Consideration of the Magnetic Field Penetration through the Blank Wall in the Processes of Pulse-Magnetic Forming

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Abstract

The results of the investigation of the effect of the magnetic field penetration through a blank wall on the necessary parameters of the pulse-magnetic forming are presented in this paper. The purpose of the work is to determine the permissible scope of engineering techniques for calculating the processes of pulse-magnetic forming of thin-walled parts. Process studies include conducting experiments, calculating by engineering methods and computer simulation of the process using LS-DYNA. As a result of the research it has been established that the engineering technique allows calculating the processes with sufficient accuracy at a blank thickness exceeding the value of the penetration depth of the pulse magnetic field into the blank material.

Keywords

Pulse-magnetic forming, thin-walled parts, skin depth, magnetic field penetration

Introduction

The phenomena occurring in the system "inductor – blank being processed" are very complex. In this regard, the development of an exact universal methodology for calculating the processes of pulse-magnetic processing of metals (PMPM) is associated with considerable difficulties. Therefore, analytical calculations and numerical modeling of PMPM processes are usually carried out on simplified models under assumptions regarding the parameters of the pulse-magnetic generator discharge circuit and the magnetic field in the insulating gap, in the material of the inductor and the blank, and the physical and mechanical properties of the inductor and blank materials [1].

The most accurate results are obtained by numerical simulation of the processes, since it uses the least number of simplifying assumptions. In recent years, numerical simulation of various PMPM processes is most often performed using LS-DYNA, which allows taking into account the phenomena of electromagnetism, heat and mechanics [2].

However, the use of digital simulation of PMPM processes allows solving only the direct problem, that is, to determine the results of the operation under the specified initial parameters of the process. In addition, it takes quite a long time. So the generator time for calculating one version of the technological process of PMPM using a complex LS-DYNA on a modern personal computer is several hours. The volume of calculations can be significantly reduced if we first estimate the boundaries of the search area for optimal initial process parameters using simplified engineering techniques. At the basis of most engineering techniques is the calculation of analytical formulas, so the time for calculating the process on a personal computer does not exceed a few seconds. Engineering techniques can be used to develop industrial technology with subsequent experimental development of the process.

The aim of the work is to determine the area of acceptable use of one the engineering techniques, the main elements of which are described in [3].

Methods

This calculation method is based on the assumption that the blank's part being deformed is accelerated during t_p, equal to 3/8 of the period of oscillation of the discharge current T, and further deformation of the blank occurs due to the kinetic energy accumulated at the site of acceleration. This assumption is made due to the fact that according to the results of numerous theoretical and experimental studies, described, for example, in [4], in pulse-magnetic processing the blank gets the maximum speed by this time. This is due, firstly, to the fact that by this time the value of current in the inductor is significantly lower than its amplitude value and secondly, the gap between the inductor and blank's part being deformed reaches the values at which the efficiency of power action of the magnetic field on the blank is quite small.

The calculation of mechanical characteristics of the process is carried out using power approximation of the hardening curve.

$$a_s = \frac{B_d}{1+m_m} \varepsilon_s^{1+m_m} \tag{1}$$

where $\boldsymbol{\varepsilon_s}$ – the degree of deformation, average over the blank's surface being deformed; $\mathbf{B_d}$ and $\mathbf{m_m}$ – coefficients of power approximation of the hardening curve.

Formulas for calculating the average degree of deformation of the blank for different forming operations are taken from the work [5].

$$V_c = \sqrt{\frac{2a_s}{\rho}} \tag{2}$$

where $\boldsymbol{\rho}$ – density of the material of the blank.

For sinusoidal law of change of discharge current, the expression for determining the PMF pressure amplitude providing acceleration of the blank to the velocity $\mathbf{V_c}$ by the time $\boldsymbol{\omega t = 0{,}75\pi}$, has the form:

$$P_m = 4{,}4 \cdot V_c \cdot f_w \cdot \rho \cdot s \tag{3}$$

where $\mathbf{f_w}$ – the operating frequency of the discharge current; $\mathbf{s}$ – thickness of the blank.

