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EXTERNAL MAGNETIC-PULSE STRAIGHTENING OF CARS BODY PANELS

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Abstract. *The basics of magnetic-pulse attraction of both ferromagnetic and non-ferromagnetic thin-wall sheet metals are investigated. The design models of inductor systems-magnetic-pulse straightening tools are presented. The final analytical expressins for excited efforts design in the tools under consideration are introduced. The practical testing of magnetic-pulse straightening with the tools under study is given*

Key words*: external straightening, removal of dents, body repair, magnetic-pulse metal processing, car body panels.*

ЗОВНІШНЄ МАГНІТНО-ІМПУЛЬСНЕ РИХТУВАННЯ КУЗОВНИХ ПАНЕЛЕЙ АВТОМОБІЛІВ

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Анотація. *Розкрито основи магнітно-імпульсного притягання як феромагнітних, так і неферомагнітних тонкостінних листових металів. Наведено розрахункові моделі індукторних систем – інструментів магнітно-імпульсного рихтування. Подано остаточні аналітичні вирази для розрахунку збуджених зусиль у розглянутих інструментах. Наведено практичну апробацію магнітно-імпульсного рихтування з досліджуваними інструментами.*

Ключові слова: *зовнішнє рихтування, видалення вм'ятин, кузовний ремонт, магнітно-імпульсна обробка металів, кузовна панель.*

ВНЕШНЯЯ МАГНИТНО-ИМПУЛЬСНАЯ РИХТОВКА КУЗОВНЫХ ПАНЕЛЕЙ АВТОМОБИЛЕЙ

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Аннотация. *Раскрыты основы магнитно-импульсного притяжения как ферромагнитных, так и неферромагнитных тонкостенных листовых металлов. Представлены расчетные модели индукторных систем – инструментов магнитно-импульсной рихтовки. Приведены окончательные аналитические выражения для расчета возбуждаемых усилий в рассматриваемых инструментах. Приведена практическая апробация магнитно-импульсной рихтовки с исследуемыми инструментами.*

Ключевые слова: *внешняя рихтовка, удаление вмятин, кузовной ремонт, магнитно-импульсная обработка металлов, кузовная панель.*

Introduction

Number of cars in the world grows at a huge rate year by year. Unfortunately, quantity of road traffic accidents in which car body panels are damaged in a varying degree, but imminently, grows at the same time. Therefore, car body panels repair and restoration related operations are relevant and in increasing demand. And, as statistics shows – up to 80 % of the damages are small and medium. Half of them are dents not requiring replacement of the entire element and removable by straightening. Over 50% of these damages are in the areas with difficult or completely closed reverse access. As a result, car body recovery methods, which allow you execute the so-called external straightening without the necessity of disassembly of car body elements and existing protective paint damage, are of special interest [1–3].

Publications analysis

The implementation of magnetic-pulse technology in repair and recovery of transport vehicles body elements led to creation of a whole new direction, which can be formulated as development of repair and recovery of transport vehicles body methods, based on the energy of electromagnetic fields.

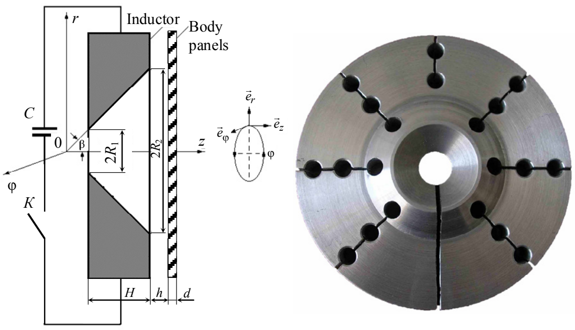
It should be noted that while working with metal by conventional mechanical methods (straightening, pressing, stamping etc.) metal becomes thin and stretched. In such case top metal layer undergoes a deformation that leads to its structure disruption [3–5]. Magnetic-pulse straightening methods are devoid of these drawbacks because the interaction of the magnetic field with the induced current (full-thickness of processed metal) initiates a metal stretching by attraction forces that act throughout its full-thickness [1, 2, 6–9].

