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MAGNETIC-PULSED FORMING WHEN DIRECT HOOK-UP OF SHEET METAL TO SOURCE OF ELECTRICAL CURRENT

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Abstract. ***Problem.*** *A distinctive feature of this work is that it combines theoretical and experimental studies of electrodynamic processes in a tool for processing sheet metal materials. It was proposed to use the phenomenon of magnetic-pulse attraction when directly connecting the processed sheet metal to a source of electric current. The investigated tool was considered under conditions close to the corresponding real production operation. In earlier scientific publications, such a tool was called an instrument with "direct current flow" through the object being processed.* ***Methodology.*** *In this article, analytical expressions were obtained for the excited currents and forces of attraction by solving the boundary electrodynamic problem, including the integration of Maxwell's equations.* ***Results****. The advantages of the low-frequency mode with intense penetration of fields through the conducting components of the system under study are illustrated by numerical estimates, in particular, it has been found that reducing the width of the main conductor of the inductor can significantly increase the energy characteristics of the system. According to the obtained ratios for currents and forces of attraction, the corresponding characteristics were calculated and the design of the operating experimental model of the magnetic-pulse device for the attraction of sheet metal with "direct current transmission" through the treated area was designed.* ***Originality****. It is shown that the dosed magnetic-impulse force action allows to control the deformation of sheet metal in the processing zone. It has been practically proven that the proposed technique can be very effective in the design of technological equipment used in the elimination of deformations both on steel objects and on aluminum objects.* ***Practical value.*** *Successful practical testing of the proposed tool was carried out in conditions close to real production.*

Keywords*: magnetic-pulsed attraction, thin-walled sheet metal, “direct passage of current”, theoretical justification, flattening automobile bodies.*

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 the 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 a particular interest is 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 the leading European concern “Betag Innovation” and American industry companies such as «Boeing Company», «Electroimpact», Flextronics [3, 4] are meeting to this requirements [2–4].

Analysis of publications

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 [3, 4].

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 [5–8]. As the theory and experiments showed, during ferromagnetic steels processing the repulsing action of Lorentz forces is suppressed and attraction becomes prevalence because of magnetic properties of the processed metal [6]. The authors of paper [7] proposed and designed “inductor systems with attracting screen” (ISAS), allowing excitation of high forces of attraction as for ferromagnetic as non-ferromagnetic metals (so named “the universal tools of attraction”). The proposition essence consists in including rigidly-fixed auxiliary conductive screen into the construction of the inductor system. Conductors with unidirectional currents induced in the screen and in the processed metal experience the mutual attraction. If the screen is rigidly fixed, the metal being processed will move towards the screen. The papers [9, 10] unite a complex of all theoretical and experimental researches of the methods of 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 speaking about progressive technologies with usage 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 [2]. The method of vacuum dent removing on a body car is defended by the Patent of «Dent Defyer Inc» [11]. A special suction cup is placed on the area with a dent. In the internal cavity between them a rarefaction creates. 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.

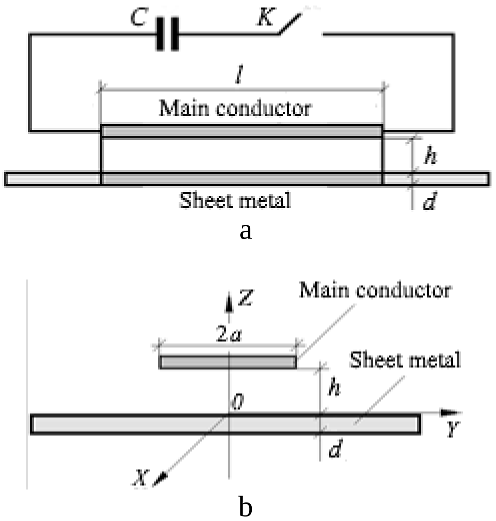
Back to the mentioned below progressive technologies of the magnetic-pulsed attraction of the defined areas of sheet metals, it should be described not only their benefits. The main disadvantages are the power possibilities finiteness conditioned of induction effects with which the electromagnetic energy essential losses are connected [12-14]. In this regard, a method of the Electromagnetic Metals Forming (the known special abbreviation – EMF [9, 10]) with the direct hook-up of the electrical current source which was firstly suggested in former USSR and named as the method “direct passage of current” through the processed metal becomes a very appealing way of the magnetic-pulsed attraction of thin-walled sheet conductors. 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 [15]. 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 were given in papers [16, 17].

