UDC 681.5:519.24:621.74
DOI: 10.15587/2706-5448.2021.247667
Article type «Reports on Research Projects»

Sergii Shlyk

APPLICATION OF INTELLIGENTLY CONTROLLED TECHNOLOGIES IN DESIGNING OF TECHNOLOGICAL PROCESSES FOR EXPLOSIVE FORMING OF SHELL PARTS

The object of research is the processes of pulse metalworking (hydroexplosive, magnetic pulse, electrohydraulic, gas detonation forming, etc.). Among these methods of forming for the production of aircrafts engines parts from cylindrical and conical blanks, the most efficient in terms of its energy capabilities and overall dimensions is explosive. The modern level of theory and practice of metal forming processes allows, on the basis of a systematic approach and control theory, to determine the optimal parameters of plastic forming processes, select the best technical solutions, and create a precondition for the transition to complex automation. The most difficult task of metals forming methods optimizing is to find the best solution among many potentially possible ones, considering the introduced restrictions and efficiency criteria, environmental, economic, technical, ergonomic, and other requirements. The most problematic is that it is impossible to optimize the process of forming post-factum (finishing works, elimination of defects in shape and size, welding of cracks, etc. are required), therefore, when solving optimization problems, the implementation of the feedback principle is required – comparison of the value of the controlled variable, determined by the control program, with the desired value. In general, the processes of metal forming by pressure are characterized by a variety of problems of the theory of optimal control, the solution of which is carried out by methods of mathematical programming. And, although the equipment for pulse processing can have a different design, it necessarily includes structural elements that make it possible to convert the energy of the source and with its help (through the action of a solid body, transmitting medium, or field) to deform the metal of the workpiece. Due to this, in this work, it is proposed to control the quality of the obtained parts by varying the degree of deformation of the workpiece in the process of forming. The result of the work is the development of an integrated intelligent system, with the help of which it is possible to carry out the computer-aided design of almost all pulse-action processes based on the intelligent selection of suitable forming parameters.

Keywords: *explosive forming, shell part, aircrafts engines parts, weld seam, intelligent system, finite element method.*

Received date: 13.05.2021
Accepted date: 15.07.2021
Published date: 21.12.2021

How to cite:
Shlyk, S. (2021). Application of intelligently controlled technologies in designing of technological processes for explosive forming of shell parts. Technology Audit and Production Reserves, 6 (1 (62)), 6–13. doi: https://doi.org/10.15587/2706-5448.2021.247667

1. Introduction

All the variety of methods for manufacturing shells with the energy of an explosion can be reduced to two principal forming schemes: protrusion and crimping. In the first case, the workpiece is deformed along with a rigid die, and the pulse load is applied to the inner surface of the shell. In the second case, an external load is applied to the outer surface of the workpiece, which compresses the punch. The main advantage of the protrusion scheme is that the workpiece simultaneously serves as a container, in which the transmission medium is contained. This allows for the forming of shells in open areas without the use of special explosive devices (pools, armored pits, and similar equipment).

The second, more significant advantage of the protrusion scheme is that the explosion of a charge of a high explosive is carried out under conditions close to an explosion in a confined space, and the efficiency of the explosion is much higher than in the case of crimping. It should also be noted, that modern approaches and methods of designing technological processes of forming by explosion and others are carried out using methods of addressing, synthesis, pattern recognition, and an ontological approach. Given the rapid change in production and its small-scale nature, it is advisable to use complex mathematical models.

A complex of theoretical and experimental studies on the forming of flat and cylindrical thin-walled workpieces was carried out by the author of [1]. He introduced the concept of «effective pressure» P_{max} and «effective pulse»

J, which made it possible to significantly simplify the equations of motion since in this case the function $P(z, t)$ is replaced by its effective value. The author of [1] showed that to determine the final deformation, the load and pulse can be replaced with a constant value. Plastic deformation y of cylindrical and conical blanks is a functional of the form:

$$y(z,t_{end}) = F\left[\Phi(z)\cdot\psi(t)\right], \qquad (1)$$

where $\Phi(z)$ – pressure distribution function along the z axis; $\psi(t)$ – pressure change function over time; t_{end} – the end time of the pulse pressure.

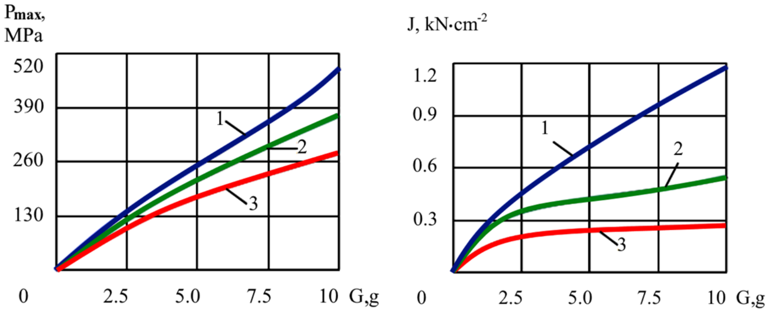
One of the main parameters, by which the nature of the possible destruction of the workpiece material during explosive forming is determined in the field of the external load, generated by the concentrated charges of the explosive. For explosive forming at the JSC «Motor Sich» (Zaporizhzhia, Ukraine), spherical charges are used, and explosions occur in equipment with a certain configuration.

