Stipo Buljan
Darko Šunjić ✉
Muhamed Sućeska
Safet Isić

https://doi.org/10.21278/TOF.492071524
ISSN 1333-1124
eISSN 1849-1391

DEEP DRAWING OF SPHERE USING EXPLOSIVE FORMING

Summary

Explosive energy can be used in metal forming processes, e.g. for bulk forming, sheet forming and for other processes. This paper presents the experimental research and numerical modelling of the process of sphere deformation by explosive forming. The assembly for forming a sphere with a diameter of 210 mm was welded from flat segments and annealed after welding. The material of the sphere was steel St12 according to DIN 1629/3. The thickness of the sheet metal was 2.0 mm. The sphere was modelled in the SolidWorks program and 3D-printed with the polylactic acid (PLA) material. The Poladyn 31ECO explosive was used for the experimental investigation into the process of deep drawing of the sphere by explosion, while the LS-DYNA hydrodynamic software was used for simulation. The pressure in the sphere was measured with a pair of copper crushers. It is shown that the simulation satisfactorily reproduces the experimentally measured pressure.

Key words: *explosive forming, deep drawing of sphere, deformation, pressure, copper crusher, simulation*

1. Introduction

Unconventional forming technologies are also known as "new forming technologies" even though some of these technologies appeared more than 100 years ago. The first records of explosive forming date back to 1889. As the name suggests, explosives are used as a source of energy in this technology, and it is theoretically possible, by correctly choosing the type and mass of explosives, to obtain any required amount of energy.

The explosive forming of spheres or spherical shapes by explosion is a technology that has been recently developed. The whole process is based on the detonation of an explosive charge inside the assembly so that the shock wave generated by the detonation deforms the assembly into a regular sphere.

Authors [1, 2] investigated explosive free forming through numerical and experimental analyses. Some authors [3-6] used many assumptions and simplified the analytical expressions because of their complexity, but only after the development of computers and software it was possible to obtain more precise results. Also, research was done on the application of this technology with segments that were first slightly bent and only then welded into a spherical shape. The interior of the assembly is filled with water as a shock wave transmission medium, and the explosive charge is then placed in the centre of these assemblies through the opening at the top, and the assembly is transformed into a complete sphere after the explosion inside it.

In this paper, the sphere is modelled in the SolidWorks software program, and it is made using the rapid prototyping technology with the PLA material, as shown in Fig. 1. In this way, the prototype was obtained that served to confirm the possibility of setting the measuring equipment inside the sphere.

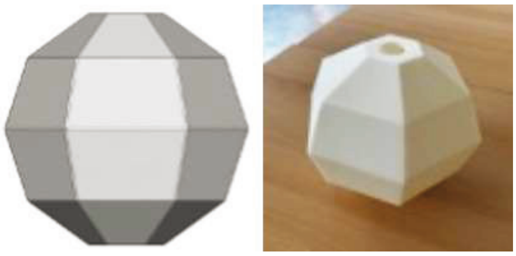

Fig. 1 The sphere model (left) and the finished piece (right)

In contrast to previous research, bent pieces were not used in this experiment, but the assembly was welded and composed of straight segments, as shown in Fig. 2.

Fig. 2 Explosive forming assembly

2. Material and preparation of experiment

Cold-rolled low-carbon steel St12 according to DIN 1629/3 was chosen. This steel is used for deep drawing, punching, and cutting due to its good plastic properties. The chemical composition of the material is shown in Table 1, and the mechanical properties are shown in Table 2.

Table 1 Chemical composition of the steel

C	Mn	P	S
max 0.12	max 0.6	max 0.045	max. 0.045

Table 2 Mechanical properties of the steel

R_m (MPa)	R_{eH} (MPa)	Elongation %	HV
270-410	280	28	105

The segments were obtained from sheet metal by laser processing and then welded. After welding, the assembly was annealed in a furnace. Figure 3 shows the nesting, i.e., the laser cutting plan for maximum material utilisation. Tests were performed on the material with a thicknesses of 2 mm. The assembly consists of six symmetrical segments, and the upper and the lower segment differ only in an opening, which is left on the upper part, for the medium and explosive. The assembly is first filled with water through the opening on the top, and then the explosive is placed exactly in the centre of the assembly. Given that it is an explosive process, it is necessary to carry out safety measures, thus the experiment was carried out at the training ground of the company PS "Vitezit" d.o.o. Vitez that fulfils safety regulations.

