Pressure Fields Repeatability at Electrohydraulic Pulse Loading in Discharge Chamber with Single Electrode Pair

J. San Jose[1], I. Perez[1], M. K. Knyazyev[2], Ya. S. Zhovnovatuk[2]

[1] Transport Unit, Tecnalia Research & Innovation, Spain
[2] Department of Aircraft Engine Technology, National Aerospace University “KhAI”, Ukraine

Abstract

The paper is devoted to improvements in technology of electrohydraulic impact forming (EHF) via investigation of stability of high-voltage underwater discharges and pressure fields they generate along surface of a sheet blank.

The experimental research is held with use of conical discharge chamber equipped with one pair of electrodes. Measurements of pressure fields along round flat area are based on application of multi-point membrane pressure gauge (MPG). The tests conditions include wide range of spark gaps with four levels of charge voltage and energy.

The investigation results showed strong influence of geometric parameters of discharge work volume and electric parameters of discharge circuit on repeatability of pressure fields. The spark gap value should be in severe correlation with distance to a sheet blank and dimensions of a loaded area. Parameter “normalised spark gap” is proposed for determination of geometric characteristics of discharge volume.

The results confirm the validity of charge voltage-to-spark gap ratio of 1 kV/mm recommended for approximate setting the gap in order to ensure high pressure generation. This ratio is also good for repeatability of pressure fields and can be also expended. The factors that influence the stability of discharge parameters, shock wave generation and pressure fields are analysed.

Keywords

Pressure, Impact, Stability

1 Introduction

Electrohydraulic impact forming is one of the methods of metalworking. Therefore proper pressure distribution along sheet blank surface plays a leading role in deformation process and quality of sheet components produced. Another aspect is a stability of pressure fields generated by high-voltage underwater discharges in order to obtain the same pressure distributions from one discharge to another at permanent electric parameters and, hence, the same sheet blank shape at a certain stage of forming process.

Many factors influence stability of shock wave pressure at non-initiated discharges: efficiency variations of energy evolving in a discharge channel, variations in shape and position of discharge channel relative to electrodes, discharge chamber walls and a blank surface, condition of work surfaces of electrodes, etc.

Previous investigations [1, 2] showed instability of pressure fields generated by non-initiated and wire initiated discharges that result in instability of sheet blank deformation under the same discharge conditions. The problem of repeatability of pressure fields for discharges initiated with aluminium and copper wires was earlier investigated in the work [3].

In this work a research of stability of pressure fields generated by discharge chamber of conical shape equipped with one pair of electrodes has been carried out. Conical discharge chambers with single electrode pair are rather typical for manufacture of small-size sheet components under small-batch production conditions. The purpose of work is an experimental determination of electric and geometric parameters, at which stability (repeatability) of pressure fields will be the highest at non-initiated discharges.

Methods of mathematic statistics are used to process experimental pressure data. Coefficient of variation is chosen for estimation of pressure fields' repeatability under the same test conditions.

2 Experimental Setup and Measuring Procedure

Tests have been carried out in the technological unit of experimental electrohydraulic installation UEHSh-2 equipped with conical discharge chamber (Figure 1) of 170 mm exhaust hole diameter. Loaded area was limited by spacer rings with internal diameters D = 150 mm.

The clamping force of tooling pack was applied via columnar frame by hydraulic cylinder with power of 60 kN. Water supply and air evacuation were realised with holes in the discharge chamber adaptor 2 (ref. Figure 1).

The intended spark gap value l was set up with threads performed in sleeves of electrodes and discharge chamber holes (Figure 2). Distance H between electrodes (discharge channel) and membrane 11 was approximately 110 mm with slight deviations when changing electrodes positions for spark gap setting. These deviations were taken into account when making a processing of tests data.

During the tests performance the discharge generator provided the following electrical parameters: voltage V = (10–30) kV, capacitance C = 33.2 µF, charged energy E = (1.66–14.94) kJ, inductance L = 0.5 µH.

Measurements of pressure fields were performed based on application of multi-point membrane pressure gauge (MPG) methodology [4]. Diameters of holes in MPG body (d = 6 mm) and thickness of membrane (A5052-O, thickness t = 1.0 mm) were selected of such values to record only the pressure of shock waves to exclude influence of hydraulic flows and pressure of vapour-gas bubble.

