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Application of Titanium to Ocean Development — A Challenge to Water Depth of 10,000 m —

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Abstract:

Application of titanium to ocean development has been centered on such a speciality field as deep-sea exploration. Recently, however, titanium has come to attract increasing attention in general ship and fishery applications. This report describes the concepts underlying the utilization of the physical properties of titanium in ocean development, introduces some cases of titanium application in ocean development, and outlines the manufacturing process, quality, and other aspects of the pressure vessel and frame supplied by Nippon Steel for the 10,000-m deep-sea unmanned exploration vehicle ''Kaiko''. Reference is made also to such other equipment supplied by Nippon Steel as the water sampling rope and conductivity, temperature and depth (CTD) observation cable for the oceanographic research ship ''Hakuho Maru'' of the Ocean Research Institute, University of Tokyo.

1. Introduction

Titanium has a long history and wide scope of usage in the marine field. Its applications may be grouped into three main categories where:

(1) Merits of titanium properties, light weight and high strength, in particular, more than offset its economic drawback (deep-sea exploration and development)
(2) Seawater resistance, the best property of titanium, is utilized to the utmost extent (heat exchangers and snorkels)
(3) Various other properties of titanium in addition to its light weight, high strength and seawater resistance are utilized in miscellaneous applications (fishing banks, screws, and riser pipes).

Titanium has been traditionally used in such specialized field as deep-sea exploration. Recently, however, it has come to draw increasing attention from shipbuilding and fishery industries. The current situation of titanium use is briefly described below.

2. Ideas Behind Utilization of Titanium Properties and Examples of Titanium Application in Marine Engineering Field[1)]

2.1 Utilization of combined physical properties

There is a wide field of application in which the three principal properties of titanium (seawater resistance, light weight, and high strength) are utilized in combination.

The combination may vary as follows:

(1) Utilization of seawater resistance, light weight, and high strength combined

High-speed craft that travel clear of the water by use of hydrofoils, for example, require material properties similar to those aircraft do. The high specific strength of titanium alloys is best exploited in this application. Cables for measuring conductivity, temperature, and depth (CTD) in very deep seas can be made only from titanium with its high specific strength.

(2) Utilization of light weight and high strength combined

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The pressure hull and drive shaft of deep-sea submersible craft are relatively thick and can withstand the applied stress, and do not need very heavy protection against corrosion. Therefore, titanium alloys with their high specific strength are used in this application. Typical examples are the manned deep-sea submersible craft "Shinkai 6500" and the unmanned deep-sea exploration craft "Kaiko".

(3) Utilization of light weight and corrosion resistance combines

Low-stress and light-section structures are required to possess some degree of stiffness, but not such high strength as in the applications mentioned above. Among such examples are the manned deep-sea submersible craft "Shinkai 2000" and the unmanned deep-sea exploration craft "Dolphin 3K".

2.2 Utilization of corrosion resistance

Titanium is used in marine heat exchangers using seawater as coolant, let alone its use in on-land heat exchangers. Submarine snorkels where hot exhaust gas and seawater coexist are exposed to an extremely corrosive environment and have been traditionally made from titanium.

2.3 Utilization of nontoxity

Titanium is an excellent biomedical material from which no metallic ions are dissolved and is used in medicine and surgical implants. Nontoxity is a property necessary for submarine structures to attract and nurture marine organisms (fishing banks). When titanium is immersed in seawater, many marine organisms deposit on its surface.

2.4 Utilization of nonmagnetism

Titanium somewhat lags behind aluminum in nonmagnetism, but its magnetism is one-tenth to one-hundredth of that of stainless steels. The all-titanium submarines of the former Soviet Union make use of this property.

2.5 Utilization of surface slipperiness

Since titanium is covered with a tight titanium oxide, foreign matters find it difficult to stick fast to its surface. Utilization of this property is under study for repelling snow, ice, and marine organisms from titanium alloy structures.

2.6 Utilization of low Young's modulus

The recent trend in oil drilling from a sea bottom of 300 m or deeper is to install, drilling risers (609.6 mm in outside diameter) made of titanium alloy in order to prevent interference with production risers that are made of steel (254 mm in outside diameter).

