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Studying the processes of creation of high-energy submerged liquid jet and its interaction with deforming blank

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The article describes the results of experimental work on substantiating the possibility of using electrode systems of directed influence for electrohydraulic sequential stamping of large-sized sheet metal parts. These systems generate a concentrated flow of energy, which is directed in the desired direction and in specific places. Thus, these systems reduce energy consumption in arbitrary directions.

It is shown that in many cases of successful use of this type of forming of sheet metal parts, the mechanism of loading a blank with shock waves is considered, which propagate in all directions of the discharge volume and transfer a certain fraction of the released energy. When stamping large parts, due to their large dimensions, with such a loading mechanism, part of the energy is used unproductively. To increase the efficiency of energy use, it is necessary to use electrode systems of directed influence.

The research was carried out in stages - first preliminary computer modeling, and then physical modeling.

The computer simulation of the process revealed the mechanism of loading the blank with high-energy submerged liquid jets. The presented results of field studies confirmed the mechanism of such loading.

Physical modeling was carried out using complex techniques using high-speed registration of the object's motion and electrical methods for registering rapidly changing parameters.

Experimentally obtained dependences of the distribution of the energy flux density coming from the discharge cavities of such systems. Empirical dependences of the energy flux density, pressure pulse and other parameters depending on the conditions of the stamping process were synthesized.

The goal of the work is to increase the efficiency of stamping large sheet metal parts by more rational and productive conversion of electrical energy into plastic forming work.

The tasks set have been completed. Conclusions have been obtained that predict positive results.

Methods used in the study. The study used the method of computer modeling, experimental studies, which include high-speed photographic reading, recording of oscillograms of pulse parameters.

Keywords*:* electrohydraulic forming, electrode systems of directional influence, local deformation.

Introduction

The processes considered are the initial ones in the sequential electrohydraulic forming (EHF) of large-sized sheet metal parts.

The generally accepted mechanism of loading the blank in such stamping is considered to be loading it with shock waves that come from the thermal explosion zone. This is quite justified when forming parts of small overall dimensions (< 300 mm). However, with large overall dimensions of the parts being manufactured and, as a consequence, large sizes of the discharge chambers, more than 90% of the released energy is spent unproductively. Therefore, a proposal has appeared to conduct EG discharge in small-volume chambers and sequentially move the discharge zone along the surface of the blank.

The goal of this work is to increase the efficiency of converting the energy

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released during discharge into the work of plastic deformation by means of targeted optimization of the technological environment to implement various technical requirements imposed on parts and conditions for their manufacture.

Research methods – experimental and mathematical modeling.

Review of previous studies

Originally, the idea of using a high-voltage underwater electric discharge for stamping (forming) was proposed by L.O. Yutkin [1] in the middle of the 20th century. Some practical applications of this effect are given in the works [2, 3]. Intensive research of EHF processes was carried out in the 1970s-1980s in the USA, Russia, Japan, and France. In Ukraine, comprehensive research and industrial work was carried out in the Electrohydraulics Design Bureau (now the Institute of Pulsed Processes and Technologies of the National Academy of Science of Ukraine). An extensive review of the results of these works has been published in a number of monographs [4-6]. Large-scale research and work on the industrial use of pulsed energy sources was carried out at the Kharkiv Aviation Institute. Part of the results of these works are presented in the monograph [7].

Since the 2000s, the study of individual features of the EHF has accelerated worldwide. Many publications have appeared about the positive properties of the process and the potential possibilities of its use for practical purposes..

In the English-speaking sector of scientific and technical literature, one of the first reviews of pulse stamping methods was proposed by Hapley [8]. It noted which features of EGS compared to electromagnetic forming (EMF) and explosive forming (EF) are more desirable to use in industrial production. The possibilities of using EHF for sheet stamping and dispensing of tubular blanks were considered [9-12]. Callendar [11] reported on the results of EHF of a plate-shaped component with a diameter of 3 m. In all these studies, an explosive wire (bridge) was used to shape the discharge channel. This is what hindered the wider use of EHF in production.

Mamutov A.V. et al. [12] concluded that a significant improvement in the formability of sheet metal can be explained by the high deformation rate, low friction and the effect of all-round compression, which manifests itself, for example, during forming.

The above-mentioned and a few other studies were the basis for the use of EHF processes at US aviation and rocket and space enterprises with their special requirements for the manufacture of parts.

Over the past decade, the following researchers and practical engineers have worked most actively: Golovashchenko S.F. in the field of automotive engineering [13-16], Mamutov V.S., Mamutov A.V. with co-authors [13, 16-19], Avrilland G. with co-authors [20-23]. Some features of the EHF are highlighted in the works of Yan Ledoux [21] and others.

In the Ukrainian-Russian sector of literature on the use of EHF, the books of G. A. Guly [4], B. Ya. Mazurovsky [5], P. P. Malyushevsky [6] should be noted. These employees of the design bureau of Electrohydraulics (Mykolaiv, Ukraine) highlighted scientific and practical issues of discharge-pulse technologies, developed electro-hydraulic equipment and technological equipment.

