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Non-die explosive forming of spherical pressure vessels

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Industrial Summary

This paper presents a newly developed method of manufacturing spherical pressure vessels based on the technology of non-die explosive forming. Compared with the traditional method, this technology does not need any dies and pressing equipment, so that the cost of the production process can be greatly reduced, especially for vessels of less than 100 m^3 capacity.

1. Engineering background

The classical technology of manufacturing spherical vessels needs huge presses and special dies, is costly and gives less size-selection. Thus, few spherical pressure vessels of less than 100 m^3 have been made. The Warsaw Institute of Precision Mechanics studied the explosive forming of elements of spherical vessels [1], but was restrained by the problem of special dies. Wang Zhong-Ren of Harbin University of Industry has explored successfully the technology of the hydraulic expansion forming of spherically-inscribed polyhedrons to manufacture spherical vessels [2].

The technology of explosive forming of spherical vessel without dies is first to fill a pre-manufactured spherically-inscribed multi-cone container with water and then to explode a charge at its centre to deform it dynamically into a spherical shape. Through technological tests and theoretical analysis, the principles of designing the structure of the multi-cone spherical container have been established, the equation for the dosage calculation has been validated and the technological laws relating to the forming operation have been elucidated. Thus, both an experimental and a theoretical basis are provided for the application of this technology. It is believed that this new idea

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for the manufacture of small and medium-sized spherical vessels will have a promising future in the developing countries.

2. Principles of forming

Explosive forming with dies depends mainly on the dies to control the shape and size of the products. However, in explosive forming without dies there is relative movement between each mass point of the sheet metal under dynamic load. In the process of deformation, dynamic energy released from the explosive package is converted into work of deformation and the velocity of each mass point is changed, dropping to zero as the component achieves its final shape.

The major steps in the process of manufacturing a spherical vessel with non-die forming are as follows: first, two or more frustra of a cone are rolled; next, they are welded together to produce a spherically-inscribed container; then the container is filled with water and a spherical explosive package at the center of the container is detonated. The spherically expanding impulsive wave created in the water will firstly push the surface of the container that is closest to the center of the sphere. The energy density of the spherical impulsive wave attenuates approximately in an inverse squared relationship with distance, its peak pressure also decreasing with distance. Consequently, the velocity difference of the mass points acts to push the shell to the circumscribed sphere as closely as possible.

3. Structure design and analysis

In order to achieve the best effect, comparisons and tests were made on various spherical structures, the following two principles being obtained: (i) the multi-cone container should be spherically-inscribing; and (ii) the length of the generatrix of each conical frustum of the container should be equal to the diameter of its base plate.

The structure sketch of a four-cone spherically-inscribed container is shown in Fig. 1. Each conical frustum is rolled from a sectorial piece of sheet metal, Fig. 2. presenting a drawing of the unfolded No. 1 frustum.

The total number of conical frustra, N, is a major parameter, affecting the deformation of the container and the size of the blank. The effect of different N values on each parameter of deformation is shown in Table 1. To select a proper N value, the following items should be taken into account.

(i) The effect of the cold deformation on the mechanical performance of the material. The degree of deformation in the cold processing of spherical segments recommended by many countries is less than 5%, correspondingly $N \geqslant 4$;

(ii) Increasing the utilization rate of the material and shortening the length of the welding seams. If the size of the sheet metal is fixed, the N value and the number of sectorial pieces can be optimized with the aid of a computer program.

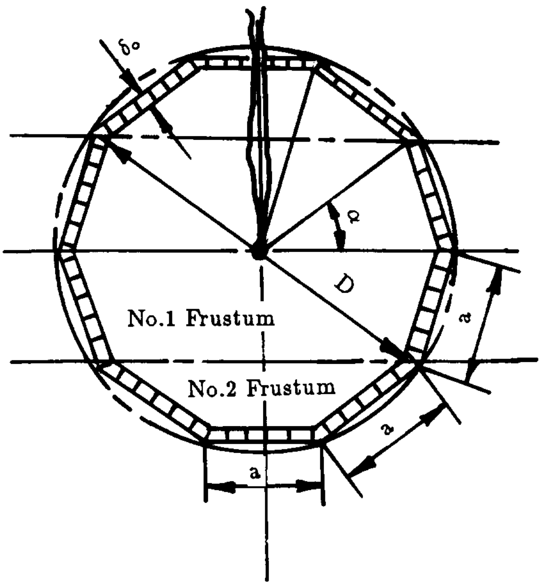

Fig. 1. Sketch of the structure of four-cone spherically-inscribed container.