The properties and applications of titanium are schematically shown in **Fig. 1**.

3. Nippon Steel's Titanium Products Challenging Very Deep Seas

Table 1. lists Nippon Steel's titanium products challenging the mysteries of very deep seas down to 10,000 m. They will help the unmanned deep-sea exploration craft "Kaiko" to explore the mysterious deep-sea world and transmit television images from the depth of 10,000 m for the first time in the world. They are introduced below.

3.1 Pressure vessels and frame of unmanned exploration craft "Kaiko"'s vehecle

The Japan Marine Science and Technology Center decided on the development of the unmanned exploration craft "Kaiko" for the purpose of investigating the mysterious deep sea of 10,000 m with the latest in technology and completed it in 1993. The configuration of its 10K subsystem is illustrated in **Fig. 2**. The Kaiko is designed mainly for: (1) scientific survey of deep seas; and (2) rescue of manned deep-sea submersible craft in case of

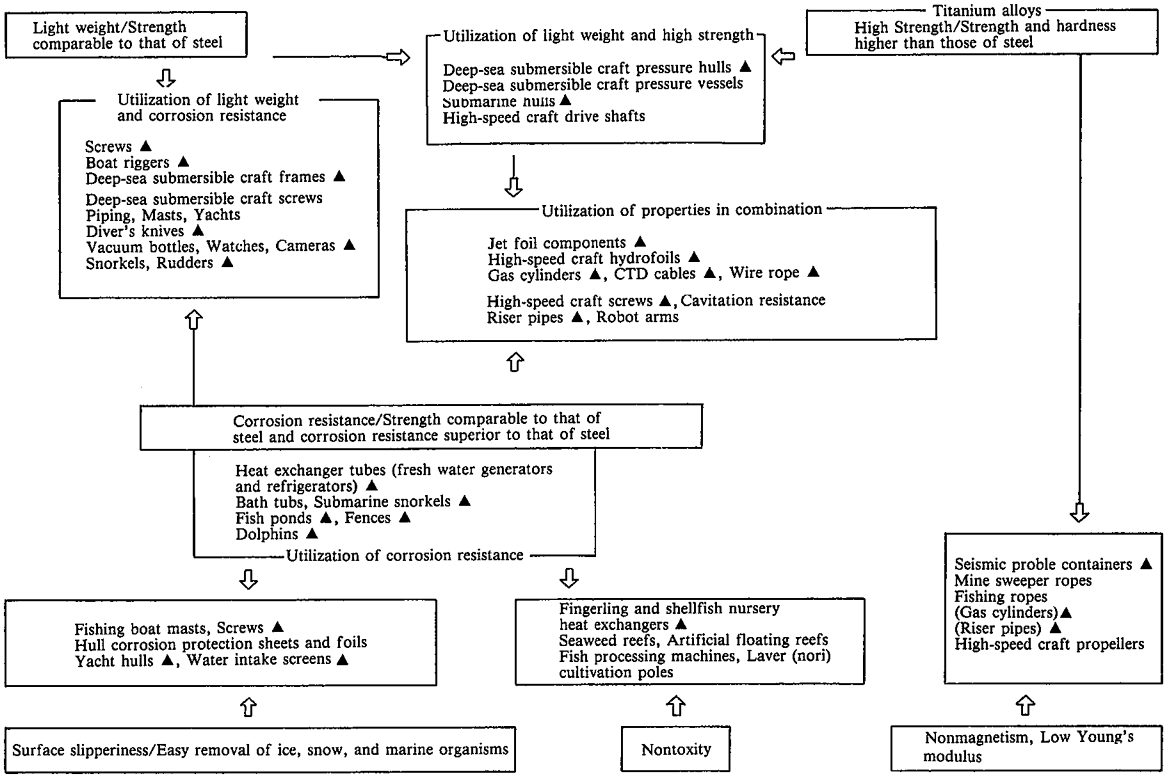

Fig. 1 Titanium properties and applications (▲ Applied or tested)

Table 1 Nippon Steel's titanium products used in challenging mysteries of very deep sea at 10,000 m