They describe the mechanism of EH-discharge development, propose mathematical models of energy transfer processes from the discharge zone to a blank, describe the optimization of the energy release process depending on the parameters of the electrical circuit. In the work of Yu. E. Shamarin [24], a description of large EH-

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presses of the ПЕГ-25, ПЕГ-60, ПЕГ-100 and ПЕГ-150 brands is given, which are designed for forming medium and large-sized parts.

In the monograph of M. Taranenko (2011) [25], previous works in the direction of EHF of medium and large-sized parts are summarized; the concept of spatio-temporal loading of large-sized parts is developed and experimentally confirmed, and the existence of a few of its advantages is shown. The design of a multi-circuit EH-press with energy up to 500 kJ, which can be stored, is proposed and experimentally tested.

In the works considered above, the main loading factor is taken to be a shock wave (or a shock wave package) and the fluid hydroflow following it. The energy contained in the expanding steam-gas bubble (SGB) is clearly not considered.

Separately, it is worth noting the works of Solomyany O. U. with co-authors [26, 27]. They show that the pressure pulse or energy flux density acting on the blank during a thermal explosion in a limited volume of a gas bubble is several times higher than the similar parameter generated by a shock wave (Fig. 1).

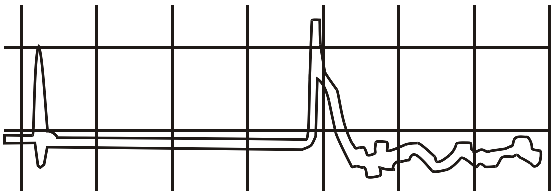

Fig. 1. Typical pressure waveform diagram generated by a shock wave (at the left) and a fluid jet created by a gas bubble (at the right). Resolution is 10^{-4} s/division

This oscillogram demonstrates the records of two pulses – the action of a direct shock wave (at the left) and a jet created by a bursting gas bubble (at the right). It is clearly visible that the amplitude and pressure pulse of the second force impact are more than 3 times higher than the first impact.

It should be noted that a special piezoelectric sensor was used in the experiments, which excluded the registration of reflected signals.

The general conclusion from these calculations and experiments is the statement about a significantly larger amount of energy stored in the gas bubble, which must be used productively to increase the efficiency of pulse forming.

Schematic diagram for organization of submerged pulsed jets

The simplest scheme for implementing sequential local stamping of large parts is shown in Fig. 2. It shows a schematic diagram of combining a certain number of small-volume discharge cavities (DC) into a single discharge block. The electrodes in each cavity are connected to a separate circuit of a current pulse generator. The calculated scheme of loading the blank during EH discharge in one cavity is called the electrode system of directed influence (ESDI). Its scheme is shown in Fig. 3.

In such a system, a high-voltage EH-discharge is performed between the central electrode and the inner surface of the chamber (see Fig. 2). As a result, a SGB is formed in the upper part of the cavity (Fig. 3). It is filled with evaporated liquid with high values of thermodynamic parameters, elements of evaporated electrode parts, and discharge plasma residues. The lower boundary of the SGB pushes the water in front of it towards the open end of the cavity into the space between chamber 2 and blank 1.

It is necessary to investigate the mechanism of further energy transfer from the

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discharge zone to a blank for its optimization.

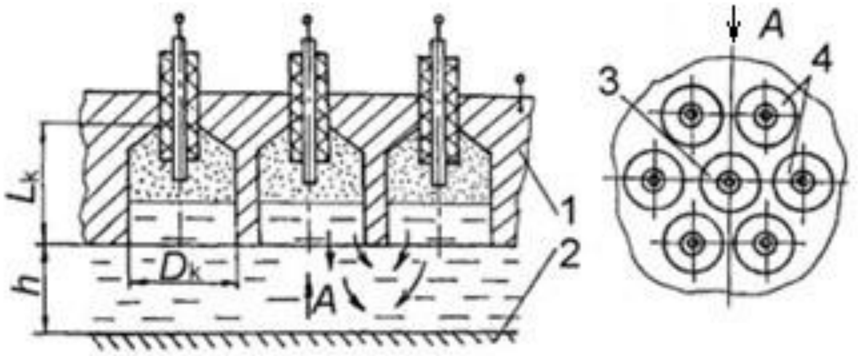

Fig. 2. Principal scheme of MDB: 1 – discharge chamber; 2 – forming blank; 3 – the chamber where main discharge is conducted; 4 – six chambers in which auxiliary discharges occur; dots show zone of SGB [25]

