Materials for Deep Submergence Research Vehicle

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Abstract

Following the 2,000m deep submergence research vehicle "SHINKAI 2000", the 6,500m deep submergence research vehicle is under construction in Japan. For the research vehicle of this class, light weight and compact size are of utmost importance.

To make the vehicle's weight light as possible, for a pressure sphere, which is the single component of the maximum weight of the vehicle, ultrahigh strength steel, NS90, was adopted for "SHINKAI 2000", and titanium alloy (Ti-6Al-4VELI) for 6,500m deep submergence research vehicle. To use titanium alloy for the pressure sphere of 6,000m-class deep submergence research vehicle, the investigation in several fields were carried out, those were the researches of base metal and welded joint on mechanical the mechanical properties, on fracture toughness, on fatigue strength, on stress corrosion cracking characteristics, on the production procedure of heavy thickness and large scale plate and forging and on the fabrication procedure of the pressure sphere by the fabrication of a full scale model. The collapse behaviour was checked by collapse tests and by analysis using scale models fabricated according with the procedure equivalent to the actual pressure sphere to confirm the adoptability of design procedure. The paper presents outline of those investigation for 6,000m-class deep submergence research vehicle, and the investigation on material characteristics necessary for a deeper (10,000m-class) submergence research vehicle.

KEY WORDS : (Deep Submergence Research Vehicle) (Titanium Alloy) (Buoyancy Material) (Electron Beam Welding) (Pressure Sphere)

1. Development of 6,000m-Class Deep Submergence Research Vehicle

1.1 Basic philosophy for development

The necessity of 6,000m-class deep submergence research vehicle has been comprehended in Japan, as the importance of ocean development came to be recognized. In those days, however, since Japan had not enough experience in the systematic operation of a deep submergence research vehicle with an exclusive support ship, as an intermediate stage, the 2,000m deep submergence research vehicle system which consisted of "SHINKAI 2000", support ship "NATSUSHIMA" and base on land was decided to be developed. "SHINKAI 2000" has been in operation since 1982. Through successful experience of operations and research activity by "SHINKAI 2000", the basic concept of the total system and the design philosophy of the vehicle was confirmed to be practical. As a result, the design philosophy of 6,000m-class deep sumbergence research vehicle shall follow that of "SHINKAI 2000", and the 6,000m-class deep submergence research vehicle shall be light in weight and compact in size as possible within those of "SHINKAI 2000" to maintain the manuevalabity and operationability. The outline of the 6,000m-class deep submergence research vehicle is shown in Table 1 compared with "SHINKAI 2000".

Table 1 Outline of 6,000m-class deep submergence research vehicle

	6,000m-class deep submergence research vehicle	"SHINKAI 2000"
Principal dimensions	Equivalent to "SHINKAI 2000"	9.3m × 3.02m × 2.92m
Weight in air	25 ton Max.	23.2 ton
Max. operating depth	6,000m	2,000m
Operating time	Diving time 2.5 hours	Diving time 1.5 hours
	Bottom survey 3 hours	Botton survey 3 hours
Complement	3 persons	3 persons
Life support	Ordinary operating time + 5 days	Ordinary operating time + 3 days
Max. speed	Approx. 2.5 knots	Approx. 3 knots
Payload	200kg	100kg
ID of pressure sphere	2m	2.2m

1.2 Candidate material for the pressure sphere

For a deep submergence research vehicle, weight and size are the primary concerns in design. In order to keep the weight of a vehicle as light as possible, material for the pressure sphere of 6,000m-class is examined from the viewpoints of total weight of the vehicle and the availability of material. Since the materials for the pressure sphere are required to be higher in strength/weight ratio than NS90, and to have adoptability for the pressure sphere structure which covers the fields of material characteristics, large scale material production, fabrication process including hot forming, welding and machining and collapse behaviour, only two materials, ultrahigh strength steel of 10Ni-8Co ($\sigma_{0.2} \geqq 120 kgf/mm^2$) and titanium alloy of 6Al-4VELI grade ($\sigma_{0.2} \geqq 81 kgf/mm^2$), can be said as the candidates. The comparison of the pressure sphere made of 10Ni-8Co steel and 6Al-4VELI titanium alloy is shown in Table 2. By using 6Al-4VELI titanium alloy the reduction of weight of pressure sphere is expected to be 1.16 t and that of the vehicle is to be 2.79 t. On the basis of this estimation, 6Al-4VELI for titanium alloy is decided as the material for the pressure sphere of 6,000m-class deep submergence research vehicle.

1.3 Research on the characteristics of titanium alloy for the use of pressure sphere

While 6Al-4VELI titanium alloy was already adopted for the vessels housing electric device for "SHINKAI 2000", to use the material for the heavy thickness and large scale structure of 6,000m-class deep submergence research vehicle, it is necessary to confirm the production of large scale ingot and heavy thickness plate, hot forming, welding and collapse behavior.

Table 2 Merit of 6Aℓ-4V ELI titanium alloy for Deep Submergence Research Vehicle

Material	0.2% Proof Stress (kgf/mm^2)	Specific Gravity (g/cm^3)	Strength to Weight Ratio	Pressure Sphere*				Weight of Submersible** (ton)
				Thickness (mm)	Weight (ton)	Buoyancy (ton)	Weight in Seawater (ton)	
6Aℓ-4V ELI Titanium Alloy	≧81	4.42	18.3	68.0	4.66	5.28	-0.62	-
10Ni-8Co Steel	≧120	7.85	15.3	48.5	5.82	4.98	0.84	-
Difference of Weight	-	-	-	-	-1.16	0.30	-1.46	-2.79

* Inside diameter 2m, Safety factor 1.55, Sphericity 1.00
** Considering weight of buoyancy material

2. Fabrication of Full-Scale Model

To confirm the fabrication procedure as well as the production of large scale material, a full scale model of the pressure sphere was built. The configuration of full scale model is shown in Fig. 1. The model consists of N hemisphere and S hemisphere. For the N hemisphere and equator ring, 6Al-4VELI titanium alloy was applied and two viewports (120mmϕ), penetrator for electric cables (800mmϕ), and hatch opening (500mmϕ), are welded or machined to simulate the actual pressure sphere. The equator ring and N hemisphere were welded together to simulate the equator welding. The fabrication procedure is shown in Fig. 2. The hemisphere was fabricated by hot forming and the insert welding of penetrator and rough machining. After the final machining except the equator zone, the equator welding was carried out and the machining of external surface around the equator welded joint followed.