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 the direct hook-up of the electrical current source to the processed metal allowing the effective implementation of the required operation. For example, this is the restoration of metal coating of vehicle of any purpose (ground-based, aircrafts, aqueous etc.).

The purpose and statement of the problem

The purpose of the given paper is the theoretical and experimental justification of workability of the method of the magnetic-pulsed attraction when direct hook-up of the electrical current source to the processed thin-walled sheet metal, experimental researches fulfilling and practical testing of the proposed method in conditions closed to the real production operation.

The principal scheme of the tool model for magnetic-pulsed attraction of the sheet metal when it direct hook-up to the electrical current source is shown in the Fig. 1.



a

b

Fig. 1. Principal scheme: a – electrical equivalent circuit; b – calculated electric-dynamical model

The algorithms which were presented and developed by the authors of scientific publications [9, 13, 14] will be used in the present solution. In fairness, it should be mentioned that the analogical questions were already considered before in the works [13, 14]. However, the direct use of the obtained relations is impossible what is caused by features of the accepted physical-mathematical models and the methodical approach to solving the formulated problems.

The following assumptions were made in order to simplify the mathematical model of the process:

– 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 acting fields, so its metal has no influence on occurring electromagnetic processes;

– there is a geometric symmetry of the system relative to the coordinate plane *ZOX*;

– the system is homogeneous and is a sufficiently long along the *X*-axis, so $\frac{\partial}{\partial x}=0$;

– a uniformly distributed current with a density $j_m(t)=j_m\cdot j(t)$ 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-stationary is defined by inequality – $\frac{\omega}{c}\times b<<1$ [13, 14], 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: $E_x\neq 0, H_{y,z}\neq 0$.

Action principle, space-temporal dependencies for calculations

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 [9, 13, 14]:

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

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

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

where *p* – is the *L* – transforming parameter; μ₀ – is the permeability of vacuum:

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

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

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

In the general case, the current density *L*-image 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;

$j_{xi}(p,y,z)=j_m(p)\cdot f(y)\cdot\delta(z-h)$;

$j_m(p)=j_m\cdot j(p)$, – is the amplitude-temporal dependence;

$f(y)$ – is the transverse distribution of current density;

$\delta(z-h)$ – is the Dirac impulse function;

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

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

In order to solve the formulated problem, the areas with homogeneous electric-physical characteristics have to be separated. In the each separated area the differential equations (1)–(3) have to be integrated taking into account the equation for the current density (4). Next step is to apply the Fourier integral cosine-transform [19]. Its admissibility is determined by the geometric and electrical symmetry of the problem under consideration relative to the *ZOX* plane.

Thus, we have:

$$E_x(p,y,z)=\int_0^\infty E_x(p,\lambda,z)\cdot\cos(\lambda y)d\lambda;\quad (5)$$

$$j_x(p,y,z)=\int_0^\infty j_x(p,\lambda,z)\cdot\cos(\lambda y)d\lambda,\quad (6)$$

where: $j_x(p,\lambda,z)=\int\limits_0^\infty j_x(p,y,z)\cos(\lambda y)\,dy=$

$$=j(p)\,f(\lambda)\,\delta(z);$$

$$f(\lambda)=\frac{1}{\pi}\cdot\int\limits_0^\infty f(y)\cdot\cos(\lambda y)\,dy.$$

According to the accepted assumption of uniform distribution of the exciting current in the main conductor, integrating will give the following result:

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

where λ – is a parameter of Fourier transforming.

