Pressure Test of a Pressure Vessel with Glass Dome and Cylinder of Other Material

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Abstract

Glass dome is a very good component for pressure vessel. A sphere by two domes becomes very strong pressure vessel. However, combination with cylindrical housing of the other material is not good. Young's modulus of glass is 64GPa and is very low compared with conventional steel, titanium alloy, aluminum alloy or ceramics, which means that a glass dome shrinks larger than a cylinder made of the other material. The glass dome is very strong against outer pressure when it shrinks evenly, but when it shrinks unevenly by any reasons, tensile stress or stress concentration on edge of the dome may come out, which leads to crack and to collapse of the glass dome. The author tested a glass dome with ceramic cylinder, but it collapsed at a little higher pressure than the planned operational pressure. Analysis showed that the collapse was due to the uneven shrinkage of glass dome. In order to avoid uneven shrinkage of glass dome, the friction at the rim of glass dome with the supporting structure must be zero or very small. However, conventional low-friction material like Teflon sheet is not good for this purpose because of the plastic flow by the large contact stress. Thus, the author introduced a special coating technology, Diamond-Like Carbon (DLC) coating. This coating requires very smooth surface with Ra<0.02μm, and the coated surface becomes very hard like diamond, which makes the friction coefficient as 0.05~0.15 at the manufacturer's data.

The pressure test was conducted for a pressure vessel of a steel cylinder with two glass dome caps. The glass domes were supported by DLC-coated seats at both ends of the steel cylinder. The maximum test pressure was targeted to 110% of the operational pressure, but the pressure vessel collapsed at a little lower pressure than the planned operational pressure. However, the analysis of this collapse gave us new knowledge on the structural strength of the pressure vessel with glass dome.

This paper discusses about the design philosophy of a pressure vessel with glass dome and a cylinder.

Keyword: Pressure vessel, Glass dome, Cylinder, Friction

I. INTRODUCTION

Glass dome is a very good component for pressure vessel. A glass sphere by two glass domes becomes a very strong pressure vessel. However, combination with a cylindrical housing of the other material is not good. Young's modulus of glass is 64GPa and is very low compared with conventional steel, titanium alloy, aluminum alloy or ceramics, which means that a glass dome shrinks larger than a cylinder made of the other material. The glass dome is very strong against outer pressure when it shrinks evenly, but when it shrinks unevenly by any reasons, tensile stress or stress concentration on edge of the dome may come out, which leads to crack and to collapse of the glass dome[1].

The author is now developing pressure vessel of an AUV Jellyfish Catcher which can dive to 7,300m deep and can catch a jellyfish living there. The tentative form of this AUV is shown in Fig.1. The pressure vessel is a ceramic cylinder with two hemispherical caps, one is made of ceramics, and the other is a glass dome as shown in Fig. 2. TV cameras will be installed in this pressure vessel and they look for a jellyfish through this glass dome.

The characteristics of the pressure vessel are shown in Table 1. There are various types of ceramics, and typical ones are shown in Table 2. In this development, Silicon Carbide is selected because of its high Young’s modulus, high compression strength, low specific gravity, and high thermal conductivity. The last item is very important as a container of electric-electronic system for thermal dissipation especially during test run on the deck of the ship. This value is nearly 2.5 times of the steel.

The diameter of the cylinder comes from a glass dome of 13-inch ball. Its inside diameter is 306mm and the outside

