Study on spherical pressure vessel of ceramics for deep-sea buoyancy module applications

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Abstract - Remotely operated vehicles (ROVs) for deep-sea operation should be as light as possible for improvement of maneuverability and payload increase. Engineering ceramics has been one of the candidate materials for deep-sea pressure vessels because of its high compressive strength. The plan, which lessens its specific gravity and enlarges its pressure tolerance, had been prepared with installation of ceramic macro-spheres into syntactic foam, however it had failed due to the chain reaction of collapse of the ceramics macro-spheres.

The main purpose of this study is to establish the methodology of fabricating the ceramic pressure vessels for deep-sea operation. As the first step, the spherical pressure vessel of ceramics was studied for deep-sea buoyancy module application. It is very important to keep the reliability on the macro-sphere, and the shape (= sphericity and thickness) should be controlled as good as possible. Thus, the ceramic hemispheres were fabricated, and their local radius of curvature and wall thickness was precisely measured by use of the simple measuring instruments. The measured results showed that the spherical irregularities were significantly improved compared with the sample of approximately 20 years ago.

I. Introduction

Japan Agency for Marine-Earth Science and Technology (JAMSTEC) has been and is now developing ROVs for scientific researches. The densities of material such as titanium alloy or aluminum alloy for pressure vessel and frame etc. equipped on those ROVs are heavy compared with that of sea water. Therefore, additional buoyancy material such as syntactic foam is usually provided to compensate the negative buoyancy of the body.

Syntactic foam used for deep-sea operation is composed of glass microballoons and epoxy resin. The outer diameter of glass microballoons is 40-200[µm]. Syntactic foam for 6500m diving submersible “SHINKAI 6500” is a binary mixture type which is a combination of different sizes of microballoons, and its specific gravity is 0.54. On the other hand, those for 11000m ROV “KAIKO, it is a conventional one with thicker wall and stronger resin and its specific gravity is 0.63. Although the improvement of material strength has been continued, considerable advancement of its density cannot be expected by the improvement with the same concepts.

The main purpose of this study is to develop the lightweight buoyancy module and pressure vessel, which can be used in deep-sea. Therefore, engineering ceramics was examined as a structural material because of its high compressive strength. Ceramics usually involves minute cracks, and the shape deforms in the sintering process. Although number of years has passed after the start of study of engineering ceramics, practical applications for structural material has not been advanced so much except for limited field.

At the initial stage of this study, several experimental ceramic hemispheres with different wall thickness were fabricated from alumina ceramics and their local radii of curvature and wall thickness were measured. Then, their collapse strengths were estimated by use of those values, and the application methodology for manned submersible and ROV was investigated.

II. Background

In the development stage of 3000m class ROV “Dolphin 3K”, which JAMSTEC started the operation in 1985, combination of ceramics macro-spheres and syntactic foam was considered as hybrid type buoyancy module. If this hybrid type buoyancy module were applied to ROVs operation in the deep sea, a large number of ceramic spheres would be needed in order to satisfy required buoyancy.

Since the shape of sphere influences pressure tolerance, all spheres need to be fabricated with high processing accuracy. Moreover, in case of this type buoyancy module, the chain reaction of collapse by shock wave due to collapse of a single balloon would be a serious matter to be considered.

Although ceramics is a brittle material as mentioned before, the compression strength and Young's modulus are particularly high compared with metal material. On the other hand, its specific gravity is small (Refer to Table 1).

<table>
<thead>
<tr>
<th>Density [g/cm³]</th>
<th>Alumina</th>
<th>Silicon carbide</th>
<th>Silicon nitride</th>
<th>Zirconia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending strength [MPa]</td>
<td>310</td>
<td>450</td>
<td>610</td>
<td>1000</td>
</tr>
<tr>
<td>Compressive strength [MPa]</td>
<td>2160</td>
<td>---</td>
<td>3820</td>
<td>5690</td>
</tr>
<tr>
<td>Young's modulus [GPa]</td>
<td>360</td>
<td>440</td>
<td>290</td>
<td>200</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.23</td>
<td>0.17</td>
<td>0.28</td>
<td>0.31</td>
</tr>
<tr>
<td>Fracture toughness [MPa/m]</td>
<td>3-4</td>
<td>2-3</td>
<td>5</td>
<td>4-5</td>
</tr>
</tbody>
</table>
Although it is necessary to estimate larger safety factor for ceramics compared with metal material as a structural material, ceramics will be one of the top-rated structural materials under high-pressure environment, when its strength reliability is established.

