UDC 624.318 **doi: 10.20998/2074-272X.2019.6.05**

Yu.V. Batygin, E.A. Chaplygin, S.A. Shinderuk, V.A. Strelnikova

NUMERICAL ESTIMATES OF CURRENTS AND FORCES IN LINEAR TOOLS OF THE MAGNETIC-PULSE ATTRACTION OF METALS. PART 2: HIGH ELECTRICAL CONDUCTANCE METALS

Purpose. The purpose of the present work is substantiating workability of the linear tools of the magnetic-pulse attraction of thin-walled sheet metals with high electrical conductance, the principle of which is based on the force interaction of two conductors with unidirectional currents during intensive penetration of the acting electromagnetic fields. Constructively, one of these conductors in the linear tools is the so-called main current lead (an analog of the inductor in EMF) and the second one is the part of the sheet metal which has to be deformed. Methodology. For numerical estimates the analytical dependences are obtained with help of the methods of electromagnetic field theory as well the standard programs from the Wolfram Mathematica package used. Results. The fulfilled calculations illustrate the amplitude-temporal dependences for the excited currents and forces under the demanded decrease of the operating frequencies of the acting electromagnetic fields. The efficiency of the linear magnetic-pulse tools is based on the excitation of the mutual attraction forces of conductors with low-frequency unidirectional currents. Originality. By the example of aluminum, which is the main raw material in modern aviation and automotive industry, it has been found that for processing the metals with high electrical conductance demand a significant decreasing operating frequencies, what is necessary for intensifying the penetration processes of acting fields and, accordingly, for exciting the real attractive forces. Practical value. The results of the work allow formulating the based recommendations for the creation and practical application of the linear magnetic-pulse attraction tools for the progressive technologies of restoring the damaged areas of bodies coatings from the thin-walled sheet metals with the high specific electrical conductivity. References 10, figures 4.

Key words: **metals with high electrical conductance, intensive field penetration, magnetic-pulse attraction of conductors with unidirectional currents, linear tools for eliminating dents in body coatings.**

Мета. Метою роботи є обґрунтування дієздатності лінійних інструментів магнітно-імпульсного притягання тонкостінних листових металів з високою питомою електропровідністю, принцип дії яких заснований на силовій взаємодії провідників з односпрямованими струмами при інтенсивному проникненні збуджених полів. Методика. Для чисельних оцінок використовувалися аналітичні залежності, отримані за допомогою методів теорії електромагнітного поля, і стандартні програми з пакету «Wolfram Mathematica». Результати. Проведені обчислення ілюструють амплітудно-часові залежності для збуджених струмів і сил при необхідному зниженні робочих частот діючих електромагнітних полів. Обґрунтовано дієвість лінійних магнітно-імпульсних інструментів, заснованих на збудженні сил взаємного притягання провідників з низькочастотними односпрямованими струмами. Наукова новизна. На прикладі з алюмінієм, який є основним сировинним матеріалом у сучасному авіа- та автомобілебудуванні, встановлено, що для металів з високою питомою електропровідністю потрібно значне зниження робочих частот, що необхідно для інтенсифікації процесів проникнення діючих полів і, відповідно, для збудження реальних сил притягання. Практичне значення. Результати роботи дозволяють сформулювати обґрунтовані рекомендації щодо створення та практичного застосування лінійних інструментів магнітно-імпульсного притягання в прогресивних технологіях відновлення пошкоджених ділянок корпусних покриттів з тонкостінних листових металів з високою питомою електропровідністю. Бібл. 10, рис. 4.