For solving problems of dynamic fracture, a detailed analysis of the physical mechanism of fracture under shock-wave loading is of great importance. Fracture surfaces are always formed as a result of the previous plastic flow, but its intensity and contribution to the fracture process depend significantly on the amplitude and time of action of stress waves. The main goal of studying this type of fracture is to establish a functional relationship between the breaking stresses and the load parameters. The relationship between stress and time makes it possible to obtain the most complete information about the resistance of a material to fracture, such as the change in the velocity of movement of the free surface of the sample of the material under study, the size of the crack, the shape of the load pulse, and the velocity of movement of the breakaway parts.

Thus, the *object of study* is the processes of pulsive explosive loading in an explicit formulation for modeling complex nonlinear dynamics of solids, liquids, gases, and their interactions, associated with the transition from a stationary deformation zone to a nonstationary one with force intensification. *The aim of the work* is to improve the technical and economic indicators of technological processes of pulsed metal processing by developing control and diagnostic tools based on the laws of metals shape change under the influence of pulsed action and calculating energy-power parameters.

2. Methods of research

To analyze the plastic deformation under pulse loading of cylindrical and conical workpieces, its one-dimensional flow is considered. The method of solving approximate equilibrium equations together with the von Mises-Hencky [2] plasticity condition is used. The dependences $P_{max}=f(G)$ and $J=f(G)$ (where G is the explosive charge mass) are constructed by the author of [1] for equipment, the geometry of which is a copy of the real equipment, used for stamping serial parts. Charts of these dependencies are presented on Fig. 1.



a

b

Fig. 1. Dependence from the mass of the charge G: *a* – maximum pressure P_{max}; *b* – pressure pulse J

The limiting state of pulse-deformed materials should be determined by the criteria of deformability, plasticity resource, stress state indicators, taking into account the limiting deformation rates and the dynamic nature of stresses. In the technological processes of the expansion of shells with the energy of the explosion, the central location of the explosive charge is mainly used [3]. Usually, in production conditions, the sequence for determining the parameters of explosive shaping is recommended as follows. The dynamic compression (tension) diagram is used to determine the ultimate uniform deformation. By the value and overall dimensions of the part, we determine the amount of charge for the forming processing according to the dependence:

$$G = 1.5\sigma_b F \varepsilon_p S^2 D_{\max}^2, \qquad (2)$$

where G – the explosive charge mass; σ_b – temporary resistance; F – the surface area of the die engraving (formed part); ε_p – current strain intensity; S – part thickness; D_{max} – the largest diameter of the inner surface of the die (formed part).

Based on the following assumptions [4–6]:

a) we consider a sufficiently thin shell, which allows us to consider the distribution of stresses throughout the thickness to be uniform;

b) the shell material is incompressible;

c) shear stresses are small [7];

d) the mass of the shell does not change during deformation [8, 9].

Then the equation of deformation of the shell takes the form:

$$\frac{d^2 r}{dt^2} + \frac{\sigma_i}{\rho r} = \frac{1}{\rho\delta}\cdot P(t), \qquad (3)$$

where r – current radius; ρ – material density; δ – shell thickness; σ_i – stress intensity.

The pressure over time t dependence $P(t)$ on the right side of the equation can be written as [3]:

$$P(t) = P_m \exp(-t/\theta), \qquad (4)$$

where θ is the explosive time constant [10, 11].

The dependence of the time constant θ on the magnitude of the charge and its distribution over the shaping are shown in Fig. 2. The value of θ decreases with an increase in the value of the charge *G*, while the distribution over the shaping has the same character as in pressure P and pressure pulse *J*.

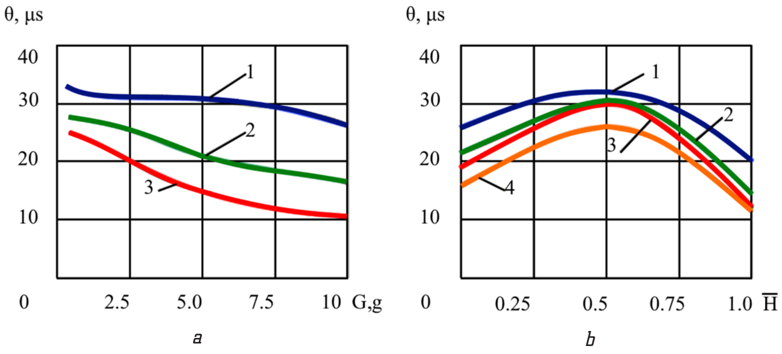


Fig. 2. Dependence of the time constant θ from:
a – the charge magnitude G; *b* – the charge distribution on the forming equipment for fixed charges 1 – 2.5 g; 2 – 5 g; 3 – 7.5 g; 4 – 10 g