III. Fabrication of hemispheres of alumina ceramics

Spherical shape can make the ratio of mass per unit volume the smallest, and the strongest as a pressure vessel. Therefore, the sphere was considered as the shape of prototype of pressure vessel for initial stage of this research, and alumina ceramics was selected as the material. Alumina ceramics is the sintering material of the same crystal ($\alpha$-Al₂O₃) as sapphire or ruby, and has such features, as corrosion-resistance, wear-resistance, and high strength. Moreover, processing of alumina ceramics is easy compared with other engineering ceramics. Therefore, it is widely used for the industrial machine part etc.

The designed outer diameter of prototype spheres was 100 [mm], and their wall thicknesses are 1.5 [mm] and 2.0 [mm]. As it was impossible to fabricate the ceramics spheres of one body, two hemispheres were fabricated and they were sticked each other with epoxy adhesives.

A. Collapse strength and specific gravity of ceramics sphere

A brittle material like ceramics is destroyed within small deformation, even if acting load increases. Therefore, collapse strength and required wall thickness of ceramics sphere were confirmed by using "Theory of elastic buckling", then, principal specifications of a prototype sphere were determined. Wall thickness of prototype sphere can be calculated by using (3.1) by setting up the allowable stress (yield stress) of material and the radius of sphere.

$$\sigma_t = \frac{P_0}{2t} \rightarrow t = \frac{P_0}{2\sigma_t} \quad (3.1)$$

Where:
- $r$ : Design radius [m]
- $t$ : Wall thickness [m]
- $P_0$ : Hydraulic pressure [MPa]
- $\sigma_t$ : Membrane stress [MPa]

In this case, the elastic backling pressure $P_0$ can be calculated by (3.2). In this calculation, $P_0$ must be larger than $P_c$. After the check of the two values, wall thickness is determined.

$$P_0 = \frac{2E}{(3(1 - v^2))^{1/2} (t/r)^2}. \quad (3.2)$$

Where,
- $P_0$ : Elastic backling pressure [MPa]
- $E$ : Young's modulus [MPa]
- $v$ : Poisson's ratio

By use of the above equation, collapse strength of alumina ceramic sphere with wall thickness of 1.5 [mm] can be calculated as 130 [MPa], and its specific gravity of sphere is 0.342 (Measured value). In the case of wall thickness of 2.0 [mm], collapse strength is 170 [MPa], and its specific gravity of sphere is 0.450 (Measured value).

IV. Relationship between Spherical Irregularities and Pressure-resistant

If the fabricated ceramics sphere is perfect as designed, internal stress produced by water pressure, is uniform at the point of the same radius from center. However, since the fabricated sphere has distortion due to the sintering process, internal stress is not uniform. Therefore, when considering the collapse strength, the shape after fabrication such as maximum local radius of curvature, and wall thickness are more important than design radius of sphere. (Refer to Fig. 2) In order to evaluate the deviation of this radius of curvature quantitatively, the measurement of sphericity is generally used as criterion. Sphericity is defined as (4.1) by using the average radius of sphere, and the maximum local radius of curvature.

$$\text{Sphericity} = \frac{\text{Maximum local radius of curvature}}{\text{Average radius of sphere}} \quad (4.1)$$

If the value of sphericity equals to 1, fabricated sphere is perfect. Here, the local radius of curvature in minute range does not affect directly to collapse strength of sphere, and the curvature in a critical arc length $L_c$, defined below is used where $r_c$ is the local radius of curvature and $t_c$ is an average wall thickness in this length.
\[ L_c = 2.2 \sqrt{(r_w)^2 - (3(1-v^2)d)^2} \]  \[ \text{[mm]} \]  \[ (4.2) \]

Although necessary wall thickness can be estimated by determining the hydrostatic pressure, and radius of the sphere, the sphericity is the another factor for fabricating the actual ceramic spheres of the buoyancy module, and bad sphericity gives the sphere superfluous thickness of wall and weight. Thus, estimation of spherical irregularities during the fabrication process are necessary in order to materialize the practical use of this module.

A. Measurement method of irregularities of hemispheres

Measurement of local radius of curvature and wall thickness was performed in order to evaluate the degree of deformation of sphere. The critical arc length: \( L_c \) of prototype sphere was calculated by use of (4.2). In case of wall thickness of 1.5 [mm], \( L_c \) equals 20.808 [mm], and in case of 2.0 [mm], \( L_c \) equals 24.025 [mm]. Therefore, standard of \( L_c \) was set to 20[mm] in this measurement, and the length between two needles of attachment was designed in accordance with this arc length.

