагнітного формування силовому впливу одночасно із заготовкою піддається і основний елемент технологічного обладнання – індуктор. При певних рівнях електромагнітного поля деформування індуктора стає настільки значним, що може приводити до втрати його працездатності.* ***Мета.*** *Проведення розрахункового аналізу тонкостінної вигнутої заготовки та двовиткового індуктора за умов електромагнітної обробки кутової зони заготовки. Визначення розподілу кількісних характеристик електромагнітного поля і напружено-деформованого стану та проведення на їх основі оцінок стосовно ефективності технологічної операції.* ***Методологія.*** *Розрахункове моделювання із використанням методу скінченних елементів в якості методу чисельного аналізу. Одержані* ***результати*** *з розподілу кількісних характеристик електромагнітного поля та компонентів напружено-деформованого стану для тонкостінної заготовки та індуктора. Показано, що для заданих характеристик технологічної операції індуктор залишається працездатним, а у заготовці виникають пластичні деформації. Проведено серію розрахунків, у яких варіювалися деякі параметри технологічної системи.* ***Оригінальність.*** *Вперше представлено результати розрахункового аналізу з розподілу кількісних характеристик електромагнітного поля процесу деформування для системи «індуктор – тонкостінна вигнута заготовка».* ***Практичне значення.*** *Представлена розрахункова схема вигнутої тонкостінної заготовки та двовиткового індуктора, використаний метод розрахункового аналізу та деякі отримані результати можуть використовуватися при аналізі електромагнітної обробки тонкостінних конструкцій, які містять вигнуті елементи.* Бібл. 16, табл. 1, рис. 6.

Ключові слова: **розрахунковий аналіз, електромагнітне поле, електромагнітна обробка, деформування, метод скінченних елементів.**

Introduction. Electromagnetic field (EM-field) energy is widely used in various modern technological operations. The force effect of the EM-field is used in a class of technological operations traditionally called electromagnetic forming (EMF). A fairly complete overview of the current state of issues related to the classification of various technological operations of the EMF is presented in works [1, 2]. In general, the standard EMF technological operation can be characterized as follows: the using of the EM-field energy to influence a conductive workpiece with the aim of plastically changing its shape. It should be noted that non-traditional directions of the EMF are currently being developed. The basic questions of some modern trends in the development of EMF technologies are presented in articles [3-5].

Currently, thin-walled structural elements are widely used in various branches of mechanical engineering. Very often such structural elements have a pre-produced curvature. Usually, the necessary curved structural elements are manufactured in two stages: in the first stage, they reach the required general (overall) dimensions and shape, in the second stage they achieve the required quality directly in the corner zone. Part of the technological operations of EMF is aimed at creating conditions for the occurrence of residual deformations in curved thin-walled metal workpieces directly in the corner zone. This zone can be called the «target zone» of the technological operation. This group of technological operations was named technological operations of «filling corners». In practice, it means the reduction of rounding radii to acceptable values in the bending zones of thin-walled workpieces. From the point of view of the conditions of the technological operation, it is necessary to exert the maximum force around the «target zone». In works [6, 7], it is proposed to use an inductor with two turns, which have one common current line directed along the bend, to «fill the corners» on thin-walled curved workpieces, each of the turns is a plane that makes an angle of up to 15° with the wall of the workpiece.

At the modern stage of development, the design of new technological operations of the EMF and the improvement of existing ones is impossible without computer modeling and computational studies. Creating calculation models that are closest to reality is impossible without the use of numerical methods. The most popular is the finite element method (FEM), which allows, within the same design model, to perform a computational analysis of various physical processes. This is especially important in the case of analyzing EMF technological systems, since here it is very important to study the processes of workpiece deforming. As an example of a computational analysis of EMF processes using FEM, works [8-12] can be considered.

Note that in most cases, the object of study when analyzing deforming is the workpiece. At the same time, the main element generating the EM-field, the inductor, is also subject to intense force action. Under certain conditions, the deforming of the inductor can become quite intense and lead to its destruction. Therefore, from our point of view, analysis of the inductors deforming under the conditions of technological operations of the EMF is also an important task.

The goal of the paper is the computational analysis of the EM-field distribution under the conditions of the «filling corners» technological operation of a thin-walled curved workpiece and determination of the stress-strain state (SSS) components of the inductor and the workpiece for the assess the effectiveness of this technological operation.