The amount of movement of the blank $\mathbf{h_a}$ at the end of acceleration stage is

$$h_a = 0{,}141 \frac{V_c}{f_w} \tag{4}$$

The value of the operating frequency of the discharge current $\mathbf{f_w}$ is determined when calculating the parameters of the inductor. This model can be used if the gap between the blank and die or mandrel exceeds the value $\mathbf{h_a}$ from the **Eq. 4**.

In the PMPM processes, to regulate the pressure distribution along the length of the blank, schemes are often used in which the inductor length is longer than the length of the blank zone being processed. In this case, the part of the inductor turns appears to be uncovered by the blank as it is shown in **Fig. 1a** [7].

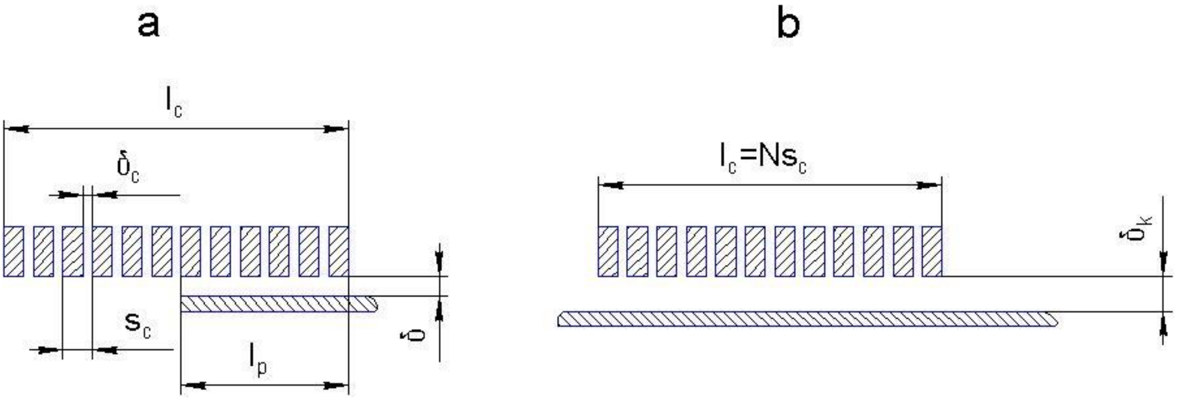


***Figure 1**: Scheme for calculation of the gap between the inductor and blank*

To account for the effect of free turns of the inductor, the following technique can be used. The scheme of mutual arrangement of the inductor and blank, shown in **Fig. 1a**, is replaced by the scheme presented in **Fig.1b**, that is, it is accepted that the blank completely overlaps the inductor. But the value of the insulating gap between the inductor and blank $\boldsymbol{\delta}$ increases to the value $\boldsymbol{\delta_k}$, that is evaluated by the **Eq. 5**:

$$\delta_k = \frac{\delta_e \cdot N_w + \sum_1^{N_f} \sqrt{(s_c \cdot (N_f - 1))^2 + \delta^2}}{N} \tag{5}$$

where $\boldsymbol{\delta_e}$ – value of the equivalent gap between the inductor and blank; $\boldsymbol{\delta}$ – value of geometrical gap between the inductor and blank; $\mathbf{N_w}$ and $\mathbf{N_f}$ – number of operating and free turns of the inductor, respectively; $\mathbf{N=N_w+N_f}$ – the total number of turns of the inductor; $\mathbf{s_c}$ – pitch of the turns of the inductor.

Analysis of the scheme of replacement of the inductor, which operates according to the expansion scheme, made it possible to obtain the formula for the coefficient $\mathbf{k_e}$, taking into account the loss of energy to create the field in the inner hollow of the inductor, in the following form:

$$k_e = (2\frac{R_c}{R_i} \cdot \frac{\delta_e}{R_i} + 1)^2 \tag{6}$$

where $\mathbf{R_c}$ and $\mathbf{R_i}$ – external and internal diameters of the inductor.