	Product	Customer	Delivered	Observation
1	Unmanned exploration craft "Kaiko" • Pressure vessels for vehicle • Frame for vehicle	Mitsui Engineering & Shipbuilding/Japan Marine Science and Technology Center	February 1992	Mariana Trench and Challenger Cliff in March 1994
2	Oceanographic research ship "Hakuho Maru" • CTD cable • Water sampling rope	Ocean Research Institute, University of Tokyo	 1991 1989	Mariana Trench and Challenger Cliff (10,966 m) in December 1992

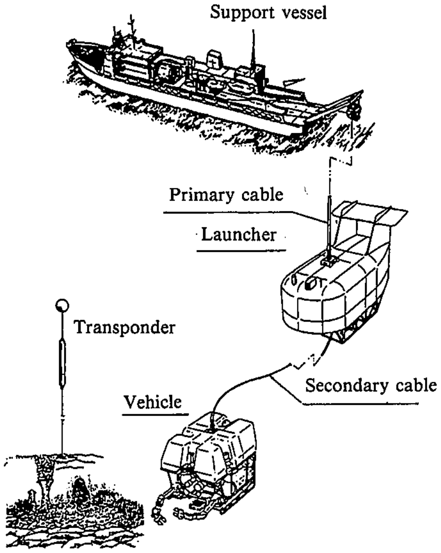

Fig. 2 Schematic illustration of 10K subsystem of deep-sea survey system

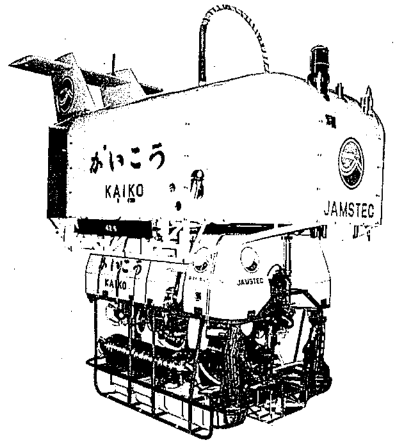

Photo 1 General view of "Kaiko" (courtesy of Japan Marine Science and Technology Center)

trouble[2,3].

The Kaiko consists of a launcher (underwater launching pad) and a vehicle (free-swimming survey craft capable of descending to a maximum depth of 11,000 m). Nippon Steel fabricated the pressure vessels and frame of the vehicle. The general view of the "Kaiko" is shown in **Photo 1.**

3.1.1 Pressure vessels

A pressure vessel was made from the Ti-6Al-4V alloy in a preliminary development test[4]. According to the test results, two pressure vessels, namely, the communication control vessel and the power supply vessel, were fabricated. They were basically the same in specifications. The basic specifications are as given in **Table 2.** Each pressure vessel was machined from a round forged bar and built giving considerations to: (1) the method and conditions to obtain a homogeneous metallurgical structure over a large section; (2) the chemical composition and heat treating method to obtain the desired strength; and (3) the machining method with fail-proof accuracy.

(1) Fabrication process

The fabrication process is outlined in **Fig. 3.**

(2) Fabrication results

(i) Chemical composition

Table 3 gives the main chemical constituents of the Ti-6Al-4V alloy. High aluminum and vanadium contents were aimed at to obtain strength higher than that in the development test stage. A maximum possible oxygen content was obtained as originally aimed at.

(ii) Forging

An ingot must be forged directly into a round bar measuring

Table 2 Basic specifications of pressure vessels

Design conditions
(1) Pressure
Maximum operating pressure: 113.75 MPa
Collapse pressure: 147.77 MPa
(2) Test pressure: 119.64 MPa
Material specifications
(1) Material: Ti-6Al-4V
(2) 0.2% yield strength: ≥ 835 N/mm^2 (Aim: ≥ 880 N/mm^2)
(3) Tensile strength: 880 N/mm^2 (Aim: ≥ 980 N/mm^2)
(4) Elongation ≥ 10%
(5) Young's modulus: ≥ 110,620 N/mm^2