We introduce a system of dimensionless parameters, where:
– dimensionless radius:

$$R=\frac{r}{r_0};\tag{5}$$

– dimensionless time:

$$\tau=\nu t,\tag{6}$$

where $\nu=\sqrt{\frac{\sigma_s}{\rho r_0^2}}$;

– dimensionless velocity:

$$V=R;\tag{7}$$

– dimensionless complex:

$$V_m=\frac{P_m\cdot r_0}{\sigma_s\delta_0}\nu_0.\tag{8}$$

Differential equation of motion (3) taking into account dimensionless parameters (5)–(8) takes the form:

$$R''+\frac{1}{R}=\frac{V_m}{\nu\theta}R\exp(-\tau/\nu\theta),\tag{9}$$

and the initial conditions in the new variables are:

$$R=1,\ V_o=R_o^{'}=0.\tag{10}$$

Since at the beginning of deformation equation (9) is simplified:

$$P''+1=\frac{V_m}{\nu^{\theta}}\exp(-\tau/\nu\theta),\tag{11}$$

then, integrating it under the initial conditions (10), we obtain an asymptotic solution close to the exact one for small *R*:

$$R'=V=V_m\left(1-\exp(-\tau/\nu\theta)\right)-\tau,\tag{12}$$

$$R=1+\nu_m\tau-V_m\nu\theta\left(1-\exp\left(-\frac{\tau}{\nu\theta}\right)\right)-\frac{\tau}{2}.\tag{13}$$

Upon reaching the maximum speed of the shell acceleration *R*″=0, it follows from (11) that:

$$\tau=T=\nu\theta\ln\frac{V_m}{\nu\theta}.\tag{14}$$

Substituting the value *T* into equation (14), we obtain:

$$R_T=1+\nu\theta V_m\left(\ln\frac{V_m}{\nu\theta}-1\right).\tag{15}$$

From formula (15) we conclude that R_T increases with increasing V_m; that is, the deflection of the workpiece increases.

As can be seen from expression (8), V_m in turn, depends on the parameters of the external load. The higher the pressure, the higher the value of V_m, the more the shell deforms.

In [12], the possibilities of using software packages that use an explicit method for solving the equations of continuum mechanics in problems of nonstationary processes, accompanied by high strain rates, are considered. Ansys AUTODYN is an example of such an application – a software tool that provides a wide range of simulation capabilities.

To build a «stress-strain» diagram for a material, subjected to explosive forming, the authors of [12] propose to use the following dependencies:

$$\begin{cases}\sigma_i=C(\varepsilon_o+\varepsilon_i)^n\\ \sigma_1=C(\varepsilon_o+\varepsilon_1)^n\\ \sigma_2=C(\varepsilon_o+\varepsilon_2)^n\\ \sigma_3=C(\varepsilon_o+\varepsilon_3)^n\end{cases},\tag{16}$$

$$\frac{\partial^2\sigma_i}{\partial\varepsilon_i^2}=n(n-1)C\varepsilon_i,\tag{17}$$

$$\sigma_2=\sqrt{\sigma_1\cdot\sigma_3},\tag{18}$$

$$\sigma_i=\frac{3}{2}H\varepsilon_i^n/\left[0.29-2D+\ln C_3\left(n_c+0.75\varepsilon_i^n\right)\varepsilon_i^n\right],\tag{19}$$

$$n=\frac{\lg\sigma_3-\lg\sigma_1}{\lg(\varepsilon_o+\varepsilon_3)-\lg(\varepsilon_o+\varepsilon_1)},\tag{20}$$

$$C=\frac{\sigma_1}{(\varepsilon_o+\varepsilon_i)^n},\tag{21}$$

where σ_1, σ_2, σ_3, ε_1, ε_2, ε_3 are the current values of stresses and deformations, passing through the points of the curve of actual strains ε_i; *C*, *n* – the constants, which are satisfying the system of equations (16); σ_i, ε_i – the stresses and the strains intensities. *D* – detonation velocity of the explosive (Chapman – Jouguet condition [13, 14] for the pressure at the detonation front is used).

To determine σ_i and ε_i by known σ_1, σ_2, σ_3, and ε_1, ε_2, ε_3, the authors according to the method, proposed in [15], propose to use the following iterative procedure when determining the model of material behavior in the Ansys AUTODYN (Fig. 3).

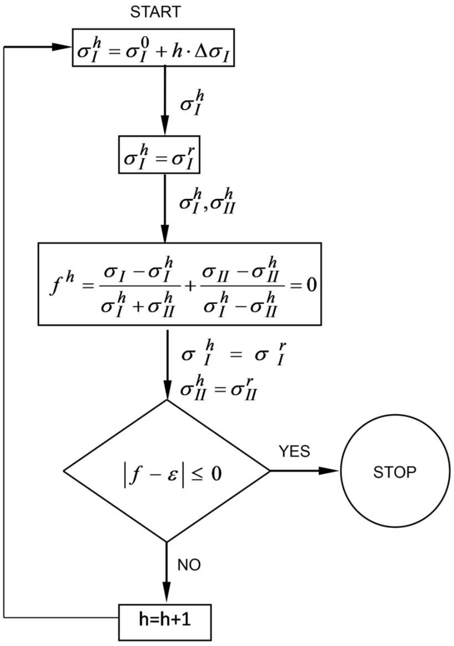
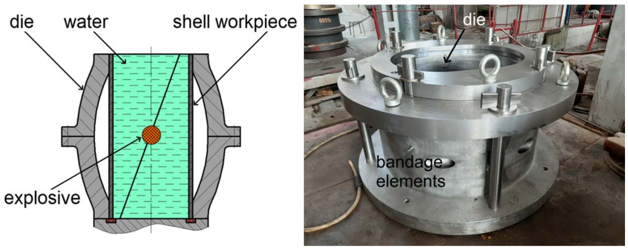


