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MAGNETIC-PULSED ATTRACTION OF SHEET BILLETS WITH "DIRECT PASSAGE OF CURRENT"

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ABSTRACT *The theoretical substantiation of the efficiency of magnetic-pulse attraction method of sheet metal with "direct current transmission" through the object being processed is presented. The analysis of well-known works in this area is carried out, it is shown that the lack of sufficiently complete theoretical studies does not allow effectively performing a given production operation. By solving the boundary-value electrodynamic problem, analytical expressions are obtained for the phase dependences of currents in the experimental system and the excited forces of attraction of the processed object. It is proved by numerical estimates that the low-frequency mode of the ongoing electromagnetic processes is preferable when the fields penetrate intensively through the conducting components of the system under study. It was found that the calculated dependence of the developed forces on the discharge voltage of the capacitive storage allows an approximate estimate of the efficiency of attraction when operating in the accepted range of energy capabilities of the power source. It is shown that the degree of inhomogeneity of the transverse distribution of attractive forces in the region under study does not exceed ~ 20%. A working experimental model has been designed and created, consisting of a tool for magnetic-pulse attraction of sheet metal and a power source - an energy unit. Based on the obtained ratios, the characteristics of the pilot plant and the test modes were calculated. A dosed magnetic-impulse force action has been practically implemented, which makes it possible to control the deformation of sheet metal in the processing zone. Experiments have been carried out to remove dents on samples made of various types of steel under conditions close to the corresponding real production operation. The practical possibilities of the means of magnetic-pulse attraction of certain sections of sheet metals with "direct current transmission" through them have been successfully demonstrated. The effectiveness of the method under consideration is proved when using the indicators of the technological operation, calculated based on theoretically obtained dependences.*
Keywords: *magnetic-pulsed attraction; thin-walled sheet metal; electromagnetic processes; "direct passage of current"; experimental approbation; flattening automobile bodies*

МАГНІТНО-ІМПУЛЬСНЕ ПРИТЯГАННЯ ЛИСТОВИХ ЗАГОТОВОК ПРИ «ПРЯМОМУ ПРОПУСКАННІ СТРУМУ»

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АНОТАЦІЯ *Представлено теоретичне обґрунтування працездатності методу магнітно-імпульсного притягання листового металу з «прямим пропусканням струму» через оброблюваний об'єкт. Проведено аналіз відомих робіт в цій галузі, показано, що відсутність досить повних теоретичних досліджень не дозволяє ефективно виконувати задану виробничу операцію. Шляхом вирішення крайової електродинамічної задачі отримані аналітичні вирази для фазових залежностей струмів в експериментальній системі і порушених сил притягання оброблюваного об'єкта. Доведено чисельними оцінками, що низькочастотний режим електромагнітних процесів, що протікають, кращий при інтенсивному проникненні полів через провідні компоненти досліджуваної системи. Встановлено, що розрахована залежність сил, що розвиваються, від напруги розряду ємнісного накопичувача дозволяє приблизно оцінити ефективність притягання при роботі в прийнятому діапазоні енергетичних можливостей джерела живлення. Показано, що ступінь неоднорідності поперечного розподілу сил притягання в досліджуваній області не перевищує ~ 20%. Спроектована і створена діюча експериментальна модель, що складається з інструменту магнітно-імпульсного притягання листового металу і джерела живлення - енергетичного блоку. На основі отриманих співвідношень розраховані характеристики дослідної установки та режими проведення випробувань. Практично реалізовано дозований магнітно-імпульсний силовий вплив, що дозволяє контролювати деформацію листового металу в зоні обробки. Були проведені експерименти з усунення вм'ятин на зразках, виготовлених з різних видів стали в умовах, наближених до відповідної реальної виробничої операції. Успішно продемонстровані практичні можливості засобів магнітно-імпульсного притягання певних ділянок листових металів при «прямому пропущенні струму» через них. Доведено ефективність розглянутого методу при використанні показників технологічної операції, розрахованих на підставі теоретично отриманих залежностей.*

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Ключові слова: *магнітно-імпульсне притягання; тонкостінний листовий метал; електромагнітні процеси; "Пряме проходження струму"; експериментальна апробація; сплющування автомобільних кузовів*

Introduction

The attraction methods of defined areas of sheet metals using the energy of pulsed magnetic fields for different types of processing technologies are purchasing more relevant in different industries [1]. Special attention is paid to the development of dent removal and leveling surfaces of sheet metals technologies during the restoration of aircraft hulls and car bodies. Firstly, the necessity of such operation is due to defection of aerodynamic characteristics of the aircraft down to the loss of stability in flight. Secondly, it's not only aesthetic considerations but often impossibility of further maintenance of the vehicle with a damaged body. That is why of particular interest are on devices allowing for restoration of the damages (dents) on the surface from the outside of metallic coating without dissembling of aircraft hull or car body. For example, the suggestions of American industry companies ("Boeing Company", "ElectroImpact" etc.) [2,3] and also European firms leading in the field of modern cars body repair [4] are meeting to this requirements.

A brief publications review

Propositions of using pulsed electromagnetic fields for the attraction of defined areas of sheet metals have a long history. One of the first is the proposal of some inductor system the action principle of which is based on antiphase superposition low frequency (LF) and high frequency (HF) magnetic fields. Firsts of them penetrate through the metal and the second without penetration concentrate on its surface from inductor side – the source of pulsed magnetic field. Superposition of the LF and HF-fields leads to their mutual cancel from one side of sheet metal and concentration of the penetrated LF-field from the other side. The metal being processed undergoes action unilateral magnetic pressure and attracts to the inductor. This type of systems was developed by American engineers and implemented in restoring technologies of the aircraft hulls [2,3].

The physical meaning of other propositions suggested using exclusively low-frequency magnetic fields allowing work in the mode of their intensive penetration through sheet metals [5,6]. As the theory and experiments showed, during ferromagnets, processing the repulsing action of Lorentz forces is suppressed and attraction becomes prevalence because of magnetic properties of the processed metal. By the authors of paper [5], there were proposed and designed "inductor systems with attracting screen", allowing excitation of high forces of attraction as for ferromagnets as non-ferromagnets (so named the universal tools of attraction). The proposition essence is consisting of including rigidly-fixed auxiliary conductive screen into the construction of the inductor system. Conductors with unidirectional currents induced in the screen and processed metal experience the mutual attraction. When the screen is rigidly fixed, the metal being processed will move towards the screen. The papers [5,7] unite a complex of all theoretical and experimental researches of the methods on magnetic-pulsed attraction based on different physical nature phenomena. As well here are shown main directions of their practical usage in the modern repair technologies of vehicles.