Mathematical formulation of the problem. The effectiveness of the EMF technological operation can be considered achieved if, on the one hand, the inductor remains operational, and on the other hand, an irreversible change in the shape of the workpiece is achieved. If we conduct a computational analysis, then we must determine the presence or absence of plastic deformation zones in the inductor and the workpiece. Thus, it is necessary to obtain the distribution of quantitative characteristics of the EM-field and then solve the problem of elastic-plastic deformation.

The solution to this problem must be based on a correct mathematical formulation. The complete mathematical formulation of the problem of the EM-field quantitative characteristics distribution and further elastic-plastic deforming of systems of conductive bodies is presented in work [13].

Figure 1 shows a design diagram of a curved thin-walled workpiece and a two-turn inductor designed to concentrate the force in the rounding zone (this is where plastic deformations should occur).

The problem of numerical EMF calculation was considered under the assumption of a plane-parallel distribution of the field. Physically, this assumption is valid for the case when the length of the workpiece and the inductor along the z coordinate is significantly (several times) larger than the dimensions along the other two coordinates. The formulation of the problem in this assumption allows not paying attention to specific ways of closing the turns of the current conductor of the inductor.

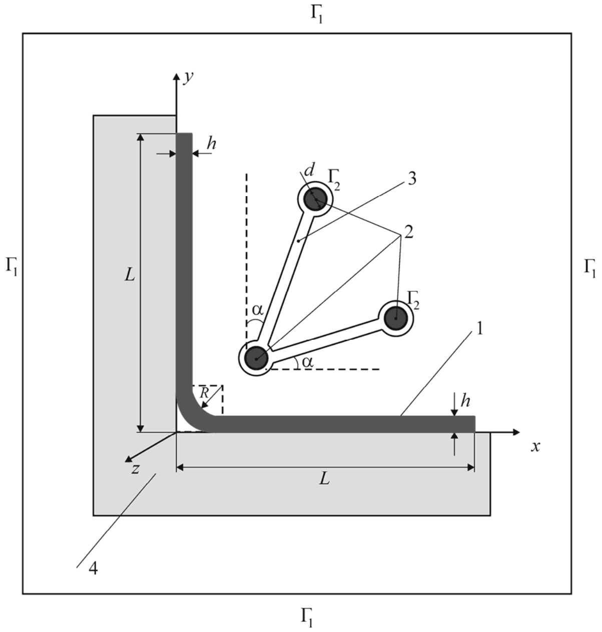

Fig. 1. Design diagram of a curved workpiece together with a two-turn inductor and a dielectric mold: 1 – workpiece; 2 – turns of the current conductor of the inductor; 3 – inductor insulation; 4 – dielectric mold

As in work [13], the resolving equation for the EM-field is formulated with respect to the vector magnetic potential $\vec{A}$. In the setting of the plane-parallel distribution, the vector magnetic potential has only one non-zero component: $\vec{A}$ = (0, 0, A_Z); $A_Z = A$. This also applies to the current density vector $\vec{j}$. The magnetic field intensity and magnetic induction instead have two non-zero components, in the chosen coordinate system: $\vec{H}$ = (H_x, H_y, 0); $\vec{B}$ = (B_x, B_y, 0); $\vec{B} = \mu_a \vec{H}$, where $\mu_a = \mu_0 \mu_r$, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant, μ_r is the relative magnetic permeability of the system elements material. The defining equation for the non-zero component of the vector magnetic potential in this case takes the form (in the case of a material with constant magnetic permeability μ_a and constant specific electrical conductivity γ):

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} - \mu_a \gamma \frac{\partial A}{\partial t} = -\mu_a j(t) . \quad (1)$$

At the same time, the components of the magnetic induction vector can be found as follows:

$$B_x = \frac{\partial A}{\partial y}; \; B_y = -\frac{\partial A}{\partial x} .$$

We use initial and boundary conditions:

$$A(0) = 0; \; A\big|_{\Gamma_1} = 0 , \quad (2)$$

where Γ_1 is the boundary of the calculation area, on which the EM-field attenuation conditions must be met.

The variational formulation of the problem requires the determination of the stationarity of the functional, which has the form:

$$MAG = \int\limits_S \left[\frac{1}{2} \left\{ \left(\frac{\partial A}{\partial x} \right)^2 + \left(\frac{\partial A}{\partial y} \right)^2 \right\} + \mu_a \gamma \frac{\partial A}{\partial t} A - \mu_a j A \right] \mathrm{d}S , \quad (3)$$

where S is the area occupied by the design scheme.

