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Modelling of the process of interaction of multi-impulse local loading at electrohydraulic forming of large-dimensional bottoms

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Abstract. *Forming of large-dimensional thin-sheet bottoms usually leads to great complexity of technological processes. When forming is conducted on mechanical presses using male- and female dies one can observe phenomenon of loosing stability of bottom shape with uniform through perimeter movement of the workpiece flange during drawing and large areas of thin workpiece that do not support by rigid surfaces of the die and are prone to be loaded with compressive stresses. This leads to the formation of folds and corrugations on the flange and dome part. Application of presses for stamping with elastic media and high pressure is irra-tional from energy considerations, because different parts of the workpiece require different pressures for their shaping. Electro-hydraulic (EG) forming is more effective when stamping such parts occurs consequently by zones of the workpiece and require different loading at each zone. It is possible to implement sequence control and load locations on multi-electrode EG-presses.*

Objective of the presented research was, on the one hand, to study the possibility of the formation of pulsed submerged flows of liquid medium, that transmits the load, their interaction with each other and the deforming workpiece in the technological zones of EG presses, and on the other hand, the possibility of using the LS Dyna software in combination with ALE method.

To achieve the specified goal, methods of mathematical modeling of forming processes and interaction of deformed environments having different mechanical parameters were used, as well as experimental methods to confirm the processes being studied.

The results obtained consider the possibility of creation of high energy-containing immersed jets of liquid, their interaction between themself and the deformable workpiece depending on the technological pa-rameters. The parameters of the workpiece deformation process were studied. It is shown that blank shape change has a wave-like character and, by changing the temporal and spatial parameters of the load, it is possible to control the parameters of the blank stress-strain state.

Comparison of simulation results with experimental data substantiated the possibility of using the proposed modelling method in the study of pulsed flows in heterogeneous media.

The conclusions state the achievement of the mentioned goal, describe the mechanism of interaction of liquid jets in the case of energy concentration necessity in the given zones of the workpiece and the possibility of changing the direction of energy flows when the moment of the of EG discharges beginning in adjacent discharge cavities is changed. The accuracy of the simulation results was assessed when compared with experimental data.

Keywords: *electrohydraulic discharge, discharge cavity, blank, impact waves, hydrostream, porous-gas cavity, plastic deformation, deformation work.*

Introduction

Thin-walled large-dimensional articles (TLA) are widely used in in up-to-date machinebuilding. These group of articles include bottoms of different shape-elliptical and semispherical in cross-section and round in the plan, car body articles for different vehicles, space communication antenna mirrors; rigidity panels for air-planes and helicopters, heatexchangers and articles of chemical apparatus. Different requirements to dimensional precision, deformation distribution or residual stress apply to mentioned articles.

Main manufacturing processes for such articles for producing them on widely used sheet-forming equipment in majority are well-proven. But in case of necessity of manufacturing TLA in low-volume production some difficulties appear related to technical-economic parameters of existent manufacturing processes.

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There are such processes for TLA manufacturing by impulse methods: explosive forming with brizant explosive and electrohydraulic forming (EHF) [1], [2]. Presses with large saved energy (up to 500 kJ) and spatial-temporary loading control are developed and used for trial production for the second above-mentioned method of forming [2]. Such presses can be implemented for consequent local forming of TLA.

In view of this the problem for determination rational consequence of loading of deformable blank with different goals appears. These goals can be: maximum energy efficiency, required distribution of deformations to minimize blank sagging or residual stress and also to satisfy other technical requirements. Results of a part of prepared natural experiments and results of trial developing of manufacturing process are shown in papers [2]–[5]. These results are shown high potential possibility of loading control for increasing forming processes efficiency but also high labor intensity and cost of natural studies. Reduction of these parameters can realized by means of numerical modeling of forming processes.

The article presents new results. The parameters of the workpiece deformation process are obtained and investigated. It is shown that the change in the shape of the workpiece is wave-like and, by changing the time and spatial parameters of the load, it is possible to control the parameters of the stress-strain state of the workpiece. Comparison of the modeling results with experimental data substantiated the possibility of using the proposed modeling method in the study of pulsed flows in heterogeneous media.

References review

Quite comprehensive review of equipment, forming schemes and main problems appeared during forming is observed in the [2]. In the papers [3], [4] description of mechanisms of appearing and development of gas-steam cavities, which cause starting of movement of immersed energy jets of liquid is shown. Paper [5] deals with consideration of studies and derivation of numerical values of parameters of electrical energy transformation to gas-dynamic energy form. Results of studies of mechanisms of blank deformation under influence of impulse loading are analyzed in [6]. Paper [7] describes experience of application of LS Dyna software at modelling of processes of EH-forming. Grounding of possibility of loading control for definite tasks is done in the [8]. Article [9] shows the approach and results of studies devoted to estimation of precision of forming process modelling by means of FEM of ALE.

Results of Preliminary Experiments

Preliminary (prearranged) experiments were conducted on trial multi-electrode installation developed by KhAI. On this installation following experimental data were obtained: about shape of locally created blank zone at different consequence of loading and distribution deformation of thinning along radius of loading zone (see below). Manufacturing processes of TLA of different shapes forming were conducted on natural equipment. Trial batches of articles with different shape were formed on trial-industrial press PEG-500 [2].

Some forming results of thin-walled bottoms are shown on the Fig. 1.

Generalized preliminary conclusions are the following:

– at central loading of flat blank one can observe intensive and progressive wrinkles appearing on flange and dome part of a blank (Fig. 1, *a*). Wrinkles (corrugations) move over female die rib and pass to dome part at increasing degree of flange drawing.