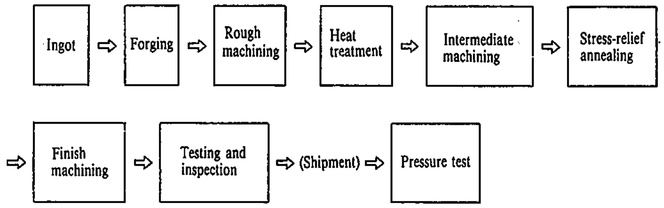

Fig. 3 Fabrication process of pressure vessels for vehicle

Table 3 Chemical composition of pressure vessel material (main elements only)

(wt%)

Element	Al	V	Fe	O	H
Specified (as per AMS 4928)	5.50-6.75	3.50-4.50	≤0.30	≤0.20	≤0.0125
Measured	6.44	4.13	0.14	0.19	0.0024

about 470 mm in diameter, and machined. To achieve micro-structural grain refinement and homogeneity three dimensionally a large ingot measuring about 830 mm in diameter and weighing about 5 tons was used. Since stretch provided only a small reduction of area at about 68%, upsetting and stretch were repeated at high temperatures in the β region, followed by stretch in the $\alpha + \beta$ region, in order to obtain a homogeneous microstructure. The method of forming equiaxed α grains was incorporated in the middle of stretch and in the final step (forging was performed at Japan Casting and Forging Corporation). **Photo 2** shows the microstructure of a portion corresponding to a cylindrical shell. An extremely homogeneous microstructure was obtained also in other portions and directions.

(iii) Machining

According to the findings obtained in the development test, machining operations were efficiently carried out with proper scheduling and jig and tool selection. Machining was performed entirely on a numerically controlled (NC) lathe. Since no retouching was allowed, machining was performed most carefully. As a result, the pressure vessels were fabricated to very close dimensional tolerances as evident from **Table 4. Photo 3** shows the general view of the finish-machined pressure vessels.

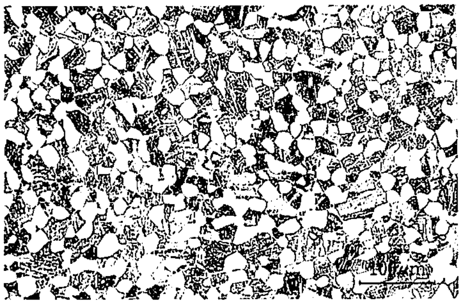

Photo 2 Microstructure of part corresponding to cylindrical shell

Table 4 Measured results of representative parts

Part	Item	Reference value (mm)	Tolerance (mm)	Measured value (mm)
Shell	Wall thickness	30	±0.5	−0.05 to +0.15
	Inside diameter	280	±0.5	+0.01 to +0.06
End plate	Wall thickness	35	±0.5	+0.01 to +0.07
	Inside diameter	280	±0.5	−0.04 to 0
	Height	168	±0.5	+0.01 to +0.03

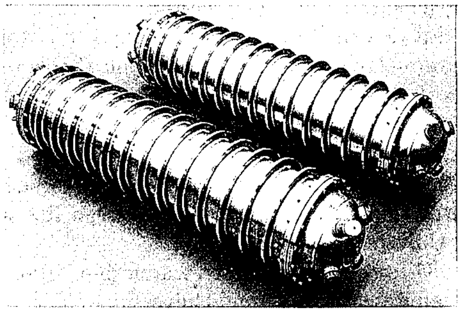

Photo 3 General view of pressure vessels (shell length of 1,400 mm)

(iv) Heat treatment and mechanical properties

The pressure vessels were solution treated and overaged (STOA) (heated at 940°C for 2 h, water quenched held at 720°C for 2 h, and air cooled) to ensure high strength. A furnace modification was made to minimize the time lag until the start of water quenching. Stress-relief annealing was performed at 540°C for 4 h, followed by air cooling. The mechanical test results of the pressure vessels are presented in **Table 5**. As indicated, homogeneous and stable mechanical properties were obtained.

(v) Pressure test

After internal quality and surface inspection, the pressure vessels were delivered to Mitsui Engineering & Shipbuilding Co., Ltd. that had ordered them. They were then pressure tested in a high-pressure water tank at the Japan Marine Science and Technology Center. When exposed to pressure of up to 119.64 MPa, the pressure vessels did not deform, nor did they develop any leak, proving that they can withstanding a water depth of 11,550 m.