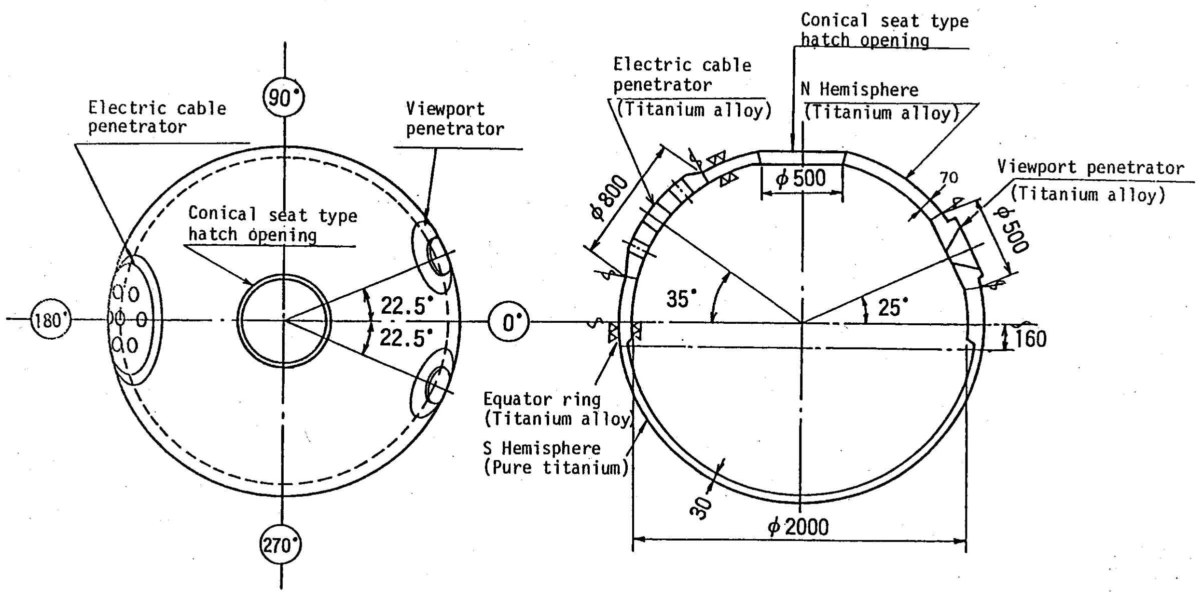


Fig. 1 Configuration of full scale model

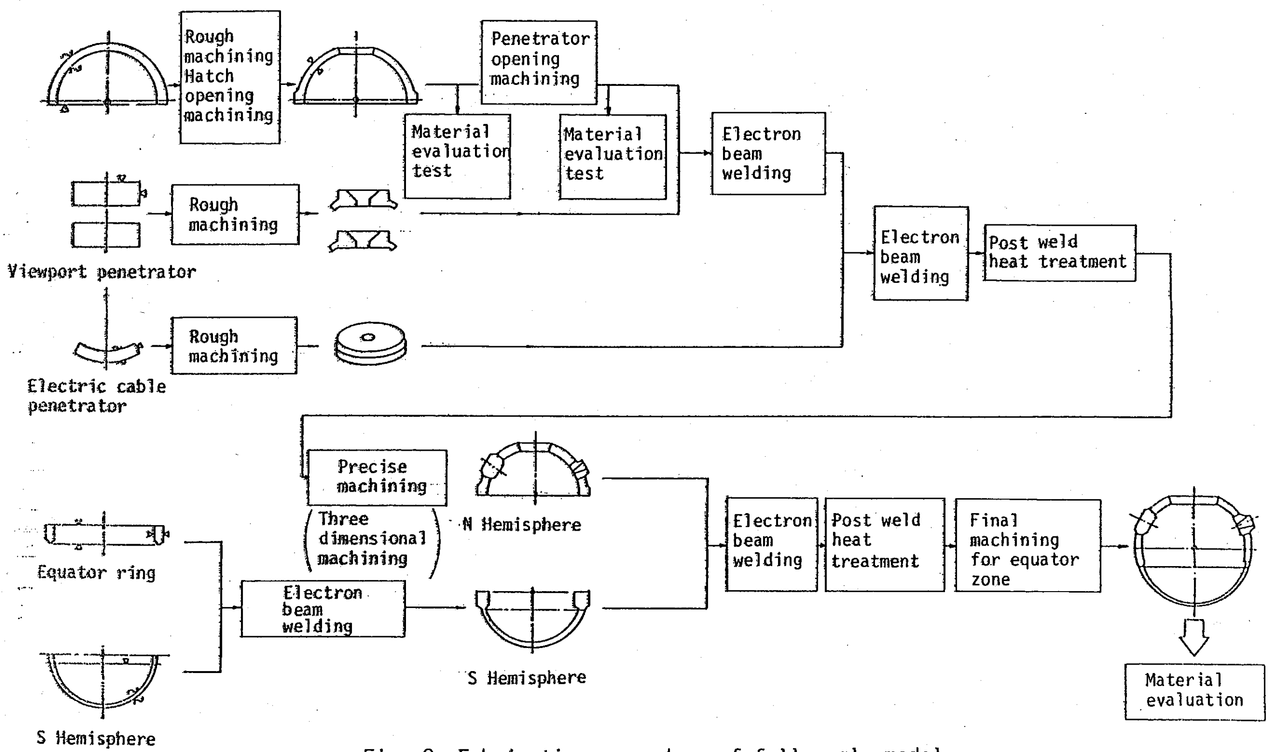


Fig. 2 Fabrication procedure of full scale model

2.1 Fabrication of hemisphere

To fabricate the hemisphere which was 80mm in thickness and 1990mm in inside diameter considering the allowance of machining and welding deformation, the ingot of 9 tons was melted in a vacuum furnace. By forging and rolling the ingot, the plate of 115mm in thickness, 3.4m in width, and 5m in length was obtained, which was hot formed with 8,000 tons press into the hemisphere. The mechanical properties examined at the flange of hemisphere are shown in Table 3.

Table 3 Result of tensile test of hemisphere

Location	Direction and position		spec.	0.2% Proof stress (kgf/mm²)	Tensile strength (kgf/mm²)	Elongation (%)	Reduction of area (%)
				≥81	≥88	≥10	-
N Hemisphere	L	Surface		89.2	97.5	17A	46
				89.2	97.2	16A	44
		1/2T		84.4	91.4	14A	23
				84.3	91.7	14A	27
	T	Surface		88.6	97.1	15A	41
				88.6	96.6	14A	38
		1/2T		86.9	94.5	14A	26
				84.7	92.5	13A	19

Specimen (ASTM E8) ϕ8.75mm, GL=35mm

2.2 Insert welding of penetrators

After the hemisphere was roughly machined, the insert welding of penetrators by Electron Beam Welding and the postweld heat treatment were carried out. The preparation for EBW is shown in Fig. 3. The configuration after the postweld heat treatment is shown in Fig. 4. The maximum tolerance from a true sphere after the Electron Beam Welding measured to be 2.7mm around the boundary of viewport coaming.