If we are talking about progressive technologies with using of magnetic-pulsed fields energy there should be mentioned some other existing methods of dents removing. So, among mechanical devices, there are widely known so named pulling out tools. Their main functional components are a pulling out element – a rod, one end welded or glued to the metal in the center of the dent to be removed, and lever mechanism allowing gradual pulling of the rod free end to the level of the surface being restored [4]. The method of vacuum dent removing on a body car is defended by the Patent of "Dent Defyer Inc." concern [8]. A special suction cup is placed on the area with a dent. In the internal cavity between them creates a rarefaction. The appeared forces of attraction are pulling out the dented metal. The main disadvantages of mechanical and vacuum methods of attraction are the complexity of their technical implementation, unreliability (damages are possible), high requirements for the qualification of the performer, etc.

Back to the mentioned below progressive technologies of the magnetic-pulsed attraction of the defined areas of sheet metals, should describe not only their benefits. The main disadvantages are the power possibilities finiteness conditioned of induction effects with which the electromagnetic energy essential losses are connected [9]. In this regard, a method of "direct passage of current" through the processed metal becomes a very appealing way of the magnetic-pulsed attraction of thin-walled sheet metals. This method can become a basis for the design of an effective tool for external restoration of metal coatings of any vehicles. Its attractiveness is caused by simple technical realization and quite high energy indicators. Description of propositions and experimental testing results of the magnetic-pulsed tools with the "direct passage of current" for dents removing on the body cars are given in papers [10,11].

A common disadvantage of well-known works in this area is the lack sufficiently complete theoretical studies with output to optimal designs of tools with "direct passage of current" allowing the effective implementation of a given production operation, for example, the restoration of metal coatings of vehicle of any purpose (ground-based, aircrafts, aqueous etc.).

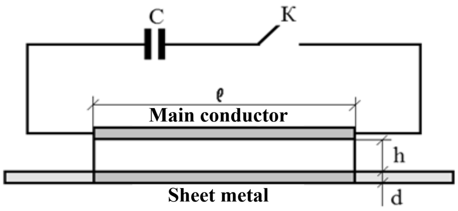
Purpose of the work

The aim of the this paper is the theoretical justification of workability of the method of the magnetic-pulsed attraction of sheet metals with "direct passage of current" through the processing object, experimental researches fulfilling and practical testing of the proposed method in conditions closed to the real production operation.

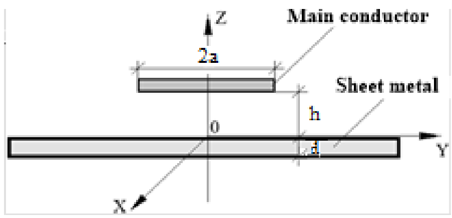
Main text

Calculated ratios for currents and forces

The principal model scheme of the tool for magnetic-pulsed attraction with "direct passing of current" is shown in the fig. 1.



a



b

Fig.1 – The principal scheme: a) electrical equivalent circuit; b) calculated electrodynamical model

In the solution will be used the algorithms presented and developed by the authors of scientific publications [7, 9]. In fairness, it should be mentioned that the analogical questions were already considered in [9]. However, the immediate use of obtained solutions and relations is impossible what is conditioned by the accepted conditions formulating and solving of the considered problems.

Let us formulate assumptions quite adequate to reality and allowing obtaining analytical dependencies in quadratures.

Processing object (here and after – this is the billet) is non-magnetic sheet metal with quite big transverse dimensions, thickness – *d* and conductivity – γ.

The main conductor is "transparent" for the active fields, so its metal has no influence on occurring electromagnetic processes.

There is a geometric symmetry of the system relative to the coordinate plane *Z*0*X*.

The system has a sufficiently long length along the *X*-axis, so $\frac{\partial}{\partial x} = 0$.

A uniformly distributed current with a density $j(t) = j_m \cdot j(t)$ flows in the main conductor in the direction of the axis OX, where $j_m = \frac{I_m}{2a}$ – is the amplitude (I_m – maximum current), $j(t)$ – is the time dependence.

The frequency characteristics of the exciting current are such that the condition of quasi-stationarity is defined by inequality – $\frac{\omega}{c} \cdot b << 1$ [6,8], here ω – is the cyclic process frequency, c – is the light speed in the vacuum, b – is the characteristic system size.

The non-zero components of the electromagnetic field intensities are excited in the system: $E_x \neq 0, H_{y,z} \neq 0$.

<u>Maxwell's integral equations in *L*-image space</u>

Within the accepted assumptions Maxwell's equations for non-zero components of the electromagnetic field intensities converted on Laplace (*L*-transforming), taking into account zero initial conditions, take the form [12,13]:

$$\frac{\partial H_z(p,y,z)}{\partial y} - \frac{\partial H_y(p,y,z)}{\partial z} = j_x(p,y,z), \quad (1)$$

$$\frac{\partial E_x(p,y,z)}{\partial z} = -p\mu_0 H_y(p,y,z), \quad (2)$$

$$\frac{\partial E_x(p,y,z)}{\partial y} = p\mu_0 H_z(p,y,z), \quad (3)$$

where *p* – the *L*-transforming parameter;

$$E_x(p,y,z) = L\{E_x(t,y,z)\};$$

$$H_{y,z}(p,y,z) = L\{H_{y,z}(t,y,z)\};$$

$$j_x(p, y\, z) = L\{j_x(t, y, z)\};$$

μ_0 – is the vacuum permeability.

In the general case, the current density on the right side of equation (1) is written as:

$$j_x(p, y, z) = (p \cdot \varepsilon_0 + \gamma) \cdot E_x(p, y, z) + j_{xi}(p,y,z), \quad (4)$$

where ε_0 is the vacuum permittivity, $j_{xi}(t, y, z)$ – is the current density in the main conductor, $j_{xi}(p, y, z) = j(p) \cdot f(y) \cdot \delta(z-h)$, $j(p) = j_m \cdot j(p)$, $j_m = \frac{I_m}{2a}$ – is the amplitude, $j_t(p) = L\{j_t(t)\}$, $j_t(t)$ – is the time dependence of exciting current, $f(y)$ – is the transverse distribution of current density, $\delta(z-h)$ – is the Dirac impulse function.

Solving the problem in the accepted model of calculation, it is necessary to select areas with homogeneous electrophysical characteristics.

According to fig. 1b, it can be believed that these areas are:

a) the free half-space above the sheet metal of the billet from the side of the main conductor, where $z \in [0, \infty)$;

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b) the area of sheet metal billet, $z \in [-d, 0]$;

c) the free half-space from the external side of the billet,, $z \in (-\infty, 0]$.