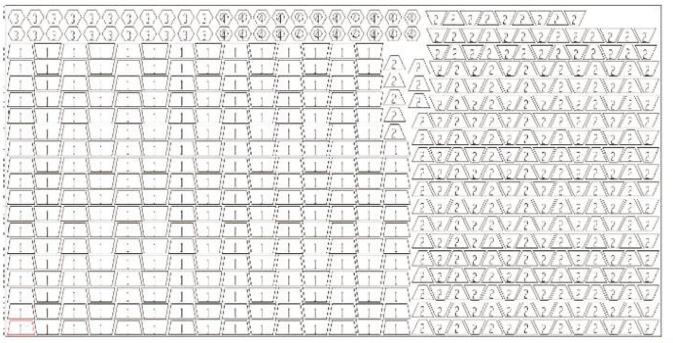

Fig. 3 Extended cutting plan

3. Numerical analyses

LS-DYNA, a hydrodynamic software, was used to simulate the process of metal deformation by explosion. The following elements of the model were used for modelling: explosive as an energy source, water as a liquid medium, a sphere as an object of deformation, and the air surrounding the sphere. In the initial phase of the simulation, a 3D model was used, and due to the symmetry of the model, the deformation problem of the steel lining (shell) was modelled for 1/8 of the spherical volume to reduce the calculation time. Despite this, the duration of the calculation on a standard computer was several days. Therefore, the final simulation was performed using a 2D model, whereby the problem was simulated for 1/4 of the cross section. In this way, the calculation time was significantly reduced, without a negative effect on the final simulation results [7]. The units used in the model are gram (g) for mass, millimeter (mm) for length, milliseconds (ms) for time, and megapascal (MPa) for pressure. Figure 4 shows the model in the LS-DYNA software.

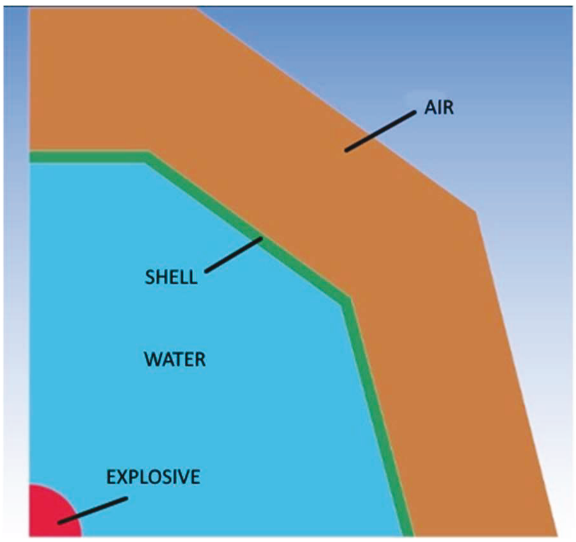

Fig. 4 Model in LS-DYNA software

The arbitrary Lagrangian-Eulerian (ALE) method was used in modelling. The explosive, water, and air are modelled by the Eulerian method to allow the material flow between the cells, while the shell element is modelled by the Lagrangian method. The air zone surrounding the sphere has the role of preventing the influence of conditions outside the sphere on the deformation. At the boundaries of the air zone, the "outflow" boundary condition was applied, thus the fluid is free to overcome the Eulerian external boundary. The mesh size was 0.5 mm. The modelling was performed using commercial explosives based on ammonium nitrate (Poladyn 31 ECO) with detonation characteristics shown in Table 3.