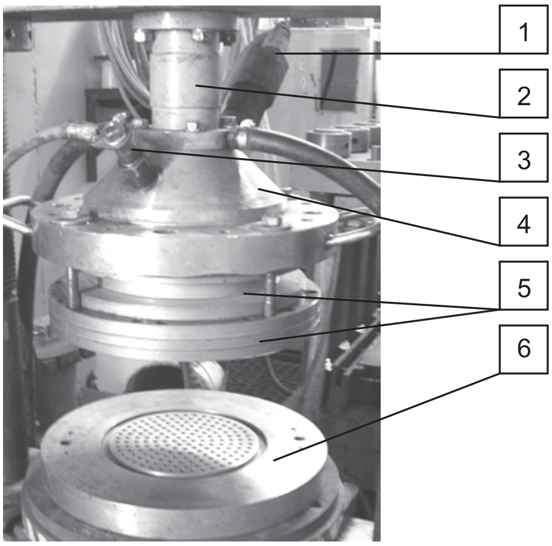

***Figure 1**: General view of tooling pack: 1 – insulated (positive) electrode; 2 – discharge chamber adaptor for water supply and air evacuation; 3 – mass (negative) electrode; 4 – conical discharge chamber; 5 – spacer rings; 6 – body plate of membrane pressure gauge*

The resulting action of shock wave pressure was estimated by parameter “equivalent static pressure”, that is, by static pressure, which causes the same membrane deflection (plastic deformation) h. Equivalent static pressure was calculated from the Laplace's equation for spherical shell

$$P = \frac{2\sigma \cdot t}{R}, \tag{1}$$

where t – membrane thickness; R – radius of spherical segment, $R = (d^2/4 + h^2)/2h$; σ – stress, at which deformation occurs.

It has been noted before [4] that membrane gauges with geometric ratio $d/t < (6\ldots8)$ have linear proportionality between equivalent static pressure P and peak pressure of shock wave P_m.

For different deformation levels the σ value could be equal to yield limit σ_y, ultimate strength σ_u or intermediate value between σ_y and σ_u. In this work the average stress σ for a spherical dimple was calculated from the condition of equality of dimple material volumes before and after deformation. Stress-strain curve for the membrane material [5] at the segment between σ_y and σ_u values was approximated with the formula (confidence factor $R^2 = 0.9988$)

$$\sigma = 0.0015\,\varepsilon^3 - 0.1667\,\varepsilon^2 + 7.1258\,\varepsilon + 92.802, \tag{2}$$

where ε is an average strain along spherical dimple shape

$$\varepsilon = 1 - (A_0/\,A_\mathrm{d}), \tag{3}$$

where $A_0 = \pi d^2/4$ is area of membrane round segment before deformation; $A_\mathrm{d} = 2\pi Rh$ is area of spherical dimple obtained after pulse loading; h is depth of a dimple.

Influence of geometric parameters of discharge chamber and spark gap was taken into account with a dimensionless characteristic “normalised spark gap”

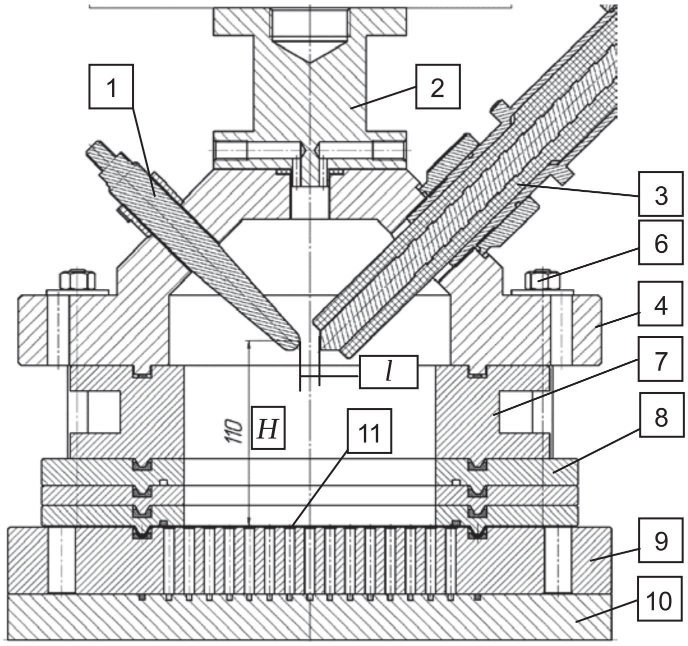

***Figure 2**: Test diagram: 1 – mass (negative) electrode; 2 – upper adaptor; 3 – insulated (positive) electrode; 4 – discharge chamber; 6 – studs, nuts, washers; 7 – spacer ring of 55 mm in height; 8 – spacer rings with 150 mm hole diameter; 9 – membrane pressure gauge body; 10 – lower adaptor; 11 – membrane; l – spark gap; H – distance between discharge channel and pressure gauge*