From the differential equations (1–3) taking into account the expression (4) there are obtained equations for the longitudinal component of the electric field strength $E_x(p, y, z)$ in the highlighted areas:

a) $z \in [0, \infty)$,

$$\frac{\partial^2 E_x(p,y,z)}{\partial y^2} + \frac{\partial^2 E_x(p,y,z)}{\partial z^2} = p \cdot \mu_0 \cdot j_x(p,y,z), \quad (5)$$

b) $z \in [-d, 0]$,

$$\frac{\partial^2 E_x(p,y,z)}{\partial y^2} + \frac{\partial^2 E_x(p,y,z)}{\partial z^2} = \gamma \cdot E_x(p,y,z), \quad (6)$$

c) $z \in (-\infty, 0]$,

$$\frac{\partial^2 E_x(p,y,z)}{\partial y^2} + \frac{\partial^2 E_x(p,y,z)}{\partial z^2} = 0. \quad (7)$$

Next step is to apply the Fourier integral cosine-transform [13] for equations (5–7). Its admissibility is determined by the geometric and electrical symmetry of the problem under consideration relative to the *Z0X* plane.

Thus, we have

$$\int_0^\infty E_x(p,y,z) = E_x(p,\lambda,z) \cdot \cos(\lambda y) d\lambda; \quad (8)$$

$$j_x(p,y,z) = \int_0^\infty j_x(p,\lambda,z) \cdot \cos(\lambda y) d\lambda; \quad (9)$$

where

$$j_x(p,\lambda,z) = \int_0^\infty j_x(p,y,z) \cdot \cos(\lambda y) dy = j(p) f(\lambda) \delta(z);$$

$f(\lambda) = \frac{1}{\pi} \cdot \int_0^\infty f(y) \cdot \cos(\lambda y) dy$, according to the accepted assumption of uniform distribution of the exciting current in the main conductor, integrating will give the following result:

$$f(\lambda) = \frac{2a}{\pi} \cdot \frac{\sin(\lambda a)}{(\lambda a)}.$$

Taking into account (8) and (9), the equations (5–7) can be written in the kind of ordinary linear differential equations of the second order [13]:

a) $z \in [0, \infty)$,

$$\frac{d^2 E_x(p,\lambda,z)}{dz^2} - \lambda^2 E_x(p,\lambda,z) = K(p,\lambda) \cdot \delta(z-h), \quad (10)$$

where $K(p,\lambda) = \mu_0 \cdot p \cdot j(p) \cdot f(\lambda)$;

b) $z \in [-d, 0]$,

$$\frac{d^2 E_x(p,\lambda,z)}{dz^2} - q^2(p,\lambda) \cdot E_x(p,\lambda,z) = 0; \quad (11)$$

where $q(p,\lambda) = \sqrt{\lambda^2 + p \cdot \mu_0 \cdot \gamma}$ is the separation parameter, the physical sense of which is the wave number in a non-magnetic metal with an electrical conductivity γ;

c) $z \in (-\infty, 0]$,

$$\frac{d^2 E_x(p,\lambda,z)}{dz^2} - \lambda^2 \cdot E_x(p,\lambda,z) = 0. \quad (12)$$

The general integrals of equations (10), (11) and (12) for defined areas are the following [13]:

a) $z \in [0, \infty)$, to the condition of boundedness at z→0 the following function satisfies:

$$E_x^{(1)}(p,\lambda,z) = C(p,\lambda) e^{-\lambda \cdot z} + \frac{K(p,\lambda)}{\lambda} \times$$
$$\times \left(sh(\lambda(z-h)) \cdot \eta(z-h) - 0.5 e^{\lambda(z-h)} \right), \quad (13)$$

where $C(p, \lambda)$ is an arbitrary integration constant;

b) $z \in [-d, 0]$,

$$E_x^{(2)}(p,\lambda,z) = D_1(p,\lambda) \cdot e^{q(p,\lambda) \cdot z} + D_2(p,\lambda) \cdot e^{-q(p,\lambda) \cdot z}, \quad (14)$$

where $D_{1,2}(p, \lambda)$ is an arbitrary integration constants;

c) $z \in (-\infty, 0]$, to the condition of boundedness at z→0 the following function satisfies:

$$E_x^{(3)}(p,\lambda,z) = B(p,\lambda) \cdot e^{\lambda(z+d))}, \quad (15)$$

where $B(p, \lambda)$ – is an arbitrary integration constant.

Images of the tangential components of the magnetic field intensities can be found using equations (13–15) and (3):

a) $z \in [0, \infty)$,

$$H_y^{(1)}(p,\lambda,z) = \frac{\lambda}{p\mu_o} \left(C(p,\lambda) e^{-\lambda \cdot z} - \frac{K(p,\lambda)}{\lambda} \times \right.$$
$$\left. \times \left(\mathrm{ch}(\lambda(z-h)) \eta(z-h) - 0.5 e^{\lambda(z-h)} \right) \right) \quad (16)$$

b) $z \in [-d, 0]$,

$$H_y^{(2)}(p,\lambda,z) = -\frac{q(p,\lambda)}{p\mu_0} \times$$
$$\times \left(D_1(p,\lambda) \cdot e^{q(p,\lambda) \cdot z} - D_2(p,\lambda) \cdot e^{-q(p,\lambda) \cdot z} \right) \quad (17)$$

c) $z \in (-\infty, 0]$,:

$$H_y^{(3)}(p,\lambda,z) = -\frac{\lambda}{p\mu_0} \cdot B(p,\lambda) \cdot e^{\lambda(z+d)}. \quad (18)$$

From the condition of continuity of the tangent components of the electromagnetic field intensities at the distinguished areas boundaries there are obtained systems of algebraic equations for determining unknown arbitrary constants of integration in the expressions (13–18) [12].

1. $z=0$:

$$\begin{cases} C(p,\lambda)-\dfrac{K(p,\lambda)\cdot e^{-\lambda h}}{2\lambda}=D_1(p,\lambda)+D_2(p,\lambda) \\ C(p,\lambda)+\dfrac{K(p,\lambda)\cdot e^{-\lambda h}}{2\lambda}=-\dfrac{q(p,\lambda)}{\lambda}\times \\ \times\left(D_1(p,\lambda)-D_2(p,\lambda)\right) \end{cases}; \quad (19)$$

2. $z=-d$:

$$\begin{cases} D_1(p,\lambda)\cdot e^{-q(p,\lambda)\cdot d}+D_2(p,\lambda)\cdot e^{q(p,\lambda)\cdot d}=B(p,\lambda) \\ \dfrac{q(p,\lambda)}{\lambda}\left(D_1(p,\lambda)\cdot e^{-q(p,\lambda)\cdot d}-D_2(p,\lambda)\cdot e^{q(p,\lambda)\cdot d}\right)= \\ =B(p,\lambda). \end{cases} \quad (20)$$

Further, we are interested in excitation of electromagnetic field in the sheet metal. Therefore, we are looking for only unknown arbitrary constants $D_{1,2}(p,\lambda)$.

