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Experimental testing results of the sheet metal magnetic-pulsed attraction when direct hook-up of the current source

The purpose of the given paper is a workability experimental test of the magnetic-pulsed attraction method of the predetermined part of the sheet metal when its direct hook-up to the external source current in conditions close to the corresponding real production operation. In the native scientific publications, the given method is known as the method of «the direct passage of current» through the object being processed. Its main particularity supplying the practical workability is the work in the low-frequency regime when the intensive penetration of the electromagnetic fields through the functional components in the tool working zona. On the basis of the preliminary calculation, the corresponding experimental model of the high voltage magnetic-pulsed system including a power source and the work tool was elaborated and created. It is experimentally shown that the induction effects lead to essential decreasing the forces of the magnetic-pulsed attraction. The practical capabilities of the magnetic-pulsed attraction when the processed object direct hook-up to the current source («direct passage of current» were successfully demonstrated. The controlled (dosed) feed of the magnetic-pulsed force action allowing controlling the deformation process of the processed object was practically implemented. The elaborated experimental model was successfully approbated on an example of the removal of the dents in metal coating car bodies. The experimentally approbated magnetic-pulsed attraction method has to be particularly interesting for technologies of the dents removal in the car bodies, because, unlike known analogs, it does not require the overall construction disassembly for access from the inside to the dent being removed.

Keywords: *magnetic-pulsed attraction; thin-walled sheet metal; «direct passage of current»; experimental approbation; flattening automobile bodies.*

Introduction. The methods of the magnetic-pulsed metal processing (in other special terminology this is EMF – Electromagnetic Metal Forming) are getting more relevant and claimed in the different industrial technologies [1, 2]. The list of the traditional practical applications includes such production operations as the «expansion», «compression», «flat stamping» realized with the help of the so-called «magnetic pressure» [1]. The new scientific direction of the magnetic-pulsed stamping assumes transforming the natural repulsive of the forces of the «magnetic pressure» in the attraction force of the sheet metals. One among the industrial applications of this direction is «Sheet metal blank destaker» represented by authors of Patent USA [2]. A special attention is paid to development of dent removal and leveling surfaces of sheet metals technologies during the restoration of airplane 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 is not only aesthetic considerations, but also often impossibility of further maintenance of the vehicle with damaged body. That is why the devices allowing for restoration of the damages (dents) on surface from the outside of metallic coating without dissembling of hull or body are of particular interest. Therefore, concretely American industrial companies («Boeing Company», «ElectroImpact» etc.) [2, 3] and also European firms, leading in the field of modern car body repair [4] are very interested in the technologies like these.

A brief publications review. Propositions of usage of pulsed electromagnetic fields for the attraction of the defined areas sheet metals have a long history. One of the first is the proposal of the inductor system which uppermost effectiveness is based on antiphase superposition low frequency (LF) and high frequency (HF) magnetic fields. The one penetrates the metal and the other, without penetration, concentrates on its surface from the inductor side – the source of a pulsed magnetic field. The superposition of the LF and HF-fields leads to the zero result from one side of sheet metal and the concentration of penetrated LF-field from the other side. The metal being processed is experienced under unilateral magnetic pressure and is attracted to the inductor. This type of inductor 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 only low-frequency magnetic fields allowing work in the mode of their intensive penetration through sheet metal [5, 6]. As the theory and experiments showed, during ferromagnetic metal processing because of their magnetic properties the repelling action of Lorentz forces, the attraction became prevailing [5]. According to the authors of the paper [6], «induction systems with attracting screen», allowing excitation of high forces of attraction as for ferromagnetic as non-ferromagnetic metals were proposed, studied and designed. The contribution is to include a rigidly fixed auxiliary conductive screen into the construction of the inductor system. The conductors with unidirectional currents induced in the screen and in the metal being processed are experienced the mutual attraction. And when the screen is rigidly fixed, the metal will move towards the screen. The works [7, 8] combine a complex of all theoretical and experimental researches on the magnetic-pulsed attraction based on different physical nature phenomena. The research paper shows the main ways of practical using attraction for modern repair technologies of vehicles.

In addition to technology using the energy of magnetic pulsed fields, there are some other methods of removing dents. For example, a patent of the concern «Dent Defyer Inc.» protects the method of vacuum body straightening [9]. A special suction cup is applied to the dent area. In the internal cavity between them, a vacuum is created. There are gravitational forces that stretch the deformed metal. But mechanical methods of attraction demonstrate some shortcomings as complexity of technical execution, unreliability (possible gaps!), high requirements to qualification of the executor, etc.

