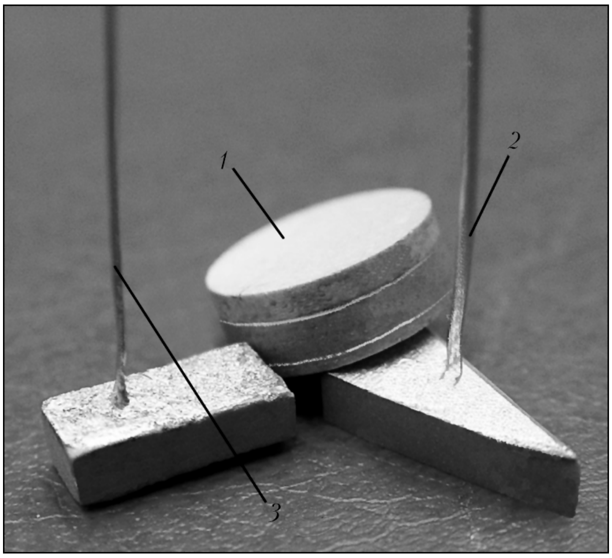

Figure 3. Brazing and metallization of $BaTiO_3$ ceramics using metal-oxygen technology: *1* — ceramics–ceramics joint; *2* — platinum wire–ceramics; *3* — silver wire–ceramics

homogeneity of the coating was preserved. Specimens of the metallized $BaTiO_3$ ferroelectric ceramics are presented in Figure 2.

Using the metal-oxygen technology brazed joints of the $BaTiO_3$ ferroelectric ceramics, brazed with each other and with metal electrodes, were produced (Figure 3).

So, for the first time wetting of the $BaTiO_3$ ceramics in pure oxygen was investigated. Application of oxygen environment at pressure 100 kPa intensifies capillary properties of the Ag–Cu–O system melts and reduce contact wetting angle up to full spreading at content 7–10 at.% Cu in the melt.

On basis of the data obtained the metal-oxide technology for metallization and brazing of the $BaTiO_3$ ceramics in air and pure oxygen was developed.

1. Rubashov, A.M., Berdov, G.I., Gavrilov, N.V. et al. (1980) *Heat-resistant dielectrics and their brazed joints with metals in new engineering*. Moscow: Atomizdat.
2. Bursian, E.V. (1974) *Nonlinear crystal (barium titanate)*. Moscow: Nauka.
3. Najdich, Yu.V., Sidorenko, T.V., Durov, A.V. (2007) Processes of metallization and brazing of perovskite ceramics on the base of barium titanate. *Adgeziya Rasplavov i Pajka Materialov*, **40**, 63–69.
4. Eremenko, V.N., Najdich, Yu.V. (1959) Wetting of oxide surfaces by metal-oxygen solutions. *Elektronika*, **4**, 136.
5. Eremenko, V.N., Najdich, Yu.V., Nosonovich, A.A. (1960) Surface activity of oxygen in copper-oxygen system. *Zhurnal Fiz. Khimii*, 34(**5**), 1018.
6. Najdich, Yu.V., Eremenko, V.N. *Method of brazing of ceramic parts*. USSR author's cert. 149020. Int. Cl. 49 H 25. Publ. 05.08.62.
7. Najdich, Yu.V. (1972) *Contact phenomena in metallic melts*. Kiev: Naukova Dumka.
8. Erskine, K.M., Meier, A.M., Pilgrim, S.M. (2002) Brazing perovskite ceramics with silver/copper oxide braze alloys. *J. Mater. Sci.*, **37**, 1705.
9. Najdich, Yu.V., Sidorenko, T.V. (2008) Processes of wetting of perovskite $BaTiO_3$-ceramics by metallic melts. *Dopovidi NAN Ukrainy*, **9**, 99–104.

IMPROVED METHOD FOR CALCULATING MAGNETIC-PULSE WELDING CONDITIONS

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The method for calculating magnetic-pulse welding conditions is suggested allowing for changes of inductivity of the parts being joined at their relative displacement. It is shown that it has to be used in those cases when energy necessary for processing of the metals constitutes a significant portion of the energy accumulated in the capacitor bank (for example, for joining parts of big diameter).