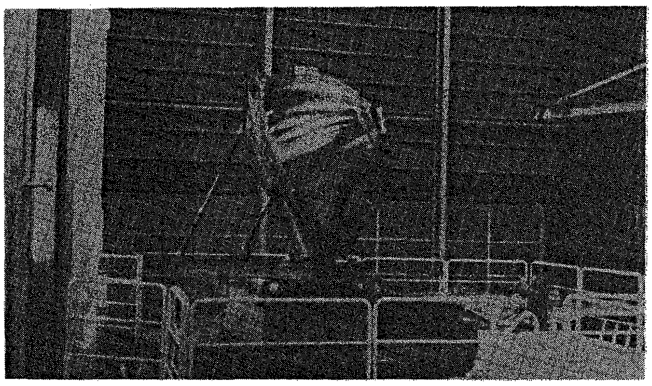
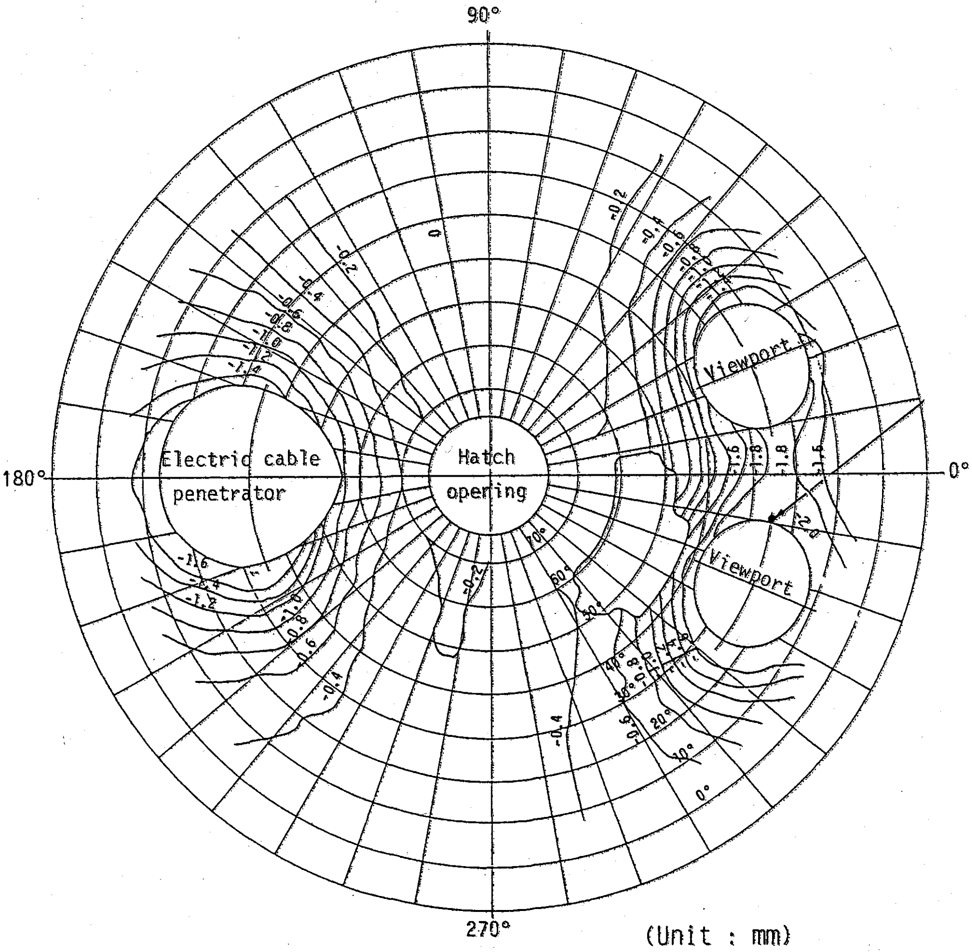


Fig. 3 Preparation for penetrator electron beam welding



(Unit : mm)

Fig. 4 Result of shape measurement of full scale model (after postweld heat treatment)

2.3 Three-dimensional machining

After the insert welding, the three-dimensional machining was carried out for the hemisphere. The outline of three-dimensional machining process is shown in Fig. 5. The machining is divided into three stages by the machining devices and position. Those are machining of sphere latitudes, of openings and reinforcements and of the local sphere of the latitudes of the reinforcements. At this stage, the surface except the equator exteria is machined to the final configuration.

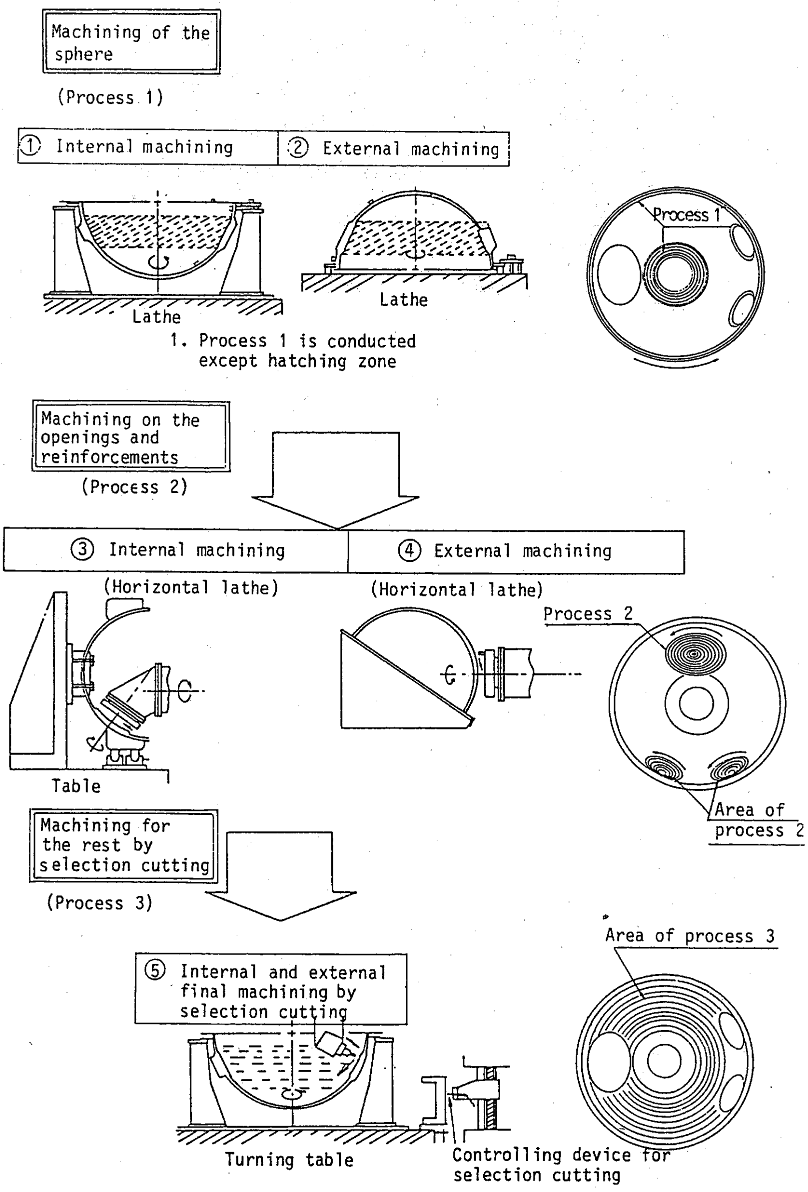


Fig. 5 Three-dimensional machining

2.4 Equator welding and final machining

After the three-dimensional machining, the equator welding was carried out by Electron Beam Welding. The final postweld heat treatment and the final machining process on the external surface of the equator zone followed. The equator welding is shown in Fig. 6. The final configuration of the model is shown in Fig. 7 and the completed model in Fig. 8. The sphericity was measured to be 1.003 and the thickness tolerance was in the range from -0.1mm to 0.3mm for sphere except the equator and 0.3mm to 0.8mm at equator zone.