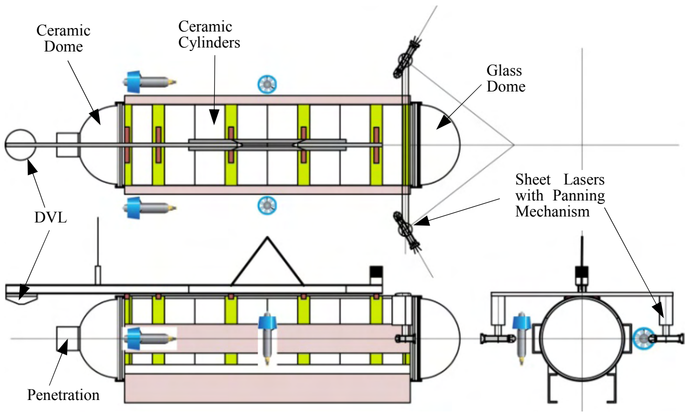

Fig. 1 General Configuration of a Jellyfish Catcher AUV

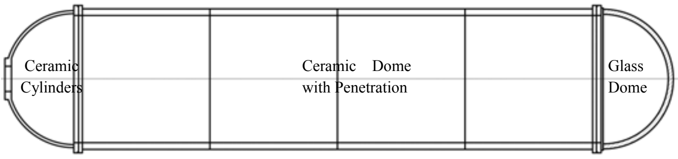

Fig. 2 Configuration of Pressure Vessel for Jellyfish Catcher AUV
Cylinder part is composed of four ceramic cylinders. Head (right in this figure) is a glass dome and end is a ceramic dome with penetration

Table 1. Principal Characteristics of the Pressure Hull for the AUV Jellyfish Catcher

	Cylinder	Dome	Glass Dome
Maximum Operation Depth(m)	7,300m		
Inside Diameter (mm)	300.8	309.4	306
Outside Diameter (mm)	332.2	323.6	330
Length (mm)	300 x 4	---	---
Material	SC-1000	SC-1000	Borosilicate Glass

Table 2. Typical Characteristics of Some Ceramics

	Alumina A-601 (99.9%)	Silicon Nitride SN-300	Silicon Carbide SC-1000	Boro-Silicate Glass
Specific Gravity	3.9	3.2	3.16	2.23
Young's Modulus(GPa)	380	300	440	64
Poisson's Ratio	0.23	0.28	0.17	0.2
Compression Strength (MPa)	2350	4000	2500	---
Thermal Conductivity (W/mK)	34	27	200	1.2

diameter is 330mm with wall thickness of 12mm. The total weight of the pressure vessel is about 70kgf and its volume is about 130 liter, and its buoyancy in sea is about 60kgf. Thus, buoyancy material is not necessary[2].

Structural analysis and pressure tests showed that a pressure vessel made of ceramics was of no problem. The author had made a small ceramic cylindrical pressure vessel with full ocean depth capability and tested it successfully. However, the combination with glass dome becomes a big issue for the development of this type of pressure vessel.

II. NOMENCLATURES

E: Young's Modulus
F_V: Vertical Force
F_L: Lateral Force
P_0: Outer Pressure
P_{cr}: Collapse Pressure of Sphere
P_k: Collapse pressure of Cylinder
k: Proportional constant
r: Radius
r_c: Radius of Thickness Center for Cylindrical Shell
r_i: Inside Radius
r_o: Outside Radius
r_{sp}: Radius of Thickness Center of the Spherical Shell
t: Wall Thickness of the Cylindrical Shell
t_{sp}: Wall Thickness of the Spherical Shell
u: Shrinkage
u_r: Radial Shrinkage of Cylindrical Shell
u_{sp}: Shrinkage of Spherical Shell
ε_z: Axial Strain of Cylinder
μ: Friction Coefficient
ν: Poisson's Ratio
σ_θ: Circumferential Stress
σ_r: Radial Stress
σ_z: Axial Stress

III. STRUCTURAL DESIGN AND SHRINKAGE

As is shown in most textbooks or handbooks, collapse pressure of a cylinder by outer pressure is given as (1):

$$P_k = \frac{E}{4(1-\nu^2)}\left(\frac{t}{r_c}\right)^3 \quad (1)$$

Also, its shrinkage and stresses are given as (2)~(6):

$$u_r = \frac{-r_i r_o^2 P_0}{E(r_o^2-r_i^2)}\left\{(1-2\nu)\frac{r}{r_i} + (1+\nu)\frac{r_i}{r}\right\} \quad (2)$$