Table 3 Detonation characteristics of explosives

Density (ρ_0)	Velocity of detonation (*D*)	Detonation pressure (*p*)
$8 \cdot 10^{-4}$ g/mm^3	3,250 mm/ms	2,200 MPa

The velocity of detonation was determined experimentally using the Dautrich method, and the detonation pressure was calculated using the EXPLO5 thermochemical program [8]. Jones-Wilkins-Lee (JWL) equation of state of the reacted explosive (i.e., detonation products), which describes the connection between volume and pressure during isentropic expansion, was used. The relation between the relative volume and pressure during the isentropic expansion of the detonation products is described by the Jones-Wilkins-Lee (JWL) equation of state [9] as follows:

$$p = A\left(1 - \frac{\omega}{R_1 v}\right)^{-R_1 v} + B\left(1 - \frac{\omega}{R_2 v}\right)^{-R_2 v} + \frac{\omega E_0}{v} \tag{1}$$

where p is the pressure, v is the relative volume (V/V_0, where V is the volume and V_0 is the initial volume of gas products), A, B, C, R_1, R_2, and ω are JWL coefficients, and E_0 is the detonation energy. The values of JWL coefficients given in Table 4 were calculated using the thermochemical program EXPLO5 [8].

Table 4 Coefficients in JWL equation and detonation energy

A	*B*	R_1	R_2	ω	E_0
$2.577 \cdot 10^4$ MPa	587.1 MPa	3.19962	0.78957	0.20851	3449 J/mm^3

The Mie-Gruneisen equation of state was used to describe the behaviour of water [8]:

$$p = \frac{\rho_0 C_0^2 \eta}{(1 - S\eta)^2}\left[1 - \frac{\Gamma_0 \eta}{2}\right] + \Gamma_0 \rho_0 E \tag{2}$$

where ρ_0 is the initial density of water, E is the internal energy, C_0, S and Γ_0 are constants, and $\eta = 1 - \rho_0/\rho$, where ρ is the density of water. The values of the constants were taken from the LS-DYNA software library [10]:

Table 5 Coefficients in Mie-Gruneisen equation of water [10]

ρ_0	C_0	*S*	Γ_0
0.001 g/mm^3	1,490 mm/ms	1.79	1.65

The air is modelled by the gamma-law equation of state [9]:

$$p = (\gamma - 1)\frac{\rho}{\rho_0}E \tag{3}$$

where γ is the ratio of specific capacities, E is the internal energy, and ρ and ρ_0 are the density and the initial density of air, respectively. The values of the constants in Equation 3 are given in Table 6.

Table 6 Coefficients in gamma-law equation of state of air [10]

ρ_0	γ	E
$1.225 \cdot 10^{-6}$ g/mm^3	1.4	0.2553 J/mm^3

The strength of the material is modelled by the Johnson-Cook model [9]:

$$\sigma_{eq} = (A + B\varepsilon_{eq}^{n})(1 + C\ln\dot{\varepsilon}_{eq}^{*})(1 - T^{*m}) \tag{4}$$

where σ_{eq} is the equivalent stress, ε_{eq} is the effective plastic strain, A, B, n, C, and m are material constants, $\dot{\varepsilon}_{eq}^{*} = \dot{\varepsilon}_{eq}^{*}/\dot{\varepsilon}_0$ is the dimensionless strain rate, $\dot{\varepsilon}_0$ and $\dot{\varepsilon}_{eq}$ are the reference strain rate and strain rate, T* is the dimensionless temperature $((T^{*} = (T - T_r)(T_m - T_r)$, where T is the temperature, T_r is the room temperature, and T_m is the melting temperature. Steel properties and constants in the Johnson-Cook equation are given in [10, 11].

Table 7 Material properties and coefficients in Johnson-Cook equation [10, 11]

Material properties					Coefficients in Johnson-Cook equation							
ρ_0	E_Y	μ	c_p	α	$\dot{\varepsilon}_0$	A	B	C	T_r	T_m	n	m
$7.85 \cdot 10^{3}$ g/mm^3	$210 \cdot 10^{5}$ MPa	0.33	452 J/g K	$1.2 \cdot 10^{-5}$ 1/K	$5 \cdot 10^{-7}$ 1/s	1,200 MPa	$5 \cdot 10^{4}$ MPa	0	298 K	1,800 K	1	1

Legend: ρ_0 is the density, E_Y is Young's modulus, μ is Poisson's ratio, and α is the coefficient of thermal expansion.