Ключові слова: **метали з високою питомою електропровідністю, інтенсивне проникнення поля, магнітно-імпульсне притягання провідників з односпрямованими струмами, лінійний інструмент усунення вм'ятин в корпусних покриттях.**

Цель. Целью работы является обоснование дееспособности линейных инструментов магнитно-импульсного притяжения тонкостенных листовых металлов с высокой удельной электропроводностью, принцип действия которых основан на силовом взаимодействии проводников с однонаправленными токами при интенсивном проникновении возбуждаемых полей. Методика. Для численных оценок использовались аналитические зависимости, полученные с помощью методов теории электромагнитного поля, и стандартные программы из пакета «Wolfram Mathematica». Результаты. Проведенные вычисления иллюстрируют амплитудно-временные зависимости для возбуждаемых токов и сил при требуемом понижении рабочих частот действующих электромагнитных полей. Обоснована действенность линейных магнитно-импульсных инструментов, основанных на возбуждении сил взаимного притяжения проводников с низкочастотными однонаправленными токами. Научная новизна. На примере с алюминием, который является основным сырьевым материалом в современном авиа- и автомобилестроении, установлено, что для металлов с высокой удельной электропроводностью требуется значительное понижение рабочих частот, что необходимо для интенсификации процессов проникновения действующих полей и, соответственно, для возбуждения реальных сил притяжения. Практическое значение. Результаты работы позволяют сформулировать обоснованные рекомендации по созданию и практическому применению линейных инструментов магнитно-импульсного притяжения в прогрессивных технологиях восстановления повреждённых участков корпусных покрытий из тонкостенных листовых металлов с высокой удельной электропроводностью. Библ. 10, рис. 4.

Ключевые слова: **металлы с высокой удельной электропроводностью, интенсивное проникновение поля, магнитно-импульсное притяжение проводников с однонаправленными токами, линейный инструмент устранения вмятин в корпусных покрытиях.**

Introduction. The growing interest in advanced environmentally friendly high-performance technologies based on the use of pulsed magnetic field energy is due to the practical needs of various branches of modern industry, including not only the production of nomenclature products, but also their recovery from damage during operation [1-3].

An extensive sector of processing technologies, the development of which is determined by the requirements of, for example, vehicle manufacturers, combines a set of methods for the restoration of metal coatings of the elemental base of their hull components. The demand for such technologies follows from the negatives of operational practice. So, dents on the surface of the aircraft lead to a change in its aerodynamic characteristics and a number of possible emergency situations. Damage to the bodies of water and land vehicles is not only a violation of aesthetics. In some force majeure circumstances, they can cause crashes on the water and deaths on the roads [4].

Literature review. Well-known and widespread mechanical dent-cleansing technologies are simple and relatively cheap to implement. But their performance, reliability, quality and environmental performance remain very low. So, quite often, the mechanical pulling of a dent metal leads to a violation of its integrity. The problem that has arisen requires its own separate approach to solving it.

Using the energy of pulsed magnetic fields opens up new possibilities for creating progressive restoration technologies that are free from the above disadvantages. Among them, the elimination of dents using linear tools of magnetic-pulse attraction of damaged sections of thin-walled sheet metal coatings of automobile bodies, airframes and water vehicles. The effectiveness of such tools is based on Ampere law, according to which conductors with unidirectional currents experience mutual attraction [5, 6]. Structurally, such conductors in a linear tool are the main current lead (an analog of an inductor in traditional magnetic pulse metal processing [1, 3]) and a restored area of damaged metal. Geometrically, they (current lead and processed metal) are parallel. Electrically, their connection with respect to common point contacts with a high-voltage power source can be parallel or serial [1, 7, 8]. As follows from physical considerations, the main obstacle to the effective excitation of the electrodynamic forces of interaction between the conductors in such a system is the induction effects, and, respectively, which the current in the main current lead induces a countercurrent in the sheet workpiece, and the current in its metal induces a countercurrent in the main conductor.

In general, the main advantages of a linear tool of magnetic-pulse attraction of sheet metals are, first of all, the simplicity of technical implementation, high production rates and the reliability of the production operation performed (in the sense of preservation of the restored object) [8]. Among the promising technologies of magnetic-pulse attraction of sheet metals, allowing the restoration of damaged areas from the outside of the vehicle bodies, it is worth noting the theoretically and experimentally sound proposals formulated by the authors of [9, 10].