The **Eq. 7** for calculation of the required energy of discharge of the pulse-magnetic installation takes the following form [3]:

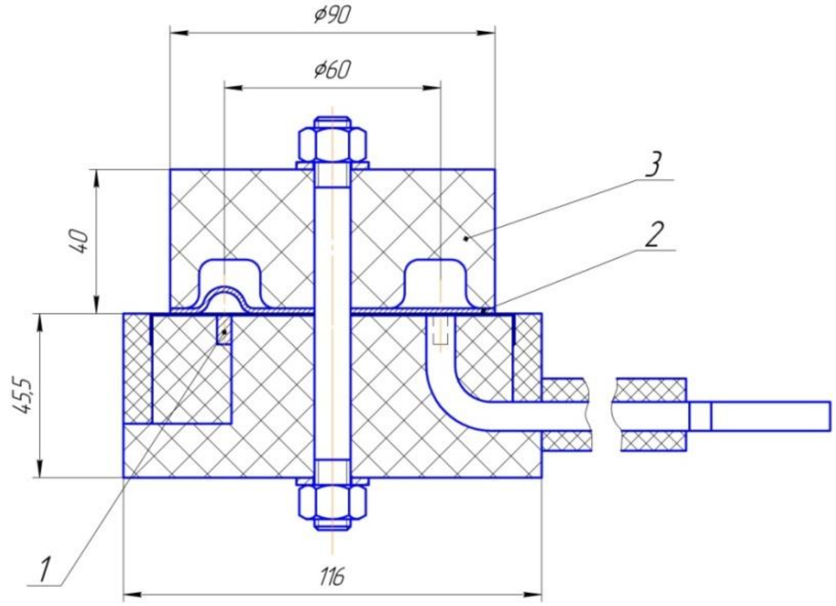
$$W = \frac{P_m \cdot \Omega \cdot (\delta_k + 0{,}5\mathrm{h_a}) \cdot \mathrm{k_e}}{K_1 \cdot K_2 \cdot K_3 \cdot K_4} \tag{7}$$

where $\mathbf{\Omega}$ – area of the zone being processed.

The coefficients, included in the Eq. 7, characterize parasitic energy losses in the system “installation-inductor-blank”. The coefficient $\mathbf{K_1}$ takes into account inductive losses in the PMI, $\mathbf{K_2}$ – active losses in the inductor and blank, $\mathbf{K_3}$ – edge effects, i.e. non-uniformity of the field in the volume $\mathbf{\Omega \cdot \delta_e}$, $\mathbf{K_4}$ – penetration of the field through the blank material. Approaches to the calculation of these coefficients are described in the work [7].

But this technique does not take into account the impact of penetration of the pulsed magnetic field through the blank wall when forming of thin-walled blanks with the wall thickness less than the depth of penetration of the magnetic field into the blank material. Therefore the complex of researches of the process of forming an annular rift on sheet aluminum blanks of different thickness was carried out. The complex included performance of experiments, calculation of the value of discharge energy of the pulsed-magnetic installation, required to form the height of the annular rift obtained by the engineering technique, and simulation of the process with the help of LS-DYNA.

The scheme of the experiments is shown in **Fig. 2**, where the original form of the part is shown to the right of the symmetry axis, and the form of the part for the operation is shown to the left.



1 – inductor; 2 – blank; 3 – die

***Figure 2**: The scheme of the experiment*

The experiments were carried out with the help of a single-turn inductor 1, which allowed obtaining the annular rift on a sheet blank 2. The diameter of the centers of the rift was 60 mm. Thickness of the sheet blanks from aluminum alloy 8011 A was from 0.18 to 1.5 mm. The experiments were carried out with the use of the installation with the following parameters: capacity of the capacitor bank C = 101 μF; internal inductance L_0= 89μHn, the frequency of short-circuit current f_0= 53 kHz. Forming of the annular rift was performed in three modes for each blank thickness. Such processing modes were chosen which excluded the possibility of collision of the blank 2 with the inner surface of the die 3. During the experiments, parameters of the discharge current flowing through the inductor were measured. These parameters were used in modeling of the process with the help of LS-DYNA.