3.1.2 Frame

The vehicle must be lightweight and built of high-strength members to ensure its maneuverability. JIS Class 3 and ASTM Grade 4 round and square pipes were used as its members. A new filler metal, designated TIX-80 and specially developed for this project, was used to make high-strength welds. The chemical composition of TIX-80 is given in **Table 6**, and the test results of welds using TIX-80 are presented in **Table 7**.

Weldability was as good as that of commercially pure titani-

Table 5 Results of mechanical test

Part/Direction	0.2% YS (N/mm^2)	TS (N/mm^2)	El (%)	RA (%) (Reference)
Power supply vessel	893-947	963-1,003	11.8-16.6	28.1-37.0
Communication controller vessel	905-949	979-1,009	12.8-16.2	30.1-36.0
Specification	≥835	≥880	≥10	—

(Maximum value to minimun value of 8 measurements made in three directions, inciding both shell and end plate)

Table 6 Chemical composition of TIX-80 (wt%)

Material	Type	Size (mm)	O	N	Fe	C	H	Ti
Base metal	TIX-80	20t	0.21	0.05	0.50	0.014	0.0006	Balance
Filler metal	TIX-80	1.6φ	0.20	0.05	0.54	0.014	0.0023	Balance
Weld metal			0.29	0.042	0.51	0.014	0.002	Balance

Table 7 Test results of welds

Test item	Weld metal evaluation
Weld metal chemical analysis	H: 0.002%, N: 0.042%
Hardness test	Hv: 251-281
Macrostructure and microstructure	Sound
Short-gage tensile test	σ_B: 718 N/mm^2
Impact test	${}_{v}E_{20^\circ C}$: 40 J
Bend test (face bend and side bend)	Roller bend (R = 5t), good

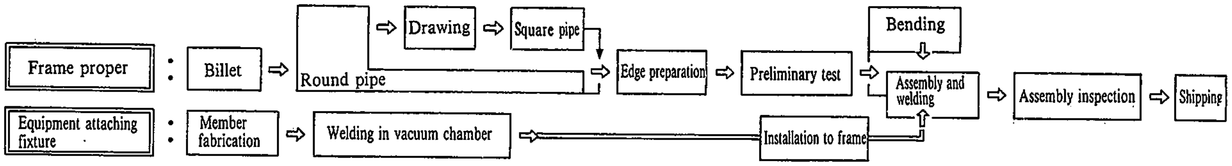

Fig. 4 Schematic diagram of fabrication process

Table 8 Structural members

Component	Number of members			Number of welds	
	Material	Shape	Total quantity	Number of joints	Total length
Frame proper	ASTM Grade 4	40□ 40ϕ	40.6 m 21.9 m	226	36.66 m
	JIS Class 3	40□ 40ϕ	15.4 m 15.7 m		
	Ti-6Al-4V	Plate	24.3 kg	24	5.44 m
Equipment attaching fixture (204 parts)	JIS Class 2	□, plate, ϕ, L	428	523	54.88 m
Total				773	96.98 m

um, and bend test results and joint tensile performance were also good. **Fig. 4** schematically shows the frame fabrication process, and **Table 8** the frame members.