An electric current evenly distributed over the cross-section of the current conductor turns of the inductor is considered as a source of EM-field. The magnitude of the non-zero component of the current density vector varied over time t according to the next law:

$$j(t)=j_m e^{-\delta_0 \omega t}\sin(2\pi\nu t), \qquad (4)$$

where $j_m \approx \dfrac{4I_m}{\pi d^2}$ is the current density amplitude; $I_m = 40$ kA is the amplitude of the current in the inductor, $\nu = 2$ kHz is the pulse current frequency, $\omega = 2\pi\nu$ is the cyclic frequency of the current change, $\delta_0 = \delta/\omega = 0{,}3$ is the relative coefficient of the inductor current attenuation δ.

The second and main stage of the analysis is the study of the elements deforming of the inductor and workpiece, which are presented within the framework of a single scheme. In this case, the bodies system deforming is considered within the framework of plane deformation. The distribution of the main tensor-vector components that describe the deforming process of the inductor elements and the workpiece is subjected to the following group of equations. Equilibrium equation:

$$\begin{cases} \dfrac{\partial \sigma_x}{\partial x}+\dfrac{\partial \tau_{xy}}{\partial y}+f_x=0 \\ \dfrac{\partial \tau_{xy}}{\partial x}+\dfrac{\partial \sigma_y}{\partial y}+f_y=0 \end{cases}, \qquad (5)$$

where σ_x, σ_y, τ_{xy} are non-zero components of the stress tensor; $f_x = -jB_y$, $f_y = -jB_x$ are the components of the volumetric electromagnetic force vector.

Geometric dependences in the Cauchy form:

$$\varepsilon_x=\frac{\partial u_x}{\partial x};\ \varepsilon_y=\frac{\partial u_y}{\partial y};\ \gamma_{xy}=\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}, \qquad (6)$$

where ε_x, ε_y, γ_{xy} are the non-zero components of the deformation tensor; u_x, u_y are the non-zero components of the displacement vector.

The relationship between stresses and deformations is accepted according to the elastic model:

$$\{\varepsilon\}=[A]\{\sigma\},\quad [A_{ij}]=\frac{(1+\nu)}{E}\begin{bmatrix} 1+\nu & -\nu & 0 \\ -\nu & 1+\nu & 0 \\ 0 & 0 & 2 \end{bmatrix}, \qquad (7)$$

where E is the modulus of elasticity, ν is the Poisson ratio.

The following can be stated regarding the fixing conditions: the conductive workpiece must be freely located on the dielectric mold; its edges must not be fixed in any way (article [14] shows that in the case of fixed edges of the workpiece, the highest stress levels occur around them). In turn, since the force effect on the mold in this case is not of interest to us, we will not dwell on the specific method of its fastening, we will assume that the its lower outer border is fastened.

In the case when the workpiece is freely located on the mold (see Fig. 1), the conditions of one-sided contact between them must be taken into account. In this case, during the numerical solution, the contact was modeled by introducing a layer of special contact elements (similar to how it was done in [15]). Also, layers of contact elements are introduced between the turns of the inductor and the insulation. The inductor was considered fixed on the boundaries indicated in Fig. 1 as Γ_2:

$$u_x\Big|_{\left(\begin{smallmatrix} x\in\Gamma_2 \\ y\in\Gamma_2 \end{smallmatrix}\right)}=0,\quad u_y\Big|_{\left(\begin{smallmatrix} x\in\Gamma_2 \\ y\in\Gamma_2 \end{smallmatrix}\right)}=0. \qquad (8)$$

The solution was based on finite element modeling. The defining equations for which in similar problems are generally given in [16]. A three-node finite element (FE) with a linear approximation of the non-zero component of the vector magnetic potential and displacements is used as the basis. At the first stage of the analysis, the spatio-temporal distributions of the main quantitative characteristics of EM-field were found. Here, a series of calculations was carried out, in which the rational parameters of the calculation model were determined: the dimensions of the environment, the number of FEs, and the time integration step. All this was done in order to satisfy the boundary conditions (2) and prove the reliability of the obtained results.