Keywords: *magnetic-pulse welding, inductivity of parts, method of calculation, optimum welding conditions*

In [1] a simplified method for calculating magnetic-pulse welding (MPW) conditions is suggested with complex application of analytical and numeric methods of calculation on a personal computer.

Below the attempt is made to develop an improved method for analysis of the processes occurring in MPW of cylindrical pipes with a single-turn inductor (Figure 1) which most fully correspond to the real processes. It is assumed that at a discharge of the capacitor bank on the inductor and in process of movement of the flyer part inductance of the discharge circuit increases, whereby movement of the pipe starts at the instant in which its material achieves state of plasticity.

Time of the capacitor bank discharge is divided into small sub-intervals of Δt duration, and all parameters of the discharge circuit in each such n-th time sub-interval are assumed invariable.

Values of all necessary parameters at the end of the first sub-interval Δt are initial conditions for the next time sub-interval. Indices of the parameters indicate their value in certain instants of time. Zero index indicates value of the parameter at the beginning of the first time sub-interval, index 1 — at the end of the first time sub-interval and beginning of the second time sub-interval, etc.

The whole process of the discharge is divided into three time intervals:

I — beginning of the discharge. Pressure on the flyer part is not yet equal to a certain limit value of

P_0. At such value yield strength of the material σ_y is not achieved yet, the flyer part is immovable, and current in each sub-interval is determined according to the formula for the fluctuation process of the capacitor bank discharge, whereby all parameters of the discharge circuit are invariable in the process of the discharge interval;

II — continuation of the capacitor bank discharge process at the pressure higher than P_0 from the instant of beginning of the flyer part motion till the instant of collision. The discharge current in each interval changes according to another law for which first of all non-zero initial conditions and change of inductivity of he flyer pipe are characteristic;

III — discharge process from the instant of collision of the parts till termination of the capacitor bank discharge. For the discharge current in each sub-interval of this interval constancy of the discharge circuit parameters is characteristic, whereby initial value of current and voltage in the capacitor bank corresponds to values of current and voltage at the end of the second time interval of the capacitor bank discharge.

Let us consider the processes which occur in I interval when the flyer part is still immovable. We will use the following dependence for the considered method of calculation [1]:

$$B(t) = \frac{\mu_0 K_R}{b_p}\, i(t), \qquad (1)$$

where $B(t)$ and $i(t)$ are respectively the magnetic induction in the working gap and the discharge current in I interval; μ_0 is the magnetic constant equal to $4\pi \cdot 10^{-7}$ H/m [2]; $K_R = 1 - \frac{\Delta_1}{\pi b_p}\left(1 - e^{-\pi \frac{b_p}{\Delta_1}}\right)$ is the Rogowski coefficient [3].

Pressure of the magnetic field on the flyer part is determined from the expression

$$P(t) = \frac{B^2(t)}{\mu_0}. \qquad (2)$$

Pressure on the flyer part, at which yield strength σ_y of the material is achieved and which depends only upon properties of the material and the geometrical dimensions, is determined from the expression which proceeds from the balance of forces acting on surface of the pipe and in its cross section:

$$P_0 = \frac{\Delta_p}{R_p}\sigma, \qquad (3)$$

where R_p is the mean radius of spread outward area of the flyer part in the welding zone.

Inductance of the discharge circuit L_0 consists of the constant within the capacitor bank discharge time inductance L, which is inductance of the external circuit, and invariable within the time of I interval inductance of the inductor–flyer part system L_{pt0}:

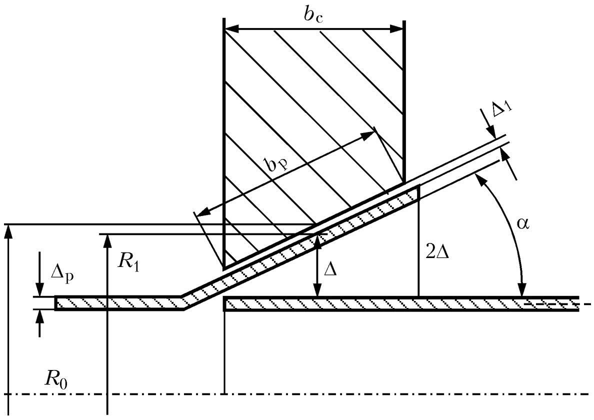

Figure 1. Scheme of MPW implementation at acceleration of pipe area to be deformed: R_0, R_1 — respectively internal diameter of inductor-concentrator and external diameter of flyer part in center of spread outward area; Δ_p — wall thickness of flyer pipe; Δ, Δ_1 — mean values of gap between pipes being joined, as well as between inductor-concentrator and pipe respectively; α — angle of pipe spreading outward; b_p — width of overlapping; b_c — width of working area of inductor-concentrator