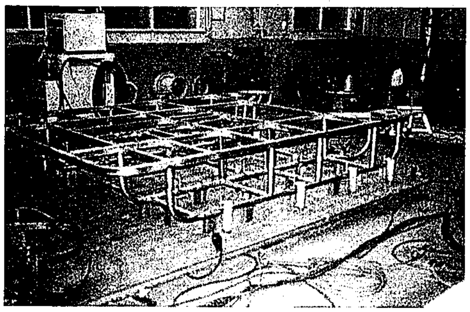

Photo 4 Frame being assembled

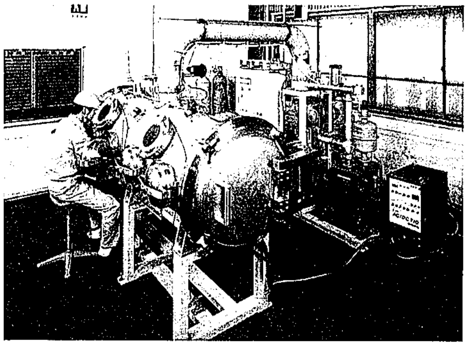

Photo 5 Weld being made in vacuum chamber

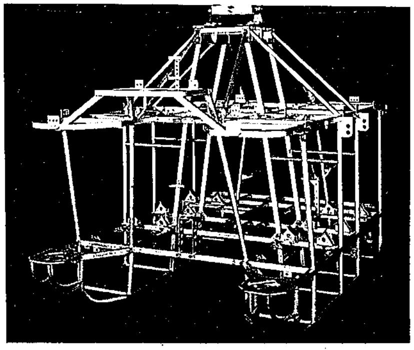

Photo 6 Outside view of completed frame

Table 9 Dimensional tolerances and total weight

Item	Reference value (mm)	Tolerance (mm)	Measurement (mm)
Height	2,130	±4	−0.5 to +1
Width	2,000	±4	−4 to −1
Length	2,750	±4	−2 to 0
Weight	Predicted: 250 kg		247 kg

Table 10 Mechanical properties of main members

Property	0.2% yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
Specified value	≥ 483	≥ 550	≥ 15
Base metal	520	686	20
Welded joint strength	—	657	—

Example of square pipe (equivalent to ASTM B 348 Grade 4): 40 × 40 × 13

The frame members were welded in a clean room (protected against wind and dust) by a titanium welding technician under the supervision of a welding technology engineer to obtain sound welds. Many shielding jigs befitting the weld structure were devised and used in back shields and weld positions. Welds were also made at low heat input and low interpass temperature to ensure the desired performance and dimensional accuracy of joints. The frame blocks were restrained and assembled on a flat plate and were welded in a symmetrically alternate pattern to prevent welding strains. **Photo 4** shows the frame being assembled. To ensure the complete shielding of tight welds, frame members were placed in the chamber as shown in **Photo 5** and then welded after evacuation and filling with argon gas.

A general view of the completed frame is shown in **Photo 6.** The dimensional tolerances and total weight all met the standard values (see **Table 9**) and attested to the good assembly accuracy of the frame. Mechanical properties also fully met the specification, as shown in **Table 10.**

3.2 Water sampling rope and CTD cable for oceanographic research ship "Hakuho Maru" of Ocean Research Institute, University of Tokyo

The 3,987-ton oceanographic research ship "Hakuho Maru" of the Ocean Research Institute, University of Tokyo, was completed in 1988. The Hakuho Maru adopted the world's first long deep-sea titanium wire rope and titanium alloy-armored cable. The wire rope and cable were made and supplied by Nippon Steel and its colleagues[5)]

3.2.1 Water sampling titanium rope

Table 11 gives the specifications of the water sampling titanium rope.

(1) Manufacturing process

Fig. 5 outlines the manufacturing process of the water sampling titanium rope.

(2) Manufacturing results

(i) Size of wire rope

The titanium rope was made to a diameter of 6.51 mm with three strands of seven 1.15-mm diameter wires each. The wires were laid into the strand by S-lay, and the strands were laid into the rope by Z-lay.

(ii) Chemical composition and mechanical properties of wire rope material

The wire rope was made of high-strength commercially pure titanium (equivalent to ASTM Grade 4). **Tables 12** and **13** give the chemical composition and mechanical properties of the titanium wire rope, respectively. The breaking strength of the completed wire rope was 24,320 N, which met the specified value of 23,500 N or more.

(iii) Other properties

Wire ropes must be evaluated for kink due to rotation under load and for durability against friction with the sheave. Against the former problem, the wire rope was controlled to rotate very slightly in the positive (tightening) direction by the lay make up and the locked process. **Fig. 6** shows the rotation test results of the wire rope. Against the latter problem, the oxygen-diffused layer or alpha case, which may degrade the fatigue resistance of the wire rope, was completely removed from each wire in the intermediate stage, and the wire rod was rolled without oxide layer. This precaution provided good results of fatigue test by loaded cyclic bending on the sheave, as shown in **Fig. 7.**