Concluding our review of publications on this topic, we emphasize the versatility of magnetic-pulse power tools on sheet metals with various electrophysical characteristics. The objects of processing can be not only of steel, but also of aluminum alloys. Moreover, the latter are increasingly used for the manufacture of light and durable technical structures for various purposes. From the physical point of view, the noted universality is provided by the possibilities of adjusting the operating frequencies from the source of the acting electromagnetic fields, which allows the attraction or repulsion of predetermined sections of sheet metals in any stamping and restoration production operations [1, 3, 7].

The goal of the paper is determination of conditions and performance assessment of linear tools of magnetic-pulse attraction of specified sections of sheet metals with a high value of electrical conductance.

To achieve this goal, it is necessary to calculate the characteristics of electrodynamic processes while lowering the operating frequencies of current pulses, which, physically, allows to vary the intensity of the penetration of excited fields into the metal elements of the object of study. The result of the calculations should be the numerical estimates and the physical and mathematical illustrations necessary to determine the conditions for the effective excitation of electrodynamic forces in the working areas of linear tools of magnetic-pulse attraction. In fairness, it should be noted that a similar problem has already been considered by the authors of publications [7, 8]. However, the direct use of the formulas obtained by them for calculations and analysis of the ongoing processes is not possible due to the limited results found in [7, 8] for the formulation and solution of the problems under consideration.

In solving this problem, we use the physic-mathematical model of the magnetic-pulse attraction tool under study and the functional dependencies for the characteristics of the ongoing electrodynamic processes described in [6]. For clarity of the further presentation, we indicate the main provisions, partially repeating the publication material [6].

Accepted assumptions and problem definition:

- schematic diagrams of the implementation of magnetic-pulse attraction of thin-walled metals in linear tools, as well as the calculation model (cross section of the system under study) are presented in Fig. 1;
- non-magnetic sheet metal (for example, aluminum or its alloys) with sufficiently large transverse dimensions, the thickness d and the electrical conductance γ is subject to attraction;
- there is geometric symmetry with respect to the ZOX coordinate plane. Along the abscissa axis OX, the system under study has a sufficiently large extent, so that the corresponding differentiation operator is $\partial/\partial x = 0$;
- in the main current lead connected to the high-voltage power source and in a parallel section of sheet metal, exciting currents with given amplitude-temporal characteristics flow only in the longitudinal direction (Fig. 1,*b*).