Processes in ferromagnetic materials

The objective of this part is to describe the concept, provide a simplified mathematical model predicting attracting electromagnetic forces for ferromagnetic materials and illustrate this concept with experimental results supporting the major conclusions of the analytical study.

Analytical model of the process and numerical estimates

The inductor design in the form of flat cylindrical turn leads to the concentration of attractive forces directly under the inductor turn. This fact is caused by magnetic field strength vector module growth in radial direction from the system center with a maximum in the coil area. This issue is specified in publications [1, 8, 10, 11]. The physical considerations showed that we can change the field distribution nature in the inductor system and the acting forces distribution nature, accordingly, if we configure inductor profile to frustum-of-a-cone shape (fig. 1). In this case, the maximum of the acting attraction forces must move to the geometric coil center. The inductor system calculation model with internal opening in frustum-of-a-cone shape is presented in figure 1, a.



a b

Fig. 1. Conical induction system: a – calculation model; b – physical model ($\vec{e}_r, \vec{e}_\varphi, \vec{e}_z$ – are the unit vectors in the cylindrical coordinate system)

Maxwell's equations were set up according to the calculation model, displayed in figure 1. Without dwelling on their solving (solving approach is expounded in publication [10]) let's write the final expression for the magnetic attraction force acting on the car body panel.

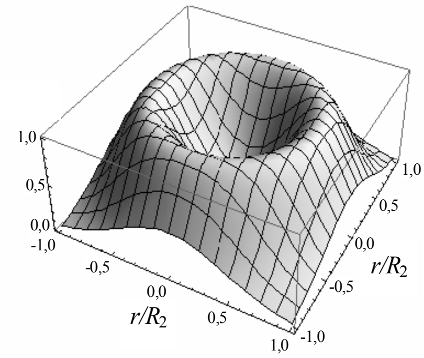
$$P_F(\rho,t) = -\left(1-\frac{1}{\mu_r}\right)\frac{\mu_0 H_m^2}{8}\cdot\frac{i^2(t)}{\left(1-\cos(\beta)\right)^2}\times \quad (1)$$

$$\times\left\{\left[\frac{\left(\mathrm{ctg}(\beta)+\frac{h}{R_2}\right)^2}{\left(\rho^2+\left(\mathrm{ctg}(\beta)+\frac{h}{R_2}\right)^2\right)^2}-\frac{\left(\mathrm{ctg}(\beta)+\frac{h+d}{R_2}\right)^2}{\left(\rho^2+\left(\mathrm{ctg}(\beta)+\frac{h+d}{R_2}\right)^2\right)^2}\right]+\right.$$

$$\left.+\frac{\rho}{\mu_r}\left[\frac{1}{\left(\rho^2+\left(\mathrm{ctg}(\beta)+\frac{h}{R_2}\right)^2\right)^2}-\frac{1}{\left(\rho^2+\left(\mathrm{ctg}(\beta)+\frac{h+d}{R_2}\right)^2\right)^2}\right]\right\},$$

where $H_m = L_i I_m/(\mu_0\mu_r\pi R_2^2)$ – conditional amplitude of magnetic field intensity; L_i – inductivity of system; I_m – current amplitude; $i(t)$ – time dependence of current pulse; $\rho = r/R_2$ – relative radial coordinate.

Numerical estimates for conical induction system were carried out for the following values: $R_1 = 0{,}0075$ m, $R_2 = 0{,}02$ m, $h = 0{,}0005$ m, $d = 0{,}0005$ m, slope angle of generatrix of inner cone turn β = 60°–75°, current amplitude in the inductor 50 kA. The results of calculations are presented in Figure 2.



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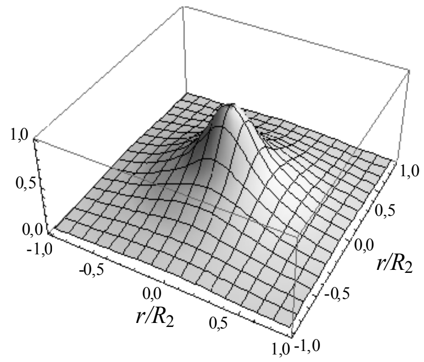


b

Fig. 2. Volume epure of the attraction force radial distribution to inductor work surface: a - with a cylindrical bore; b – with conical bore when β = 60°

Summing calculations results up, let's formulate main conclusions.