During this process blank tearing is observed (Fig. 1, *b*);

– this processes become more intensive with increasing blank flexibility (ratio of blank diameter to its thickness);

– flange non-uniform drawing degree along perimeter of matrix space is observed that can be explained by non-uniform conditions of drawing. To increase uniformity of drawing it is necessary to shift loading zone from the center to zones with less drawing degree;

– higher drawing degree can be realized at definite consequence of local loading (Fig. 1, *b*) but in this case one has to control less thinning on loaded blank zones because elevation of thinning above allowable values can lead to local tearing (Fig. 1, *c*).

Results of determination of thinning distribution on formed article (Fig. 1, *d*) permit to make conclusion that at definite consequence of local impulse loading it is possible to control both the shape of article in wide range and distribution of thinning deformations along article surface. Examples of positive results of consequent local forming of TLA can be found in [2]. For rational application of such technology one has to use computer modelling with application of interrelated mathematical models of processes of load creation and blank deforming.

Conditions of Modelling. The system shown on Fig. 2 is considered. It consists of three discharge cavities immersed to liquid. Deforming blank is disposed below, it is installed on drawing die with diameter 252 mm. Diameter of a blank is 320 mm and it is clamped to the die. Such conditions exclude material drawing from the flange zone to die cavity.

Zone of energy releasing in discharge cavity was located asymmetrically with respect to axis of cavity and at definite spacing from its bottom. This corresponds to real structure.

Geometrical dimensions of model are following:

– diameter of discharge cavity is 40 mm, depth of zone of energy releasing from the edge of cavity − 30 mm;

– spacing of discharge cavities location − 60 mm;

– distance from the edge of discharge cavity to blank was selected in four variants: 40, 32, 20 and 12 mm. This corresponds to relative distances of discharge d/h

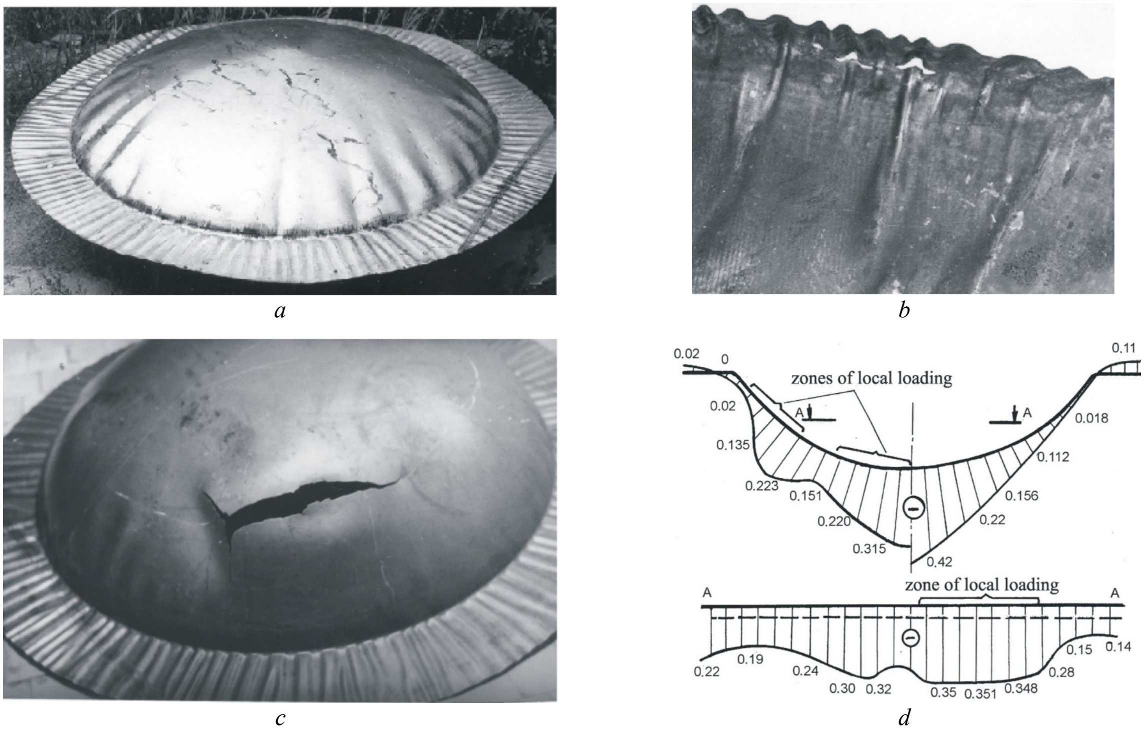


Fig. 1. Typical examples of defects at forming of thin-walled sheet large-dimensional bottoms [2]: *a* – intermediate shape of a blank after central loading, diameter of drawing rib of female-die is 1050 mm, diameter of semi-finished article is 1480 mm, material – steel X18H9T with thickness 1.6 mm; *b* – progressive wrinkle-creation after consequent forming stages: wrinkles can be seen which transfer ty dome part and torn zones at the tops of wrinkles; *c* – blank discontinuities at the zone of bending local loading; *d* – distribution of logarithmic deformations of thinning at local consequent loading over entire surface (at the left) and central loading (at the right) of a bottom with diameter 1070 mm, depth is 415 mm, material – steel 08kp, thickness is 1.6 mm. Diametral section is above, latitudinal section is below. Bold line-article outline, dashed line-distribution of εδ in latitude direction at central loading

equals to 1.0; 0.75; 0.5 and 0.25. The last value is the most close to experimental conditions.

The model equations are solved in a Cartesian coordinate system.