The measuring points were set up as shown in Table 2. In measurement of local radius of curvature, it is necessary to measure the radius of curvature to plural direction. Since two hemispheres had not joined yet, it was impossible to measure the radius of curvature to meridian direction near the connecting surface. Therefore, only the radii of curvatures of the direction normal to the meridian were measured.

A1. Measurement method of local radius of curvature

In a measurement of large diameter sphere such as pressure hull of manned submersible, sphericity is calculated by the measurement of radii at many points on the wall of sphere from the center by special equipment installed in the sphere. However, if the same measuring method is applied to a sphere of small diameter, the sphericity cannot be calculated accurately, since the relative measurement error of radius on a sphere becomes large.

Therefore, in this research, a method using a dial gauge and its attachment was used for measurement of local radius of curvature by the three-point method. Width of the needles of measurement equipment \( = 2a \) was set to 20 [mm] as described before. (Refer to Fig. 3) Although the measurement method and the equipment used in this research are very simple, this method can detect the minute change of curvature on sphere surface which is considered to be the trace of fixing tools used during the sintering process.

If the measured length in the critical arc length is found to be "b", the relationship can be described as (4.3) by using of Pythagorean theorem. (Refer to Fig. 4)

\[ R^2 = (R - a)^2 + (b)^2 \]

\[ b = R - (R^2 - a^2)^{1/2} \]  \[ (4.3) \]

On the other hand, local radius of curvature \( R_{local} \) on the surface of a sphere can be calculated by (4.4) utilizing known values of \( a \) and \( b \).

\[ R_{local} = (a^2b + b)/2 \]  \[ (4.4) \]

After 240 points of measurement of local radius of curvature on a hemisphere surface, the sphericity can be calculated by (4.1). Before and after the measurement, accuracy of measurement was confirmed by use of a surface plate (Flatness 1[\mu m]) and gauge blocks of zirconium. As a result of this examination, the maximum error was confirmed under 4/1,000[mm].

![Local radius of curvature on hemisphere.](image)

![Figure 4.](image)

A2. Measurement method of thickness

Since radius and wall thickness of the prototype sphere is small compared with a pressure hull of manned submersible, thickness was measured by use of a micrometer.
In order to control the measurement error minimum, the wall thickness of whole region of hemisphere needs to be measured with the same equipment. Therefore, the micrometer with special frame as shown in Fig. 5. was fabricated.

### Table 3 Measured sphericity of ceramic hemispheres.

<table>
<thead>
<tr>
<th></th>
<th>'03 Prototype</th>
<th>'03 Prototype</th>
<th>'03 Prototype</th>
<th>'03 Prototype</th>
<th>'03 Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average radius [mm]</td>
<td>46.344</td>
<td>49.867</td>
<td>49.631</td>
<td>49.135</td>
<td>49.835</td>
</tr>
<tr>
<td>Sphericity</td>
<td>1.258</td>
<td>1.179</td>
<td>1.152</td>
<td>1.138</td>
<td>1.120</td>
</tr>
<tr>
<td>Range</td>
<td>0.400</td>
<td>0.247</td>
<td>0.210</td>
<td>0.201</td>
<td>0.178</td>
</tr>
<tr>
<td>Variance</td>
<td>$1.04 \times 10^{-2}$</td>
<td>$7.69 \times 10^{-2}$</td>
<td>$5.82 \times 10^{-2}$</td>
<td>$5.79 \times 10^{-2}$</td>
<td>$5.81 \times 10^{-2}$</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.102</td>
<td>0.028</td>
<td>0.024</td>
<td>0.024</td>
<td>0.024</td>
</tr>
</tbody>
</table>

B. Measured result of local radius of curvature

Sphericity and wall thickness of the prototype sphere fabricated in the initial stage of this research (Outer diameter : 100 [mm], Wall thickness : 1.5 [mm] and 2.0 [mm]), and the prototype sphere fabricated at the time of development of "Dolphin 3K" were measured by use of the method described before.

B1. Measured result of local radius of curvature

The measured contour lines of sphericity of the prototype sphere ("N" hemisphere) of design thickness of 1.5 [mm] is shown in Fig. 6, and that of "Dolphin 3K" is shown in Fig. 7 by Azimuthal Equidistant Projection method with center as pole. Also, the result of the statistical analysis of the measured local radius of curvature is shown in Table 3. The four yellow parts shown in Fig. 6 indicate the effect of supporting jigs during the sintering process.