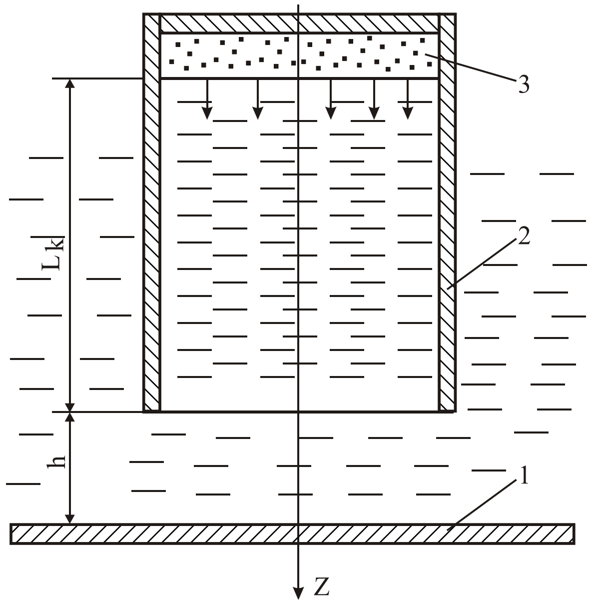

Fig. 3. Scheme of blank loading at discharge in ESDI:
1 – blank; 2 – ESDI chamber; 3 – steam-gas cavity

Modeling the process of energy flow distribution in a restricted and adjacent volumes of a blank in the ESDI

To simulate mechanical processes in the DC of MDB and in the volumes of the technological space combined with them, the LS-DYNA package was selected, the computational environment of which allows you to choose the appropriate variants of the heterogeneous system under study. It is (Fig. 4) an axisymmetric pipe, which is combined with a cylindrical chamber body, the cavities of which are filled with liquid. In the upper part, the pipe has a blind wall. In the radial direction, the liquid in the chamber is limited by rigid walls at a sufficient distance. In the lower part, the chamber is closed by a flat deformable obstacle (blank). At the periphery, a blank rests on a pulling ring. The system is axisymmetric, which makes it possible to simulate processes in it in a two-dimensional formulation.

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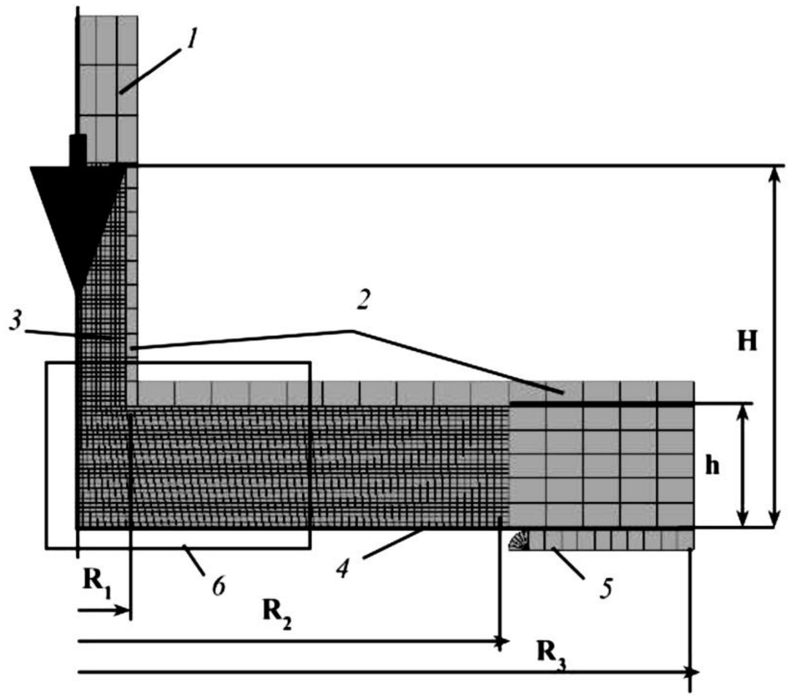

Fig. 4. The scheme of analytical model:
(1 – rigid piston that simulates boundary of steam-gas cavity with high pressure; 2 – ESDI chamber; 3 – liquid; 4 – blank; 5 – drawing ring); R_1 = 20; R_2 = 175 mm; R_3 = 250 mm; H = 150 mm; h = 50 mm; blank thickness is 5 mm; arrow shows direction of the piston movement at original moment of time

The blank is made of elastic-plastic material with stepwise deformation hardening of the D16 aluminum alloy. Liquid is linearly compressible and viscous elastic, it has tension strength up to 10^4 Pa. Bulk elastic modulus is $0.4{\cdot}10^{11}$ Pa, viscosity index is 0.5. The blank is clamped between an unmovable chamber and a drawing ring but has the ability to move in a radial direction with Coulomb friction; friction coefficient is μ=0.4.

The piston moves according to a given law, which has the form of an unequal triangle. Initially, a pressure wave propagates in a stationary liquid, Fig. 5 shows a fragment of the liquid and tone patterns of the pressure distribution at the stages of the pressure wave movement in the DC (a) and in the chamber at the moment the front reaches the blank surface (b). The arrows show the direction of the wave front movement, the light tone below and on the right shows the zones of undisturbed liquid. When the wave moves in the channel, the front (1) and rear (2) pressure fronts are pronounced, which have a practically flat shape. When leaving the channel mouth to the chamber, the front of the pressure wave acquires a spherical shape and moves in the radial direction.