$$l_n = \frac{4 \cdot l \cdot H}{\pi \cdot D^2}, \tag{4}$$

where D is diameter of rigid side walls of work volume (diameter of hole in tooling rings). For the test tooling configuration D = 150 mm (ref. Figure 2).

Analysis of preliminary tests and previous literature sources allowed developing the formula (4): increase of spark gap l and distance H, reduce of loaded area limited by diameter D should improve uniformity of the pressure distribution along loaded area. It was supposed that the increase of combined parameter l_n would improve repeatability characteristic too.

3 Tests Results and Data Processing

The values of dimples depths h_i were measured and pressure values P_i were calculated from formulas (1), (2), (3) for each i point of a membrane after impact loading at selected test conditions. Then the following parameters were calculated:

- Average pressure for each i point (i = 1…127) of MPG membrane for the m quantity of pressure fields under the same test conditions (m = 3-6)

$$P_{ave.i} = \frac{1}{m}\sum_{j=1}^{m} P_{ij}\ ; \tag{5}$$

- Standard deviation of pressure value in each i point

$$S_i = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(P_{ij} - P_{ave.i}\right)^2} \; ; \tag{6}$$

- Coefficient of variation in each i point for the same series of tests

$$C_{Vi} = \frac{S_i}{P_{ave.i}} \cdot 100\% \; ; \tag{7}$$

- Maximum C_{max} and minimum C_{min} values of variation coefficient selected from 127 points along loaded area for the series of tests;
- Average value of variation coefficient among n = 127 points for the series of tests

$$C_{V.ave} = \frac{1}{n}\sum_{i=1}^{n} C_i \; . \tag{8}$$

In comparison with a standard deviation the coefficient of variation C_V gives not absolute, but relative measure of scatter of parameter values in its statistical population. The larger the C_V, the population is less homogeneous. A population is considered to be homogeneous at C_V = (0-30) %, intermediate – at C_V = (30-50) % and non-homogeneous (heterogeneous) – at C_V = (50-100) %. Variation coefficient can be equal to more than 100 %, if a population is extra heterogeneous.

Due to its properties coefficient of variation was selected as a basic parameter for estimation of repeatability of pressure fields obtained in several tests under the same conditions. Values of average variation coefficient 10 % and less were accepted as a satisfactory level of repeatability.

Tests conditions and results of data processing are submitted in Table 1.The parameter $P_{max\text{-}ave}$ is the average maximum pressure and parameter S_{ave} is the average standard deviation obtained in m number of pressure fields under the same test conditions. They additionally characterise pressure fields in a manufacturing aspect.

Figures 3 and 4 represent a top view of membrane, where pressure field and variation coefficient distribution maps are shown. Small zone of increased values of variation coefficient near to insulated electrode end in Fig. 4 in comparison with the zone increased pressure in Fig. 3 shows instability of discharge channel position from one discharge to another. But this level of instability does not influence greatly the repeatability of pressure on the rest area. This means that the length of discharge channel should be in geometric correlation with discharge chamber dimensions and sizes of loaded area for higher stability.