Fig. 3. Block diagram of the iterative procedure

The obtained iterative procedure allows determining the values and intensity of stresses and strains at any time during the simulation of pulsed metal processing.

3. Research results and discussion

In the conditions of the JSC «Motor Sich» workpieces loading is carried out by charges of Ammonite. In this case, the splittable die is covered by a strong bandage (Fig. 4).



a *b*

Fig. 4. Explosive forming tool: *a* – a typical scheme of forging a shell workpiece with an axisymmetric arrangement of the explosive charge; *b* – tooling design

Methods of pulse metalworking that use detonation of condensed explosives in water as an energy carrier have their own specificity, which is associated with the fact that during the forming operations the workpiece is under the action of high pressures, which significantly exceed those, required for plastic deformations. It should also be noted the difference in the mechanisms of localization of plastic deformation under pulsed and static loading. When forming axisymmetric workpieces, these features practically do not have a significant effect on the forming process. Therefore, in this case, the optimization problem is reduced to the selection of the required effective pressure P_{max} values.

A typical representative of parts, formed by the explosion from shell workpieces, is the «Stator housing» part. The finished part has eight radii of curvature in the plane of symmetry (the smallest is 268 mm, the largest is 330 mm). The part is made from a conical welded 1.5 mm AISI 321 (X10CrNiTi18-9 in DIN marking) steel workpiece (Fig. 5).

The application of the iterative procedure, proposed in the work, at the design stage of the forming technological process made it possible to determine based on the plastic properties of the workpiece material the field of peak effective pressures $P_{max,}$ required to fill the die cavity within 12 GPa.

a

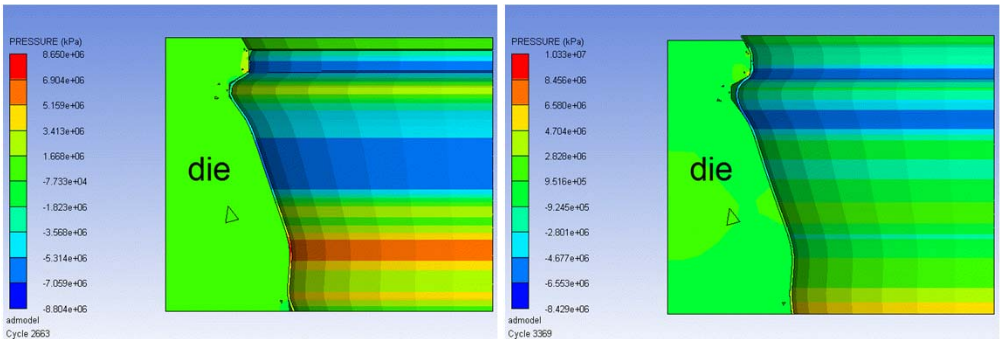
b

Fig. 5. Preparation for forming a «Stator housing» part: *a* – semi-die; *b* – workpiece

It should be noted, that in the case when the heights of the original workpiece and the die are the same, the plastic flow of the workpiece material is insufficient to fill the entire cavity of the die and there is no upper conical neck on the stamped part (Fig. 6). To avoid this, it is proposed to increase the height of the workpiece by 50 mm in the upper part. In this case, in order to avoid water entering the gap between the workpiece and the die, this gap is pre-sealed with hydrophobic putty, as shown on the Fig. 7.

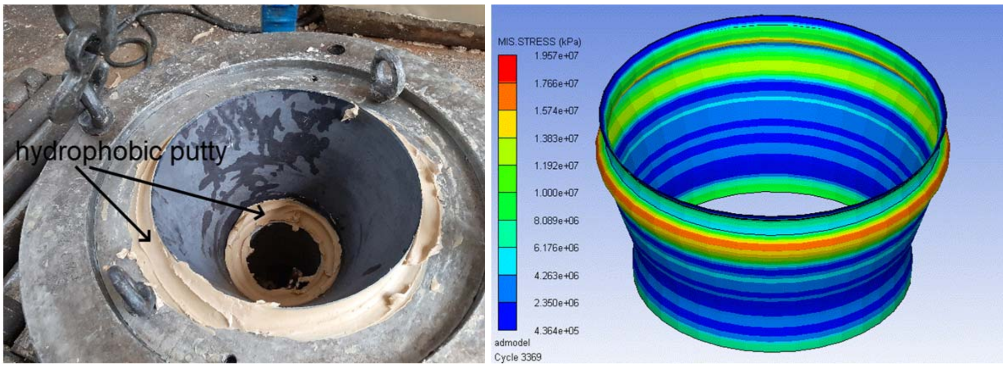
At the same time, the forming of asymmetric parts with a variable taper angle and an uneven degree of expansion around the perimeter causes many problems and, therefore, practical interest.