From the system of the linear algebraic equations it is received that,

$$\begin{cases} D_1(p,\lambda)=-\dfrac{K(p,\lambda)\cdot e^{-\lambda h}}{2\lambda}\cdot\dfrac{e^{q(p,\lambda)\cdot d}\cdot\left(1+\dfrac{q(p,\lambda)}{\lambda}\right)}{\Delta(p,\lambda)} \\ D_2(p,\lambda)=\dfrac{K(p,\lambda)\cdot e^{-\lambda h}}{2\lambda}\cdot\dfrac{e^{-q(p,\lambda)\cdot d}\cdot\left(1-\dfrac{q(p,\lambda)}{\lambda}\right)}{\Delta(p,\lambda)} \end{cases}, \quad (21)$$

where $\Delta(p,\lambda)=\left(1+\left(\dfrac{q(p,\lambda)}{\lambda}\right)^2\right)\cdot \mathrm{sh}\left(q(p,\lambda)d\right)+$
$+2\cdot\left(\dfrac{q(p,\lambda)}{\lambda}\right)\cdot \mathrm{ch}\left(q(p,\lambda)d\right)$.

$D_{1,2}(p,\lambda)$ from the relations (21) should substitute into expression (14). After simple mathematical transformations, it is obtained that,

$$E_x(p,\lambda,z)=-\frac{K(p,\lambda)e^{-\lambda h}}{\lambda}\times$$
$$\times\frac{\left(sh\left(q(p,\lambda)(z+d)\right)+\left(\dfrac{q(p,\lambda)}{\lambda}\right)ch\left(q(p,\lambda)(z+d)\right)\right)}{\Delta(p,\lambda)}. \quad (22)$$

The obtained dependence is an image of the longitudinal component of the electric field intensity excited in the sheet metal.

The expression (22) should multiply by the electrical conductivity of the sheet metal – γ. The result should substitute in the formula (8).

After all necessary substitutions, the density of induced current in *L*-space will be found.

$$j_x(p,y,\zeta)=-\left(\frac{2a\tau}{\pi d^2}\right)\cdot\left(p\cdot j(p)\right)\times$$
$$\times\int_0^\infty \frac{\sin(\lambda a)}{(\lambda a)}\cdot\frac{e^{-\lambda h}}{\lambda}\cdot\frac{F(p,\lambda,\zeta)}{\Delta(p,\lambda)}\cdot\cos(\lambda y)\,d\lambda, \quad (23)$$

where $\tau=\mu_0\gamma d^2$ is the characteristic time of diffusion in the sheet metal which was introduced by the author of the monograph [12],

$$F(p,\lambda,\zeta)=\mathrm{sh}\left(q(p,\lambda)d\cdot(1-\zeta)\right)+$$
$$+\frac{q(p,\lambda)}{\lambda}\mathrm{ch}\left(\left(q(p,\lambda)d\right)\cdot(1-\zeta)\right),$$

$\zeta=\left(-\dfrac{z}{d}\right)$ – is a spatial variable associated with the thickness of the sheet metal, $\zeta\in[0,1]$.

Currents and forces in originals space

In expression (23), we make the transition to the space of originals [12, 13].

To calculate the singular points of the integrand function the fraction denominator in expression (23) it is necessary to equate to zero. The product of the wave number and the thickness of the sheet should be represented as the imaginary quantity:

$$\begin{cases} \Delta(p,\lambda)=0 \\ \left(q(p,\lambda)\cdot d\right)=i\cdot\beta_k \end{cases}, \quad (24)$$

where $i=\sqrt{-1}$ – the imaginary unit.

Using system (24) we obtain the equation for β_k:

$$\mathrm{ctg}\beta_k=0.5\cdot\left(\frac{\beta_k}{(\lambda d)}-\frac{(\lambda d)}{\beta_k}\right), \quad (25)$$

As follows from the (24) and (25), the singular points of a function of a complex variable under the sign of the integral in the expression (23) are the distinguished from zero the simple poles – p_k [18]:

$$p_k=-\frac{1}{\tau}\cdot\left(\beta_k^2+(\lambda\cdot d)^2\right),\quad k=0,\pm1,2....... (26)$$

Further, in accordance with the theorem on the original of the rational fraction and the theorem on the functions convolution we find the corresponding temporal dependence from the expression (23):

$$\frac{p\cdot j(p)}{\Delta(p,\lambda)}\times$$
$$\times\left(\mathrm{sh}\left(q(p,\lambda)\cdot d(1-\zeta)\right)+\frac{q(p,\lambda)\cdot d}{(\lambda d)}\cdot\mathrm{ch}\left(q(p,\lambda)\cdot d(1-\zeta)\right)\right)\leftrightarrow$$

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$$\leftrightarrow \sum_{k=0}^{\infty} \left. \frac{i \cdot \left(\sin\left(\beta_k (1-\zeta)\right) + \frac{\beta_k}{\lambda d} \cdot \cos\left(\beta_k (1-\zeta)\right) \right)}{\frac{d}{dp}\left[\Delta\left(p,\lambda\right)\right]} \right|_{p=p_k} \times$$

$$\times \frac{dj_t(t)}{dt} * e^{p_k \cdot t}, \qquad (27)$$

where $\zeta = -\frac{z}{d}$, $\zeta \in [0, 1]$ – the coordinate associated with the thickness of the sheet metal, in relative units;

$$\delta_k = \begin{cases} 1.0 \text{ for } k = 0 \\ 2.0 \text{ for } k \neq 0 \end{cases}$$

Remark. The presence of the Kronecker symbol – δ_k is due to the evenness of the roots β_k in equation (25).

Finally, using the dependence (27) after the necessary identical transformations we find the original for the current density excited in the sheet metal.

$$j_x(t,\zeta,y) = I_m \frac{2}{\pi} \int_0^{\infty} \frac{\sin(\lambda a)}{(\lambda a)} e^{-\lambda h} \times$$

$$\times \sum_{k=0}^{\infty} \delta_k \frac{F(\beta_k,\lambda,\zeta)}{\Phi(\beta_k,\lambda)} \left(\frac{dj_t(t)}{dt} * e^{p_k \cdot t} \right) \lambda \cos(\lambda y) d\lambda, \qquad (28)$$

where

$$F(\beta_k,\lambda,\zeta) = \beta_k \cdot \left[\sin\left(\beta_k (1-\zeta)\right) + \left(\frac{\beta_k}{(\lambda \cdot d)} \right) \cdot \cos\left(\beta_k (1-\zeta)\right) \right],$$

$$\Phi\left(\beta_k,\lambda)\right) = \cos\left(\beta_k\right) \cdot \left[\left(\lambda d\right)^2 + 2\left(\lambda d\right) - \beta_k^2 \right] +$$

$$+2\beta_k \sin\left(\beta_k\right) \cdot \left[\left(\lambda d\right) + 1 \right].$$