The main disadvantage of all known technologies with magnetic-pulse force action is the power limitation caused by induction effects, which, as usual, led to significant losses of electromagnetic energy [10]. In this regard, a very appealing way of magnetic-pulsed attraction of thin-walled sheet metals is a method with its direct hook-up to a current source. The name of the «direct passage of current» method is given through the processed metal. Its attractiveness is caused by simple technical realization and quite high energy indicators. Reviews of propositions and experimental testing of such magnetic-pulsed tools for straightening car bodies can be found in publications [11, 12], and the analysis of electrodynamic processes in magnetic-pulse attraction tools with direct current flow through the processed metal – in [13]. But in all cited works, there are no sufficiently complete theoretical and experimental studies with proposals for optimal designs of tools with «direct passage of current» that can effectively carry out this production operation, such as restoration of metal coatings of car bodies for any purpose. Therefore, the solution to this problem seems very important.

The aim of the given paper is the workability of experimental justification of method of magnetic-pulsed attraction of the sheet metals when their direct hook-up to a current source («direct passage of current» through the processed object) in conditions close to the reality of predetermined production operation performing.

Functional principle. First, there should be underlined, that the represented experiments on magnetic-pulsed attraction with «direct passage of current» unlike the cited works [11, 12] are conducted in view of the new theoretical and experimental results received before in a given area of the scientific investigations. It allowed moving from initial simplest approbation to the more complicated experiments with an understanding of the physics of the processes and the specific recommendations of development for the creation of equipment for the effective implementation of the predetermined production operation. On this basis, the obligatory requirement of the low frequency mode was laid when intensive penetration of the excited electromagnetic fields through metal components of the high voltage magnetic-pulsed system tool takes place.

Design of the accepted experimental model corresponds essentially to the scheme in Figure 1, *a* and it is universal. That is this system can work as with ferromagnetic as non-ferromagnetic metals (in particular, with steel and aluminum).

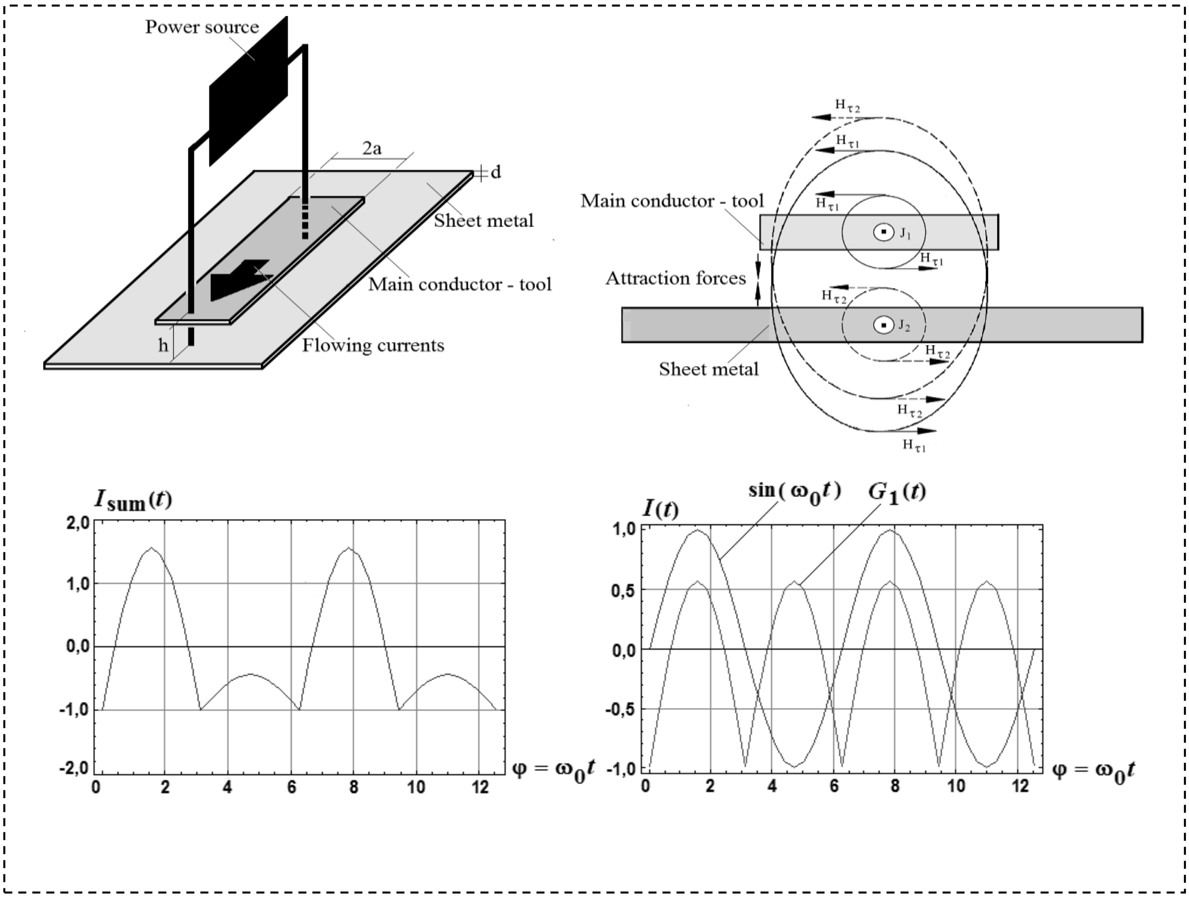
The given model consists of the following components:

- the main conductor (the method tool), that is a metal strip with a given width;
- the flat metal sheet, which predetermined part, is a subject for attraction, and located on the certain distance from the main conductor;
- geometrical and electric-physical parameters of the tool are supposed to be given (dimensions and conductivity);
- the tool and the sheet metal are connected to a power source through a matching device that provides the required operating frequency [8].

The considered system is working in the following way.

After direct hook-up the power source to the sheet metal, the unidirectional currents are flowing in the main conductor (this is the tool) and in the metal sheet. The excited forces interaction is displayed by the Ampere Law. For further explanations and simplicity let us assume all values of the magnetic field intensities are equal $H_{\tau 1} = H_{\tau 2} = H$. However, their directions are different according to the current directions in the main conductor and the sheet metal.

When both metals are not «transparent» for the excited fields, their mutual penetration is absent and the frequencies are quite high (HF-regime). Then the summary magnetic field intensity in the inner space between the metals doubles, $H_{inside} \approx H_{\tau 1} + H_{\tau 2} \rightarrow 2H$. However, in the external space of the system the resulting magnetic field intensity will be equaled to zero, $H_{outside} \approx H_{\tau 1} - H_{\tau 2} \rightarrow 0$. It means that between sheet metals a repulsion will take place.



a) *b)*

Fig. 1. The essential schemes illustrating the electrical-dynamical processes in the magnetic-pulsed system for the sheet metal attraction:
a) the system of the magnetic-pulsed attraction of the sheet metal when its direct hook-up to the power source;
b) the physical picture of exciting the magnetic-pulsed attraction of the sheet metals when flowing the unidirectional currents

If the working frequencies are quite low (LF-regime), both metals are «transparent» for the excited fields and the penetration is intensive enough. Then the summary magnetic field intensity in the inner space between the metals will be equaled to zero, $H_{inside} \approx H_{\tau 1} + H_{\tau 2} \to 0$. However, in the external space of the system the resulting magnetic field intensity doubles, $H_{outside} \approx H_{\tau 1} - H_{\tau 2} \to 2H$. That means that between sheet metals an attraction, caused by the well-known magnetic pressure, will take place.

The main conclusion from the conducted statement considers the low working frequencies resulting in magnetic intensity between interacting conductors equaled to zero, but above the main conductor and the sheet metal the excited field intensity doubles. The corresponding integral of magnetic pressure force from without can reach value – $p \approx \frac{\mu(2H)^2}{2}$. This pressure is the force attracting both interacting conductors to each other.

Experimental equipment, experimental samples. According to the aim of the given work, the described below experiments are dedicated to the approbation of the magnetic-pulsed attraction in the system with the direct hook-up of the sheet metal billet to a current source («direct passage of current» through the processed object) in conditions closed to the reality of the dent removal on the metal coating body cars.

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

1. The tool of the magnetic-pulsed attraction;
2. The power source is the power unit (magnetic-pulsed installation).

The power source – Magnetic-Pulsed Installation Serial, MPIS-2 was developed at the laboratory of electromagnetic technologies of Kharkov National Automobile & Highway University [7]. In the whole, the installation is shown in Figure 2.