The pressure fields in tests No. 13 also demonstrate good level of uniformity

Tests conditions						Tests results				
No.	l, mm	V_0, kV	E_0, kJ	H, mm	k	$P_{max\text{-}ave}$, MPa	S_{ave}, MPa	C_{Vmax}, %	C_{Vmin}, %	C_{Vave}, %
1.	5	10	1.66	102.5	6	10.65	1.99	105.69	34.68	73.46
2.	5	15	3.73	102.5	3	29.04	5.05	112.16	35.58	75.99
3.	5	20	6.64	102.5	3	22.18	3.87	79.50	35.02	53.72
4.	5	30	14.94	102.5	5	57.71	7.13	72.18	35.89	50.74
5.	10	10	1.66	105.0	3	32.75	6.44	79.43	37.96	55.39
6.	10	15	3.73	105.0	3	49.41	8.06	60.30	33.09	49.60
7.	10	20	6.64	105.0	4	69.46	8.79	46.27	26.26	35.62
8.	10	30	14.94	105.0	3	78.53	9.18	41.99	11.92	16.63
9.	15	10	1.66	107.5	3	12.64	1.77	117.76	80.65	104.60
10.	15	15	3.73	107.5	3	46.91	5.25	57.56	43.56	51.45
11.	15	20	6.64	107.5	3	84.09	8.82	15.67	1.02	7.38
12.	15	30	14.94	107.5	3	89.93	7.94	26.45	2.01	6.12
13.	20	20	6.64	110.0	3	71.44	6.63	15.52	0.57	5.49
14.	20	30	14.94	110.0	3	86.36	6.69	21.07	6.47	15.58
15.	25	20	6.64	112.5	3	80.81	9.69	23.87	1.64	12.25
16.	25	30	14.94	112.5	5	101.15	7.27	21.27	5.38	13.00

Table 1: *Tests conditions and results*

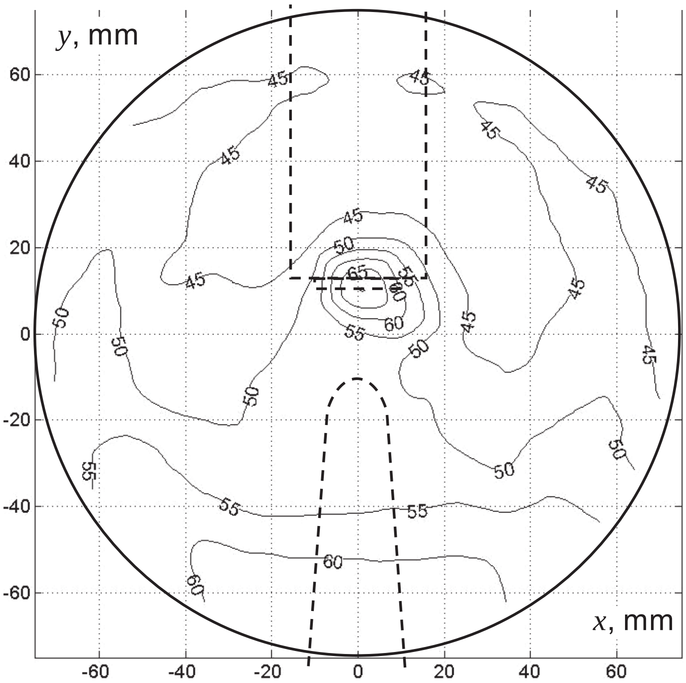

***Figure 3**: Representative pressure map (MPa) for test conditions No. 13 at l = 20 mm and V_0 = 20 kV*

along loaded area. In comparison, at other tests conditions, especially with smaller spark gap values (less than 15 mm), pressure fields show both low uniformity and repeatability.

The map of variation coefficient in tests No. 13 has the largest level of coefficient values in the region near to insulated electrode work end and the smaller – along side wall. Other maps obtained for other test conditions have the analogous distribution or the larger coefficient values near the side wall as compared with central region.