Results

Fig. 3 shows the results of the discharge current measurements.

Processing the results of measurements of the discharge current parameters shows that the operating frequency of the discharge current $\mathbf{f_w}$ is independent of the thickness of the blank and is 36.9 kHz. The deviation of the measured values from this value does not exceed 3%. Consequently, the penetration depth of the pulse magnetic field into the blank material makes up b_p= 0.44 mm. The value of the working frequency of the discharge current, obtained during the calculation by the engineering technique, is 37.4 kHz.

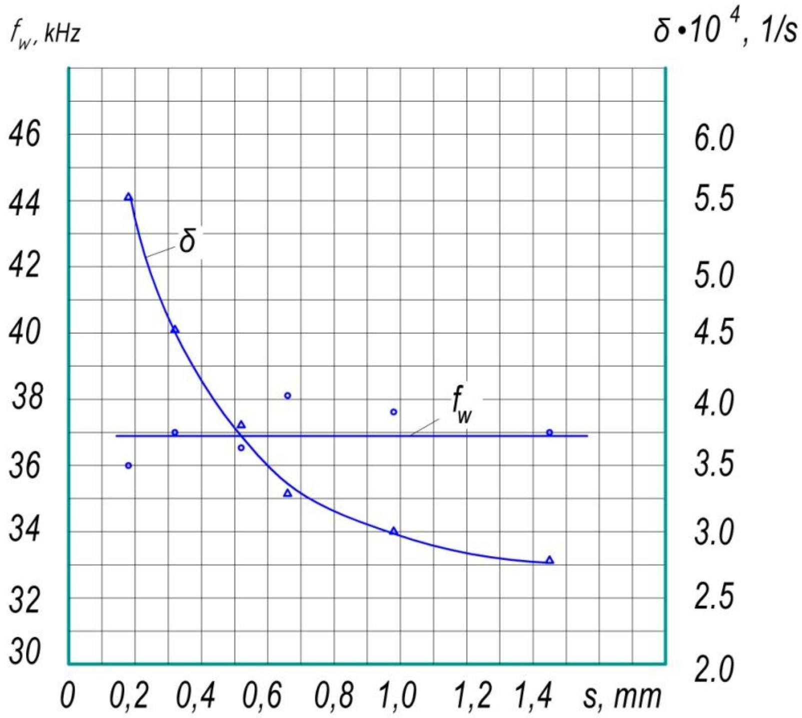


Figure 3*: Dependence of the oscillation frequency and decrement of the discharge current damping on the thickness of the blank*

It follows from the measurement results shown in Fig. 3 that the current attenuation decrement increases significantly as the thickness of the blank decreases which is explained by the increase in the active resistance in the blank.

After the performance of the experiments, the rift height was measured, discharge energy of the pulse-magnetic installation, required to obtain this rift height, was calculated by engineering technique and was compared with the experimental value. The results of the comparison of values of discharge energy of the installation obtained in the experiment $\mathbf{W_t}$ and calculated by the engineering technique $\mathbf{W_c}$, which provide the same height of the rift, are presented in **Fig. 4**.