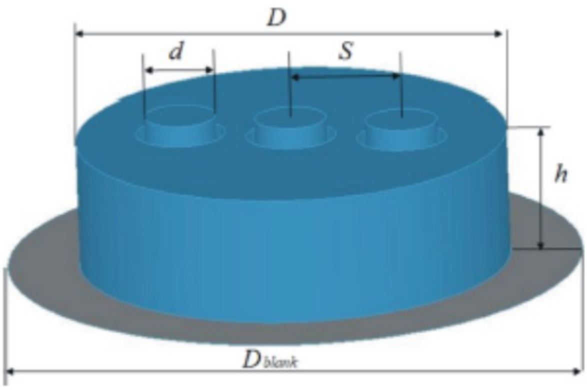


Fig. 2. Triple-planed analysis scheme of numerical modeling: *D* – chamber diameter; *d* – discharge cavity diameter; *S* − spacing between axes of immersed chambers; *h* − discharge spacing; D_{blank} − blank diameter

Consequence of numerical experiment was selected as following.

1. Mechanism of blank deforming was considered at single discharge at central discharge cavity on selected distances;

2. Mechanism of impulse loading appearing was considered at discharges in two cavities (central and side) shifted in time;

3. Interaction of three discharges was considered: in two side cavities simultaneously and in central cavity − shifted in time.

Analysis of energy releasing process at high-voltage underwater discharge was considered at condition that definite quantity of heat energy (9.375 kJ) releases during 32 μs in the volume of channel with continuous conductivity. In this case energy losses on impact waves creation, electrode material evaporation and heat losses were not consider at all.

Thus power function of heat releasing is assumed to be a triangle with height 400 MW and basement 32 μs. These values come in an agreement with analogous parameters given in the paper [5].

Blank had diameter 320 mm and thickness 1.0 mm. Its material is considered to be elastic-plastic aluminum alloy with deformation strengthening describes as following power law.

$$\sigma_T = Ae^n ,$$

where A = 604.9 MPa; n = 0.275.

Original value of yielding strength is 100 MPa, density – 2100 kg/m^3, elasticity modulus – $7{\cdot}10^{10}$ Pa, Poisson's ratio 0.33. These mechanical properties correspond approximately to widely used aluminum alloys like AMg6 or D16AT.

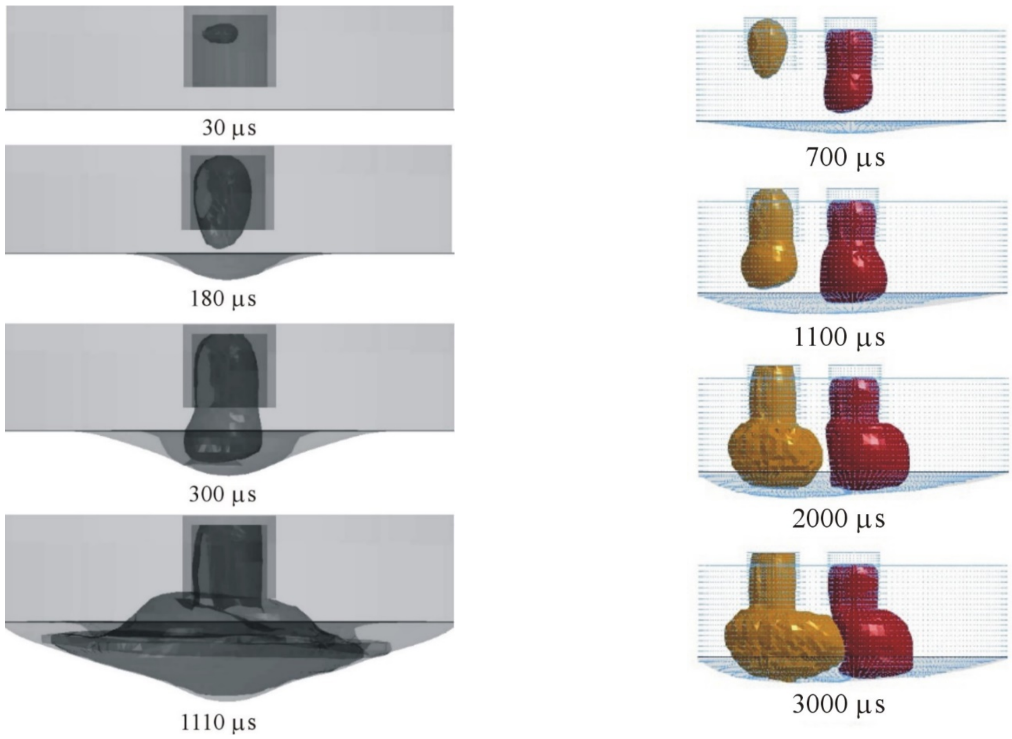
Modeling was conducted in medium LS-DYNA by means of ALE [3], [7] method application.

For numerical experiments following parameters of analysis scheme was selected:

– high-voltage discharges are conducted in central discharge cavity (DC) and simultaneously in central and two side DC with the same level of released energy;

– discharges spacing with respect to a blank h were selected as a consequence: 40 (1.0*d*), 32 (0.75*d*). 20 (0.5*d*) and 12 (0.3*d*) mm that corresponds to conditions of natural experiments.