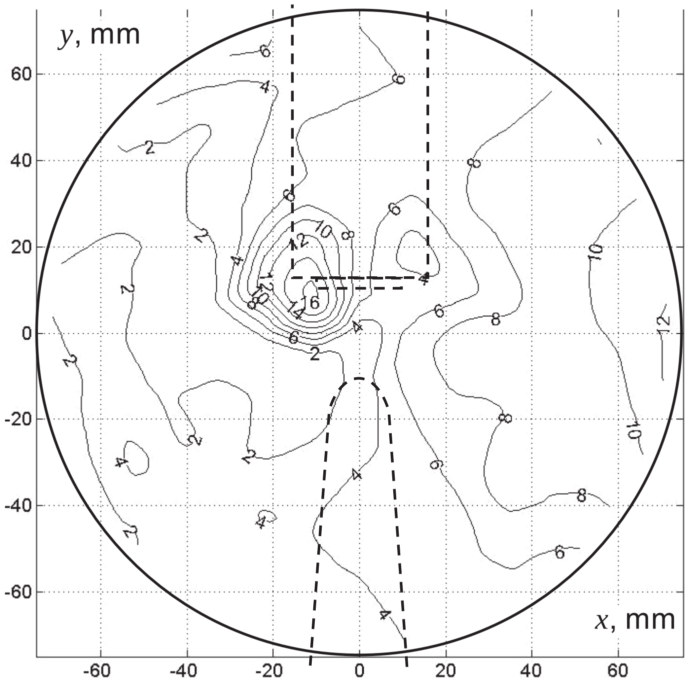

***Figure 4**: Map of variation coefficient (%) for test conditions No. 13 with 3 pressure maps processed*

4 Discussion

When analysing the tests results, many factors should be taken into account that influence repeatability of pressure fields. Electric parameters of discharge circuit (V_0, E_0, l) influence stability of a discharge channel, its configuration in a spark gap between electrodes ends, efficiency of electric energy evolving and its transformation into energy of pressure. Geometric parameters of discharge work volume (H, D, l, shapes of discharge chamber and side walls, configurations of electrodes and condition of their work ends) determine length of discharge channel, its position relative to loaded area, distribution of direct shock waves, conditions for reflected shock waves and their interaction with direct shock waves, conditions for interaction of direct and reflected shock waves with side walls near to loaded area, and finally influence the resulting pressure distributions and their repeatability. Value of spark gap l influences both the efficiency of electric discharge, because it determines initial resistance of discharge circuit, and geometric characteristics, because it determines length of discharge channel in its ratio with loaded area limited by diameter D and distance H.

In common action the influence of mentioned significant and other factors is described by curves depicted in Figure 5. The curves are concave by shape and have minimum values at certain values of normalised spark gap. Both increments and decrements of spark gap from this certain value will cause enlarge of instability of pressure fields.

The curves evidently show that satisfactory level of repeatability ($C_{Vave} \leq 10$ %) can be achieved only at voltage of 20 kV and more. This is confirmed by tests data of Table 1 for tests 11 to 16 with the value $C_{Vmax} < 30$ % peculiar to homogeneous populations of data. The highest level of repeatability was obtained in the tests Nos 11, 12 and 13 with the C_{Vave} values 7.38, 6.12 and 5.49 respectively at spark gap values of 15 and 20 mm, charge voltage values of 20 and 30 kV and charge energy of 6.64 and 14.94 kJ. Tests conditions, which are able to generate pressure fields with high repeatability, are also characterised by high level of pressure values $P_{max\text{-}ave}$ (ref. Table 1).

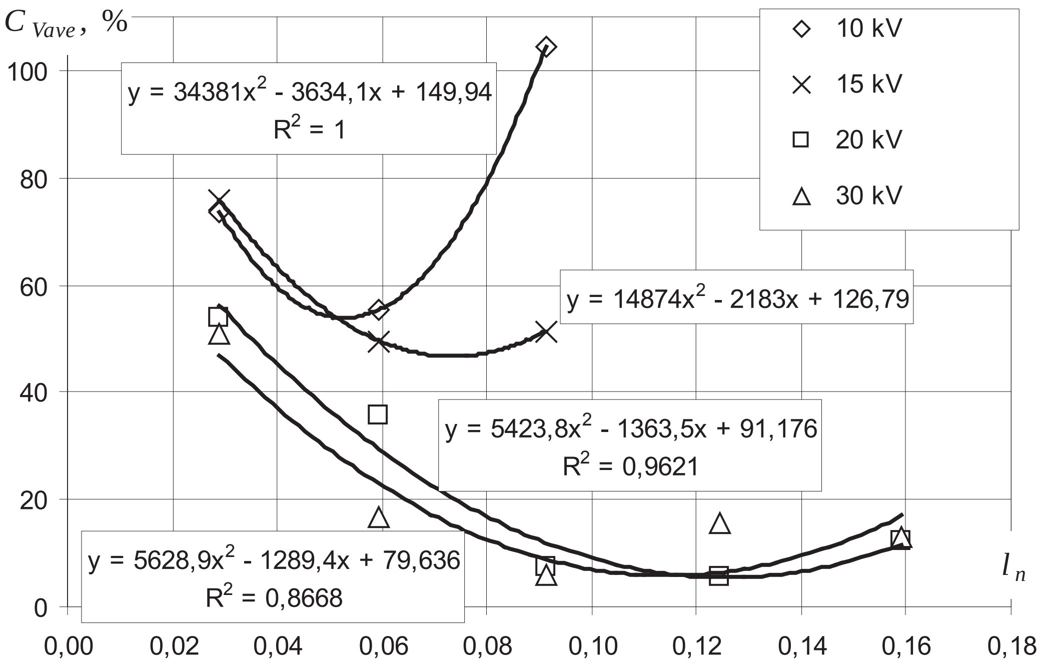

***Figure 5**: Dependences of average variation coefficient C_{Vave} from normalised spark gap l_n at specified values of charged voltage V_0*