1. Changing to the conical shape of the inductor inner window significantly changes the nature of the field radial distribution and the acting forces:

– the magnetic flux concentrate in the central zone of the inner window, unlike the flat cylindrical inductor where strength maximum occurred at the edge of the single turn inductor internal opening;

– the field concentration at the system center leads to the acting forces concentration in the central area of the processed sheet.

2. The increase of the angle of slope of the cone generator of the inner window of the inductor massive turn affects excited forces value significantly. As the angle β is increased from 60° to 75° the amplitude of the attraction grows from $3\cdot10^5$–$46\cdot10^5$ Н/м^2.

Experimental validation

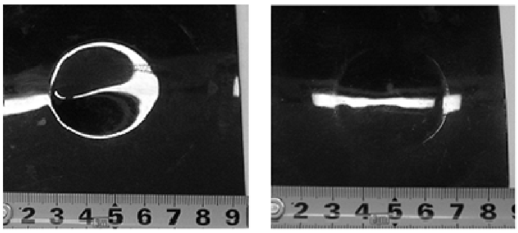
Experimental validation of the proposed concept was done with the intent of practical application of the proposed process to dent removal from automotive exterior panels manufactured from steel. The experimental setup is shown in fig. 3.

The single turn massive inductor with the working zone diameter of 40 mm was connected to the pulse generator via current pulse transformer with the coefficient of transformation of five. The discharge frequency was measured as 1,9 kHz. The amplitude of electric current flowing through the coil was 38 kA.

Fig. 3. The laboratory equipment for EMF attraction processes with maximum charging voltage of 2kV and accumulated energy of 2kJ: 1 – pulsed current transformer; 2 – single turn inductor; 3 – cable connection; 4 – pulse generator

The DDQ (Deep Drawing Quality) flat sheet steel samples 0,8 mm thick (the steel DDQ yield strength is equaled to 180 MPa, stainless steel – 350–300 MPa) were positioned next to the single turn coil. The sample was insulated from the coil with ~1 mm layer of insulation. Initially flat samples were bulged by attraction inside the working zone of the single turn coil. The bulge was axisymmetric and had the maximum height of 1,5 mm at the axis of symmetry of the coil.

After the initial bulge was produced on a flat blank using the described process of electromagnetic attraction, it was flipped over, and dent removal process was physically simulated by pulling the bulge back with the electromagnetic attraction process. The experimental sample is shown on Fig. 4. The dent was successfully removed which confirmed the suggested concept.



a b

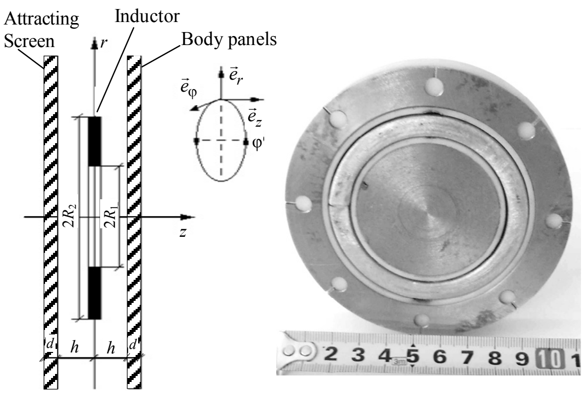
Fig. 4. The experimental DDQ steel sample: a – after producing the dent; b – after removing the dent

Process for non-magnetic materials

The objective of this part is to describe the concept and provide a simplified mathematical model of pulsed electromagnetic attraction of non-magnetic materials in the «Inductor System with an Attracting Screen» as well as to illustrate the experimental results supporting the suggested concept and the major conclusions of the analytical study.