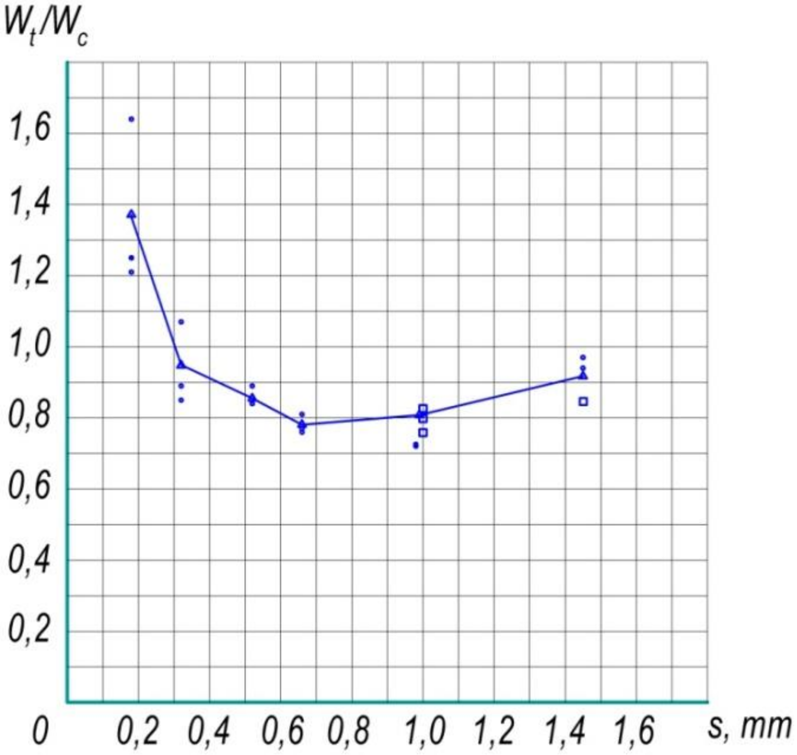


***Figure 4**: Dependence of the ratio of the experimental and calculated values of discharge energy on the thickness of the blank*

The analysis of the results obtained, shows that with the thickness of the blank exceeding the value of the depth of the magnetic field penetration into the material of the blank, the calculation by the engineering technique gives fairly accurate results. If the thickness of the blank is less than the value of the skin layer, then the error value becomes significant, and, in addition, in this region it essentially depends on the magnitude of the deformation or the energy supplied. With increasing energy supplied to the inductor, the value of the calculation error increases. The results of modeling the process with the LS-DYNA complex show that the ratio between the intensity of the pulse magnetic field on the surface of the blank facing the inductor and on the surface opposite from the inductor when processing blanks having a thickness smaller than the skin layer in the material not dependent on the energy of the discharge. Therefore, it can be assumed that the growth of the calculation error by the engineering method with increasing energy input is related to the heating of the blank and, as a consequence, to a drop in the resistance to deformation. In order to be able to calculate the processes of deformation of semi-finished products by means of an engineering technique, further research is needed.

Simulation of the process with the LS-DYNA complex has yielded the results that are in conform with measurements of the height of the corrugation obtained during the experiments. To describe the material of the blank, the Cowper-Symonds model is used. Table 1 show the characteristics of the blank and inductor materials, and Table 2 shows the parameters of the Cowper-Symonds model for the aluminum alloy 8011A.

Material	Part	Density (*kg/m3*)	Young’s modulus (*GPa*)	Poison ratio	Electrical conductivity (*S/m*)	Specific heat capacity (*J/kg.K*)	Thermal conductivity (*W/m.K*)
8011A	Blank	2700	71	0.35	3.42×10^7	950	237
Copper alloy	Coil	8960	123	0.35	5.62×10^7	1000	401

Table 1: *Mechanical, thermal and EM properties of materials used in this model for individual parts Material*

Cowper-Symonds parameters	*K (MPa)*	*n*	*C*	*p*
Numerical values	315	1	6500	3

Table 2: *Cowper-Symonds parameters used for the aluminum alloy 8011A*

Figure 5, for example, shows the resulting corrugation with a blank thickness of 0.18 mm.