Analysis of both curves obtained at 20 and 30 kV (ref. Figure 5) allow to determine range of spark gap values more carefully – from 17 to 22 mm that corresponds to the normalised gap values l_n = 0.10–0.14. The highest level of repeatability of pressure fields is expected at the discharges with the value l_n = 0.12 (l = 19.5 mm).

Figure 6 shows more precisely effect of geometric parameters on repeatability. Spark gaps of 5 and 10 mm are not able to provide the satisfactory level of repeatability even at large voltages. The effect of geometric ratio between spark gap l and distance H and diameter D does not allow generating a stable shock wave pressure at small lengths of discharge channel.

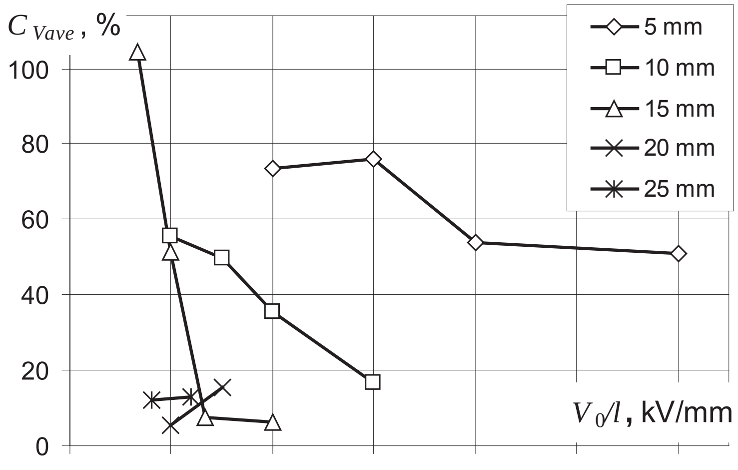

***Figure 6**: Dependences of average variation coefficient C_{Vave} from electrostatic intensity V_0/l at specified values of spark gap l*

Also geometric configurations of electrodes work ends create barriers for propagation of direct shock waves and this influence becomes stronger with decrease of spark gap.

At larger spark gap values the geometric ratio becoming more favourable for shock waves propagation and here the mode of energy evolving has a critical role. For rough estimation of spark gap value optimal for the highest level of pressure it is recommended to apply electrostatic intensity V_0/l = 1 kV/mm. For optimisation of repeatability characteristic it is appeared that this ratio should be 1.33 and more, up to 2, for spark gap of 15 mm. For spark gap of 25 mm good repeatability is obtained even at V_0/l = 0.8 kV/mm. Large C_{Vave} values at 15 mm gap and V_0/l = (0.67–1.0) kV/mm are explained by harmful effect of small geometric length of discharge channel and its low stability because of low electrostatic intensity and energy density per 1 mm of the gap.

Considering influence of electric parameter V_0 (and, hence, charge energy, because $E_0 = CV_0^2/2$) it is possible to estimate its quantitative characteristic (Figure 7). Though the low level of approximation reliability is evident, the tendency of repeatability increase with the voltage rise is observed. The highest level of repeatability of pressure fields is expected at the discharges with voltage of 27 kV and energy of 12.1 kJ.

Finally the analysis led to a conclusion that stable pressure fields under this discharge chamber conditions can be obtained at relatively large spark gaps, charge voltages and energies.

The problem of repeatability at small spark gaps and small voltages can be solved with taking into account geometric parameters of discharge volume. Complex parameter l_n equals (0.10–0.14) at the condition of $C_{Vave} \leq 10$ %. Using the formula (4) the optimised diameter of loaded area can be determined as D = 108 mm at the same distance H = 110 mm and l_n = 0.12, spark gap of 10 mm. For these conditions the optimised voltage equals 13.5 kV and energy – 3.02 kJ. These changes should be accompanied with proportional decrease of electrodes dimensions.