Theoretical analysis, numerical calculations

The schematic of the proposed process of sheet metal attraction is employing an Inductor System with Attracting Screen (ISAS) shown in Fig. 5,a.



a b

Fig. 5. Schematic of ISAS: a – calculation model; b – physical model

The operating principle of this system (Fig. 5) is founded on the utilization of Ampere's law, according to which conductors with collinear equally directed currents attract each other. As distinct from inductor systems which are founded on natural ferromagnetic attraction, when the existing fields operating frequency descents, ISAS is the technical solution. Here, besides the inductor (magnetic field source) and sheet billet – car body panel we add additional structural unit. This is so called Attracting Screen. It is arranged parallel and symmetrically to the inductor subspace and the car body panel. If the screen and car body panels are identical, than equal by magnitude, time dependence and direction currents are excited in them. Their interaction leads to mutual attraction. But the screen is fixedly locked. Therefore, only car body panel is flexed - its site in the internal window area will be attracted to the inductor.

The analytical solution of this problem is described by Batygin, Hnatov et al. (2014) [10, 12].

Without dwelling on the solving of Maxwell's equations were compiled for the calculated model, we write the expression to determine the attraction force according to Ampere's Law.

$$P_A(\varphi,r)=P_{Am}(\varphi)\left(\int\limits_0^{\infty}\Phi_3(x)J_1\left(x\frac{r}{d}\right)dx\right)^2, \quad (2)$$

where

$$\Phi_3(x)=\frac{F(x)\cdot\left((1-\mathrm{ch}(x))-\frac{1}{\mu_r}\mathrm{sh}(x)\right)}{x^3\left(\mathrm{sh}(x)\left[\mathrm{sh}\left(x\frac{h}{d}\right)+\frac{1}{\mu_r^2}\mathrm{ch}\left(x\frac{h}{d}\right)\right]+\frac{1}{\mu_r}e^{x\frac{h}{d}}\mathrm{ch}(x)\right)};$$

$$F(x)=\int\limits_{\left(x\cdot\frac{R_1}{d}\right)}^{\left(x\cdot\frac{R_2}{d}\right)} y\cdot J_1(y)\,dy;$$

$$P_{Am}(\varphi)=\frac{\mu_0}{2}\cdot\frac{r}{h}\left(I_m\cdot\frac{dj(\varphi)}{d\varphi}\cdot\frac{(\omega\cdot\tau)}{2}\right)^2.$$

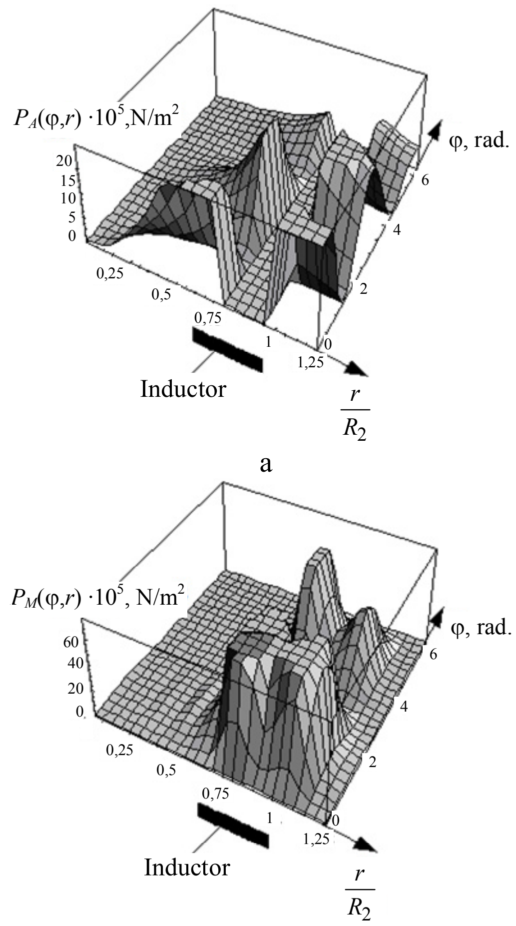
The attraction force, determined by magnetic behavior of car body panel metal, is described by the dependence

$$\begin{aligned}P_M(\varphi,r)=&-\frac{\mu_0}{2}(\mu_r-1)\times\\ &\times\left(\mu_r\left[H_z^2(\zeta=0)-H_z^2(\zeta=d)\right]+\right.\\ &\left.+\left[H_r^2(\zeta=0)-H_r^2(\zeta=d)\right]\right),\end{aligned} \quad (3)$$

where $H_{z,r}(\zeta=0), H_{z,r}(\zeta=d)-\{z \text{ i } r\}$ – the magnetic field strength components on the edge surfaces of car body panel [12].