The expression (28) should reduce to a form suitable for calculations. For this, we introduce a new integration variable $\alpha = \lambda d,\ \alpha \in [0,\infty),\ d\lambda = \frac{1}{d} \cdot d\alpha$.

$$j_x(t,\zeta,y) = I_m \left(\frac{2}{\pi d^2} \right) \int_0^{\infty} \frac{\sin\left(\alpha \frac{a}{d}\right)}{\left(\alpha \frac{a}{d}\right)} \cdot e^{-\alpha \frac{h}{d}} \times$$

$$\times \sum_{k=0}^{\infty} \delta_k \frac{F(\beta_k,\alpha,\zeta)}{\Phi(\beta_k,\alpha)} \left(\frac{dj_t(t)}{dt} * e^{p_k t} \right) \alpha \cos\left(\alpha \frac{y}{d}\right) d\alpha, \qquad (29)$$

where

$$F(\beta_k,\alpha,\zeta) = \beta_k \cdot \left[\sin\left(\beta_k (1-\zeta)\right) + \left(\frac{\beta_k}{\alpha} \right) \cdot \cos\left(\left(\beta_k (1-\zeta)\right)\right) \right],$$

$$\Phi\left(\beta_k,\alpha)\right) = \cos\left(\beta_k\right) \cdot \left[\alpha^2 + 2\alpha - \beta_k^2 \right] + 2\beta_k \sin\left(\beta_k\right) \cdot \left[\alpha + 1 \right]$$

β_k satisfied the equation: $\mathrm{ctg}\beta_k = 0.5 \cdot \left(\frac{\beta_k}{\alpha} - \frac{\alpha}{\beta_k} \right)$.

Dependence (29) is integrated over the thickness of the sheet metal. By this way we obtain the expression for calculation describing the transverse distribution of the induced current:

$$J_x(t,y) = I_m \left(\frac{2}{\pi d} \right) \int_0^{\infty} \frac{\sin\left(\alpha \frac{a}{d}\right)}{\left(\alpha \frac{a}{d}\right)} e^{-\alpha \frac{h}{d}} \times$$

$$\times \sum_{k=0}^{\infty} \delta_k \frac{G(\beta_k,\alpha)}{\Phi(\beta_k,\alpha)} \left(\frac{dj_t(t)}{dt} * e^{p_k t} \right) \alpha \cos\left(\alpha \frac{y}{d}\right) d\alpha, \qquad (30)$$

where $G(\beta_k,\alpha) = \left[\left(1 - \cos\beta_k\right) + \left(\frac{\beta_k}{\alpha} \right) \cdot \sin\beta_k \right]$.

The integral of dependence (30) in a transverse variable gives the expression for the magnitude of the current induced in the sheet metal – $y \in [-a,a]$:

$$I_x(t) = I_m \left(\frac{4a}{\pi d} \right) \times$$

$$\times \int_0^{\infty} \left(\frac{\sin\left(\alpha \frac{a}{d}\right)}{\left(\alpha \frac{a}{d}\right)} \right)^2 e^{-\alpha \frac{h}{d}} \sum_{k=0}^{\infty} \delta_k \frac{G(\beta_k,\alpha)}{\Phi(\beta_k,\alpha)} \left(\frac{dj_t(t)}{dt} * e^{p_k t} \right) \alpha\, d\alpha \quad (31)$$

Let the external current from a third-party source be supplied into the sheet metal and its cross distribution under the main conductor is also uniform.

Summing the third-party and induced signals, we find the dependencies for the resulting current and its density in the specified limited area of the sheet metal.

The total current is written in the form:

$$I_x^{(S)}(t) = I_m \left[j(t) - \left(\frac{4a}{\pi d} \right) \int_0^{\infty} \left(\frac{\sin\left(\alpha \frac{a}{d}\right)}{\left(\alpha \frac{a}{d}\right)} \right)^2 \times \right.$$

$$\left. \times e^{-\alpha \frac{h}{d}} \sum_{k=0}^{\infty} \delta_k \frac{G(\beta_k,\alpha)}{\Phi(\beta_k,\alpha)} \left(\frac{dj_t(t)}{dt} * e^{p_k t} \right) \alpha\, d\alpha \right] \qquad (32)$$

The resulting current density flowing in this part of the sheet metal, taking into account the expression (29), is written in the form:

$$j_x^{(S)}(t,\zeta,y) = \frac{I_m}{(2ad)} \left[j(t) - \left(\frac{4a}{\pi d} \right) \cdot \int_0^{\infty} \frac{\sin\left(\alpha \frac{a}{d}\right)}{\left(\alpha \frac{a}{d}\right)} \cdot e^{-\alpha \frac{h}{d}} \times \right.$$

$$\left. \times \sum_{k=0}^{\infty} \delta_k \frac{F(\beta_k,\alpha,\zeta)}{\Phi(\beta_k,\alpha)} \left(\frac{dj_t(t)}{dt} * e^{p_k t} \right) \alpha \cos\left(\alpha \frac{y}{d}\right) d\alpha \right]. \quad (33)$$

Equation (33) allows the calculation of the current distribution in the cross section of the sheet metal, where a superposition of the induced and the external current has a place.

An illustrative characteristic of the flowing electromagnetic processes is the linear density of the total current in the sheet metal in the area under the main conductor. It describes the lateral distribution of the current and, ultimately, illustrates the degree of homogeneity of the excited attractive forces along the coordinate $y \in [-a, a]$.

Integrating the equation (33) at $\zeta \in [0,1]$ taking into account that $\zeta = -\frac{z}{d}$, $z \in [-d, 0]$, we obtain

$$J_x^{(S)}(t,y) = \frac{I_m}{(2ad)}\left[j(t) - \left(\frac{4a}{\pi d}\right) \cdot \int_0^\infty \frac{\sin\left(\alpha \frac{a}{d}\right)}{\left(\alpha \frac{a}{d}\right)} e^{-\alpha \frac{h}{d}} \times \right.$$

$$\left. \times \sum_{k=0}^{\infty} \delta_k \frac{G(\beta_k, \alpha)}{\Phi(\beta_k, \alpha)} \cdot \left(\frac{dj_t(t)}{dt} * e^{p_k t} \right) \cdot \alpha \cos\left(\alpha \frac{y}{d}\right) d\alpha \right]. \quad (34)$$

Speaking of the electromagnetic processes in the investigating system with the parallel electrical connection of the main conductor with *l* – length to a section of the same length on sheet metal, the following circumstances should be mentioned.