In addition to the Johnson-Cook strength model, a damage model (failure model) was also used, according to which the equivalent fracture strain is calculated by the equation [9]:

$$\varepsilon_f = [D_1 + D_2\exp(D_3\sigma^{*})]\left[1 + D_4\ln\dot{\varepsilon}_{eq}^{*}\right][1 + D_5T^{*}] \tag{5}$$

where ε_f is the equivalent fracture strain, σ^{*} is the equivalent stress, and D_1 to D_4 are constants. The values of the constants are given in Table 8 [10].

Table 8 Coefficients in damage equation [10]

D_1	D_2	D_3	D_4	D_5
0.05	3.44	-2.12	0.002	0.61

After defining the input parameters, a simulation was performed in the LS-DYNA software, and the simulation results were processed in the LS-PrePost software for data processing.

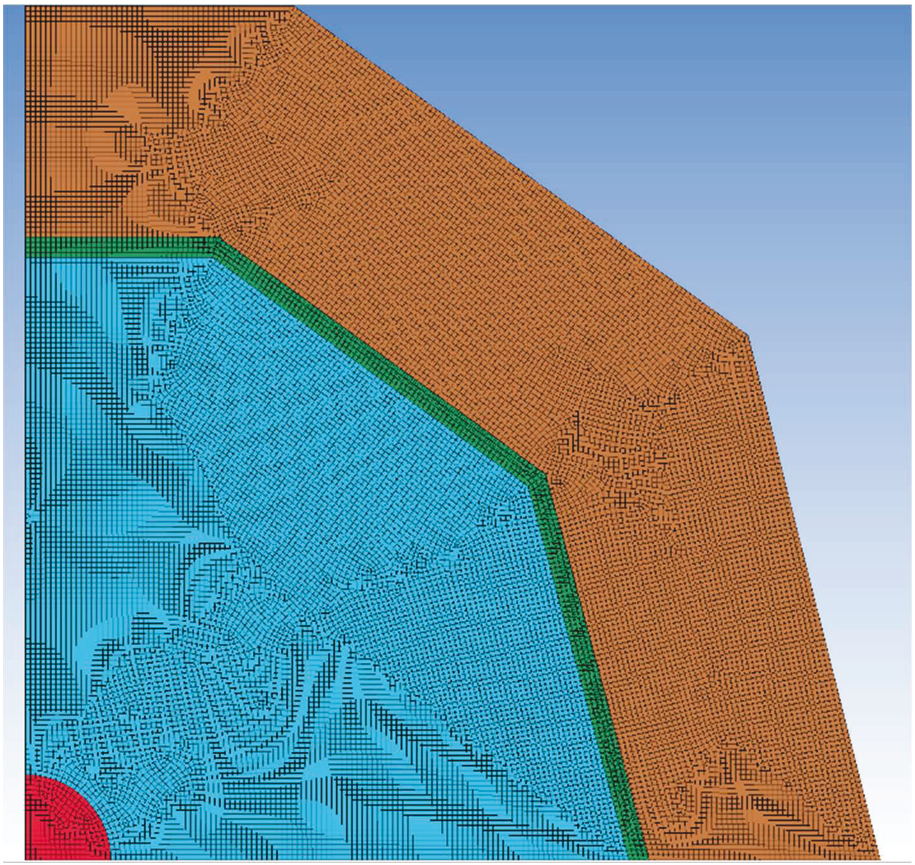

Fig. 5 Mesh created in LS-PrePost

Figure 6 shows the pressure development inside the wall of the metal sphere. The maximum developed pressure is 300 MPa in 0.114 microseconds, and after that, a pressure of almost 400 MPa occurs as a result of the reflection of the shock wave from the walls of the sphere.