Results of Researches. At realization of the first stage, i. e. modelling of process of interaction single impulse jet with blank following situation was met – developing of steam gas bubble (SGB) inside DC, SGB leaving out and distribution in space of transferring medium between side of DC and blank, interaction of jet (directed by head part of SGB of liquid stream) with blank (Fig. 3).



a *b*

Fig. 3. Consequence of porous-gas bubble development: *a* – at single discharge and bubble interaction with deformable blank at spacing 12 mm (0.3*d*); *b* – at double electrode discharge

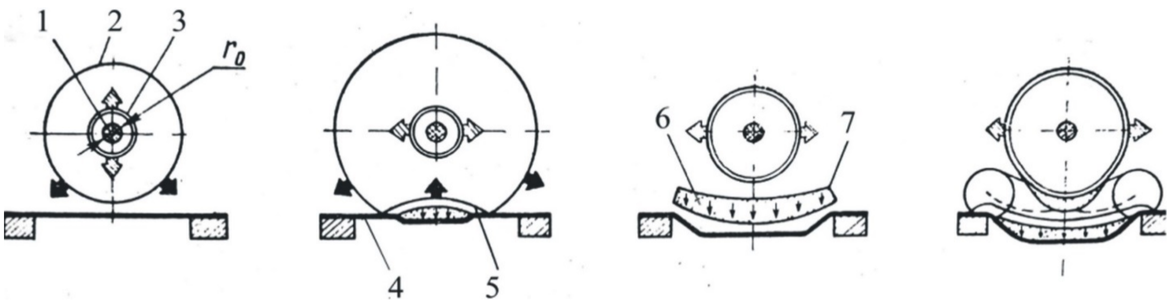


Fig. 4. Schematic imaging of interaction of impulse loading with thin-walled blank at charge explosion in water [6]: *1* − charge; *2* − impact wave front; *3* − SGB boundaries; *4* − blank; *5* − reflected wave of compression; *6* − cavitation zone; *7* − upper boundary of cavitation zone

During first 30 μs after beginning of energy releasing (32 μs) impact waves leave discharge zone (not shown on Fig. 3), then waves distribute at first in DC and then pass through the side of DC. Velocity of waves movement from side to direction of blank lays in the range 1600…1900 m/s. They lead to beginning of blank movement and create directed to blank the field of liquid velocities movement. After that boundaries of SGB begin to move at first in frames of DC rigid boundaries and then in space between DC side and blank. SGB become stretched egg-like shape and its head part pushes ahead definite volume of liquid which supports blank has begun to move. Next stage is the following: axial translation of SGB boundaries starts to change its direction (frame 300 μs), i. e. horizontal components of SGB boundaries movement appear. This leads to non-productive kinetic energy consumption of moving liquid.

On the frame 1110 μs one can see definite zone of selected analysis scheme – low width of rigid wall of DC, which is began to be enveloped by SGB at its expansion upper (out of blank. In future this drawback was eliminated).

At the beginning of deformation blank takes convex axis-symmetrical shape. Then this monotonic convex shape begins to distort – zones with non-monotonic shape as movable wave appear in transversal section. This distortion of shape is shown with arrow on the frame 1110 μs.

Deforming impact-waved zone of blank has the shape of truncated cone basement boundaries of which move to boundaries of blank clamping.

Analysis of plate movement at such conditions shows that two types of waves distribute in blank: longitudinal and transversal. They move with different velocity which depend on stress-strain state parameters. Changing of this state under influence of impulse jet loading has complicated waved character (Fig. 5). Deformations of thinning (third principal deformation) appear inside epicenter of loading and my means of longitudinal waves transfer to peripheral zones of deformation. This considerations are adjusted well between each other.

To estimate adequacy of used mathematical model to real process it was decoded to conduct comparison of results got with experimental results given in the paper [2]. Fig. 6 shows frames from high-rate photo registering the process of leaving of liquid impulse jet from horizontally disposed DC and interaction of jet with perpendicularly installed rigid plate (Fig. 6, *b*) and the same plate but which applies angle with respect to cavity axis (Fig. 6, *c*). It can be seen consequently on frames that at first the cloud of small energy particles are removed from DC cut and then move in axial direction. This cloud is braked up by impact wave (foggy zone). Then certain morphosis (black color) having cylindrical shape appears and leaves at the cut. This is immersed liquid jet moves away from the chamber side, begins to expand in sides and then close up with rigid plate.

At interaction of sloped plate with jet the last expands in radial direction nonuniformly: at less gap between chamber edge and plate radial expansion is less than at large gap. One can see a sort of jet changes direction to the side of more gap.

Frame-by-frame increment of both time and velosity of jet side translation are comparable in numerical and natural experiments.

This permits to make conclusion about quite adequate numerical model to reality in respect with of mechanism of jet leaving from DC and jet interaction with rigid blank.

It is possible to compare shapes of obtained local formings and distribution of logarithmic deformations of thinning by means of results of natural experiments and numerical modelling (Fig. 7). One can see that at comparison of dependencies predefined shape of local forming climbs above value of natural local forming depth in center on 30 %. It can be explained by certain non-compatibility of mechanical properties of natural blank (aluminum alloy АМцАМ) and blank thickness: natural blank has thickness 1.5 mm but modelled – 1.0 mm.

Calculated value of thinning in center of local forming equals to 0.13, that twice less that natural blank has. This mismatching also can be explained by the same reasons.

Based on above-mentioned considerations one can make conclusion that used in numerical analysis mathematical model is adequate to reality from the point of view of SGB developing mechanism and SGB interaction with deformable blank but not very precise at calculation of thinning deformations and shape of local forming.

Compressing of impulse jet from side, i. e. increased resistance of jet to spreading in horizontal direction has to stipulate more effective usage of released energy at electrohydraulic discharge. This is possible to realize by generation of pressure increasing in liquid by sides of main jet.