The first. As it was pointed out in the formulation of the problem the main conductor is "transparent" for the active fields and does not affect the occurring electromagnetic processes. But let us suppose that it is made of the same metal as the sheet billet.

The second. In the first approximation, the influence of induction effects on the current characteristics in the excitation source of the system – the main conductor – can be taken into account if, based on the physical principles of similarity, we assume that the electromagnetic processes in it and in zone of the sheet metal under it are identical [17].

Taking into account the above circumstances, the total values of the current characteristics in the main conductor can be represented by dependencies (32–34).

The integral force of attraction, excited by the interaction of parallel currents, described by expression (32), takes the form [17]:

$$F_{attr}(t) = \frac{\mu_0}{2\pi} \cdot \left(I_x^{(S)}(t) \right)^2 \cdot \frac{\ell}{h}. \quad (35)$$

Expression (35) in combination with dependence (32), as well as relations (33) and (34) for the linear density of the excited currents are the solutions of the electrodynamic problem posed. They adequately describe the processes in the tool of magnetic-pulsed attraction with the "direct passage of current" through the metal being processed.

Experimental approbation

First, there should be underlined, that the represented experiments on the magnetic-pulsed attraction with "direct passage of current" unlike the cited works [15, 16] were conducted in view of the new groundworks and experiences in a given scientific area. It allowed moving from the first approbations of the action principle to experiments with an understanding of the physics of the processes and the specific recommendations development for the creation of equipment for the effective implementation of a given production operation. In addition, the experience of previous studies was taken into account, according to which the low-frequency mode of the flowing electromagnetic processes is preferable. This is about an intensive penetration of the fields being excited through the conductive components of the investigated system.

Calculation of the experimental tool model characteristics

Design of the given experimental model is principal corresponding to fig.1 and it is equally as for ferromagnet as non-ferromagnet materials (in particular, steel and aluminum).

The given model consists of the following components:
– the main conductor – is a metal strip with a given width;
– the flat metal sheet which defined part is a subject for attraction is located on the certain distance from the main conductor;
– all geometrical and electrophysical parameters of the tool are supposed given (dimensions and conductivity);
– the instrument is connected to a power source with a voltage through a matching device that provides the specified operating frequency [10].

The calculation of the characteristics of the developed experimental model of the magnetic-pulsed attraction tool with the "direct passage of current" through a given area of sheet metal – the billet, is carried out using the equations for the excited currents and forces (32-35).

Let us start from the calculations for the steel sheet, $\gamma \approx 0,5 \cdot 10^7 \frac{1}{\text{Ohm} \cdot \text{m}}$.

Operating frequency is *f*=1500 Hz, discharge voltage is *U*=2000 V, operating zone is: $l \times 2a = 0,06 \times 0,01$ m^2.

From the calculations it follows that:

– the maximum capacity of the power source while reducing the transverse size of the inductor main conductor to ~ 0,01 m is corresponding to the attraction force maximum ~4000 N (Fig. 2), which is more than ~ 2 times higher of the same maximum for the width of the conductor ~ 0,06 m;

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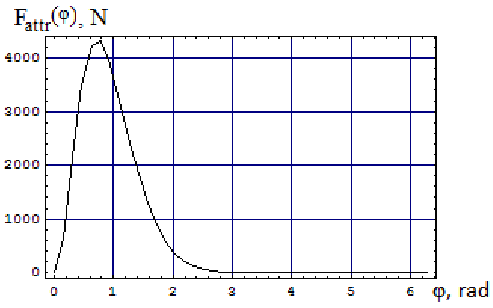


Fig. 2 – Excited attraction force (steel sheet), φ=ωt is a phase of a signal

– from the physical viewpoint, the reason of attractive forces increasing with a decrease in the transverse size of the main conductor can be explained by increasing the excited fields amplitudes (effect of concentration), that obviously leads to the intensification of the induction processes;

– the transverse distribution of total currents, reflecting the level of the transverse distribution of attractive forces, is almost uniform (fig. 3).

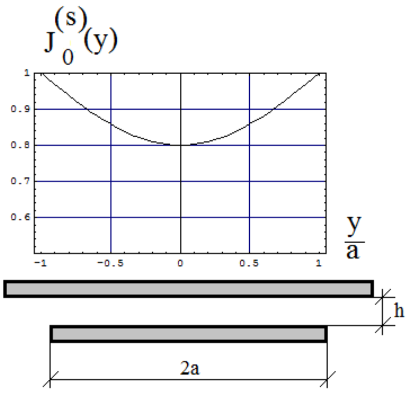


Fig. 3 – The transverse distribution of the relative magnitude of the total current normalized to a maximum

Summary. Reducing the width of the main conductor of the inductor can significantly increase the power performance of the system of magnetic-pulsed attraction with a "direct passing of current" through the metal being processed.

Calculations conducted for under voltage *U*=1500 V show that

– the force of the magnetic-pulsed attraction is ~1100 N, that is almost ~4 times less the developed force at maximum discharge voltage for the given power source;

– there is a quadratic dependence between the excited forces of attraction and the magnitude of the discharge voltage, that is, when the voltage drops to ~ 1500 V the attraction with an amplitude ~1778 N can be expected;

– physically, the established functional relationship between the voltage and the excited forces of attraction is determined by the quadratic relationship between the voltage of the capacitive storage and the stored energy spent on the excitation of the corresponding forces.

Remark. The established quadratic relationship between forces and discharge voltage does not take into account losses during the transmission of electromagnetic energy from a source into the working area of the instrument.

Summary. The established quadratic dependence of the developed forces on the discharge voltage allows approximate estimates of the attraction effectiveness when operating in the accepted range of energy possibilities of the power source.

Let us turn to numerical estimates for the aluminum sheet with $\gamma \approx 3,75 \cdot 10^7 \dfrac{1}{\text{Ohm} \cdot \text{m}}$.

The operating frequency is *f*=1500 Hz, the voltage is *U*=2000 V, the operating zone is: $l \times 2a = 0{,}06 \times 0{,}01$ m^2.

The main results:

1. The maximum force of attraction is ~1750 N (Fig. 4);
2. The level of heterogeneity of the transverse distribution of the total current, which characterizes the degree of uniformity of the transverse distribution of attractive forces, does not exceed ~ 20%.

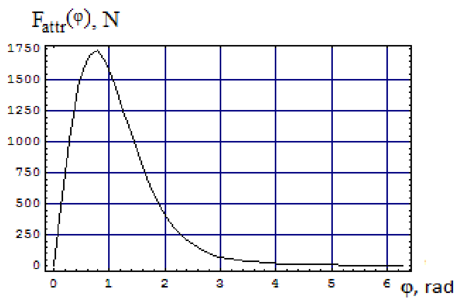


Fig. 4 – Excited attraction force (aluminum sheet), φ=ωt is a phase of a signal

Summary. The magnetic-pulsed attraction with the “direct passage of current” through the processed aluminum is quite effective when using technological equipment and the characteristic indicators of the manufacturing operation, which were adopted to deform the steel sample.