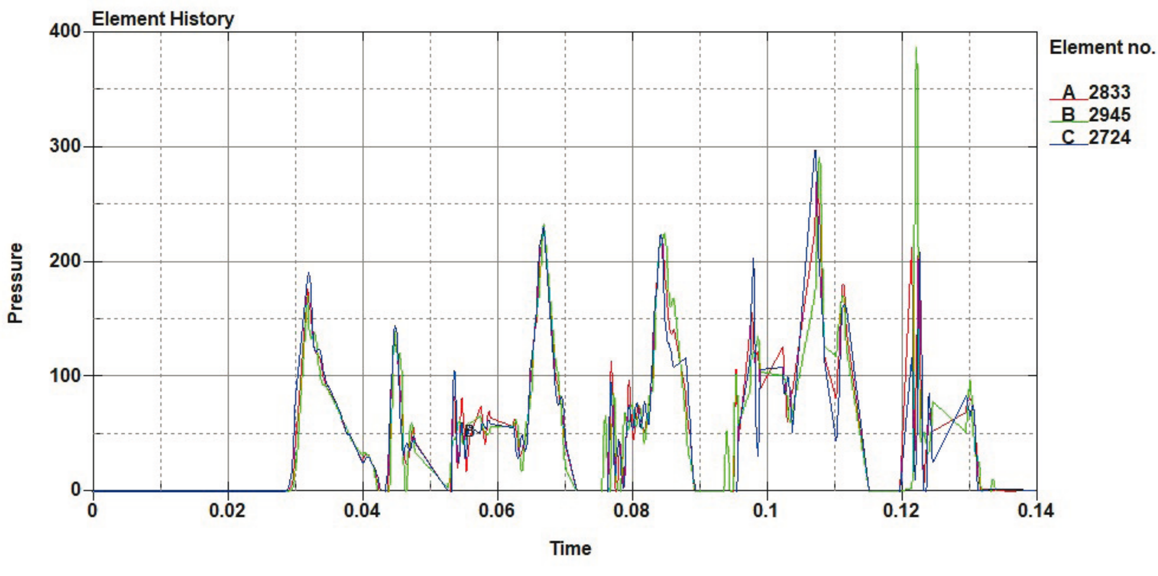

Fig. 6 Development of pressures inside the wall

Through the simulation, a displacement of the wall of the metal sphere was established, where it is clearly seen that the pressure of the shock wave acted uniformly on the entire inner surface. As a result, the sphere was deformed in such a way that every point on its inner wall moved equally and shaped the assembly into a sphere. The maximum displacement of the points is 3.24 mm in the middle of the segment in 0.12 microseconds after the detonation of the charge, which can be seen in Figure 7. Apart from this, it was experimentally confirmed that there was no reduction in the wall thickness of the workpiece.