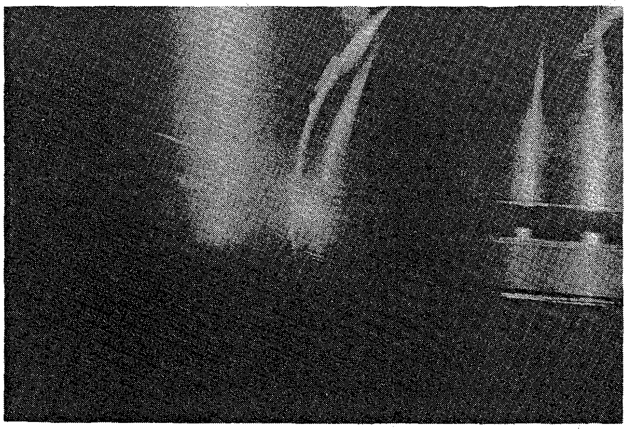


Fig. 6 Equator welding by electron beam welding method

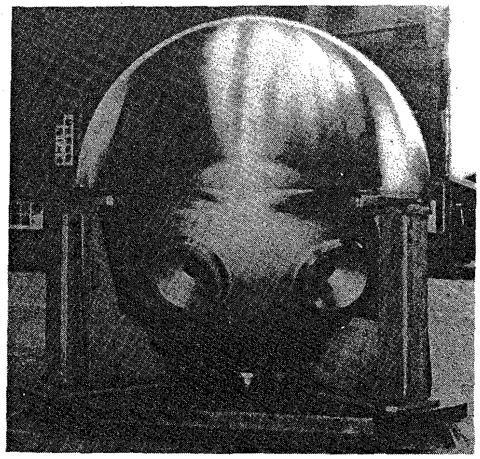


Fig. 8 Full scale model at completion

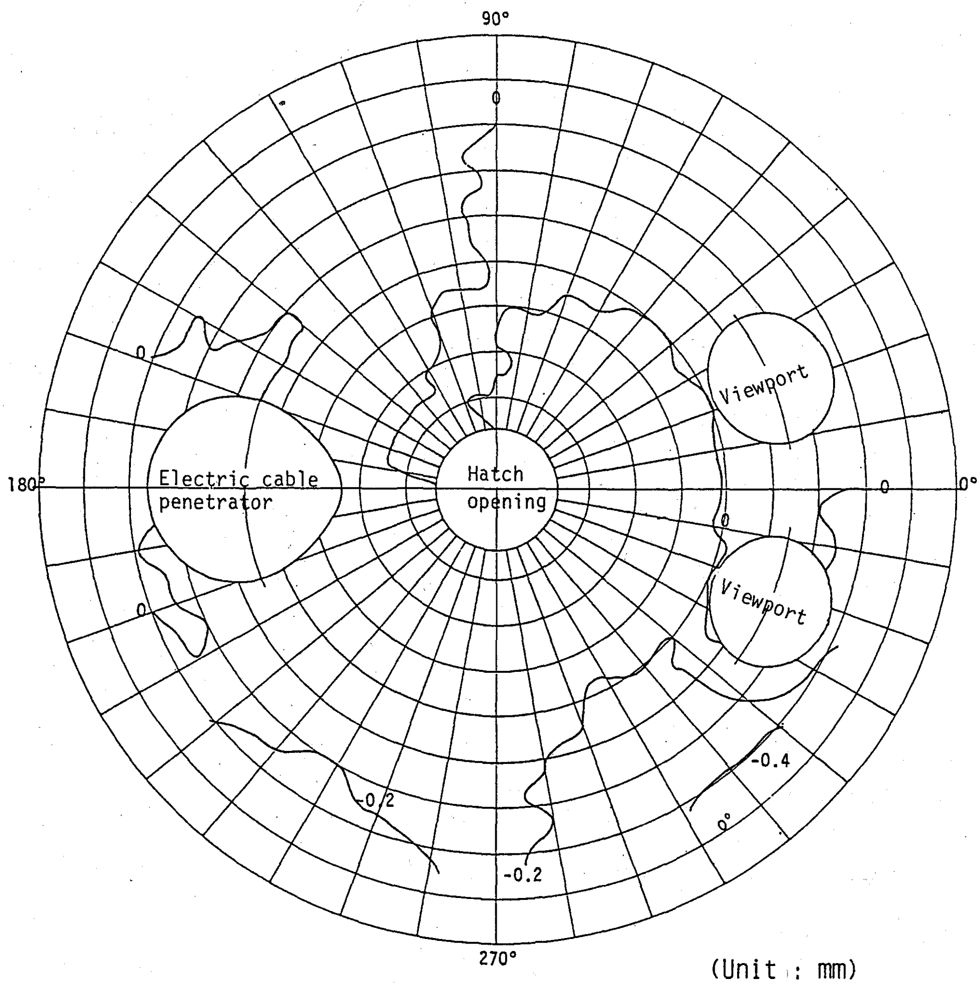


Fig. 7 Result of shape measurement of full scale model (after completion of full scale model)

3. The Evaluation of Material Characteristics

To evaluate the material characteristics, the model was cut into specimens. The test items are shown in Table 4. The major test results are as follows.

Table 4 List of evaluation test

	N Hemisphere	Electric cables penetrator	Equator joint	Penetrator joint
Tensile test of base metal	○	○	—	—
Tensile test of weld metal	—	—	○	○
Tensile test of welded joint	—	—	○	○
Bend test	—	—	○	—
Charry impact test	○	○	○	—
DT test	○	—	○	—
Fracture toughness test	○	○	○	—
SCC test	○	—	○	—
Low cycle fatigure test	○	—	○	—
High cycle fatigure test	○	—	○	—
Fatigure crack propagation test	○	—	○	—
Hardness check	○	—	○	—
Macro structure	○	—	○	○
Micro structure	○	—	○	○
Chemical analysis	—	—	○	○
Residual stress distribution	○	—	○	○

(1) Mechanical properties of welded joint are shown in Table 5, which satisfies the requirement.
(2) The result of the dynamic tear test are shown in Fig. 9. Minimum fracture toughness was obtained to be 210kgf/mm$^{3/2}$ at -20^{o}C. Considering the residual stress level (described later) measured less than 10% of 0.2% proof stress, the critical crack length was approximately 940mm, which is enough to be detected by the ordinary nondestructive test method.
(3) The results of stress corrosion cracking are shown in Fig. 10. In 3.5% NaCl water solution, the level of K_{ISCC} are 160kgf/m$^{3/2}$ for the N hemisphere base material and 165kgf/m$^{3/2}$ for the weld metal. Considering the level of K_{ISCC} to be 150kgf/m$^{3/2}$, and the residual stress level to be 10% value of 0.2% proof stress, the critical crack length is 530mm, which is enough to be detected by the ordinary nondestructive test.
(4) The level of residual stress measured is less than approximately 3kgf/mm^2 by postweld heat treatment process as shown in Fig. 11.