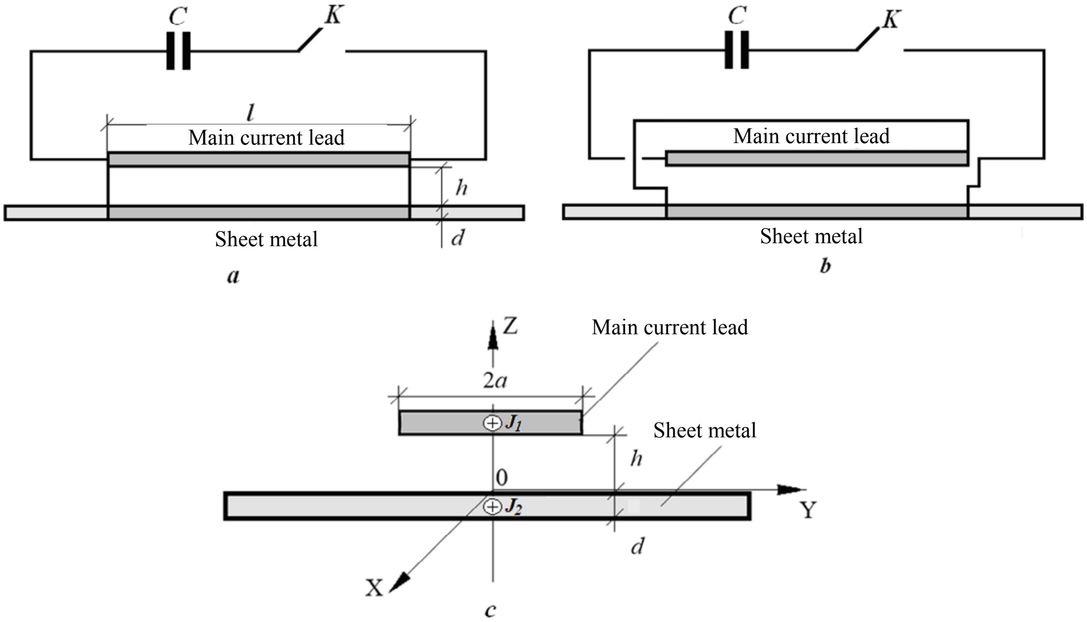

Fig. 1. Linear tools of magnetic-pulse attraction of thin-walled sheet metals:
a – circuit diagram of parallel connection, *b* – circuit diagram of serial connection; *c* – calculation model;
C – capacitive energy storage, *K* – switch; $J_{1,2}$ – flowing currents in the current lead and the metal being processed

Solution algorithm. As follows from the assumptions made, nontrivial components of the electromagnetic field vector are excited in the system under study: $E_x \neq 0$, $H_{y,z} \neq 0$, which are found by integrating the Maxwell equations.

From Ohm law in differential form, the currents induced in the main current lead and the corresponding section of the sheet metal are determined from the known electric field strength. The superposition of the current from the high-voltage power source and the induced current makes it possible to find the amplitude-temporal characteristics of the total currents in each of the conductive elements of the linear tool of magnetic-pulse attraction.

To maximize the force interaction of the conductors, the currents flowing in them should be the same (this condition is practically ensured by the appropriate choice of the parameters of the linear tool). In this case, according to Ampere law, the force of attraction, excited in the working area between the main current lead and sheet metal, is found as a value proportional to the square of the currents flowing in them.

Omitting the cumbersome calculated analytical dependences rather strictly justified and given in [6], we turn to numerical estimates of the characteristics and analysis of processes in a linear tool of magnetic-pulse attraction.

Numerical estimates are carried out for the following initial data:

1. Aluminum sheet samples with thickness of d = 0.0008 m and the specific conductance of $\gamma = 3.75 \cdot 10^7$ 1/Ω·m are subject to deformation.
2. The tool's main current lead is also made of aluminum of the same thickness as the object being processed (the electrodynamic system «aluminum-aluminum» is considered).
3. The length and width of the working area l = 0.06 ... 0.1 m and $2a$ = 0.01 m, respectively, the distance between the conductors of the linear tool is h = 0.002 m.
4. The main current lead and the given section of the metal being processed are identical, geometrically and electrically parallel, so that the exciting currents flowing in the circuit of each of them are the same.

Note. According to Ampere law, the last initial premise makes it possible to achieve maximum forces of interaction of conductors with unidirectional currents [5, 6].

The parameters of current pulses are determined by the characteristics of the power source – magnetic pulse installation МИУС-2 [2], developed and created at the Laboratory of Electromagnetic Technologies of the Department of Physics of Kharkiv National Automobile and Highway University [1]. We assume that for the specified electrical installation:

1. The maximum voltage on the capacitive storage is U = 2000 V.
2. The natural operating frequency (in a short-circuit discharge circuit) is f_{max} = 7000 Hz and the relative attenuation coefficient is $\delta/\omega = 0.3$.
3. The temporal shape of the exciting current in the attraction operation is an aperiodic unipolar signal with operating frequency of f_p = 1000 ... 1500 Hz and the relative attenuation coefficient of $\delta/\omega \approx 0.3$.
4. The tool is connected to the power source through a matching device, providing a decrease in the operating frequency to the required value, with the coefficient of energy transfer to the working area of $K \approx 4$.

The calculations were carried out similarly to how it was done in [6] using standard programs from the Wolfram Mathematica package. Separately, it should be pointed out that the mathematical rigor of the performed calculations (with an average error up to ~ 7.5 %) was established by the appropriate choice of the intervals of numerical integration and the number of terms in the sums of discrete expansions in the expressions for the characteristics of the electromagnetic processes under study.

Graphs of excited currents and electrodynamic attractive forces depending on their phase ($\varphi = \omega \cdot t$, ω is the circular frequency, t is time) are presented in Fig. 2-4.