$$L_0 = L + L_{pt0},$$

where

$$L_{pt0} = 2\pi \frac{\mu_0 K_R}{b_p} R_p \Delta_1.$$

Angular frequency of the discharge is found from the formula

$$\omega_0 = \sqrt{\frac{1}{CL_0} - \frac{R^2}{4L_0^2}}. \qquad (4)$$

Instant value of the discharge current in I interval is determined from expression [4]

$$i(t) = \frac{U_c}{\omega_0 L_0} e^{-\frac{R}{2L_0}t} \sin \omega_0 t, \qquad (5)$$

where U_c is the capacitor bank initial voltage; R is the discharge circuit active resistance.

By means of the discharge current passage, pressure on the flyer part increases till it gets equal to pressure P_0 determined from formula (3). By substitution in (2) of the expressions (1), (5) and equating $P(t)$ to P_0 value we get after transformations equation for determining t_0 — the time at which pressure on the flyer part achieves the P_0 value:

$$\sqrt{\frac{P_0}{\mu_0}}\, \frac{b_p}{K_R} = \frac{U_c}{\omega_0 L_0} e^{-R\frac{t_0}{2L_0}} \sin \omega_0 t_0. \qquad (6)$$

Transcendent equation relative t_0 (6) is solved by numeric methods using a personal computer.

In II time interval, inductance of the discharge circuit L_n consists of a constant inductance L during discharge of the capacitor bank and inductance of the inductor– flyer part system L_{ptn}. Inductance L_{ptn} in process of the capacitor bank discharge changes in II interval thus changing conditions of the capacitor bank discharge, that's why in the index the interval number is present.

For calculating parameters of welding conditions on the personal computer we find initial conditions for II time interval of the capacitor bank discharge (current i_0, active losses within time of I time interval W_{R_0}, pressure on the flyer part p_0 and the capacitor bank voltage U_0):

$$i_0 = \frac{U_c}{\omega_0 L_0} e^{-\frac{R}{2L_0}t_0} \sin \omega_0 t_0, \quad (7)$$

$$W_{R_0} = \int_0^{t_0} i^2(t) R dt, \quad (8)$$

$$p_0 = \frac{\mu_0 K_R^2}{b_p^2} (i_0)^2, \quad (9)$$

$$U_0 = U_c - \frac{1}{C}\int_0^{t_0} i(t) dt. \quad (10)$$

Initial conditions of other parameters necessary for calculation in II interval equal zero.

In second area the flyer part starts to move. Movement of the part causes increase of the discharge circuit inductance thus changing conditions of the capacitor bank discharge.

When determining regularity of the discharge circuit inductance change, one has to take into account the fact that it consists of the inductance, which within the time of the capacitor bank discharge remains invariable, and the inductance, which increases within the time of the discharge. Constant inductance L is usually known, while variable part of the inductance $L_{pt(n+1)}$ for $(n + 1)$-th interval Δt is found from the expression

$$L_{pt(n+1)} = \pi \frac{\mu_0 K_{R_n}}{b_p} [R_0^2 - (R_1 - S_n)^2], \quad (11)$$

where S_n is the way passed by the flyer part in n-th interval; K_{R_n} is the Rogowski coefficient in n-th interval.

Value of current in II time interval for $(n + 1)$-th time interval is found from formula proceeding from Kirchhoff equation for a considered circuit in n-th time sub-interval:

$$i_{n+1} = i_n + \frac{U_n - i_n R}{L_n}\Delta t, \quad (12)$$

where U_n is the voltage in capacitors in n-th interval.