The pressure level drops, the maximum pressure is observed in the channel and below it in the chamber, their values are two times smaller compared to the first stage. In the following, an even more significant decrease in pressure is observed, which is due to the separation of the wave from the source of disturbance, an increase in the front area and the work of blank deforming. The zone of increased pressure becomes layered and inhomogeneous, which is associated with re-reflection and interference, as well as the limitation of liquid resistance by tensile stress. Two zones of the liquid column are observed (light areas 3, Fig. 5, b). In the following, the damping

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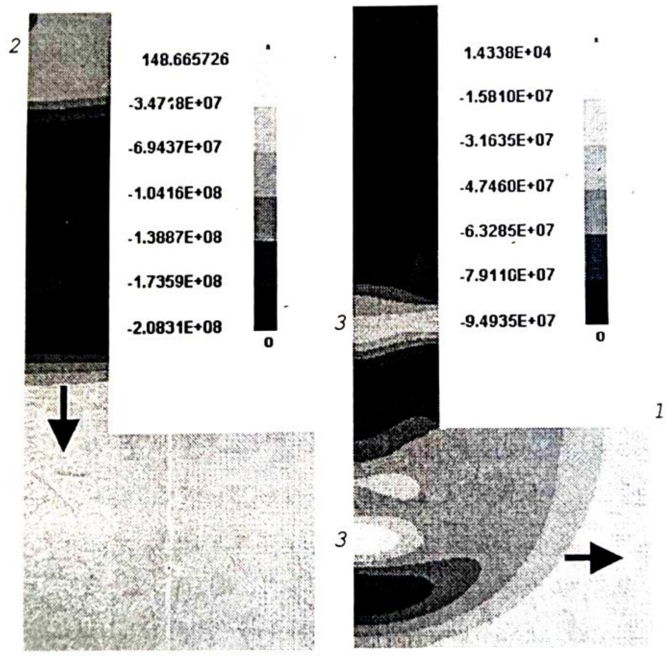
of the pressure wave and significant liquid movement are observed.



a b

Fig. 5. Patterns of pressure wave motion in the DC channel (a) and chamber (b)

Fig. 6 shows a fragment 6 (Fig. 4) of the system, on top of which the trajectories of the fluid points are plotted. The group of points (a) is located at the mouth of the channel, the group (b) is in the chamber near the mouth, the group (c) is in the bottom part of the chamber on the surface of a blank, the group (d) is at a distance of three radii of the channel from the mouth. The points of group (a) create a jet expanding downwards. The trajectories of the points are curvilinear and at the end of the considered process rise upwards. The points of group (b) have initially straight trajectories inclined at an angle of 45º, and then curvilinear, raised upwards, trajectories. The movement of the points of groups (a) and (b) can be characterized as vortex. The points of group (c) move initially downwards together with a blank, and then horizontally, creating a bottom flow. The points of group (d) mainly move in the radial direction and downwards together with a blank. The fluid motion is highly inhomogeneous, and the displacements are large, reaching 108 mm.

Fig. 7 shows a tone picture of the fluid velocity distribution in the deformed configuration for fragment 6. The velocity scale is shown on the right (the darker the area, the higher the velocity). The arrows show the prevailing velocity directions. The grid lines correspond to the lines of the material coordinate system. Changes in the grid show the nature of the fluid motion. Radial compression is observed at the top of the jet, while in the lower zone under the cavity (b) the fluid motion has a layered nature.

The liquid separated from the solid surfaces of the rod (area (a)), and partially from the chamber and a blank, forming a cavity (b). The velocity field is highly inhomogeneous, two separate zones of high velocity are observed simultaneously, marked in dark tone. Near the cavity (c) a vortex motion is observed in the liquid. Due to the inhomogeneity of the velocity field in area (c) a collapse of part of the boundary of the free surface of the cavity is expected.

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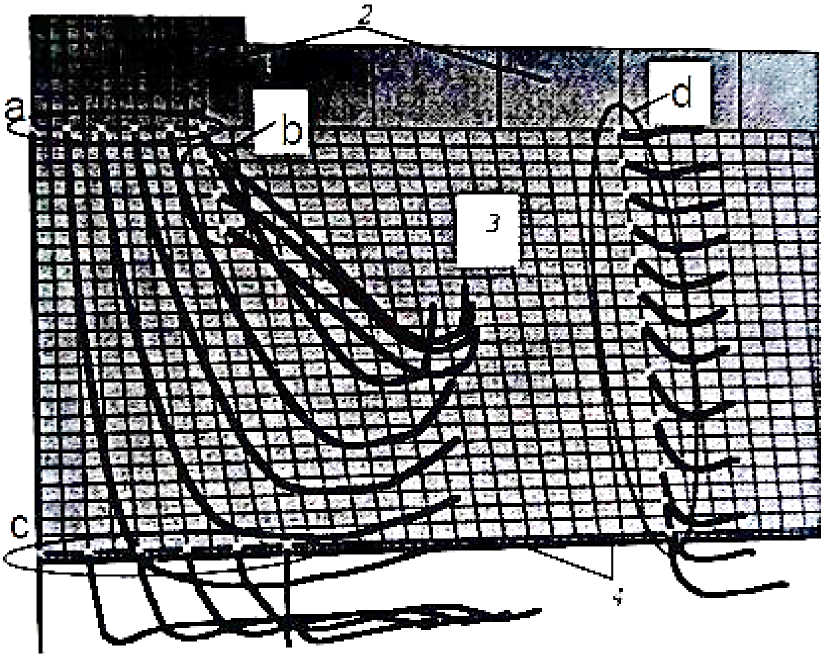