Table 11 Specifications of titanium wire rope

Item	Specification
Outside diameter (mm)	6.40 + 0.26, − 0
Construction (wire diameter)	3 × 7 (1.15 mm)
Lay direction (wire/strand)	Z-lay/S-lay
Lay pitch	9 to 12 times outside diameter
Tensile strength (N)	≥ 23,500
Length (m)	≥ 12,000

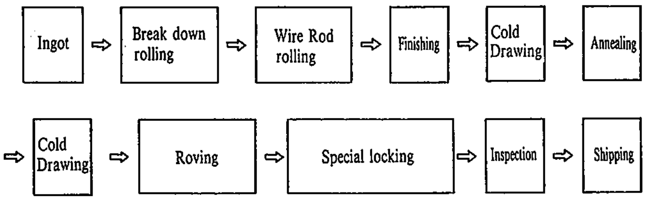

Fig. 5 Manufacturing process of titanium wire rope

Table 12 Chemical composition of wire rope titanium (wt%)

Element	O	Fe	N	H	Remarks
Specified	≤ 0.40	≤ 0.50	≤ 0.050	≤ 0.0125	Equivalent to ASTM Grade 4
Measured	0.35	0.43	0.004	< 0.01	

Table 13 Mechanical properties

Property	Rod (6.0mmφ)				Wire(1.15mmφ)
	0.2% YS (N/mm^2)	TS (N/mm^2)	El (%)	RA (%)	TS (N/mm^2)
Target	≥ 480	≥ 550	≥ 15	≥ 25	≥ 1,180
Measured	627-677	755-794	28-33	44-51	1,333-1,451

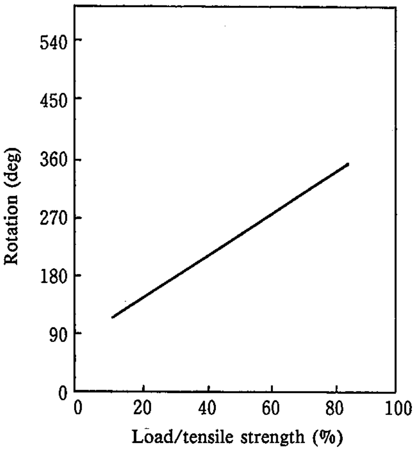

Fig. 6 Results of rotation test (measured length: 2,000 mm)

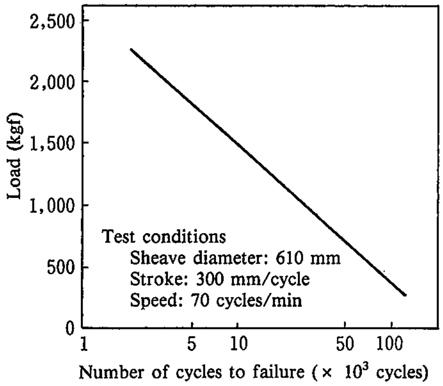

Fig. 7 Results of fatigue test by loaded cyclic bending on sheave

3.2.2 CTD titanium alloy cable

A 12,000-m long cable having annealed copper wire strand conductors armored with wires of the high-strength b titanium alloy Ti-3Al-8V-6Cr-4Mo-4Zr (socalled Beta C) was supplied by Nippon Steel and its colleagues[6,7)]. For more details, refer to "Manufacturing Technology and Application of Titanium Alloy Wire Rod for Deep-Sea Cable" in this issue of the Nippon Steel Technical Report.

4. Conclusions

The world's deepest Challenger Cliff is located at 320 km south of Guam, the southernmost of the Mariana Islands in the West Pacific. It is claimed to be about 11,000 m deep.

Japan's deep-sea submersible craft "Kaiko" with main components made from Nippon Steel's titanium products was reported to have reached the depth of 10,909 m on March 10, 1994 (broadcast on an NHK TV program on March 28). These titanium products still remain a technical symbol and are not for popular use, but certainly have stimulated the exploratory imagination of those concerned. For the maritime nation Japan, ocean engineering is an important thesis which is expected to grow in diversity, sophistication, and complexity. As it expands its scope three-dimensionally, titanium will find mounting demand for its aptitude for this particular field of application.

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