On the basis of the fabrication procedure and material characteristics, which satisfy the design condition, confirmed with the full scale model, the fabrication procedure for the pressure sphere of 6Al-4VELI titanium alloy is established.

Table 5 Result of tensile test of weld metal

	Welding Condition	Position	0.2% proof stress (kgf/mm²)	Tensile strength (kgf/mm²)	Elongation (%)	Reduction of area (%)
Equator joint	Regular A	Surface	88.0	97.5	12.9A	20.7
		1.4t	89.8	99.4	11.4B	16.2
		1.2t	87.9	98.2	10.7A	16.7
	Regular B	Surface	88.1	98.2	12.1B	23.3
		1.4t	88.6	98.4	11.4A	22.4
		1.2t	89.4	98.9	11.4A	21.2
	Starting and ending	Surface	88.6	99.1	12.9A	24.6
		1.4t	88.8	98.7	14.3B	25.9
		1.2t	88.8	98.3	11.4A	23.3
Pnetrator	Regular	Surface	87.5	97.4	12.9B	20.3
		1.4t	86.6	97.1	12.1A	20.7
		1.2t	85.2	94.9	11.4A	18.5
	Starting and ending	Surface	90.8	99.2	10.7A	19.3
		1.4t	89.3	99.2	9.3A	15.3
		1.2t	89.4	98.8	10.7A	18.9

specimen : ϕ4.0mm, G.L.=14mm

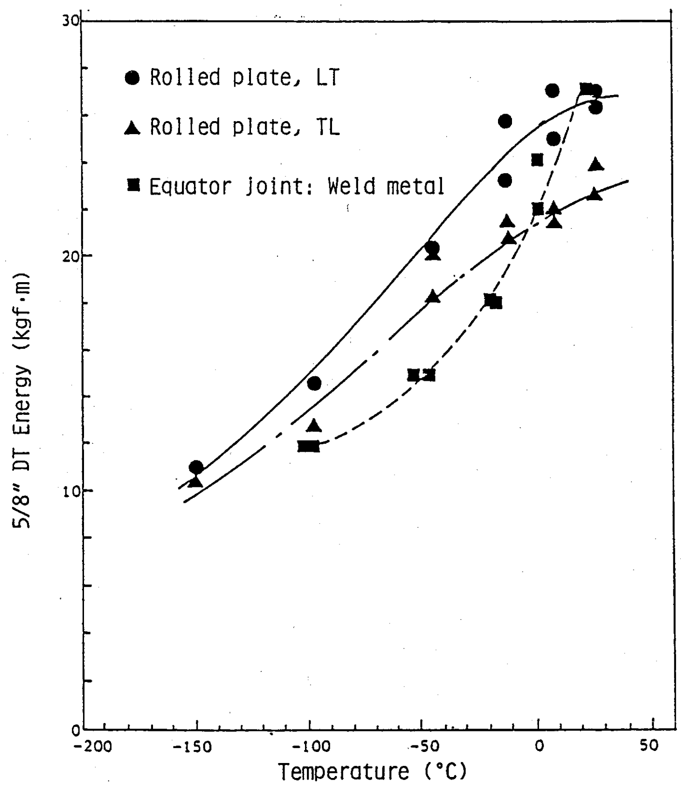


Fig. 9 Result of DT test

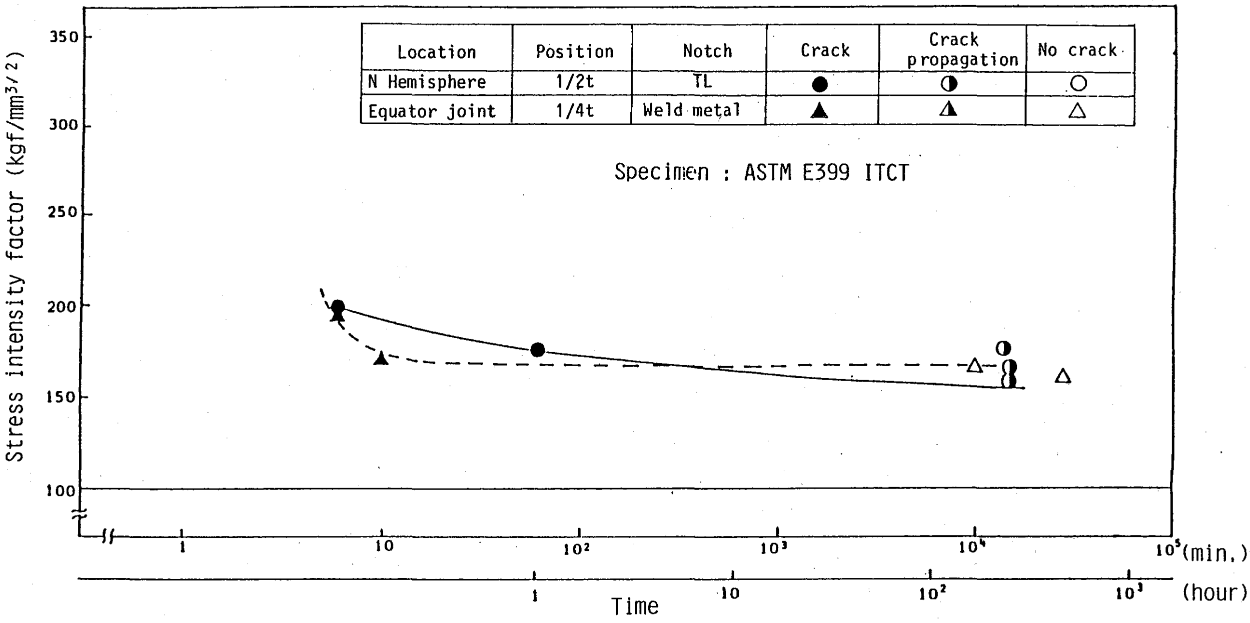


Fig. 10 Result of SCC Test

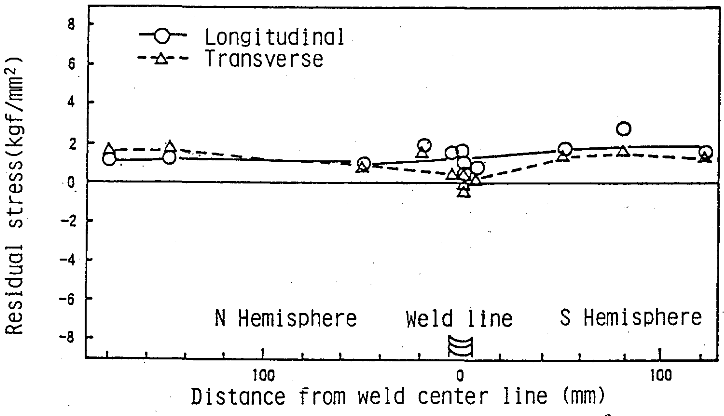


Fig.11.1 Distribution of residual stress
(Equator welded joint)