Equipment, experimental objects for processing

Experimental equipment for performing a given production operation included two main components:

– the tool of magnetic-pulsed attraction;

– the power source – the energetic block (magnetic-pulse installation).

The power source – the magnetic-pulse installation MPIS-2 was elaborated and created at the laboratory of electromagnetic technologies of Kharkov National Automobile&Haighway University. The general view of the installation (together with a tool) is shown in fig. 5.

Fig. 5 – The magnetic-pulsed installation MPIS-2 with a tool, (maximum of the stored energy is ~ 2,4 kJ at voltage ~ 2 kV)

Structurally, MPIS-2 is formed as a single unit in which all electrical equipment is concentrated, as well as an air cooling system for the switches and for the charging device.

On the upper plane of the body, a horizontal massive dielectric board is placed, which is used as a technological table. Current collectors (electrical terminals) are brought to its surface to connect the load – a tool of the production operation.

Characteristics of the magnetic-pulsed installation MPI-2 [9]:

– the maximum stored energy W≈2.0 kJ;

– the capacity of the condenser battery C=1200 μF;

– the own frequency f_0≈7 kHz;

– the voltage in the range ~100÷2000 V;

– the repeat frequency of generated current pulses 1÷10 Hz;

– the multiple repetition regime is provided by an electronic control unit that synchronizes the processes "charge - discharge";

– the switch type is the thyristor switches;

– the supply voltage is ~380/220 V.

Remark. The choice of the geometric shape of the instrument is due to the requirement of the minimum inductance of the current-leads in order to reduce the loss of electromagnetic energy during its transportation from the source to the instrument.

Experimental samples are metal plates of a rectangular geometry with the dents: the steel of the vehicle bodywork coating "Ford" and the special electrical steel.

Plate thickness is 0.08 m, dents diameter is 0.02÷0.25 m.

Practical approbation, the main results

The sequence of operations for force approbation of the developed tool of magnetic-pulsed attraction and indicators of the process of eliminating dents during the experiment are the following:

– the inspection and visual study of the processing object – of the metal plate with the dent;

– the mutual mechanical fixation of the object of processing and the tool using bolted joints;

– setting the voltage on the capacitive storage ~1800÷2000 V;

– switching on the tool electrical circuit and the force impact on the processing metal surface in the regime (5÷10)–fold repetition of the magnetic-pulsed attraction;

– the inspection and visual study of the experimental sample with the eliminated dent, the conclusion about the effectiveness of the completed production operation.

Remark. In case of an insufficient smooth surface, the operation of the pulsed magnetic attraction of the dent should be repeated until the desired level of quality performed manufacturing operation.

Below (fig 6,7) are the illustrations of the experiment.

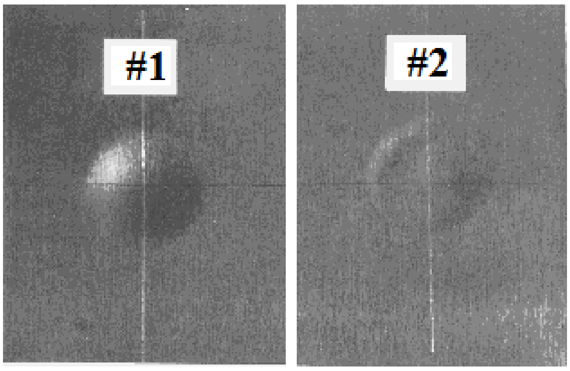
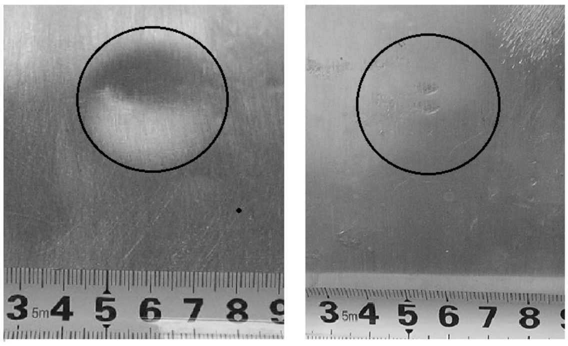


Fig. 6 – Experimental samples from the special electrical steel, #1 – the sample before the attraction; #2 – the sample after attraction (5-multiple repetition of magnetic-pulsed attraction)



a *b*

Fig. 7 – Experimental samples of car body coating "Ford", a) the sample before the attraction; b) the sample after attraction (9-multiple repetition of magnetic-pulsed attraction)

The main results of the experiments are as follows.

– The practical capabilities of the tools of the magnetic-pulsed attraction of the determined areas of the sheet metals at "direct passage of current" through them were successfully demonstrated.

– The dosed magnetic-pulsed force action, allowing the controlled deformation of sheet metal in the treatment area was practically implemented.

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– The magnetic-pulsed attraction method is particularly interesting for eliminating dents in car bodies, because, unlike known analogs, it does not require disassembly into the elements for the purpose of mandatory access from the inside of the sheet metal with a dent what was confirmed experimentally.

Conclusions

The theoretical justification of the method of magnetic-pulsed attraction of sheet metals with the "direct passage of current" through the object being processed has been carried out.

The analytical dependencies for the numerical estimates of the amplitudes and time functions of the excited currents and electrodynamic forces are got.

The experimental model of a tool for magnetic-pulsed attraction of sheet metals with "direct passage of current" through the object being processed was elaborated and created.

The successful practical approbation of the proposed method was carried out in conditions close to the reality of the corresponding production operation.