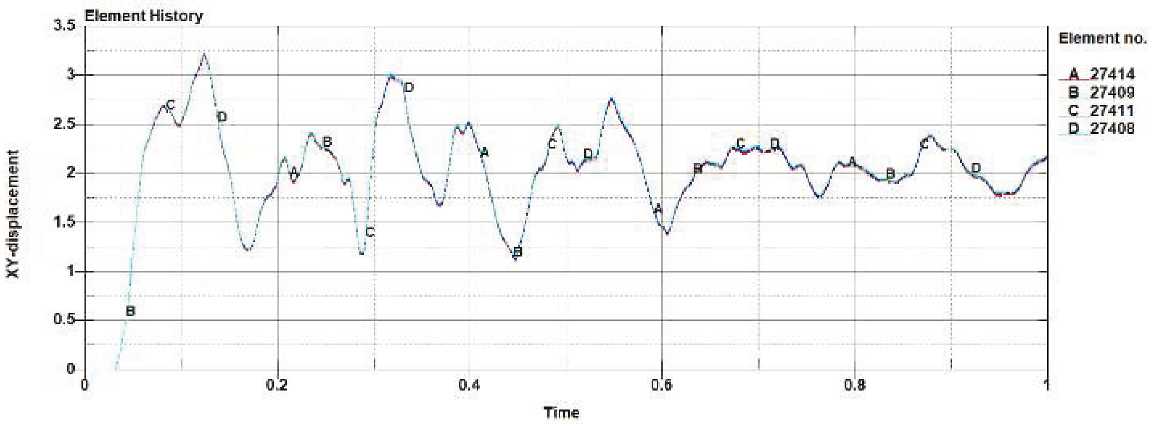

Fig. 7 Movement of the sphere wall

4. Experimental research

The experimental part of the research was carried out at the training ground of the company PS "Vitezit" d.o.o. Vitez, which meets all the conditions for this type of experiment (polygon, velocity of detonation measuring devices, explosives) as well as safety requirements related to the explosive forming technology. Figure 8 shows a successfully deformed sphere with a wall thickness of 2 mm in which the shock wave energy transfer medium was water, the explosive was Poladyn 31 ECO, and it was placed in the centre of the assembly. When working with such workpieces, the characteristics of the explosive used, the type of medium for energy transfer, and the dimensions of the assembly (diameter and thickness of the material) play a major role. With smaller workpiece diameters, it is extremely difficult to obtain a suitable workpiece.

Fig. 8 2-mm thick sphere successfully formed by explosive

As the medium for transferring the energy of the shock wave was water, the amount of explosive was determined experimentally to be 0.5 grams to obtain a 2.0 mm thick sphere with 1 g of PETN.

Also, the pressure of the shock wave was measured by a copper crusher system in the sphere, and the obtained result is shown in Table 9.

Table 9 Pressure measurement with crushers

Sheet thickness	Explosive	Medium	Velocity of detonation	Pressure
2 mm	Poladyn 0.5 g with electric capsules 1 g PETN	Water	6000 m/s	135.6 MPa
2 mm	Poladyn 0.5 g with electric capsules 1 g PETN	Water	3333 m/s	98.9 MPa

The pressure was measured on a sphere with a thickness of 2 mm using 0.5 g of plastic explosive Poladyn 31 ECO, detonation velocity 6,000 m/s, and an electric capsule containing 1 g of PETN with a detonation velocity of 7,000 m/s. The compression of the copper roller from the initial 4.9 mm was performed to 3.75 mm. Analogously to the tables, this compaction corresponds to a shock wave pressure of 135.6 MPa. The pressure was measured with a copper crusher system and an explosive whose detonation velocity was slowed down to 3,333 m/s. The detonation velocity was slowed down by mixing the explosive into an inert salt, and the velocity of detonation was tested using the Dautrich method. In this experiment, the copper roller was compressed to 4.18 mm, which, according to the measurement table, corresponds to a shock wave pressure of 98.9 MPa.

Also, deformations were measured using a strain gauge, Spider amplifier, and CATMAN software, and sand was used as the medium. The medium was changed to establish the amount of explosive required to successfully form the sphere using sand as the medium, and to check the underpressure after forming that occurred at the top of the sphere near the opening. Deformation measurements were made on the top part of the sphere, where minimal deformation was expected and where the strain gauge would remain in the elastic field.