If to skip the cumbersome mathematical transformations the solution of the problem formulated above can be written as Fourier-Laplace image of the longitudinal component of the electric field intensity excited in the sheet metal shown in Fig. 1, ($z\in[-d,0]$, $y\in(-\infty,+\infty)$):

$$E_x(p,\lambda,z)=-\frac{K(p,\lambda)e^{-\lambda h}}{\lambda}\times$$
$$\times\Bigg[\frac{\operatorname{sh}\big(q(p,\lambda)(z+d)\big)}{\Delta(p,\lambda)}+ \qquad (7)$$
$$+\frac{\frac{q(p,\lambda)}{\lambda}\operatorname{ch}\big(q(p,\lambda)(z+d)\big)}{\Delta(p,\lambda)}\Bigg],$$

where $\Delta(p,\lambda)=\left(1+\left(\frac{q(p,\lambda)}{\lambda}\right)^2\right)\cdot$

$$\cdot\operatorname{sh}\big(q(p,\lambda)d\big)+2\left(\frac{q(p,\lambda)}{\lambda}\right)\operatorname{ch}\big(q(p,\lambda)d\big).$$

The expression (7) should multiply by the electrical conductivity of the sheet metal – γ. The result should substitute in the formula (5).

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

$$j_x(p,y,\zeta)=-\left(\frac{2a\tau}{\pi d^2}\right)\cdot\big(p\cdot j(p)\big)\times$$
$$\times\int\limits_0^\infty\frac{\sin(\lambda a)}{(\lambda a)}\cdot\frac{e^{-\lambda h}}{\lambda}\cdot\frac{F(p,\lambda,\zeta)}{\Delta(p,\lambda)}\cdot\cos(\lambda y)\,d\lambda, \qquad (8)$$

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 [13];

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

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

In expression (8) it is necessary transiting to the space of originals [19]. Skipping the necessary but quite cumbersome mathematical transformations we shall write the original for the current density excited in the sheet metal:

$$j_x(t,z,y)=I_m\frac{2}{\pi}\times$$
$$\times\int\limits_0^\infty\Bigg(\frac{\sin(\lambda a)}{(\lambda a)}e^{-\lambda h}\sum_{k=0}^{\infty}\delta_k\frac{F(\beta_k,\lambda,\zeta)}{F(\beta_k,\lambda)}\times \qquad (9)$$
$$\times\left(\frac{dj_x(t)}{dt}\cdot e^{p_k t}\right)\lambda\cos(\lambda y)\Bigg)d\lambda,$$

where $p_k=-\frac{1}{\tau}\cdot\left(\beta_k^2+(\lambda\cdot d)^2\right)$,

$k=0,\pm1,\pm2...$ – are the simple poles in the expression (8) [19];

β_k – are the roots of equation:

$$\operatorname{ctg}\beta_k=0{,}5\cdot\left(\frac{\beta_k}{(\lambda d)}-\frac{(\lambda d)}{\beta_k}\right);$$

$$\delta_k=\begin{cases}1,\ \text{for } k=0,\\ 2,\ \text{for } k\neq 0,\end{cases}$$

(the presence of the Kronecker symbol – δ_k is due to the parity of the roots);

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

$$F\big(\beta_k,\lambda)\big)=\cos\big(\beta_k\big)[(\lambda d)^2+2(\lambda d)-$$
$$-\beta_k^2]+2\beta_k\sin\big(\beta_k\big)\cdot[(\lambda d)+1].$$

The expression (9) should be reduced to a form suitable for calculations. For this, we introduce a new integration variable –

$$\alpha = \lambda d,\ \alpha \in [0,\infty),\ d\lambda = \frac{1}{d}\cdot d\alpha.$$

They got dependence should be 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:

$$I_x(t,y) = I_m\left(\frac{2}{\pi d}\right)\int_0^{\infty}[\frac{\sin\left(\alpha\frac{a}{d}\right)}{\left(\alpha\frac{a}{d}\right)}e^{-\alpha\frac{h}{d}}\times$$
$$\times\sum_{k=0}^{\infty}\delta_k\frac{G(b_k,\alpha)}{F(b_k,\alpha)}\left(\frac{dj_x(t)}{dt}\times e^{p_k t}\right)\times \qquad (10)$$
$$\times\alpha\cos\left(\alpha\frac{y}{d}\right)]d\alpha,$$