Optimization of the forming of such a part (a part called a «Volute» or sometimes a «Cochlea») is described by the authors in [6]. The workpiece is a welded cylinder, made of AISI 321 steel 0.8 mm thick, 400 mm in diameter, and 120 mm high. The finished part has seven different radii of curvature. Considering that in some zones of the part during explosive forming, the relative elongation of the workpiece material reaches 71 %, the most vulnerable is the workpiece weld seam (Fig. 8). In [6], thanks to intelligent optimization of the workpiece pulse loading, it was possible to determine the peak effective pressure field P_{max} within 600 MPa and the value of the explosive charge location eccentricity in the range from 19.5 to 68 mm. It is also proposed to increase the height of the original blank by 60 mm at the top and 30 mm at the bottom. The areas of the greatest load of the workpiece material, in which the location of the weld seam is undesirable, have been determined (Fig. 9).



a *b*

Fig. 6. Diagram of the effective pressure distribution over the surface of the workpiece and filling the cavity of the die: *a* – at the same height of the workpiece and the die; *b* – with an increase in the height of the workpiece by 50 mm



a *b*

Fig. 7. Forming of a «Stator housing» part: *a* – preliminary application of hydrophobic putty; *b* – von Mises equivalent stress distribution diagram

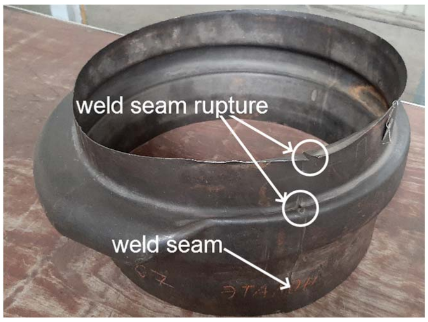


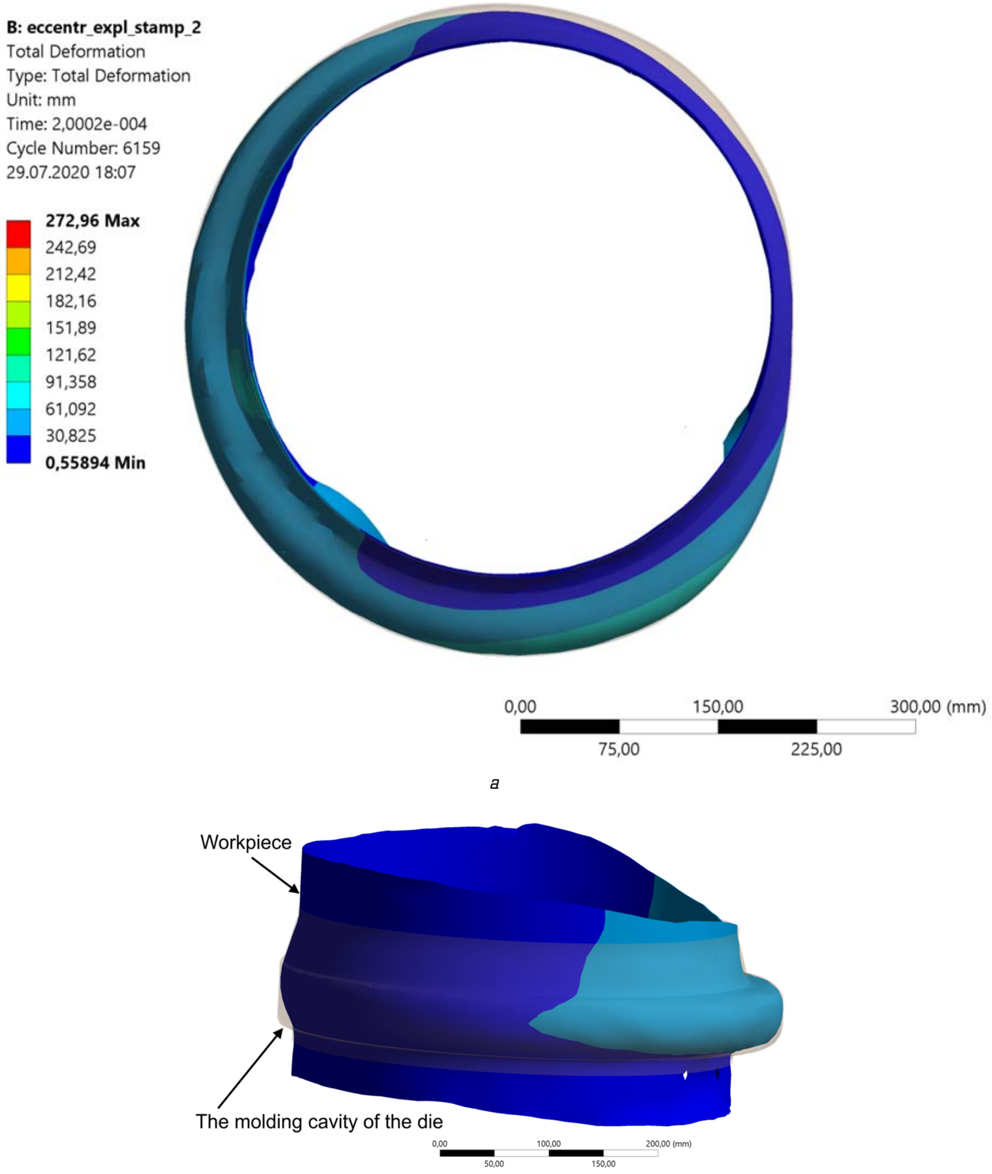
Fig. 8. The appearance of the weld seam rupture after the explosive forming