Pressure on the flyer part in $(n + 1)$-th sub-interval is determined from formula

$$p_{n+1} = \mu_0 \frac{K_{R_n}^2}{b_p^2} i_n^2. \quad (13)$$

Losses in active resistance of the machine discharge circuit in time interval $t = (n + 1)\Delta t$ equal

$$W_{R_{(n+1)}} = R i_n^2 \Delta t + W_{R_n}. \quad (14)$$

Increment of the flyer part velocity within time Δt in the n-th sub-interval is determined from formula

$$\Delta v_n = [p_n - P_0] \frac{\Delta t}{\Delta_p \gamma_p}. \quad (15)$$

Velocity of the flyer part at the end of the $(n + 1)$-th interval is

$$v_{n+1} = v_n + \Delta v_n, \quad v_0 = 0. \quad (16)$$

The way passed by the flyer part at the end of the first sub-interval in II interval is

$$S_{n+1} = S_n + v_n \Delta t, \quad S_0 = 0. \quad (17)$$

Time of the process is determined according to the expression

$$t_{n+1} = t_0 + \Delta t n. \quad (18)$$

Inductance of the discharge circuit at the end of $(i + 1)$-th time sub-interval is

$$L_{n+1} = L + L_{ptn}. \quad (19)$$

Using expressions (11)–(19) for $(n + 1)$-th time sub-interval we make a system of equations for calculating on a personal computer which has the form:

$$\begin{cases} i_{n+1} = i_n \dfrac{U_n - i_n R}{L_n} \Delta t, \\ K_{R_n} = 1 - \dfrac{\Delta_1 + S_n}{\pi b_p} \left(1 - e^{-\pi \frac{b_p}{\Delta_1 + S_n}}\right), \\ p_{n+1} = \mu_0 \dfrac{K_{R_n}^2}{b_p^2} i_n^2 n, \\ W_{R_{(n+1)}} = R i_n^2 \Delta t + W_{R_n}, \\ v_{n+1} = v_n + \left[\mu_0 \dfrac{K_{R_n}^2}{b_p^2} i_n^2 - P_0\right] \dfrac{\Delta t}{\Delta_p \gamma_p}, \\ S_{n+1} = v_n \Delta t + S_n, \\ L_{n+1} = L + \pi\mu_0 \dfrac{K_{R_n}}{b_p} [R_0^2 - (R_1 - S_n)^2], \\ U_{n+1} = U_n - i_n \dfrac{\Delta t}{C}, \\ t_{n+1} = t_0 + \Delta t n. \end{cases} \quad (20)$$

II time interval finishes after the flyer part that passes the way S (mean value of the gap between the pipes being joined) touches the immovable part.

In Figures 2 and 3 the curves are built, from which it follows that the results obtained from the improved method differ approximately by 15 % from the results obtained according to the method that does not take into account change of the inductance, that proves the fact that by means of the pipe diameter increase one has to use the developed methodology.

For determining in a specific case necessary version of the calculation method (without allowing or allowing for inductance change of the parts during welding) it is necessary to calculate value of kinetic energy of the flyer part W_k using the given below formula:

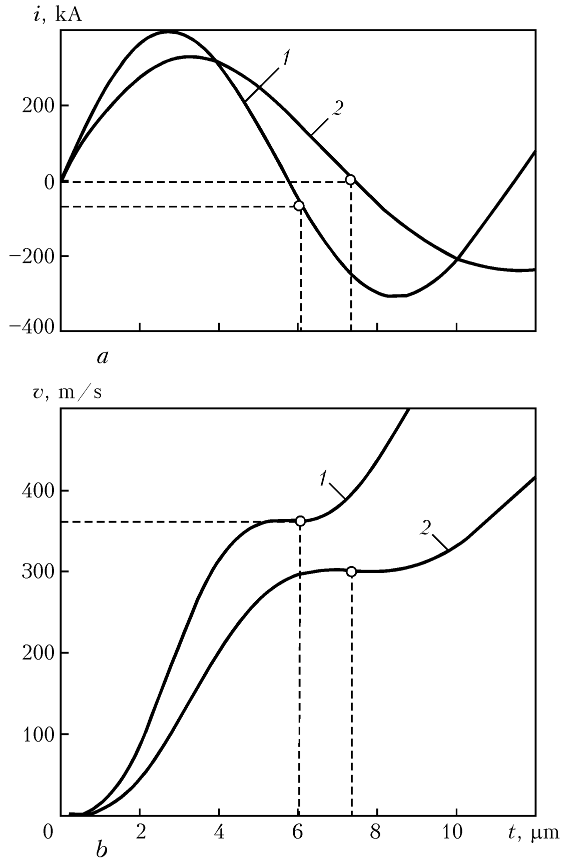

Figure 2. Curves of discharge current (*a*) and speed at acceleration of area to be deformed (*b*) of aluminium pipe of 80 mm diameter: *1* — simplified methodology of calculation [1]; *2* — developed methodology