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

$$I_x(t) = I_m\left(\frac{4a}{\pi d}\right)\int_0^{\infty}[\left(\frac{\sin\left(\alpha\frac{a}{d}\right)}{\left(\alpha\frac{a}{d}\right)}\right)^2 e^{-\alpha\frac{h}{d}}\times \qquad (11)$$
$$\times\sum_{k=0}^{\infty}\delta_k\frac{G(b_k,\alpha)}{F(b_k,\alpha)}\left(\frac{dj_x(t)}{dt}\times e^{p_k t}\right)\alpha]d\alpha.$$

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 (from power source) 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:

$$I_x^{(S)}(t) = I_m j(t) - I_x(t). \qquad (12)$$

Speaking of the electromagnetic processes in the investigated system, the influence of induction effects on the current in the main conductor can be taken into account if, based on the physical principles of similarity, to assume that the electromagnetic processes in it and in area of the sheet metal under it are identical [18]. If to take into account this assumption, the total current in the main conductor can be represented by dependence (12) as well.

The integral force of attraction, excited by the interaction of parallel currents (12), takes the form [18]:

$$F_{attr}(t) = \frac{\mu_0}{2\pi}\cdot\left(I_x^{(S)}(t)\right)^2\cdot\frac{l}{h}. \qquad (13)$$

Experimental approbation

First of all, there should be underlined, that the represented experiments on the metal magnetic-pulsed attraction when direct hook-up to the electrical current source unlike the cited works [16, 17] were conducted in view of the new ground-works 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 ferromagnetic as non-ferromagnetic metals (in particular, steel and aluminum).

The given model consists of the following components:

– the tool of the magnetic-pulsed attraction method this is the main conductor which is a metal strip with a given width;

– the metal sheet a defined part of which is a subject for attraction is located on a certain distance from the tool;

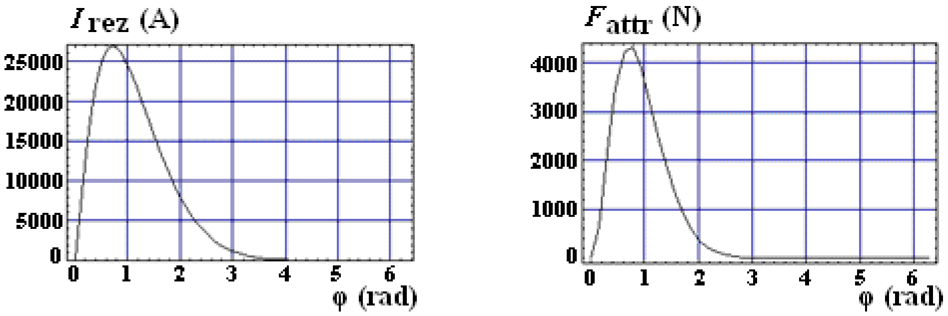
– the attraction object and the tool can be connected in parallel or consequently;

– all geometrical and electric-physical parameters of the tool and the attraction object are specified (dimensions and conductivity);

– the tool and the attraction object are connected to a power source through a matching device that provides the specified operating frequency [9, 10].

Let start from the calculations for the steel plate $\gamma \approx 0{,}5 \cdot 10^7$ (Ohm·m)$^{-1}$. The exciting current has the aperiodic temporal shape with the main frequency – $f = 1500$ Hz, discharge voltage is $U = 2000$ V, operating zone is: $l \cdot (2a) = 0{,}06 \cdot (0{,}01\ldots0{,}06)$ m^2.

The typical amplitude-phase dependencies characteristics of the flowing electric-dynamical processes are represented in Fig. 2.



a b

Fig. 2. Amplitude-phase dependences for a steel sheet:
a – interacting currents; b – excited force of attraction; $\varphi = \omega t$ is a phase

The influences of the transverse size of the attraction tool main conductor on the electromagnetic processes are illuminated below.