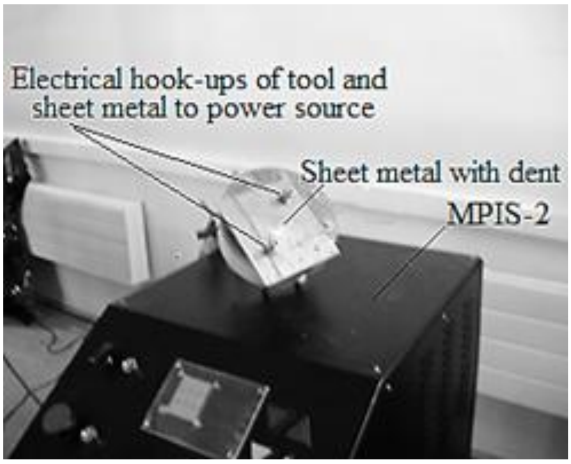


Fig. 2. Magnetic-pulsed installation MPIS-2 with a maximum stored energy of ~ 2,0 kJ at voltage ~ 2,0 kV

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

On the upper plane of the body, there is a horizontal massive dielectric plate, which can be 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 MPIS-2 [9, 10]:

- the maximal stored energy W ~ 2,4 kJ;
- the storage capacity C = 1200 μF;
- the eigen frequency f_0 ~ 7 kHz;
- the capacitor voltage in the range ~ 100 ÷ 2000 V;
- the follow frequency of generated current pulses – 1 ÷ 10 Hz;
- an electronic control unit that synchronizes the processes «charge – discharge» provides the multiple repetition mode;
- the switch type – thyristor switches;
- the supply voltage ~ 380/220 V.

The tool is fulfilled in a view of the steel ($\gamma \approx 0{,}5 \cdot 10^7$ (Ohm·m)$^{-1}$) strip with dimensions according to the working zone on the sheet metal surface: $l \times 2a = 0{,}06 \times 0{,}01$ m^2. It is made from the same metal and the same thickness that the experimental sample. The hook-up to the power source is realized through the matching device (the air pulsed transformer [8]) that allows receiving quite low working frequency ~ 1500 Hz in a discharge.

Experimental samples are the steel plates of a rectangular geometry with dents. Their thickness is ~ 0,08 m, dents size ~ 0,02 ÷ 0,25 m.

Notes.

1. The discharging circuit design allows getting the currents of different temporal forms. They can be the unipolar or the harmonic pulses.

2. The choice of the geometric shape of the tool is due to the requirement of the minimal inductance of the discharging circuit including the current-conductors, tool proper, and the power source. It is necessary in order to reduce the loss of electromagnetic energy during its transportation from the source to the tool-working zone.

Practical approbation, the main results. The sequence of operations for the force approbation of the magnetic-pulsed attraction and indicators of the process of eliminating dents during the experiment are the following:

- inspection and visual study of the processing object – of a metal plate with a dent;
- mutual mechanical fixation of the object of processing and tool using bolted joints;
- setting the voltage on the capacitor bank at ~1800 ÷ 2000 V;
- switching on the discharging circuit of the system:
- force impact on the metal with a dent in the mode of the $(5 \div 10)$ – fold repetition of the magnetic-pulsed attraction;
- inspection and visual study of the experimental sample with the eliminated dent, a determination of the effectiveness of the completed production operation.

Note. In case of insufficient surface smoothing the dent, removal should be repeated until the desired level of the quality performed manufacturing operation.

Some results of the conducted experiments are described below. Firstly, induction effects, influenced the currents in the main conductor and sheet metal, were investigated. Physically, this influence is conditioned by «the current from the source» in each of them and excites the induced current in the metal of the opposite conductor. Thus, the resulting current as in the main conductor and as in sheet metal will be equaled to the algebraic sum of «the current from the source» and the induced current. As the conducted experiments showed, this circumstance can essentially decrease the fulfilled production operation effectiveness. One of the possible relationship illustrations between the current from the power source and the induced current is represented in Figure 3. As it is seen from oscillogramms, the induced current can reach about ~ 20 % of the exciting current magnitude. Taking into account the fact that the attraction force is proportional to the interacting currents square [7], it can be expected the decrease more than ~1,5 times in this case. And as a result, it should be marked that the given estimates can service approximate quantitative estimates of the induced currents influence on the process effectiveness of the magnetic-pulsed attraction.