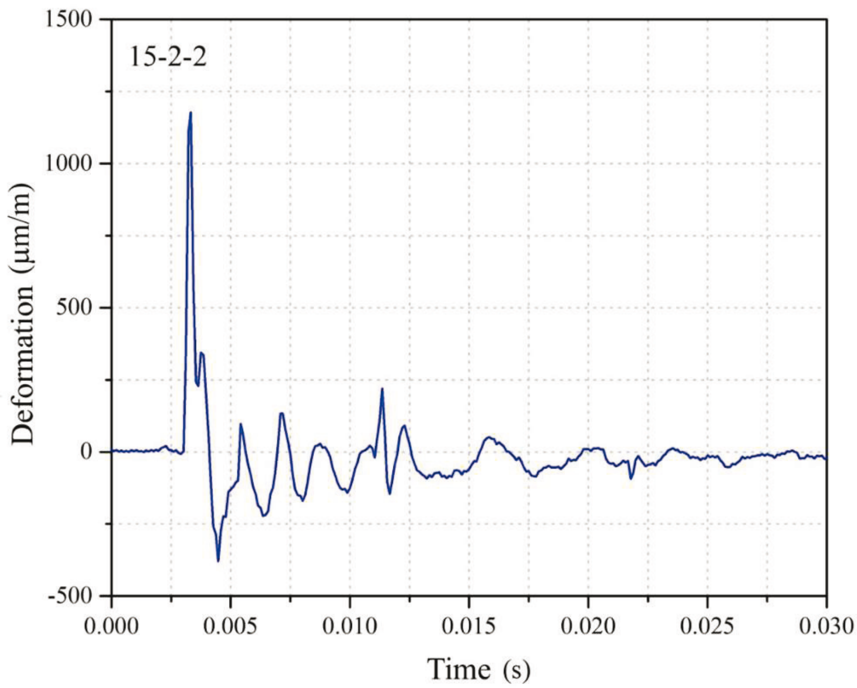

Fig. 9 Deformations by time

The maximum deformation recorded in this measurement was 1,178.16 μm/m, which is shown in Figure 9. In contrast to the experiments in which water was used as a medium, in this experiment, the amount of explosives increased multiple times, so that for the successful forming of the sphere, 10 g Poladyn 31 ECO together with an electric initiation capsule with 1 g of PETN were used. From the diagram in Figure 9, the appearance of underpressure is evident that occurs as a reflection of the shock wave, which is also shown in the numerical simulation.

The sphere was scanned on a 3D scanner before and after explosive forming, and the appearance of underpressure on the top part of the sphere is visible after the scan and is shown in Fig. 10, and the appearance of underpressure is also confirmed by the measurement presented in Fig. 9.

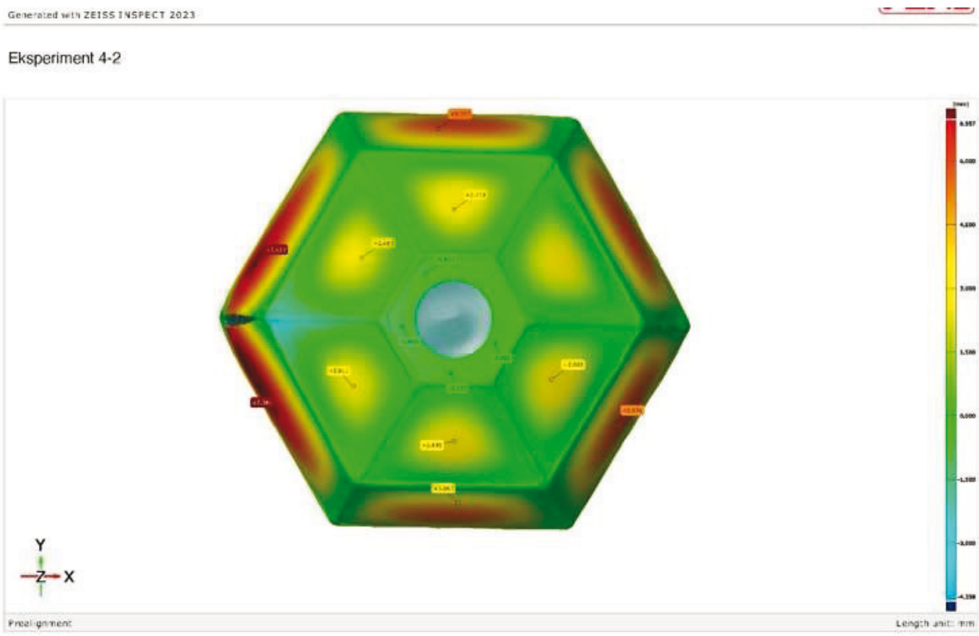

Fig. 10 Deviations on the sphere opening of 2 mm

5. Conclusions

This paper presents the process of obtaining a metal sphere by explosive deep drawing, where the medium used for energy transfer was water. In these types of technologies, it is very difficult to get the required amount of explosives, the energy of which would successfully shape the workpiece. Using expressions available in the literature, deviations when calculating the required amount of explosives can be greater than 200%. This is why, in these technologies, one starts with minimal amounts of explosives and gradually increases the amounts until a complete formation is achieved.