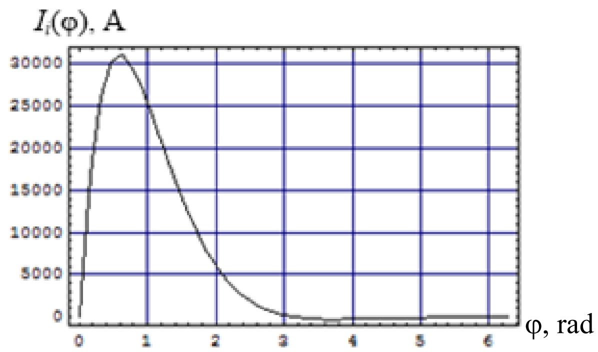

Fig. 2. Excitation current from a high voltage power source

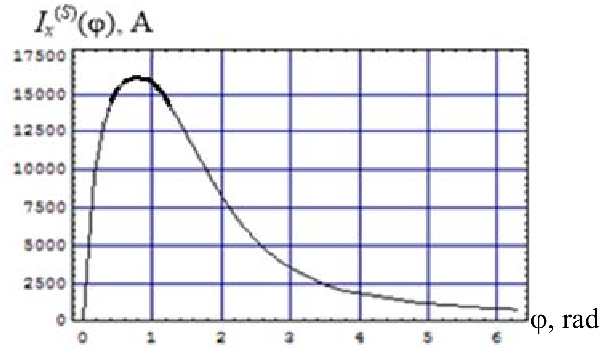

Fig. 3. Total current in each of the conductors of the linear tool

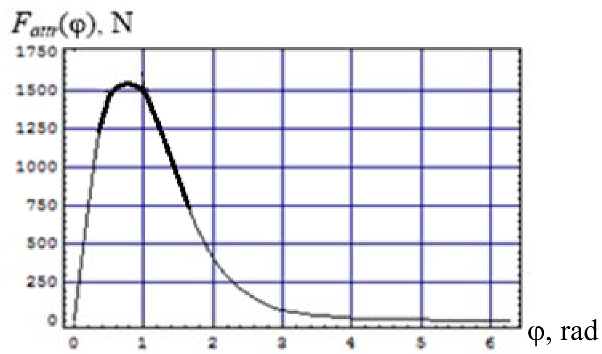

Fig. 4. Excited magnetic-pulse attraction force

An analysis of the results of the calculations shows that:

• in the accepted operating conditions of a linear instrument, induction effects have a significant influence on electromagnetic processes in the conductors of the system under study;

• the amplitude of the total current in the main current lead and sheet metal decreases and is up to ~ 49 % of the current amplitude from a high-voltage power source (~ 32 kA – source, ~ 15.7 kA – induced current, ~ 16.3 kA – total current);

• the amplitude of the excited attractive force is close to ~ 1520 N;

• under accepted conditions, this force indicator should provide magnetic-pulse attraction of sheet aluminum (metal with high electrical conductance) using the linear tool under consideration [3];

• an appropriate choice of the geometry of the working zone and the temporal characteristics of the exciting current makes it possible to obtain fairly close numerical indicators of electrodynamic processes in the system under study when working with both aluminum and steel [6].

Conclusions.

1. On the example of aluminum processing, the performance conditions of linear tools of magnetic-pulse attraction of specified sections of sheet metals with high value of electrical conductance are determined.

2. It has been established that successful magnetic-pulse attraction is possible at sufficiently low operating frequencies of exciting currents (~ 1500 Hz), which provides intensive penetration of electromagnetic fields into the conductors of the tool of the production operation and the excitation of powerful forces of magnetic pressure from the outside.

3. It is shown that, under the accepted conditions, induction effects have a significant influence on electromagnetic processes in the conductors of a linear tool and reduce the excited currents by ~ 45 % relative to the current from the high-voltage power source.

Acknowledgment.