For numerical modelling of such process triple-cavity analysis scheme was used (see Fig. 2). Saved energy releases simultaneously or with definite shifting in time in three DC. Illustration of final stages of such process is shown on Fig. 8. One can see as side SGB compress central one and as consequence concentrate its energy in direction to blank. At different time delay values degree of compression of central (main) SGB is different. Optimal delay time of discharges in side SGB equals to 300 μs in considered variants of structural-manufacturing parameters values of given analysis scheme. But value of this optimal time depends on distance of blank disposing from discharges zone, released energy in side cavities and spacing between cavities.

Center of blank loading zone with impulse jet it is possible to shift in frames of definite range at double discharge. This mechanism of jet controlling rationally to use at calibration stage of zone of conjunction of sides with bottom of box-like article.

Kinetics of blank behavior at delaying of side discharges with respect to central one can be demonstrated by temporal dependences of velocity and translations of reference points (Fig. 9 and 10).

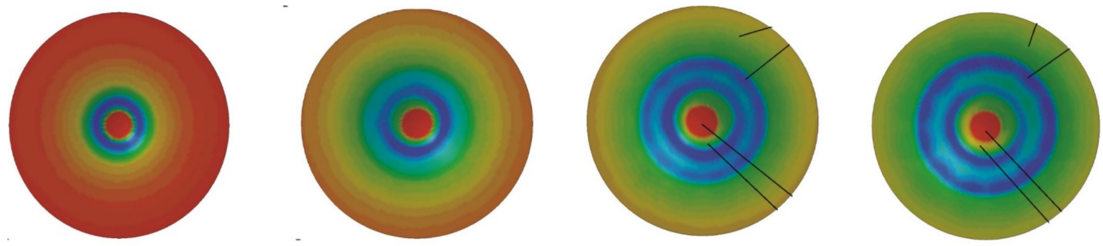


Fig. 5. Character of changing of the third principal strain at impulse loading at the distance 12 mm (0.3 *d*/*h*)

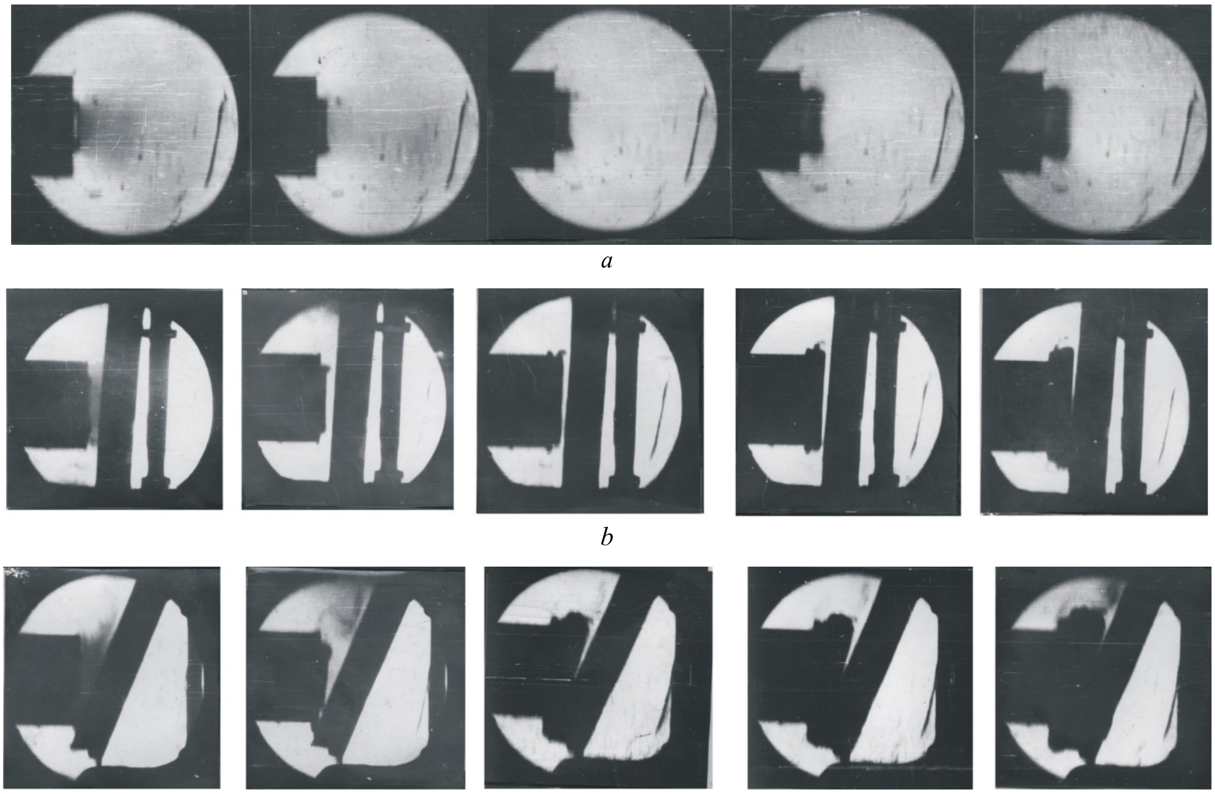


Fig. 6. High-rate photo registering-gramma of impulse jet appearing process at electrohydraulic discharge in low volume chamber with cylindrical inner cavity: *a* – original stage of SGB leaving from DC – leaving of small particles of liquid under impact wave influence (frame 1) and cylindrical SGB leaving (frame 3, 4 and 5), time between frames is 64 μs; *b* – interaction of cylindrical shape SGB with rigid barrier, installed perpendicular to DC, time between frames is 96 μs; *c* – interaction of SGB with sloped rigid barrier, time between frames is 96 μs [6]