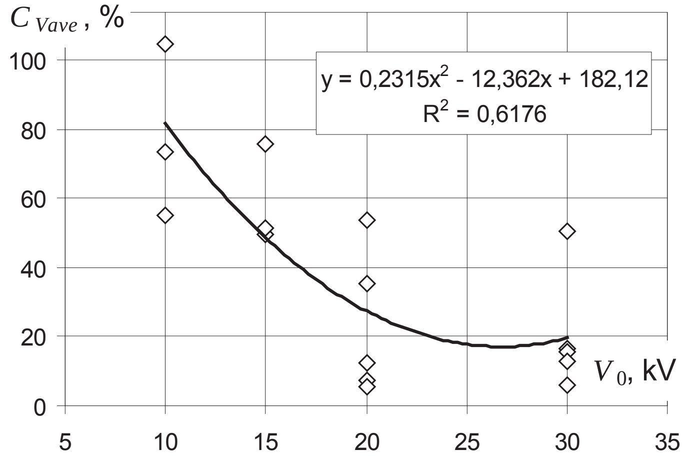

***Figure 7**: Dependency of average variation coefficient C_{Vave} from charge voltage V_0 for all tests*

If, for example, it is necessary to select spark gap of 30 mm and diameter D = 200 mm, the distance will be H = 126 mm (V_0 = 40.5 kV, E_0 = 27.2 kJ). Of course, these estimations are to be checked during further investigations.

In comparison with wire-initiated discharges the stability of non-initiated discharges is much lower. In the work [3] the tests were carried out in the same discharge chamber with the same distance H at voltage of 20 kV and energy of 6.64 kJ. Here also the dependency of pressure fields' stability from wire diameter and material nature is evident: at aluminium wire of 0.75 mm diameter the CVave = 1.65 % and at 1.00 mm – CVave = 4.43 %; at copper wire of 0.72 mm diameter the

CVave = 3.0 % and at 0.90 mm – CVave = 8.26 %.

5 Conclusions

The investigation results showed strong influence of geometric parameters of discharge work volume and electric parameters of discharge circuit on repeatability of pressure fields. In particular the spark gap value should be in severe correlation with distance to a sheet blank and dimensions of a loaded area. Here the parameter "normalised spark gap" is proposed for determination of geometric characteristics of discharge volume.

Voltage and energy of discharge have optimal values. All deviations (both positive and negative) of their values from the optimums cause increasing instability of discharge channel position and, hence, low repeatability of pressure fields.

For the specified geometric parameters of discharge chamber at the condition of average variation coefficient value being of up to 10 % (satisfactory level of repeatability) the following electric parameters are recommended: range of spark gap is 17 to 22 mm, voltage range of 20 to 30 kV and charge energy range of 6.64 to 14.94 kJ.

The further investigations with discharge chambers of other geometric parameters for verification of the proposed method are planned.

References

[1] Vohnout, V.J.; Fenton, G.; Daehn, G. S.: Pressure heterogeneity in small displacement electrohydraulic forming processes. Proceedings of the 4th International Conference on High Speed Forming “ICHSF2010”, Columbus, Ohio, March 9-10, (2010), p. 65-74.

[2] Homberg, W.; Beerwald, C.; Pröbsting, A.: Investigation of the Electrohydraulic Forming Process with respect to the Design of Sharp Edged Contours. Proceedings of the 4th International Conference on High Speed Forming “ICHSF2010”, Columbus, Ohio, March 9-10, (2010), p. 58-64.

[3] Eguia, I.; San José, J.; Knyazyev, M.K.; Zhovnovatuk, Ya.S.: Pressure Field Stabilization in High-Voltage Underwater Pulsed Metal Forming Using Wire-Initiated Discharges. Key Engineering Materials, Vol. 473, 2011, p. 965-972.

[4] Knyazyev, M.K.; Zhovnovatuk, Ya.S.: Measurements of Pressure Fields with Multi-Point Membrane Gauges at Electrohydraulic Forming. Proceedings of the 4th International Conference on High Speed Forming “ICHSF2010”, Columbus, Ohio, March 9-10, (2010), p. 75-82.

[5] http://products.asminternational.org/datasheets/metaview.do?record=8555&database=datasheets