Compared with the ceramics sphere fabricated at the time of development of "Dolphin 3K", the variation of local radius of curvature of the prototype spheres fabricated in this research are very small. This means that this sphere is very close to the perfect sphere.

This is related to the improvement of machine tools and processing technology of engineering ceramics compared with about 20-year ago. However, the larger radius of curvature at the polar part, and deformation by the supporting jigs during the sintering process of ceramic sphere needs to be improved in future fabrication.

B2. Measured result of wall thickness

The measured contour lines of wall thickness of the prototype sphere ("N" hemisphere) of design thickness of 1.5 [mm] is shown in Fig. 8, and that of "Dolphin 3K" is shown in Fig. 9 in the same manner. Also, the result of the statistical analysis of the measured wall thickness is shown in Table 4.

The wall thickness of the prototype spheres fabricated in this research is close to the design value, however, wall thickness at the polar part is a little thinner compared with design value. On the other hand, the prototype sphere at
Fig. 8. Contour line of thickness of Prototype Hemisphere '03 (1.5mm-N).

The thickness of prototype spheres fabricated in this research is very small. This is related to the improvement of machine tools and processing technology of ceramics compared with about 20-year ago.

C. Collapse strength

Collapse strength of ceramics hemispheres are estimated by use of measured radius of curvature and wall thickness. Fig. 10 shows the distribution of collapse strength of the prototype sphere ("N" hemisphere) of design thickness of 1.5[mm], and Fig. 11 shows that of the "Dolphin 3K".

The calculated collapse strength of prototype sphere fabricated in this research is 107[MPa] (About 82[%] of the design strength), and that of the "Dolphin 3K" is 94[MPa].

This means that the reliability of practical use of ceramics as structural material is improved very much.

Fig. 9. Contour line of thickness of Prototype Hemisphere '85.

The time of development of "Dolphin 3K" has the large deviation of wall thickness, and the difference of maximum thickness and minimum is about 0.7[mm]. (About 53[%] of average thickness) The wall thickness near the polar part is thick, but it is thin in a circle near 60 [deg] latitude. Moreover, although the wall thickness of longitude of nearly 0 [deg] is thin, it is thick near 180 [deg].

Compared with the ceramics sphere fabricated at the time of development of "Dolphin 3K", the deviation of wall thickness of prototype spheres fabricated in this research is very small. This is related to the improvement of machine tools and processing technology of ceramics compared with about 20-year ago.

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Fig. 10. Contour line of collapse strength [MPa] of Prototype Hemisphere '03 (1.5mm-N).

Fig. 11. Contour line of collapse strength [MPa] of Prototype Hemisphere '85.

IV. Conclusion

In summary, prototype spheres of ceramics have been fabricated for buoyancy module applications, and their shape (= sphericity and thickness) has been validated by simple measuring methods. As a result of the measurement,
Improvement in the fabrication accuracy of prototype spheres has been confirmed, compared with ceramics sphere fabricated at the time of development of "Dolphin 3K".

However, compared with spherical pressure hulls of manned submersible, deformation is still large. (Sphericity of pressure hull of the manned submersible "SHINKAI 2000" (1981) was 1.07, and that of "SHINKAI 6500" (1990) improved to 1.004.) This deviation of local radius of curvature and wall thickness comes from sintering and grinding processes of ceramics, and is improvable by reconsideration of fabrication process in accordance with the measured result of this prototype spheres.

Since hemispheres did not have been joined yet, only the radii of curvatures of the direction normal to the meridian, were measured. After the measurement of the local radius of curvatures of the meridian direction on the full sphere, the relationship between spherical irregularities and collapse strength will be experimentally validated by pressure test. After the clarification, it is planned to fabricate spheres of the other materials with higher compression strength, such as silicon carbide.

If ceramics spheres, fabricated in this research are applied to manned submersible or ROV as buoyancy module, the number of ceramics spheres should be hundreds to thousands.

We become so nervous when the ceramic pressure vessels are introduced into underwater robots because of its brittleness. This may cause a chain reaction of implosion by shock wave due to a collapse of a single sphere. This is just the matter of quality control of the fabrication process, and we will try to establish the fabrication process for stable characteristics of the ceramics spheres.

REFERENCES