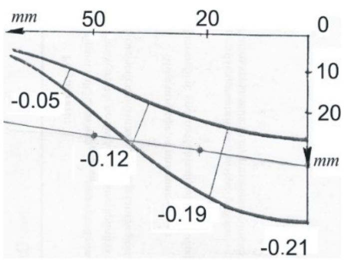


Fig. 7. Shape of local forming (half of diametral section) – bold line with values; distribution of logarithmic deformations of thinning – bold line; estimated shape of local forming – thin line with dots [2]

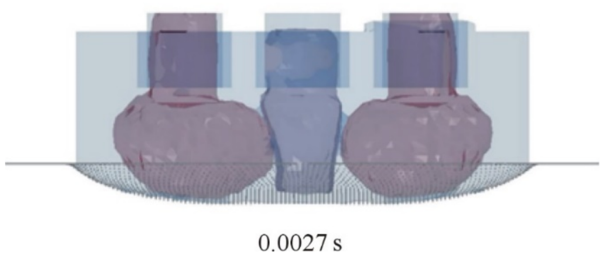


Fig. 8. Longitudinal section of triple SGB interacting with deformable blank at equal value of energy released in each DC and delay of electrohydraulic discharges in side LC on 300 μs and spacing 40 mm

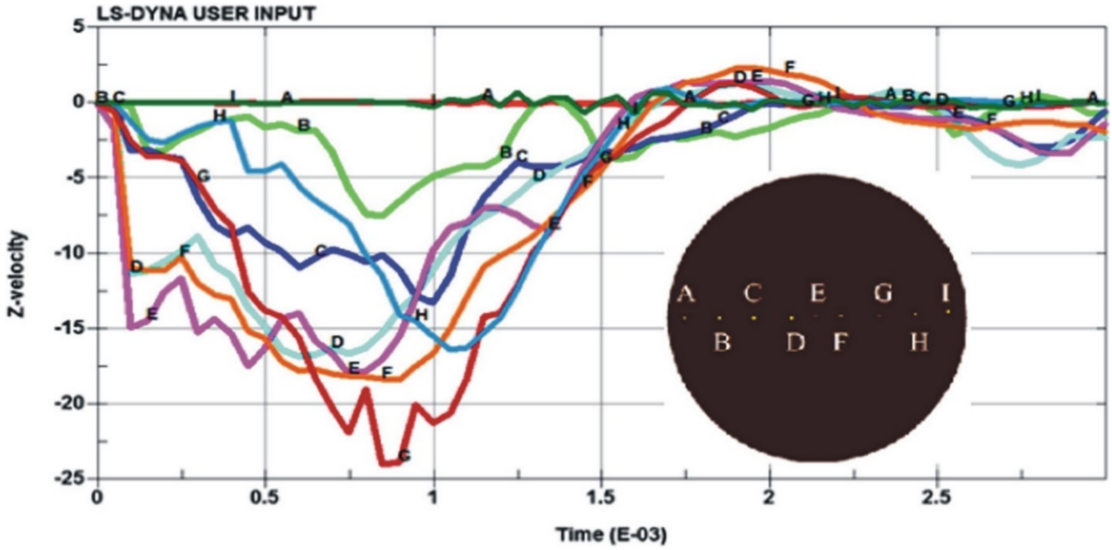


Fig. 9. Dependence in time of blank reference points shifting rates at triple discharge with delay 300 μs

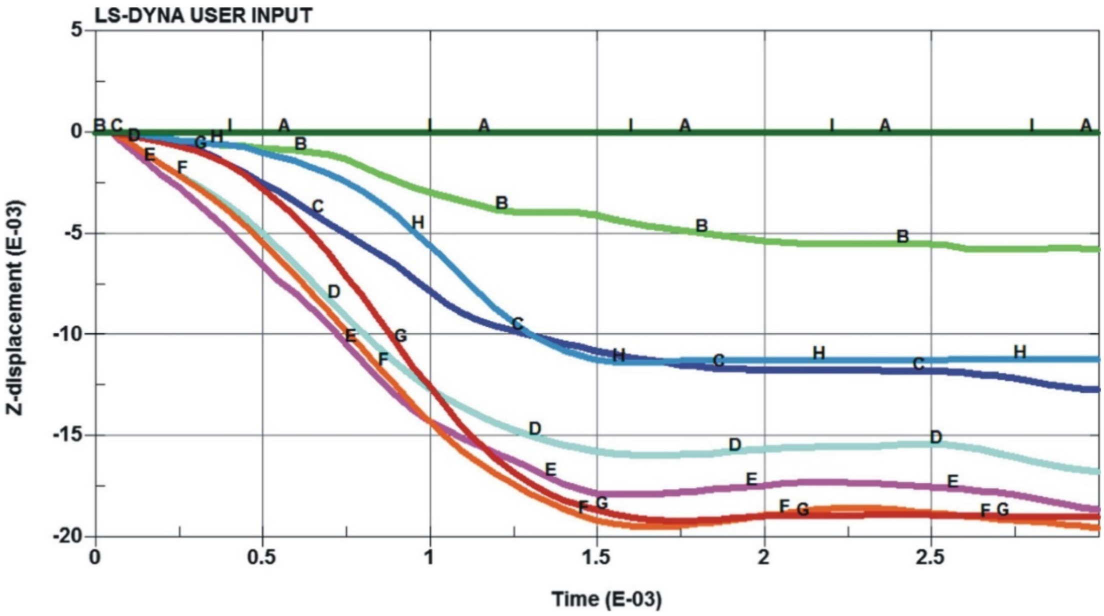


Fig. 10. Dependence in time of blank reference points translations at triple discharge with delay 300 μs

From the process beginning central zone of a blank (points *D*, *E*, *F*) start intensive movement which continues during 190 μs, i. e. moment of energy releasing in central DC. It is possible under impact waves influence only. Then uniform accelerated movement of this zone stops but movement of peripheral zones of blank starts. After that dependence of the velocity on time has monotonic growing character. It can be called as oscillatory and velocity of central point reaches values up to 25 m/s. After reaching maximum (duration is about 0.5…1.0 μs) decelerated motion starts which also has oscillatory character. After total running out negative (reversed) movement with oscillations can be observed. Suspectedly these oscillations can be explained by elastic aftereffect.