$$\varepsilon_z = -\frac{(1-2\nu) r_o^2 P_0}{E(r_o^2-r_i^2))} \quad (3)$$

$$\sigma_r = -\frac{(r_o/r_i)^2-(r_o/r)^2}{(r_o/r_i)^2-1}P_0 \quad (4)$$

$$\sigma_\theta = -\frac{(r_o/r_i)^2+(r_o/r)^2}{(r_o/r_i)^2-1}P_0 \quad (5)$$

$$\sigma_z = -\frac{(r_o/r_i)^2}{(r_o/r_i)^2-1}P_0 \quad (6)$$

Collapse pressure of a sphere by outer pressure is given as (7) and its stresses and shrinkage are given as (8)~(10):

$$P_{cr} = \frac{2E}{\sqrt{3(1-\nu^2)}}\left(\frac{t_{sp}}{r_{sp}}\right)^2 \quad (7)$$

$$\sigma_r = -\frac{P_0 r_o^3}{r_o^3-r_i^3}(1 - r_i^3/r^3) \quad (8)$$

$$\sigma_\theta = -\frac{P_0 r_o^3}{r_o^3-r_i^3}(1 + r_i^3/r^3) \quad (9)$$

$$u_{sp} = \frac{-r_i r_o^3 P_0}{E(r_o^3-r_i^3)}\left\{(1-2\nu)\frac{r}{r_i} + \frac{(1+\nu)}{2}\frac{r_i^2}{r^2}\right\} \quad (10)$$

A. *Shrinkage Adjustment*

Important point for coupling the cylinder and the ceramic dome is to adjust the shrinkage the same with each other at the connecting location. If this condition is not satisfied, bending stress occurs and crack shall happen which may originate collapse. In order for this adjustment, the wall thickness of the hemisphere is increased. Size of flange is also adjusted to meet with this requirement.

As for penetration hole on the dome, the outer diameter of the penetration coaming is so selected to adjust the shrinkage of the penetration coaming with the shell of the dome at the outer rim of the coaming.

Glass dome is very good item for pressure vessel. However, Young's modulus of the glass is 63-64GPa and this value is nearly 1/3 of that of steel, and glass dome shrinks larger than pressure vessel constructed with the other material of high Young's modulus. Glass is also very brittle material, and the shrinkage difference with the other pressure vessel becomes a serious issue of collapse when they are structurally connected.

The important point for designing pressure vessel composed with glass dome and the other material is to make the shrinkage of both the glass dome and the other pressure vessel at the connection the same each other, or to allow slip with so low friction coefficient that each part shrinks independently.

Titanium alloy or aluminum alloy has medium Young's modulus, and it is a good material for cylinder to be connected with glass dome caps at some pressure range, and the shrinkage of the cylinder can be adjusted to be the same as that of glass dome. This method is applied for glass dome housing with metallic O-ring seal flange for easy coupling/decoupling.

B. Shrinkage Compensation by Slip

In case there is no way to adjust the shrinkage, slip method has to be considered. Typical example is the acryl-plastic conical frustum viewport. This viewport slides along the slope of the viewport coaming when it receives pressure.

For glass dome, however, the stress on the contact surface becomes very large, and conventional plastic material for sliding such as Teflon or others cannot be used to support this large stress.

Although zero friction is ideal, it cannot be realized. It is necessary to grasp the relation between the friction coefficient and the shrinkage.

The shrinkage u is proportional to the lateral force under frictionless condition. But the lateral force becomes F_L-μF_V by friction and the shrinkage becomes smaller as u-Δu where Δu is the remaining shrinkage as is shown in Fig. 3.