1. The attraction force maximum value ~ 4300 N can be reached when the transverse size of the inductor main conductor is reducing to ~ 0,01 m.

2. Increasing the transverse size of the inductor main conductor till ~ 0,06 m leads to falling down the attraction maximal force more than ~ 2 times (~2100 N).

3. 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 field amplitudes (effect of concentration).

4. The transverse distribution of total currents, reflecting the level of the transverse distribution of attractive forces, is almost uniform.

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 undervoltage U=1500 V showed the next.

1. 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.

2. 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 amplitude 1778 N can be expected.

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

Note that the established quadratic relationship between the forces and the discharge voltage does not take into account losses during the transfer of electromagnetic energy from the source to the working area of the device.

Thus, the established quadratic dependence of the exciting forces on the discharge voltage makes it possible to approximately estimate the attraction efficiency under various conditions.

Let turn to numerical estimates for the aluminum sheet with $\gamma \approx 3{,}75 \cdot 10^7$ (Ohm·m)$^{-1}$. The exciting current has the aperiodic temporal shape with the main frequency $f = 1500$ Hz (the equivalent frequency of the initial part of the pulse [5-10], [14]), the voltage is $U = 2000$ V, the operating zone is: $l \cdot (2a) = 0{,}06 \cdot (0{,}01\ldots0{,}06)$ m^2.

The typical characteristics of the flowing electric-dynamical processes are represented in Fig. 3.

The main result of the conducted calculations consists in the next: the force indexes of effectiveness for the aluminum processing is lower than effectiveness for the steel processing, because when the same conditions the maximum of the excited forces does not exceed ~ 1750 N (for steel was ~ 4300 N). But if to take into account that aluminum is much more plastic metal than steel this amplitude of the excited force can be quite enough for the aluminum sheet attraction.

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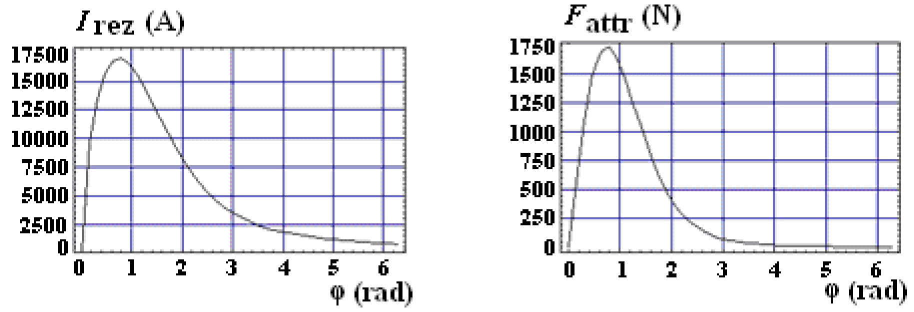


a b

Fig. 3. Amplitude-phase dependences for a aluminum sheet: a – interacting currents; b – excited force of attraction; $\varphi = \omega t$ is a phase

Equipment, experimental objects for processing. Experimental equipment for performing a given production operation included two main components:

1) the tool of magnetic-pulsed attraction;

2) the power source – the energetic block (magnetic-pulsed 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. 4, 5.

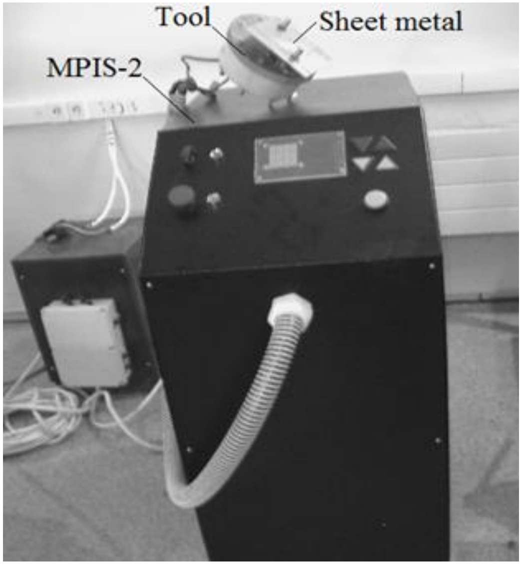


Fig. 4. General view: The magnetic-pulsed Installation MPIS-2 with a tool (the stored energy is ~ 2,4 kJ at voltage ~ 2 kV)

Structurally, MPI-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.