Fig. 6. Trajectory of movement of liquid points (3) and blank (4)

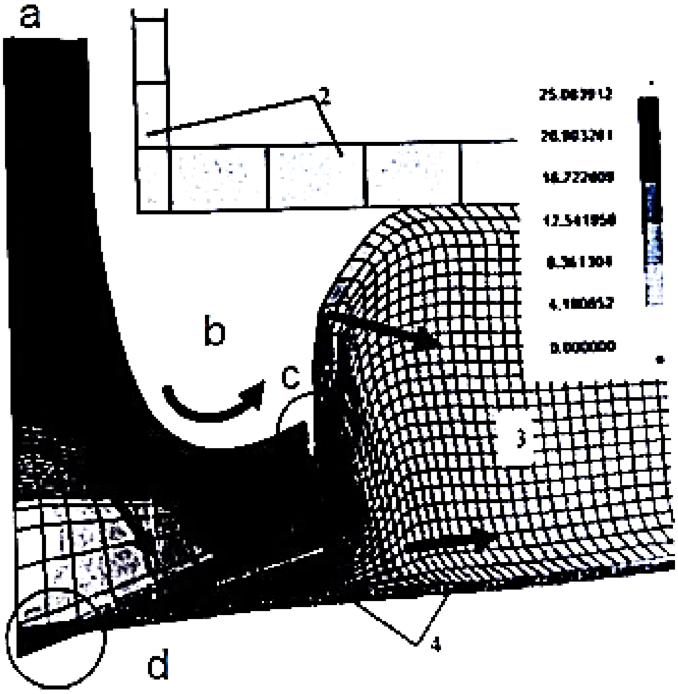

Fig. 7. The picture of fluid speeds distribution. The items correspond to Fig. 4

In zone (d) there is a computational artifact – liquid penetration through a blank. Distortion of the shape of the cells leads to computational instability of the modeling process, as a result of which the computational process is interrupted. As is known, this is a disadvantage of all mesh methods when solving problems with large inhomogeneous deformations..

Comparison of the calculated and further described experimental results allows us to draw the following conclusions.

The fluid motion has a jet character and causes a local effect on the blank.

The axisymmetric heterogeneous model can be used to determine the nature and magnitude of the fluid pressure on the deformed blank for use in simple and

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computationally efficient models of blank deformation under pressure, considering the motion of the blank.

Without considering in this part of the work all the technically relevant features of the mechanisms of interaction of the fluid flow and the deformed blank, we will note two of them. On the upper solid boundaries of the zones of change in the cross-section of the fluid jet, regions of intensively cavitating fluid are created. This applies to the upper boundary of chamber 2 (Fig. 4) or, otherwise, the upper wetted surface of the MDB, the lower end of the working electrode and other surfaces of the technological block. Under the influence of intensive multiple pulse loading, significant cavitation erosion (surface destruction) is observed on these surfaces.

As the liquid jet approaches the blank, it expands in the radial direction and zones of reduced pressure are created in it (Fig. 5, b). That is, the energy transferred by the jet is spent irrationally. It is possible to reduce the costs by creating zones of increased pressure around the jet.

Experimental results of physical modeling

To verify the obtained calculation results of the process of formation of a submerged liquid jet as a result of an EH-discharge in the ESDI, experiments were conducted according to the scheme shown in Fig. 8.

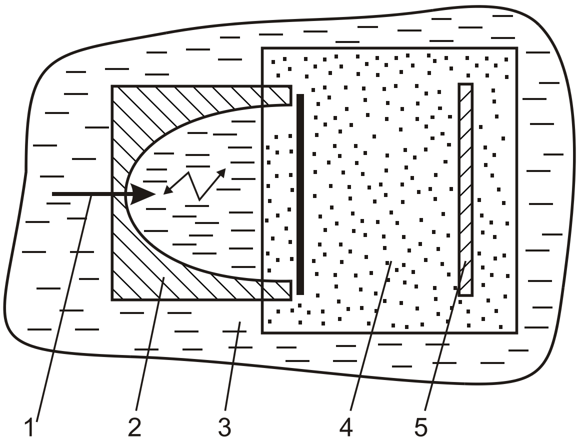

Fig. 8. Scheme of the experiment: 1 – electrode; 2 – ESDI chamber;
3 – water in the experimental chamber; 4 – light spot; 5 – rigid obstacle

In experimental chamber 3 of the IAB-451 light device (heating vision device), an ESDI chamber 2 with a central electrode 1 was horizontally located. A rigid obstacle 5 was located along the axis of the chamber 2 at an adjustable distance.