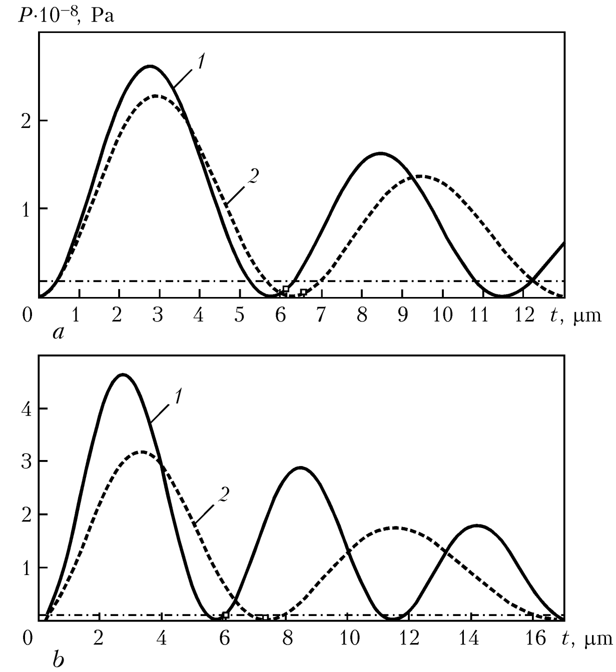

Figure 3. Calculated instant value of magnetic pressure $P(t)$ for pipes from aluminium alloy of 20 (*a*) and 80 (*b*) mm diameter: *1* — curve according to simplified methodology of calculation [1]; *2* — according to developed methodology; dash-dotted curve — according to given methodology

$$W_k = \frac{m v^2}{2}, \quad (21)$$

where

$$m = 2\pi R_p \Delta_p \gamma_p b_p. \quad (22)$$

Comparison of this value with value of the whole accumulated in the capacitor bank energy $W = (C U_c^2)/2$, calculated using the simplified calculation, allows selecting the version of the calculation method. If difference of the energies does not exceed 10 %, one may use method of calculation described in [1]; if difference is more than 10 % it is necessary to use the method suggested in this work which takes into account change of inductance of the parts being joined.

It should be noted that when using considered method for producing quality welded joints, the time of the magnetic field penetration through the flyer pipe should be longer than flight time of the flyer pipe.

CONCLUSIONS

1. Calculation of the MPW conditions with a single-turn inductor in joining of cylindrical pipes of big diameter has to be carried out taking into account change of inductance of the parts being joined, that will allow ensuring high accuracy of calculations in comparison with the known methods and real reflecting processes occurring in the welding.

2. It was determined that the higher is kinetic energy acquired by the flyer part, the higher is amendment ensured by the suggested method of calculation. If amendment is less than 10 %, one may use a simplified method of calculation, if more — the improved one.

3. For ensuring high accuracy of the suggested method for calculating the MPW conditions it is necessary to take into account time when the part starts to move, within which the flyer part is in immovable state till pressure on it still has not yet achieved a certain boundary value, at which yield strength of the material of the parts is achieved.

4. The developed method is fit not just for calculating the MPW conditions, but also for application in related technologies (for example, in pressure processing of metals, etc.).

1. Pismenny, A.S., Pentegov, I.V., Stemkovsky, E.P. et al. (2004) Calculation of modes of magnetic-pulse welding. *The Paton Welding J.*, **11**, 13–16.
2. Key, D., Lebi, T. (1962) *Tables of physical and chemical constants*. Moscow: Fizmatgiz.
3. Vasyutinsky, S.B. (1970) *Problems of theory and calculation of transformers*. Leningrad: Energiya.
4. Paton, B.E., Lebedev, V.K. (1969) *Electric equipment for resistance welding. Theory elements*. Moscow: Mashinostroenie.