During calculations, the following values of geometric dimensions were considered: d = 10 mm, L = 100 mm, h = 2 mm, α = 15°.

The physical and mechanical parameters of the system elements, which were used in all subsequent calculations, are given in Table 1.

Table 1

Physical and mechanical parameters of system elements

The elements characteristics name	The inductor current conductor parameters, copper	The workpiece parameters, aluminum alloy	The insulation parameters, kaprolon	The data of the dielectric mold, fiberglass
μ_r	1	1	1	1
γ, $(\Omega\text{m})^{-1}$	$7{\cdot}10^7$	$4{,}6{\cdot}10^7$	0	0
E, GPa	120	71	2,5	200
ν	0,33	0,29	0,3	0,27
σ_y, MPa	380	190	–	–
σ_B^+, MPa	–	–	70	100
σ_B^-, MPa	–	–	90	120

In Table 1 adopt the following designations: σ_y is the yield strength of the material; σ_B^+ is the tensile strength limit; σ_B^- is the compressive strength limit.

The dimensions of the surrounding environment were characterized by the distance from the vertical and horizontal walls of the workpiece. Based on the results of the calculations, the maximum values of the tangential component of the magnetic field intensity on the inner surfaces of the workpiece around the corner were compared. The first calculation was carried out at a distance of $L/10$ (see Fig. 1). The subsequent calculations were carried out with an increase in the distance by the same amount of $L/10$. It turned out that when the distance goes from $L/2$ to $3L/5$, the difference in the values of the tangential component of the magnetic field intensity around the corner does not exceed 2,32 %. Therefore, all subsequent calculations were carried out under the condition that the boundaries of the surrounding medium are at a distance of $L/2$ from the walls of the workpiece.

To establish the reliability of the finite element modeling results, studies were conducted in which the number of FEs was changed by increasing them. It should be noted that since the main object of consideration was the workpiece and the inductor, the FE concentration was carried out precisely in the areas of the calculation scheme corresponding to these elements. The initial FE mesh consisted of 1650 elements. Further calculations were carried out by doubling the number of elements, while comparing the maximum values of the magnetic field strength in the vicinity of the rounding. When moving from 13200 FEs to 26400 FEs, it turned out that the value of the maximum magnetic field strength changes slightly – by 1,214 %. Therefore, all further calculations were carried out for a finite element mesh containing 13200 FEs.

Regarding the variation of the integration step over time, it was found that the reduction of the time step does not lead to significant changes in the results of the distribution of EM-field components. All calculations were performed for a step of 0.1 ms.

Analysis of the calculation results. Let us consider some calculation results. At the first stage, the spatio-temporal distributions of the main quantitative characteristics of EM-field were obtained. In Fig. 2 shows the distribution of the H_y-component of the magnetic field intensity corresponding to it maximum in the time interval.

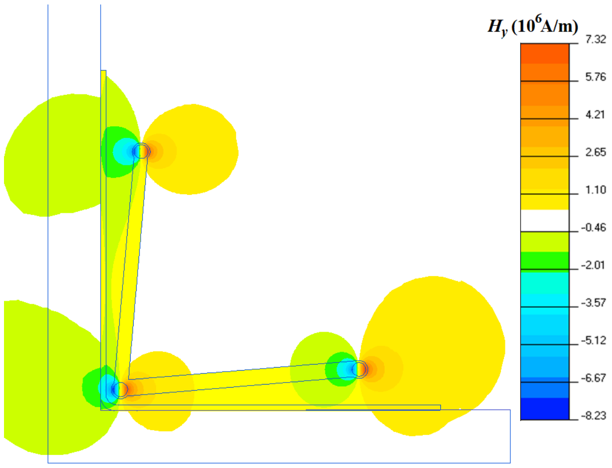

Fig. 2. Distribution of the H_y-component of the magnetic field intensity

From the data of Fig. 2 is seen that the maximum values of intensity H_y are observed around the turns of the inductor current conductor and it is here that the maximum force impact on the workpiece should be expected.

Let's consider in more detail the results of SSS calculations of the workpiece, mold and inductor. Calculations were performed in a quasi-stationary setting, for EM-field components that have maximum values from the considered time interval.