Another example of such a shell workpiece explosive forming is the «Housing» part. The height of this part is 558 mm. It is made from a 1.5 mm AISI 321 steel workpiece in the shape of a truncated oblique cone in order to make its shape as close as possible to the complex shape of the die cavity (Fig. 10, *a*). Such a part does not have a single plane of symmetry, and the areas of the highest deformations during forming are two unequal depressions from the opposite to the parabolic area of the die cavity surface (Fig. 10, *b*, top image).

The application of the optimization algorithm, proposed in this work, made it possible to establish the effective pressure field necessary for the normal filling of the die cavity within 22 GPa. It is proposed to shift the explosive charge towards the areas of highest deformation relative to the axis of rotation of the die contour within 139 mm, as well as downward as much as possible. This will make it possible to implement the scheme of the workpiece walls loading with the so-called «oblique» shockwave (the workpiece is deforming from bottom to top).

As can be seen from Fig. 11, *a*, such a loading scheme ensures the normal filling of the die cavity with the workpiece. However, when the height of the workpiece is equal to the height of the die, the filling of the cavity along the height is not observed. Similar to the «Stator housing» part manufacturing scheme, it was proposed to increase the height of the workpiece by increasing its upper part up to 70 mm, sealing the gap between the cavity of the die and the wall of the workpiece with hydrophobic putty.

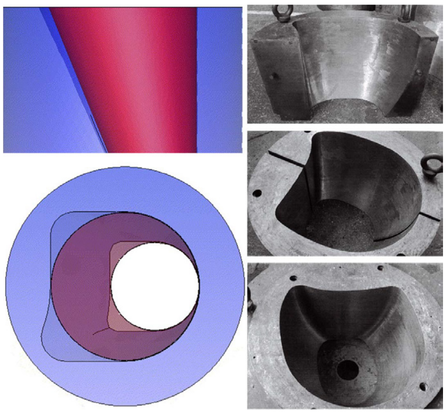
However, in this case, the nature of the workpiece protrusion is such that the workpiece's upper free part, protruding above the die, is deformed before normal filling of the die cavity with the workpiece material occurs, thus forming a flange on the upper edge of the die Fig. 11, *b*. This, on the one hand, prevents the normal distribution of the workpiece material, as a result of which high compressive stresses lead to the formation of corrugations in the zones of the highest deformations, and, on the other hand, leads to the workpiece dissection by the rib, formed by the die upper edge and its working cavity. Therefore, in the future, it was proposed to make changes to the existing technological process of part forming, not only by increasing the height of the original workpiece but also by increasing the height of the die. In this case, the filling of the die working cavity along the height occurs normally (Fig. 12, *a*).



a

b

Fig. 9. Diagram of «Volute» part shaping with an increase in the height of the workpiece during an explosive expansion: *a* – total deformations (top view); *b* – diagram of filling the die mold cavity

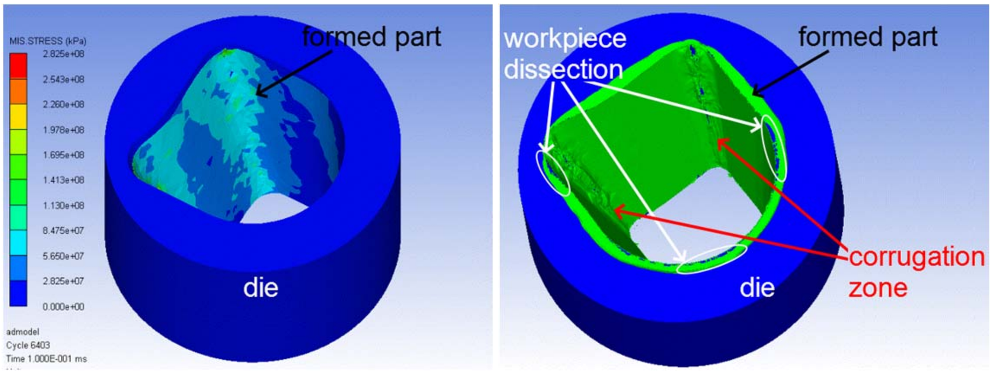


a *b*

Fig. 10. Preparation for explosive forming of a «Housing» part: *a* – layout diagram of the workpiece (red) inside the die (blue) cavity; *b* – stages of forming tooling assembly