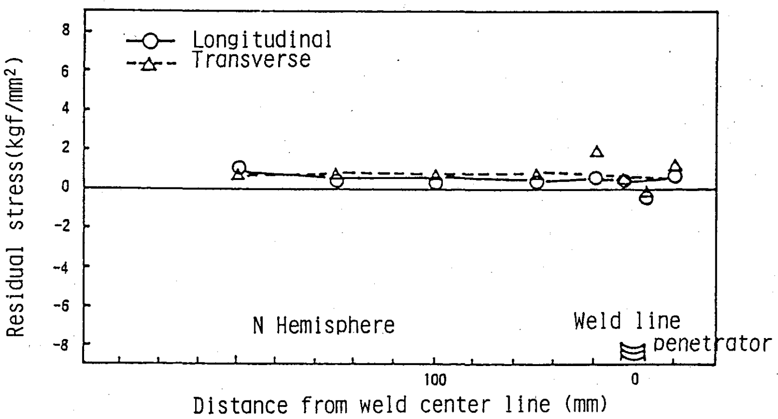


Fig.11.2 Distribution of residual stress
(Insert welded joint)

4. Collapse Strength of Pressure Sphere of Titanium Alloy

4.1 Outline of collapse models

The configuration of collapse models is shown in Table 6. The models MT-1, MT-2 and MT-3 are the sphere of 500mm in diameter and 16mm in thickness. MT-1 is a simple sphere. MT-2 is a sphere with a viewport which is pressurized to collapse after being pressurized continuously for 160 hours to investigate the effect of room temperature creep. MT-3 is sphere with a conical seat hatch to investigate the influence of a sliding behaviou around the hatch boundary. The fabrication procedure of the models is foundamentaly the same as that of the actual pressure sphere. The mechanical properties of the models are shown in Table 7 and 8.

Table 6 Spherical models of Ti-6Aℓ-4V ELI for collapse test

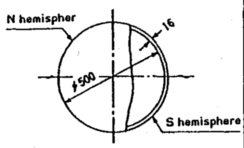
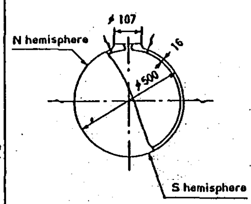
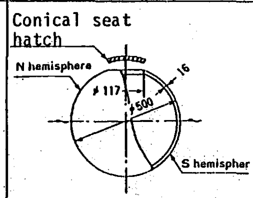
Model		MT-1	MT-2	MT-3
Outline		Simple sphere	(1) Sphere with viewport (2) Model for collapse test after 160 hours' continuous pressurizing	Sphere with conical seat hatch
Confi-gura-tion	Diameter (mm)	500 (outside)	500 (outside)	500 (outside)
	Nominal thickness (mm)	16	16	16
Model Figure (Unit in mm)				

Table 7 Tensile properties of base metal

Model	Tensile direc-tion	Sampled position	Tensile strength (kgf/mm^2)	0.2% proof stress (kgf/mm^2)	Elonga-tion (%)	Reduction of area (%)
(Specif-ication)	—	—	≧88	≧81	≧10	—
MT-1, 2 & 3	L	Center of plate thick-ness	94.1 93.8	87.2 87.2	14 13	32 34
	T		95.8 94.5	88.9 87.5	14 13	32 38

L : Rolling direction of plate
T : Perpendicular to rolling direction of plate

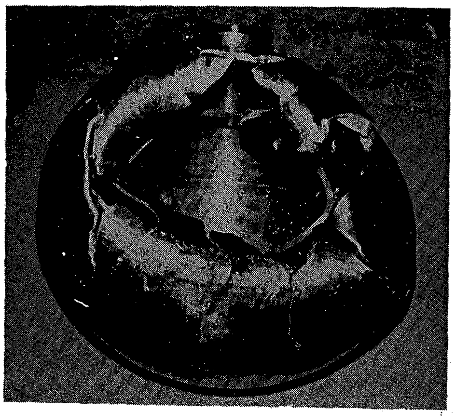
Table 8 Tensile properties of base metal

Model	Sampled position	Tensile strength (kgf/mm^2)	0.2% proof stress (kgf/mm^2)	Elongation (%)	Reduction of area (%)
(Specification)	——	$\geqq$ 88	$\geqq$ 81	$\geqq$ 5	——
MT-1,2 & 3	Center of plate thickness	100.1 99.8	86.5 85.7	11 13	30 28

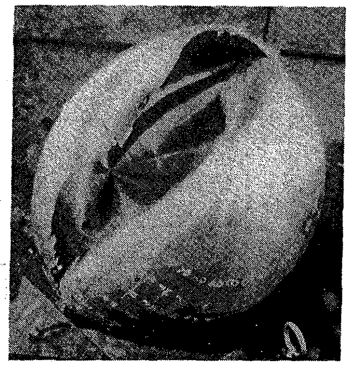
Specimens were obtained from a Ti-6Al-4VELI plate welded under the same welding condition as the actual equator joint.

4.2 Collapse test results

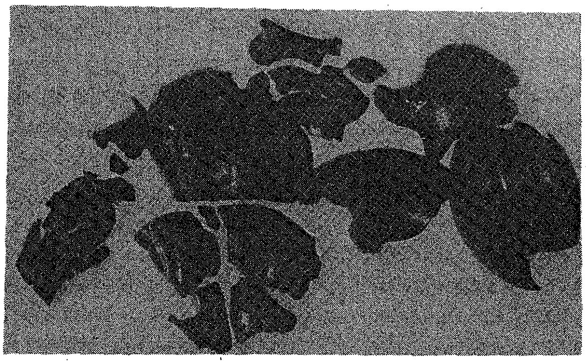
From the deformation of models after collapse, there is observed a fully deformed portion, which is caused by enough plastic deformation, over a large area and some cracks around it. The example of the models after collapse is shown in Fig. 12 compared with the models of ultrahigh strength 10Ni-8Co steel and 18% nickel maraging steel. The configuration after the collapse of the models made of titanium alloy is similar to that of 10Ni-8Co steel with enough plastic deformation which is different from the models of 18% nickel maraging steel which collapsed into pieces. From these experimental results, the spherical models made of titanium alloy can be said to collapse with enough plastic deformation, which requires sufficient toughness level for collapse. In addition, at the test of MT-2 model, differences in strain and in the sphericity between before and after the continuous pressure loading of 160 hours were not observed.