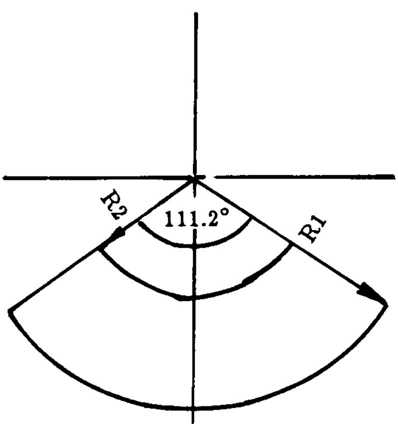

Fig. 2. Unfolded structure of the No. 1 frustum of Fig. 1.

In Table 1: α is the central spherical angle faced by each cone and base plate; W_{max}/D is the maximum degree of deformation divided by the diameter; $\Delta\delta/\delta_0$ is the maximum relative reduction of the thickness; and $\Delta t_0/t$ is the maximum relative extension.

Table 1

Effect of the N value on the parameters of deformation

N	2	4	5	6	7	8
α	60°	36°	30°	25.7°	22.5°	20°
W_{max}/D	0.067	0.024	0.017	0.013	0.009	0.008
$\Delta\delta/\delta_0$	13.4%	4.9%	3.4%	2.5%	2.0%	1.5%
$\Delta t/t_0$	15.4%	5.1%	3.5%	2.6%	2.0%	1.5%

4. Calculation of the forming energy and of the size of the explosive charge

In order to arrive at a rational method for predicting the amount of explosive charge needed for a particular forming operation, it is necessary to compute the strain energy of plastic deformation of the metal part or workpiece. Over the last twenty years, a lot of test results have indicated that strain rate has a significant effect on the flow stress of the material [3]. However, in the process of isolated explosive forming in water, it is very difficult to establish the strain rate–strain–stress relationship under the conditions of a loading rate of from 10^{-6} to 10^{-5} s. In order to facilitate engineering practice, a plastic mechanical model is still used to calculate strain energy, employing the following assumptions: (i) the effect of strain rate can be ignored; (ii) the sheet material is an incompressible rigid–plastic hardening material; (iii) the equivalent strains along the generatrix of each conical frustum and along the diameter of the base plates are distributed evenly; (iv) the stress is distributed evenly over the thickness of the shell, ignoring bending effects; and (v) the multi-cone container is turned into a sphere after deformation, the circumferential welding seams do not participate in the deformation.

Based on the above assumptions, the strain energy per unit volume, dU, caused by a small increase in strain is given by

$$dU = \sigma_1\, d\varepsilon_1 + \sigma_2\, d\varepsilon_2 + \sigma_3\, d\varepsilon_3 \tag{1}$$

where $\sigma_1, \sigma_2, \sigma_3$ are the principal true stresses and $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are the principal natural strains. Using St. Venant's theory of plastic flow for the stress–strain relationship, based on the deviator strain rate tensor, and assuming that the spherical strain rate tensor is zero (i.e. the material volume remains constant during deformation) it can be shown that eqn. (1) is equivalent to:

$$dU = \sigma_{eff}\, d\varepsilon_{eff} \tag{2}$$

where

$$\sigma_{eff} = \tfrac{1}{2}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \tag{3}$$

and

$$\varepsilon_{\mathrm{eff}}=\frac{\sqrt{2}}{3}\sqrt{(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_1)^2} \tag{4}$$

For most strain-hardening materials, the following empirical stress–strain relationship can be used

$$\sigma_{\mathrm{eff}}=K\varepsilon_{\mathrm{eff}}^{n} \tag{5}$$

The values of K and n are obtained conveniently from a uniaxial test, where $\sigma_1=\sigma_{\mathrm{eff}}$ and $\varepsilon_1=\varepsilon_{\mathrm{eff}}$. Therefore, the total strain energy of the container U can be determined:

$$U=\int\sigma_{\mathrm{eff}}\,\mathrm{d}\varepsilon_{\mathrm{eff}}=\frac{K}{n+1}\,\varepsilon_{\mathrm{eff}}^{n+1} \tag{6}$$

The amount of energy delivered by an explosive charge to the sheet metal inside the sphere is given by

$$E_{\mathrm{T}}=\eta\, me\;[4] \tag{7}$$

where η is the efficiency of energy transfer in the sealed container ($\eta=55\%$ [5]); m is the weight of the explosive package; and e is the specific energy of the explosive material.
Let

$$U=E_{\mathrm{T}} \tag{8}$$

The weight, m, of the explosive package in the deformation process can now be calculated.

5. Conclusions of the tests

Experiment into the non-die explosive forming of spherical vessels using four-cone containers of 1Cr18Ni9Ti material have been carried out successfully. The appearance of a four-cone container after expansion is shown in Fig. 3, the values of the experimental parameters for this test being presented in Table 2. From the results of the experiments, the following two conclusions are obtained:

(1) The circumferential welding seams on the container are virtually undeformed, their non-spherical degree being $\leqslant 1\%$;

(2) Stainless steel, such as 1Cr18Ni9Ti, is very sensitive to the effects of the shock wave, the material becoming explosive hardened after expansion. If the workpiece requires multi-shot forming, it must be heat-treated between successive shots.