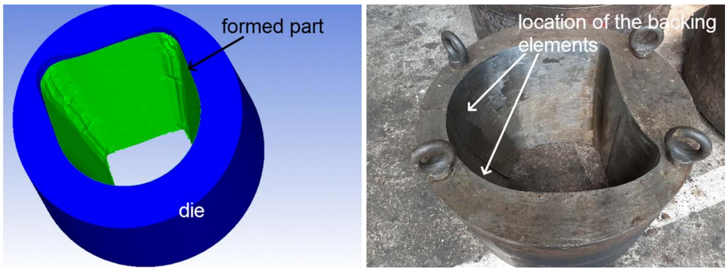
However, it should be noted, that due to the complex nature of the material flow when forming such a part, it is impossible to avoid the formation of corrugations (Fig. 12, *a*). Thus, even the use of intelligent optimization methods does not completely solve the problem of obtaining a «Housing» part by explosive forming. In this case, it is necessary either to change the geometry of the part itself in order to avoid the occurrence of extreme compressive stresses in the areas of highest deformations. A simpler solution is to use elastic backing elements on the shaping surfaces of the die, allowing to change the stress state patterns of the most deformable workpiece areas, as is shown on Fig. 12, *b*.

At present, industrial testing of the production of these parts by explosive forming (Fig. 13) has been carried out using the intelligent system for optimizing the technological processes, proposed in the work.



a *b*

Fig. 11. The results of a «Housing» part explosive forming simulations: *a* – with an equal height of the workpiece and the die (von Mises equivalent stress distribution); *b* – with an increase in the workpiece (green) height without fixation its upper edge



a *b*

Fig. 12. Obtaining a «Housing» part by explosive forming: *a* – simulation of filling the die cavity (blue) with the workpiece material (green) with a simultaneous increase in the workpiece and the die height; *b* – areas of the location of the backing elements

a *b* *c*

Fig. 13. Samples of parts, obtained by explosive forming using an intelligent process optimization system: *a* – series of «Stator» parts; *b* – «Volute» («Cochlea») part; *c* – «Housing» part

Thus, the paper proposes a numerical calculation method in the Ansys AUTODYN due to the introduction of a universal iterative procedure for adjusting the pulsed load of materials to control the dynamic behavior of the material. This made it possible to determine the optimal location of explosive charges based on the load parameters of the workpiece material, taking into account its resistance to deformation. By establishing the peak values of the effective pressures for the case of each specific type of parts, it makes it possible not only to determine the most loaded areas of the workpieces in the process of forming but also to more accurately determine, based on ballistic characteristics, the required mass of explosive charges. So, for «Stator» parts, the mass of the ammonite charge was reduced from 200 g to 135 g (67.5 % of the initial mass), for «Volute» parts it was reduced from 45 g to 39 g (87 %), for «Housing» parts it was reduced from 150 g to 110 g (73 %).

As already mentioned above, the proposed method of shell parts pulse forming intelligent optimization does not allow to fully solve the problems of forming optimization of a complete list of such parts. This problem is especially acute in relation to asymmetrical parts of complex configuration, in which the complex nature of the material flow, when deformed, can lead to the formation of unwanted corrugations or cracks, as in the case of the «Housing» part.

This problem appearance is since the proposed optimization algorithm allows solving the problem of optimal pulse loading based on the mechanical properties of the deformable material and the ballistic characteristics of the initiator (explosive) of the process.

However, as follows from dependence (4), the value of the achieved effective pressure P_{max} depends on the time constant θ, which, in turn, depends on the distance between the charge and the loaded surface (Fig. 2, *b*).

At the moment, for parts of complex shapes, the asymmetric arrangement of the explosive charge is selected empirically. Further development of intelligent optimization of pulse forming of such parts is the setting of the loading factor in the form of a function and the ability to determine the geometric coordinates of the point of initiation, based on the achieved optimal deformation values. This will make it possible to automatically select not only the parameters of the workpiece (thickness and properties of the material) and the mass of the charge but also to more accurately design the tooling and set the location of the charge in it.

4. Conclusions

The paper investigates the possibility of using a developed intelligent iterative procedure during the explosive forming of shell parts with constant and variable curvature. Analytical dependencies are obtained that allow determining the optimal arrangement of explosive charges and loading parameters of the workpiece material, taking into account its resistance to deformation.

The results of the work are proved by simulations in the Ansys AUTODYN system, as well as experimental data. The performed experimental studies have shown slight deviations in the values of local deflections of the produced parts in comparison with the data, obtained analytically in ranges from 0.95 to 7.58 % at key points for asymmetric parts. Intelligent optimization made it possible to reduce the loading of the workpiece material by reducing the explosive mass by 32.5 % for axisymmetric parts («Stator housing» part) and by 13–27 % for asymmetric parts («Volute» and «Housing» parts).