The results of the simulation using the LS-DYNA hydrodynamic software showed that the simulation can be a very useful tool when searching for an optimal mass of the explosive charge, as well as for determining the optimal or orientation values in a way that would reduce research time and costs. Also, for certain parameters, such as the appearance of underpressure, the numerical simulation convincingly describes the process, which was also confirmed by the experimental tests.

It should be borne in mind that any change in the type of medium for transmitting the energy of the shock wave significantly changes the mass of the explosive. Furthermore, the preparation of the experiment and the technology of explosive forming requires an interdisciplinary approach.

Acknowledgment

This paper was published as a part of the scientific research project *"The influence of detonation velocity on the mechanical properties of materials during freeform explosive forming"* 05-35-2042-1/22 supported by the Federal Ministry of Education and Science, Federation of Bosnia and Herzegovina. The authors would like to thank their colleagues from Nanyang Technological University, Singapore (NTU Singapore) for their help with the process simulation.

REFERENCES

[1] Akbari Mousavi, S. A. A., Riahi, M., & Hagh Parast, A. (2007). Experimental and numerical analyses of explosive free forming. Journal of Materials Processing Technology, 187–188, 512–516. https://doi.org/10.1016/j.jmatprotec.2006.11.208

[2] Mehrasa, H., Liaghat, G., & Javabvar, D. (2012). Experimental analysis and simulation of effective factors on explosive forming of spherical vessel using prefabricated four cones vessel structures. Open Engineering, 2(4), 656–664. https://doi.org/10.2478/s13531-012-0036-y

[3] Fengman, H., Zheng, T., Ning, W., & Zhiyong, H. (2000). Explosive forming of thin-wall semi-spherical parts. Materials Letters, 45(2), 133–137. https://doi.org/10.1016/S0167-577X(00)00092-6

[4] Kosing, O. E., & Skews, B. W. (1998). An investigation of high-speed forming of circular plates in a liquid shock tube. International Journal of Impact Engineering, 21(9), 801–816. https://doi.org/10.1016/S0734-743X(98)00033-5

[5] Rui, Z., & Tie-Sheng, Z. (1994). Non-die explosive forming of spherical pressure vessels. Journal of Materials Processing Technology, 41(3), 341–347. https://doi.org/10.1016/0924-0136(94)90170-8

[6] Tiesheng, Z., Zhensheng, L., Changji, G., & Zheng, T. (1992). Explosive forming of spherical metal vessels without dies. J. Mater. Process. Technol., 31. https://doi.org/10.1016/0924-0136(92)90014-J

[7] Aquelet, N., & Souli, M. (2008). 2D to 3D ALE mapping. 10th International LS-DYNA Users Conference, 23–34.

[8] M. Suceska, Evaluation of detonation energy from EXPLO5 computer code results, Propellants, Explos. Pyrotech. 1999, 24, 280-285. https://doi.org/10.1002/(SICI)1521-4087(199910)24:5%3C280::AID-PREP280%3E3.3.CO;2-N

[9] Hallquist, J. O. (2006). LS-DYNA Theory manual. Livermore Software Technology Corporation, 3, 25–31.

[10] LS-DYNA® KEYWORD USER'S MANUAL, Volume II Material Models, R14@ad6b3a9c5 (02/24/23), LS-DYNA R14, ANSYS Inc., Worcester, 2002.

[11] Johnson, G.R., & Cook, W.H. (1985). Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressure. Engineering Fracture Mechanics 1985, 21 (1), 31-48. https://doi.org/10.1016/0013-7944(85)90052-9

Submitted: 12.09.2024

Accepted: 27.11.2024

Stipo Buljan
Federal Ministry of Energy, Mining and Industry, Mostar, Bosnia and Herzegovina
Darko Šunjić*
University of Mostar, Faculty of Mechanical Engineering, Computing and Electrical Engineering, Mostar, Bosnia and Herzegovina
Muhamed Sućeska
Faculty of Mining, Geology and Petroleum Engineering, Zagreb, Croatia
Safet Isić
University of "Džemal Bijedić" Mostar, Faculty of Mechanical Engineering, Mostar, Bosnia and Herzegovina
*Corresponding author:
darko.sunjic@fsre.sum.ba