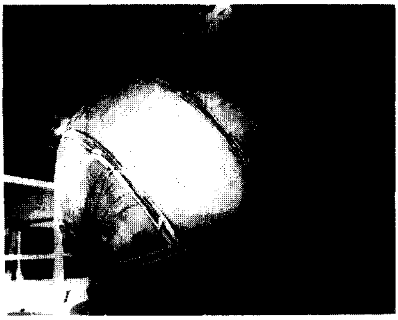

Fig. 3. The four-cone container after expansion.

Table 2

D (mm)	δ (mm)	K (kgf/mm)[a]	n 2	e (kgfm/g)[b]	η (%)	m (g)	Detonator
920	2.0	1.13×10^2	0.3	527	55	21	8# electric detonator

[a] 1 $kgf/mm^2 = 9.81$ MPa.
[b] 1 kgfm/g = 9.81 J/g.

6. Engineering applications

The test results indicate that the technology of liquid-filled explosive forming without dies has opened a new way of manufacturing spherical pressure vessels. It needs no special dies and it is easy to change size and variety. The process does not need any forming equipment and it can save energy more effectively. In practical production, the energy of the explosive charge is sealed in a spherical space: there is no pollution, so that the process can be conducted within any environment.

The authors have also applied this technology to the manufacturing of spherical vessels of different materials and of different volume, achieving success in all instances. Figure 4 is the photograph of a storage vessel for liquid synthetic ammonia, manufactured for a chemical factory, which has a diameter of 4 m (volume 33 m^3) and a thickness of 18 mm, the material used being 16MnR steel. In practical production, an overall check on the quality of the welding seams is required before the carrying out of explosive forming operation, with a further check being needed after the operation has been completed. There is no evident difference in the quality and performance of the material in the welding seam region in the present experiments from those in the classical cold-forming of spherical segments. Both the reduction of the thickness and the percentage elongation of the material are lower than the international limit of the degree of deformation in the cold forming of spherical segments, which is 5%.

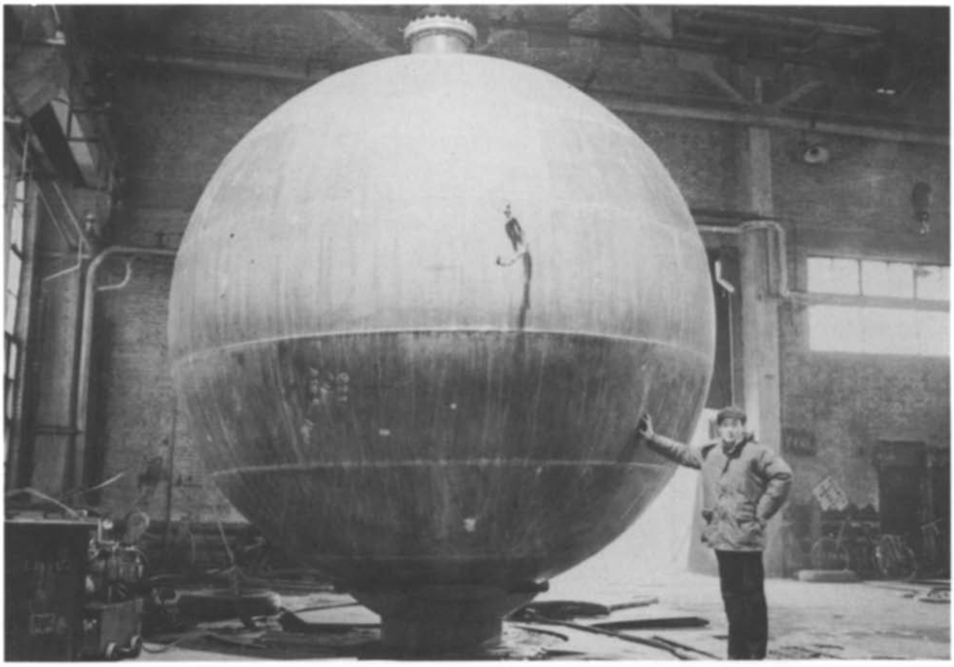

Fig. 4. The vessel for storing synthetic ammonia made by explosive forming ($D = 4$ m).

This technology can be used also to produce special structures, such as double-layered spherical vessels (vessels for storing liquid hydrogen, liquid oxygen, etc.,), hemispherical domes, large-sized ellipsoidal heads and decorative spheres for architecture, and so on.

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