The found distributions of the tensor components of the SSS make it possible to carry out quantitative assessments of the strength of the workpiece and the elements of the inductor, which in turn allows drawing conclusions about the efficiency of the technological operation. When carrying out the relevant assessments, we used the approach given in article [16], when the equivalent stresses were determined and compared with the material strength characteristics. The stress intensity was calculated for the elements of the calculation scheme made of conductive materials (workpiece, inductor conductor), and the equivalent stress was calculated for dielectrics (inductor insulation) according to Mohr's criterion.

Figures 3 and 4 show the spatial distributions of stress intensity σ_i and equivalent stresses according to Mohr's criterion σ_{Mo} in the workpiece.

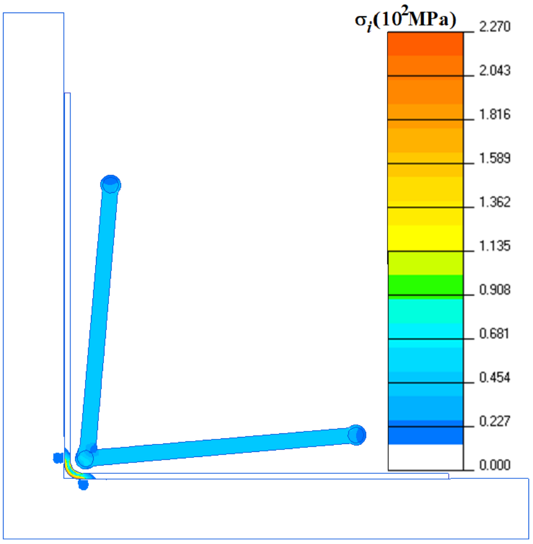

Fig. 3. Distribution of stress intensity

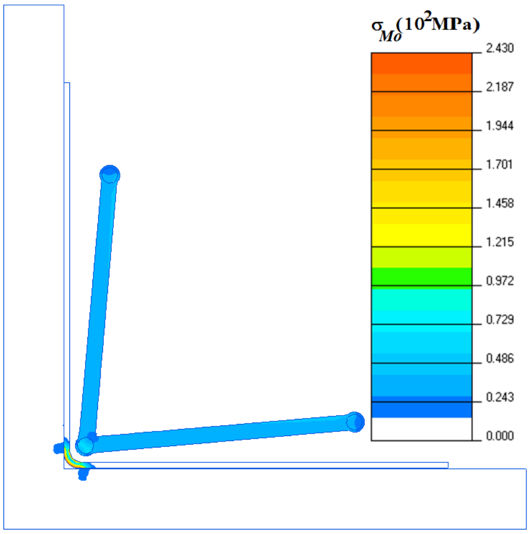

Fig. 4. Distribution of equivalent stresses according to Mohr's criterion

The given distributions of equivalent stresses allow us to conclude that the most loaded are: the workpiece zone around the rounding («target zone» of the technological operation), the current conductor and the insulation zones bordering the current conductor.

The maximum value of the stress intensity in the workpiece, which is observed on the workpiece surface (directly in the vicinity of rounding – in the «target zone» of the technological operation), is 227 MPa, which is greater than the yield strength of the aluminum alloy. Thus it can be stated that from the point of view of the plastic deformations possibility in the workpiece, the technological operation is efficient. The maximum intensity of stress in the current conductor of the inductor is approximately 60 MPa, which does not exceed the yield strength of it material. The maximum value of the equivalent stress according to Mohr's criterion in the insulation of the inductor is 52 MPa, which also does not exceed the limit of the tensile strength of the material. So, it can be concluded that in this case the inductor remains operational.

Next, a series of calculations was carried out in order to determine the influence of the design and operational parameters of the technological operation on the process of elastic-plastic deformation of the workpiece. The purpose of these calculations was to determine the inductor application limits of this type and size, as well as to determine the rational values of some design and operational parameters of the technological system.

One of the series of calculations was aimed at finding out the degree of influence of the distance between the inductor and the workpiece on the distribution of SSS components in it. Here, the value of the distance between the coil of the inductor, which is close to the workpiece, and the workpiece varied, while other parameters of the technological operation (the dimensions of the workpiece, the values of the characteristics of the external EM-field) remained constant. The analysis of the results shows that when the inductor is moved away from the workpiece, the value of the maximum stress intensity in it decreases (Fig. 5), at a distance of 14 mm, the maximum stress intensity in the workpiece is approximately equal to the yield point of the aluminum alloy, i.e., with further distance, the workpiece will deform elastically. Thus, the most rational option is when the inductor touches the workpiece, and the largest distance between the inductor and the workpiece should not exceed 14 mm.