Dependencies of blank points translations in time have monotonic character (Fig. 10). Velocities oscillations are not shown at this figure because velocity oscillation period is quite low (up to 30 μs) and comparing with scale of temporary dependencies is not seen. One has to pay attention that maximum deflection is shown not in the blank center (point *E*) but at epicenters of side discharge cavities (points *F* and *G*) that is quite understandable. Blank plastic deformation appears in DC epicenter (point *A*, Fig. 11) in which first by time discharge is conducted. Three focal points of plastic deformation in corresponding epicenter appear in case of energy releasing simultaneously in three DC. Deformations spread in wavy mode as ring zones from blank center to peripheral zones after plastic focal point appearing. Duration of this process of deformation close to 1.0 μs that corresponds to duration of maximum sagging of blank central zone (Fig. 10).

It is easier to estimate quantitative indexes of intensive deformation changing as function of time by graph shown on Fig. 11. It can be seen that developing and accumulation of parameter $\dot{\varepsilon}_i^{plast}$ differs for different points. For point A close to blank center and point *E* close to die rib accumulation of plastic deformations happens monotonically with average deformation rates, for point *A* it equals to 14×10^2 s^{-1} and point *E* − 49 s^{-1}. Accumulation of plastic deformations in points *B*, *C*, and *D* occurs non-monotonically, in stepped way. It is result of waved deformation accumulation. Average deformation rate in these points close to 20…30 s^{-1}. Velocity of plastic deformation wave distribution from point *A* to point *B* equals to 240 m/s, but in point *B* and point *C* − 54 m/s. These values of waves velocities of deformation transferring to a blank significantly less that velocity of sound in aluminum alloy in 20 times (sound wave is an elastic distortion).

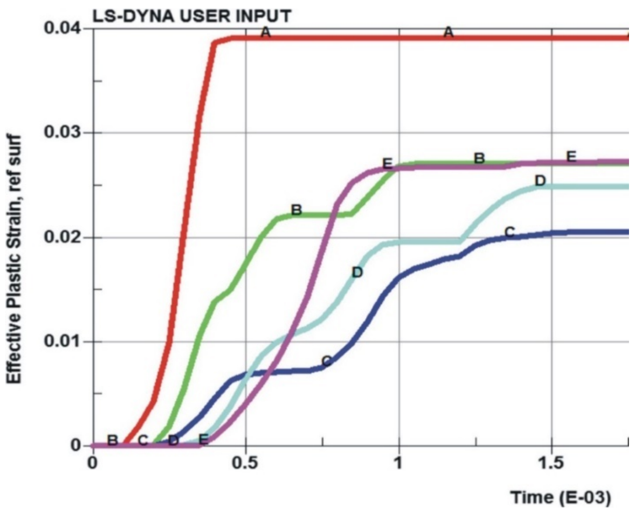


Fig. 11. Temporary dependence of plastic deformation intensity ($\dot{\varepsilon}_i^{plast}$) for correspondent points of a blank at double power developed. Duration of energy releasing is 16 μs. Increment of points is near 27 mm, point *A* is disposed at the center of a blank

Comparison of deformation velocities at the blank center for loading variant in triple-cavity discharge system with duration of energy releasing 32 μs and variant under consideration shows, that in first variant even at releasing factually triple quantity of energy average deformation rates at point located near female die rib are equal to 14 s^{-1} that is in 4 times less comparing with variant considered. In another words one can say that blank deformation rates become more with increasing rate of energy releasing and this growing prevail over the rate of parameter growing as function on quantity of energy released.

As confirmation of possibility to control sheet blank deformation rate in quite wide range one can consider selection of optimal combination of electrical parameters of discharge circuit which is very important for creation of necessary regime of vibroimpulse loading to reduce deformation warping of such kind of articles [4], [5].

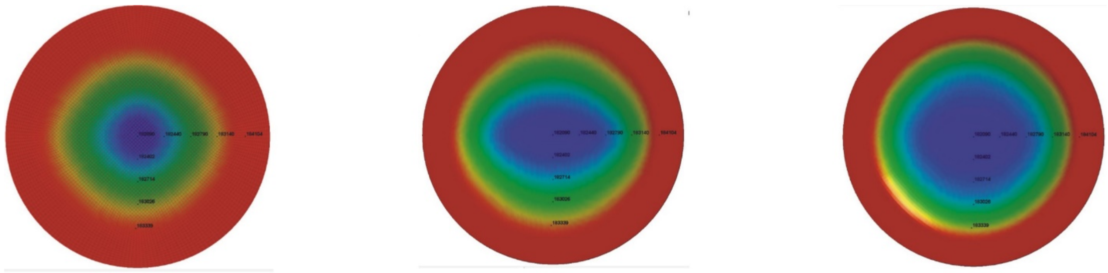
One has to mention that intensive oscillations of blank zones disposed out of direct influence of immersed jet. Maximum of displacements shift periodically over poor deformable field of such zones (Fig. 12) that corresponds to obertons of oscillations. This evidences about complicated oscillational process of deformable blank.

One can suggest that fixation of obertons is stipulated by influence of transversal waves reflected from rigidly clamped perimeter of blank, velocity of these waves distribution is near several dozens meters per second, the intensity of the waves reduces sharply close to blank center.