The cavity of the ESDI chamber was filled with water and tinted with ink. The end of this chamber was covered with a thin rubber shell. The chamber of the IAB-451 device was filled with water, which was allowed to stand for a certain time. The axis of the light flux perpendicularly intersected with the axis of the ESDI camera. The EH-discharge in the ESDI was synchronized with the light flash of the device and the opening of the shutter of the high-speed photorecorder lens.

The experiments were carried out in a darkened room to exclude premature exposure of the film. Frame-by-frame shadow moments of the formation of a submerged jet are shown in Fig. 9.

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a

b

Fig. 9. SFR-grams of the process of pulse jet creation
at EH-discharge in a chamber of low volume with inner cylindrical cavity:
a – original stage of SGB releasing from DC – releasing of fine particles inder influence of impact wave (frame 1) and releasing of SGB of cylindrical shape (frames 3, 4 та 5), delay between frames is 64 μs; b – interaction of SGB of cylindrical shape with a rigid obstacle installed perpendicularly to DC, delay between frames is 96 μs

In the frames (Fig. 9, a) the rigid obstacle is located at a great distance from the end of the EHSV chamber. Frame 1 – a cloud of liquid particles, which are crushed by a direct shock wave, emerges from the open opening of the chamber. Their axial velocity is within 1480…1520 m/s. The diameter of the particle cloud corresponds to the diameter of the outlet opening of the ESDI chamber (40 mm). Frame 2 – the appearance of a jet shadow, which increases in length (frames 3 and 4). Its exit velocity is 450…520 m/s. The jet has an almost cylindrical shape with a flat end. Frame 5 – the beginning of the main part of the jet spreading in the radial direction is noticeable. Further, the jet velocity decreases to values of 200…300 m/s. It should be noted that due to the specifics of the experiment, the current pulse generator circuit had inflated inductance and capacitance values. This did not allow creating “fast” discharges.

In the frames of Fig. 9, b, a rigid obstacle was installed at a short distance from the end of the chamber. This sharply slowed down the speed of the jet movement. Direct shock waves (a packet of shock waves) are reflected from the rigid obstacle by compression waves that move towards the jet. Its main part quickly expanded in the radial direction and “stuck” to the obstacle. Thus, a complete correspondence is created in the nature of the jet movement with the results of numerical modeling (see Fig. 7).

The results of the physical experiment confirmed the assumption that the EH-discharge in the ESDI leads to the formation of a high-speed submerged liquid jet in unlimited volumes.

Experimental determination of energy flux density at the exit of the ESDI

Theoretical determination of the energy flux density at the exit of the ESDI is quite complicated due to the action of many factors. These include a large degree of expansion of the SGB, the presence of boundaries of different nature - solid undeformed, moving liquid, as well as liquid-gas boundaries. To identify the features

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of energy transfer from the plasma channel to the blank, a study was conducted according to the following scheme (Fig. 10).

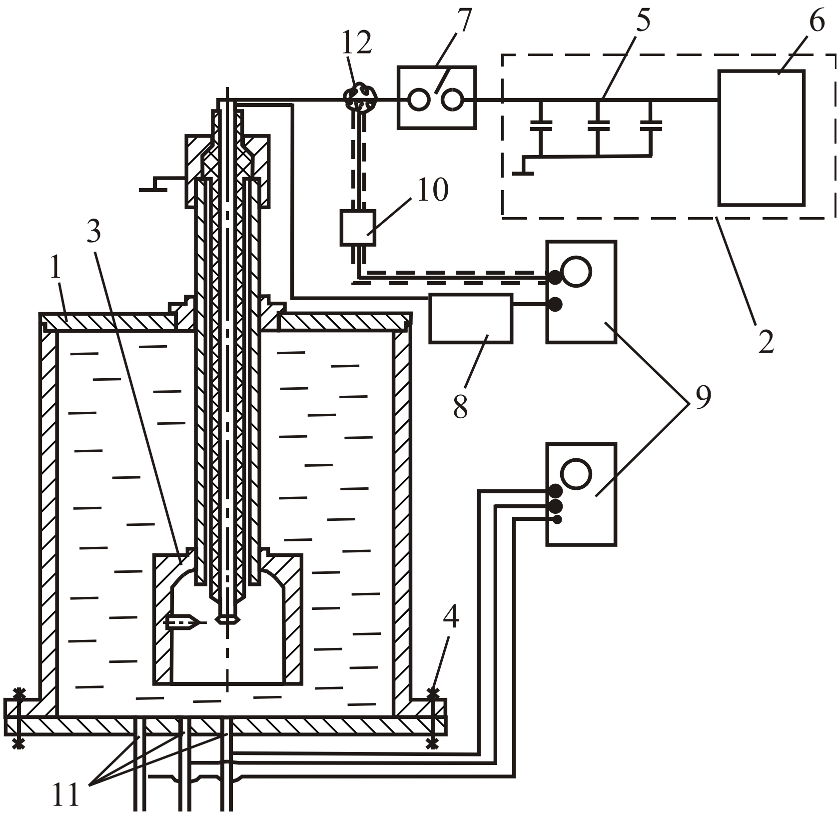

Fig. 10. Scheme of the stand for conducting experimental research:
1 – universal discharge chamber; 2 – current pulse generator; 3 – electro-bottom system; 4 – tie pins; 5 – capacitor bank; 6 – high-voltage power supply; 7 – air discharger; 8 – voltage divider; 9 – oscilloscopes; 10 – Rogovski coil integrating circuit; 11 – pressure sensors; 12 – Rogovski coil