(Ti-6Al-4V ELI MT2)



(10Ni-8Co steel)



(18% Ni Maraging steel)

Fig. 12 Models after collapse

4.3 Results of collapse strength analysis

(1) The collapse strength was calculated using the tensile properties and compressive properties obtained from the specimens of the same material as the models, by Krenzke's method. The results are shown in Fig. 13. The relationship between the test result and analytical one is very close to that obtained from the collapse tests using spherical models of various kinds of ultrahigh strength steel. As a result it is proved that collapse strength can be estimated also in the case of titanium alloy by the Krenzke's method. The collapse strength was estimated by the large deflection elasto-plastic analysis using the finite element method. The result obtained by the analysis shows closer agreement than that by Krenzke's method as shown in Table 9. The relationship between pressure and displacement of MT-2 is shown in Fig. 14. The collapse initiates from any position except the viewport coaming where the maximum bending stress occurs.

(2) In order to investigate the effect of room temperature creep on the collapse strength, a creep analysis is carried out under the continuous pressure loading, by the finite element method for the MT-2. The collapse strength after the continuous pressure loading of 5,000 hours is estimated on the basis of the creep test result using the specimens obtained from the same material as the model. As for the relationship between creep strain and loading time. Norton-Bailey's law is applied. The estimated collapse strength after the continuous loading of 5,000 hours is 1,250 kgf/cm^2 on the basis of the compressive properties, which is the same pressure as that before the continuous loading. It is concluded that the continuous pressure loading has no influence on the collapse strength in the case of 6Al-4VELI titanium pressure sphere.

Table 9 Theoretical and experimental results of collapse strength

(Unit in kgf/cm^2)

Model		MT-1	MT-2	MT-3
Experiment		1230	1260	1274
Krenzke	T	1085	1112	1129
	C	1177	1207	1210
FEM	T	1150	1150	1170
	C	1220	1250	1270

T & C : Indicate the mechanical properties used for analysis obtained from tension and compression test respectively

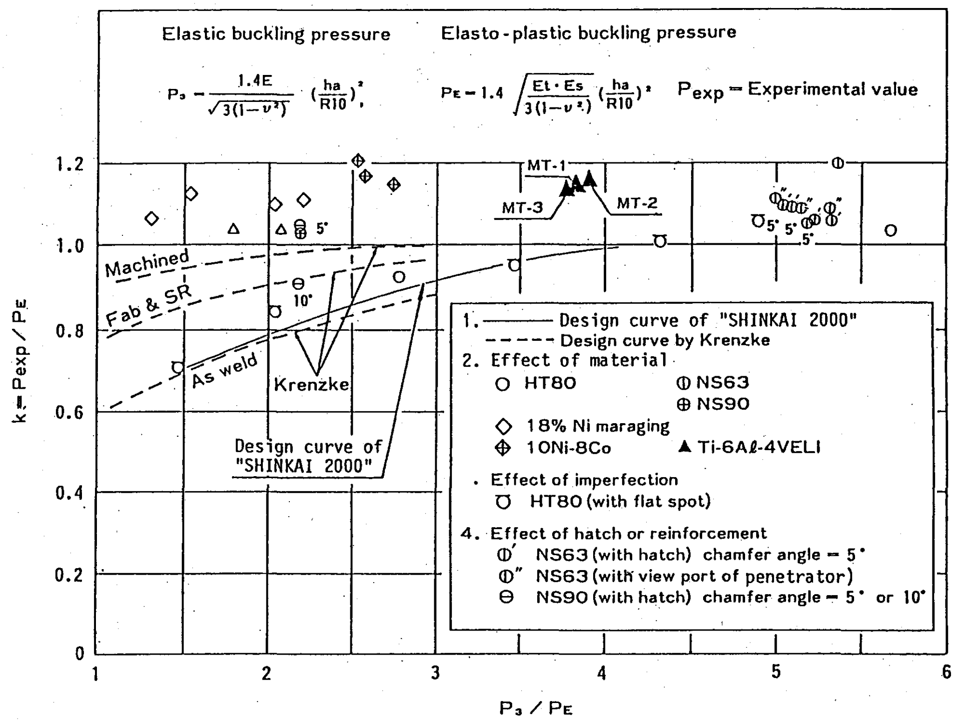


Fig. 13 Collapse test results

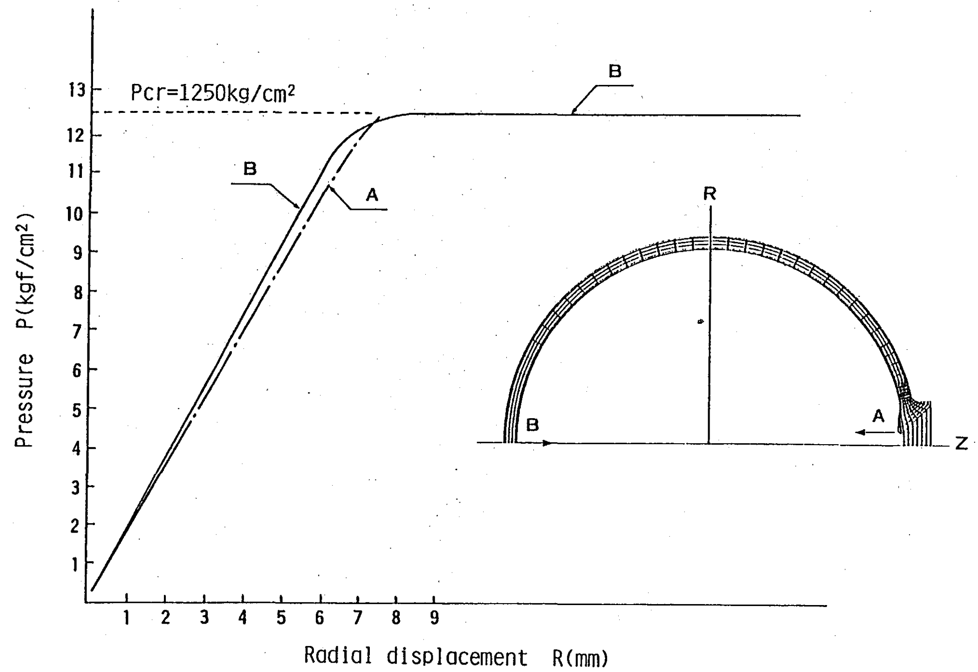


Fig. 14 Pressure - displacement Relationship

5. Materials Required for Deeper Submergence Research Vehicle

The process of the determination and confirmation of the material for the pressure sphere of 6,000m-class deep submergence research vehicle is described before. On the basis of the process, the material required for deeper (10,000m-class) submergence research vehicle are studied in this article.

5.1 Conditions for study of 10,000m-class deep submergence research vehicle.

The conditions for the study are as follows.

(1) The fabrication procedure of the pressure sphere is the same as that of the 6,000m-class.