The proposed method of intelligent control for producing shell parts fully satisfies the requirements for parts of this type, avoids local destruction of workpieces in the weld zone, and also significantly simplifies and accelerates the design and R&D stage of manufacturing. It also reduces the metal consumption in conditions of small and middle production programs due to a significant reduction in the required effective pressure values and mass of the explosives, initiating the forming process.

References

1. Youngdahl, C. K. (1970). Correlation Parameters for Eliminating the Effect of Pulse Shape on Dynamic Plastic Deformation. *Journal of Applied Mechanics, 37 (3),* 744–752. doi: https://doi.org/10.1115/1.3408605
2. Bazant, Z., Cedolin, L. (2010). Three-Dimensional Continuum Instabilities and Effects of Finite Strain Tensor. *Stability of Structures.* World Scientific, 706–759. doi: https://doi.org/10.1142/9789814317047_0011
3. Dragobetskii, V., Shapoval, A., Naumova, E., Shlyk, S., Mospan, D., Sikulskiy, V. (2017). The technology of production of a copper – aluminum – copper composite to produce current lead buses of the high – voltage plants. *2017 International Conference on Modern Electrical and Energy Systems (MEES).* IEEE. 400–403. doi: https://doi.org/10.1109/mees.2017.8248944
4. Anishchenko, A., Kukhar, V., Artiukh, V., Arkhipova, O.; Abramov, A. D., Murgul, V. (Eds.) (2018). Superplastic forming of shells from sheet blanks with thermally unstable coatings. *MATEC Web of Conferences, 239,* 06006. doi: https://doi.org/10.1051/matecconf/201823906006
5. Markov, O., Gerasimenko, O., Aliieva, L., Shapoval, A., Kosilov, M. (2019). Development of a new process for expanding stepped tapered rings. *Eastern-European Journal of Enterprise Technologies, 2 (1 (98),* 39–46. doi: https://doi.org/10.15587/1729-4061.2019.160395
6. Shlyk, S., Drahobetskyi, V., Trotsko, O., Chencheva, O., Klets, D. (2020). The Explosive Expansion of Electrical Equipment Housings with Variable Curvature. *2020 IEEE Problems of Automated Electrodrive. Theory and Practice (PAEP).* IEEE, 381–385. doi: https://doi.org/10.1109/paep49887.2020.9240822
7. Kukhar, V., Artiukh, V., Butyrin, A., Prysiazhnyi, A. (2017). Stress-Strain State and Plasticity Reserve Depletion on the Lateral Surface of Workpiece at Various Contact Conditions During Upsetting. *International Scientific Conference Energy Management of Municipal Transportation Facilities and Transport EMMFT 2017.* Springer International Publishing, 201–211. doi: https://doi.org/10.1007/978-3-319-70987-1_22
8. Lutsenko, I. (2016). Definition of efficiency indicator and study of its main function as an optimization criterion. *Eastern-European Journal of Enterprise Technologies, 6 (2 (84),* 24–32. doi: https://doi.org/10.15587/1729-4061.2016.85453
9. Raskin, L., Sira, O., Sukhomlyn, L., Bachkir, I. (2017). Symmetrical criterion of random distribution discrimination. *2017 International Conference on Modern Electrical and Energy Systems (MEES).* IEEE, 320–323. doi: https://doi.org/10.1109/mees.2017.8248922
10. Zagirnyak, M. V., Drahobetskyi, V. V. (2015). New methods of obtaining materials and structures for light armor protection. *2015 International Conference on Military Technologies (ICMT).* IEEE, 709–710. doi: https://doi.org/10.1109/miltechs.2015.7153695
11. Jones, N., Alves, M. (2010). Post-failure behaviour of impulsively loaded circular plates. *International Journal of Mechanical Sciences, 52 (5),* 706–715. doi: https://doi.org/10.1016/j.ijmecsci.2009.11.014
12. Trotsko, O., Shlyk, S. (2018). Development of the Mathematical Model for Sheet Blanks Forming Calculation Using Simulation in ANSYS Software. *2018 IEEE 13th International Scientific and Technical Conference on Computer Sciences and Information Technologies (CSIT).* IEEE, 169–173. doi: https://doi.org/10.1109/stc-csit.2018.8526614
13. Cooper, P. W. (1996). *Explosives Engineering.* New York: Wiley-VCH, 480.
14. Duff, R. E., Houston, E. (1955). Measurement of the Chapman-Jouguet Pressure and Reaction Zone Length in a Detonating High Explosive. *The Journal of Chemical Physics, 23 (7),* 1268–1273. doi: https://doi.org/10.1063/1.1742255
15. Li, D. Y., Peng, Y. H., Yin, J. L. (2006). Optimization of metal-forming process via a hybrid intelligent optimization technique. *Structural and Multidisciplinary Optimization, 34 (3),* 229–241. doi: https://doi.org/10.1007/s00158-006-0075-1

Sergii Shlyk, *PhD, Associate Professor, Department of Manufacturing Engineering, Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine, e-mail: svshlyk@gmail.com, ORCID: https://orcid.org/0000-0001-9422-1637*