The experiments were carried out on a stand (Fig. 10). It is a closed chamber with a diameter of ~600 mm with an ESDI (3) installed inside with an output diameter of 100 mm and an output channel length of 150 mm. The ESDI had the ability to move along the axis, i.e. the parameter h changed - the distance from the ESDI inlet to the obstacle. An acoustic isolation was installed inside the obstacle - piezoelectric pressure sensors (4) with waveguides. The sensors 4 were located in the center of the ESDI and further with a step of 50 mm. The sensors were previously tarred by an explosive method in accordance with the generally accepted method. To control the stability of the discharge modes, the corresponding voltage divider and pulse current sensor (Rogowski belt - air transformer) were used.

All pulse parameters were recorded by an electronic oscilloscope. The recorded pulses were the dependences of the pressure change over time at the measurement point. The area under the curve determines the pressure pulse P·t [Pa·s]. This parameter was recorded at different distances h and at points located beyond the radius of the ESDI chamber with a specified step.

An example of the dependence of P(t) on the camera axis at different distances is shown in Fig. 11.

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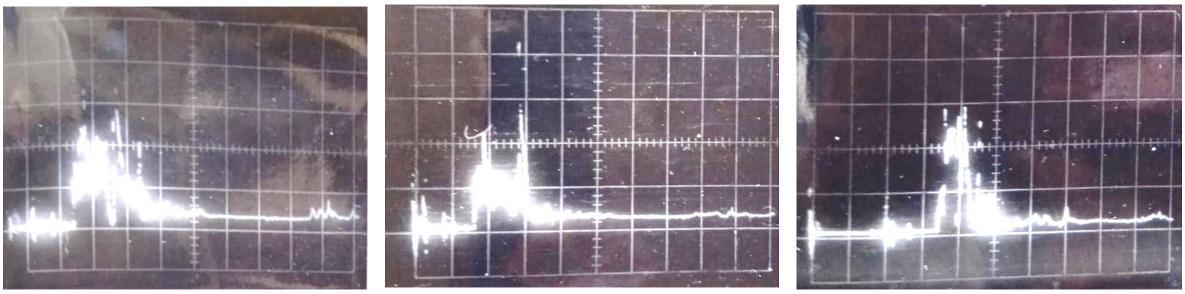

a b c

Fig. 11. Examples of P(t) dependences on distance (at different distances from the camera cross section):
a – 10 mm; b – 15 mm; c – 20 mm. Resolution is 100 μs/division

In the given oscillograms at the first moments very short pulses are visible, which correspond to the process of starting the oscilloscopes. Then at distances of 100…200 μs short double-triple pulses of small amplitude can be observed, which correspond to the process of high-voltage breakdown of the interelectrode distance – these are electrical interferences. Then when moving to the right along the time axis, a useful signal of the dependence P(t) is visible. A sequential comparison of the form of the dependences P(t) for the variants of the distance h demonstrates a characteristic change in the form. At small distances the general form of the pulse is close to a step function. At long distances the form of the pulse is close to an exponential dependence.

This confirms the above assumption about the possibility of approximating the function P(t) by two variants of the functions.

A more thorough analysis of the sequences of the components of the total impulse allows us to identify these impulses with direct, oblique and reflected from the bottom of the chamber disturbance waves.

Processing of the obtained oscillograms allowed us to derive the pressure impulse distribution function J(r) along the radius of the loading zone in the form:

$$J(r) = J(0)\cdot\left[\frac{\mathrm{arctg}\,\alpha(1-r/R_к)+\mathrm{arctg}\,\alpha(r_e/R_к-1)}{\mathrm{arctg}\,\alpha+\mathrm{arctg}\,\alpha(r_e/R_к-1)}\right], \quad (1)$$

where r_e – radius of the effective load zone. Here it is taken equal to the radius corresponding to $P(t)=0.1P_{max}$; $R_к$ – radius of the exit section of the ESDI chamber; α – experimental coefficient determined by experimental data; $J(0)$ – pressure pulse near the camera axis.

Fig. 12 shows experimental data on the distribution of the pressure pulse along the radius of the chamber for some distances.

The bell-shaped shape of the pulse distribution curves indirectly confirms the results of the impact of the submerged jet on the blank, which were calculated using a mathematical model. It should be noted that the pressure pulse parameter corresponds to the energy flux density acting on the blank.

Conclusions

A review of the world scientific and technical literature has shown that when calculating the load parameters during EH-forming, only the shock wave loading mechanism is taken into account. A large part of the energy contained inside the vapor-gas bubble is not considered. Only a few researchers claim that this energy constitutes

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a significant part of the energy released during a thermal explosion.