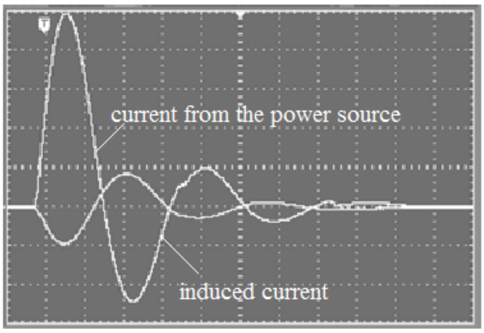


Fig. 3. The currents in the system conductors

The experimental approbation of the elaborated and created magnetic-pulsed complex for the dent removal was realized in regime of the unipolar discharge current pulses. The experimental approbation of the elaborated magnetic-pulsed system for the dent removal in the steel samples was realized in regime of the unipolar current pulses. Their typical temporal form is represented in the Figure 4.

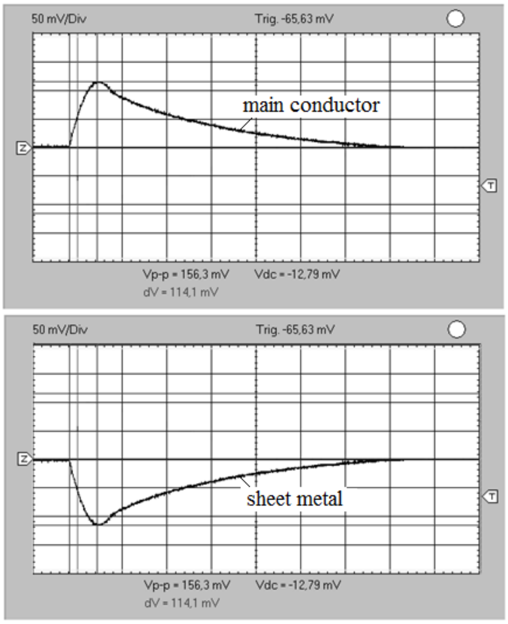


Fig. 4. The typical oscillograms of the working currents in the system conductors in the force approbation

The main advantage of the chosen regime of the force action lies in the fact that at the unipolar pulses the work reliability of the thyristor commutators of the discharging circuit is essentially increasing though the amplitude of the generated currents is falling down.

The force operation of the dent removal was realized quite successfully that the experimental results in Figure 5 are confirming.

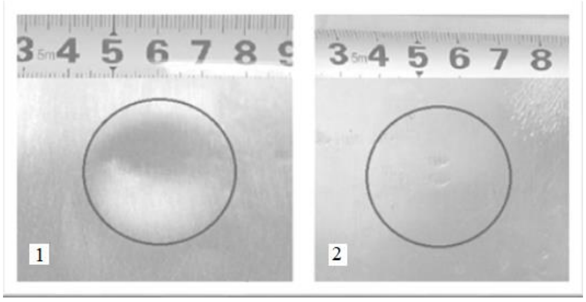


Fig. 5. Experimental steel samples, 1 – the sample before the attraction; 2 – the sample after attraction (5-multiple repetition of magnetic-pulsed attraction)

The main results of the conducted experiments are generalized in the following statements.

−It is experimentally shown the induction effects lead to essential decreasing the forces of the magnetic-pulsed attraction.

−The practical capabilities of the magnetic-pulsed attraction were successfully demonstrated when the processed object direct hook-up to the current source («direct passage of current»).

−The controlled (dosed) feed of the magnetic-pulsed force action allowing to control the deformation process of the processed object was practically implemented.

−The experimentally approbated magnetic-pulsed attraction method has to be particularly interesting for technologies of the dents removal in the car bodies, because, unlike known analogs, it does not require the overall construction disassembly for access from the inside to the dent being removed.

Conclusions:

1. It is experimentally shown that the developed and created model of the complex, which includes a power supply and a tool for magnetic-pulse attraction of sheet metal when connected directly to an external current source, is operational in conditions close to the actual production operation;

2. The method of magnetic-pulse attraction of sheet metals at direct connection of the processed object to a power supply («direct passage of current» through the object of processing) has passed successful practical approbation and can be used to remove dents in car bodies.

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