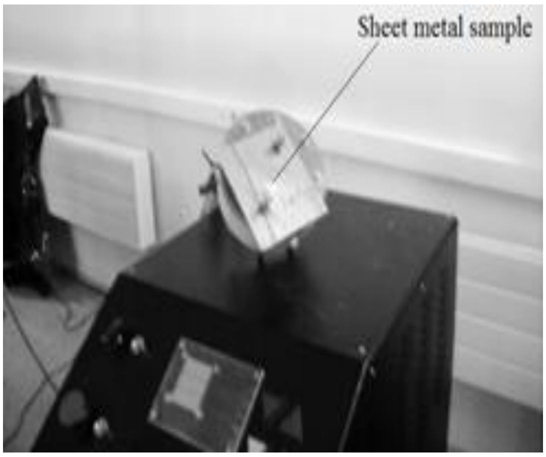


Fig. 5. The sheet sample with the dent to be eliminated

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, 10]:

– the maximum stored energy – $W \approx 2{,}0$ kJ;

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

– the own frequency – $f \approx 7$ kHz;

– the voltage in the range 100,0…2000,0 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.

It should be noted that in doing so 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…0,025 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;

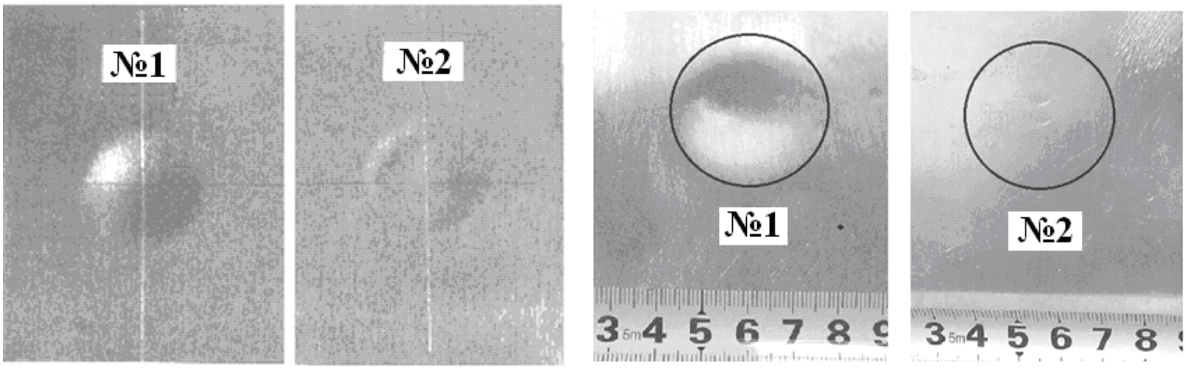
– setting the voltage on the capacitive storage 1500…2000 V;

– 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.

Note that 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.

The illustrations of the experimental results are represented below in Fig. 6, 7.



a b

Fig. 6. Experimental samples: a – from the special electrical steel: №1 – the sample before the attraction; № 2 – the sample after attraction (5 – multiple repetition of magnetic-pulsed attraction); b – from car body coating “Ford”: № 1 – the sample before the attraction; № 2 – the sample after attraction (9 – multiple repetition of magnetic-pulsed attraction)