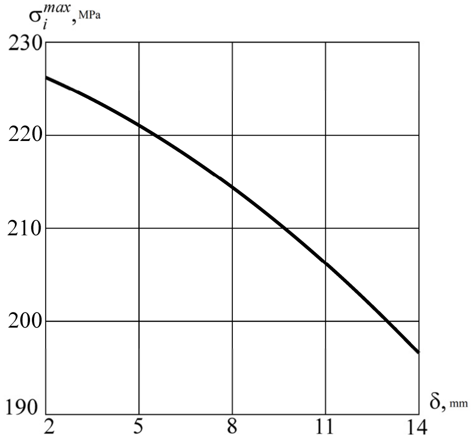

Fig. 5. Dependence of the maximum stress intensity in the workpiece on the distance between the inductor and the workpiece

Another series of calculations was aimed at finding out the influence degree of the current amplitude in the inductor on the distribution of SSS components in the elements of the technological system. Calculations were performed for the case of contact between the inductor and the workpiece. Five calculations were carried out, in which the amplitude of the current I_m was assumed to be equal to 40, 45, 50, 55 and 60 kA.

As the current strength increases, the qualitative patterns of distribution of SSS components in the workpiece are preserved, and the stress values increase. Figure 6 shows graphs illustrating the growth of the maximum stress intensity in the workpiece and in the current conductor, as well as the maximum equivalent stress according to Mohr's criterion in the dielectric insulation with increasing current magnitude in the inductor.

It can be seen that when the amplitude of the current I_m exceeds the level of 50 kA, the values of the equivalent stresses in the insulation of the calculated system reach dangerous values: at the same time ($\sigma_{Mo} > \sigma_B^+$).

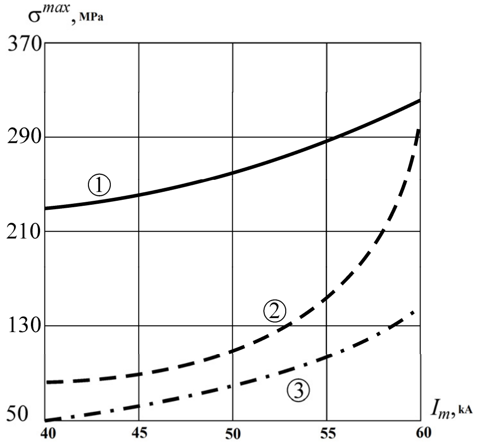

Fig. 6. Dependence of the equivalent stresses on the magnitude of the current amplitude: 1 – in the workpiece (stress intensity); 2 – in the inductor coil (stress intensity); 3 – in insulation (equivalent stress according to Mohr's criterion)

Thus, with the considered design parameters, the amplitude of the current I_m in the inductor should not exceed 50 kA, because with its further increase, there is a possibility of operability loss of the used inductor due to the destruction of the dielectric insulation.

Conclusions.

1. The design scheme of the technological operation of «filling corners», which includes a curved thin-walled workpiece and a two-turn inductor, is considered. A mathematical formulation of the problem of electromagnetic field propagation and deformation is presented. The finite element method was used as a numerical method. Numerical studies were carried out to substantiate the parameters of the design scheme.

The results of calculations on the distribution of the electromagnetic field quantitative characteristics and the deformation process are given. The spatial distribution of the H_y-component of the magnetic field intensity, which corresponds to it maximum in the time interval, is presented, from which a forecast can be made regarding the zones of maximum force impact on the workpiece. Spatial distributions in the elements of the calculation system of equivalent strength indicators are also given: stress intensity and equivalent stress according to Mohr's criterion.

2. It is shown that the maximum force impact occurs directly in the area of the workpiece rounding. In this case, with the considered parameters of influence, plastic deformation begins in the workpiece, and the inductor remains operational.

A series of calculations of the electromagnetic field and the stress-strain state of the calculation system were carried out, in which the values of the distance between the inductor and the workpiece, as well as the amplitude of the inductor current, varied. Rational values of the specified parameters were found, at which the used inductor remains operational, and plastic deformations occur in the workpiece material.

3. The further development of this work consists in carrying out calculation studies of the workpiece deforming in the region beyond the yield strength of it material.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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