Thus, the remaining shrinkage Δu by the friction can be written as (11):

$$\Delta u/u = \mu F_V/F_L \tag{11}$$

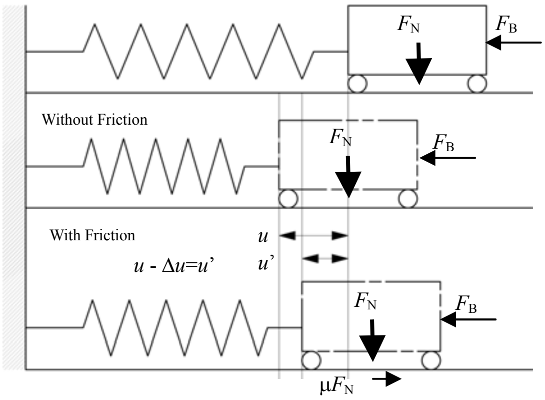

Fig. 3 Effect of Friction on Shrinkage

Fig. 4 shows the vertical force and lateral force on the supporting seat of the glass dome, where the vertical force F_N=$P_0r^2\Delta\theta/2$ and the lateral force F_B=$(\pi/4\text{-}1/3)P_0r^2\Delta\theta$. This gives:

$$\Delta u/u = \mu/(\pi/2\text{-}2/3) \tag{12}$$

The denominator $\pi/2\text{-}2/3 \approx 0.9$ and is nearly 1, then the ratio of the remaining shrinkage Δu by the friction against the frictionless shrinkage u is nearly the same as the friction coefficient μ itself. This means that 90% of shrinkage is achieved when μ=0.1. Thus the method of the smaller friction coefficient is required for the sliding seat.

This seat receives also a very large stress to support the pressing force on the glass dome by water pressure. Recent technology gives solution for this matter: the Diamond-Like Carbon coating, or DLC coating for short. The catalogue data

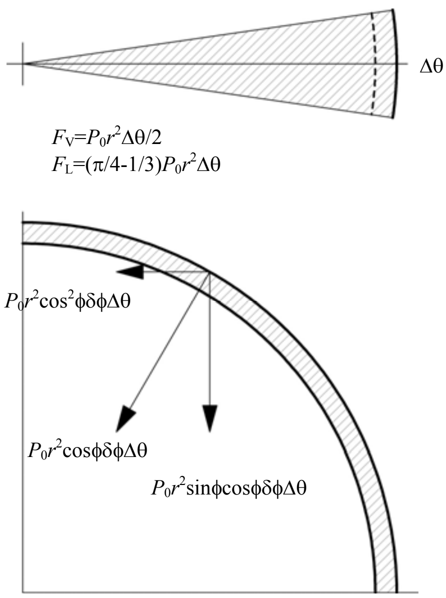

Fig. 4 Suppressing Force and Sliding Force on Dome
Suppressing force normal to the seat is F_V, and the lateral force F_L is the force to slide (shrink) the dome.

shows the friction coefficient can be 0.15~0.05 and can support 500~600MPa stress, although fabrication requires very fine machining and lapping to make the sliding surface roughness as Ra<0.02μm.

IV. EXPERIMENTS AND FAILURES

The author tried pressure test twice for glass dome with cylindrical pressure hull using IIS's high water pressure test tank facility whose maximum pressure is 118MPa.

The first one was with ceramic cylinder. The calculated shrinkages of both the glass dome and the ceramic cylinder are shown in Table 3.

The first test was done with grease lubrication between the ceramic flange and glass dome seat made of titanium as shown in Fig. 5. There was no above mentioned DLC coating. The targeted operational pressure was 73MPa, and the maximum test pressure was 80.3MPa at 10% margin. This collapsed at 77MPa. Analysis of the collapsed fragments showed that the collapse was initiated at glass dome. The author thought that the shrinkage compensation must be done by introducing friction reduction method.

Then, a pressure vessel with two glass domes and a steel cylinder was prepared as shown in Fig. 6. Each glass dome has its own seat with DLC coating. However, one seat was made of titanium and the other was made of steel. The calculated shrinkages of the glass dome, titanium seat, steel seat, and steel cylinder at the maximum operational pressure are shown in Table 4.

This collapsed at 62MPa. Analysis of the collapsed fragments showed that the collapse was initiated at glass dome with steel seat.