Such criteria were found for numerical estimates carrying out: $R_1 = 0{,}025$ m, $R_2 = 0{,}035$ m,

h = 0,001 m, f = 1150 Hz, δ = 0,2, I_m = 50 kA, d = 0,00075 m, $\gamma = 0{,}4 \cdot 10^7$ 1/(Ohm·m), $\mu_r \approx 2{,}5$. The results of calculations are presented in fig. 6.



a

b

Fig. 6. The volume epures of phase-space distribution of time highs of excited attraction forces for magnetic metals: a – Ampere's attraction force; b – the magnetic attraction force

We can draw the following conclusions after analyzing the obtained calculations results:

1. The magnetic capabilities effect of screen and car body panel is manifested in the appearance of the powerful forces of magnetic attraction.

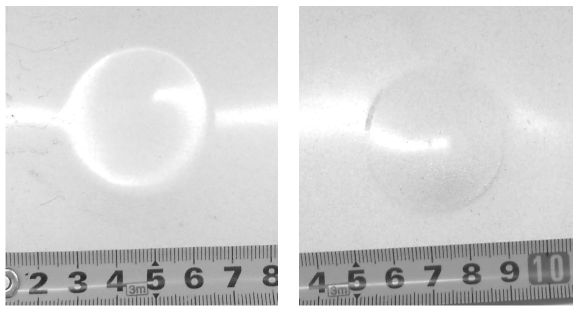
2. The superposition of Ampere's attraction forces and magnetic attraction forces in the radial distributions turn off dip of the force impact to car body panel in the single turn inductor area.

3. In general, ferromagnetic attraction in considered ISAS is more effective than a non-magnetic metal. Inductor current with time dependence in the form of an exponentially-damping sine with an amplitude of 37 kA excites the attraction force about (35–80)$\cdot 10^5$ N/m^2.

4. The evaluation of the average force values showed that the total attraction force mean value (Ampere's force plus the magnetic attraction force) during its action can come up to $110 \cdot 10^5$ N/m^2.

Experimental validation

The material had the following properties: yield stress was 310 MPa; specific conductivity was $0{,}4 \cdot 10^7$ 1/(Ohm·m). The sheet metal screen was rigidly mounted on a surface of a massive dielectric plate preventing deformation of the screen. A single-turn inductor with the inner diameter of 60 mm was mounted on top of the screen and was covered by an insulating plate 1 mm thick. The blank was made from the same 1 mm stainless steel sheet. The working zone of the investigated inductor system is the round opening with diameter 45 mm in the insulating plate on the inductor. The part of the sheet metal blank positioned against the opening in the insulating plate was expected to be deformed by the EMF attraction forces. The amplitude of the electric current running through the coil was J_m=39,2 kA, and the frequency of the discharge was f=2 kHz. The relative damping coefficient was δ_0=0,3. After eight discharges, the sheet metal blank was attracted into the inner opening of the working zone: the dent had a diameter of 40 mm and a the depth of 1mm formed on the surface of sheet metal blank (Fig. 7, a).



a b

Fig. 7. Experimental investigation with ISAS: a – after producing the dent; b – after removing the dent

Further researches were carried out similar to the previous review. After the initial bulge was produced on a flat blank using the described process of electromagnetic attraction, it was flipped over, and dent removal process was physically simulated by pulling the bulge back with the electromagnetic attraction process. The experimental sample is shown on Figure 7,b. The dent was successfully removed which confirmed the suggested concept.

It should be noted, while pilot investigating, the protective paint of the car body panels were not damaged. This fact opens up enough great opportunities and perspectives in the creation and production of new advanced equipment for repair technology.

Conclusions

The conducted theoretical analysis and experiments confirmed the proposed concepts of the inductor systems for ferromagnetic and non-ferromagnetic blank materials. The mentioned inductor system can be used as a tool of external magnetic-pulse straightening of car body panels. In such a case, efficient dents removal is made from outside of a car body panel and without painting damage.

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