Список літератури

1. Golovaschenko S. F., Batygin Yu. V. Sheet metal blank destaker. Patent US2018105373-A1. Oakland University. Publication Date: 04/19/2018.
2. Hansen K. A., Hendrickson G. I. Electromagnetic dent puller Patent US 3,998,081. The Boeing Company. Publication Date: 21/12/1976.
3. Electromagnetic Dent Removal. URL: http://www.electroimpact.com/EMAGDR/overview.asp (accessed 15.12.2019)
4. Welcome to BETAG Innovation. URL: http://www.betaginnovation.com(www.beulentechnik.com) (accessed 15.11.2017)
5. Batygin Yu. V., Chaplygin Y. A., Gnatov A. V., Golovaschenko S. F. Pulsed electromagnetic attraction processes for sheet metal components. *In Proceedings of the 6-th International Conference on High Speed Forming*, (*May 26-29, 2014, Daejeon, Korea*). Daejeon. 2014. P. 253-260.
6. Psyk V., Risch D., Kinsey B. L., Tekkaya A. E., Kleiner M. Electromagnetic Forming – A review. *Journal of Materials Processing Technology*. 2011. 211. P. 787–829. doi: 10.1016/j.jmatprotec.2010.12.012.
7. Batygin Yu., Barbashova, M., Sabokar O. *Electromagnetic Metal Forming for Advanced Processing Technologies*. Cham, Switzerland: Springer International Publishing AG. 2018. 95 p.
8. Borchert Donald Paul. Apparatus and method for vacuum dent repair. Patent US 6,538,250. Dent Defyer Inc. Publication Date: 03/25/2003.
9. Шнеерсон Г. А. *Поля и переходные процессы в аппаратуре сверхвысокого импульсного тока.* М.: Энергоиздат, 1992. 413 с.
10. Бондаренко А. Ю., Финкельштейн В. Б., Степанов А. А. Экспериментальная апробация электродинамической системы с прямым пропусканием тока для внешней рихтовки автомобильных кузовов *Електротехніка і Електромеханіка*. 2014. № 4. С. 50–52.
11. Бондаренко А. Ю., Финкельштейн В. Б., Гаврилова Т. В. Внешняя рихтовка кузовов автотранспорта с помощью электродинамических систем при прямом пропускании импульсного тока. *Вісник Національного технічного університету «ХПІ»*. 2014. № 9 (1052). С. 66–72.
12. Тамм И. Е. *Основы теории электричества*. 10-е изд., испр. Москва: Наука, 1989. 504 с.
13. Корн Г., Корн Т. *Справочник по математике (для научных работников и инженеров)*. Москва: Наука, 1973. 832 с.

References (transliterated)

1. Golovaschenko S. F., Batygin Yu. V. Sheet metal blank destaker. Patent US2018105373-A1. Oakland University. Publication Date: 04/19/2018.
2. Hansen K. A., Hendrickson G. I. Electromagnetic dent puller Patent US 3,998,081. The Boeing Company. Publication Date: 21/12/1976.
3. Electromagnetic Dent Removal. Available at: http://www.electroimpact.com/EMAGDR/overview.asp (accessed 15.12.2019)
4. Welcome to BETAG Innovation. Available at: http://www.betaginnovation.com (www.beulentechnik.com) (accessed 15.11.2017)
5. Batygin Yu. V., Chaplygin Y. A., Gnatov A. V., Golovaschenko S.F. Pulsed electromagnetic attraction processes for sheet metal components. *In Proceedings of the 6-th International Conference on High Speed Forming, (May 26-29, 2014, Daejeon, Korea)*. Daejeon, 2014, pp. 253–260.
6. Psyk V., Risch D., Kinsey B. L., Tekkaya A. E., Kleiner M. Electromagnetic Forming – A review. *Journal of Materials Processing Technology*. 2011, 211, pp. 787–829, doi: 10.1016/j.jmatprotec.2010.12.012.
7. Batygin Yu., Barbashova, M., Sabokar O. *Electromagnetic Metal Forming for Advanced Processing Technologies*. Cham, Switzerland: Springer International Publishing AG. 2018. 95 p.
8. Borchert Donald Paul. Apparatus and method for vacuum dent repair. Patent US 6,538,250. Dent Defyer Inc. Publication Date: 03/25/2003.
9. Shneerson G. A. *Polya i perekhodnye processy v apparature sverkhvysokogo impul'snogo toka* [Fields and transient processes in apparatuses of strong currents]. Moscow, Energoizdat, 1992. 413 p.
10. Bondarenko A. Yu., Finkelshtein V. B., Stepanov A. A., *Ehksperimental'naya aprobaciya ehlektrodinamicheskoj sistemy s "pryamym propuskaniem toka" dlya vneshnej rikhtovki avtomobil'nykh kuzovov* [Experimental approbation of electrical dynamical system with «direct passage of pulsed current» for external flattening body car]. *Electrical Engineering & Electromechanics*, 2014, no. 4, pp. 50–52.
11. Bondarenko A. Yu., Finkelshtein V. B., Gavrilova T. V., Vneshnyaya rikhtovka kuzovov avtotransporta s pomoshch'yu ehlektrodinamicheskikh sistem pri "pryamom propuskanii impul'snogo toka". [External flattening of bodies car with help of electrodynamic system with «direct passage of pulsed current»]. *Bulletin of NTU "KhPI"*, 2014, no. 9 (1052), pp. 66–72.
12. Tamm I. E. *Osnovy teorii ehlektrichestva* [Fundamentals of the Theory of Electricity]. M., Nauka Publ., 1989. 504 p.
13. Korn T., Korn G. *Spravochnik po matematike (dlya nauchnykh rabotnikov i inzhenerov)* [Mathematical Handbook for Scientists and Engineers]. Moscow, Nauka Publ., 1973. 832 p.

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АННОТАЦИЯ *Представлено теоретическое обоснование работоспособности метода магнитно-импульсного притяжения листового металла с «прямым пропусканием тока» через обрабатываемый объект. Проведен анализ известных работ в этой области, показано, что отсутствие достаточно полных теоретических исследований не позволяет эффективно выполнять заданную производственную операцию. Путем решения краевой электродинамической задачи получены аналитические выражения для фазовых зависимостей токов в экспериментальной системе и возбужденных сил притяжения обрабатываемого объекта. Доказано численными оценками, что низкочастотный режим протекающих электромагнитных процессов предпочтителен при интенсивном проникновении полей через проводящие компоненты исследуемой системы. Установлено, что рассчитанная зависимость развиваемых сил от напряжения разряда емкостного накопителя позволяет приближенно оценить эффективность притяжения при работе в принятом диапазоне энергетических возможностей источника питания. Показано, что степень неоднородности поперечного распределения сил притяжения в исследуемой области не превышает ~ 20%. Спроектирована и создана действующая экспериментальная модель, состоящая из инструмента магнитно-импульсного притяжения листового металла и источника питания - энергетического блока. На основе полученных соотношений рассчитаны характеристики опытной установки и режимы проведения испытаний. Практически реализовано дозированное магнитно-импульсное силовое воздействие, позволяющее контролировать деформацию листового металла в зоне обработки. Проведены эксперименты по устранению вмятин на образцах, изготовленных из различных видов стали в условиях, приближенных к соответствующей реальной производственной операции. Успешно продемонстрированы практические возможности средств магнитно-импульсного притяжения определенных участков листовых металлов при «прямом пропускании тока» через них. Доказана эффективность рассматриваемого метода при использовании показателей технологической операции, рассчитанных на основании теоретически полученных зависимостей.*

Ключевые слова: *магнитно-импульсное притяжение; тонкостенный листовой металл; электромагнитные процессы; «прямое прохождение тока»; экспериментальная апробация; рихтовка автомобильных кузовов*

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