The work was carried out by the Department of Physics of Kharkiv National Automobile and Highway University in the framework of the Research Project «Energy-saving low-cost technologies of power supply and repair of vehicles» No. 08-53-19, funded by the Ministry of Education and Science of Ukraine.

REFERENCES

1. Batygin Yu.V., Chaplygin E.A., Shinderuk S.A., Strelnikova V.A. The main inventions for technologies of the magnetic-pulsed attraction of the sheet metals. A brief review. *Electrical engineering & electromechanics*, 2018, no.3, pp. 43-52. **doi: 10.20998/2074-272X.2018.3.06.**

2. Eguia I., Mangas A., Iturbe R., Gutierrez Ma.A. Electromagnetic forming of longitudinal strengthening ribs in roll formed automotive profiles. *Proceedings of 4th International Conference on High Speed Forming. ICHSF 2010, Columbus*, 2010, pp. 198-207. **doi: 10.17877/DE290R-12593.**

3. Psyk V., Risch D., Kinsey B.L., Tekkaya A.E., Kleiner M. Electromagnetic forming – A review. *Journal of Materials Processing Technology*, 2011, vol.211, no.5, pp.787-829. **doi: 10.1016/j.jmatprotec.2010.12.012**.

4. *Welcome to BETAG Innovation*. Available at: http://www.betaginnovation.com (accessed 17 June 2018).

5. Landau L.D., Lifshits E.M. *Elektrodinamika sploshnyh sred T. 8* [Continuum Electrodynamics. Vol.8]. Moscow, Fizmatlit Publ., 2005. 656 p. (Rus).

6. Batygin Yu.V., Chaplygin E.A., Shinderuk S.A., Strelnikova V.A. Numerical estimates of currents and forces in linear tools of the magnetic-pulse attraction of metals. Part 1: Low electrical conductance metals. *Electrical engineering & electromechanics*, 2019, no.5, pp. 40-44. **doi: 10.20998/2074-272X.2019.5.07.**
7. Batygin Yu.V., Chaplygin E.A., Shinderuk S.A. Calculation of fields and currents in the induction system with the attractive screen and the additional coil as a tool for the straightening. *Electrical engineering & electromechanics*, 2015, no.1, pp. 57-62. (Rus). **doi: 10.20998/2074-272X.2015.1.11**.
8. Batygin Yu.V., Chaplygin E.A., Sabokar O.S. Magnetic pulsed processing of metals for advanced technologies of modernity – a brief review. *Electrical engineering & electromechanics*, 2016, no.5, pp. 35-39. **doi: 10.20998/2074-272X.2016.5.05**.
9. Gnatov A., Argun S. New method of car body panel external straightening: tools of method. *International Journal of Vehicular Technology*, 2015, vol.2015, pp. 1-7. **doi: 10.1155/2015/192958.**
10. Hnatov A., Arhun S., Dziubenko O., Ponikarovska S. Choice of electric engines connection circuits in electric machine unit of electric power generation device. *Majlesi Journal of Electrical Engineering*, 2018, vol.12, no.4, pp. 85-93.

Received 19.04.2019

Yu.V. Batygin[1], *Doctor of Technical Science, Professor,*
E.A. Chaplygin[1], *Candidate of Technical Science, Associate Professor,*
S.A. Shinderuk[1], *Candidate of Technical Science, Associate Professor,*
V.A. Strelnikova[1], *Postgraduate Student,*
[1] Kharkiv National Automobile and Highway University,
25, Yaroslava Mudrogo Str., Kharkov, 61002, Ukraine,
phone +380 57 7003852,
e-mail: yu.v.batygin@gmail.com; chaplygin.e.a@gmail.com; s.shinderuk.2016102@ukr.net; v.strelnikova91@gmail.com

How to cite this article:
Batygin Yu.V., Chaplygin E.A., Shinderuk S.A., Strelnikova V.A. Numerical estimates of currents and forces in linear tools of the magnetic-pulse attraction of metals. Part 2: High electrical conductance metals. *Electrical engineering & electromechanics*, 2019, no.6, pp. 39-43. **doi: 10.20998/2074-272X.2019.6.05.**