More deep studying of such oscillation process is very important since one can determine conditions of resonance at which elevation of plastic properties of blank material happens and also conditions for higher degree of residual stress (deformational) relaxation occurs.

Estimation of precision for developed mathematical model

Estimation of the precision and adequacy of synthesized mathematical model in comparison with experimental results have shown poor correlation between experimental and analytically calculated parameters by the shape of local stamping up to 20 %, but by the depth of stamping – up to 40 %. Analysis of values of such deviations allows us



700 μs 1250 μs 2200 μs

Fig. 12. Demonstration of oscillations in vertical directions of blank zones translations, located out of direct loading zone

to make the following conclusions. The first – experimental values of parameters have been obtained for a material with unknown model of plastic strengthening. In the analytical model power function for simulation of exact metal grade strengthening was used. But multiple literature sources recommend to use for such kind of analysis the model of Jonhson-Cook. The second – physical-mechanical conditions of experiment don't correspond to analytical one fully.

This is why the comparison of developed mathematical model having specific features (high values of deformations of analysis grid etc.) at modelling of simpler scheme of deformation, i. e. free expansion of cylindrical shell was conducted. This modelling was done with very fine increment by the time and with application of Jonhson-Cook strengthening model up to the full completing of expansion process. Then the shape of a shell was compared with one obtained at conditions of static expansion. Results of such research are observed in the [9]. Very briefly one can conclude them as following:

– calculation errors of main mechanical properties don't exceed 2 %:

– the best precision (0.43 %) is found for pressure value, which is the main factor that influences electrohydraulic forming quality and processing object.

These results show that calculation process for solving equations of electrohydraulic forming by means of FEM-ALE is asymptotically stable.

Conclusion

1. Conducted numerical modelling for process of interaction of impulse jet with deformable blank at electrohydraulic forming have shown qualitative adequacy of used model both for the stage of jet deformation, displacement in operational volume and at the stage of blank deformation. Numerical analysis has revealed possibility of controlling ang concentration of energy released in space and time.

2. At the same time comparison of numerical results with natural experiment has shown necessity of correction of used model by the parameters of blank material mechanical properties and parameters of analysis scheme.

3. Numerical experiments allowed to make more precise and effective the structure of energy-releasing cell, i. e. the group of seven operational cavities united in one block in which discharges are realized with definite delay in time. Exact energy-releasing cell has to be moved by definite trajectory over blank surface.

4. Blank deformation by impulse jet has waved oscillation character. In this case the changing rate of plastic deformation intensity varies in wide range from 1400 s^{-1} to 14 s^{-1} for different zones of a blank. Velocities of plastic deformation wave distribution vary from 240 m/s to zero value. In first turn these parameters depend on duration of energy releasing and then on its quantity.

5. Further researches with application of developed mathematical model allow to optimize processes of consequent local forming of large-dimensional sheet articles.

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Моделювання процесу взаємодії багатоімпульсного локального навантаження при електрогідравлічному штампуванні великогабаритних листових днищ

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Анотація. *Штампування великогабаритних тонколистових днищ зазвичай призводить до великої складності технологічних процесів. При формоутворенні на механічних пресах з використанням пуансона та матриці часто виникає втрата стійкості формоутворення з нерівномірним за периметром рухом фланцю заготовки при витягуванні та великими ділянками тонкої заготовки, які не спираються на жорсткі поверхні оснащення, та схильні до сприйняття стискаючих напружень. Це призводить до утворення складок та гофрів на фланці та купольній частині. Використання пресів для штампування еластичними середовищами з високим тиском нераціонально за енергетичними міркуваннями, тому що різні частини заготовки потребують для свого формоутворення різного тиску. Більш ефективними при штампуванні таких деталей є послідовне за ділянками заготовки та локальне за зоною навантаження електрогідравлічне (ЕГ) штампування. На багатоелектродних ЕГ-пресах можливо реалізувати управління послідовністю та місцями навантаження.*

Метою представленого дослідження було, з одного боку, вивчення можливості утворення імпульсних занурених потоків рідкого середовища, що передає навантаження, їх взаємодії між собою та заготовкою, яка деформується, у технологічних зонах ЕГ-пресів, а з іншого боку, можливість використання програмного продукту LS Dyna у комбінації із методом ALE.

Для досягнення зазначеної мети використовувалися методи математичного моделювання процесів утворення та взаємодії середовищ, які деформуються, та мають різні механічні показники, а також експериментальні методи для підтвердження процесів, які вивчаються.

Отримано результати про можливість утворення високоенергетичних занурених потоків рідини, їх взаємодії між собою та заготовкою, що деформується, в залежності від технологічних параметрів. Досліджено параметри процесу деформування заготовки. Показано, що її формозміна має хвилеподібний характер та, змінюючи часові та просторові параметри навантаження, можливо керувати параметрами напружено-деформованого стану.

Порівняння результатів моделювання з експериментальними даними обґрунтувало можливість використання запропонованого метода моделювання при вивченні імпульсних потоків у гетерогенних середовищах.

У висновках стверджується досягнення поставленої мети, описано механізм взаємодії струменів при необхідності концентрації енергії на заданих ділянках заготовки та можливість повертання напрямку потоків енергії при зміні моменту початку ЕГ-розрядів у сусідніх розрядних порожнинах. Оцінено точність результатів моделювання при порівнянні з експериментальними даними.

Ключові слова: *електрогідравлічний розряд, розрядна порожнина, ударні хвилі, гідропотік, паро-газова порожнина, пластична деформація, робота деформації.*