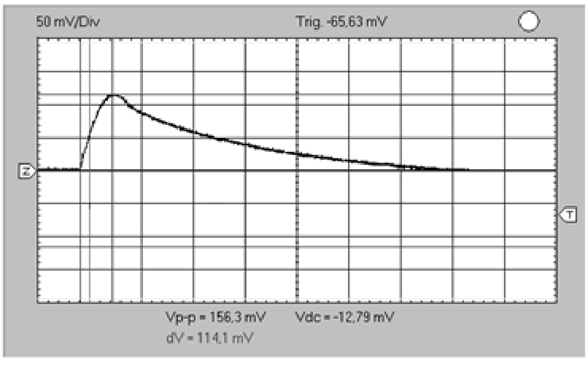


Fig. 7. A typical oscillogram of a current pulse in the discharge circuit with the magnetic-pulsed attraction tool

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;

– 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;

– it has been found that magnetic-impulse attraction with "direct current flow" through the processed aluminum can be very effective when using the technological equipment that was used to deform steel.

Conclusions

The workability theoretical and experimental 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 electrodynamics 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. Successful practical testing of the proposed method was carried out under conditions corresponding to production operations.

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Магнітно-імпульсне оброблення під час прямого підключення листового металу до джерела електричного струму

Анотація: *Відмінна риса цієї роботи полягає в тому, що вона об'єднує теоретичні та експериментальні дослідження електродинамічних процесів в інструменті для оброблення листових металевих матеріалів. Запропоновано використання явища магнітно-імпульсного притягання під час прямого підключення оброблюваного листового металу до джерела електричного струму. Досліджуваний інструмент розглядається в умовах, близьких до відповідної реальної виробничої експлуатації. У більш ранніх наукових публікаціях такий інструмент називався інструментом з «прямим пропусканням струму» через оброблюваний об'єкт. У цій статті отримано аналітичні вирази для збуджених струмів і сил притягання за допомогою розв'язання граничної електродинамічної задачі, що містить інтегрування рівнянь Максвелла. Переваги низькочастотного режиму за інтенсивного проникнення полів крізь провідні компоненти досліджуваної системи проілюстровані під час чисельних аналізувань, зокрема з'ясовано, що зменшення ширини основ-*

ного провідника-індуктора дозволяє істотно підвищити енергетичні характеристики системи. За отриманими співвідношеннями для струмів і сил притягання розраховані відповідні характеристики та спроектована конструкція експериментальної моделі магнітно-імпульсного пристрою притягання листового металу з «прямим пропусканням струму» крізь оброблювану поверхню. Продемонстровано, що дозований магнітно-імпульсний силовий вплив дозволяє контролювати деформацію листового металу в зоні оброблення. Практично доведено, що запропонована методика може бути досить ефективною під час конструювання технологічного устаткування, яке застосовується для усунення деформацій як на об'єктах зі сталі, так і на алюмінієвих об'єктах. Успішна практична апробація запропонованого інструменту була здійснена в умовах, близьких до реального виробництва.

Ключові слова: *магнітно-імпульсне притягання, тонкостінний металевий лист, «пряме проходження струму», теоретичне обґрунтування, рихтування автомобільних кузовів.*

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Магнитно-импульсная обработка при прямом подключении листового металла к источнику электрического тока

Аннотация: *Представлены теоретические и экспериментальные исследования электродинамических процессов в инструменте для обработки листовых металлических материалов. Предложено использование явления магнитно-импульсного притяжения при прямом подключении обрабатываемого листового металла к источнику электрического тока. Получены аналитические выражения для возбуждаемых токов и сил притяжения путем решения граничной электродинамической задачи, включая интегрирования уравнений Максвелла. Установлено, что уменьшение ширины основного проводника индуктора позволяет существенно повысить энергетические характеристики системы. По рассчитанным характеристикам спроектирована конструкция действующей экспериментальной модели магнитно-импульсного устройства притяжения листового металла с «прямым пропусканием тока» через обрабатываемую поверхность. Показано, что дозированное магнитно-импульсное силовое воздействие позволяет контролировать деформацию листового металла в зоне обработки. Практическая апробация предложенного инструмента доказала его эффективность для устранения деформаций как на объектах из стали, так и на алюминиевых объектах.*

Ключевые слова: *магнитно-импульсное притяжение, тонкостенный металлический лист, «прямое прохождение тока», теоретическое обоснование, рихтовка автомобильных кузовов.*

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