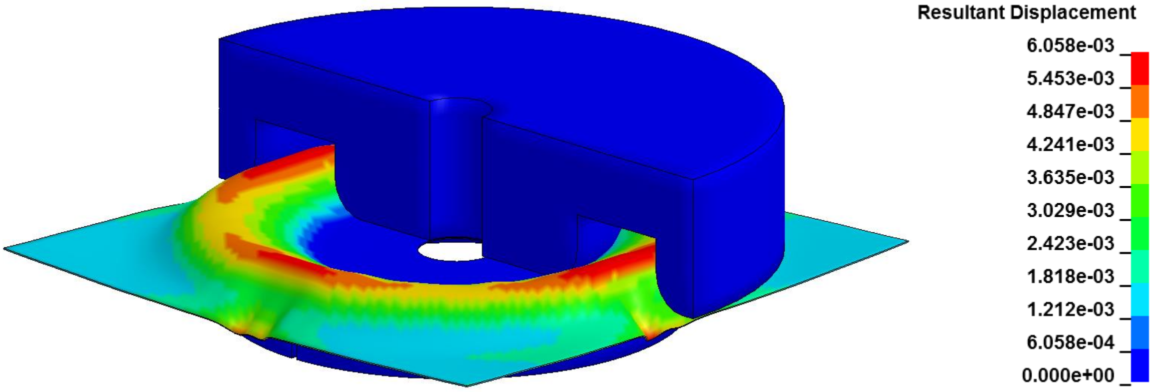


Figure 5*: The height of corrugation*

The difference between the calculated and obtained heights of the corrugation in the experiments is quite close and completely conforms with the accuracy of the initial parameters of the process. In this case, the spread of the difference between the calculated and measured values of the height of the corrugation varies within narrow limits throughout the entire range of variation in the thickness of the blanks and processing regimes.

Acknowledgments

The research conducted allowed making the following conclusions.

1. The engineering technique allows calculating with sufficient accuracy the processes of pulse-magnetic forming with a blank thickness that exceeds the depth of the magnetic field penetration into the blank material.

2. To expand the capabilities of the engineering methodology, further research should be implemented.

3. The LS-DYNA complex makes it possible to simulate the processes of pulse-magnetic forming with the blank thickness much less than the penetration depth of the magnetic field into the blank material.

References

Глущенков В.А., Карпухин В.Ф., 2014. Технология магнитно-импульсной обработки материалов: монография - Самара: Издательский дом "Федоров". – 208 с.

L'Eplattenier P., Cook G., Ashcraft C. Introduction of an Electromagnetism Module in LS-DYNA for Coupled Mechanical Thermal Electromagnetic Simulations, High Speed Forming 2008, Dortmund, Germany, pp. 85-96.

Карпухин В.Ф., 2012. Определение параметров магнитно-импульсной формовки. Вестник Самарского государственного аэрокосмического университета имени академика С.П. Королева (национального исследовательского университета). №5 (36), часть 1. – С. 228-232.

Горкин Л.Д., Хименко Л.Т., 1984. Экспериментальные исследования процесса магнитно-импульсной обработки металлов. Кузнечно-штамповочное производство. №7. – С. 4-6.

Belyy I.V., Fertik S.M., Khimenko L.T. Electromagnetic Metal Forming Handbook. Vischa Shkola, Khar'kov State University, Polytechnics Institute, Khar'kov, USSR. A translation of the Russian book: Spravochnik po Magnitno-Impulsnoy Obrabotke Metallov by Altynova M.M. At The Ohio State University, Materials Science Engineering Department, 1996.

Karpukhin V.F., Glouschenkov V.A., Voinov A.K., Al-Erhayem O., 1997. Pulse-magnetic welding of rings from aluminium alloys with steel pipes for cathodic protection of welded butts of pipelines. International conference on the joining of materials JOM-8. – Helsingor, Denmark. – p. 565-566.

Барвинок В.А., Кирилин А.Н., Комаров А.Д., 2002. Высокоэффективные технологические процессы изготовления трубопроводных и топливных систем летательных аппаратов. – М.: Наука и технологии. – 394 с.