The use of electrode systems of directed influence allows for the productive conversion of this potential energy into the work of plastic deformation when stamping large-sheet parts.

Computer modeling using modern software products has shown the mechanism of shaping high-energy submerged liquid jets that transfer this energy to the blank being deformed.

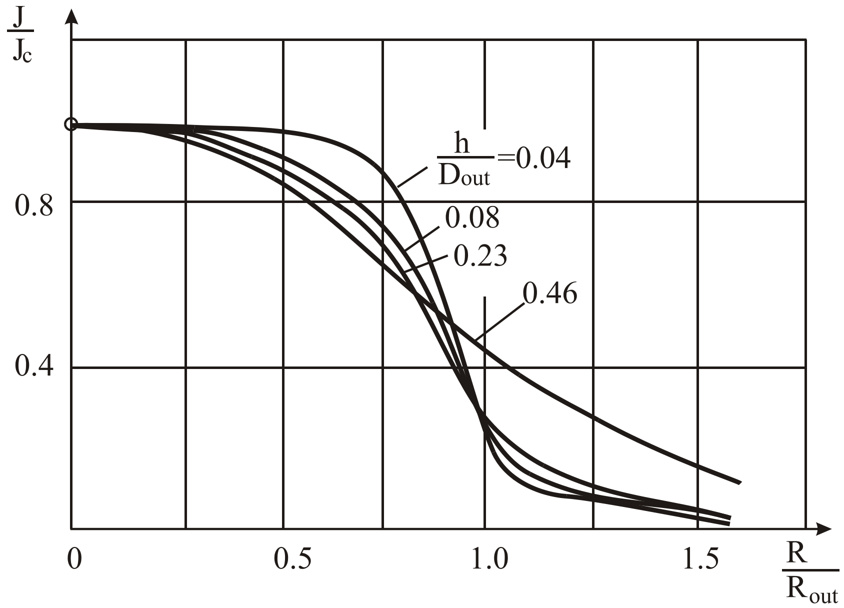

Fig. 12. Load distribution depending on the radius of the axis of a cylindrical ESDI

Experimental results on physical models:

– confirmed the formation of high-energy submerged liquid jets;

– their local effect on the blank being plastically deformed;

– obtained the dependences of the distribution of the density of energy flows along the radius of the impact zone;

– describe the form of local forming for a number of stamping materials;

– record the dependences of the distribution of thinning deformations in the deformation zone of the blank along the stamping radius as a function of the technological parameters of the forming process.

Disadvantages of the research conducted

The main drawback of the conducted studies is their insufficiently complete statistical processing, which is due to the large volume of information.

In modeling and physical experiments, the method of planning experiments is not fully used. This largely depended on the complexity of the experimental work, including the method of synchronization of pulse processes with the modes of the recording equipment. At the same time, the obtained data allow orienting further research in the necessary direction.

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Дослідження процесів формоутворення високоенергетичного затопленого струменю рідини та його взаємодія з заготовкою, що деформується

У статті описано результати експериментальних робіт щодо обґрунтування можливості використання електродних систем спрямованого впливу для електрогідравлічного послідовного штампування великогабаритних листових деталей. Ці системи генерують концентрований потік енергії, яка спрямовується у потрібному напрямку та у визначених місцях. Тим самим ці системи зменшують витрату енергії у довільних напрямках.

Показано, що у великій кількості випадків успішного використання цього виду формоутворення листових деталей розглядається механізм навантаження

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заготовки ударними хвилями, які розповсюджуються в усі сторони розрядного об'єму та переносять певну частку енергії, що виділилась. При штампуванні крупних деталей із-за їх великих габаритів при такому механізмі навантаження частина енергії використовується непродуктивно. Для підвищення ефективності використання енергії необхідно використовувати електродні системи спрямованого впливу.

Дослідженні проводилися поетапно – спочатку попереднє комп'ютерне, а потім – фізичне моделювання.

Проведене комп'ютерне моделювання процесу виявило механізм навантаження заготовки високоенергетичними затопленими струменями рідини. Приведені результати натурних досліджень підтвердили механізм такого навантаження.

Фізичне моделювання проводилося за складними методиками з використанням швидкісної реєстрації руху об'єкту та електричних методів реєстрації параметрів, які швидко змінюються.

Експериментально отримано залежності розподілу густини потоків енергії, яка виходить з розрядних порожнин таких систем. Синтезовано емпіричні залежності густини потоків енергії, імпульсу тиску та інших параметрів в залежності від умов проведення технологічного процесу штампування.

Мета роботи – підвищення ефективності штампування крупних листових деталей шляхом більш раціонального та продуктивного перетворення електричної енергії у роботу пластичного формоутворення.

Поставлені задачі виконані. Отримано висновки, що прогнозують позитивні результати.

Методи, що використані у дослідженні. У дослідженні використано метод комп'ютерне моделювання, експериментальні дослідження, які включають швидкісну фотофіксацію, запис осцилограм імпульсних параметрів.

Ключові слова*:* електрогідравлічне штампування, електродні системи спрямованого впливу, локальне деформування.

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