(2) The design collapse strength is more than 1,617kgf/cm^2 which is equivalent to the depth of 15,300m (= 10,000m x 1.5 + 300m), according to the Japanese Government Regulations.

(3) Total weight of the vehicle is from 25 tons (equivalent to 6,000m-class) to 27 tons.

(4) The diameter of the pressure sphere is 1.8m. (2m for 6,000m-class)

(5) The diving and surfacing time is 3.0 hours individually. (2.5 hours of 6,000m-class).

(6) The weight except the pressure sphere, ballast systems and buoyancy material is the same as that of 6,000m-class.

5.2 Weight and buoyancy requirement for 10,000m deep submergence research vehicle

In order to surface from the depth of 10,000m in 3.0 hours, the surfacing speed is required to be 0.93 meters a second, which is approximately 1.39 times that of 6,000m-class. Considering there is no remarkable change in vehicle's configuration, the ballast weight is estimated to be 1,544 kg, which is approximately 1.93 times that of 6,000m-class. Accordingly, the weight distribution except the pressure sphere is estimated as shown in Table 10 compared with 6,000m-class. The relationship among the weight of pressure sphere, of the vehicle, the capacity, and the specific gravity of the buoyancy material is given by the Equation (1) in the case of 10,000-class.

$$\begin{aligned} W + 12.39 + \beta B &= W_V \\ V + 4.84 + B &= W_V/1.025 \end{aligned} \qquad (1)$$

V : Capacity of pressure sphere
W : Weight of pressure sphere
W_V: Weight of vehicle
B : Capacity of buoyancy material
β : Specific gravity of buoyancy material

5.3 Thickness required for collapse strength

The collapse strength of pressure sphere can be estimated on the basis of Krenzke's method as shown in Article 4.3. Considering the sphericity to be 1.004 (same as the 6,000m-class), the thickness required is obtained in the case that 0.2% proof stress is 81kgf/mm^2 (6Al-4V ELI titanium alloy), 90kgf/mm^2, 100kgf/mm^2 and 110kgf/mm^2. The results are shown in Table 11 and in Fig. 15.

5.4 Relationship between strength of material and specific gravity of buoyancy material.

Using the thicknesses obtained by Krenzke's method, the weight (W) and capacity (V) of the pressure sphere can be calculated. By substituting the weight (W) and capacity (V) into Equation (1), the level of specific gravity required for the buoyancy material is obtained when the vehicle's weight is 25 tons and 27 tons. The result is shown in Table 12, and the relationship between the 0.2% proof stress and specific gravity is shown in Fig. 16. According to these estimation, the required levels of 0.2% proof stress when the specific gravity of buoyancy material is 0.50, 0.52 and 0.54 are obtained as shown in Table 13.

Table 10 Weight distribution

	6,000m- class deep submergence research vehicle		10,000m-class deep submergence research vehicle	
	Weight (t)	Buoyancy (m^3)	Weight (t)	Buoyancy (m^3)
Exostructure, tank etc.	3.00	1.78	3.00	1.78
Electric power system	3.36	1.85	3.36	1.85
Propulsion system	0.42	0.13	0.42	0.13
Hydraulic system	0.49	0.21	0.49	0.21
Ballast system	1.96	0.39	2.7	0.49
Navigation and communication system	0.50	0.07	0.50	0.07
Research and observation system	0.68	0.15	0.68	0.11
Environment control system, crew and others	1.24	0.16	1.24	0.16
Total	11.65	4.74	12.39	4.84

Table 11 Calculation result of thickness

0.2% proof stress (kgf/mm^2)	81	90	100	110
Proportional limit (kgf/mm^2)	60.75	67.5	75	82.5
Young modulus (kgf/mm^2)	11500			
Poison's ratio	0.3			
Inside radius (mm)	900			
Thickness (mm)	107	95	86	80

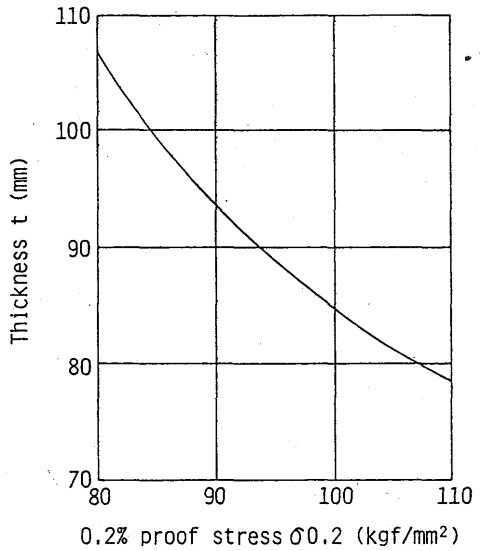


Fig.15 Relationship between 0.2% proof stress of material and thickness of pressure sphere (Inside diameter = 1.8m)

Table 12 Calculation result of specific gravity

0.2% proof stress (kgf/mm²)		81	90	100	110
Pressure hull	Weight (ton)	6.22	5.45	4.89	4.52
	Buoyancy (m³)	4.32	4.17	4.05	3.98
Ballast system	Weight (ton)	12.39			
	Buoyancy (m³)	4.84			
Summary	Weight (ton)	18.61	17.84	17.28	16.91
	Buoyancy (m³)	9.16	9.01	8.89	8.82
Specific gravity of buoyancy material at the total weight 25 tons		0.420	0.466	0.498	0.520
Specific gravity of buoyance material at the total weight 27 tons		0.488	0.529	0.557	0.576

Table 13 Calculation result of 0.2% proof stress

	Specific gravity of buoyance material		
	0.50	0.52	0.54
0.2% proof stress at total weight 25 tons (kgf/mm²)	100.8	110	—
0.2% proof stress at total weight 27 tons (kgf/mm²)	83.2	87.6	93.0

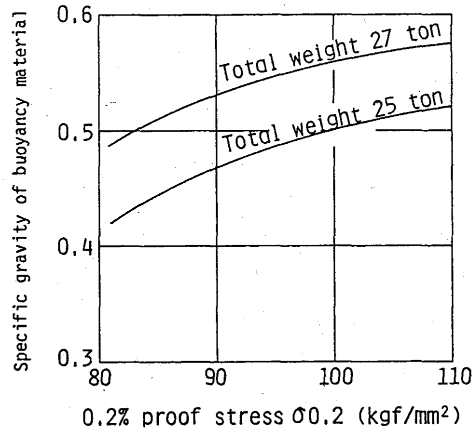


Fig. 16 Relationship between 0.2% proof stress and specific gravity of buoyancy material

6. Conclusion

(1) The technical process for the decision and confirmation of the material for the pressure sphere of 6,000m-class deep submergence research vehicle, which includes weight consideration, material characteristics, fabrication procedure, and collapse behaviour, is described.

(2) Following the process, the requirement for the materials of the pressure sphere and the buoyancy material for 10,000m-class deep submergence research vehicle is studied.