Table 3. Comparison of Shrinkage at the Max. Operation Pressure for the Initial Design of Glass Dome Seat

	Inside Dia.(mm)	Outside Dia.(mm)	Radial Shrinkage (mm) at Center
Glass Dome	306	330	-1.01516
Titanium Seat	303	337	-0.80244
Ceramic Cylinder	300.8	332.2	-0.25027

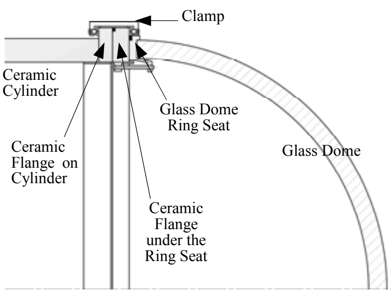

Fig. 5 Initial Design of Glass Dome Seat
The glass dome sits on ring seat, which slides on a ceramic flange.

Table 4. Comparison of Shrinkage at the Max. Operation Pressure for the Alternate Design of Glass Dome Seat

	Inside Dia.(mm)	Outside Dia.(mm)	Radial Shrinkage (mm) at Center
Glass Dome	306	330	-1.01516
Titanium Seat	301.5	337	-0.76432
Steel Seat	288	336	-0.32705
Steel Cylinder	280	360	-0.20626

*Young's Modulus of Steel=200GPa, and that of Titanium=116GPa.

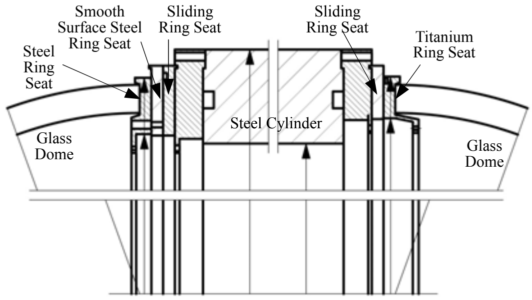

Fig. 6 Alternate Design of Glass Dome Seat
Right: Titanium Ring Seat on Sliding Ring Seat
Left: Steel Ring Seat with Smooth Surface Steel Ring Seat on Sliding Ring Seat
Center: Steel Cylinder (Shrinkage is the same as the Ceramic Cylinder)

These test results seem to imply that although friction reduction is very important, but at the same time, the glass dome seat is requested to shrink by the same level as the glass dome itself. Steel seat is very rigid compared with titanium seat and steel seat will retard the shrinking of the glass dome, then this initiates the deformation of the glass dome to collapse.

This glass dome seat should not be considered as a structural member, but should be considered as an appendage to the glass dome, and this can be made of material with lower Young's modulus like aluminum alloy.

The surface roughness of the glass dome seat where the glass dome sits on must be as smooth as or smoother than the sitting surface of the glass dome of course, otherwise, the glass dome will have cracks at low pressure level.

V. CONCLUSION

This study to couple the glass dome with ceramic cylinder is still underway. By this study, followings were obtained:

(a) Shrinkage of both the glass dome and the cylinder should be adjusted to be the same.
(b) In case it is not possible, a sliding mechanism at the contact surface between the glass dome and the cylinder should be introduced.

(c) The contact surface receives very high normal stress, and the surface is requested to have very low friction coefficient. This can be realized by introducing DLC (Diamond-Like Carbon) coating technology.
(d) The sliding glass dome seat is not a structural member, but is an appendage to the glass dome. Thus, the material of the seat should be of lower Young's modulus, so that the shrinkage becomes nearly the same as that of the glass dome.
(e) The surface roughness of the glass dome seat where the glass dome sits on must be as smooth as or smoother than the sitting surface of the glass dome.

In order to avoid the delay of the development of AUV Jellyfish Catcher due to the delay of pressure vessel development, a design alteration may be introduced to use ceramic dome instead of glass dome for the main body, and to use outside TV camera containers.

Beside this possible design change, study on coupling the glass dome with ceramic cylinder shall be continued.

REFERENCE

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